Defect creation to discriminate dark matter signal in phonon-mediated detectors

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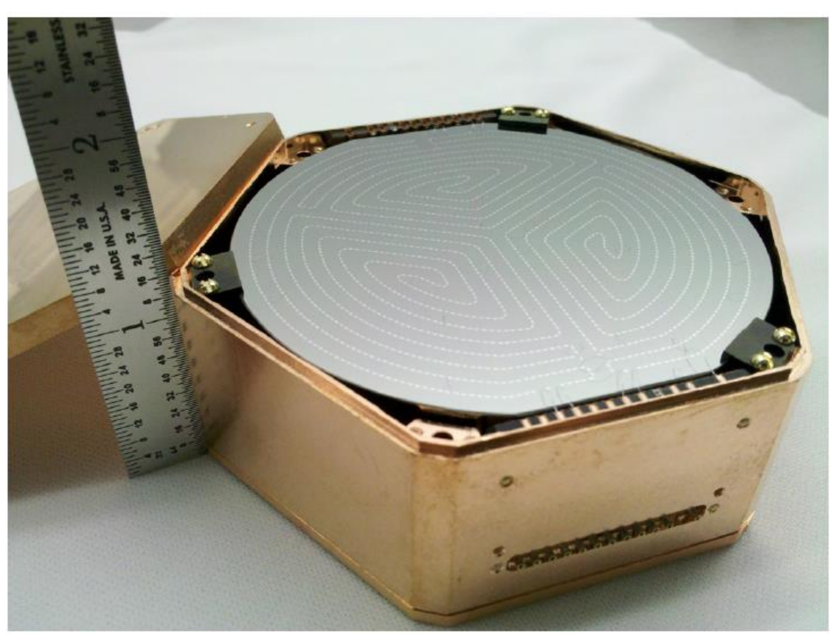
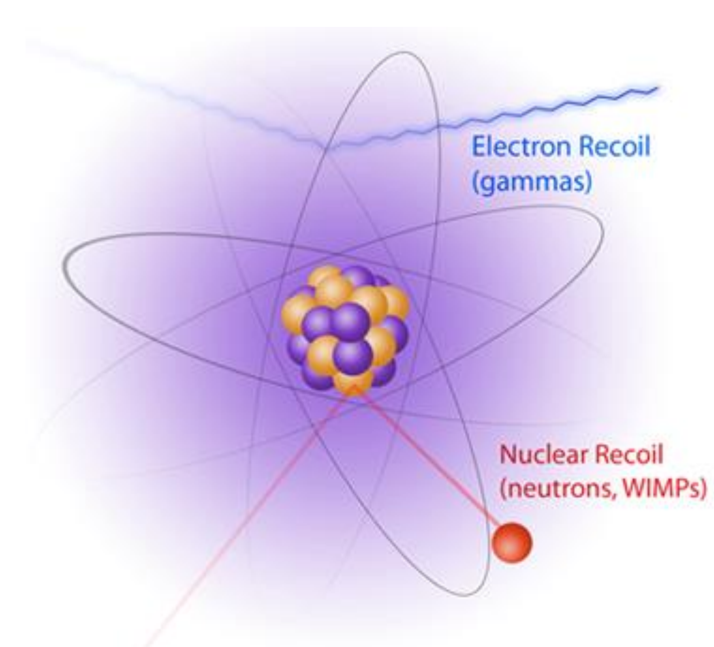
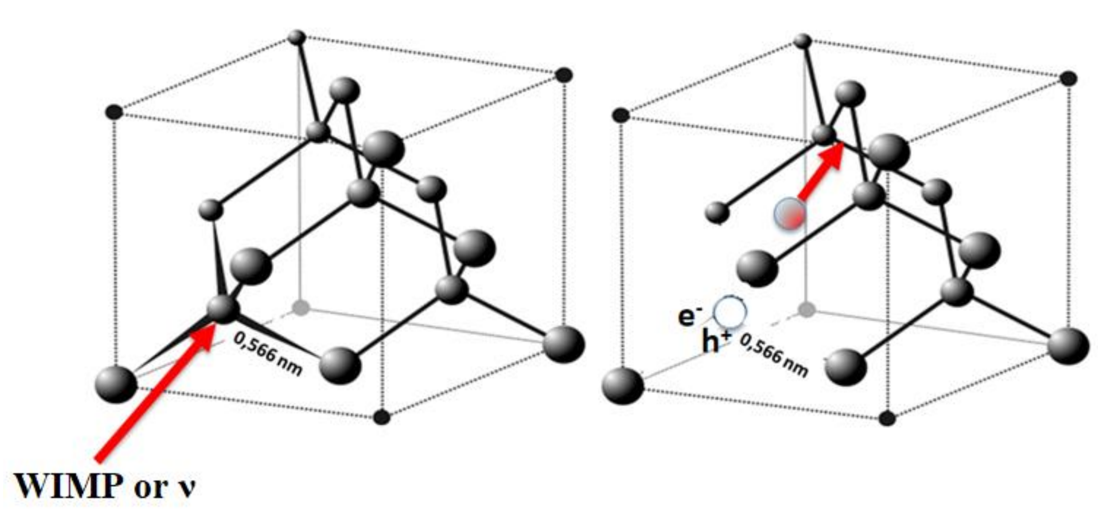
Rare event experiments, particularly ones seeking to detect dark matter or Coherent Elastic Neutrino Nucleus Scattering (CENNS), strive to develop detector technologies with the potential to discriminate signals or their nuclear recoil from the radioactive backgrounds and their electron recoils to significantly boost sensitivity. The dominant, dual measurement methods such as those developed by the Cryogenic Dark Matter Search (CDMS) or the Cryogenic Rare Event Search with Superconducting Thermometers (CRESST), generally fail at very low energies wherein second measurement fundamental noise prevents experiments from reaching the required thresholds. We examine commonly used material response to low energy nuclear recoils using numerical simulations of their respective classical interatomic potentials. Alongside more precise density functional theory simulations and experiments, they predict a nonisotropic, nonlinear energy loss that never produces phonons due to the nonzero energy required to form defects. We argue that defect creation from nuclear recoil interactions distorts the expected spectra in such a way that, statistically, one can discriminate nuclear from electron recoils with only phonon measurements, especially in the mass range below 10 GeV. Experiments such as the CDMS and the Mitchell Institute Neutrino Experiment at Reactor (MINER) are actively developing detectors to reach the resolutions necessary to observe this effect.

Introduction

- ~85% of the Universe's matter nonbaryonic
- Paradigm shift to include lower mass (<10 GeV) dark matter candidates
- Low energy threshold detectors desirable
- Dual measurement techniques fail at low energies due to second measurement fundamental noise
- Method to statistically discriminate electron from nuclear recoils with only phonon measurement using defect creation energy loss



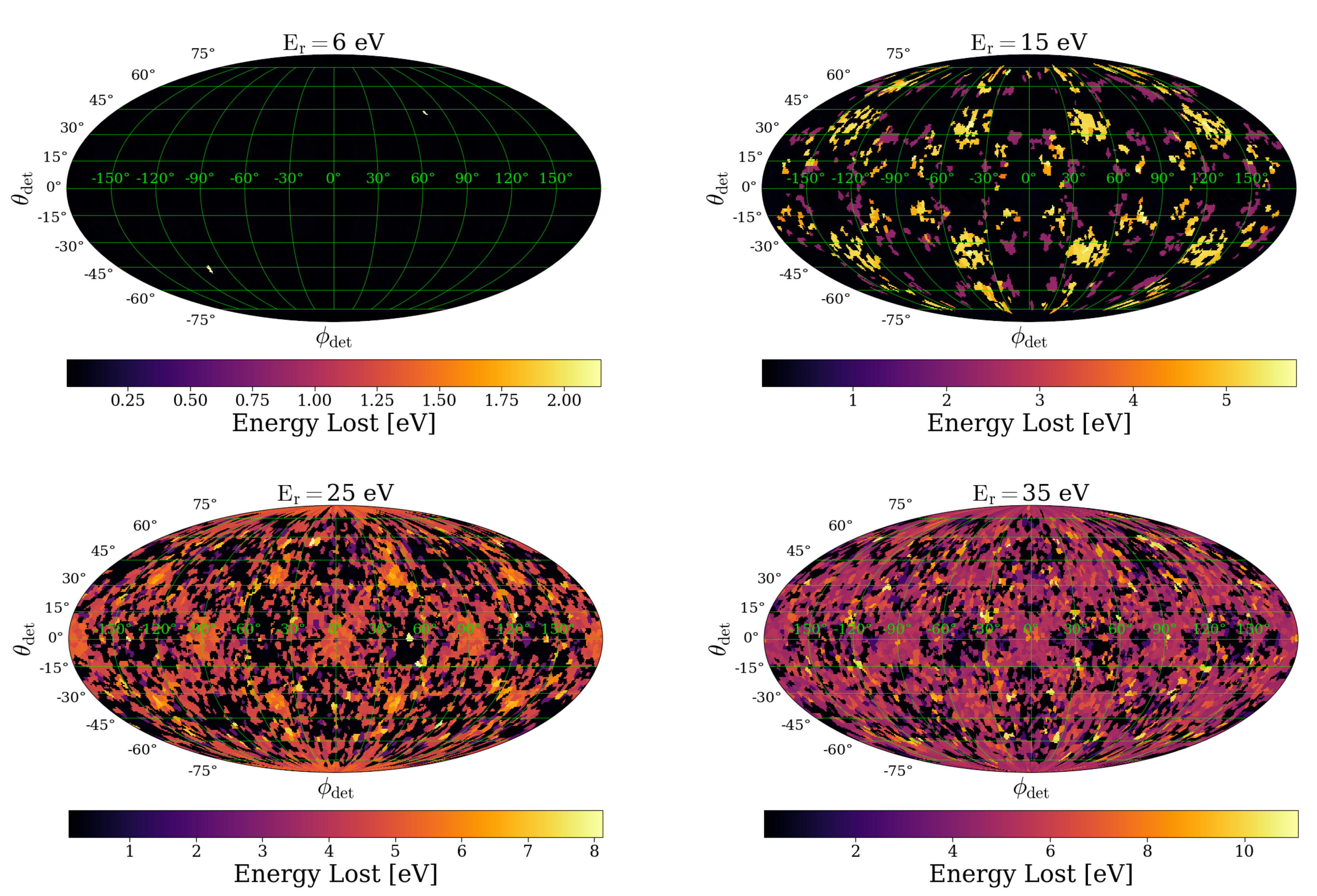




Method

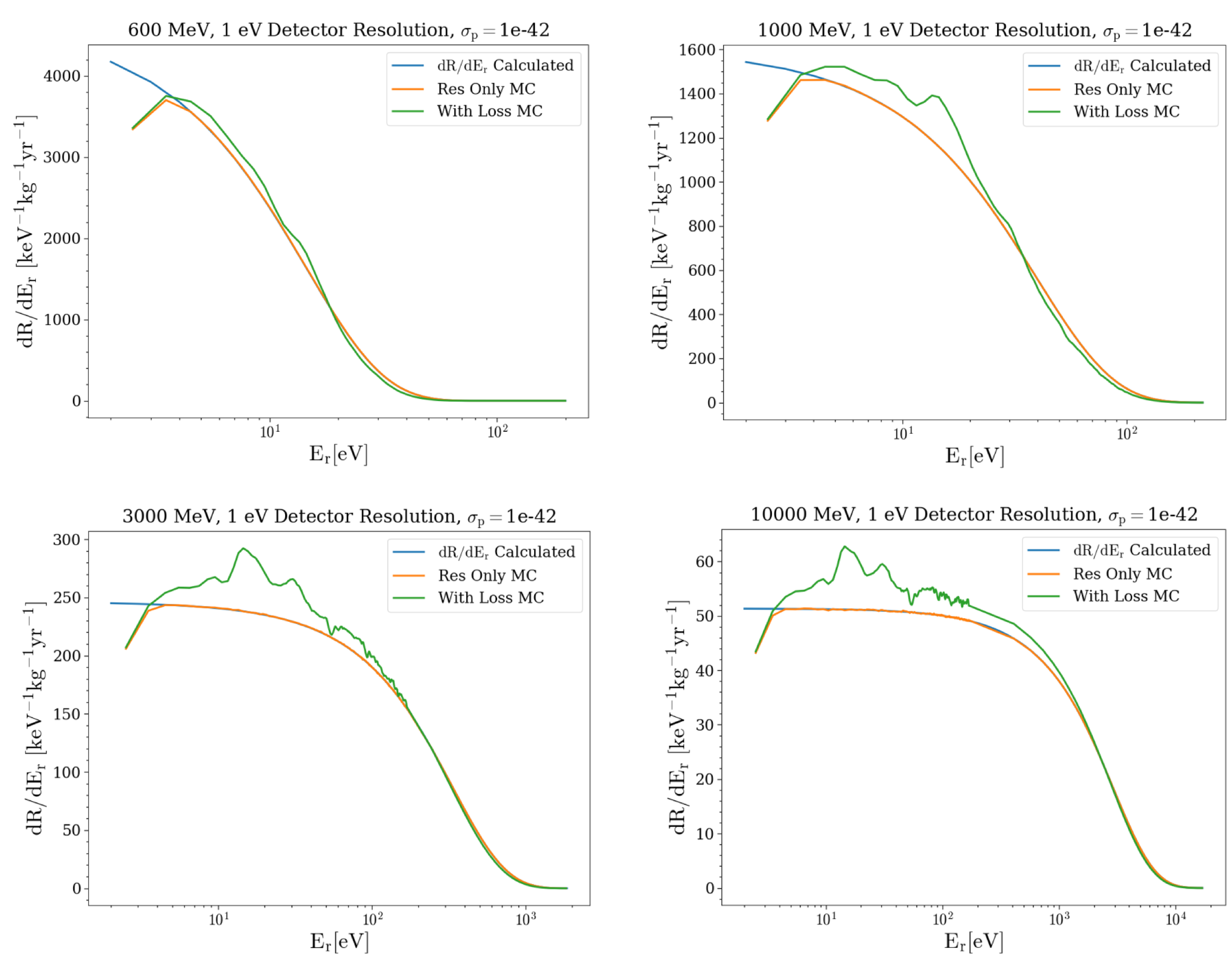
- Molecular dynamics simulations based on density functional theory (DFT) to calculate energy loss as a function of recoil energy and direction
- Monte Carlo sample differential dark matter rate at those values
- Apply Gaussian distribution for energy resolution and recalculate differential rate
- Subtract energy loss for sampled events and recalculate rate

Energy Loss vs E_r

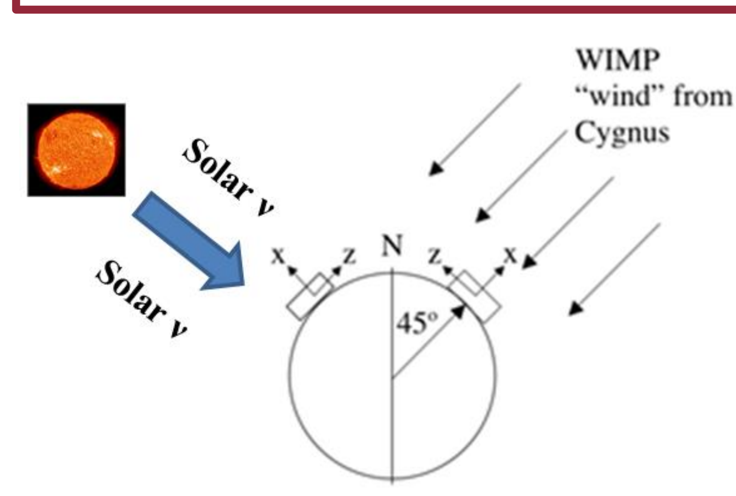


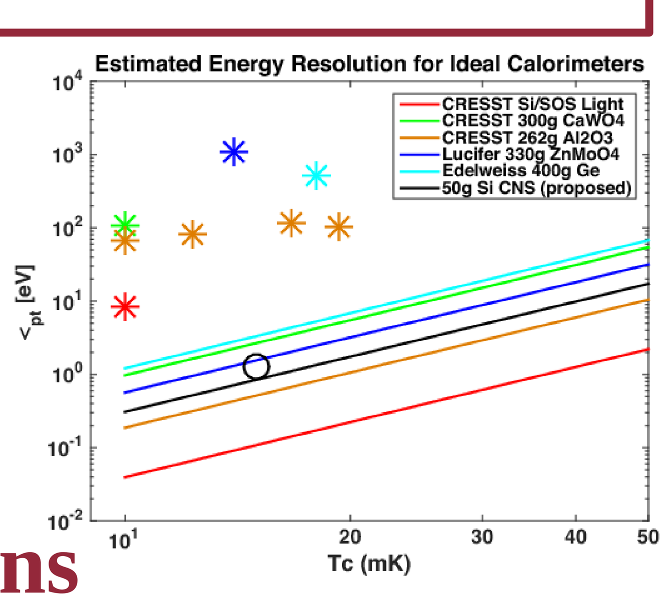
Differential Rate vs E_r

$$\frac{\partial^2 R}{\partial E_r \partial \Omega_r} = \frac{\rho_0 \sigma A^2}{4\pi m_\chi \mu_{\chi n}^2} \times F^2(E_r)\hat{f}_{\mathrm{lab}}(v_{\mathrm{min}}, \hat{\boldsymbol{q}}_{\boldsymbol{r}}; t)$$



- Blue – ideal differential rate per recoil energy
- Orange – differential rate for more realistic 1 eV energy resolution
- Green – differential rate with energy loss and 1 eV resolution
- Each peak corresponds to recoil energy at which another energy loss mechanism becomes dominant
- Linear energy loss assumed past 170 eV





Future Directions

- Different detector materials since method not limited to semiconductors
- Potential directional detectors
- Pushing to lower energy thresholds for stronger signal
- Possible experimental probe of DFT calculations
- Probable signature in CENNS experiments

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