Dark Matter in the Sun: Theory and Probes

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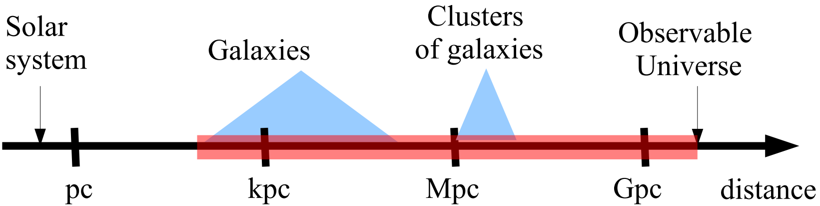
Based on
JCAP 1705 (2017) no.05, 007 (arXiv: hep-ph/1702.02768)
and Work in Preperation (arXiv: hep-ph/1807.vwxyz)
in collaboration with Sergio Palomares-Ruiz

June 21, 2018

Evidences for Dark Matter



What do we know about Dark Matter ?

DARK MATTER

$J =$?

Mass $m =$?
Mean life $\tau =$?

DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
?	?	?	?

- No electric charge, no colour charge (Smith et al. '79, Perl et al. '01).
- Non-relativistic at the time of formation of the first structures (White, Frenk, Davis '83).
- Life time longer than the age of the Universe.

$\Longrightarrow$ Evidence for physics beyond the SM.

$\Longrightarrow$ Lets find Dark Matter !

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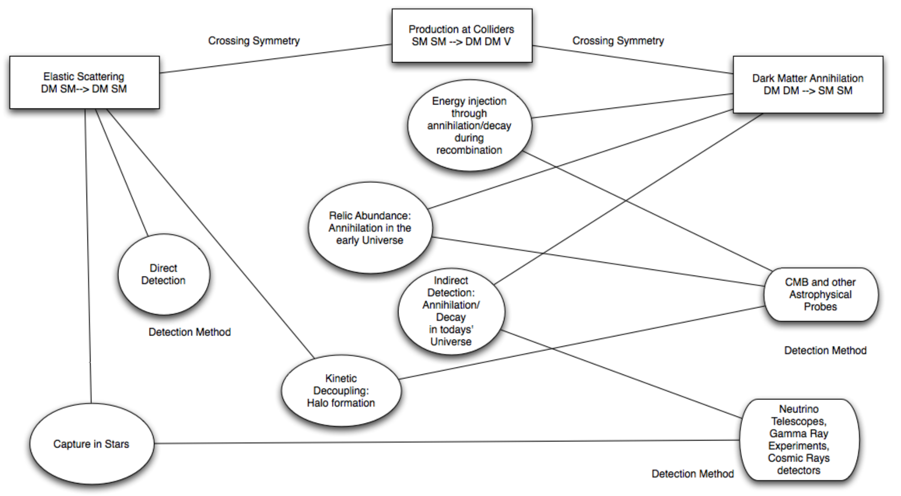
Finding Dark Matter



Outline

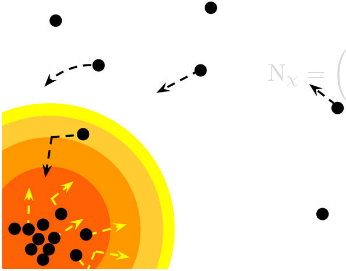
- Introduction
- Dark Matter in the Sun: Theory
  - Capture of Dark Matter by the Sun
  - Evaporation of Dark Matter from the Sun and the minimum testable mass
  - Normalization to Neutrino Flux at Production
- Probes: Constraining Dark Matter interactions with SM
  - Current Experimental Status
  - New constraints on Dark Matter-Electron interactions
- Conclusions

Introduction

- If DM (χ) has a non vanishing $\sigma_{\chi\,T}$, it can be captured in the Sun.
  Press and Spergel '85, Griest and Seckel '86, Gould '87
- Dynamics governed by the equation

$$\frac{\mathrm{dN}_\chi}{\mathrm{dt}} = C_\odot - E_\odot \mathrm{N}_\chi - A_\odot \mathrm{N}_\chi^2$$

$$\mathrm{N}_\chi = \left(\frac{C_\odot}{A_\odot}\right)^{1/2} \frac{\tanh\left(\kappa t_\odot/\tau\right)}{\kappa + \frac{1}{2} E_\odot \tau \tanh\left(\kappa t_\odot/\tau\right)}.$$



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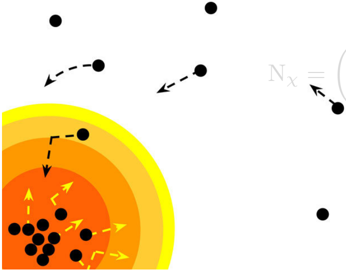

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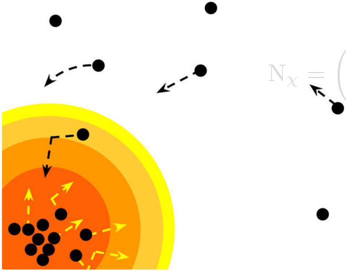

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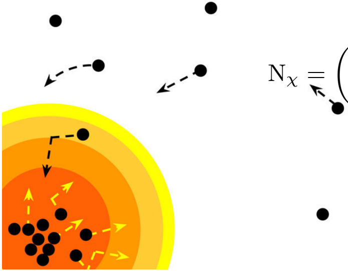
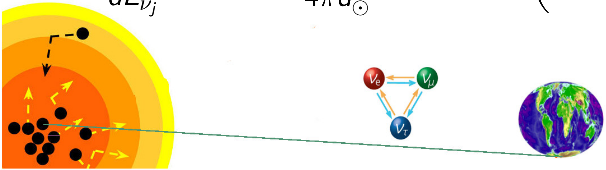


- The normalisation to neutrino flux:

$$\Gamma(m_\chi, \sigma_{\chi T}) = \frac{1}{2} A_\odot N_\chi^2.$$

- Neutrino flux at detector:

$$\frac{d\Phi^{\nu_j}}{dE_{\nu_j}}(E_{\nu_j}) = \frac{1}{4\pi d_\odot^2} \Gamma(m_\chi, \sigma_{\chi T}) \left(\Sigma_i P(\nu_i \to \nu_j) \frac{dF}{dE_{\nu_i}}(E_{\nu_i}) \right)$$



Scattering cross sections

The usual SI and SD cross sections for DM-nucleon interactions:

$$\sigma_{i,0}^{\mathrm{SD}} = \left(\frac{\tilde{\mu}_{A_i}}{\tilde{\mu}_p}\right)^2 \frac{4\,(J_i+1)}{3\,J_i}\,|\langle S_{p,i}\rangle + \langle S_{n,i}\rangle|^2\,\sigma_{p,0}^{\mathrm{SD}}\,,$$

$$\sigma_{i,0}^{\mathrm{SI}} = \left(\frac{\tilde{\mu}_{A_i}}{\tilde{\mu}_p}\right)^2 A_i^2\,\sigma_{p,0}^{\mathrm{SI}}\,.$$

Types of scattering cross sections considered here:

$$\frac{\mathrm{d}\sigma_{i,\mathrm{const}}(v_{\mathrm{rel}},\cos\theta_{\mathrm{cm}})}{\mathrm{d}\cos\theta_{\mathrm{cm}}} = \frac{\sigma_{i,0}}{2}\,,$$

$$\frac{\mathrm{d}\sigma_{i,v_{\mathrm{rel}}^2}(v_{\mathrm{rel}},\cos\theta_{\mathrm{cm}})}{\mathrm{d}\cos\theta_{\mathrm{cm}}} = \frac{\sigma_{i,0}}{2}\left(\frac{v_{\mathrm{rel}}}{v_0}\right)^2\,,$$

$$\frac{\mathrm{d}\sigma_{i,q^2}(v_{\mathrm{rel}},\cos\theta_{\mathrm{cm}})}{\mathrm{d}\cos\theta_{\mathrm{cm}}} = \frac{\sigma_{i,0}}{2}\,\frac{(1+\mathrm{m}_\chi/m_i)^2}{2}\left(\frac{q}{q_0}\right)^2\,.$$

Dark Matter in the Sun: Capture

- For velocity and momentum independent cross section (with $T = 0$), energy loss should be at least

$$\frac{\Delta E}{E} \geq \frac{\omega^2 - v^2}{\omega^2},$$

and from kinematics

$$0 \leq \frac{\Delta E}{E} \leq \frac{\mu}{\mu_+^2},$$

$$C_\odot = \int_0^{R_\odot} 4\pi r^2 dr \int_0^\infty du \left(\frac{\rho_\chi}{m_\chi}\right) \frac{f_\odot(u)}{u} \omega(r) \int_0^{v_e} R^-(\omega \to \nu) d\nu.$$

- Typical 3-momentum transfer is $\mathcal{O}(\mathrm{KeV})$ for electrons, and $\mathcal{O}(\mathrm{MeV})$ for nucleons.

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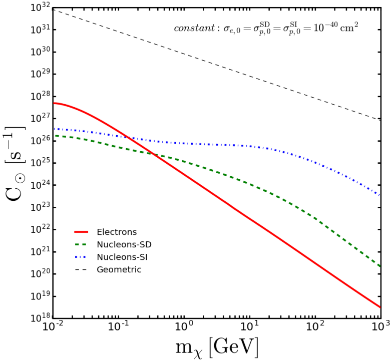
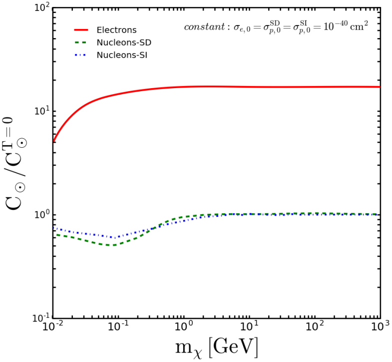
Dark Matter in the Sun: Capture Rate for Const. $\sigma_{\chi e}$

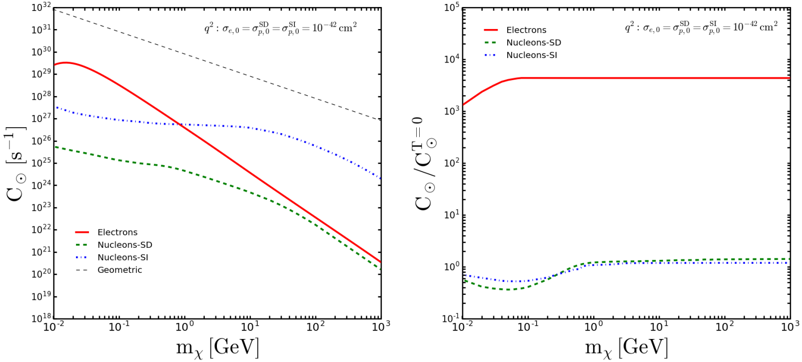
The standard case:





Capture of Dark Matter by the Sun: q^2

New !



Evaporation and Minimum Testable Mass

- Evaporation depends on the DM distribution in the Sun. Isothermal profile and Local thermodynamic equilibrium profile.

$$E_\odot = \int_0^{R_\odot} s(r)\, n_\chi(r,t)\, 4\pi r^2\, \mathrm{d}r \int_0^{v_c(r)} f_\chi(\boldsymbol{w}, r)\, 4\pi w^2\, \mathrm{d}w \int_{v_e(r)}^{\infty} R_i^+(w \to v)\mathrm{d}v \ .$$

$$s(r) = \eta_{\rm ang}(r)\, \eta_{\rm mult}(r)\, e^{-\tau(r)}$$

- Minimum testable mass:

$$E_\odot(m_{\rm evap})\, \tau_{\rm eq}(m_{\rm evap}) = \frac{E_\odot(m_{\rm evap})}{\sqrt{(C_\odot(m_{\rm evap}) A_\odot(m_{\rm evap}))}} > \frac{1}{\sqrt{0.11}} \ .$$

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Evaporation Rate: Const.

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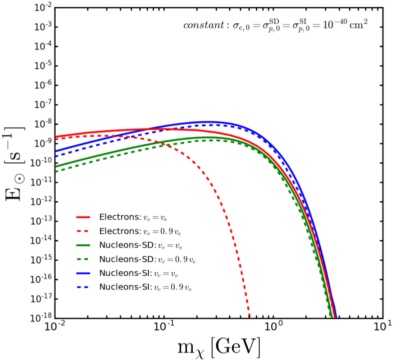

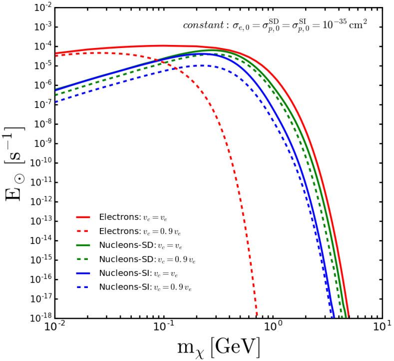

Evaporation Rate: q^2

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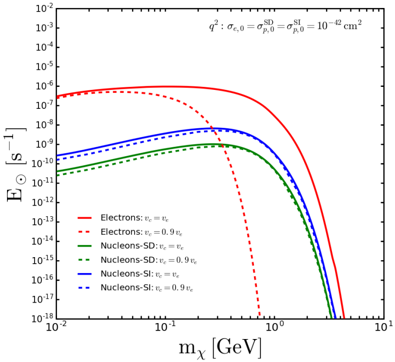

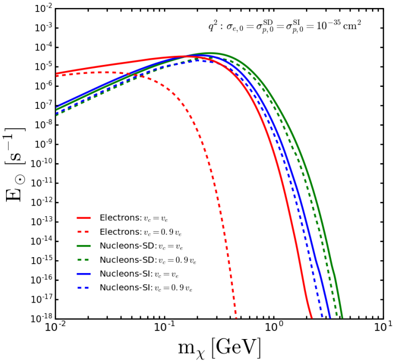

Minimum Testable Mass

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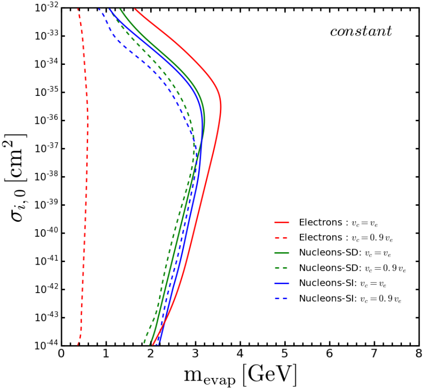
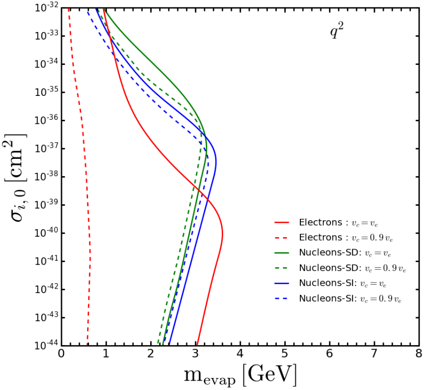
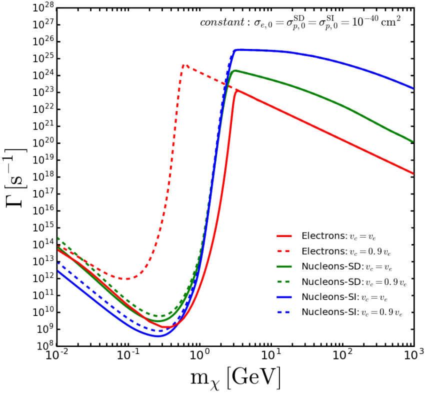
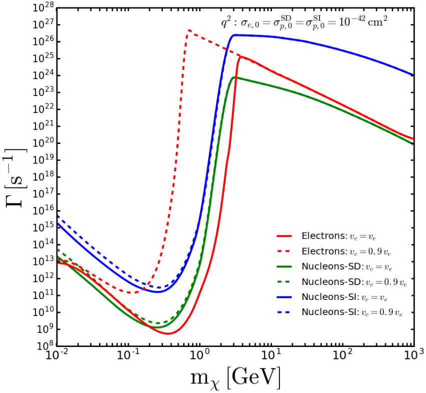




The total annihilation rate

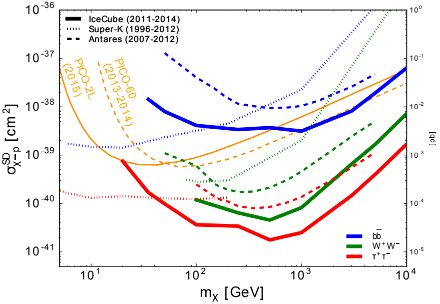
$$\frac{d\Phi^{\nu_j}}{dE_{\nu_j}}(E_{\nu_j}) = \frac{1}{4\pi d_\odot^2}\Gamma(m_\chi, \sigma_{\chi T}) \left(\Sigma_i P(\nu_i \to \nu_j) \frac{dF}{dE_{\nu_i}}(E_{\nu_i})\right)$$

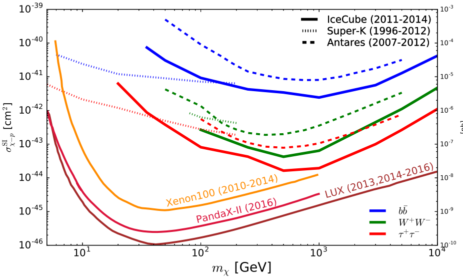




Probes: Current SD and SI limits from Neutrino Telescopes

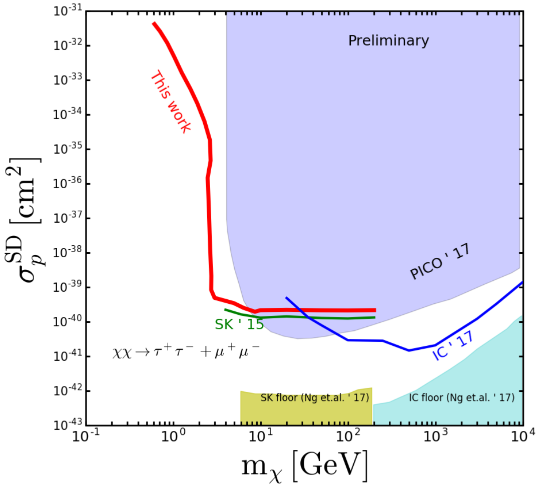
IceCube '17, SK '15





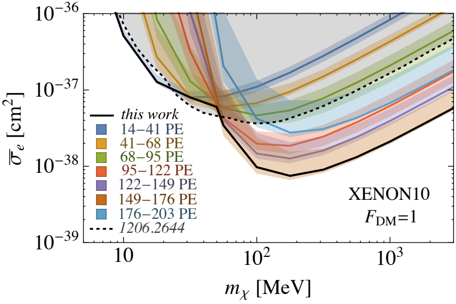
Probes: Updated SD limits from Neutrino Telescopes

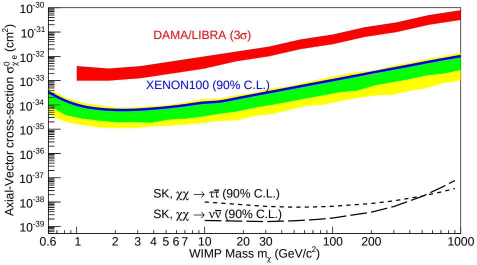
RG, Palomares-Ruiz (in preparation)



Probes: Current Limits on Dark Matter-Electron Interactions

Left: et al. '17, Right: Xenon100 '17





Probes: New Limits on Dark Matter-Electron Interactions

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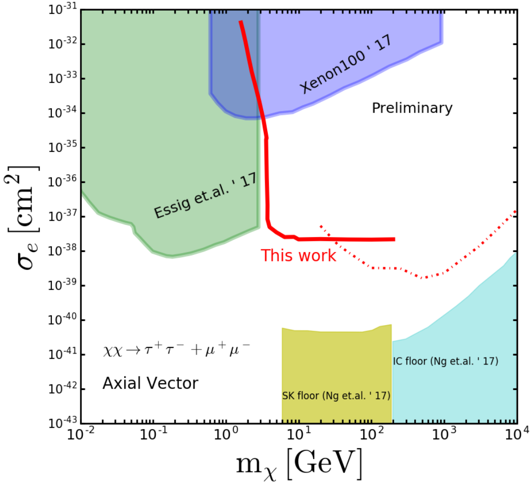


Conclusions and Outlook

- Dark Matter annihilation in the Sun: A good test for "Particle Dark Matter" paradigm.
- Phenomenology of Dark Matter - Electron scattering in the Sun is interesting. Most relevant for leptophilic models. Complete study of leptophilic models in preparation.
- Competitive limits can be placed on DM-Electron cross sections compared to ground based experiments.

Thank You !

Dark Matter Distribution in the Sun : velocity

The velocity distributions of target and DM particles can be assumed to have Maxwell-Boltzmann form with a cut-off at escape velocity. Gould and Raffelt '90

$$
\begin{aligned}
f_i(\boldsymbol{u}, r) &= \frac{1}{\sqrt{\pi^3}} \left(\frac{m_i}{2\, T_\odot(r)} \right)^{3/2} e^{-\frac{m_i\, u^2}{2\, T_\odot(r)}} \,, \\
f_\chi(\boldsymbol{w}, r) &= \frac{e^{-w^2/v_\chi^2(r)}\; \Theta(v_c(r) - w)}{\sqrt{\pi^3}\, v_\chi^3(r) \left(\mathrm{Erf}\left(\frac{v_c(r)}{v_\chi(r)} \right) - \frac{2}{\sqrt{\pi}} \frac{v_c(r)}{v_\chi(r)}\, e^{-v_c^2(r)/v_\chi^2(r)} \right)} \,,
\end{aligned}
$$

$T_\odot(r)$ and $v_\chi(r) \equiv \sqrt{2\,\mathrm{T}_\chi(r)/\mathrm{m}_\chi}$ are the solar temperature and the thermal DM velocity at a distance r from the center of the Sun

Dark Matter Distribution in the Sun: radial

- LTE:

$$n_{\chi,\mathrm{LTE}}(r,t) = n_{\chi,\mathrm{LTE},0}(t)\left(\frac{T_\odot(r)}{T_\odot(0)}\right)^{3/2} \exp\left(-\int_0^r \frac{\alpha(r')\frac{\mathrm{d}T_\odot(r',t)}{\mathrm{d}r'} + \mathrm{m}_\chi \frac{\mathrm{d}\phi(r')}{\mathrm{d}r'}}{T_\odot(r')}\,\mathrm{d}r'\right) ,$$

- Isothermal:

$$n_{\chi,\mathrm{iso}}(r,t) = N_\chi(t)\,\frac{e^{-\mathrm{m}_\chi\phi(r)/\mathrm{T}_\chi}}{\int_0^{R_\odot} e^{-\mathrm{m}_\chi\phi(r)/\mathrm{T}_\chi}\,4\pi r^2\,\mathrm{d}r} .$$

Dark matter distribution in the Sun: DM Effective temperature

Without cut-off , Press and Spergel '85

$$\sum_i \int_0^{R_\odot} \epsilon_i(r, \mathrm{T}_\chi, T_c)\, 4\pi r^2\, \mathrm{d}r = 0 \ ,$$

$$\epsilon_i(r, \mathrm{T}_\chi, T_c) \equiv \int \mathrm{d}^3\boldsymbol{w}\, n_{\chi,\mathrm{iso}}(r, t_\odot)\, f_{\chi,\mathrm{iso}}(\boldsymbol{w}, r) \int \mathrm{d}^3\boldsymbol{u}\, n_i(r)\, f_i(\boldsymbol{u}, r)\, \sigma_{i,0}\, |\boldsymbol{w} - \boldsymbol{u}|\, \langle \Delta E_i \rangle \ ,$$

Dark matter distribution in the Sun: DM Effective temperature

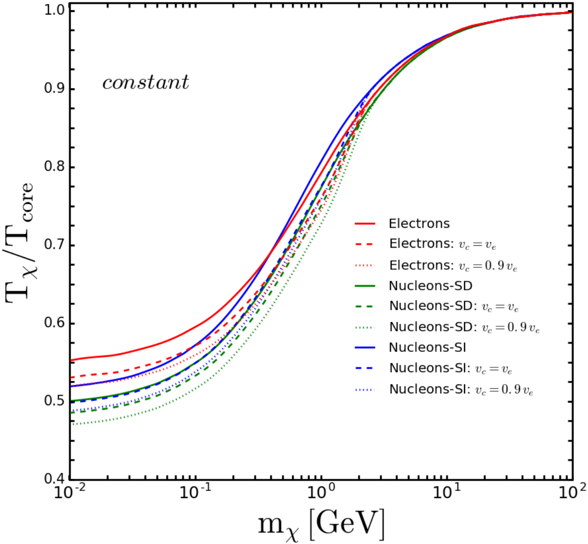
With cut-off , correction to Press and Spergel '85

$$\sum_i \int_0^{R_\odot} \epsilon_i(r, \mathrm{T}_\chi, T_c)\, 4\pi r^2\, \mathrm{d}r = \sum_i \int_0^{R_\odot} \epsilon_{\mathrm{evap},i}(r, \mathrm{T}_\chi, T_c)\, 4\pi r^2\, \mathrm{d}r \ ,$$

$$\begin{aligned} \epsilon_{\mathrm{evap},i}(r, \mathrm{T}_\chi, T_c) &= \int_0^{v_c(r)} n_{\chi,\mathrm{iso}}(r,t)\, f_{\chi,\mathrm{iso}}(\boldsymbol{w}, r)\, 4\pi w^2\, \mathrm{d}w \\ & \int_{v_e(r)}^{\infty} K_i^+(w \to v)\, \mathrm{d}v \ . \end{aligned}$$

$$\begin{aligned} K_i(w \to v) &= \int n_i(r) \frac{\mathrm{d}\sigma_i}{\mathrm{d}v} |\boldsymbol{w} - \boldsymbol{u}|\, \Delta E_i\, f_i(\boldsymbol{u}, r)\, \mathrm{d}^3\boldsymbol{u} \\ &= \Delta E_i\, R_i(w \to v) = \frac{\mathrm{m}_\chi}{2}\left(v^2 - w^2\right) R_i(w \to v) \ . \end{aligned}$$

Dark matter distribution in the Sun: DM Effective temperature



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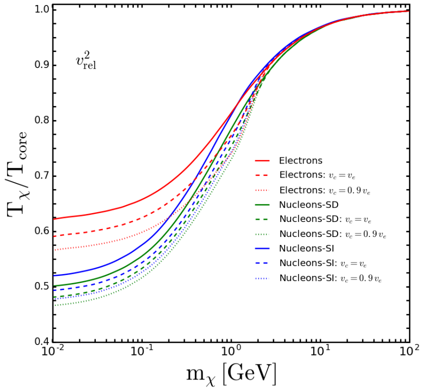

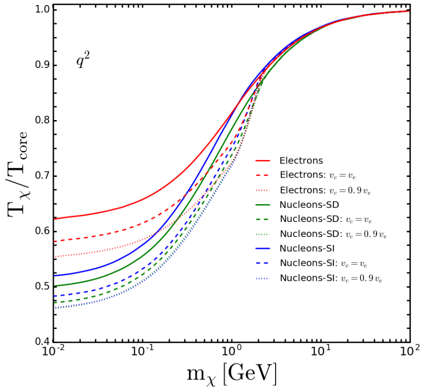

Differential Scattering Rates I

$$R_i(w \to v) = \int n_i(r) \frac{\mathrm{d}\sigma_i}{\mathrm{d}v} |\boldsymbol{w} - \boldsymbol{u}| f_i(\boldsymbol{u}, r) \, \mathrm{d}^3\boldsymbol{u}$$

$$= \frac{2}{\sqrt{\pi}} \frac{n_i(r)}{u_i^3(r)} \int_0^\infty \mathrm{d}u \, u^2 \int_{-1}^{1} \mathrm{d}\cos\theta \, \frac{\mathrm{d}\sigma_i}{\mathrm{d}v} |\boldsymbol{w} - \boldsymbol{u}| \, e^{-u^2/u_i^2(r)} ,$$

$$R^{\pm}_{const}(w \to v) = \sum_i \frac{2}{\sqrt{\pi}} \frac{\mu_{i,+}^2}{\mu_i} \frac{v}{w} n_i(r) \, \sigma_{i,0} \left[\chi(\pm\alpha_-, \alpha_+) + \chi(\pm\beta_-, \beta_+) \, e^{\mu_i \left(w^2 - v^2\right)/u_i^2(r)} \right] .$$

Differential Scattering Rates II

$$R^{\pm}_{v^2_{\rm rel}}(w \to v) = \sum_i \frac{2}{\sqrt{\pi}} \frac{\mu^2_{i,+}}{\mu_i} \frac{v}{w} n_i(r)\, \sigma_{i,0} \left(\frac{u_i(r)}{v_0}\right)^2 \left[\left(\mu_{i,+} + \frac{1}{2}\right) \left(\pm \frac{v-w}{u_i(r)} e^{-\alpha_-^2} - \frac{v+w}{u_i(r)} e^{-\alpha_+^2} \right) \right.$$
$$+ \left(\frac{w^2}{u_i^2(r)} + \frac{3}{2} + \frac{1}{\mu_i} \right) \chi(\pm\alpha_-, \alpha_+)$$
$$\left. + \left(\frac{v^2}{u_i^2(r)} + \frac{3}{2} + \frac{1}{\mu_i} \right) \chi(\pm\beta_-, \beta_+)\, e^{\mu_i \left(w^2 - v^2\right)/u_i^2(r)} \right] .$$

$$R^{\pm}_{q^2}(w \to v) = \sum_i \frac{8}{\sqrt{\pi}} \frac{\mu^4_{i,+}}{\mu_i^2} \frac{v}{w} n_i(r)\, \sigma_{i,0} \left(\frac{u_i(r)}{v_0}\right)^2 \left[\pm \frac{v-w}{u_i(r)} e^{-\alpha_-^2} - \frac{w+v}{u_i(r)} e^{-\alpha_+^2} \right.$$
$$+ \left(\frac{1}{2} \frac{w^2 - v^2}{u_i^2(r)} + \frac{1}{\mu_i} \right) \chi(\pm\alpha_-, \alpha_+)$$
$$\left. + \left(\frac{1}{2} \frac{v^2 - w^2}{u_i^2(r)} + \frac{1}{\mu_i} \right) \chi(\pm\beta_-, \beta_+)\, e^{\mu_i \left(w^2 - v^2\right)/u_i^2(r)} \right] .$$

Simplified Models for Dark Matter-Electron Interactions

- What is a simplified model ?
  - SM extended by addition of DM and a mediator.
  - Renormalisable Lagrangian which respect local $SU(3)_c \times U(1)_{em}$.
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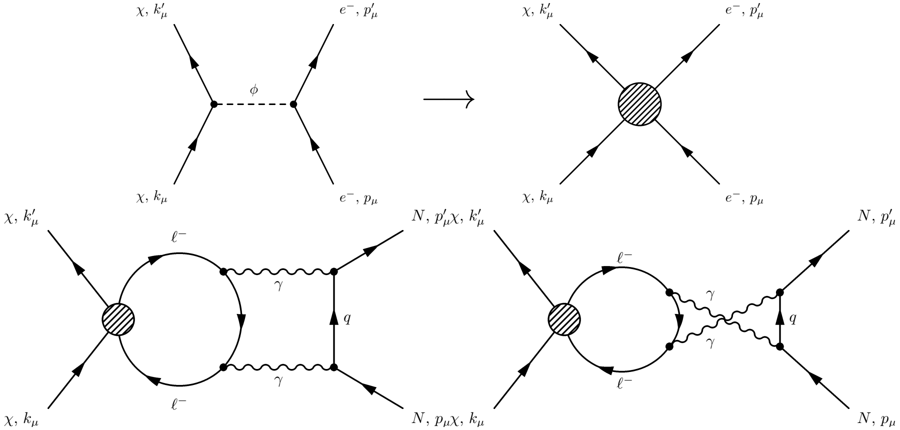
Simplified Models for Dark Matter-Lepton Interactions

DM	Mediator	$-\mathcal{L}_{int}$
Scalar (χ)	Scalar(ϕ)	$g_\chi \chi^\dagger \chi \phi + \bar{l}(g_s + i g_p \gamma_5) l \phi$
Scalar (χ)	Fermion (η)	$\bar{\eta}(g_L P_L + g_R P_R) l \chi + \mathrm{h.c.}$
Scalar (χ)	Vector (ϕ^μ)	$g \chi^\dagger \overleftrightarrow{\partial}_\mu \chi \phi^\mu + \bar{l}\gamma_\mu (g_v + \gamma_5 g_{pv}) l \phi^\mu$
Fermion (χ)	Scalar (ϕ)	$\bar{\chi}(g_s^\chi + i g_p^\chi \gamma_5)\chi\phi + \bar{l}(g_s + i g_p \gamma_5) l \phi$
Fermion (χ)	Vector (ϕ^μ)	$\bar{\chi}\gamma_\mu (g_V^\chi + g_A^\chi \gamma_5)\chi \phi^\mu +$ $\bar{l}\gamma_\mu (g_V + g_A \gamma_5) l \phi^\mu$
Vector (χ)	Scalar (ϕ)	$g \chi_\mu \chi^\mu \phi + \bar{l}(g_S + i g_P \gamma_5) l \phi$
Vector (χ)	Fermion (η)	$\bar{\eta}\gamma_\mu (g_L P_L + g_R P_R) l \chi^\mu + \mathrm{h.c.}$

Example: Scalar DM and Scalar Mediator I

$$-\mathcal{L}_{int} = g_\chi \chi^\dagger \chi \phi + \bar{\mathrm{l}}(g_s + i g_p \gamma_5)\mathrm{l}\phi$$



Example: Scalar DM and Scalar Mediator II

Model: Scalar DM - Scalar Mediator	$-\mathcal{L}_{int} = g_\chi \chi^\dagger \chi \phi + \bar{l}(g_s + i g_p \gamma_5) l \phi$
Elastic scattering $\chi - e$	$\frac{d\sigma^{\chi e}}{d\cos\theta*} = \frac{g_\chi^2}{32\,\pi\, m_\phi^4} \left(g_s^2 \frac{m_e^2}{m_\chi^2} \left(1 + \frac{q^2}{4\, m_e^2}\right) + g_p^2 \frac{q^2}{4\, m_\chi^2} \right)$
Elastic scattering $\chi - N$ (2-loop)	$\frac{d\sigma^{\chi N}}{d\cos\theta*} = \frac{1}{4608\,\pi} \alpha_{\rm em}^4 Z^4 \frac{g_s^2 g_\chi^2}{m_\phi^4} \frac{\mu_{\chi N}^2}{m_\chi^2} \frac{Q_0^2}{m_l^2} F_R^2(\lvert q \rvert)$
Figure of merit	$R_{e\,N} = \frac{d\sigma^{\chi e}}{d\sigma^{\chi N}} \sim 8 \times 10^6 \frac{1}{Z^4} \frac{1}{\mu_{\chi N}^2} F_R^{-2}(\lvert q \rvert)$. $\Gamma^{\chi\, e} \sim 10^{-2} \cdot R_{e\,N} \cdot \Gamma^{\chi\, N}$.

$$F_R(\tilde{q}) = \frac{4}{\pi} \int_0^1 dx \int_0^\infty d\tilde{l} \quad \frac{\tilde{l}^2}{(\tilde{l}^2 + (1-x)x\tilde{q}^2)^2} \times \exp\left(-\tilde{l}^2 - \tilde{q}^2\left(\tfrac{1}{2} - x + x^2\right)\right)$$
$$\times \left(\cosh\left((1-2x)\tilde{l}\tilde{q}\right) - \frac{\tilde{l}^2 - (1-x)x\tilde{q}^2 + 1}{(1-2x)\tilde{l}\tilde{q}} \sin\left((1-2x)\tilde{l}\tilde{q}\right)\right).$$

Back up: Scalar DM and Fermion mediator

Model: Scalar DM - Fermion Mediator	$-\mathcal{L}_{int} = \bar{\eta}(g_L P_L + g_R P_R) l \chi + \mathrm{h.c.}$
Elastic scattering $\chi - e$	$\frac{d\sigma^{\chi e}}{d\cos\theta^*} = \frac{\left(g_L^2 + g_R^2\right)^2}{64\,\pi\, m_\eta^2} \frac{m_e^2}{m_\chi^2} \left(1 + \frac{q^2}{2m_e^2}\right)$
Elastic scattering $\chi - N$ (2-loop)	$\frac{d\sigma^{\chi N}}{d\cos\theta^*} = \frac{1}{9216\,\pi} \alpha_{\mathrm{em}}^4 Z^4 \frac{\left(g_L^2 + g_R^2\right)^2}{m_\eta^2} \frac{\mu_{\chi N}^2}{m_\chi^2} \frac{Q_0^2}{m_l^2} F_R^2(\lvert q \rvert)$
Comments	Note that there are more terms $\propto g_L^2 \cdot g_R^2$, but are power suppressed in m_η^{-2}. $F_R(\lvert q \rvert)$ is the 2-photon exchange form factor.

Back up: Scalar DM and Vector mediator

Model: Scalar DM - Vector Mediator	$-\mathcal{L}_{int} = g\,\chi^\dagger \overleftrightarrow{\partial}_\mu \chi \phi^\mu + \bar{l}\gamma_\mu (g_v + \gamma_5 g_{pv}) l \phi^\mu$
Elastic scattering $\chi - e$	$\frac{d\sigma^{\chi e}}{d\cos\theta*} = \frac{g^2\, m_e^2}{8\,\pi\, m_\phi^4} \left(g_v^2 \left(1 + \frac{q^2}{2\, m_e^2} \right) + g_{pv}^2 \frac{q^2}{m_e^2} \right)$
Elastic scattering $\chi - N$ (1-loop)	$\frac{d\sigma^{\chi N}}{d\cos\theta*} = \frac{g^2\, g_v^2\, \mu_{\chi N}^2}{8\,\pi\, m_\phi^4} Z^2\, F^2(\lvert q\rvert)\, \mathrm{L}_1^2 \left(1 - \frac{q^2}{2\,\mu_{\chi N}(m_\chi + m_N)} - \frac{q^2}{4m_N^2} \right)$
Comments	$\mathrm{L}_1 = \frac{\alpha_{em}}{\pi} \int_0^1 dx\,(1-x)\, \mathrm{Log}\left[\frac{-x(1-x)q^2 + m_l^2 + i\,0}{\mu^2} \right]$ is the 1-loop integral, μ is chosen to be 100 GeV. $F(\lvert q\rvert)$ is the usual Helm form factor. Notice that $d\sigma^{\chi e}$ is independent of m_χ.

Back up: Fermion DM and Scalar mediator

Model: Fermion DM - Scalar Mediator	$-\mathcal{L}_{int} = \bar{\chi}(g_s^\chi + i\, g_p^\chi \gamma_5)\chi\phi + \bar{l}(g_s^l + i\, g_p^l \gamma_5) l \phi$
Elastic scattering $\chi - e$	$\frac{d\sigma^{\chi e}}{d\cos\theta*} = \frac{m_e^2}{4\,\pi\, m_\phi^4}\left((g_s^l g_s^\chi)^2\left(1 + \frac{q^2}{4m_e^2}\right) + (g_s^l g_p^\chi)^2 \frac{q^2}{4\,m_e^2}\right) + \frac{m_e^2}{4\,\pi\, m_\phi^4}\left((g_p^l g_p^\chi)^2 \frac{m_e^2}{m_\chi^2}\frac{q^2}{4\,m_e^2}\right)$
Elastic scattering $\chi - N$ (2-loop)	$\frac{d\sigma^{\chi N}}{d\cos\theta*} = \frac{1}{288\,\pi}\alpha_{\rm em}^4 Z^4 \frac{\mu_{\chi N}^2}{m_\phi^4}\frac{\mu_{\chi N}^2}{m_l^2}\frac{Q_0^2}{m_l^2} F_R^2(\lvert q\rvert)\left((g_s^l g_s^\chi)^2\left(\frac{q^2}{4m_N^2}\right)\right) + \frac{1}{288\,\pi}\alpha_{\rm em}^4 Z^4 \frac{\mu_{\chi N}^2}{m_\phi^4}\frac{\mu_{\chi N}^2}{m_l^2}\frac{Q_0^2}{m_l^2} F_R^2(\lvert q\rvert)\left((g_s^l g_p^\chi)^2 \frac{q^2}{4\,m_\chi^2}\right)$
Comments	$g_s^l = g_s^\chi = 0$ results in no interactions with nucleons at all loop orders.

Back up: Fermion DM and Vector mediator

Model: Fermion DM - Vector Mediator	$-\mathcal{L}_{int} = \bar{\chi}\gamma_\mu(g_V^\chi + g_A^\chi\gamma_5)\chi\phi^\mu + \bar{l}\gamma_\mu(g_V^l + g_A^l\gamma_5)l\phi^\mu$
Elastic scattering $\chi - e$	$\frac{d\sigma^{\chi e}}{d\cos\theta*} = \frac{m_e^2}{4\,\pi\,m_\phi^4}\left((g_V^\chi g_V^l)^2 + 3(g_A^\chi g_A^l)^2\right) + \frac{m_e^2}{4\,\pi\,m_\phi^4}\left(\left((g_V^\chi g_A^l)^2 + 3(g_A^\chi g_V^l)^2\right)\frac{q^2}{4\,m_e^2}\right)$
Elastic scattering $\chi - N$ (1-loop)	$\frac{d\sigma^{\chi N}}{d\cos\theta*} = \frac{\mu_{\chi N}^2}{8\,\pi\,m_\phi^4} Z^2\,F^2(\lvert q\rvert)\,\mathrm{L}_1^2\left((g_V^\chi g_V^l)^2 + 3(g_A^\chi g_V^l)^2\left(\frac{q^2}{4m_N^2}\right)\right)$
Comments	$\mathrm{L}_1 = \frac{\alpha_{em}}{\pi}\int_0^1 dx\,(1-x)\mathrm{Log}\left[\frac{-x(1-x)q^2 + m_l^2 + i\,0}{\mu^2}\right].$ $g_V^l = g_V^\chi = 0$ results in no interactions with nucleons L_1 is the 1-loop integral, μ is chosen to be 100 GeV. $F(\lvert q\rvert)$ is the usual Helm form factor.

Back up: Vector DM and Scalar mediator

Model: Vector DM - Scalar Mediator	$-\mathcal{L}_{int} = g\chi_\mu\chi^\mu\phi + \bar{l}(g_S + i\, g_P\gamma_5)l\phi$
Elastic scattering $\chi - e$	$\frac{d\sigma^{\chi e}}{d\cos\theta*} = \frac{g^2}{16\pi m_\phi^4}\left(g_S^2\frac{m_e^2}{m_\chi^2}\left(1+\frac{q^2}{2m_e^2}\right) + g_p^2\frac{q^2}{4\, m_\chi^2}\right)$
Elastic scattering $\chi - N$ (2-loop)	$\frac{d\sigma^{\chi N}}{d\cos\theta*} = \frac{1}{4608\,\pi}\alpha_{\rm em}^4\, Z^4\,\frac{g^2\, g_S^2}{m_\phi^4}\,\frac{\mu_{\chi N}^2}{m_\chi^2}\,\frac{Q_0^2}{m_l^2}\, F_R^2(\lvert q\rvert)$
Comments	$F_R(\lvert q\rvert)$ is the 2-photon exchange form factor.

Back up: Vector DM and Fermion mediator

Model: Vector DM - Fermion Mediator	$-\mathcal{L}_{int} = \bar{\eta}\gamma_\mu(g_L P_L + g_R P_R) l \chi^\mu + \mathrm{h.c.}$
Elastic scattering $\chi - e$	$\frac{d\sigma^{\chi e}}{d\cos\theta*} = \frac{(g_L\, g_R)^2}{16\,\pi\, m_\eta^2}\, \frac{m_e^2}{m_\chi^2} \left(1 - \frac{q^2}{2m_e^2}\right)$
Elastic scattering $\chi - N$ (1-loop)	$\frac{d\sigma^{\chi N}}{d\cos\theta*} = \frac{(g_L\, g_R)^2}{16\,\pi}\, \frac{\alpha_{em}^2}{\pi^2}\, Z^2\, F^2(\lvert q \rvert)\, \frac{m_l^2}{m_N^2}\, \frac{\mu_{\chi\, N}^2}{m_\chi^2}\, \frac{q^2}{m_N^2}\, B_0^2(q^2, m_l^2, m_l^2)$
Comments	$B_0(q^2, m_l^2, m_l^2)$ is the 2-point Passarino Veltman function.