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Constraining Secluded Dark Matter with White Dwarfs measurements

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Secluded Dark Matter Particles

- Secluded DM particles, χ, interact with SM particles through a metastable mediator Y
- Secluded DM which provides a source of γ's in the Galactic Center and Dwarf Spheroidal Galaxies:
  I. Z. Rothstein, T. Schwetz and J. Zupan, JCAP 0907 (2009) 018 (long lived mediators), S. Profumo et al., JCAP 03 (2018) 010 (short lived mediators)
- Secluded DM which annihilates into long lived mediators which provide γ's in the Sun:
  B. Batell et al., Phys. Rev. D 81 (2010) 075004, R. K. Leane et al., Phys. Rev. D 95 (2017) 123016
- Secluded DM which annihilates into long lived mediators which provide ν's in the Sun:
  N. F. Bell and K. Petraki, JCAP 04 (2011) 003, R. K. Leane et al., Phys. Rev. D 95 (2017) 123016

Fermionic Secluded Dark Matter

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- $m_Y \lesssim m_\chi$
- Main annihilation channel (on-sell) $\chi\bar{\chi} \to YY$ with the subsequent decay $Y \to \gamma\gamma$
- Mostly model independent framework
- Depending on the Y lifetime, $\tau = \gamma_Y \tau_{rest}$, these particles will be long lived or short lived$\Rightarrow$ differences in the predicted indirect signal, $\gamma_Y = \frac{1}{\sqrt{1-v_Y^2}}$ Lorentz factor and τ_{rest} the lifetime at rest
- $\tau_{rest} < 1\ s$ to avoid nucleosynthesis constraints

Fermionic Secluded Dark Matter. Constraints

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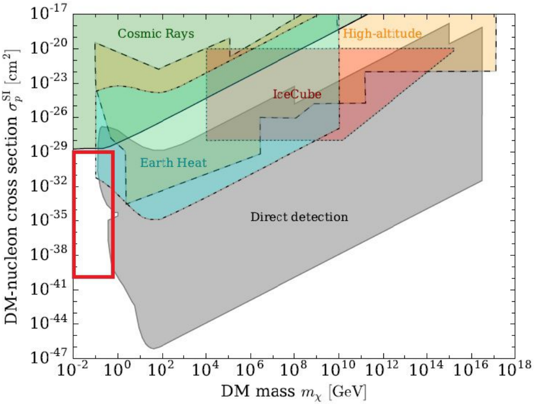
- Fermionic Light Dark Matter, $0.005\ \mathrm{GeV} \lesssim m_\chi \lesssim 1\ \mathrm{GeV}$
- DM-nucleon cross section $10^{-40}\ \mathrm{cm}^2 \lesssim \sigma_{\chi,N} \lesssim 10^{-29}\ \mathrm{cm}^2$, SIMPs

B. J. Kavanagh, arXiv:1712.04901



Accretion of DM by White Dwarfs

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- WDs are compact objects mostly made of C and O, $\rho_c \sim (10^4 - 10^7)\ \mathrm{g/cm^3}$
- Central pressure due to degenarate electrons
- WDs in the globular cluster M4, $R \sim (10^{-3} - 2.5\ 10^{-2}) R_\odot$ and $M \simeq (0.2 - 1.4) M_\odot$, large $\sim GM/R$
- The capture rate at a given local DM mass density ρ_χ,

$$\Gamma_{\mathrm{capt}} = \frac{\sqrt{24\pi} G \rho_\chi M R}{m_\chi \bar{v}} f_{\chi,A} \left[1 - \frac{1 - e^{-B^2}}{B^2}\right]$$

J. Bramante, Phys. Rev. Lett. 115 (2015) 141301

- $\sigma_{\chi,A} \gtrsim \sigma_{\mathrm{sat}} \Rightarrow f_{\chi,A} = 1$, otherwise $f_{\chi,A} \sim \frac{\sigma_{\chi A}}{\sigma_{sat}}$. $\sigma_{\mathrm{sat}} = \frac{\pi R^2 m_A}{M}$ geometrical cross section, $\sigma_{\chi,A} \simeq A^2 \sigma_{\chi,N}$ DM-nucleus cross section, A the baryonic number, $m_A = A m_N$ the nucleus mass, m_N the nucleon mass
- $\bar{v} \sim 20\ \mathrm{km/s}$ the WD velocity dispersion for $\rho_\chi = 798\ \mathrm{GeV/cm^3}$, (M. McCullough and M. Fairbairn, PRD 81 (2010) 083520)
- $B^2 = \frac{6 m_\chi v_{\mathrm{esc}}^2}{m_A \bar{v}^2 \left(\frac{m_\chi}{m_A} - 1\right)^2}$, $v_{\mathrm{esc}} = \sqrt{\frac{2GM}{R}}$ the scape velocity

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- The number of DM particles in the WD

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

- No evaporation effects, only important for $m_\chi \lesssim 2$ MeV for $T_c \sim 10^6$ K
- $\Gamma_{\rm ann} = \frac{1}{2}\int d^3\vec{r}\, n_\chi^2(\vec{r})\langle\sigma_a v\rangle = \frac{1}{2}C_a N_\chi^2$
- $\langle\sigma_a v\rangle$ 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
- DM thermalized inside the star, ages of WDs in M4 ~ 12.7 Gyr and $t_{eq} = 1/\sqrt{\Gamma_{\rm capt} C_a} \lesssim 22.1$ yr, $\Rightarrow \Gamma_{\rm ann} = \frac{1}{2}\Gamma_{\rm capt}$
- For $\rho(r) \simeq \rho_c$

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

- $n_{0,\chi}$ is the central number particle density, $\int_0^R n_\chi(r) dV = N_\chi$
- The thermal radius is given $r_{th} = \sqrt{\frac{9T}{8\pi G\rho_c mx}}$

Mediator attenuation inside the WD

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- DM inside WDs annihilate into metastable mediators which may scatter off nuclei and electrons with a cross section σ_{Yi} and a mean free path $\lambda_{int} \sim \frac{1}{\sigma_{Yi} n_i}$
- If $\tau > \lambda_{int}$, Y could be attenuated when passing through the medium
- Mostly oxygen core, $A = 16$, and interaction of Y to nuclei of O
- Nuclei number density for a polytropic index $n = \frac{3}{2}$,

$$n(r) = \frac{\rho_c}{m_A} \int_0^r \omega(r')^{\frac{3}{2}} dr'$$

F. K. Liu, MNRAS 281 (1996) 1197-1205

- $\omega(r)$ the approximated analytic solution of the Lane-Emden equation, accurate to $1~\%$ to the numerical full solution
- Initially, $E_{Y,0} = E_\chi \simeq m_\chi$ and the momentum modulus $p_{Y,0} = \sqrt{m_\chi^2 - m_Y^2}$
- After one interaction the mediator will lose momentum $p_Y = q p_{Y,0}$, $0 < q < 1$

Mediator attenuation inside the WD

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- The momentum modulus after travelling a distance r

$$\frac{dp_Y}{dr} = \frac{\Delta p_Y}{\lambda_{int}(r)} = \frac{-(1-q)p_Y}{\lambda_{int}(r)} \Rightarrow p_Y(r) = \sqrt{m_\chi^2 - m_Y^2}\, e^{\frac{-(1-q)A\sigma_{Y,N}\rho_c}{m_N} \int_0^r \omega(r')^{\frac{3}{2}} dr'}$$

- Energy and velocity radial dependence $E_Y(r) = \sqrt{p_Y(r)^2 + m_Y^2}$ and $v_Y = \frac{p_Y(r)}{E_Y(r)}$
- We consider DM particles annihilate in $r \sim 0$ due to the fact that $r_{th} << R$
- Decay probability density

$$\frac{dP_{\rm dec}}{dr} = \frac{-P_{\rm dec}}{\tau_{\rm rest}\gamma_Y(r)} = \frac{-P_{\rm dec} m_Y}{\tau_{\rm rest}E_Y(r)} \Rightarrow P_{\rm dec}(r) = N\, e^{-\int_0^r \frac{m_Y dr'}{\tau_{\rm rest}E_Y(r')}}$$

- The normalization condition $\int_0^\infty P_{\rm dec} dr = 1$ implies

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

- No attenuation for $r > R$

Mediator attenuation inside the WD: v_Y vs r

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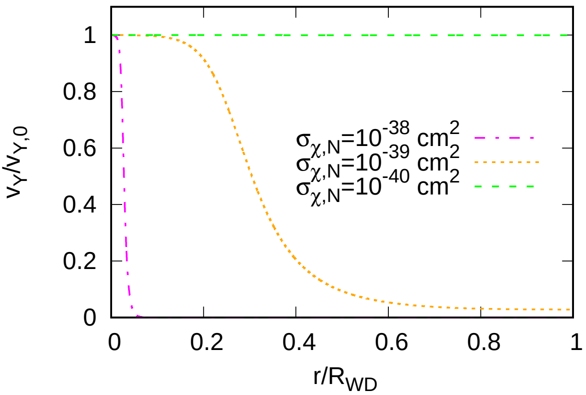
$$m_\chi = 0.5 \text{ GeV}, m_Y = 0.01 \text{ GeV}, \sigma_{\chi,N} = \sigma_{Y,N},$$
$$\rho_c = 3.78\ 10^6 \text{ g/cm}^3, M = 0.95 M_\odot$$



Internal Luminosity

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

- Each of the four photons emited per annihilation has a monochromatic energy in the rest frame of the mediator $E_{\gamma,rest} = \frac{m_Y}{2}$
- In the laboratory frame $E_\gamma = \frac{1}{\gamma_Y} E_{\gamma,\text{rest}} (1 - v_Y \cos\,\theta)^{-1}$
- The energy spectrum has a box-type shape

$$\frac{dN_\gamma}{dE_\gamma} = \frac{4}{\Delta E} \Theta(E_\gamma - E_-)\Theta(E_+ - E_\gamma)$$

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

Internal luminosity and constraints from M4 GC WDs

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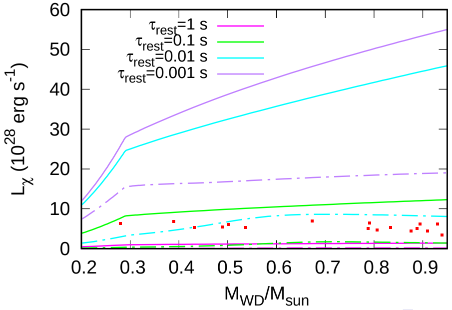
$$L_\chi = \Gamma_{ann} \int_0^R N\, e^{-\int_0^r \frac{m_Y dr'}{\tau_{\rm rest} E_Y(r')}} \int_{E_-(r)}^{E_+(r)} E_\gamma \frac{dN_\gamma(r)}{dE_\gamma} dE_\gamma dr$$

$m_\chi = 0.5$ 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 M4 GC, M. McCullough and M. Fairbairn, PRD 81 (2010) 083520



Results: Lifetime constraints

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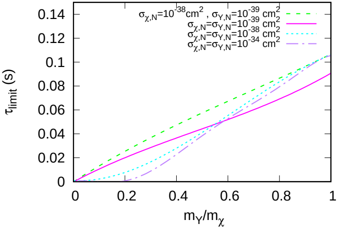
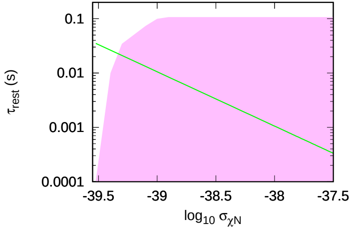
- If $L_\chi > 1.5L_{exp}$ for all the experimental data ($50\,\%$ of tolerance)$\Rightarrow$ we exclude the points of the parameter of space
- The lower limit of τ_{rest}, $L_\chi < 1.5L_{exp}$, depends on $\frac{m_Y}{m_\chi}$ in a different way depending on $\sigma_{\chi,N}$ and $\sigma_{Y,N}$, left plot
- For the most restrictive case $m_Y \sim m_\chi \Rightarrow$ we exclude values of τ_{rest} as a function of $\sigma_{\chi,N}$, pink region of the rigth plot
- Green line of the rigth plot is the attenuation (lower) limit so that the mediator interacts at least once with nuclei for the case $\sigma_{\chi,N} = \sigma_{Y,N}$





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- We have calculated the internal luminosity due to annihilation $\chi\bar{\chi} \to YY \to 4\gamma$ inside WDs in a mostly model independent framework
- We have taken into account the attenuation of the mediator Y due to the scattering of nuclei when passing through the medium
- We show that the more similar to the DM particle mass, m_χ, the mediator mass, m_Y, is, the higher the luminosity due to the fact that $v_Y \to 0$ and most of the mediators will decay inside the star as bootst is small
- The internal luminosity decreases when $\tau_{\rm rest}$ increases. This happens because the higher $\tau_{\rm rest}$ is, the smaller the probability of decaying inside the object
- Comparing our results with experimental data of WDs in the GC M4, we put constraints for the mediator lifetime as a function of the $\sigma_{\chi,N}$ in the most restrictive case $m_Y/m_\chi \to 1$
- We obtain the lower limit for τ_{rest} depends on $\frac{m_Y}{m_\chi}$ in a different way depending on the values of $\sigma_{\chi,N}$ and $\sigma_{Y,N}$

Results: L_χ vs $\sigma_{Y,N}$

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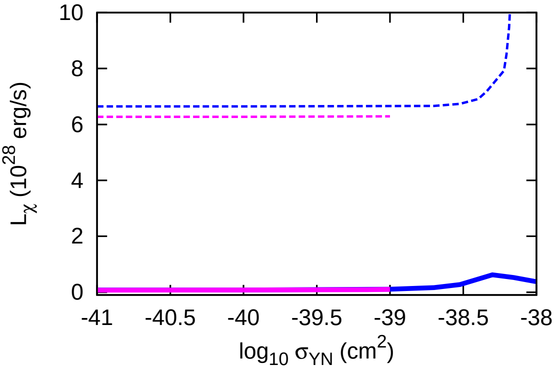
$m_\chi = 0.5$ GeV, $\tau_{rest} = 0.15$ s, $\rho_c = 3.3\ 10^5$ g/cm^3, $M = 0.28 M_\odot$
Solid lines $m_Y = 0.005$ GeV, dashed lines $m_Y = 0.495$ GeV



Magenta lines $\sigma_{\chi,N} = 10^{-39}$ cm^2, blue lines $\sigma_{\chi,N} = 10^{-38}$ cm^2

Results: Photon energy flux

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

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

$m_\chi = 0.8$ 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 $\leftrightarrow \lambda_{\text{D}} = 2.4\ 10^{10}$ cm > 2R
Dashed lines $\tau_{rest} = 0.8$ s $\leftrightarrow \lambda_{\text{D}} = 2\ 10^{11}$ cm > 2R