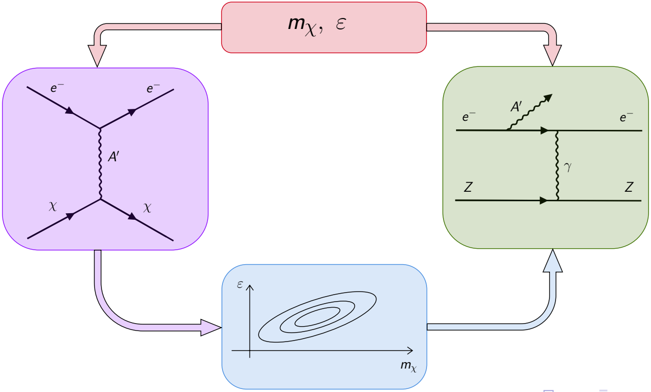
On the dark matter origin of an LDMX signal

Speaker: Andreas Lund

Authors: Riccardo Catena, Taylor Gray, Andreas Lund

Chalmers University of Technology, Department of Physics, SE-412 96 Göteborg, Sweden



Presentation Outline

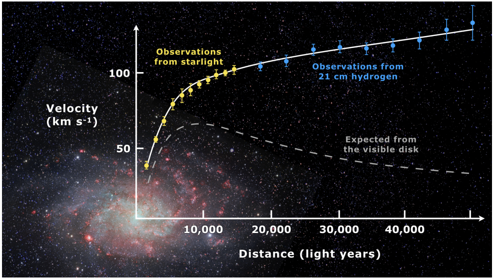
Validating the dark matter origin of an LDMX signal with direct detection experiments

- Introduction to dark matter
- Simulating a hypothetical LDMX signal
- Simulating a hypothetical direct detection signal
- Bayesian parameter estimation
- Validation results

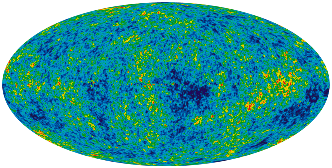
Evidence for Dark Matter

Dark matter accounts for 85% of the Universes matter content, and yet has only been seen through gravitational interactions.

- Galaxy rotation curves
- Gravitational lensing
- Cosmic microwave background
- Structure formation from simulations



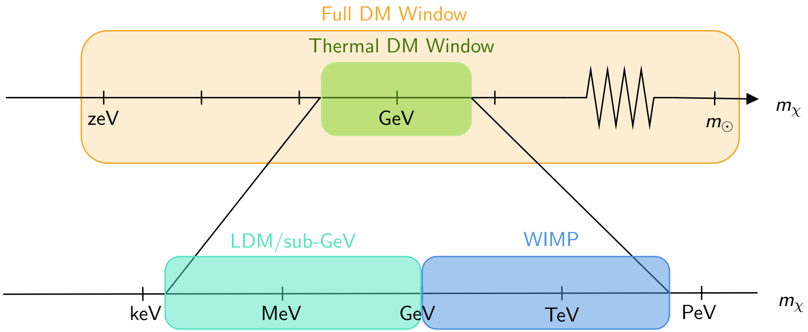
Credit: Mario De Leo, CC BY-SA 4.0 https://creativecommons.org/licenses/by-sa/4.0, via Wikimedia Commons.



Credit: NASA / WMAP Science Team WMAP # 121238 Image Caption 9 year WMAP image of background cosmic radiation (2012)

What is the Nature of Dark Matter?

- The main search effort has been for weakly interacting massive particles (WIMPs)
- Light dark matter (LDM) particle candidates are recently being explored



Representative Light Dark Matter Model

Model Lagrangian given by:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{m_{A'}^2}{2}A'_{\mu}A'^{\mu} - A'_{\mu}(\varepsilon e J_{EM}^{\mu} + g_D J_{\chi}^{\mu})$$

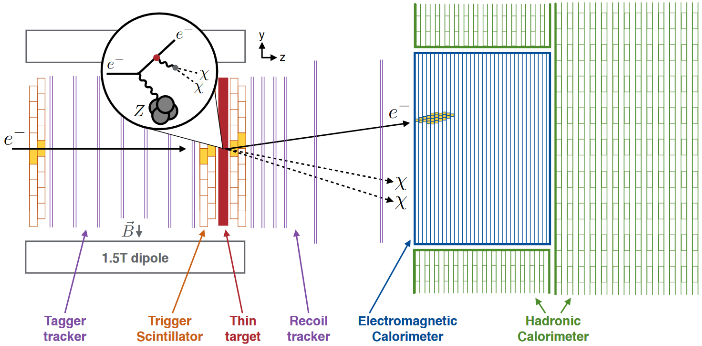
- Scalar dark matter χ with a massive dark photon A' (bosonic vector mediator).
- We specify $m_{A'} = 3m_{\chi}$ and $\alpha_D \equiv g_D^2/(4\pi) = 0.5$.
- Free parameters: DM mass m_{χ} and kinetic mixing ε.

Presentation Outline

- Introduction to dark matter
- Simulating a hypothetical LDMX signal $\Leftarrow$
- Simulating a hypothetical direct detection signal
- Bayesian parameter estimation
- Validation results

Light Dark Matter eXperiment (LDMX)

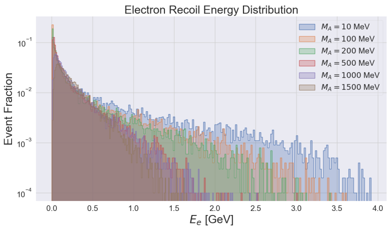
- Search for the "Dark bremsstrahlung" process
- Missing energy and transverse momentum of recoil electrons

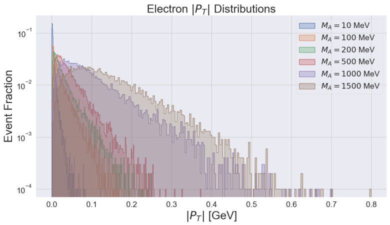


Credit: T. Åkesson *et al.*, "Current Status and Future Prospects for the Light Dark Matter eXperiment", Aug 2023.

Simulating an LDMX Signal

- Simulate scattering interactions using the **MadGraph5_aMC@NLO** software
- Generate dark bremsstrahlung events in the LDMX setup



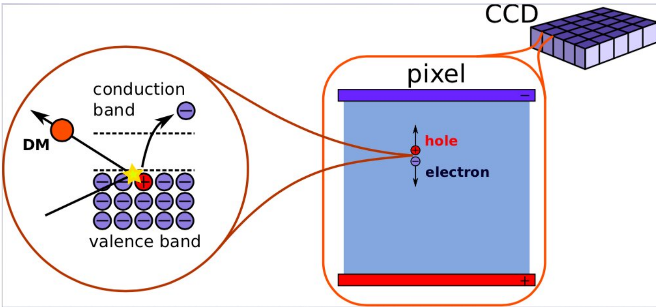


Presentation Outline

- Introduction to dark matter
- Simulating a hypothetical LDMX signal
- Simulating a hypothetical direct detection signal $\Leftarrow$
- Bayesian parameter estimation
- Validation results

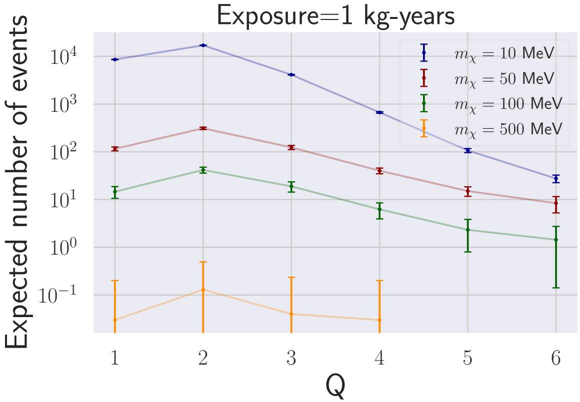
Direct Detection Experiments

- Detection in a semiconductor crystal (or a nobel liquid)
- Dark matter collision events excite electrons in the material.



Simulating a Direct Detection Signal

- To simulate these rates we use the **DarkELF** software
- Experiment signal: $dN/dQ = \text{exposure} \times dR/dQ$



Presentation Outline

- Introduction to dark matter
- Simulating a hypothetical LDMX signal
- Simulating a hypothetical direct detection signal
- Bayesian parameter estimation $\Leftarrow$
- Validation results

Bayesian Statistics

Bayes theorem to estimate posterior probability distribution.

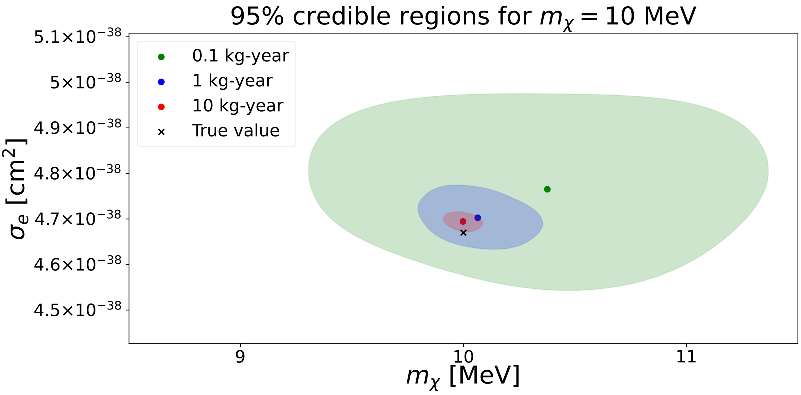
$$P(\theta|D,\mathcal{M}) = \frac{P(D,\mathcal{M}|\theta)P(\theta)}{\int P(D,\mathcal{M}|\theta)P(\theta)d\theta}.$$

In our case:

- $\mathcal{M}$ is the dark matter model, which is described by $\mathcal{L}$
- $\theta = m_\chi, \sigma_e \propto \varepsilon^2$
- $D = N^i_{\rm exp}$ where $N^i_{\rm exp}$ are the bins from the DD result

Parameter Estimation with Monte Carlo Methods

Sample posterior probability density function using Monte carlo algorithm **MultiNest** (PyMultiNest software)

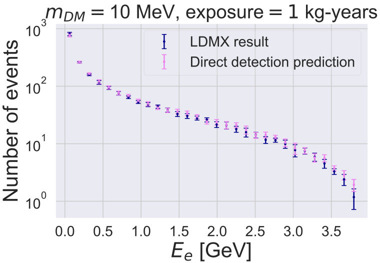


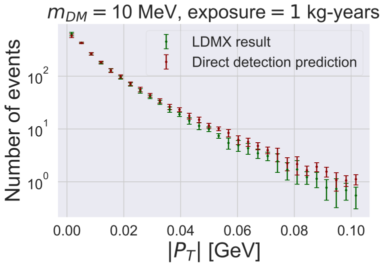
Note: $\sigma_e \propto \varepsilon^2$

Presentation Outline

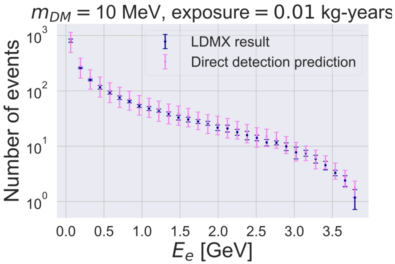
- Introduction to dark matter
- Simulating a hypothetical LDMX signal
- Simulating a hypothetical direct detection signal
- Bayesian parameter estimation
- Validation results $\Leftarrow$

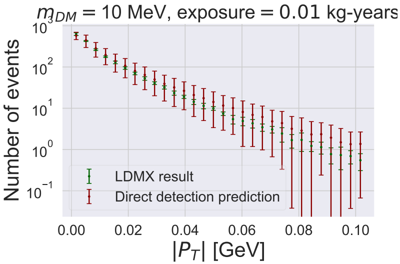
Incorporating the DD Prediction into LDMX Plots





Incorporating the DD Prediction into LDMX Plots

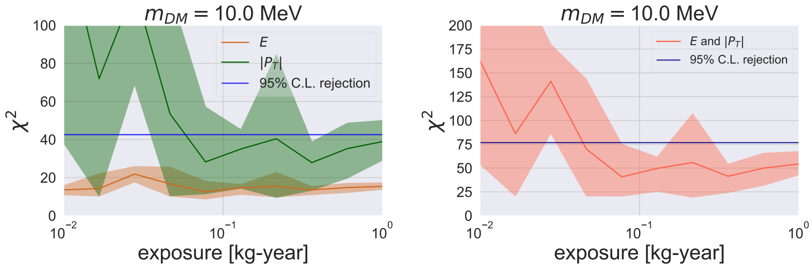




Required Exposure for Validation

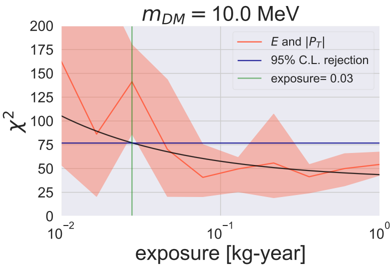
χ^2 hypothesis test. Are two distributions sampled from different underlying functions?

$$\chi^2 = \sum_i \frac{(N_{LDMX,i} - N_{DD,i})^2}{N_{LDMX,i} + N_{DD,i}}.$$

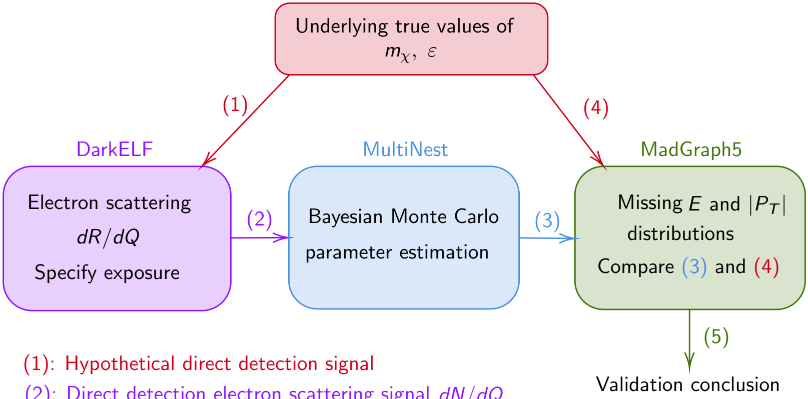


Required Exposure for Validation

The required exposure for validation depends on the dark matter parameters



Method Overview



(1): Hypothetical direct detection signal

(2): Direct detection electron scattering signal dN/dQ

(3): Posterior distribution estimates for $m_\chi,\ \varepsilon$

(4): Hypothetical LDMX signal

(5): Chi-square test applied to (3) and (4)

Backup slide: Direct Detection Processes

We consider DM-electron scattering where the rate is given by

$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}\frac{\bar{\sigma}_e}{\mu_{\chi e}^2}\frac{\pi}{\alpha}\int d^3v f_\chi(v)\int\frac{d^3\mathbf{k}}{(2\pi)^3}k^2|F_{DM}(k)|^2$$
$$\int\frac{d\omega}{2\pi}\frac{1}{1-e^{-\beta\omega}}\mathrm{Im}\left[\frac{-1}{\epsilon(\omega,\mathbf{k})}\right]\delta\left(\omega+\frac{k^2}{2m_\chi}-\mathbf{k}\cdot\mathbf{v}\right)$$

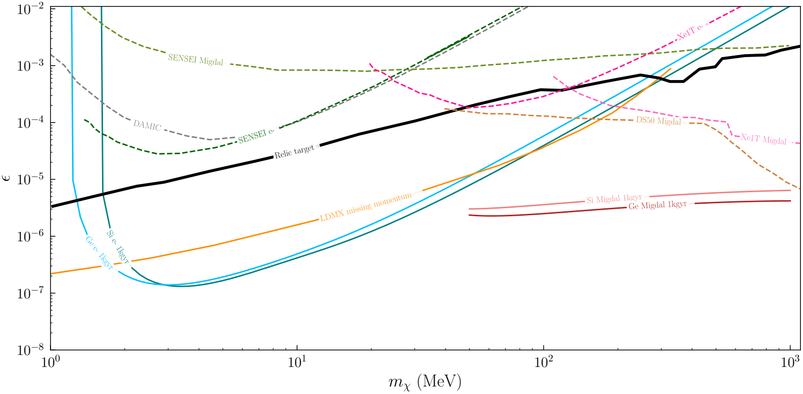
where

$$\bar{\sigma}_e = \frac{\mu_\chi^2 g_e^2 g_\chi^2}{\pi(\alpha^2 m_e^2 + m_{A'}^2)^2} = \frac{16\pi\mu_{\chi e}^2\alpha\varepsilon^2\alpha_D}{(m_{A'}^2+\alpha^2 m_e^2)^2} \propto \varepsilon^2$$

One can also consider other DM-material interactions
e.g: Migdal effect, dark photon absorption, multiphonon processes.

Backup slide: Exclusion Limits

$$\text{exclusion limit} = \frac{\sigma_{ref} \times 2.3}{R \times \text{exposure}}$$



Backup slide: Parameter estimation with Monte Carlo Methods

We specify likelihood and prior from the hypothetical direct detection experiment:

$$P^{(i)}(N^i_{\rm exp}|m_\chi,\sigma_e) = \frac{e^{-N_i(m,\sigma_e)}}{N^i_{\rm exp}!} N_i(m_\chi,\sigma_e)^{N^i_{\rm exp}} \,,$$

$$P(\{N^i_{\rm exp}\}|m_\chi,\sigma_e) = \prod_i P^{(i)}(N_{{\rm exp}^i}|m_\chi,\sigma_e)\,,$$

$$P(m_\chi) \sim 10^{\mathcal{U}(6,8)}{\rm eV}\,, \quad P(\sigma_e) \sim 10^{\mathcal{U}(-41,-35)}{\rm cm}^2$$

The posterior parameter estimate is obtained using the formula:

$$P(\theta|D,\mathcal{M}) = \frac{P(D,\mathcal{M}|\theta)P(\theta)}{\int P(D,\mathcal{M}|\theta)P(\theta)d\theta}.$$