Plasmon-enhanced Direct Detection of sub-MeV Dark Matter

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@28th LHC mini-workshop in Tonghua Normal University
July 9, 2024

Main Structure in one slide

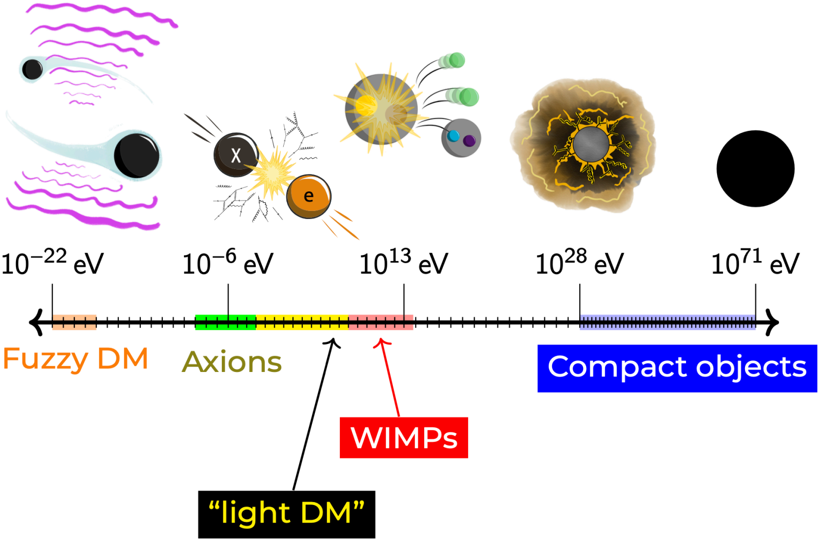
Objective:

Introduces a improved sensitivity approach to detect sub-MeV dark matter as detailed in the paper 2401.11971 with Zheng-Liang Liang, Liang-Liang Su and Lei Wu.

Overview:

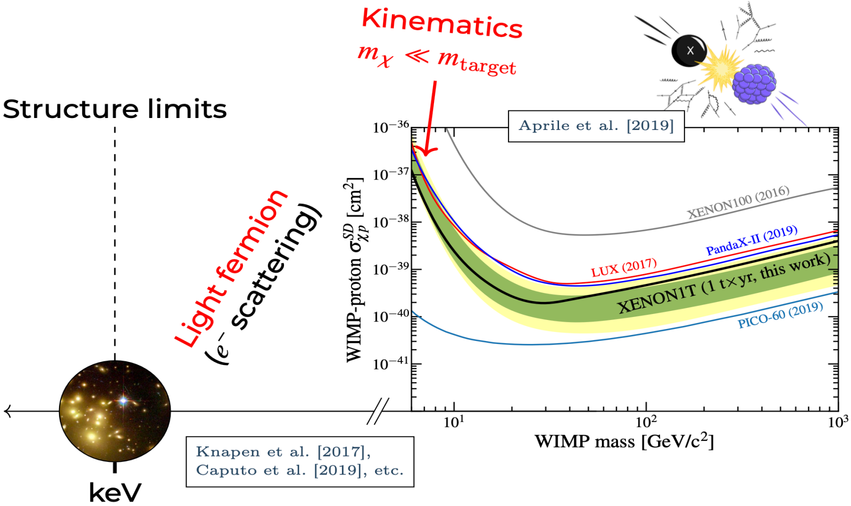
- Show why and what is sub-MeV dark matter and plasmon
- Explain why we need relativistic dark matter to excite plasmon
- Present the computational framework
- Demonstrate improved sensitivity in SENSEI experiment

Dark Matter Landscape



Why and What is Light Dark Matter?

probe keV needs significant detection analysis



A Broad Perspective

More than just nuclear recoil!

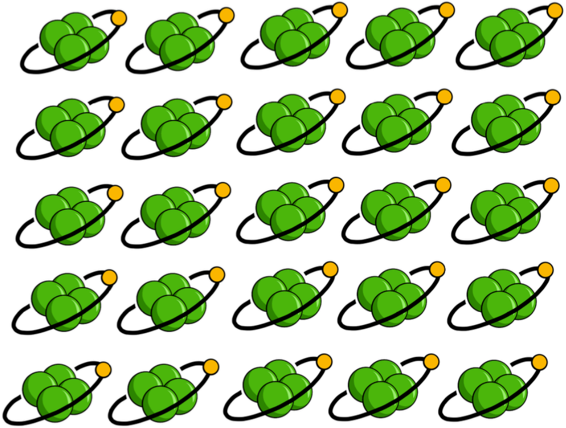
$$R \sim \int d^3\mathbf{v} f(\mathbf{v}) \int d^3\mathbf{q} F^2(\mathbf{q}) S(\mathbf{q}, \omega_{\mathbf{q}})$$

Material properties (e.g. dielectric function) for something must respond at the appropriate (q, ω):

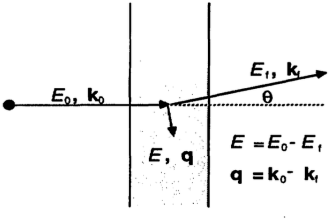
- electronic bands
- Migdal electron
- free nucleus
- phonons
- many more collective effects $\rightarrow$ Plasmons!

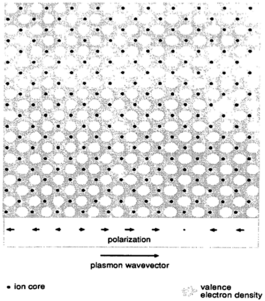
What is Plasmon?

A collective oscillation of electrons, like phonons being collective mode of nucleus

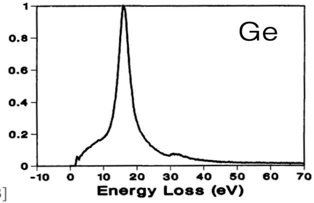


EELS and Plasmons





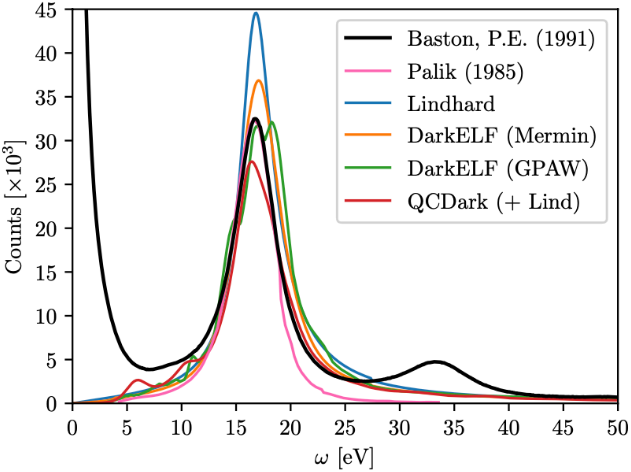
Semi-relativistic electron scattering **not** described by single-particle electron-electron scattering, but by a collective long-range charge wave (plasmon). Electron preferentially deposits ~15 eV of energy, **regardless of initial kinetic energy**



[M. Kundmann, Ph.D. thesis 1988]

Why Plasmon?

Shows up as a resonance in the loss function



Computational Framework

DM scattering in dielectrics

$$\Gamma = \int \frac{\mathrm{d}^3\mathbf{q}}{(2\pi)^3} |V(q)|^2 \left[2\frac{q^2}{e^2} \mathrm{Im}\left(-\frac{1}{\epsilon(\mathbf{q}, \omega_{\mathbf{q}})} \right) \right]$$

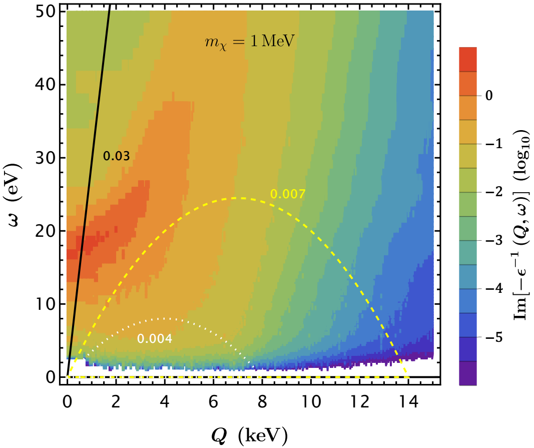
- Scattering potential, flexible for different dark models
- Dielectric function, directly measurable and predicable

Different from conventional electron ionization factor

ϵ contains all collective modes

Zeroth-order Consideration

Why halo dark matter fails exciting plasmon?



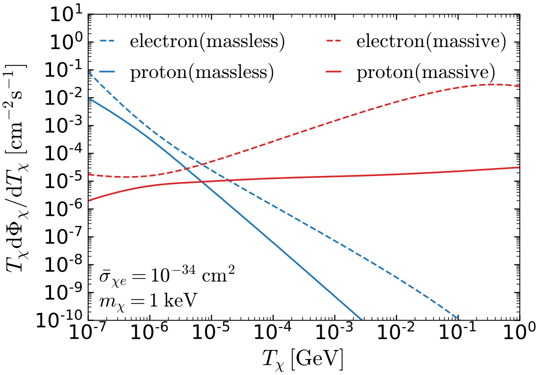
- $\mathrm{Im}\left[-\epsilon^{-1}(\mathbf{Q},\omega)\right]$ for silicon
- Resonance structure (plasmon excitation) exists ($|\mathbf{Q}| < 5\mathrm{keV}, \omega \sim 15\mathrm{eV}$)
- To excite plasmon, need small q for fixed ω from $\omega = \mathbf{q}\cdot\mathbf{v} - \frac{q^2}{2m_\chi}$

$$v_{\min} > q/\omega \sim 10^2$$

Natural Relativistic Source: CRDM

Since we assume dark matter scatters with electron, it must scatter with cosmic electro too!

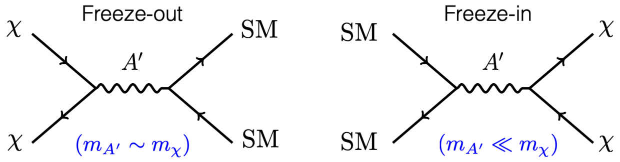
$$\frac{d\Phi_\chi}{dT_\chi} = D_{\text{eff}} \frac{\rho_\chi^{\text{local}}}{m_\chi} \sum_i \int_{T_i^{\min}}^{\infty} dT_i \frac{d\sigma_{\chi i}}{dT_\chi} \frac{d\Phi_i^{\text{LIS}}}{dT_i}$$



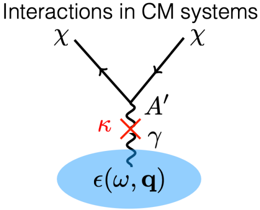
Benchmark Model

Dark Photon Mediator Model

$$\mathcal{L}_e^{\mathrm{eff}} \supset g_e A'_0 \psi_e^* \psi_e + \frac{i g_e}{2 m_e} \mathbf{A}' \cdot \left(\psi_e^* \vec{\nabla} \psi_e - \psi_e^* \overleftarrow{\nabla} \psi_e \right) + \cdots ,$$



DM interacts with anything electrically charged



(easiest to see this in interaction basis rather than mass basis; valid if $m_{A'}^2 \ll \mathbf{q}^2$)

Our Computational Framework

$$\Gamma\left(\mathbf{p}_\chi\right) = \int \frac{\mathrm{d}^3\mathbf{Q}}{(2\pi)^3} |V(\mathbf{Q},\omega)|^2 \left[2\frac{Q^2}{e^2}\mathrm{Im}\left(-\frac{1}{\epsilon(\mathbf{Q},\omega)}\right)\right]$$

- Similar Fermi's Golden Rule, but different kinematics

$$Q = |\mathbf{Q}| = \left|\mathbf{p}_\chi - \mathbf{p}'_\chi\right|, \quad \omega = E_\chi - E'_\chi = \sqrt{p_\chi^2 + m_\chi^2} - \sqrt{\left|\mathbf{p}_\chi - \mathbf{Q}\right|^2 + m_\chi^2}$$

- Scattering potential

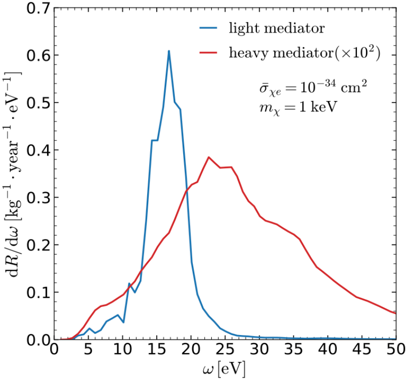
$$|V(\mathbf{Q},\omega)|^2 = \frac{\pi\bar{\sigma}_{\chi e}\left[\left(2E_\chi - \omega\right)^2 - Q^2\right]}{4\mu_{\chi e}^2 E_\chi\left(E_\chi - \omega\right)} \left|F_{\mathrm{DM}}(q)\right|^2,$$

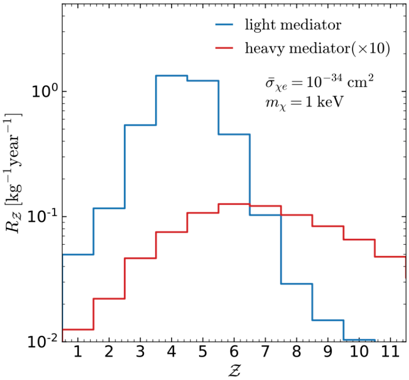
- Dielectric function remains the same
- Event rate

$$R = \frac{1}{\rho_T}\int \mathrm{d}T_\chi \int \frac{\mathrm{d}\Omega}{4\pi}\frac{\mathrm{d}\Phi_\chi}{\mathrm{d}T_\chi}\left(\frac{E_\chi}{p_\chi}\right)\Gamma\left(p_\chi\right)$$

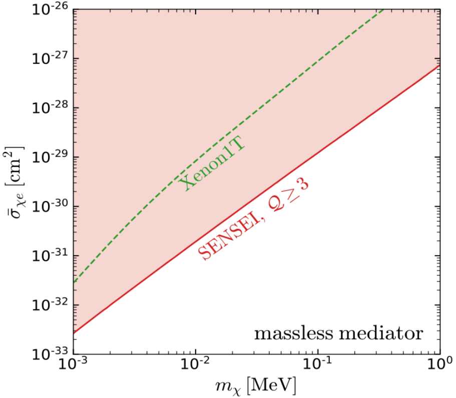
Numerical Results

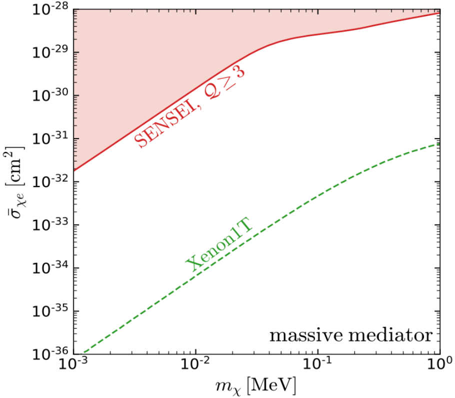
$$|F_{\rm DM}(q)|^2 = \frac{\left(\alpha^2 m_e^2 + m_{A'}^2\right)^2}{\left(q^2 + m_{A'}^2\right)^2} = \begin{cases} 1 & \text{heavy mediator} \\ \frac{(\alpha m_e)^4}{q^4} & \text{light mediator} \end{cases}$$





Plasmon + DM with high velocity + massless mediator





Summary and Outlook

- Plasmon provides resonance enhancement to the event rate for relativistic dark matter
- SENSEI is now observing similar behavior like plasmon, which can be the signal of dark mattter
- For now, only focus on the electron density operator, how to generalize the current-current operator?

Backup Slides

Rate predictions from QEDark and QCDark

electron recoil spectrum

$$\frac{dR_{\rm crystal}}{d\ln E_e} = \frac{\rho_\chi}{m_\chi} N_{\rm cell}\,\overline{\sigma}_e\,\alpha \times \frac{m_e^2}{\mu_{\chi e}^2}\int d\ln q\left(\frac{E_e}{q}\eta(v_{\rm min}(q,E_e))\right)F_{\rm DM}(q)^2\left|f_{\rm crystal}(q,E_e)\right|^2$$

crystal form factor

$$\left|f_{\rm crystal}(q,E_e)\right|^2 = \frac{2\pi^2(\alpha m_e^2 V_{\rm cell})^{-1}}{E_e}\sum_{i\,i'}\int_{\rm BZ}\frac{V_{\rm cell}\,d^3k}{(2\pi)^3}\frac{V_{\rm cell}\,d^3k'}{(2\pi)^3}\times E_e\,\delta(E_e - E_{i'\vec{k}'} + E_{i\vec{k}})\sum_{\vec{G}'} q\,\delta(q - |\vec{k}' - \vec{k} + \vec{G}'|)\left|f_{[i\vec{k},i'\vec{k}',\vec{G}']}\right|^2$$

wavefunction overlap

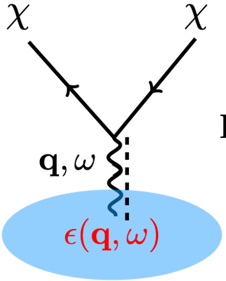
$$f_{[i\vec{k},i'\vec{k}',\vec{G}']} = \sum_{\vec{G}} u_{i'}^*(\vec{k}' + \vec{G} + \vec{G}')u_i(\vec{k} + \vec{G})$$

This is pure theory: how well does it compare with data?
How do we calibrate charge yield from recoil spectrum?

Rate predictions from dielectric

$$\mathrm{Im}\left(-\frac{1}{\epsilon(\mathbf{q},\omega)}\right) = \frac{\pi e^2}{q^2}\sum_f \left|\langle f|\hat{\rho}(\mathbf{q})|0\rangle\right|^2 \delta(\omega_f - \omega)$$

many-body electron density



DM-electron interaction (assumed spin-independent)

Dielectric function

$$\Gamma(\mathbf{v}) = \int \frac{d^3\mathbf{q}}{(2\pi)^3} |V(\mathbf{q})|^2 \left[\frac{q^2}{e^2} 2\,\mathrm{Im}\left(-\frac{1}{\epsilon(\mathbf{q},\omega)}\right)\right]$$

That's the answer, for any material.