Direct detection of Light Dark Matter with Semiconducting Electrons

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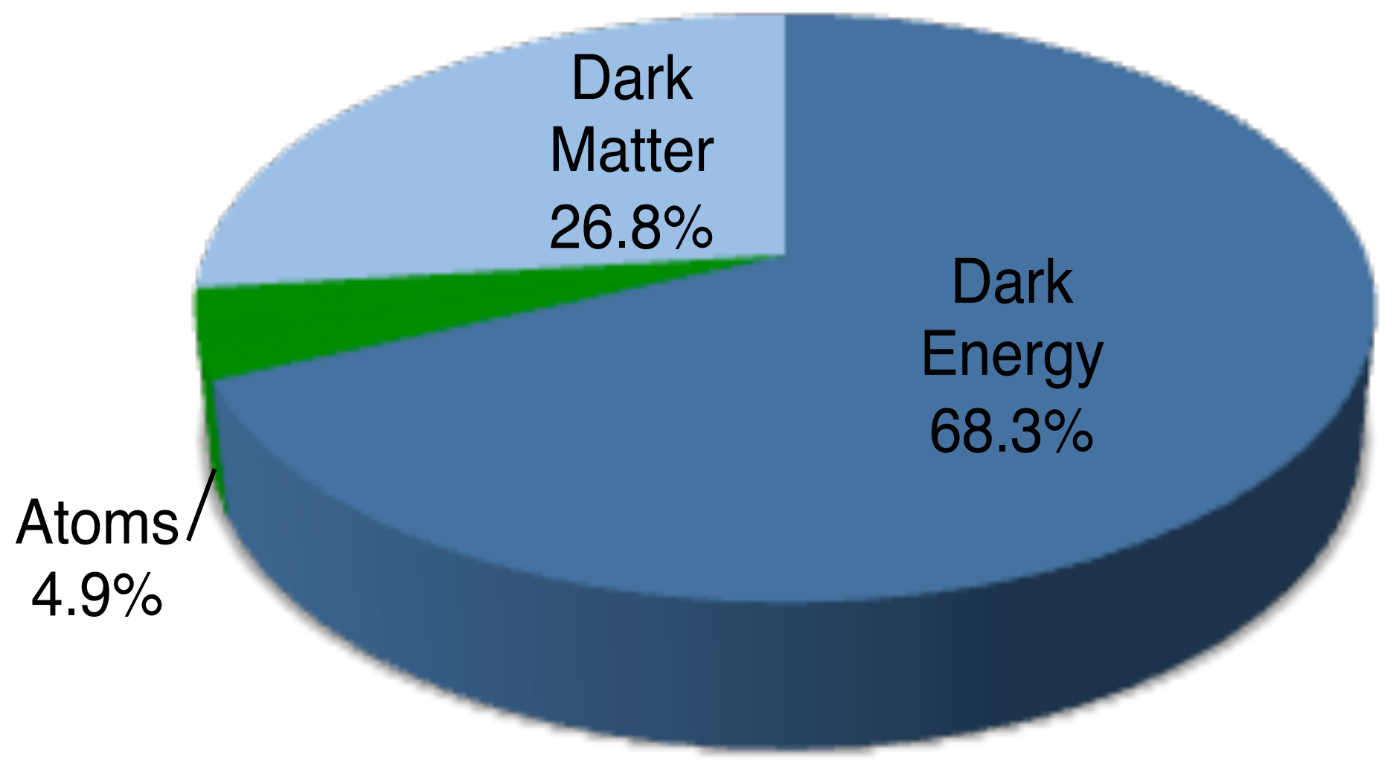
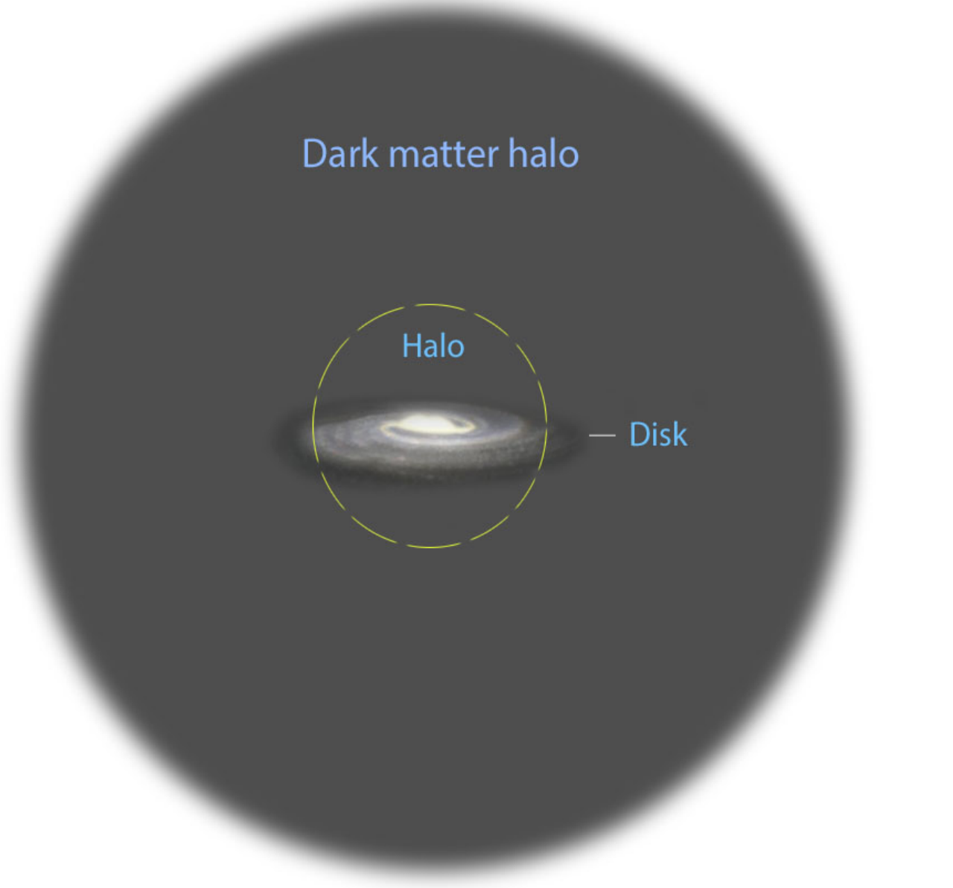
What is Dark Matter?

Based on astronomical and astrophysical observations we know that only a small fraction of the Universe is made of ordinary matter (basically atoms). It has been determined that these Dark Matter particles bind gravitationally to galaxies. In particular, in the Milky Way they travel at the speeds comparable to those of stars orbiting around the galactic center of order 100km/s, much below the relativistic regime.



Composition of the visible Universe.
Data from ESA Planck Survey.



Milky Way model

Schematic representation of the distribution of matter in our galaxy. Stars are located in the bulge, and in the disk (including arms). Dark Matter is distributed in a radially-symmetric halo.
From www.astrobob.com

Many models of DM have been proposed since its existence was hypothesized in the 50's. Dark Matter is widely believed to be made of an unknown type of elementary particles. These particles are travelling through space, interacting gravitationally and possibly also interactin very weakly through other fundamental mechanisms.

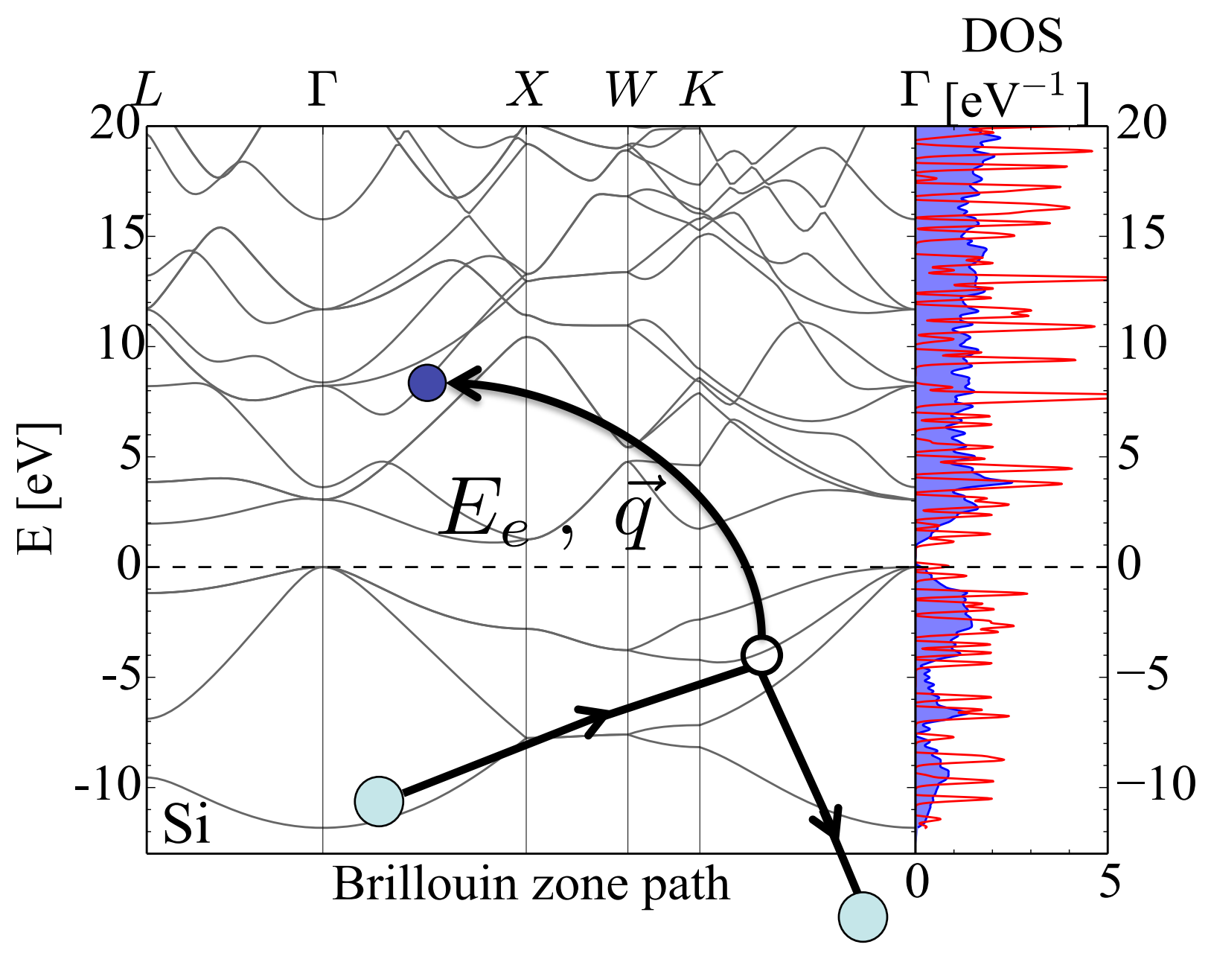
Current status: Recent experimental evidence suggests that the WIMP paradigm, which proposes masses in the GeV-TeV range, is not a good candidate for DM. This motivates to continue the search in different regions of the DM parameter space, in particular in lower masses.

How to detect sub-GeV Dark Matter

DM particles will be subject to fundamental interactions with ordinary target particles. In the recent years nuclei have been used as target. But if DM is lighter than ~1GeV, nuclei are too heavy to be good target particles because only small energy transfers can occur, which then requires extreme detector sensitivity. For example for m_χ=10MeV, the energy transferred to a typical nucleus is ~10meV. However, if we use the much lighter **electrons as target**, this energy transfer would be ~2.5eV, **reducing the required detector sensitivity by over 2 orders of magnitude**.

A DM particle can scatter off an electron in a semiconductor, transferring energy E_e and momentum **q**, bringing the electron to a conduction state. An applied bias voltage across the semiconductor will make this excitation produce a secondary cascade of electron-hole pairs and phonons that can be measured.

This work provides theoretical guidance on what regions of Dark Matter parameter space semiconductor detectors based on electron scattering will be able to probe in the sub-GeV Dark Matter mass range.



Band structure and density of states of silicon and a representation of a Dark Matter particle (light blue) scattering off a valence electron in silicon. The electron is excited from a valence state to a conduction state (blue), leaving behind a hole in the valence (white).

A note on feasibility: Existing DM detectors can be adapted from nucleus scattering to electron scattering, thus making the project economically feasible. An example of this is the Xenon10 detector, which was adapted from scattering to Xe nuclei to Xe ionization via DM-electron scattering. Likewise semiconductor detectors can be adapted to detect DM-electron events.

DM-electron scattering rates

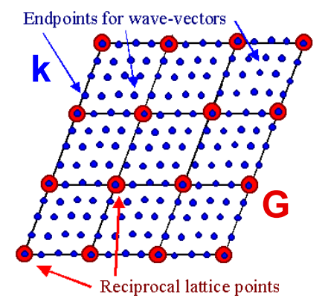
Theory

The DM-electron scattering rate is is given by the perturbative formula

$$R = N_{\text{cell}} \frac{\rho_\chi}{m_\chi} \alpha \overline{\sigma}_e \frac{m_e^2}{\mu_{\chi e}^2} \sum_{i,i'} \int q dq \int_{\text{BZ}} d^3k \left| f_{i\to i'}(\mathbf{q},\mathbf{k}) \right|^2 \left| F_{\text{DM}}(q) \right|^2 \eta(v_{\min})$$

which brings together astrophysics, particle physics and solid state physics:

- Astrophysics $$\eta(v_{min}) = \int_{v_{min}} \frac{d^3v}{v} f_{\text{MB}}(\mathbf{v}) \;,\; v_{min} = \frac{\Delta E_{i,i'}}{q} + \frac{q}{2m_\chi} \;,\; v_E + v_\chi \le v_{\text{esc}}$$
- Particle Physics $$\sigma(q) = \overline{\sigma}_e \times \left| F_{\text{DM}}(q) \right|^2 \;,\; \overline{\sigma}_e \equiv \frac{\mu_{\chi e}^2}{16\pi m_\chi^2 m_e^2} \overline{\left| \mathcal{M}_{\chi e}(\alpha^2 m_e^2) \right|^2}$$ $$F_{\text{DM}}(q) = \begin{cases} 1\,, & \text{heavy vector or MDM} \\ \alpha m_e/q\,, & \text{EDM} \\ (\alpha m_e/q)^2\,, & \text{massless or ultralight mediator} \end{cases}$$
- Solid State Physics $$\begin{aligned} \psi_{i,\mathbf{k}}(\mathbf{r}) &= \tfrac{1}{V} \textstyle\sum_{\mathbf{G}} u_i(\mathbf{k}+\mathbf{G}) e^{i(\mathbf{k}+\mathbf{G})\cdot\mathbf{r}} \\ f_{i\to i'}(\mathbf{q},\mathbf{k}) &= \textstyle\sum_{\mathbf{G}} u_{i'}^*(\mathbf{k}+\mathbf{G}+\mathbf{q}) u_i(\mathbf{k}+\mathbf{G}) \end{aligned}$$



- **q** is the momentum transfer of the DM-electron collision
- η contains information regarding the velocity distribution of DM in the vicinity of the Earth (where detectors will be located)
- σ_e is the cross section of a DM particle to a free electron at momentum transfer q=αm_e. This quantity is model independent
- F_{DM} is the DM form-factor and is model dependent. We study 3 cases
- $f_{i\to i'}$ is the crystal form-factor which is built solely from the valence and conduction wavefunctions

Computational methods

We are interested in energy transfers up to ~40eV, which set the detector thresholds. Large momentum transfers are kinematically relevant. This implies that large wavevector Fourier components (large **G**) are important, so the size of the wavefunction basis needs to be large. Additionally, a relatively fine k-vector mesh is needed to capture the low energy transitions accurately.

The main burden of this problem resides in calculating the crystal form-factor because of the N_G^2 N_k^2 scaling.

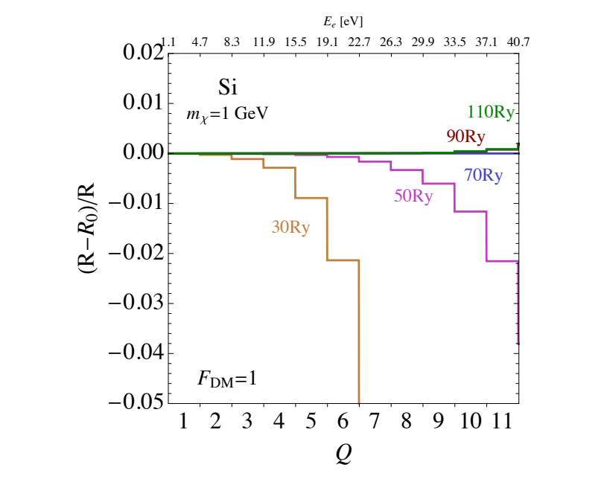
QEdark is an extension to the Quantum ESPRESSO code that calculates the crystal form-factor and the DM-electron scattering rates. The solid state wavefunctions are calculated using Density Functional Theory.

- k-vector integrals are discretized
- Finite set of G-vectors for wavefunction expansion
- Integrate crystal form-factor "on the fly" to avoid storing it in memory
- Parallelization over k-point sums (integrals)

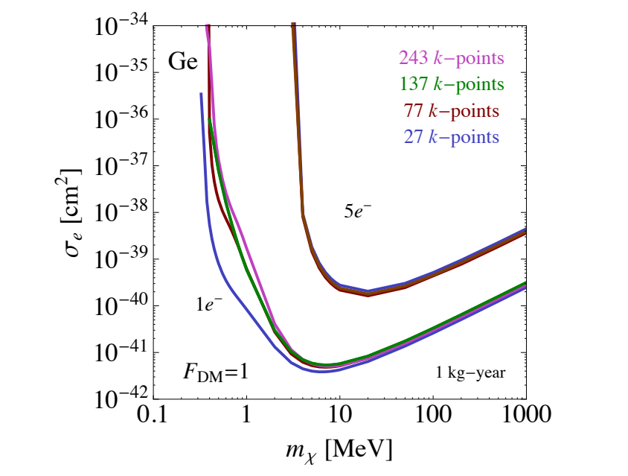
Choice of computational parameters

- Regular mesh of 216 points with additional 27 special k-points (Γ, X, L) to capture important transitions
- A cutoff value of E_{cut} = 70Ry giving approximately 2000 G-vectors. That produces a large enough q-space to get an accuracy O(1%) in the scattering rates
- 4 valence bands for Si (3s and 3p) and 14 for Ge (3d, 4s and 4p). 52 conduction bands for both. This choice covers any possible transition below ≈ 60eV.

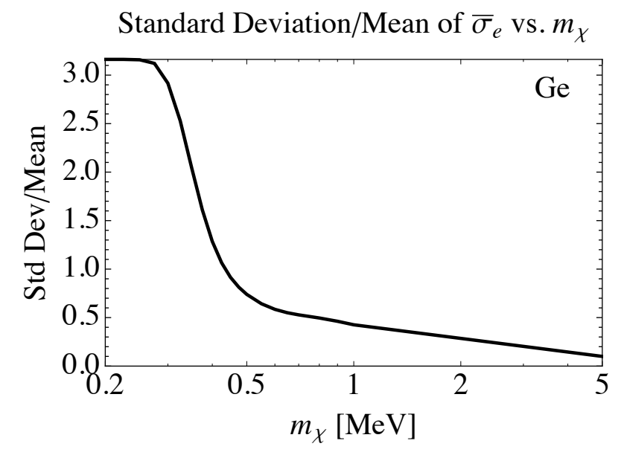
Convergence of numerical results



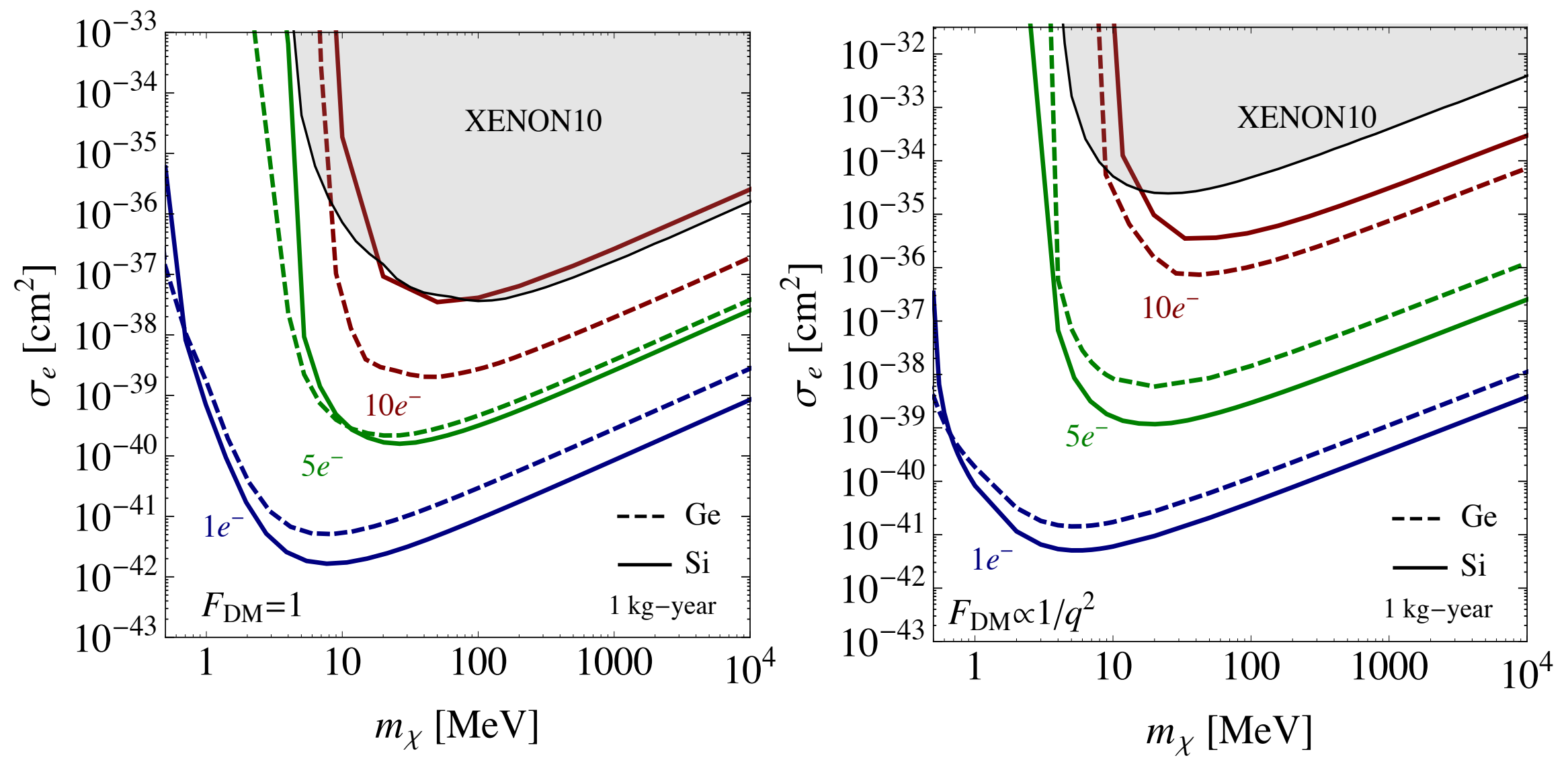
Convergence of the scattering rate with E_{cut} for Si and DM mass of 1GeV.



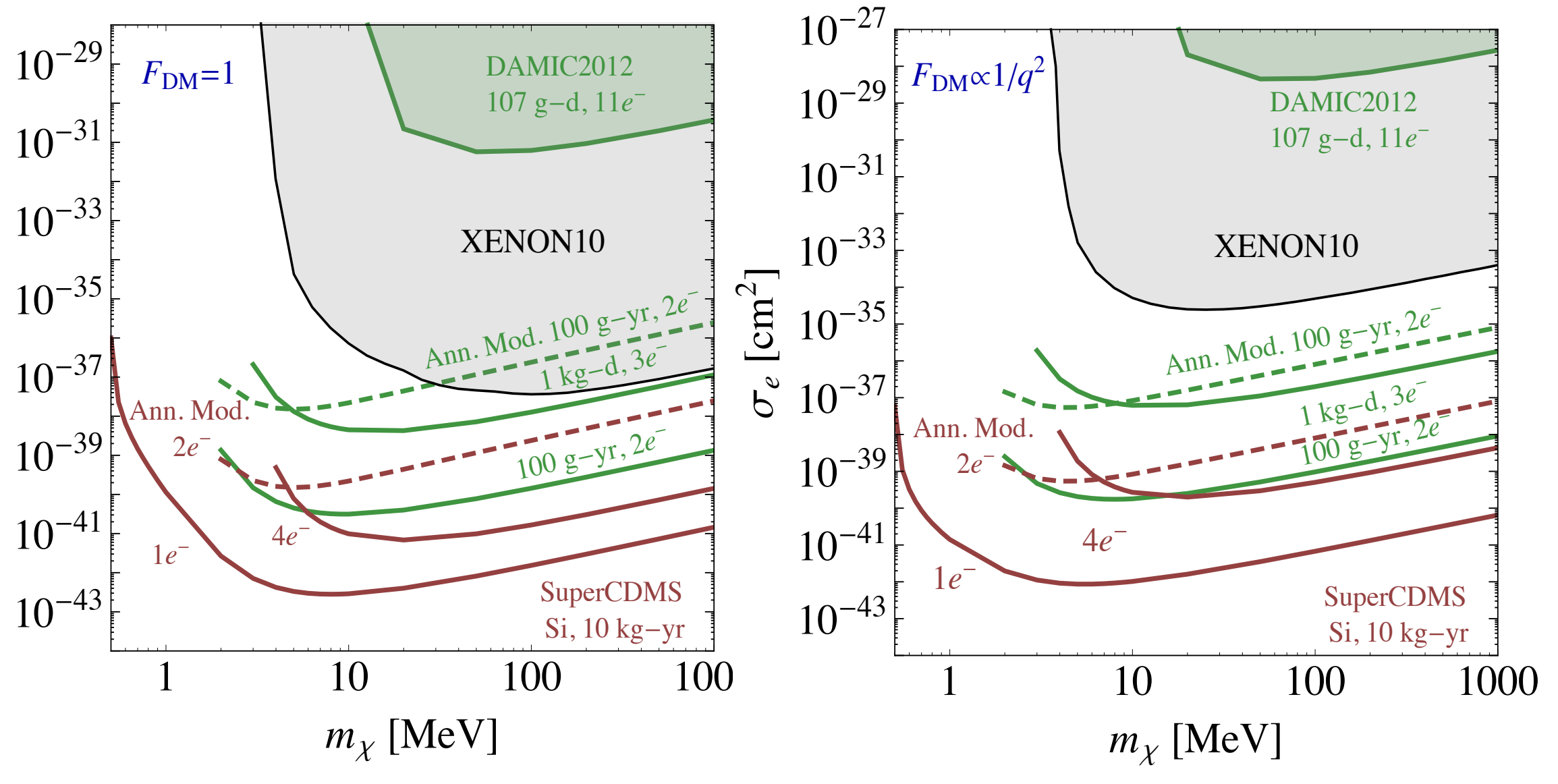
DM-electron cross section thresholds for different k-point mesh sizes.



Relative change in the cross section as the k-point coordinates are randomly displaced. N_k=243



95% C.L. exclusion reach in the DM–electron scattering cross-section, σ_e, of an experiment with 1 kg-year exposure and zero background events, for different experimental thresholds. The corresponding energy thresholds are 0, 11.6, and 26.1 eV in germanium, and 0, 14.4, and 32.4 eV in silicon. The gray shaded region shows the existing constraint from XENON10 data.



Near-term projections for the DAMIC (green curves) and SuperCDMS-silicon (dark red curves) experiments, for different ionization thresholds and (background-free) exposures. Solid curves show the 95% C.L. exclusion reach from simple counting searches, while dashed curves show the 5σ-discovery reach from annual modulation searches. The projections for SuperCDMS-germanium (not shown) are comparable to silicon.

Results and summary

- Existing Dark Matter detectors can be adapted to DM-electron scattering events
- Via semiconducting electron scattering the detectable DM masses is 3 orders of magnitude, down to the MeV mass range
- Exclusion reaches have been calculated for various experimental thresholds to allow for direct comparison with experiment
- We project our data to the values for existing detectors. These detectors, once adapted and their thresholds are lowered, will becapable of exploring low-mass, low-cross section Dark Matter parameter space
- *QEdark* code will be available for the community to study other materials, directionality, etc.