An introduction to direct dark matter detection

Markus Eichhorn

24th of June 2019

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- WIMP: Dirac fermion DM (no Majorana Fermion)

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- also no excitation N' of the nucleus $\Rightarrow$ small or vanishing momentum transfer in the elastic scattering process $\mathcal{O}(\mathrm{MeV})$

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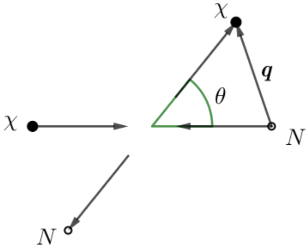

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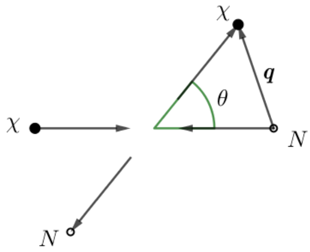

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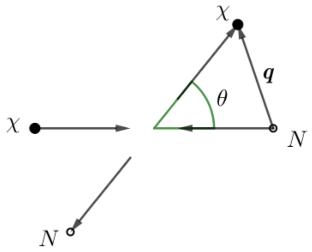

where $\boldsymbol{q}^2$ evaluates to

$$\boldsymbol{q}^2 = \tilde{\boldsymbol{p}}'^2_\chi - 2\tilde{\boldsymbol{p}}'_\chi \tilde{\boldsymbol{p}}_\chi + \tilde{\boldsymbol{p}}^2_\chi$$
$$= 2(\mu \boldsymbol{v}_\chi)^2 (1 - \cos\theta)$$

The recoil energy

The only momentum the nucleus carries is the momentum transfer $\boldsymbol{q}$ thus

$$\begin{aligned} E_{\mathrm{R}} &= \frac{\boldsymbol{q}^2}{2m_{\mathrm{N}}} \\ &= \frac{\mu^2 \boldsymbol{v}_\chi^2}{m_{\mathrm{N}}}(1 - \cos\theta) \end{aligned}$$

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- if $m_\chi \gg m_{\mathrm{N}}$ then $\mu \approx m_{\mathrm{N}}$
- if $m_\chi \approx m_{\mathrm{N}}$ then $\mu \approx \frac{m_{\mathrm{N}}}{2}$

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- achieve $m_{\mathrm{N}} \approx m_{\chi}$

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The recoil spectrum reads

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- $\langle\cdot\rangle$ denotes the average over velocities

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where $\mathrm{f}(v)$ is a halo model dependent velocity propability function

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- axial interaction with quarks

$$\mathcal{O}_{\mathrm{D8}} = \bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{q}\gamma_{\mu}\gamma_5 q \quad c^{\mathrm{q}}_{\mathrm{D8}} = \frac{1}{M_*^2}$$

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$$\mathcal{O}_5 = \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$
$$\mathcal{O}_7 = \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma_5 q$$

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Quarks and gluons are all constituents of a nucleon

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We map the combinations of operators on parton level to an operator at nucleon level

$$\mathcal{O}^{\mathrm{N}}_{\mathrm{D1}} = C\bar{\chi}\chi\bar{N}N$$

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- the full expression reads

$$C = \sum_{\mathrm{q=u,d,s}} c^{\mathrm{q}}_{\mathrm{D1}} \frac{m_{\mathrm{N}}}{m_{\mathrm{q}}} f^{(\mathrm{N})}_{\mathrm{q}} + \frac{2}{27} f^{(\mathrm{N})}_{\mathrm{G}} \left(\sum_{\mathrm{q=c,b,t}} c^{\mathrm{q}}_{\mathrm{D1}} \frac{m_{\mathrm{N}}}{m_{\mathrm{q}}} - \frac{1}{3\pi} c^{\mathrm{g}}_{\mathrm{D11}} m_{\mathrm{N}} \right)$$

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- gluon and heavy quarks are combined

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  - identify contribution of heavier quarks by gluon contribution. A detailed calculation yields the prefactors

General case

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again we have $\mathcal{O}_k^{\rm N} = \bar{\chi}\Gamma\chi\bar{N}\Gamma' N$ with $\Gamma, \Gamma' \in \{\gamma_\mu, i\gamma_5, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\}$ a full list is given in [1603.08002].

Important operators on nucleon level

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The expression of the nucleon operator yields the relations

$$\langle \mathcal{O}_{\mathrm{D8}}^{\mathrm{N}} \rangle = -\frac{1}{2} \langle \mathcal{O}_{\mathrm{D9}}^{\mathrm{N}} \rangle = -16 m_\chi m_{\mathrm{N}} \mathcal{O}_4^{\mathrm{NR}}$$
$$\langle \mathcal{O}_{\mathrm{D1}}^{\mathrm{N}} \rangle = \langle \mathcal{O}_{\mathrm{D5}}^{\mathrm{N}} \rangle = 4 m_\chi m_{\mathrm{N}} \mathcal{O}_1^{\mathrm{NR}}$$

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Examples are

$$v^2, \quad \mathrm{i}(\boldsymbol{S}_\chi \times \boldsymbol{q}) \cdot \boldsymbol{v}, \quad \boldsymbol{v}^\perp \cdot \boldsymbol{S}_N$$

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- For non zero momentum transfer additional form factors are needed

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- experimental challenge: overcome backgrounds

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Distinct behaviour from nuclear recoil. The keyword to bare in mind here is: quenching.

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- luckily multiple scattering processes and thus distinguishable from WIMP interaction

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- However there are hypothesis how to overcome the neutrino floor by looking for annual modulations

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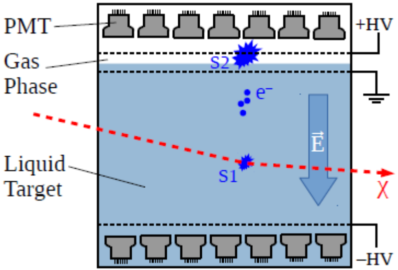
- Argon allows for pulse shape discrimination but contains $^{39}\mathrm{Ar}$. It is liquid below $87.2\,\mathrm{K}$

How to meassure a nuclear recoil in LXe?

- scintillation via photomultipliers (S1)



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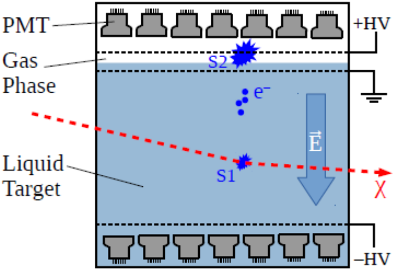

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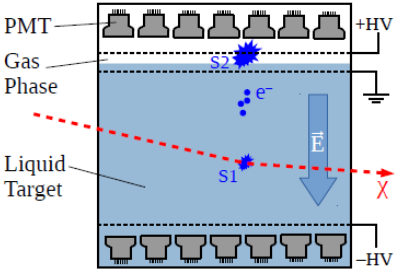

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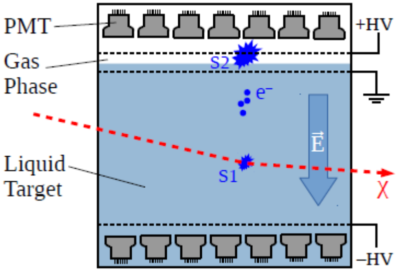

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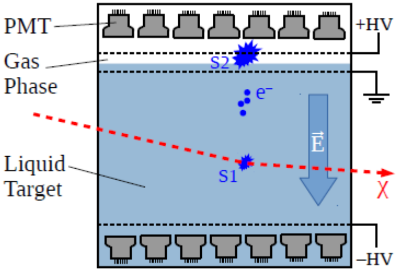
- from time difference determine location of interaction (time projection chamber)



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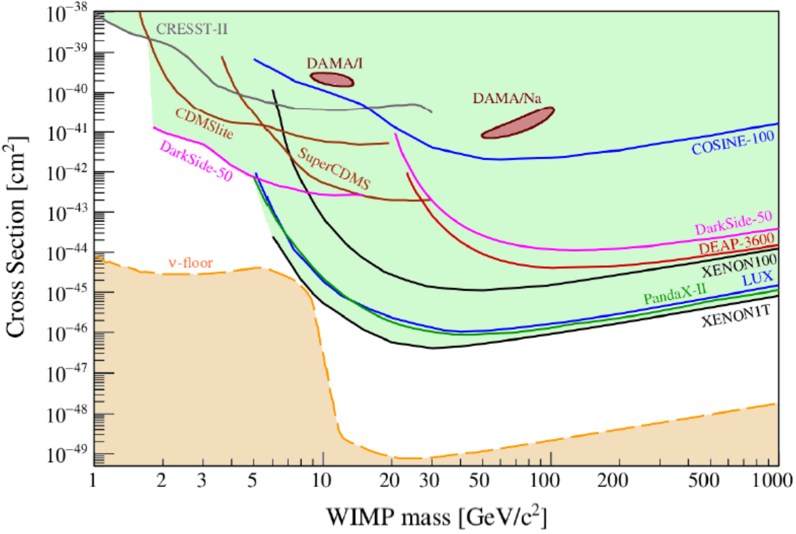
- many stages XENON10, XENON100, XENON1T

The current limits for SI interaction [arXiv:1903.03026]



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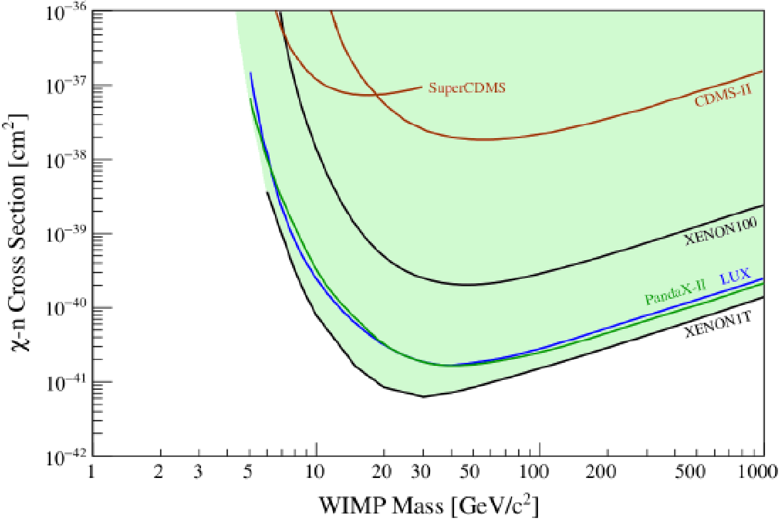

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- direct detection for fermionic WIMP DM
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- the procedure to go from the parton level to the nucleus level
- The Xenon1T experiment and its results

Thank you for your attention.

sources

- Marc Schumann, *Direct detection of WIMP dark matter*, (2019), [arXiv:1903.03026]
- Andrea De Simone, Thomas Jacques, *Simplified models vs. effective field theory approaches in dark matter searches*, (2016), [arXiv:1603.08002]
- Stefano Profuno, *An Introduction to particle dark matter*, World Scientific Publishing Europe Ltd. (2017)