



Photon emission from dark mediators in White Dwarfs

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Why DM?

Introduction

Dark Matter
inside White
Dwarfs

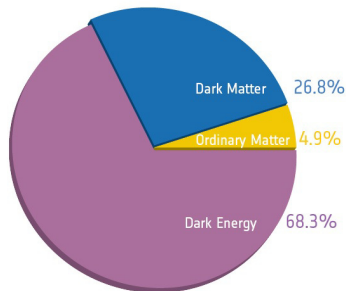
Internal
Luminosity

Results

Conclusions

- 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

After Planck





Secluded Dark Matter Particles

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- 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](#)



Our Secluded Dark Matter Model

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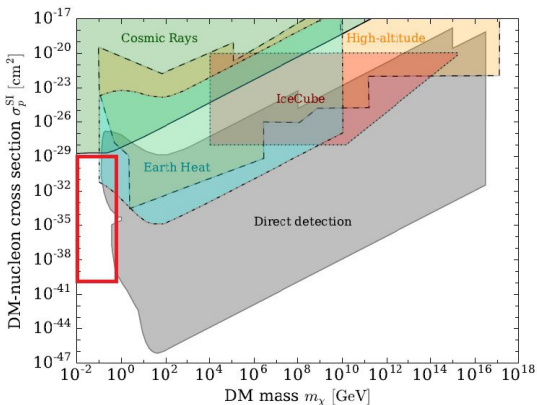
Conclusions

- $m_Y \lesssim m_\chi$
- Main annihilation channel (on-shell) $\chi\bar{\chi} \rightarrow YY$ with the subsequent decay $Y \rightarrow \gamma\gamma$
- 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

Our Secluded Dark Matter Model. Constraints

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

B. J. Kavanagh, PRD 97 (2018) 123013



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Accretion of DM by White Dwarfs

- WDs are compact objects mostly made of C and O, $\rho_c \sim (10^4 - 10^7) \text{ g/cm}^3$
- Central pressure due to degenerate electrons
- WDs in the globular cluster M4, $R \sim (10^{-3} - 2.5 \cdot 10^{-2})R_\odot$ 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 ,

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

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

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



Accretion of DM by White Dwarfs

- The number of DM particles in the WD

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

- No evaporation effects, only important for $m_\chi \lesssim 2 \text{ MeV}$ for $T_c \sim 10^6 \text{ K}$
- $\Gamma_{\text{ann}} = \frac{1}{2} \int d^3\vec{r} n_\chi^2(\vec{r}) \langle \sigma_a v \rangle = \frac{1}{2} C_a N_\chi^2$
- $\langle \sigma_a v \rangle$ 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 $\sim 12.7 \text{ Gyr}$ and $t_{\text{eq}} = 1 / \sqrt{\Gamma_{\text{capt}} C_a} \lesssim 22.1 \text{ yr}$, $\Rightarrow \Gamma_{\text{ann}} = \frac{1}{2} \Gamma_{\text{capt}}$
- For $\rho(r) \simeq \rho_c$
$$n_\chi(r) = n_{0,\chi} e^{-\left(\frac{r}{r_{\text{th}}}\right)^2}$$
- $n_{0,\chi}$ is the central number particle density, $\int_0^R n_\chi(r) dV = N_\chi$
- The thermal radius is given $r_{\text{th}} = \sqrt{\frac{9T}{8\pi G \rho_c m_\chi}}$



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 and carbon core, $A \sim 14$, and interaction of Y to nuclei of C and 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 $p_Y = qp_{Y,0}$, $0 < q < 1$



Mediator attenuation inside the WD

- 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 $r_{th} \ll R$
- Decay probability density

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

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

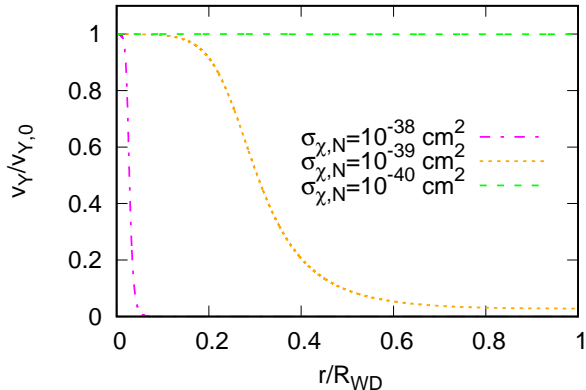
$$N \left(\int_0^R e^{-\int_0^r \frac{m_Y dr'}{\tau_{rest}E_Y(r')}} dr + \int_R^\infty e^{-\int_0^r \frac{m_Y dr'}{\tau_{rest}E_Y(r')}} dr \right) = 1$$

- No attenuation for $r > R$



Mediator attenuation inside the WD: v_Y vs r

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





Internal Luminosity

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

- Each of the four photons emitted per annihilation has a monochromatic energy in the rest frame of the mediator $E_{\gamma,rest} = \frac{m_Y}{2}$
- In the laboratory frame $E_{\gamma} = \frac{1}{\gamma_Y} E_{\gamma,rest} (1 - v_Y \cos \theta)^{-1}$
- 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 $E_{\pm} = \frac{1}{\gamma_Y(r)} \frac{m_Y}{2} (1 \mp v_Y(r))^{-1}$
- $v_Y(r) \rightarrow 0 \Rightarrow \gamma_Y(r) \rightarrow 1, E_- \rightarrow E_+$ and $\Delta E \rightarrow 0$



Internal luminosity and constraints from M4 GC WDs

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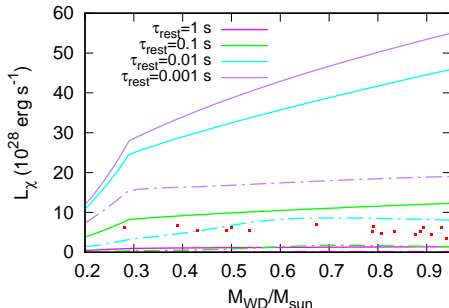
Conclusions

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

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

Solid lines $m_Y = 0.375 \text{ GeV}$, dashed lines $m_Y = 0.01 \text{ GeV}$

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

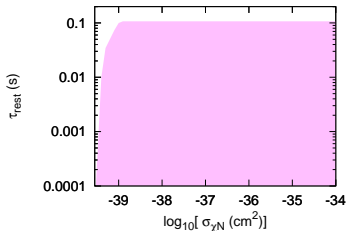
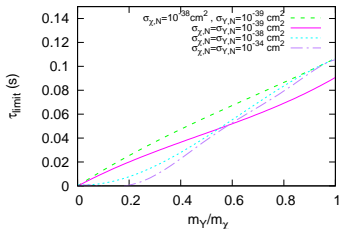


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Results: Lifetime constraints

- 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 right plot



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Conclusions

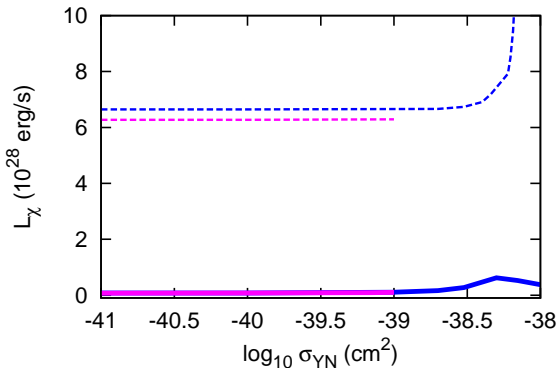
- We have calculated the internal luminosity due to annihilation $\chi\bar{\chi} \rightarrow YY \rightarrow 4\gamma$ inside WDs in a mostly model independent framework
- We have taken into account the attenuation of the mediator Y due to the scattering of nuclei when passing through the medium
- We show 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 $v_Y \rightarrow 0$ and most of the mediators will decay inside the star as boost is small
- The internal luminosity decreases when τ_{rest} increases. This happens because the higher τ_{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 $m_Y/m_\chi \rightarrow 1$
- 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 $\sigma_{Y,N}$

$$m_\chi = 0.5 \text{ GeV}, \tau_{rest} = 0.15 \text{ s}, \rho_c = 3.3 \cdot 10^5 \text{ g/cm}^3, M = 0.28 M_\odot$$

Solid lines $m_Y = 0.005 \text{ GeV}$, dashed lines $m_Y = 0.495 \text{ GeV}$



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



Results: Photon energy flux

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

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

$m_\chi = 0.8 \text{ GeV}$, $m_\gamma = 0.1 \text{ GeV}$, $\sigma_{\chi,N} = \sigma_{\gamma,N}$, $\rho_c = 3.3 \cdot 10^5 \text{ g/cm}^3$, $d = 2R = 5.4 \cdot 10^9 \text{ cm}$

Solid lines $\tau_{\text{rest}} = 0.1 \text{ s} \leftrightarrow \lambda_D = 2.4 \cdot 10^{10} \text{ cm} > 2R$

Dashed lines $\tau_{\text{rest}} = 0.8 \text{ s} \leftrightarrow \lambda_D = 2 \cdot 10^{11} \text{ cm} > 2R$

