Plasmon-enhanced Direct Detection of sub-MeV Dark Matter

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Main Structure in one slide

Objective:

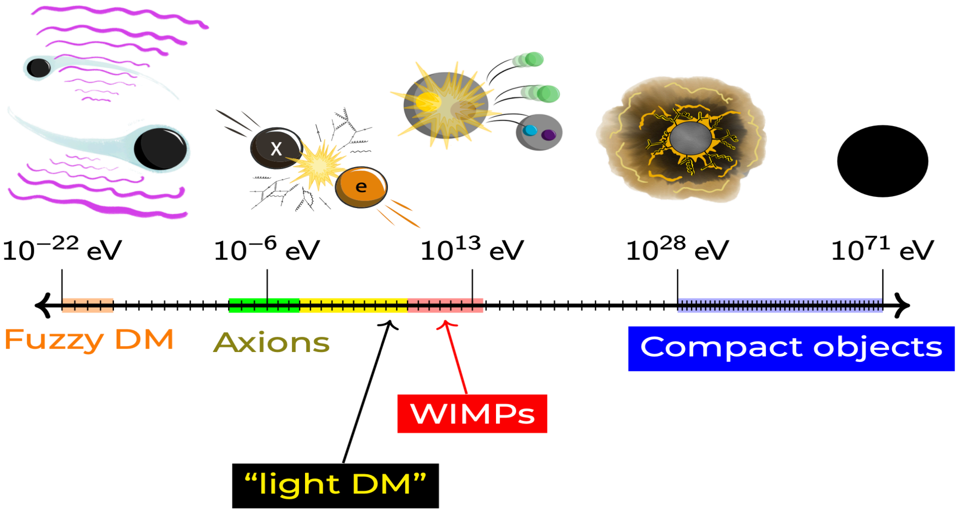
Enhances sensitivity for detecting sub-MeV dark matter, leveraging plasmon resonance techniques (2401.11971) with Zheng-Liang Liang, Liang-Liang Su and Lei Wu.

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

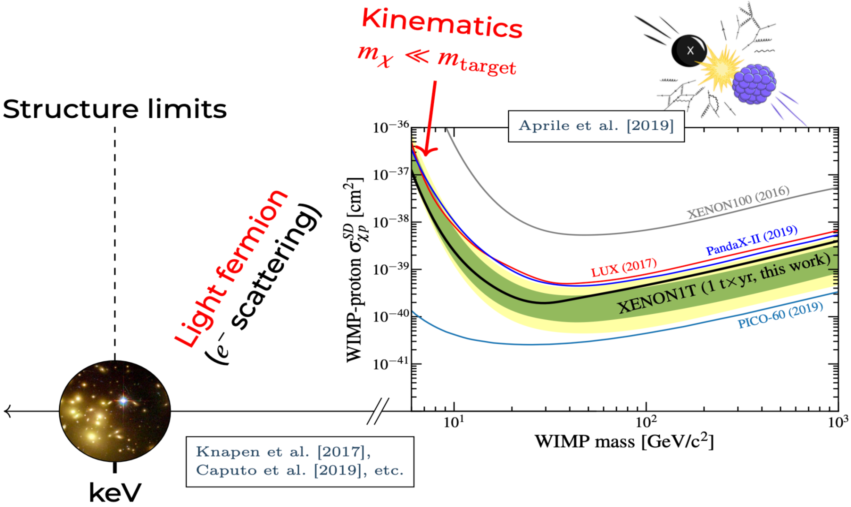
Dark Matter Landscape

From Benjamin V. Lehmann



Why and What is Light Dark Matter?

Probe keV DM needs significant detection analysis



A Broad Perspective

More than just nuclear recoil!

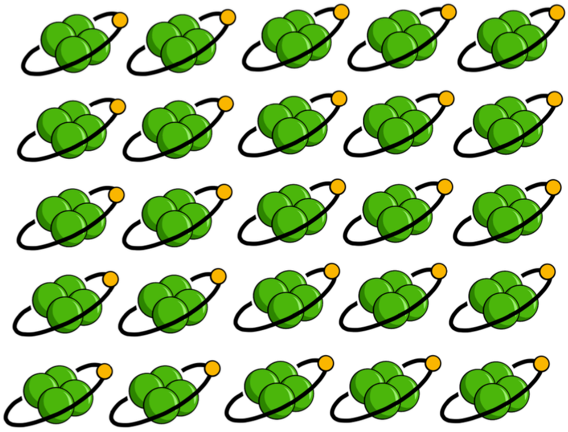
$$R \sim \int d^3\mathbf{v} f(\mathbf{v}) \int d^3\mathbf{q} F_{\mathrm{DM}}^2(\mathbf{q}) S\left(\mathbf{q}, \omega_{\mathbf{q}}\right)$$

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

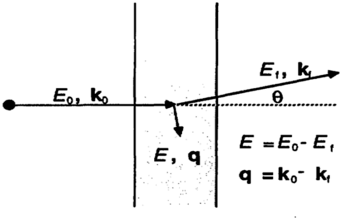
- Electrons
- Migdal effect
- Phonons or Magnons $\rightarrow$ Threaten by identification of one phonon in detector
- More collective effects $\rightarrow$ Plasmons from many electrons!

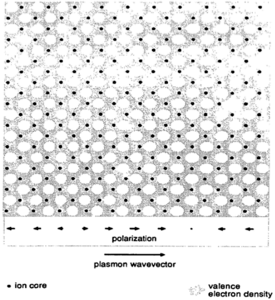
What is Plasmon?

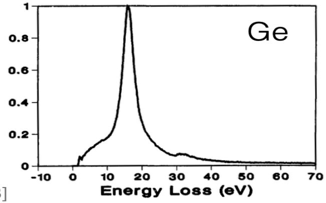
A collective oscillation of electrons, like phonons being collective mode of nucleus



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 Particular Conditions for Plasmon Excitation?

- Dielectric function ϵ describes the response of Coulomb interaction, $V = \frac{1}{4\pi\epsilon}\frac{1}{r}$
- The plasmon appears as a zero of dielectric function

$$\hat{\epsilon}_L(\omega, k) \approx 1 - \frac{\omega_p^2}{\omega^2}\left(1 + \frac{3}{5}\frac{k^2 v_F^2}{\omega_p^2} + \dots\right)$$

- ω_p is the plasmon frequency

$$\omega_p^2 = \frac{4\pi\alpha n_e}{m_e}$$

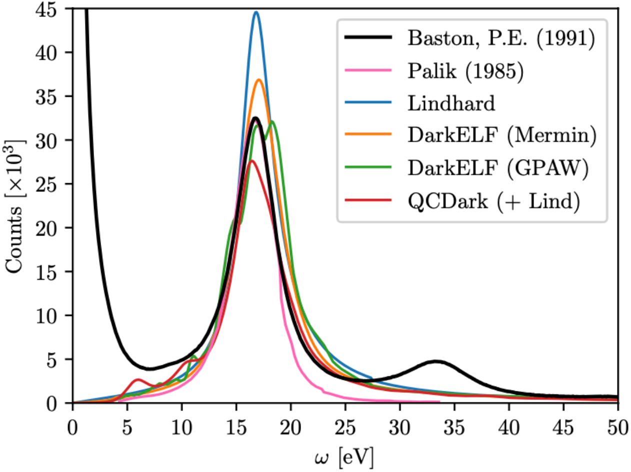
$\omega_p \sim \mathcal{O}(10\text{—}100)\ \mathrm{eV}$ across essentially all materials. In paritculuar, $\omega_p \sim 16\mathrm{eV}$ for Si

The pole structure is not arbitrarily correct

The plasmon is only well-defined for $k < \omega_p/v_F \sim \mathrm{keV}$

Why Plasmon?

Shows up as a resonance in the loss function



Computational Framework

DM scattering in dielectrics

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

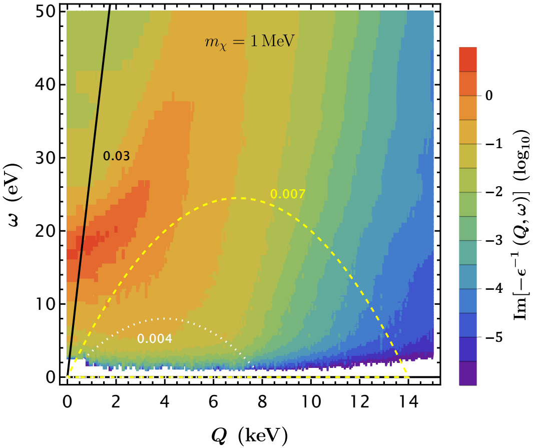
- Scattering potential, flexible for different dark models
- Dielectric function, directly measurable and predicable

Different from conventional electron ionization factor

ϵ contains all collective modes

Zeroth-order Consideration

Why halo dark matter fails exciting plasmon?



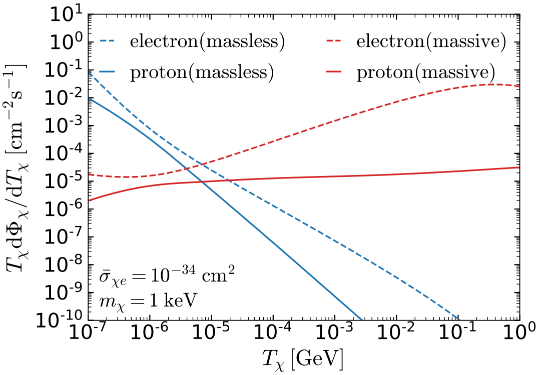
- $\mathrm{Im}\left[-\epsilon^{-1}(\mathbf{Q},\omega)\right]$ for silicon
- Resonance structure (plasmon excitation) exists ($|\mathbf{Q}| < 5\mathrm{keV}, \omega \sim 15\mathrm{eV}$)
- To excite plasmon, need small q for fixed ω from $\omega = \mathbf{q}\cdot\mathbf{v} - \frac{q^2}{2m_\chi}$

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

Natural Relativistic Source: CRDM

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

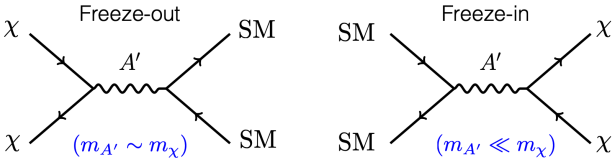
$$\frac{\mathrm{d}\Phi_\chi}{\mathrm{d}T_\chi} = D_{\text{eff}} \frac{\rho_\chi^{\text{local}}}{m_\chi} \sum_i \int_{T_i^{\min}}^{\infty} \mathrm{d}T_i \frac{\mathrm{d}\sigma_{\chi i}}{\mathrm{d}T_\chi} \frac{\mathrm{d}\Phi_i^{\text{LIS}}}{\mathrm{d}T_i}$$



Benchmark Model

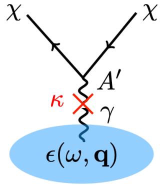
Dark Photon Mediator Model

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



Interactions in CM systems

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

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

- Similar Fermi's Golden Rule, but different kinematics

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

- Scattering potential

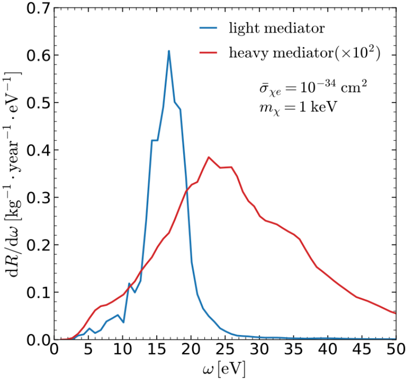
$$|V(\mathbf{Q},\omega)|^2 = \frac{\pi \bar{\sigma}_{\chi e} \left[(2E_\chi - \omega)^2 - Q^2 \right]}{4\mu_{\chi e}^2 E_\chi (E_\chi - \omega)} |F_{\mathrm{DM}}(q)|^2 ,$$

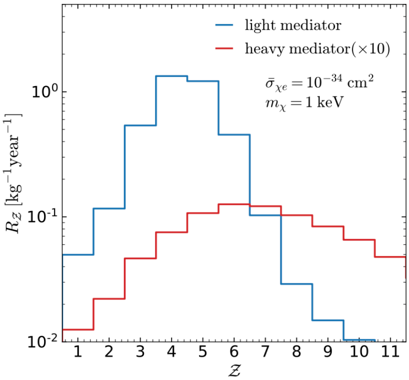
- Dielectric function remains the same
- Event rate

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

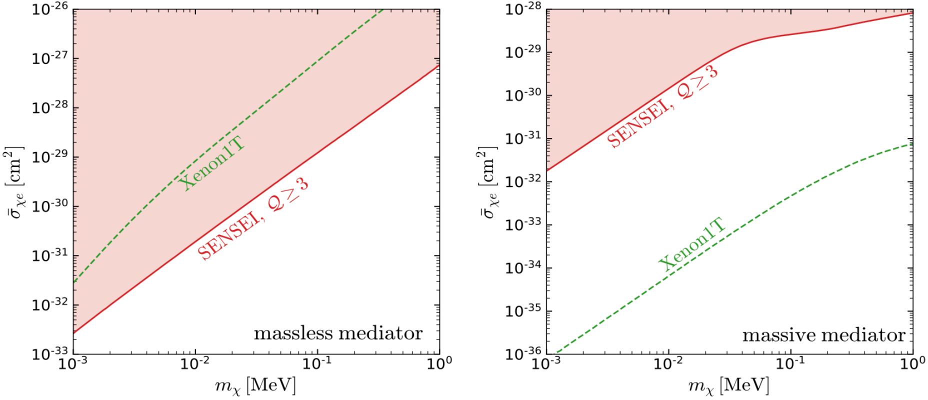
Numerical Results

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





Plasmon + DM with high velocity + light 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?