Probing the Modulation of Solar Reflected Dark Matter

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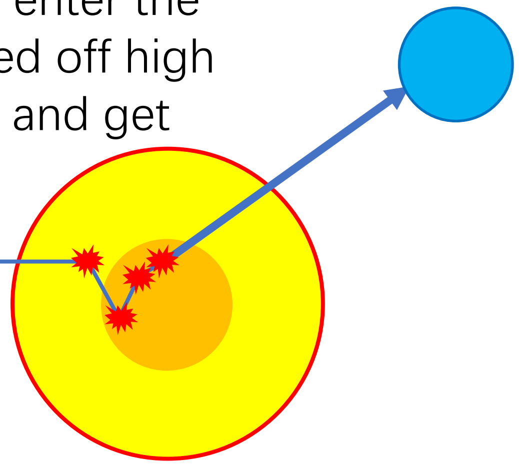
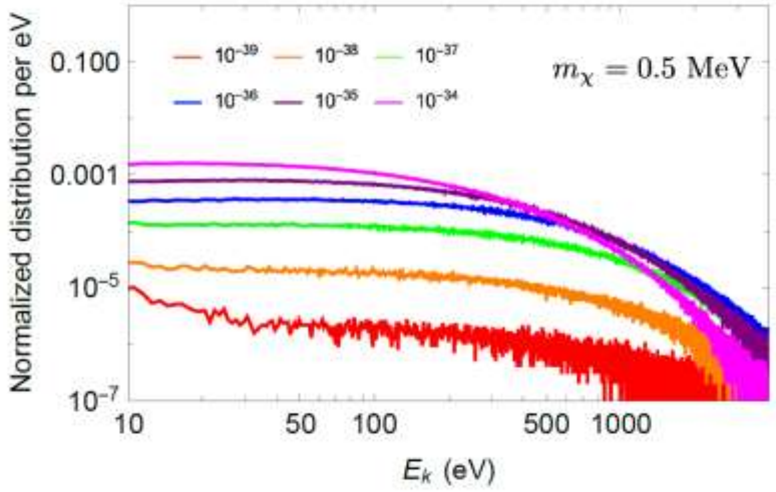
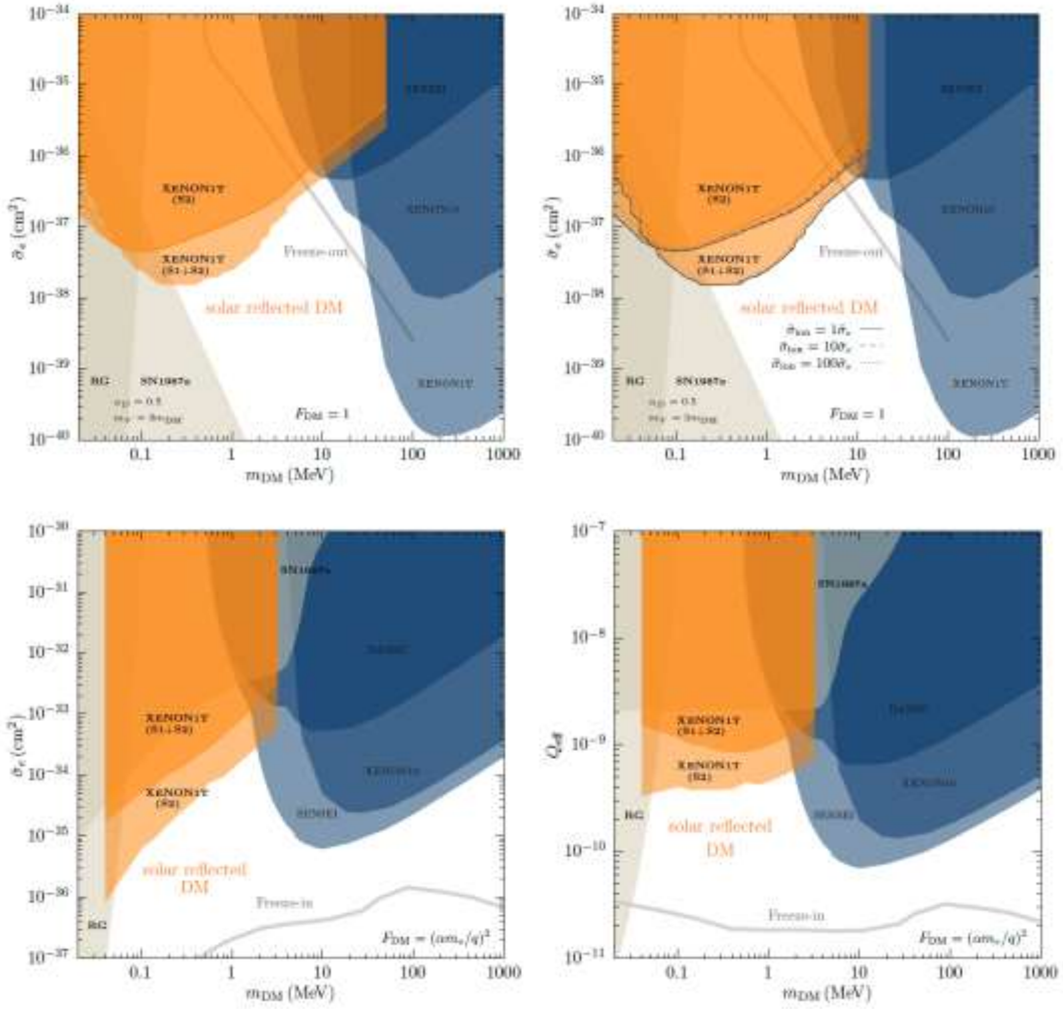
Solar Reflected Dark Matter

DM particle can enter the sun, get scattered off high energy electron and get accelerated



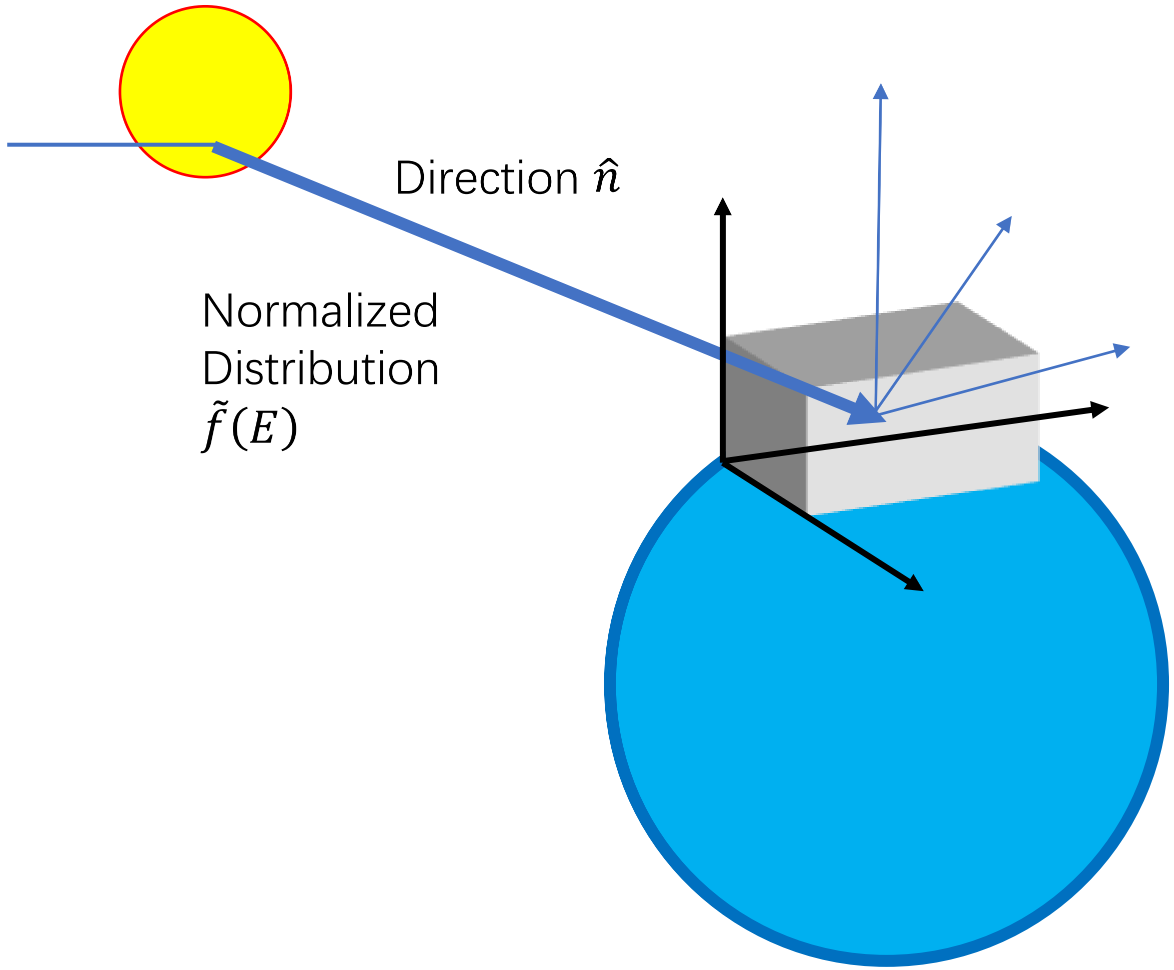
Simulated Results

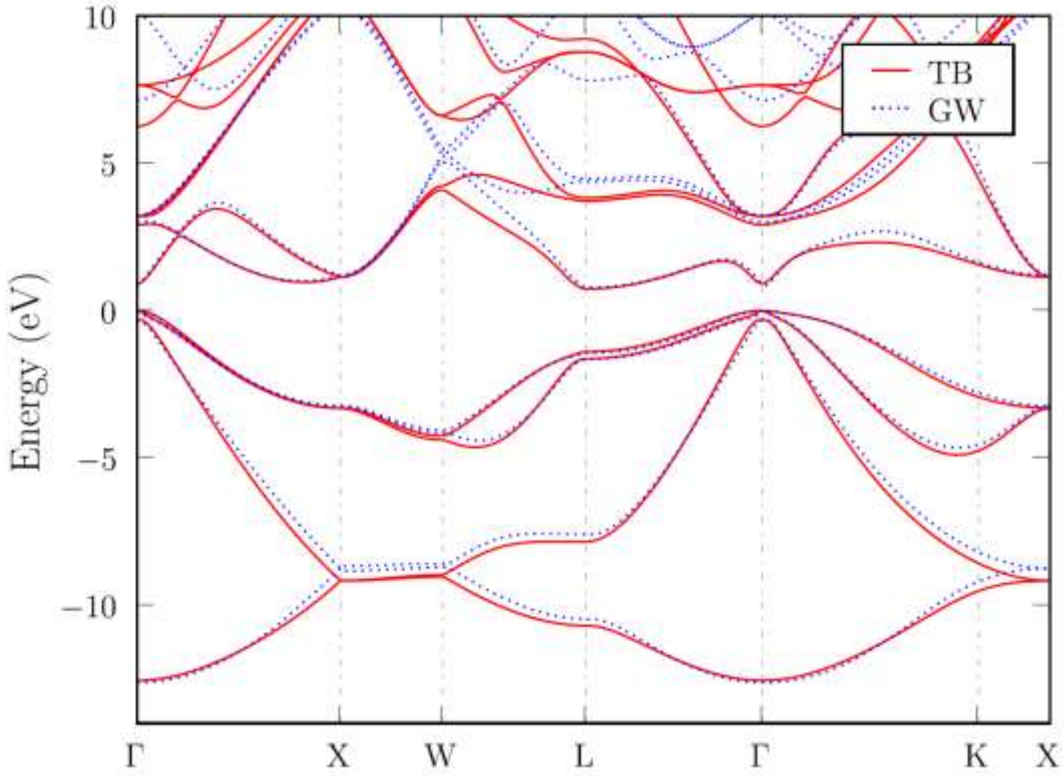




[1] Haipeng An, Haoming Nie, Maxim Pospelov, Josef Pradler, and Adam Ritz Phys. Rev. D 104, 103026, arXiv: 2108.10332

Motivation: Anisotropy of Reflected DM





Band Structure of Germanium

[2]Niquet, Y. M. ; Rideau, D. ; Tavernier, C. ; Jaouen, H. ; Blase, X.; Onsite matrix elements of the tight-binding Hamiltonian of a strained crystal: Application to silicon, germanium, and their alloys; Physical Review B, vol. 79, Issue 24, id. 245201

- Bloch state in crystal $\psi_{i\vec{k}}(\vec{x}) = e^{i\vec{k}\cdot\vec{x}} u_{i\vec{k}}(\vec{x})$
- $u_{i\vec{k}}(\vec{x}) = \frac{1}{\sqrt{V}} \sum_{\vec{G}} \tilde{u}_i\left(\vec{k} + \vec{G}\right) e^{i\vec{G}\cdot\vec{x}}$ has same periodicity as lattice
- $\psi_{i\vec{k}}(\vec{x}) = \frac{1}{\sqrt{V}} \sum_{\vec{G}} \tilde{u}_i\left(\vec{k} + \vec{G}\right) e^{i\left(\vec{k}+\vec{G}\right)\cdot\vec{x}}$
- Form factor of Bloch $i\vec{k}$ to (almost) free state $\vec{k}'$

$$|f_{i\vec{k}\to\vec{k}'}|^2 = \sum_{\vec{G}} \frac{(2\pi)^3}{V} \delta^{(3)}(\vec{k} - \vec{k}' + \vec{G} + \vec{q}) |u_i(\vec{k} + \vec{G})|^2$$

- The rate

$$R = \frac{\rho_\chi}{m_\chi} v_0 \int d^3v\, g_\chi(v)\sigma$$

$$= \frac{\rho_\chi}{m_\chi} v_0 \frac{\bar{\sigma}}{8\pi\mu_{\chi e}^2} \int \frac{d^3q}{q} \int \frac{d^3v}{v^2} g_\chi(\vec{v})\Theta(v - v_{min})\, |F_{DM}(q)|^2 |f_{ik\to k'}(\vec{q})|^2$$

- Traditionally we integrate out $\int d\cos\theta_{qv}\, d\varphi_{qv}$ of $\int d^3q$ and assume $g_\chi(\vec{v})$ to be isotropic
- But now $g_\chi(\vec{v}) = \frac{4R_\odot^2}{r_\oplus^2}\, \tilde{f}(v)\delta(\hat{n})$

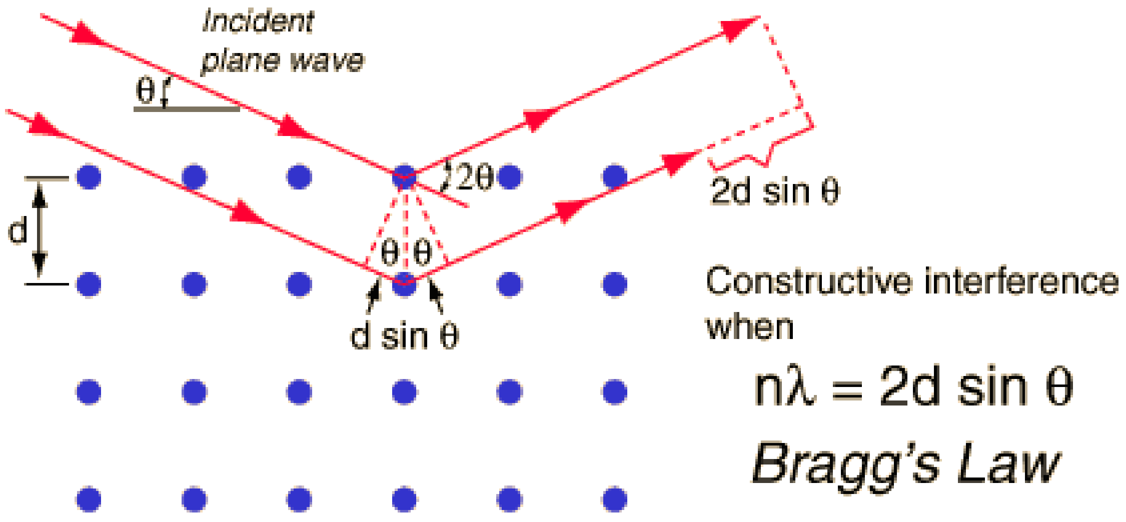
- Rate for computation

$$R_{i\vec{k}\to i'\vec{k}'} = \frac{\rho_\chi}{m_\chi}\frac{4R_\odot^2}{r_\oplus^2}m_\chi \bar{v}_0 \frac{\bar{\sigma}_e}{\mu_{\chi e}^2}\frac{2\pi^2}{V}$$

$$\sum_{\vec{G}} \tilde{f}(\bar{E})\frac{1}{q|\cos\theta_{qv}|}\Theta(v_{\min}/\cos\theta_{qv})|F_{\mathrm{DM}}(\vec{q})|^2|u_i(\vec{k}+\vec{G})|^2\Big|_{\vec{q}=\vec{k}'-\vec{G}-\vec{k}}$$

Where $v_{min} = \frac{\Delta E_{1\to 2}}{q} + \frac{q}{2m_\chi}$, and $\bar{E} = \frac{1}{2m_\chi}\left(\frac{\Delta E_{1\to 2}}{q\cos\theta_{qv}} + \frac{q}{2m_\chi\cos\theta_{qv}}\right)^2$

- Does inner shell excitation has anisotropy?
- **YES**, through **Bragg coherent scattering**.



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

$$= M_{\text{free}}(\vec{q}) \sum_i e^{i\vec{q}\cdot\vec{\alpha}_i} \sum_{\vec{R}} e^{i\vec{q}\cdot\vec{R}}$$

$$\mathcal{M} = M_{\text{free}} S(\vec{q}) \frac{(2\pi)^3}{V_{\text{cell}}} \sum_{\vec{G}} \delta^{(3)}(\vec{q} - \vec{G}).$$

$$|\mathcal{M}|^2 = |M_{\text{free}}|^2 |S(\vec{q})|^2 \left[\frac{(2\pi)^3}{V_{\text{cell}}}\right]^2 \frac{V}{(2\pi)^3} \sum_{\vec{G}} \delta^{(3)}(\vec{q} - \vec{G})$$

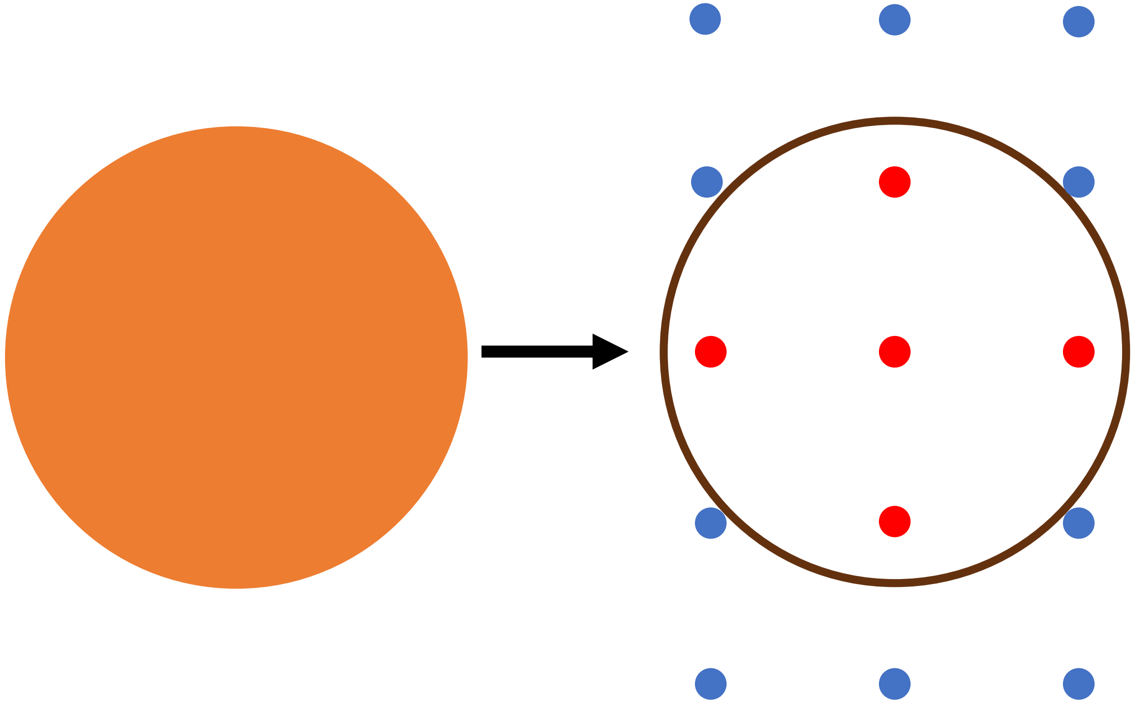
$$= |M_{\text{free}}|^2 |S(\vec{q})|^2 \frac{(2\pi)^3}{V_{\text{cell}}} N_{\text{cell}} \sum_{\vec{G}} \delta^{(3)}(\vec{q} - \vec{G})$$

Bragg Coherent Scattering

- Cross section

$$\sigma = \frac{\bar{\sigma}_e}{\mu_{\chi e}^2} \frac{(2\pi)^3}{V_{\rm cell}} \sum_i \sum_{\vec{G}} \frac{m_\chi}{4\pi} \frac{k'}{(2\pi)^3} \Theta\left(E_1 - \frac{q^2}{2m_\chi} + qv\cos\theta_{qv}\right) |F_{\rm DM}(\vec{q})|^2 |S(\vec{q})|^2$$
$$N_{\rm cell} \sum_{lm} |f_{i\to k'lm}(\vec{q})|^2$$

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



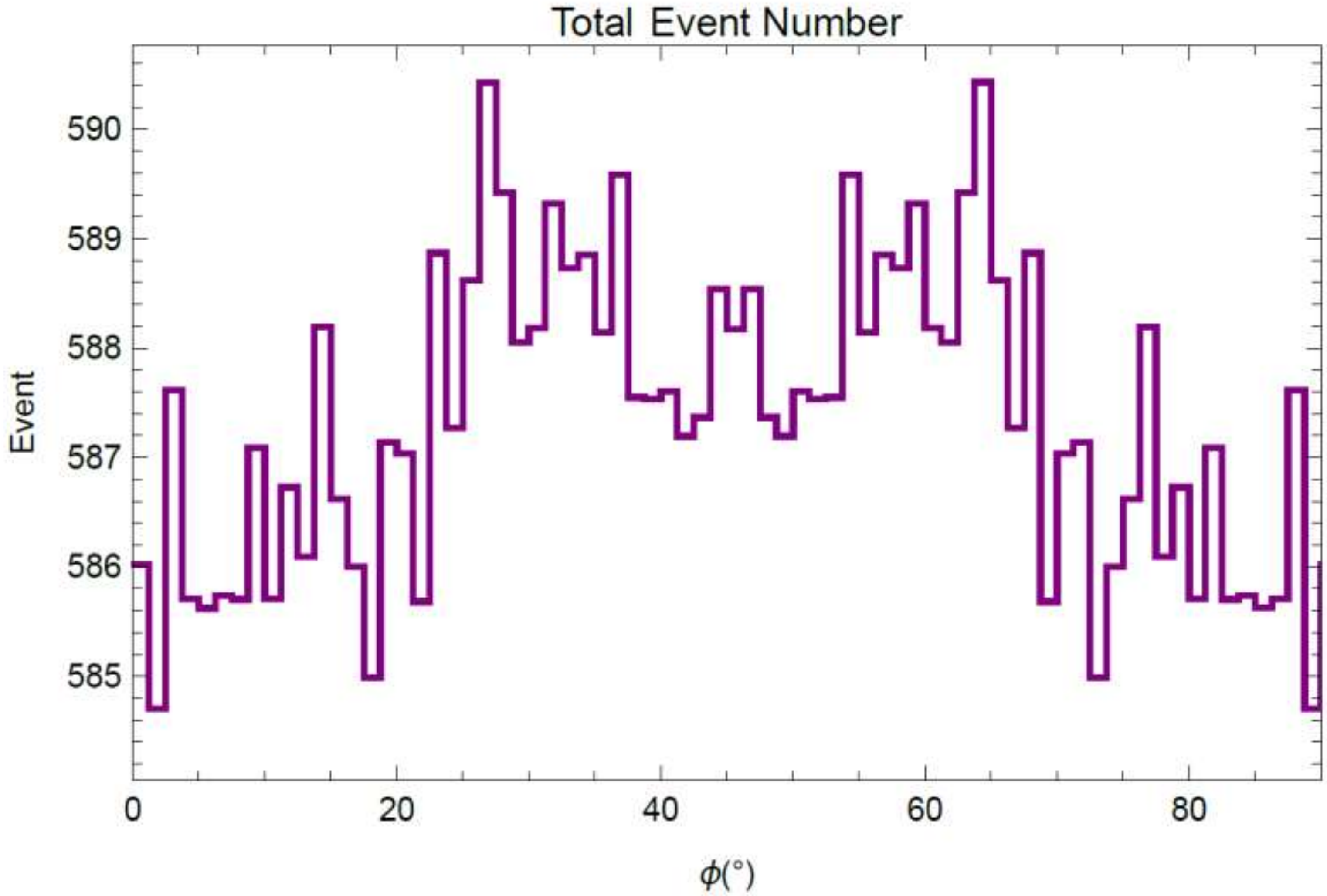


Figure 4: Total event with $\bar{\sigma} = 1 \times 10^{-36}\text{cm}^2$, $m_\chi = 0.501\text{MeV}$, $1\text{kg} \times \text{year}$, $\theta = 90°$.

Dark photon

- Stueckelberg case is bad: relativistic $2 \to 1$ process, $q \sim G \sim 2\mathrm{keV}$, need a very large initial E
- Higgs case is good: relativistic $2 \to 2$ process

$$\mathcal{L}_{int} = e' m_V h' V_\mu^2 + \frac{1}{2} e'^2 h'^2 V_\mu^2$$

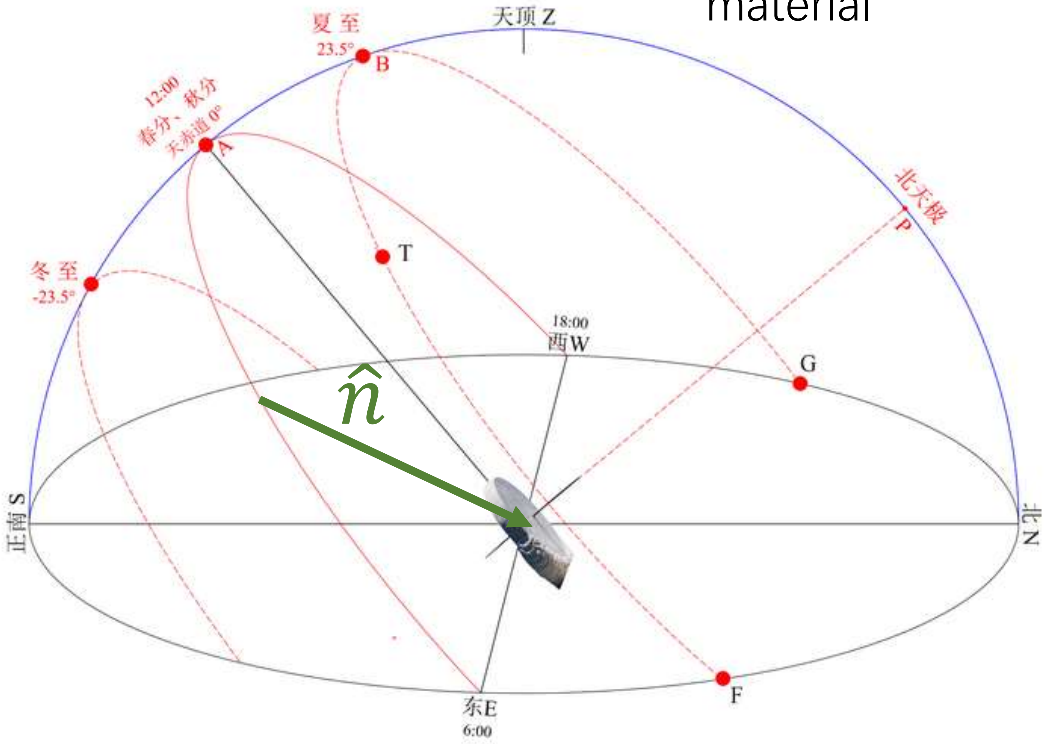
$$V(h') + e^-_{\mathrm{initial}} \to h'(V) + e^-_{\mathrm{final}}$$

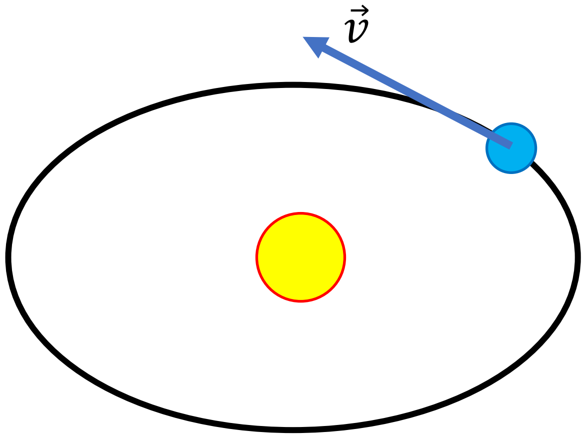
$$\frac{1}{2} \sum_{s_1 s_2} |M|^2 = 4 e^2 \kappa^2 e'^2 m_e^2 \frac{\vec{p}^2}{(q^2 - m_V^2)^2}$$

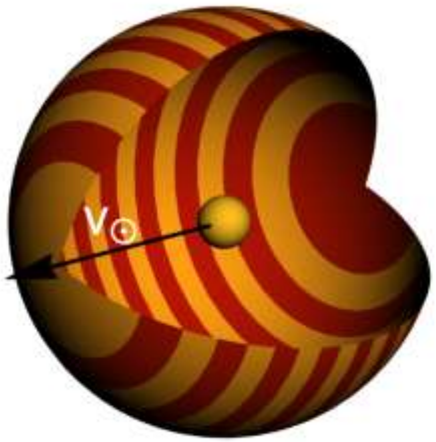
Modulations

Noise grows $\sim\sqrt{N}$
Signal grows $\sim N$
5 years O(1)

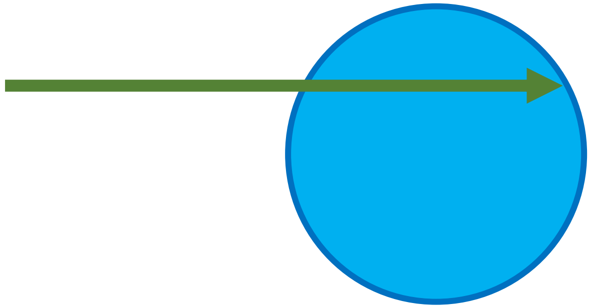
Relevant to the position of detector material







Only relevant to the motion of Earth



[4]T. Emken, solar reflection of light dark matter with heavy mediator, Phys.Rev.D 105 (2022) 6, 063020