Probing MeV Dark Matter Via Solar Reflection

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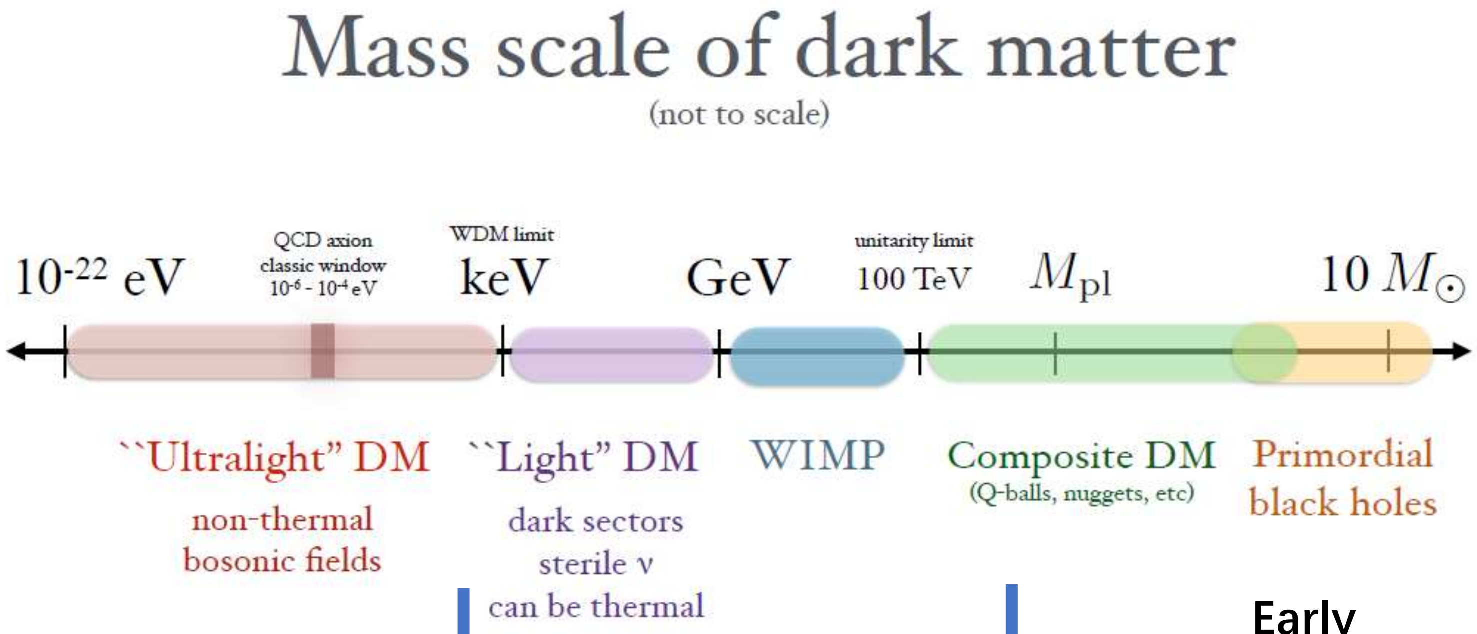
At TAUP2025

Motivation

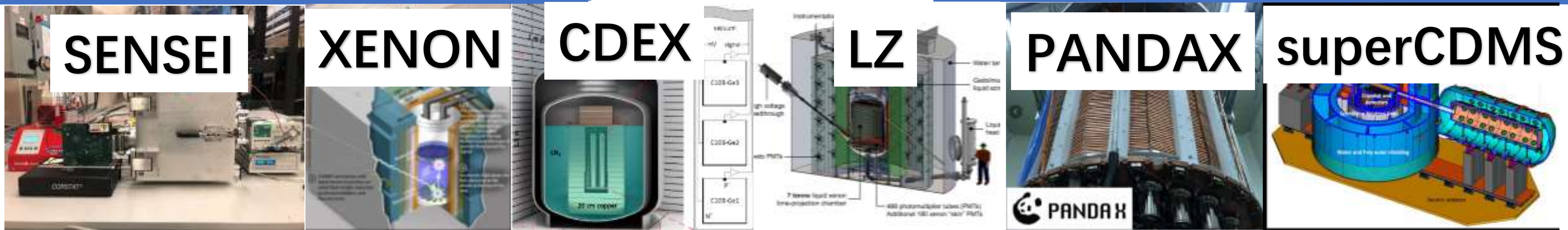


Fifth force Exp.

Electron Recoil

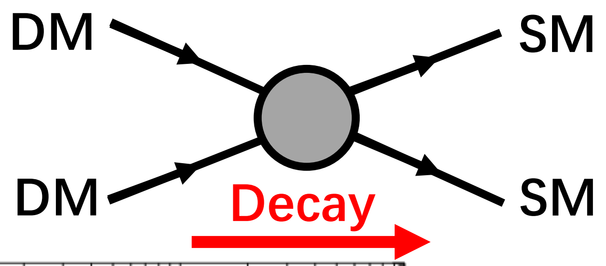
Nuclear Recoil

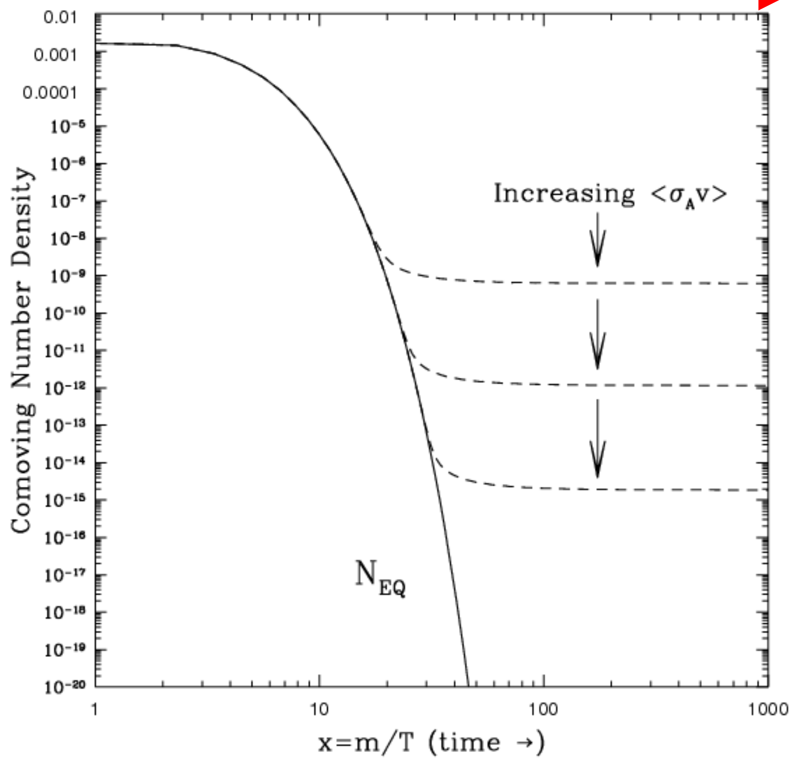
Early Anisotropy /GW

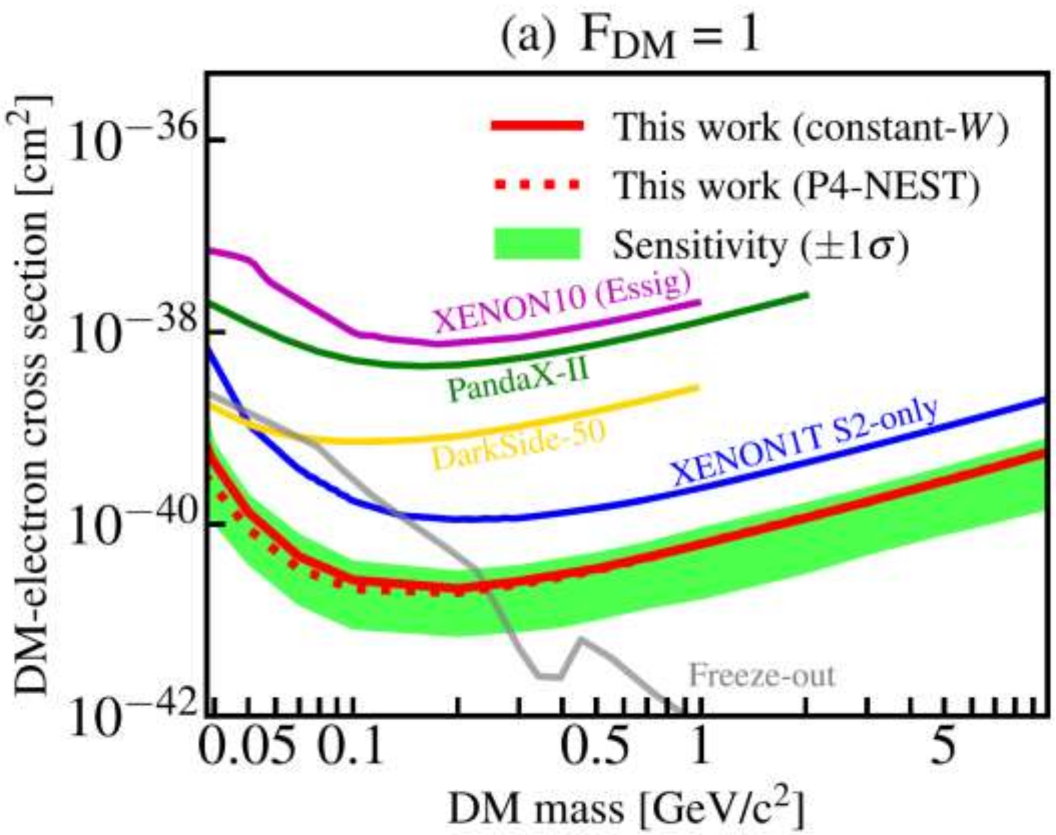


Freeze-out

- Freeze-out



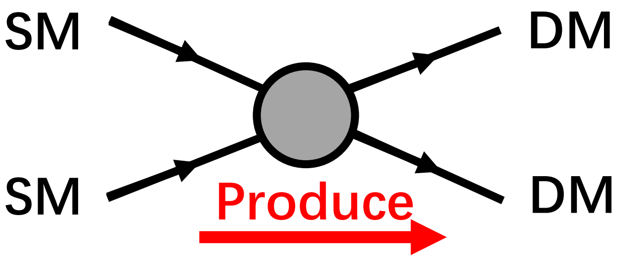


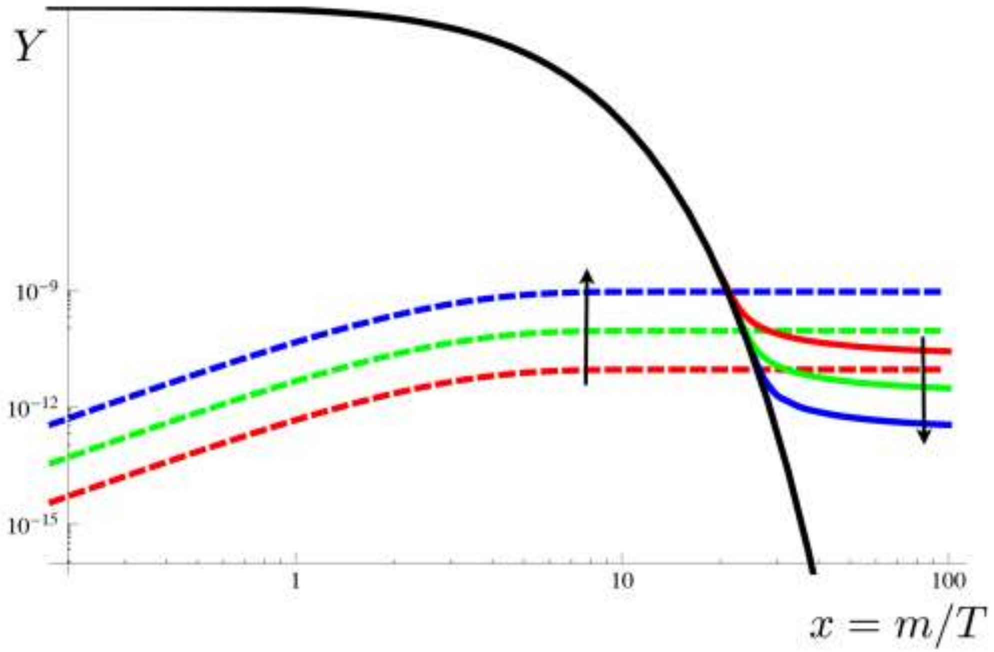


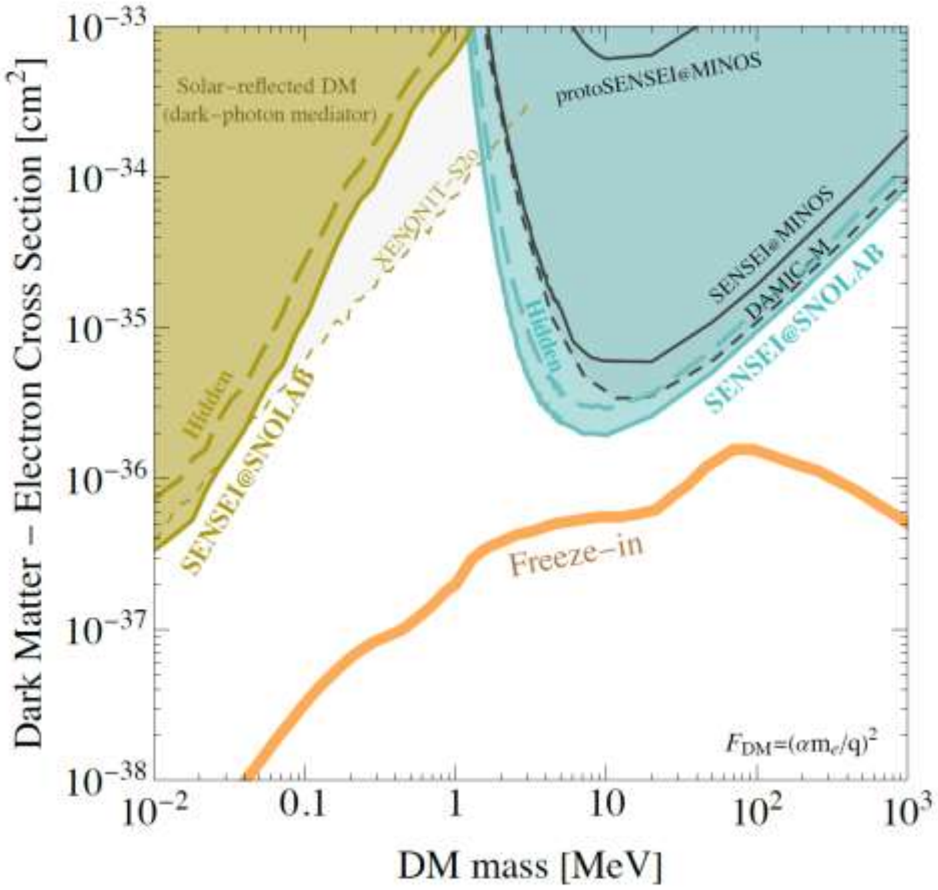
[1] S. Li et al. (PandaX), Search for Light Dark Matter with Ionization Signals in the PandaX-4T Experiment, Phys. Rev. Lett. 130, 261001 (2023), arXiv:2212.10067 [hepex].

Freeze-in

- Freeze-in

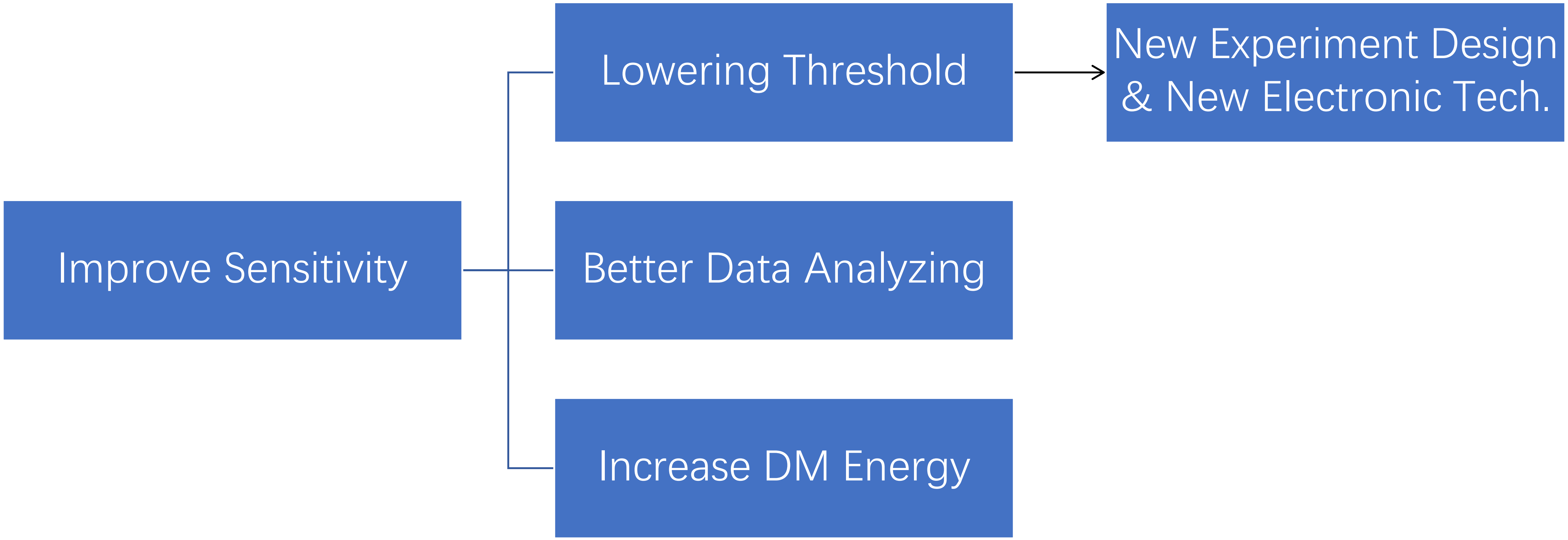




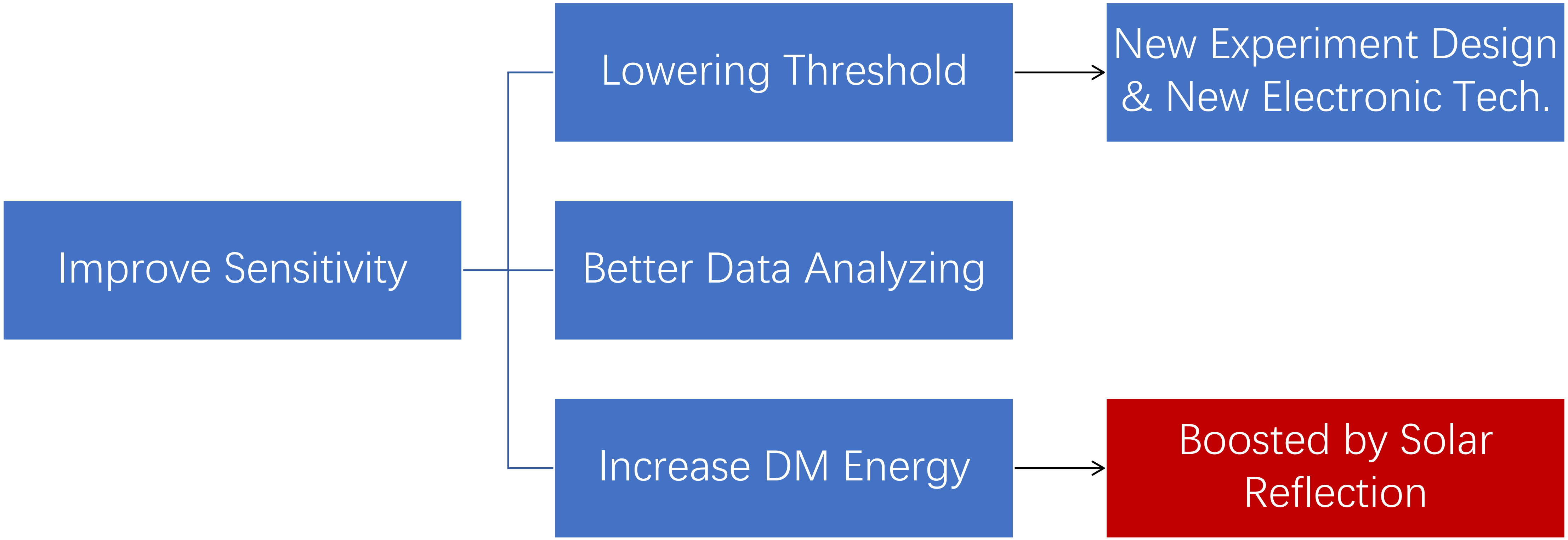


[2] SENSEI Collaboration, (2023), arXiv:2312.13342 [id='astro-ph.CO'].

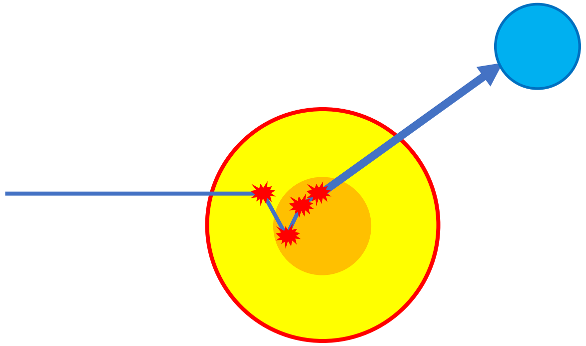
Motivation: MeV Dark Matter

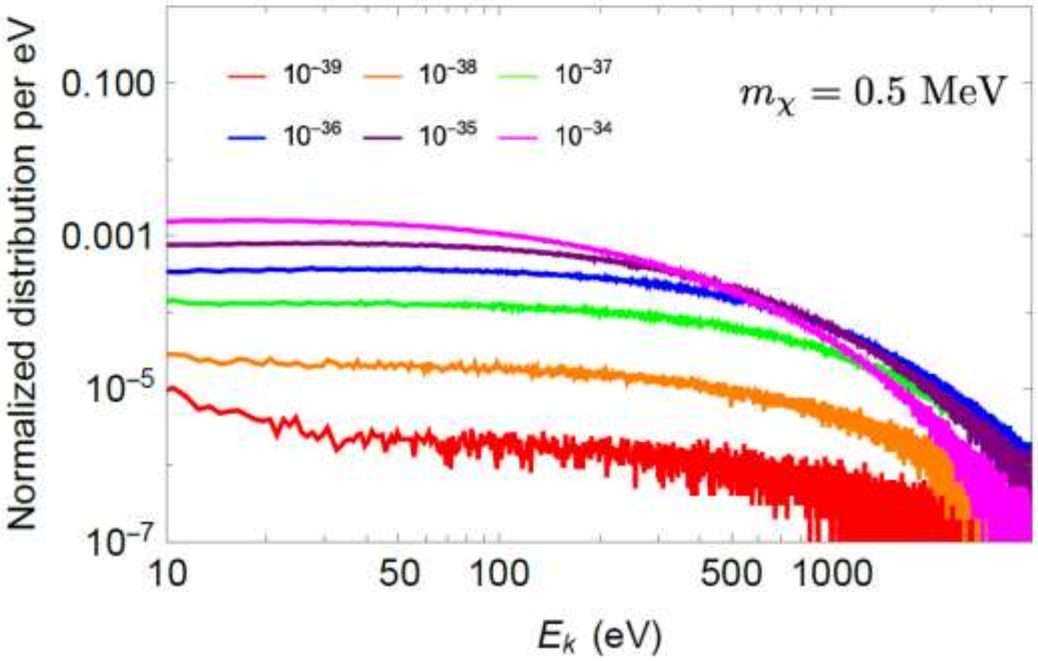


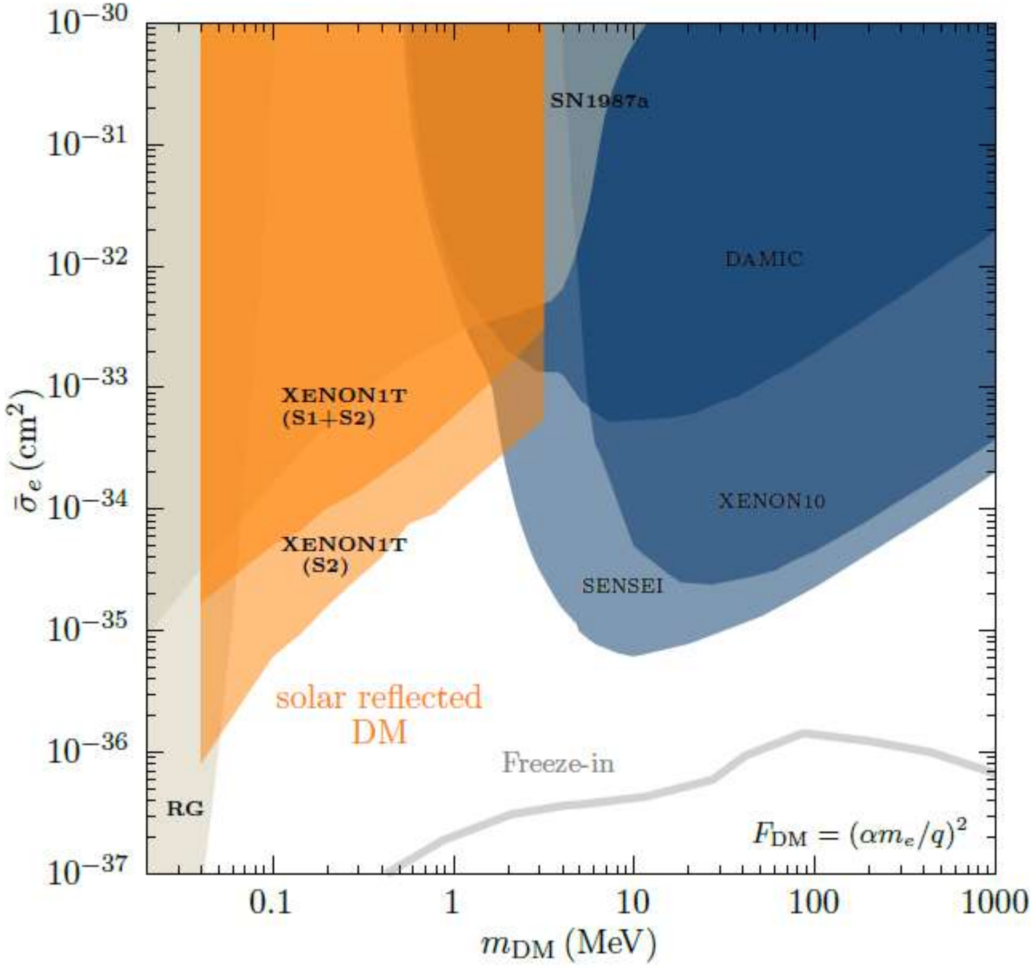
Motivation: Solar Reflected DM



Solar Reflected Dark Matter

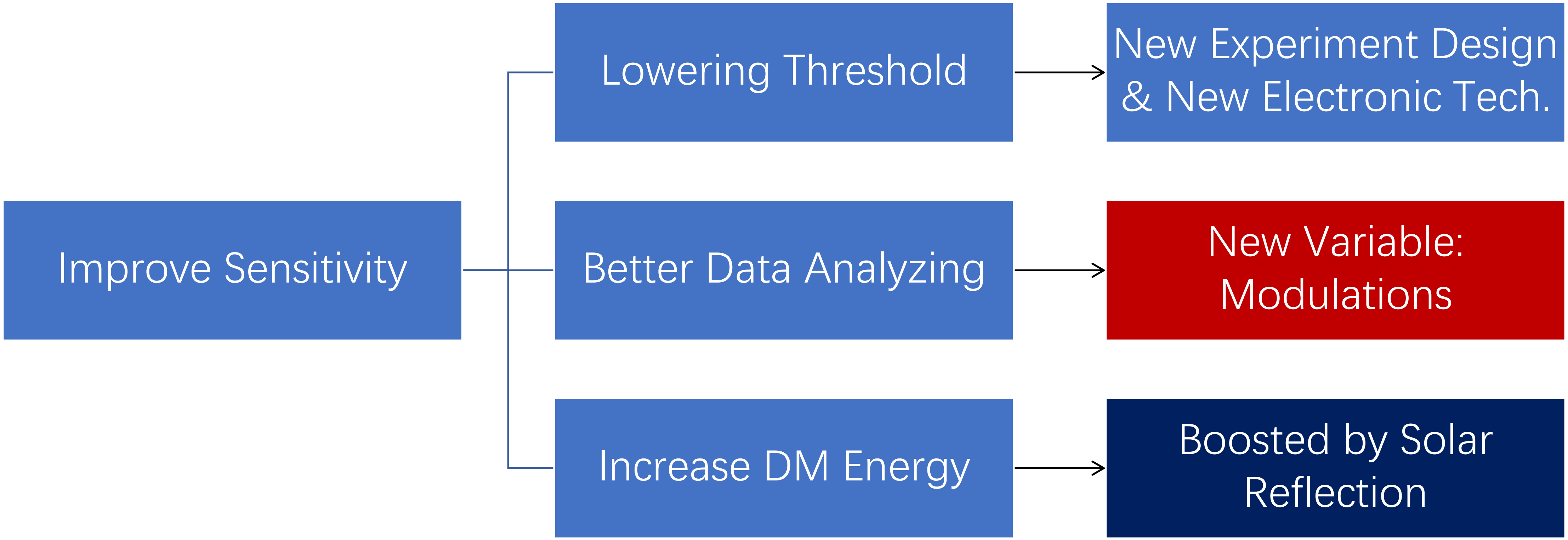




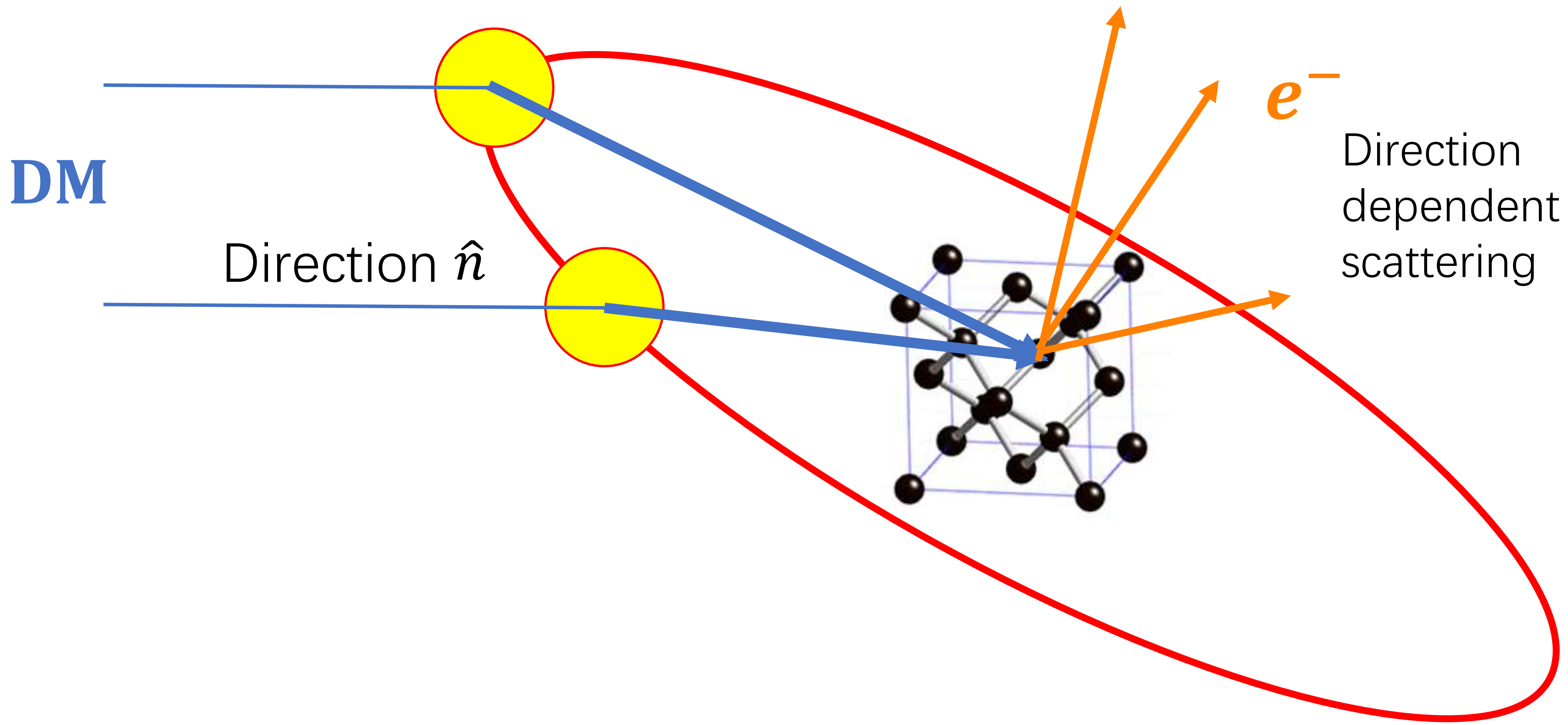


[3] Haipeng An, Haoming Nie, Maxim Pospelov, Josef Pradler, and Adam Ritz Phys. Rev. D 104, 103026, arXiv: 2108.10332

Motivation: Modulation



Motivation: Anisotropy of Reflected DM



Crystal Structure

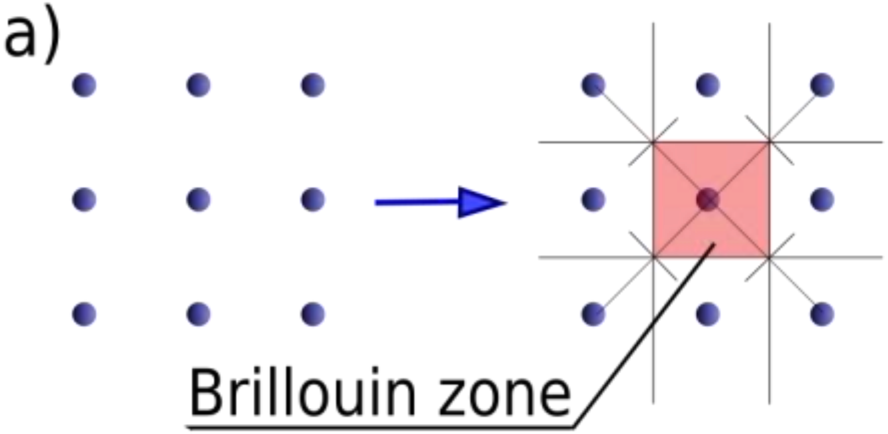
- Reciprocal lattice vector

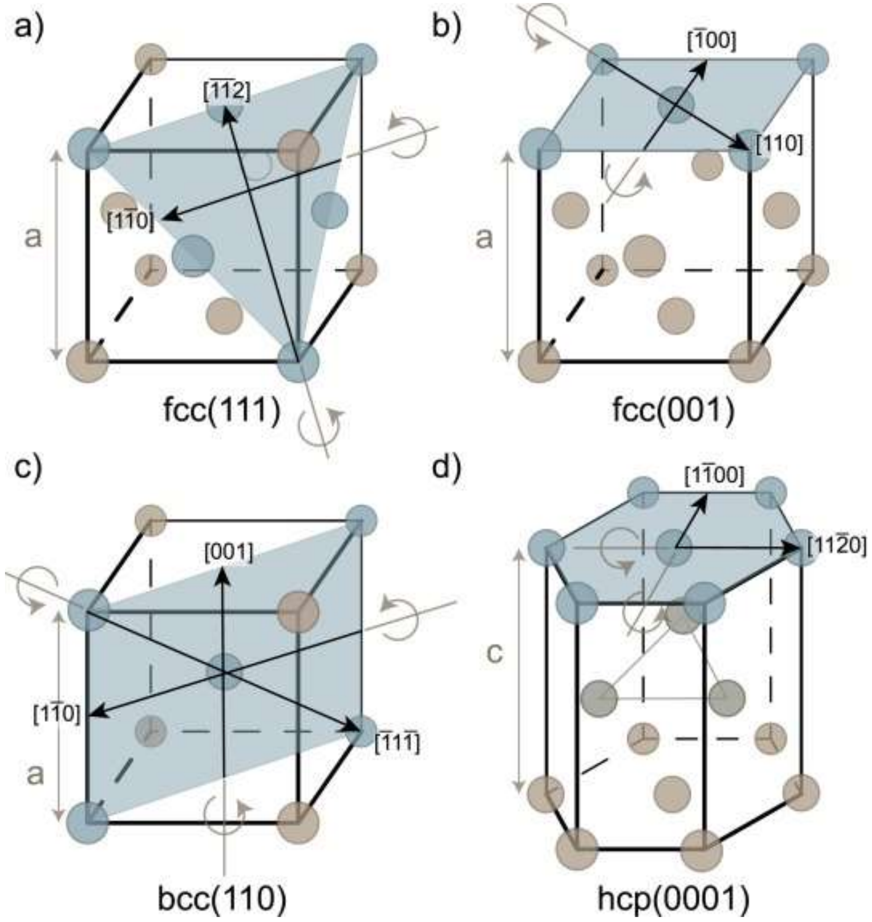
$$\vec{G} \cdot \vec{R} = 2\pi n$$

- Bloch state in crystal

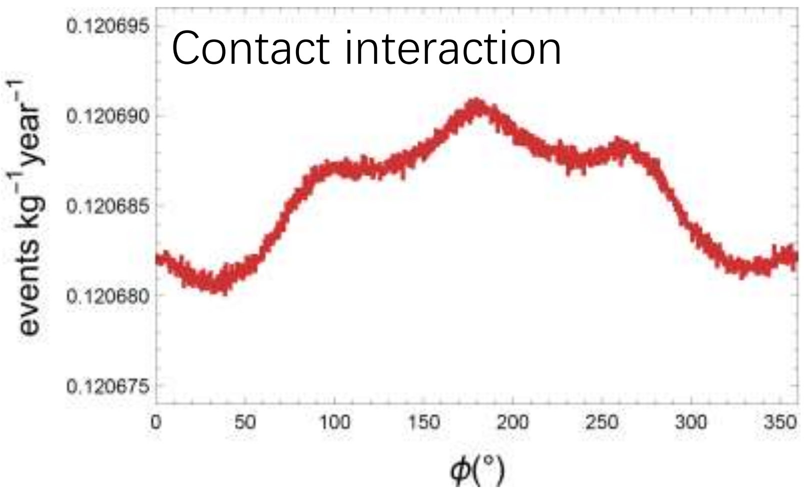
$$\psi_{i\vec{k}}(\vec{x}) = \frac{1}{\sqrt{V}} \sum_{\vec{G}} \tilde{u}_i\left(\vec{k} + \vec{G}\right) e^{i(\vec{k}+\vec{G})\cdot\vec{x}}$$

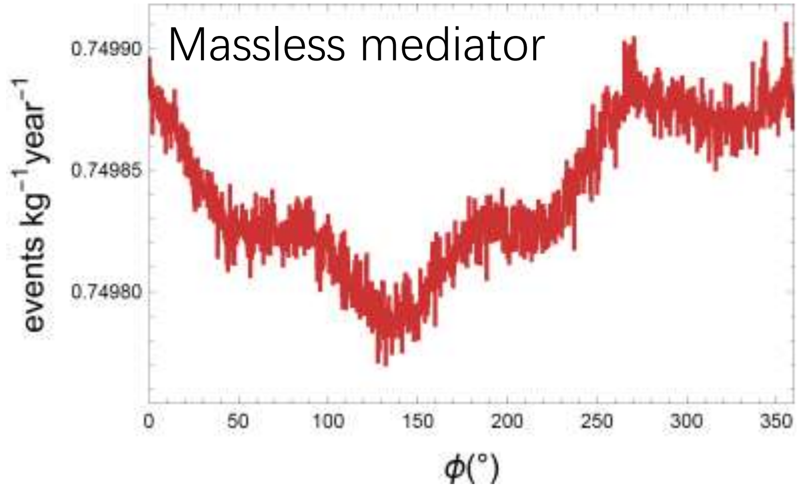
- G ~ crystal surface ~ Brillouin zone

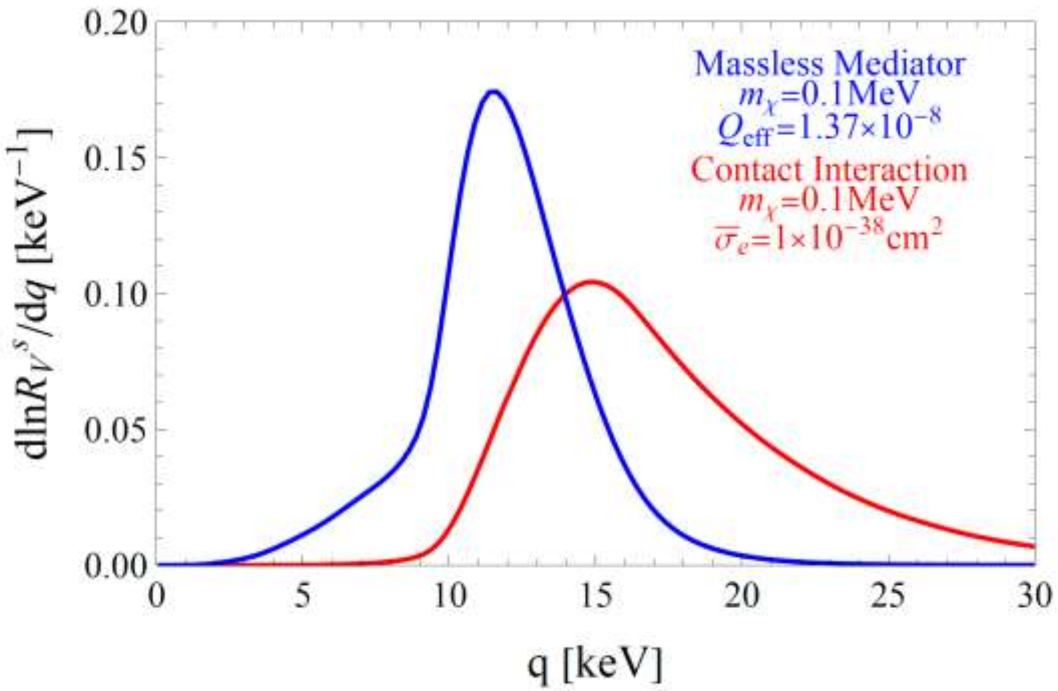




Valence Shell Scattering





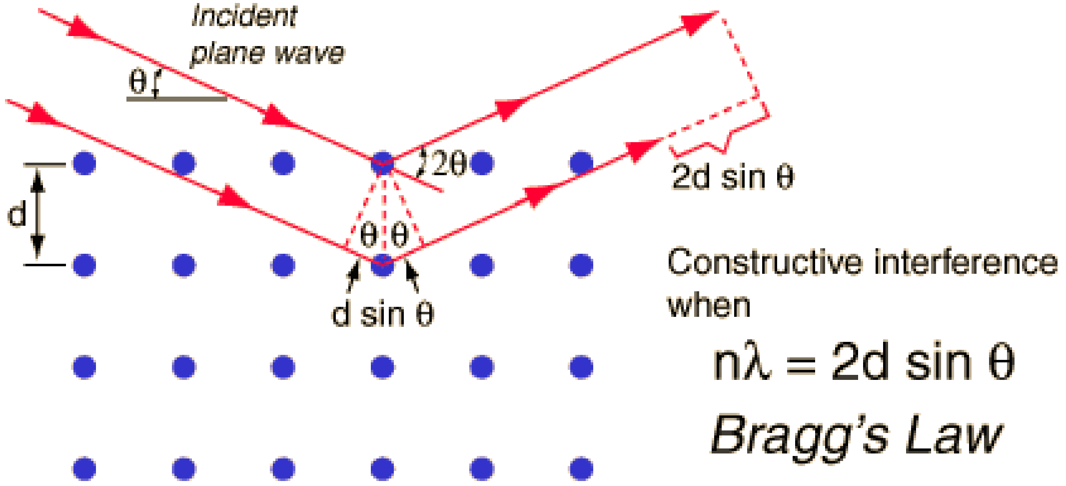


Bragg Scattering of Inner Shell Electrons

- Inner shell electron provides momentum $\sim 10\alpha m_e$

$$\mathcal{M} = \sum_{\vec{R},i} M_{atom}(\vec{q}) e^{i\vec{q}\cdot(\vec{R}+\vec{\alpha}_i)}$$

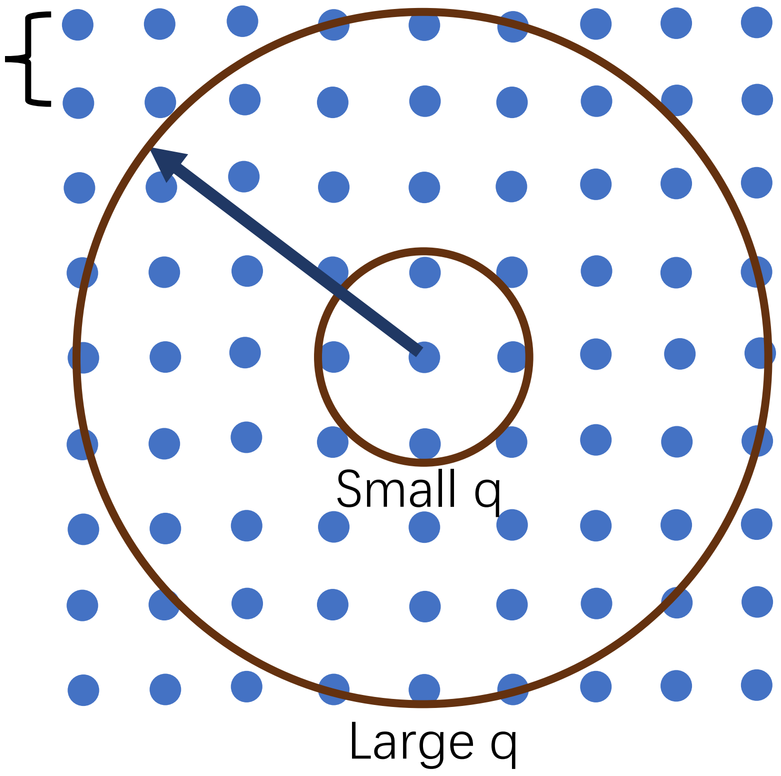
$$|\mathcal{M}|^2 = |M_{\mathrm{atom}}|^2 |S(\vec{q})|^2 \frac{(2\pi)^3}{V_{cell}} N_{cell} \sum_{\vec{G}} \delta^3\left(\vec{q} - \vec{G}\right)$$



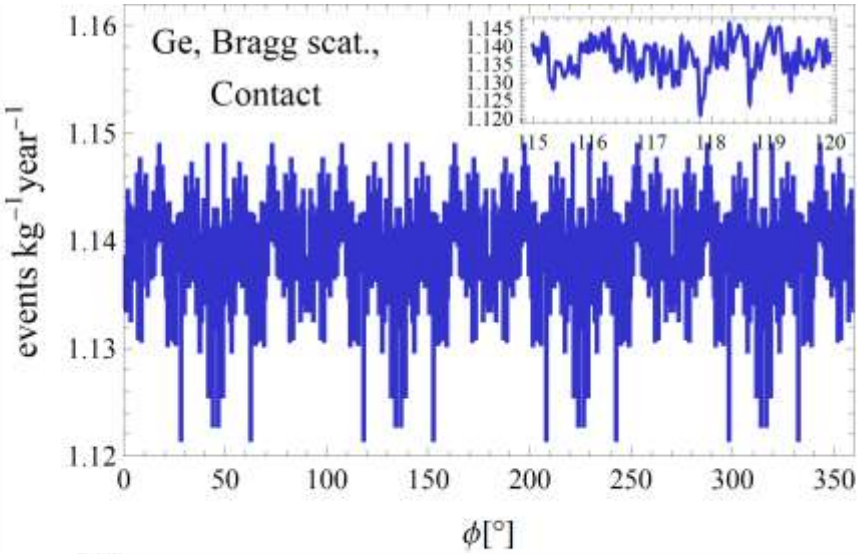
Bragg Scattering of Inner Shell Electrons

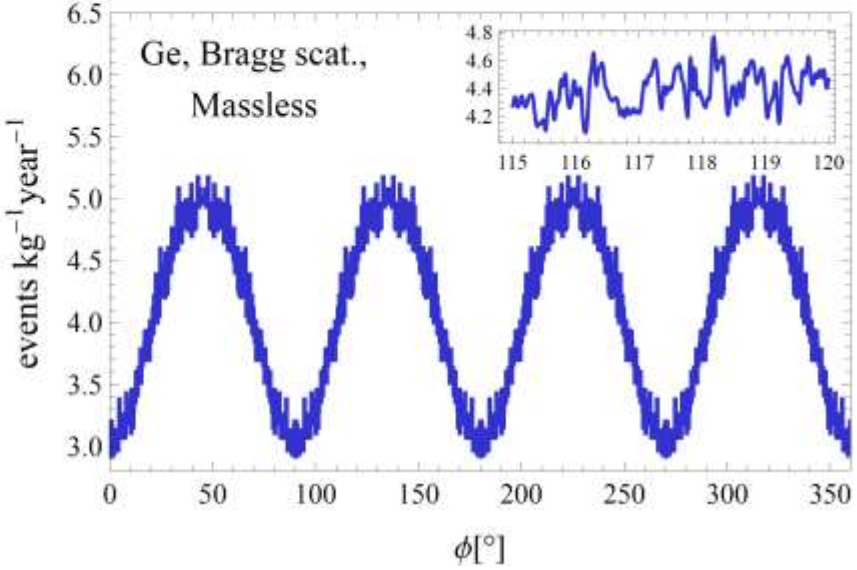
Equivalently $\int d^3q \to \frac{(2\pi)^3}{V} \sum_{\vec{G}}$

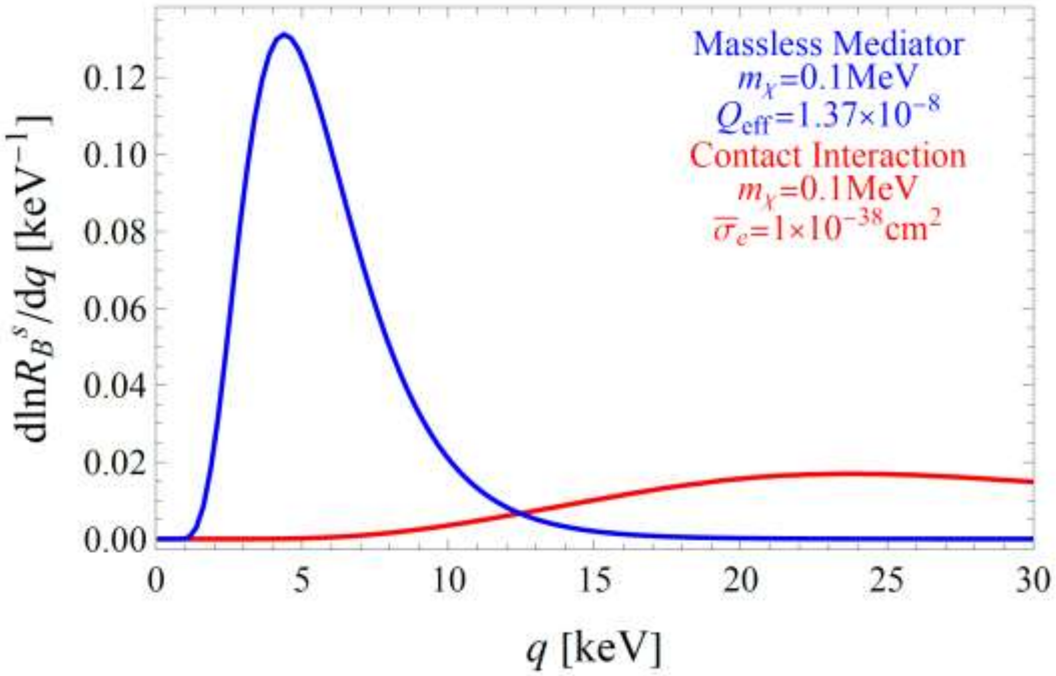
$\sqrt{3}\,\frac{2\pi}{a_{\mathrm{Ge}}} \sim 3\mathrm{keV}$



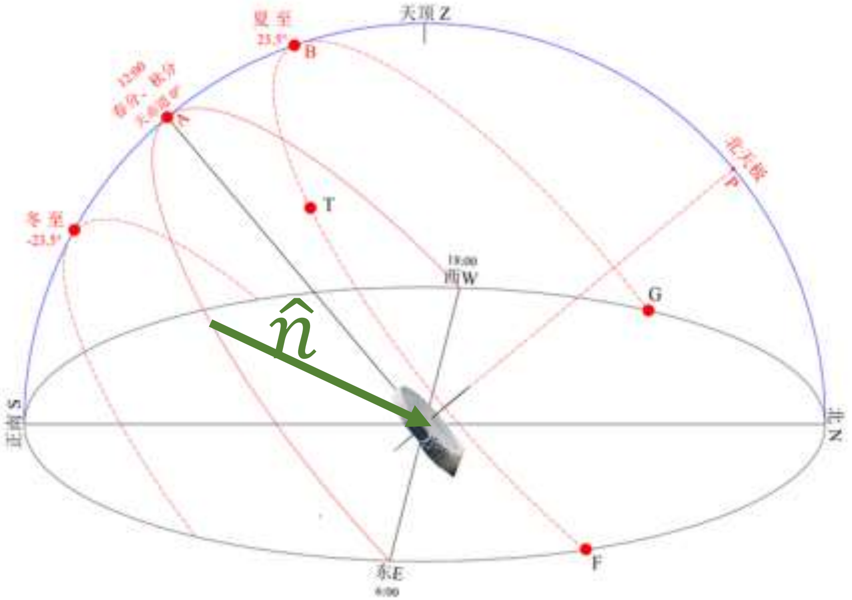
Bragg Scattering of Inner Shell Electrons







Analysis of Daily Modulation

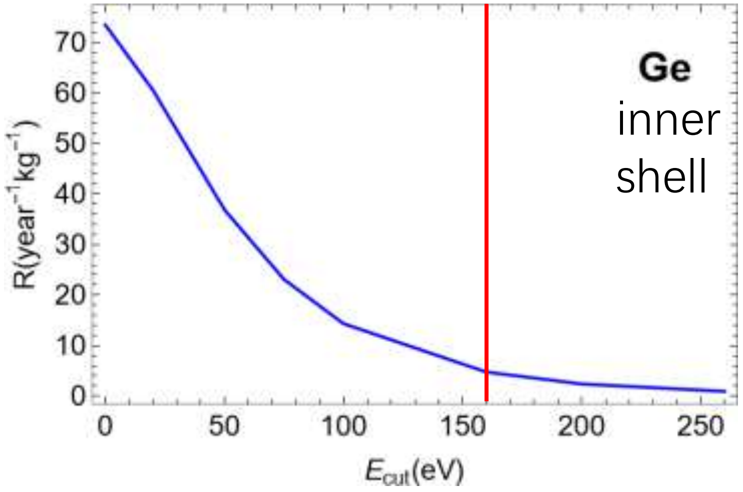


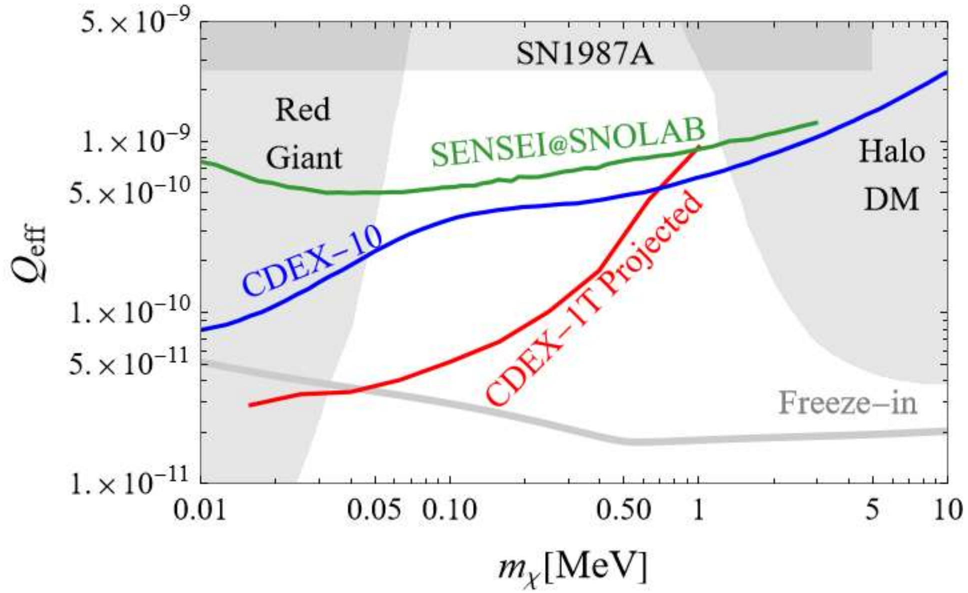
4-fold symmetry axis, 6 hour period, 6 bins:

$$A_h = \sum_i N_{ih} + N_{ih+6} + N_{ih+12} + N_{ih+18}$$

Fourier component

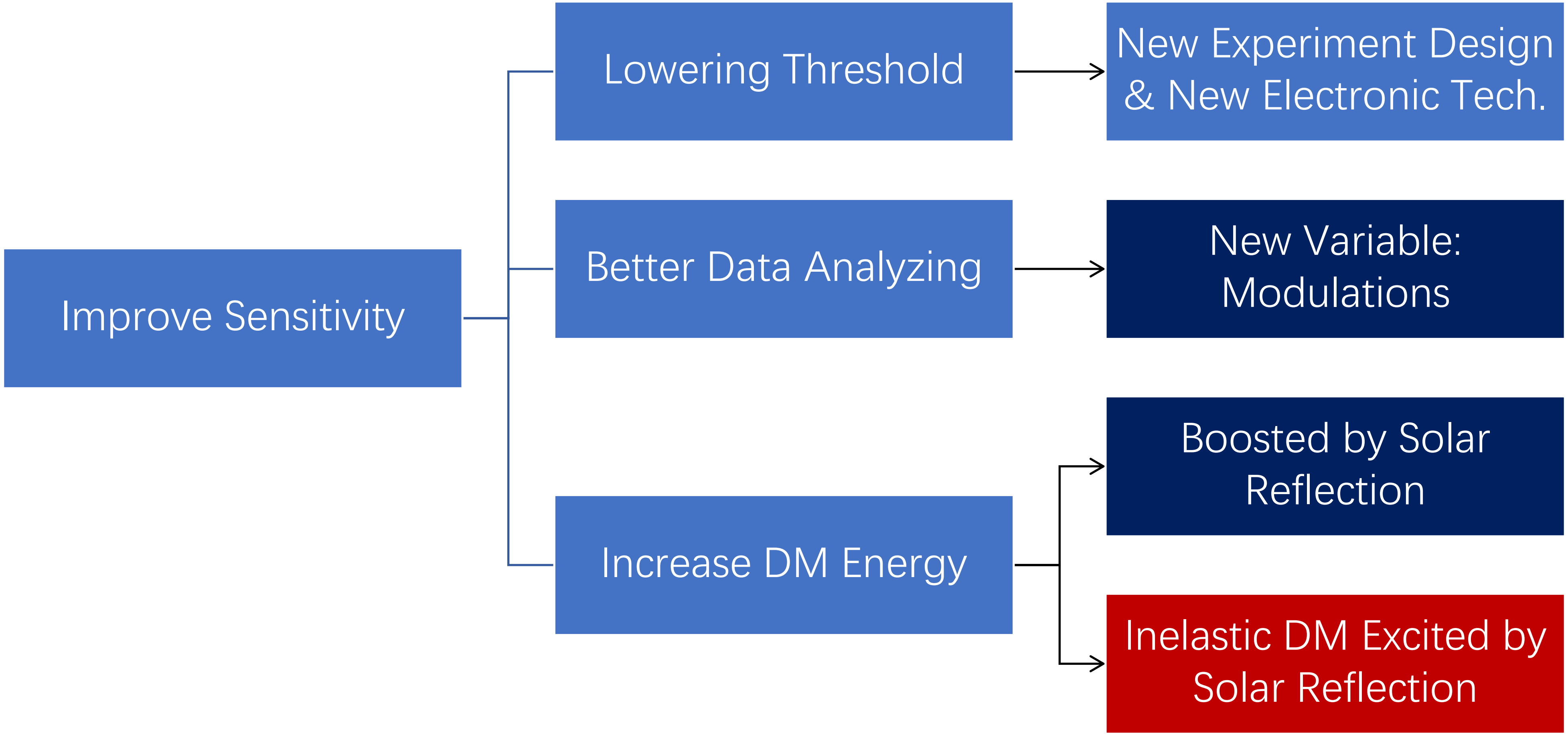
$$S = \sum_{ih} A_h \sin\frac{2\pi h}{6}, C = \sum_{ih} A_h \sin\frac{2\pi h}{6}$$





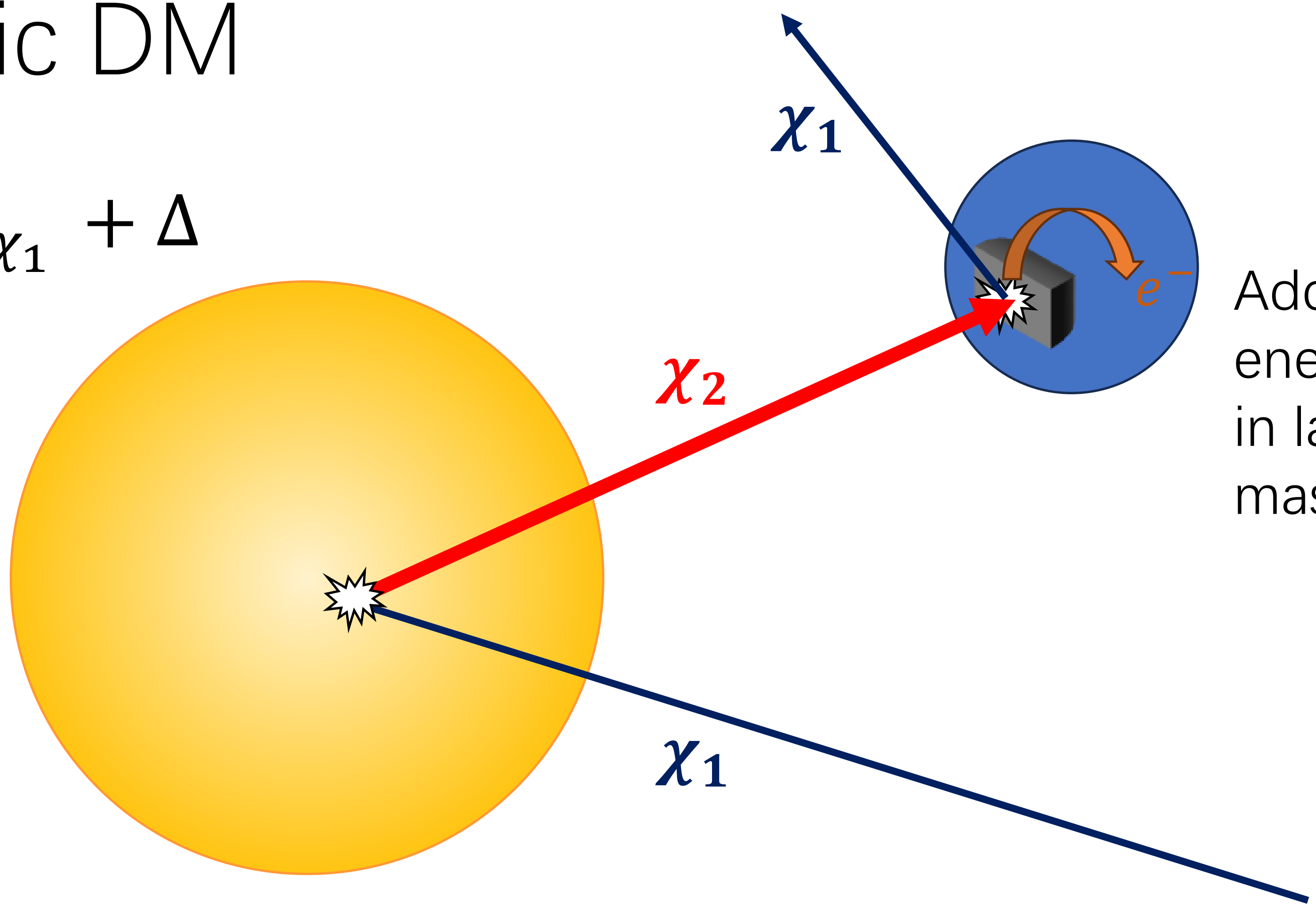
[4] Haipeng An, Haoming Nie, arxiv: 2502.21140

Motivation: Inelastic DM



Inelastic DM

$$m_{\chi_2} = m_{\chi_1} + \Delta$$

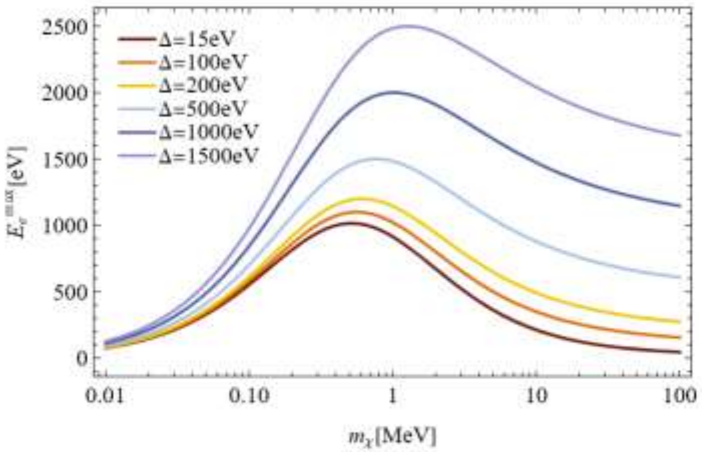


Additional energy deposit in lab from mass splitting Δ

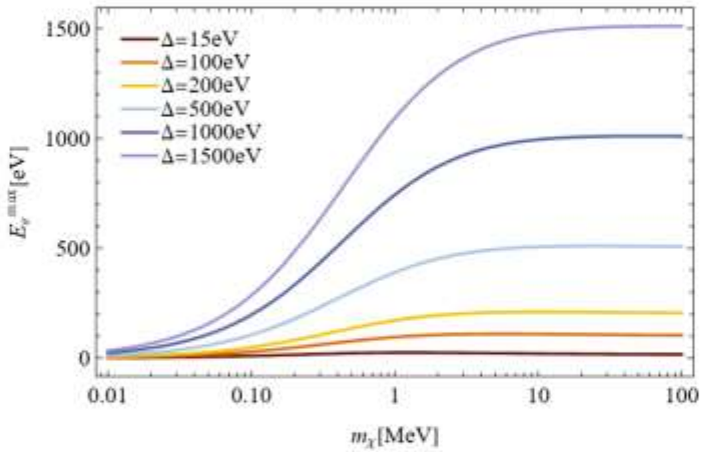
Inelastic Scattering

$$E_e < E_e^{\max} = \frac{\left(\sqrt{m_e m_\chi (E_\chi m_e + \Delta(m_e + m_\chi))} + m_e\sqrt{E_\chi m_\chi}\right)^2}{m_e(m_e + m_\chi)^2}$$

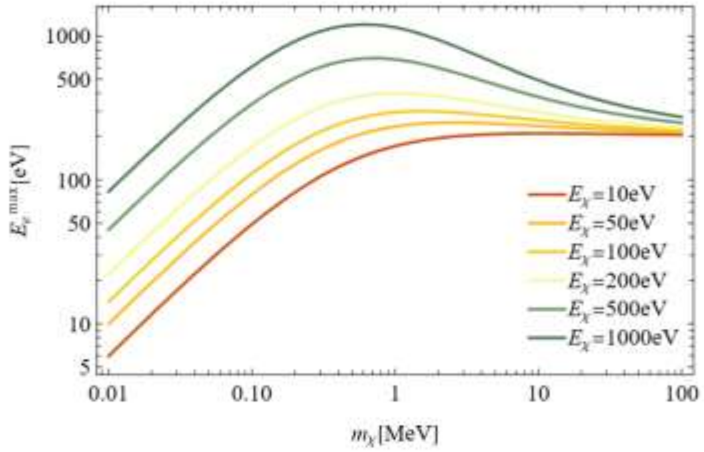
- Additional energy release carried by smaller mass particle
- Small m_χ: electron recoil is sensitive to E_χ, not to Δ
- Large m_χ: electron recoil is sensitive to Δ, not to E_χ



(a) $E_\chi = 1000\,\mathrm{eV}$

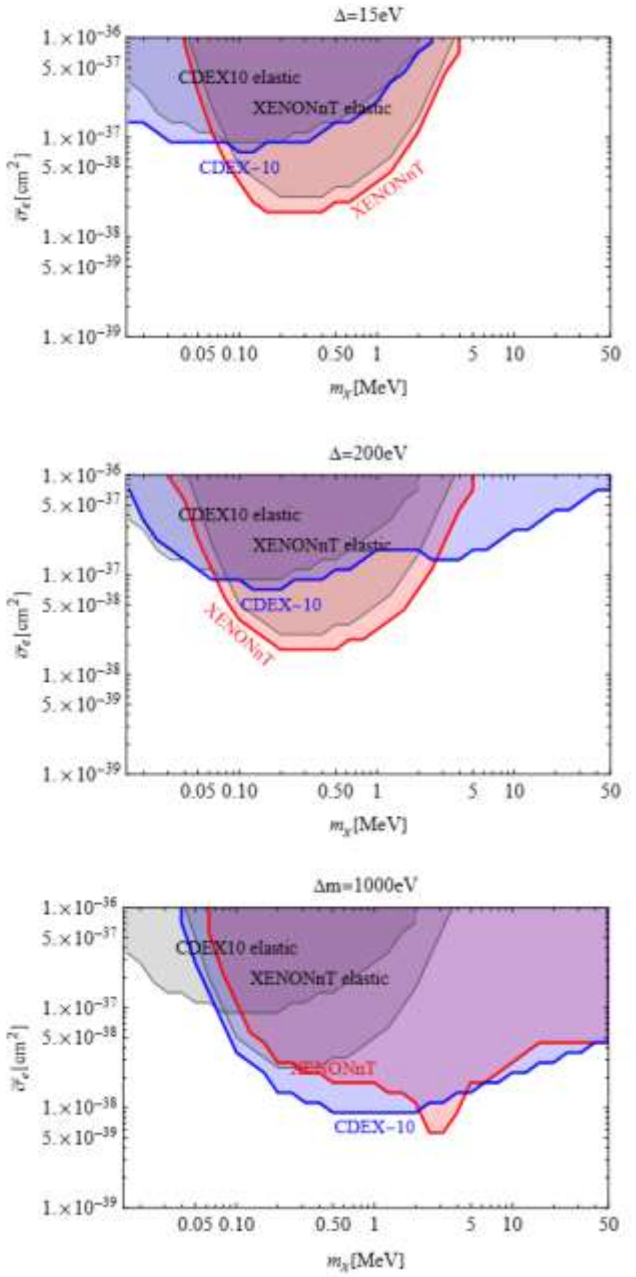


(b) $E_\chi = 10\,\mathrm{eV}$

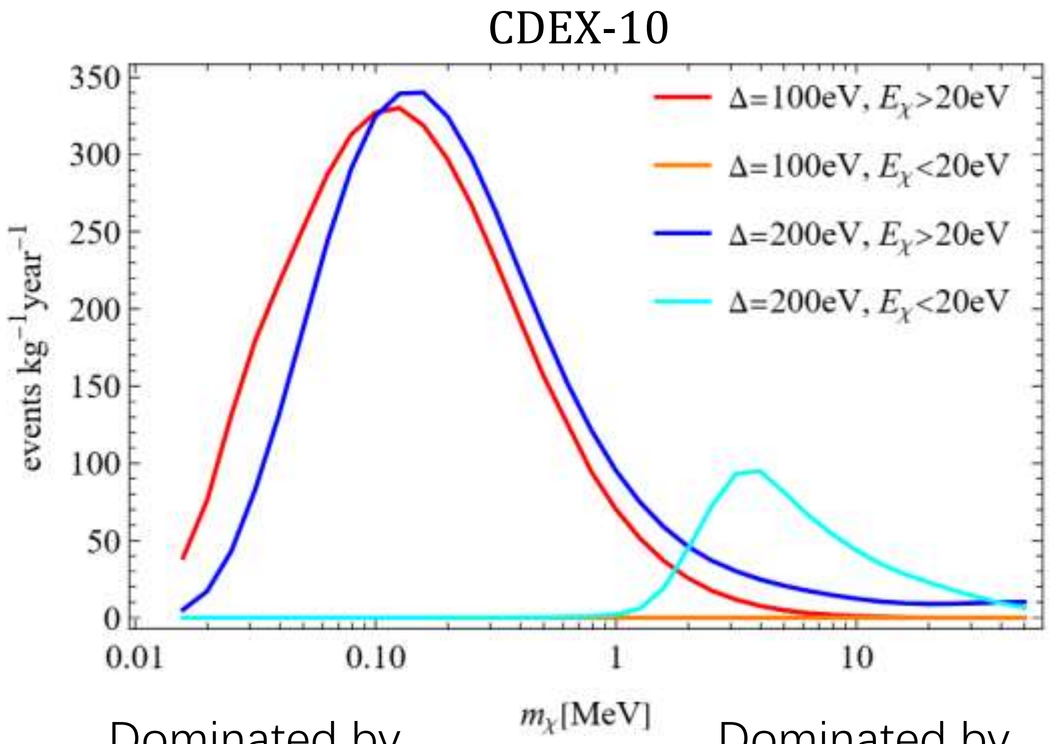


(c) $\Delta = 200\,\mathrm{eV}$

Limit of Solar Reflected Inelastic DM



Preliminary



Dominated by high-kinetic-energy DM scattering

Dominated by excited state energy release

Summary

- Solar reflected DM is crucial to test light DM freeze-in model
- Crystal structure causes anisotropic scattering, results in modulations. Largest with momentum transfer ~3keV. This method is irrelevant to the background.
- Inelastic DM can be excited inside the Sun, and then release energy in the experiment target. The electron recoil is enhanced when $m_\chi > m_e$.