Testing dark matter interactions with nuclear excitations

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based on
arxiv:1906.xxxxx

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Introduction

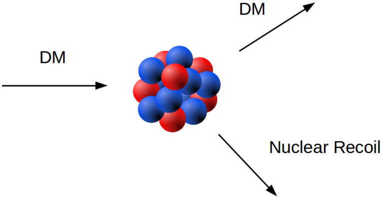
- sensitivity of direct detection increases by orders of magnitude

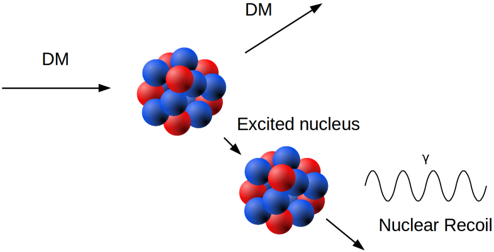
What can we learn once a signal is observed?

- initial detection with $\mathcal{O}$(a few) events $\Rightarrow$ limited information
- unlimited ignorance: mass, spin, DM-SM interaction ...?
- need more data but: more data = bigger experiment = $$$

Can we get two experiments for the price of one?

Elastic and inelastic scattering





Xenon as a target

- ^{129}Xe and ^{131}Xe have very low lying nuclear excitations ($\approx$ 40 keV and $\approx$ 80 keV)
- ^{129}Xe and ^{131}Xe are common isotopes (26% and 21% in natural xenon)
- liquid xenon detectors are leading the search for dark matter
- new, bigger detectors are on the way (XENONnT, LZ, DARWIN)

DM-nucleon interactions

- How does the dark matter interact with the nucleus?
- $v_{DM} \approx 10^{-3} \Rightarrow$ non-relativistic scattering
- model independent parametrization in terms of non-relativistic effective theory Fitzpatrick et al 1203.3542
- for fermionic DM: 14 operators as combinations are 1, $\vec{S}_\chi$, $\vec{S}_N$, q, $\vec{v}^\perp$

$$\begin{array}{ll}
\mathcal{O}_1 = 1_\chi 1_N & \mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right) 1_\chi \\
\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N & \mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right) 1_N \\
\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{q}{m_N}\right) & \mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp 1_\chi \\
\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp 1_N & \mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right) \\
..... & .....
\end{array}$$

Nuclear physics 101

Need to know:

$$\frac{\mathrm{d}\sigma_T(v^2, E_R)}{\mathrm{d}E_R} = \frac{m_T}{2\pi v^2}\langle|\mathcal{M}_{\mathrm{eff}}|^2\rangle$$

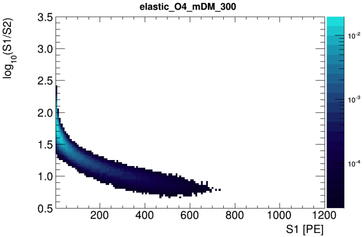
Nuclear matrix elements? Follow formalism for semileptonic weak interactions with nuclei Fitzpatrick et al 1203.3542 or review by T. Donnelly and R. Peccei '79

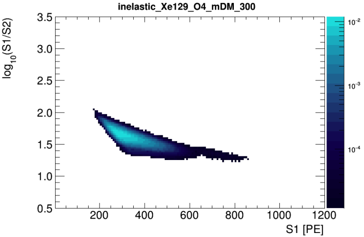
- dark matter response function $R_A^{\tau\tau'}$ analytic
- one-body nuclear matrix elements $\langle|\alpha|\vdots\vdots A_{L,\tau}\vdots\vdots|\beta|\rangle$

  known analytically in harmonic oscillator basis
- one-body density matrix elements $\psi^{f,i}_{L;\tau}(|\alpha|, |\beta|)$

  computed in shell model with Nushell@MSU

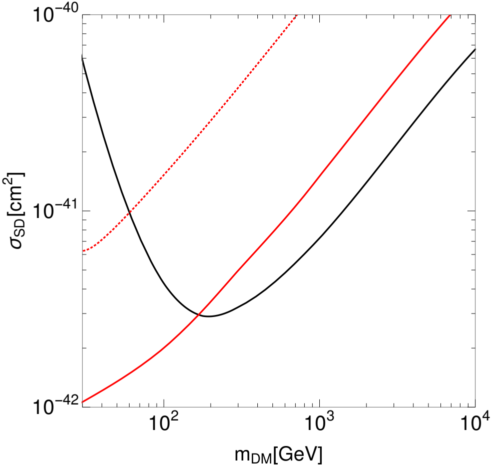
Two-phase liquid xenon detectors





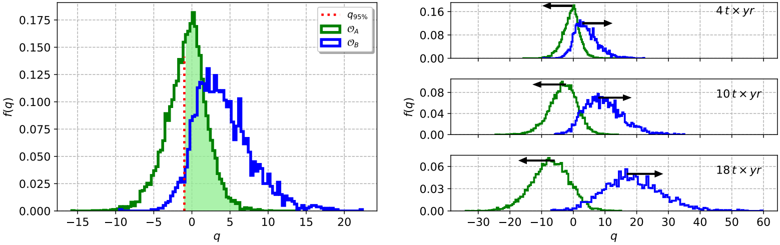
- two-phase liquid Xenon detectors observe scintillation light and ionization
- different signal strength for nuclear recoils, γ emission and electronic recoils
- elastic scattering, inelastic scattering and backgrounds can be (partially) separated

Sensitivity



90% of experiments will observe a 3σ for elastic scattering (XENONnT, 4 ton×years) and inelastic scattering (DAWRIN, 200 ton×years) at these cross sections

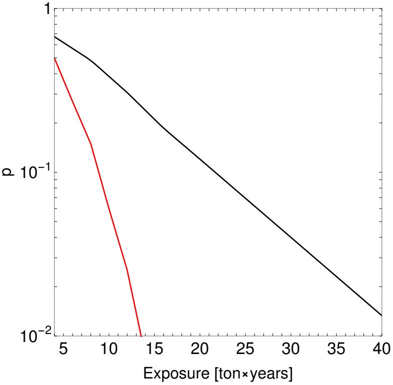
Hypothesis testing



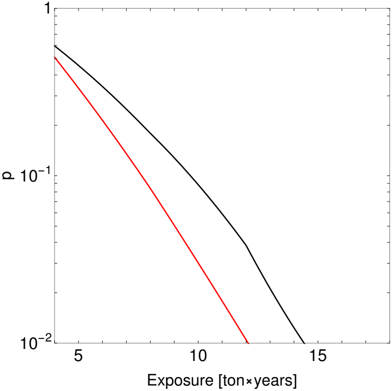
$$q_A := -2\ln\left[\frac{\max\limits_{\Theta_A,\mathbf{R}_{\mathrm{BG}}} \mathscr{L}(\mathcal{D}_A|\Theta_A,\mathbf{R}_{\mathrm{BG}})}{\max\limits_{\Theta_B,\mathbf{R}_{\mathrm{BG}}} \mathscr{L}(\mathcal{D}_A|\Theta_B,\mathbf{R}_{\mathrm{BG}})}\right] \quad \text{and} \quad q_B := -2\ln\left[\frac{\max\limits_{\Theta_A,\mathbf{R}_{\mathrm{BG}}} \mathscr{L}(\mathcal{D}_B|\Theta_A,\mathbf{R}_{\mathrm{BG}})}{\max\limits_{\Theta_B,\mathbf{R}_{\mathrm{BG}}} \mathscr{L}(\mathcal{D}_B|\Theta_B,\mathbf{R}_{\mathrm{BG}})}\right]$$

q-value distributions for the nullhypothesis $\mathcal{H}_{\mathcal{O}_A}$ and the alternative hypothesis $\mathcal{H}_{\mathcal{O}_B}$

Exclusion power



$\mathcal{O}_5$ versus $\mathcal{O}_4$



$\mathcal{O}_9$ versus $\mathcal{O}_4$

improved exclusion power due to inelastic events

Conclusions

- elastic scattering is accompanied by inelastic scattering
- Xenon-based experiments are well suited
- clear discovery potential in future experiments
- improved identification of dark matter interactions

One and a half experiment for the price of one