Direct Detection of momentum-suppressed operators

Connections with Gauge Invariant Simplified Models

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Outline

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- In Direct Detection one tries to detect DM scattering off some detector on Earth
- Scatterings may deposit $\mathcal{O}(\,\mathrm{KeV})$ energy in the detector
- Scattering is well described by EFTs
- Dimension 6: 10 operators. However, we usually consider just 2 cases: SI, and SD
- SI: scattering does not depend on spin, so at low energy the amplitude for each nucleon sums up coherently, leading to large enhancements for heavy nuclei
- SD: scattering depends on spin, so the contributions of all nucleons except the unpaired one (odd A) cancel out
- What about the other operators?

Outline

- Other Operators are q_{tr} or v_{rel} suppressed
- $\frac{d\sigma}{d\cos\theta} \propto v_{rel}^{2n}, q_{tr}^{2n}, n > 0$
- $q_{tr} \sim v_{rel}\mu \rightarrow v_{rel} \ll 1, \quad q_{tr} \ll \mu$
- This results in a suppression of a factor $v_{rel}^{2n} \ll 1$ comparing to the SI and SD, where $n = 0$

Name	Operator	Interaction
D1	$\bar{\chi}\chi\ \bar{q}q$	SI
D2	$\bar{\chi}\gamma^5\chi\ \bar{q}q$	SI, q^2
D3	$\bar{\chi}\chi\ \bar{q}\gamma^5 q$	SD, q^2
D4	$\bar{\chi}\gamma^5\chi\ \bar{q}\gamma^5 q$	SD, q^4
D5	$\bar{\chi}\gamma_\mu\chi\ \bar{q}\gamma^\mu q$	SI
D6	$\bar{\chi}\gamma_\mu\gamma^5\chi\ \bar{q}\gamma^\mu q$	SI, $q^2 + v^2$
D7	$\bar{\chi}\gamma_\mu\chi\ \bar{q}\gamma^\mu\gamma^5 q$	SD, $q^2 + v^2$
D8	$\bar{\chi}\gamma_\mu\gamma^5\chi\ \bar{q}\gamma^\mu\gamma^5 q$	SD
D9	$\bar{\chi}\sigma_{\mu\nu}\chi\ \bar{q}\sigma^{\mu\nu} q$	SD
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\ \bar{q}\sigma^{\mu\nu} q$	SI, $q^2 + v^2$

Introduction

Energy suppressed operators: Inelastic Dark Matter

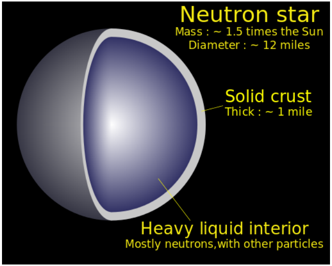
- Those are not the only energy-suppressed interactions
- Inelastic Dark matter: 2 states of similar masses, separated by small mass splitting
- Lighter state χ_1 builds up the observed DM abundance
- For some reason, elastic scattering $\chi_1 N \to \chi_1 N$ not possible
- Instead, it can upscatter to χ_2: $\chi_1 N \to \chi_2 N$
- This is however possible only if allowed kinematically
- $\delta m < \frac{1}{2}\mu v_{rel}^2$
- Note that v_{rel} is limited by the galaxy escape speed, so there is a maximum $\delta m/\mu$ testable on Earth
- If allowed, $\sigma_{inel} \sim \sigma_{el}\sqrt{1 - \frac{\delta m}{\frac{1}{2}\mu v_{rel}^2}}$

Outline

The Strategy

How to search for energy-suppressed interactions?

- Option 1: Increase the Energy!
- $v_{rel} \sim 10^{-3}$ on Earth
- $v_{rel} \sim few \times 10^{-3}$ in the Sun
- $v_{rel} \sim 1$ on Neutron Stars!
- In [1704.01577] is suggested how to use convert lower limits on observed NS to upper limits on DM-matter interactions
- In [1707.09442] follows up in the idea for q^2 and q^4 operators
- In [1807.02840] we study elastic and inelastic EFT operators limits arising from neutron star temperatures



The Strategy

How to search for energy-suppressed interactions?

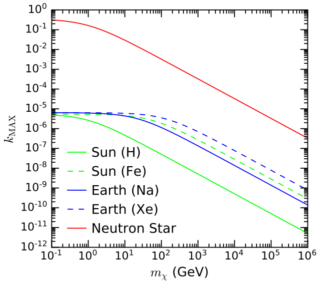
- Option 2: Check if corrections, expected to be sub-leading, are instead dominant
- To compare with LHC results, LHC operators usually associated to Simplified Models, where additional particlea appear
- q^4 suppressed operator is usually associated with the model where a PS mediators mediates interactions between the Dark and Visible sectors
- However such simple model is not suitable to be used for such comparison
- The Minimal UV completion embeds the PS mediators in a 2HDM+P model, as described in [1701.07427] [1404.3716]
- Such model is Gauge Invariant, and once calculating the loop corrections, it generated not only the q^4 operator at tree level, but also the standard SI operator

Outline

Neutron Star heating

Inelastic Scattering

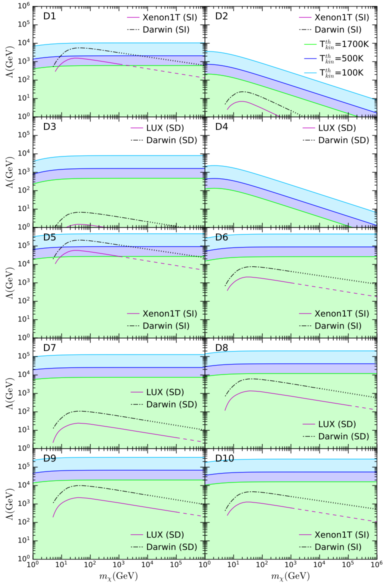
- DM loses energy during capture
- Remaining energy lost during thermalization
- $\approx$ the whole kinetic energy is transferred to the NS
- Inelastic DM: maximum mass splitting depends on target
- NS allows much larger δm than on earth
- At high DM mass, $\delta m < 330 MeV$

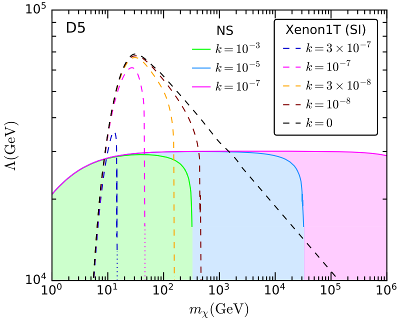


Outline

Neutron Star heating

Results





Outline

For the Scalar, the Lagrangian is

$$
\begin{aligned}
V_{2HDM} &= M_{11}^2\Phi_1^\dagger\Phi_1 + M_{22}^2\Phi_2^\dagger\Phi_2 + (M_{12}^2\Phi_2^\dagger\Phi_1 + h.c.) \\
&+ \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\
&+ \lambda_4(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \frac{1}{2}\left(\lambda_5(\Phi_2^\dagger\Phi_1)^2 + h.c.\right), \\
V_S &= \frac{1}{2}M_{SS}^2 S^2 + \frac{1}{4}\lambda_S S^4 \\
V_{12S} &= \frac{\lambda_{11S}}{2}(\Phi_1^\dagger\Phi_1)S^2 + \frac{\lambda_{22S}}{2}(\Phi_2^\dagger\Phi_2)S^2 + \frac{1}{2}(\lambda_{12S}\Phi_2^\dagger\Phi_1 S^2 + h.c.) \\
\mathcal{L}_{\mathrm{DM}} &= -y_\chi S\bar{\chi}\chi.
\end{aligned}
$$

The fields are

$$\begin{aligned}\Phi_h &= \cos\beta\Phi_1+\sin\beta\Phi_2 = \begin{pmatrix} G^+ \\ \frac{v+h+iG^0}{\sqrt{2}}\end{pmatrix},\\ \Phi_H &= -\sin\beta\Phi_1+\cos\beta\Phi_2 = \begin{pmatrix} H^+ \\ \frac{H+iA}{\sqrt{2}}\end{pmatrix},\\ H &= \cos\theta S_1-\sin\theta S_2,\\ S &= v_S+\sin\theta S_1+\cos\theta S_2,\end{aligned}$$

and the resulting mixing is

$$\sin 2\theta = \frac{2\hat{\lambda}_{hHs} v v_S}{M_{S_1}^2-M_{S_2}^2}.$$

For the PseudoScalar, the Lagrangian is similar, the only difference being

$$\begin{aligned} V_{12P} &= \lambda_{P_1}(\Phi_1^\dagger \Phi_1)P^2 + \lambda_{P_2}(\Phi_2^\dagger \Phi_2)P^2 + i\mu_P(\Phi_1^\dagger \Phi_2 + h.c.)P \\ \mathcal{L}_{\text{DM}} &= -y_\chi S \bar{\chi}\gamma_5 \chi. \end{aligned}$$

and the definition of the fields, where A in the doublet gets relabeled η, and

$$\begin{aligned} \eta &= \cos\theta A - \sin\theta a, \\ P &= \sin\theta A + \cos\theta a, \end{aligned}$$

and the mixing angle is

$$\sin 2\theta = \frac{2vb_P}{M_a^2 - M_A^2}.$$

Outline

An example where one obtains (only) inelastic interactions is Pseudo-Dirac DM:

$$
\begin{aligned}
\mathcal{L} &= \bar{\Psi}(i\partial\!\!\!/ - M_D)\Psi - \frac{m_L}{2}\left(\overline{\Psi^c}P_L\Psi + \text{h.c.}\right) - \frac{m_R}{2}\left(\overline{\Psi^c}P_R\Psi + \text{h.c.}\right) \\
&+ Q_\Psi g\bar{\Psi}\gamma^\mu\Psi\, Z'_\mu + Q_q g\sum_q \bar{q}\gamma^\mu q\, Z'_\mu
\end{aligned}
$$

Taking $m_L = m_R = \frac{1}{2}\delta m$, the Majorana mass eigenstates become

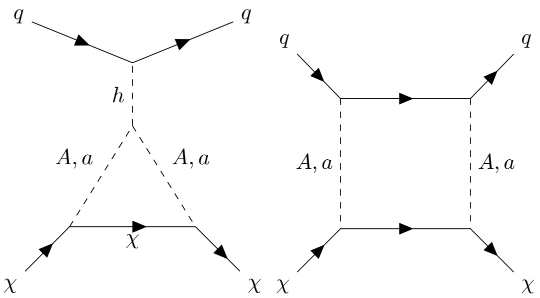
$$
\begin{aligned}
\chi_1 &= \frac{i}{\sqrt{2}}\left(\Psi - \Psi^c\right) \\
\chi_2 &= \frac{1}{\sqrt{2}}\left(\Psi + \Psi^c\right) .
\end{aligned}
$$

The DM Lagrangian effectively reads

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}\,\bar{\chi}_1(i\partial\!\!\!/ - m_1)\chi_1 + \frac{1}{2}\,\bar{\chi}_2(i\partial\!\!\!/ - m_2)\chi_2 \\ &+ iQ_\Psi g\bar{\chi}_2\gamma^\mu Z'_\mu\,\chi_1 + iQ_\Psi g\bar{\chi}_1\gamma^\mu Z'_\mu + Q_q g\sum_q \bar{q}\gamma^\mu q\, Z'_\mu\,\chi_2\end{aligned}$$

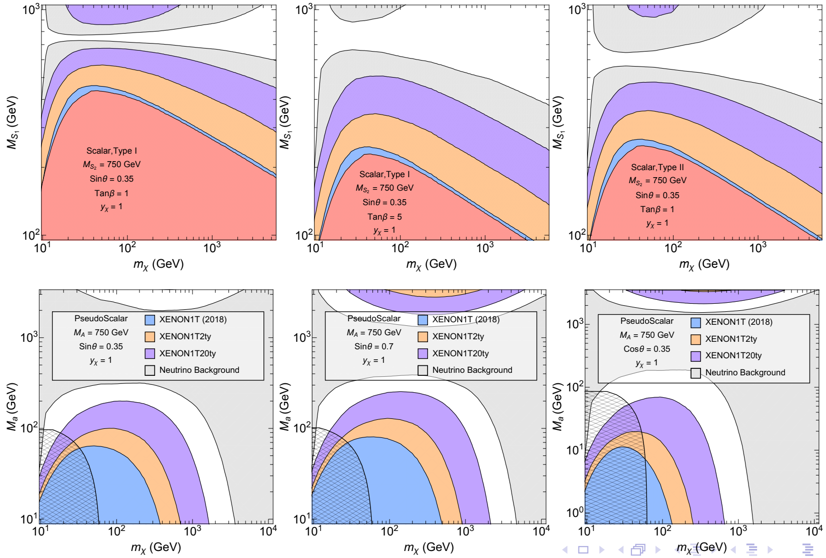
Outline

SI cross section is generated at 1-loop. $lim_{M_A \to M_a} \sigma = 0$, as in the scalar case. The main difference is the loop factor and the m_χ dependance coming from the loops functions.



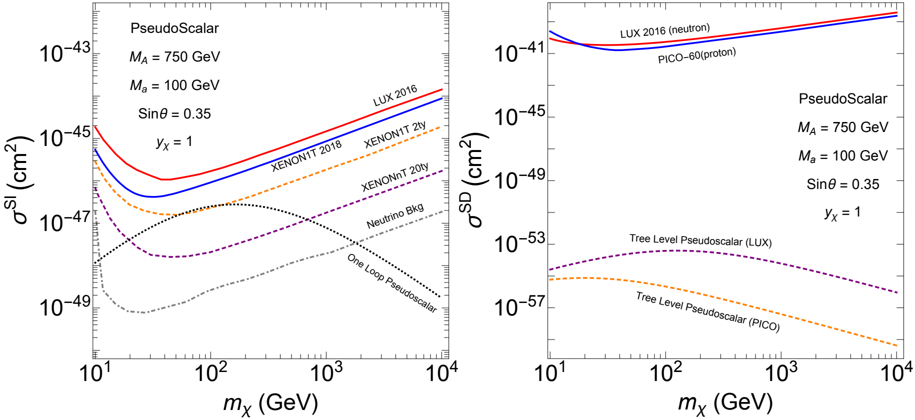
Results and Prospects

DD for the PseudoScalar



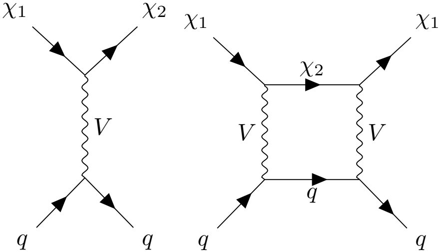
Results and Prospects

DD for the PseudoScalar: Tree vs Loop Level



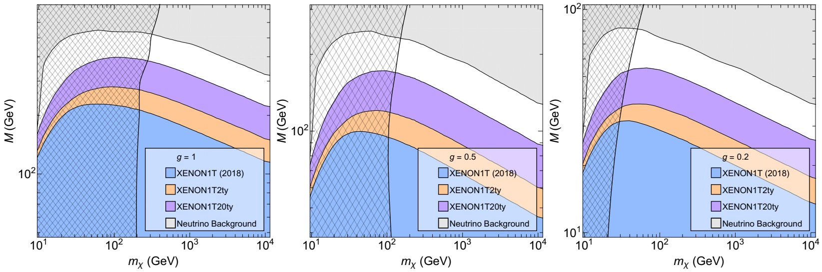
Outline

SI elastic cross section is generated at 1-loop.



Results and Prospects

DD for Inelastic DM



Outline

Conclusions

Summary

- Neutron Stars: an interesting possibility to place upper bounds on DM cross sections
- EFT good for DD, but validity issues at collider: move towards Simplified Models for collider searches
- Recasting collider results in the DD exclusion plane requires renormalizable models and to check 1-loop effects
- The low energy phenomenology of the 2HDM+P model is dominated by 1-loop processes
- Results hold for any Yukawa sector, even for inhert doublet (no yukawa couplings for second doublet)
- DD constraints comparable with collider ones
- For $\delta m \gtrsim 100\,\mathrm{KeV}$, the 1-loop elastic cross section can dominate DD, and for $\delta m \lesssim \,\mathrm{GeV}$ one can compare with monojet, and constraints are complementary
- DMWG whitepaper coming out soon