International Workshop on New Opportunities for Particle Physics 2024

Sub-GeV Dark Matter and Collective Excitation Signals

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2401.11971

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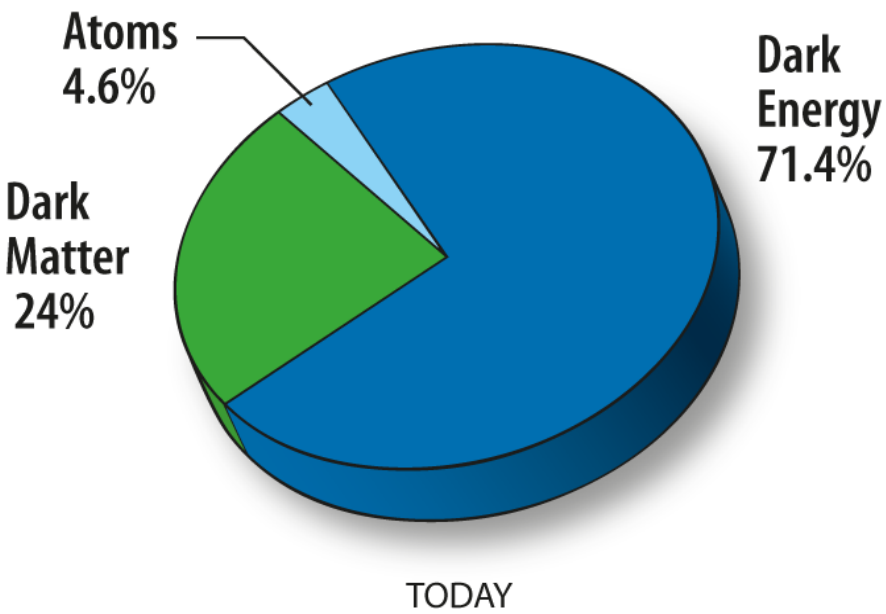
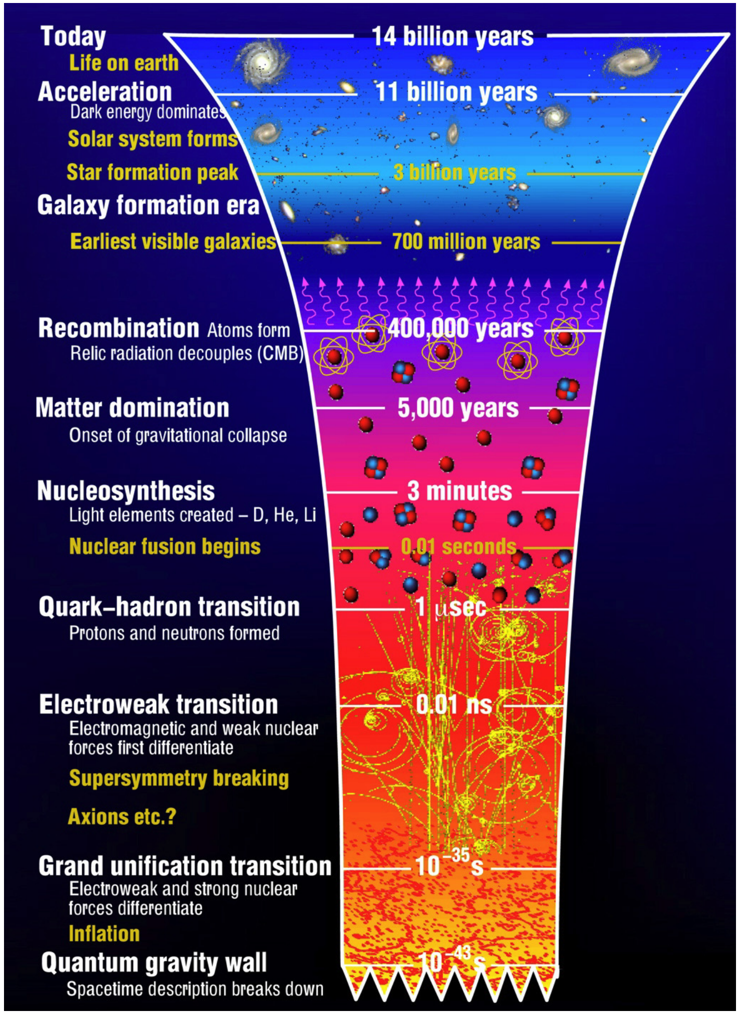
Outline

- **From WIMPs to Light Dark Matter**
- **Sub-GeV DM and Collective Excitations**
- **Conclusions**

1. From WIMPs to Light DM



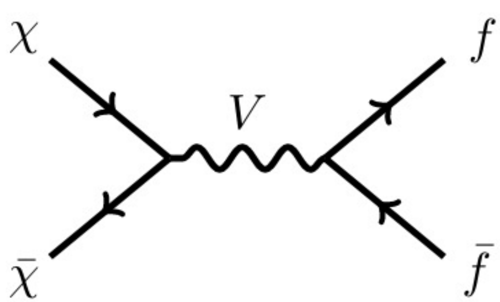


"Dark Matter Paradigm Remains the Only Viable and Simple Framework for the Full Range of Observations"

1. From WIMPs to Light DM

Weakly Interacting Massive Particles (WIMPs)

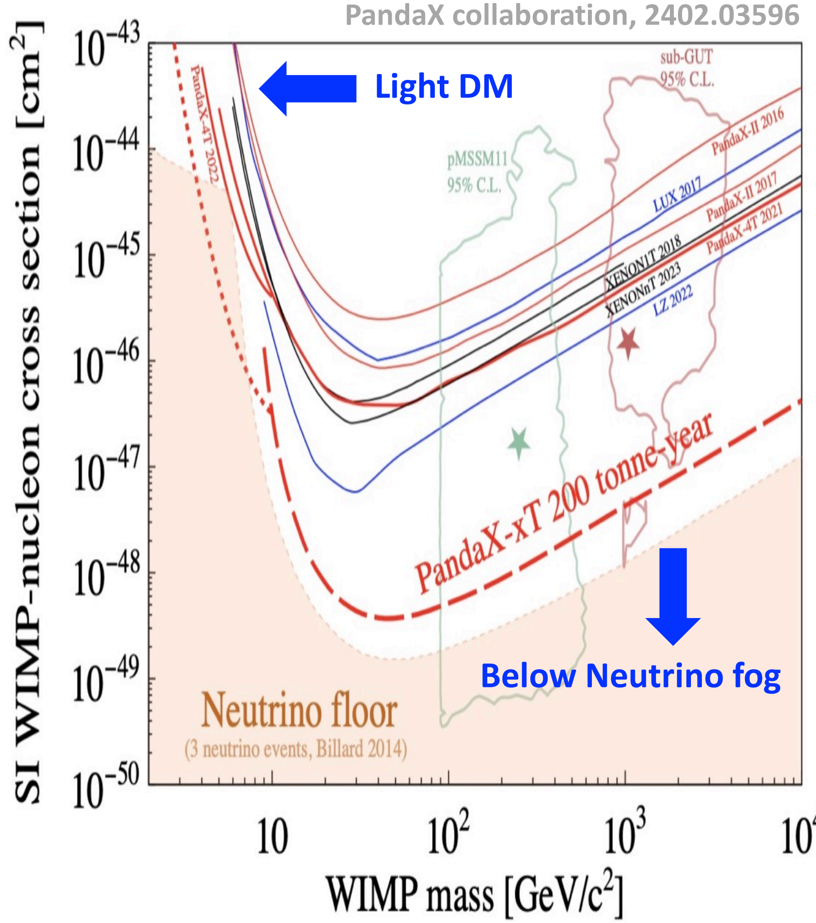
$$\Omega_\chi \propto \frac{1}{<\sigma v>} \sim \frac{m_\chi^2}{g_\chi^4}$$



$$m_\chi \sim 100 \text{ GeV}, \; g_\chi \sim 0.6 \rightarrow \Omega_\chi \sim 0.1$$

SUperSYmmetry

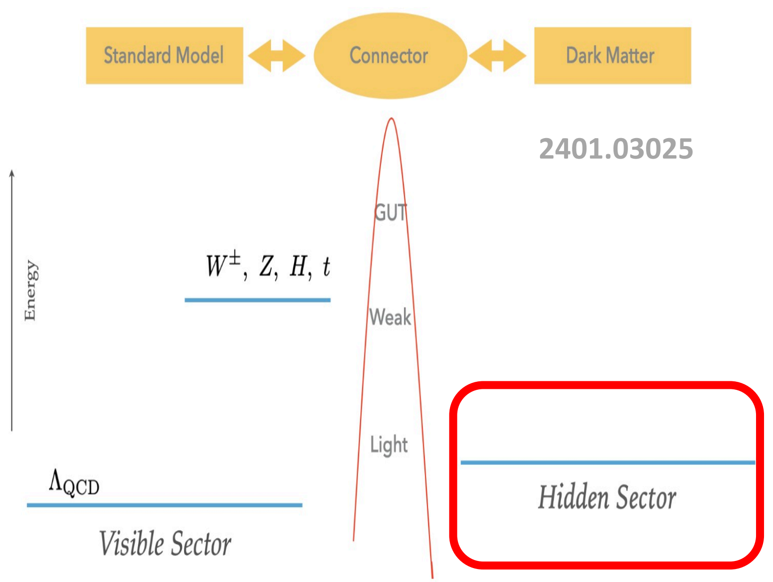
PandaX collaboration, 2402.03596

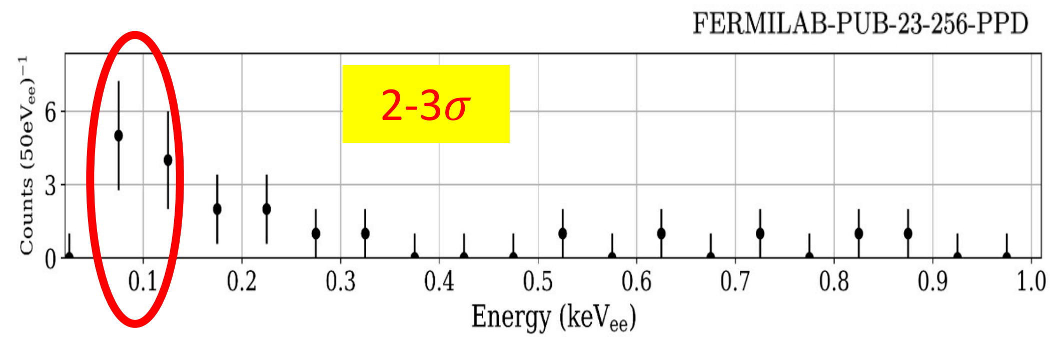


1. From WIMPs to Light DM

Theory (Hidden sector DM)

Data (excess-1)





QCD/QED-like theory,

Remnant from SUSY breaking,

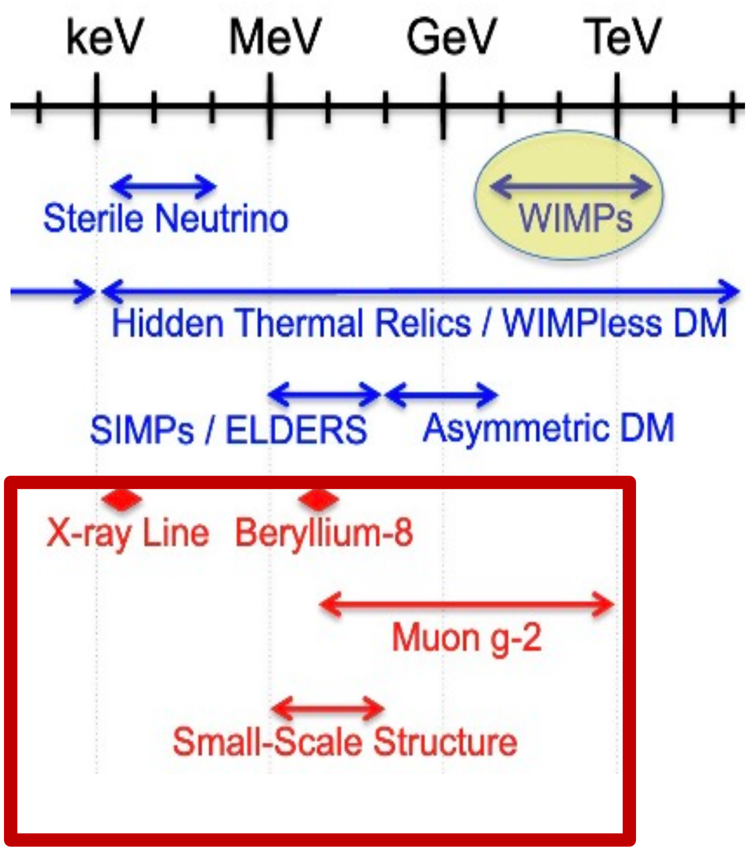
Sector arising from an RS …

2002.06937

Readout Type	Target	Resolution	Exposure	Threshold	Excess Rate (Hz/kg)	Depth	Reference
Charge (E_e)	Ge	1.6 e^-	80 g·d	0.5 eVee (∼1e^-)[a]	[20, 100]	.7 km	EDELWEISS [6]
	Si	∼0.2 e^-	0.18 g·d	1.2 eVee (<1 e^-)	[6, 400]	100 m	SENSEI [4]
	Si	0.1 e^-	0.5 g·d	1.2 eVee (<1 e^-)	[10, 2000]	∼1 m	CDMS HVeV [3]
	Si	1.6 e^-	200 g·d	1.2 eVee (∼1e^-)	[1×10^{-3}, 7]	2 km	DAMIC [7]
Energy (E_{det})	Ge	18 eV	200 g·d	60 eV	> 2	∼1 m	EDELWEISS [1]
	$CaWO_4$	4.6 eV	3600 g·d	30 eV	> 3×10^{-3}	.4 km	CRESST-III [2]
	Al_2O_3	3.8 eV	0.046 g·d	20 eV	> 30	∼1 m	νCLEUS [8]
Photo e^-	Xe	6.7 PE (∼ 0.25 e^-)	15 kg·d	12.1 eVee (∼14 PE)	[0.5, 3] $\times10^{-4}$	.4 km	XENON10 [5, 9]
	Xe	6.2 PE (∼ 0.31 e^-)	30 kg·yr	∼70 eVee (∼80 PE)	> 2.2×10^{-5}	.4 km	XENON100 [5]
	Xe	< 10 PE	60 kg·yr	∼140 eVee (∼90 PE)	> 1.7×10^{-6}	.4 km	XENON1T [10]
	Ar	∼15 PE (∼ 0.5 e^-)	6780 kg·d	50 eVee	> 6×10^{-4}	.4 km	Darkside50 [11]

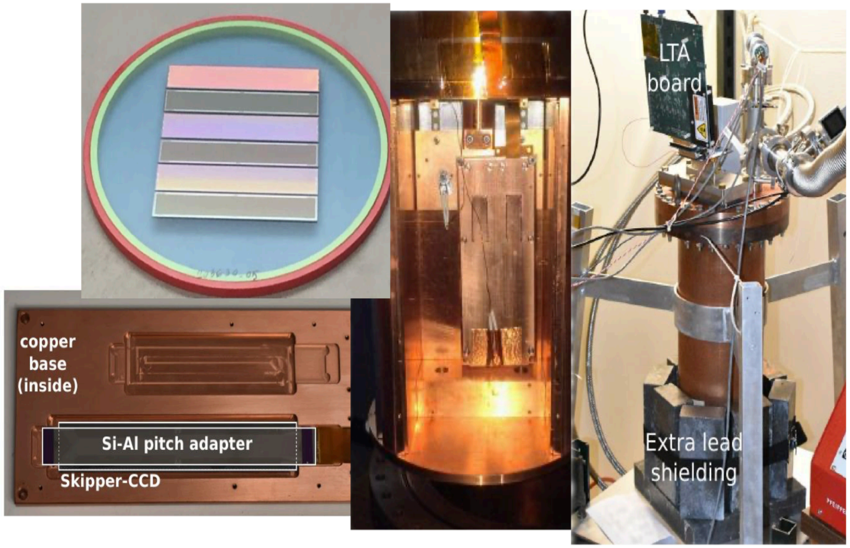
1. From WIMPs to Light DM

Data (excess-2)



Technology (Skipper-CCD)

Stephen Holland @ LBNL

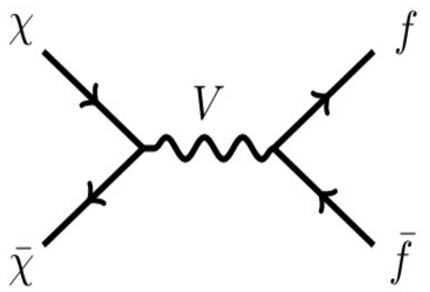


charges in pixel,

accessing to 1e$^-$ signal,

very low noise

2. sub-GeV DM and Collective Excitations



- $m_V > m_\chi \quad \langle \sigma v \rangle \simeq \frac{16\pi\alpha_\chi\alpha_f m_\chi^2}{m_V^4}$

↓

Light non-SM mediator

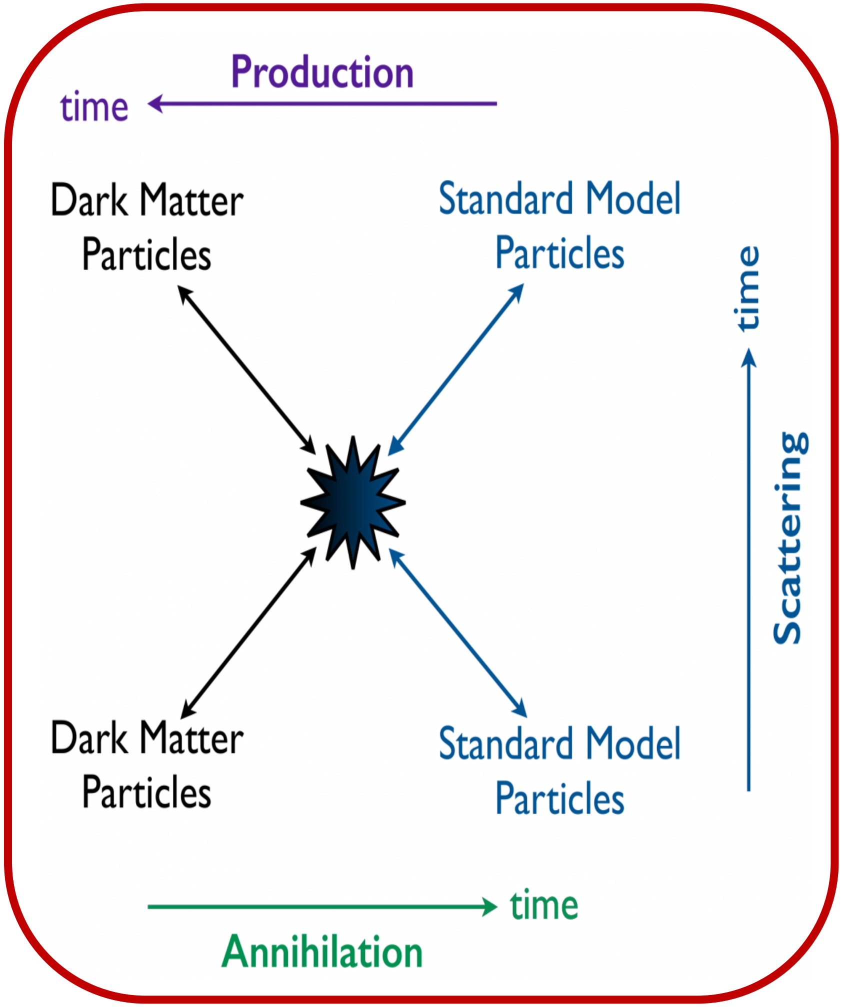
- $m_V < m_\chi \quad \langle \sigma v \rangle \simeq \frac{\pi\alpha_\chi\alpha_f}{m_\chi^2}$

1 **Relic Density and Models**

Secluded DM or WIMPless DM

- SIMPs [**YH**, Kuflik, Volansky, Wacker, 2014; **YH**, Kuflik, Murayama, Volansky, Wacker, 2015]
- ELDERs [Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2016 & 2017]
- Forbidden dark matter [Griest, Seckall, 1991; D'Agnolo, Ruderman, 2015]
- Co-decaying dark matter [Dror, Kuflik, Ng, 2016]
- Co-scattering dark matter [D'Agnolo, Pappadopulo, Ruderman, 2017]
- ......

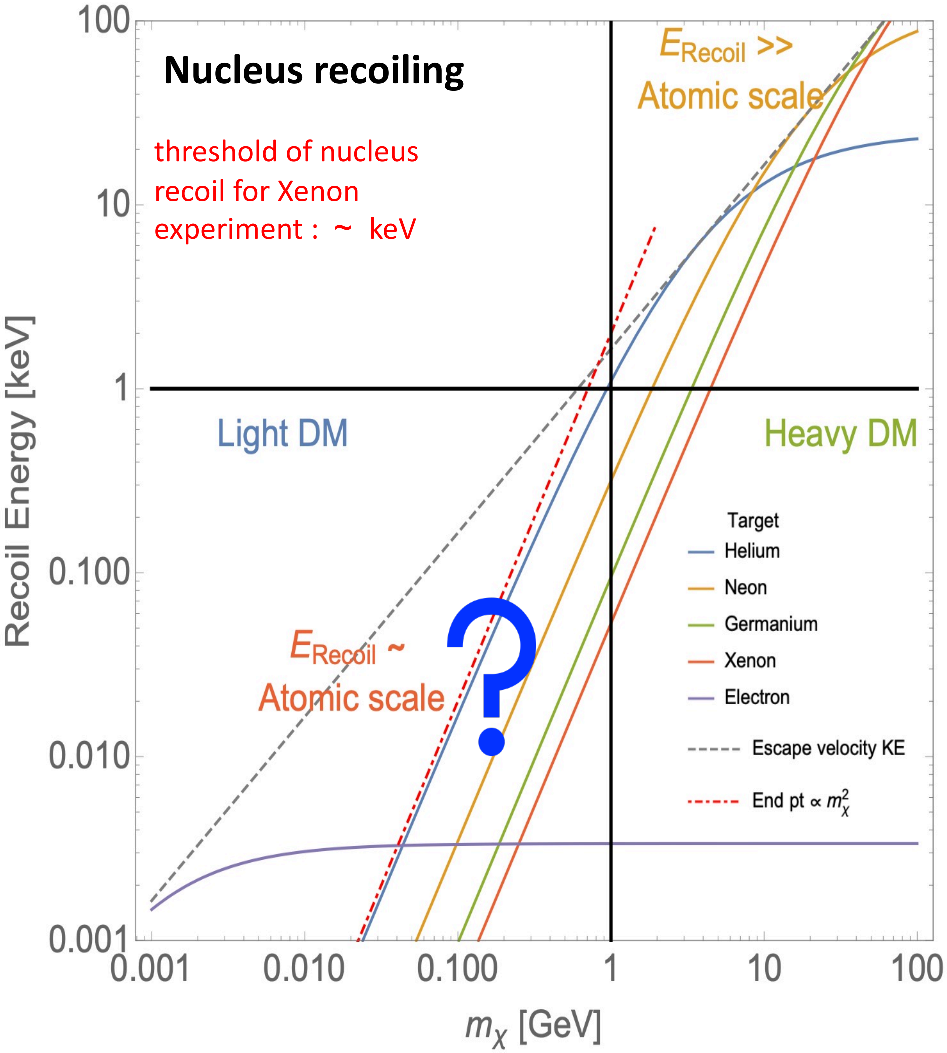
2. sub-GeV DM and Collective Excitations



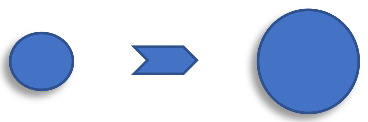
2 **How to test Light DM models**

- **BBN, CMB**
- **Large Scale Structure**
- **Stellar Evolution and Cooling**
- **BeamDump**

2. sub-GeV DM and Collective Excitations

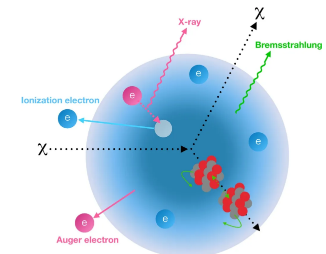


1. **Boosted Dark Matter**

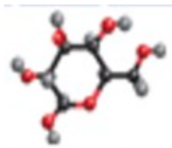


V ~ 10^{-3} c V ~ c

2. **Ionization Effects**



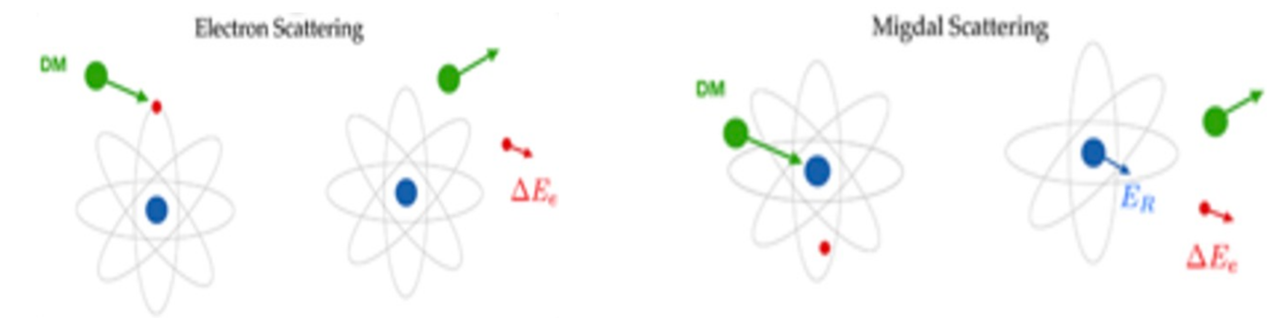
3. **New Materials**

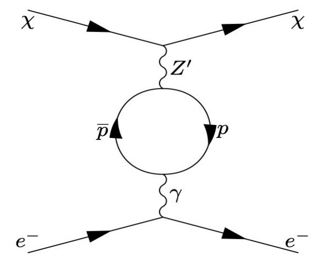


2. sub-GeV DM and Collective Excitations

Ionization signals

(DM-e, Migdal effect, Loop induced)



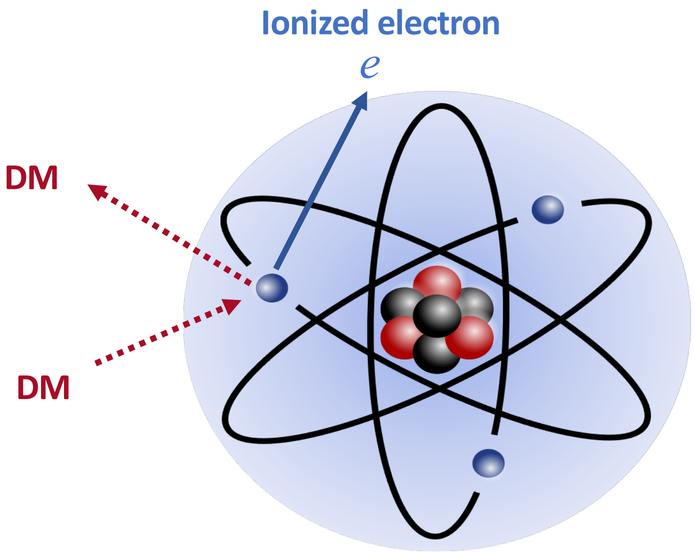


Light Dark Matter	Noble Liquid Detector (large volume, high threshold)	Solid detector (small volume, low threshold)
Non-Relativistic	✓	✓
Relativistic	✓	?

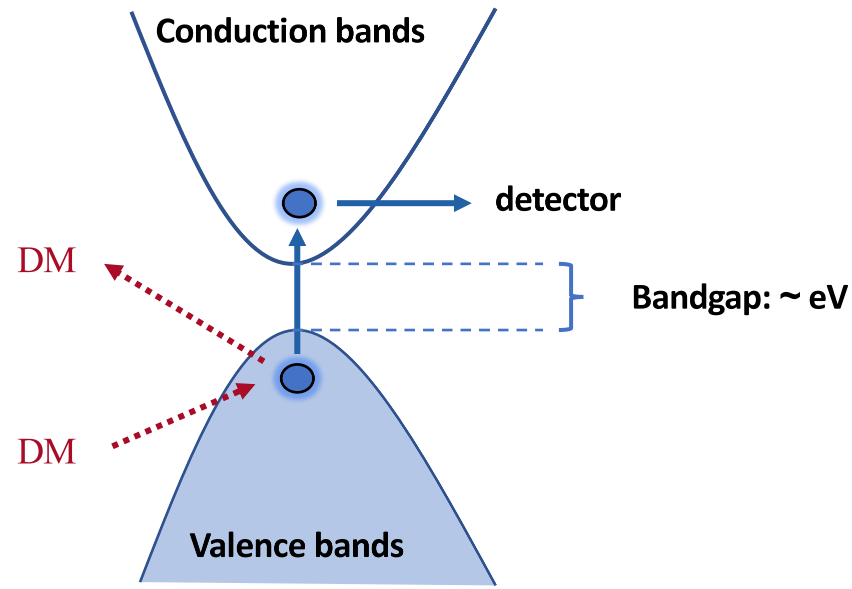
Collective Excitations

2. sub-GeV DM and Collective Excitations

Collective behavior is crucial in Solid Detector



Xenon



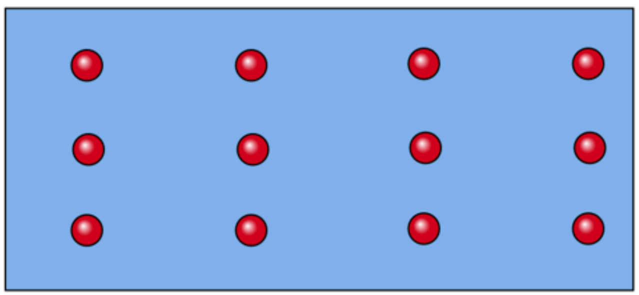
Semi-conductor

lower threshold,

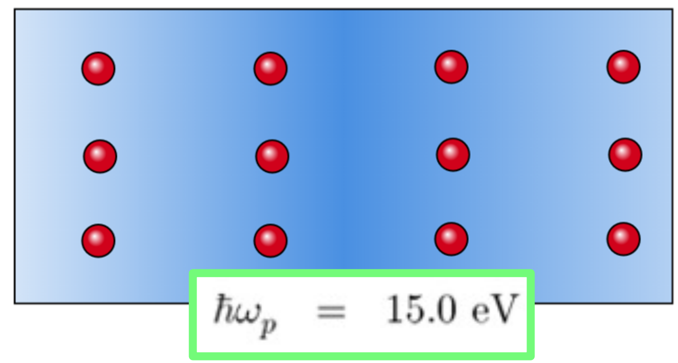
lighter dark matter

2. sub-GeV DM and Collective Excitations

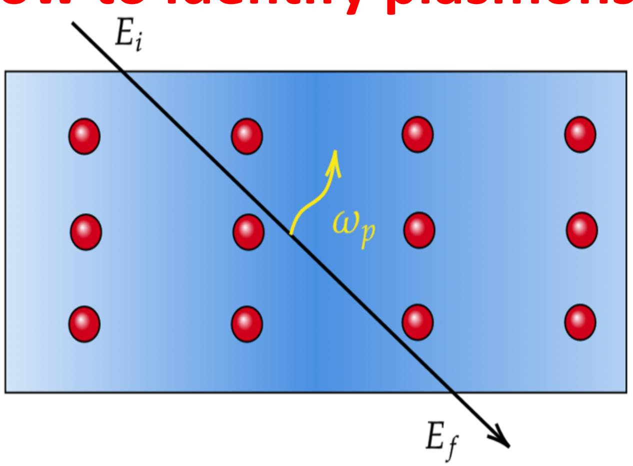
Valence electrons are free in metals and semiconductors, and form an electron gas holding the ionic lattice together.

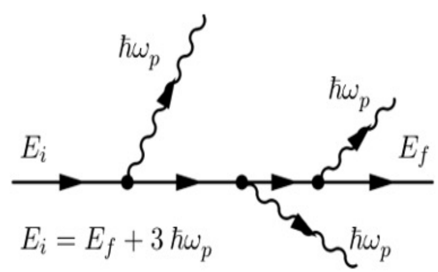


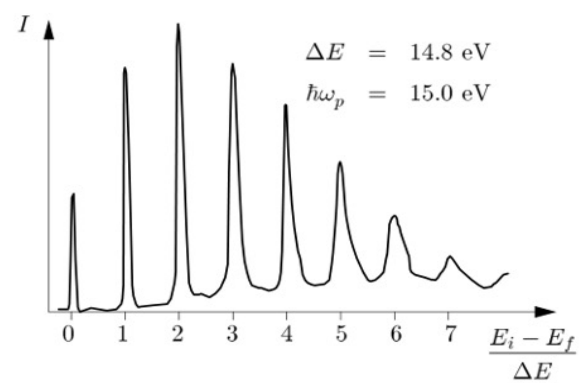
Plasmon is the quantized form of the **electron density fluctuation** in the medium, oscillating with a frequency: $\omega_p = \sqrt{\frac{4\pi\alpha n_e}{m_e}}$



How to identify plasmons: Electron Energy Loss Spectroscopy (EELS)







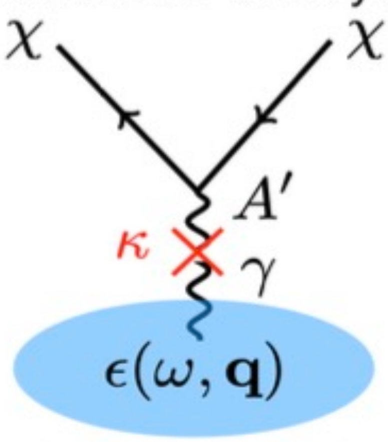
2. sub-GeV DM and Collective Excitations

Liang, Su, LW, Zhu, 2401.11971

◆ DM-induced Plasmon Signals in Solid Detector

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

Interactions in CM systems



Dielectric Function

Electronic Structure (polarization)

$$\varepsilon(Q,\omega) = \varepsilon_1(Q,\omega) + i\varepsilon_2(Q,\omega)$$

Dissipation Processes (absorption and scattering)

2. sub-GeV DM and Collective Excitations

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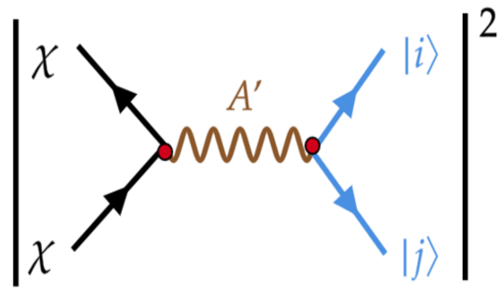
Benchmark Model :

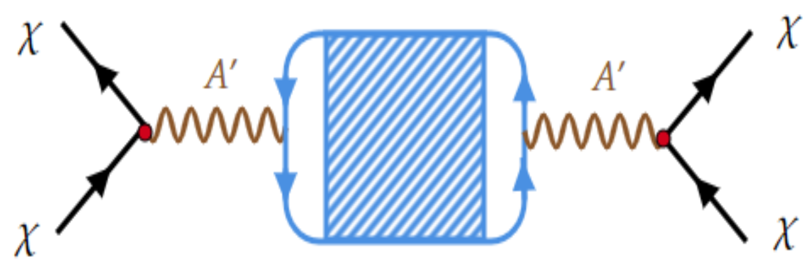
$$\mathcal{L}_{\rm int} \supset g_\chi \bar{\chi}\gamma^\mu \chi A'_\mu + g_e \bar{e}\gamma^\mu e A'_\mu$$

Non-relativistic QFT

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



In-medium effect



2. sub-GeV DM and Collective Excitations

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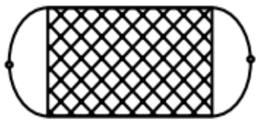
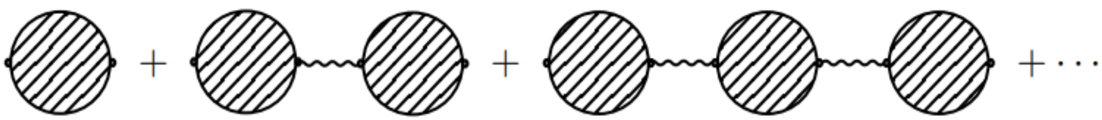
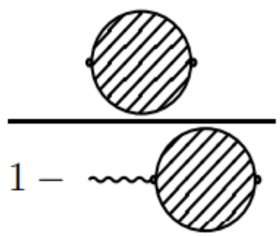
$\chi^{\mathrm{r}}_{\hat\rho\hat\rho} =$  **Density-Density correlation function (RPA)**

$=$ 

$=$  $\Rightarrow$ $\Pi_e\,(Q,\omega)$ **Lindhard function**

$$= \frac{\Pi_e}{1 - V_e\,\Pi_e}, \quad \Rightarrow \quad \frac{1}{\epsilon\,(\mathbf{Q},\omega)} = 1 + V_e\,(Q)\,\chi^{\mathrm{r}}_{\hat\rho\hat\rho}\,(\mathbf{Q},\,\omega)$$

Dielectric Function

Energy Loss Function (ELF)

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

$$\mathrm{Im}\left[\frac{-1}{\epsilon}\right] = \frac{\mathrm{Im}[\epsilon]}{\mathrm{Re}[\epsilon]^2+\mathrm{Im}[\epsilon]^2}$$

$$\frac{1}{\pi}\,\frac{\frac{1}{2}\Gamma}{(x-x_0)^2+\left(\frac{1}{2}\Gamma\right)^2} \sim \delta(x-x_0)$$

DM scattering rate **Scattering potential**

2. sub-GeV DM and Collective Excitations

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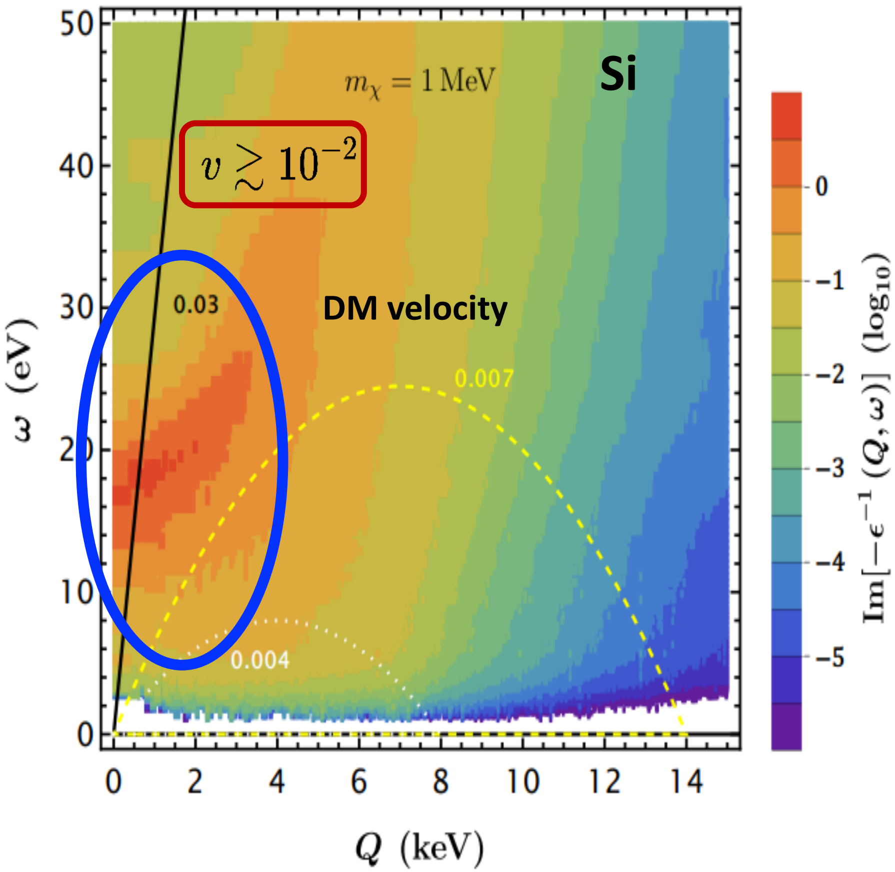


- **Energy Loss Function:**

  Density Functional Theory

- **Resonance (plasmon) :**

  $|Q| < 5$ keV, $\omega \sim 15$ eV

- **To excite plasmon:**

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

Low deposited energy

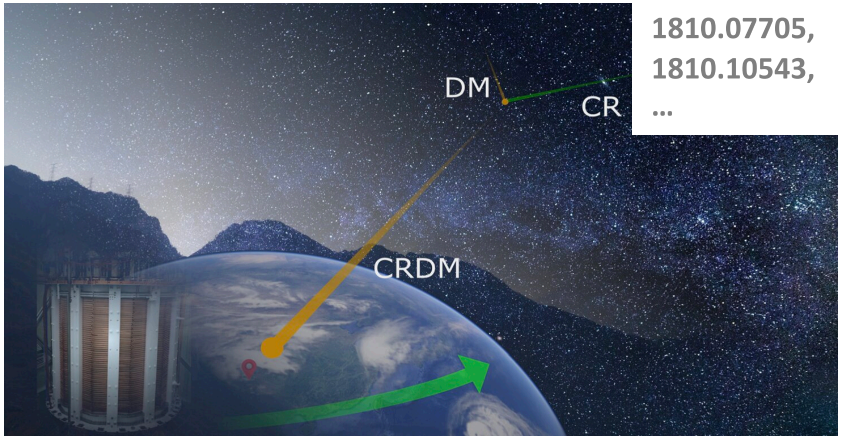
Relativistic Dark Matter

2. Light DM and Collective Excitations

Sensei @ SNOLab

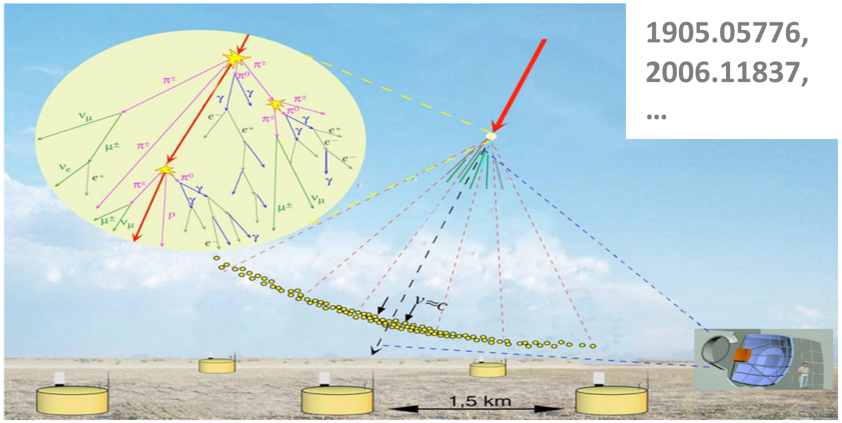
Electron recoil ionizing 1–6 e^- in the detector, which corresponds to (~1.2–20 eV) energy depositions

Cosmic ray Boosted DM



1810.07705,
1810.10543,
…

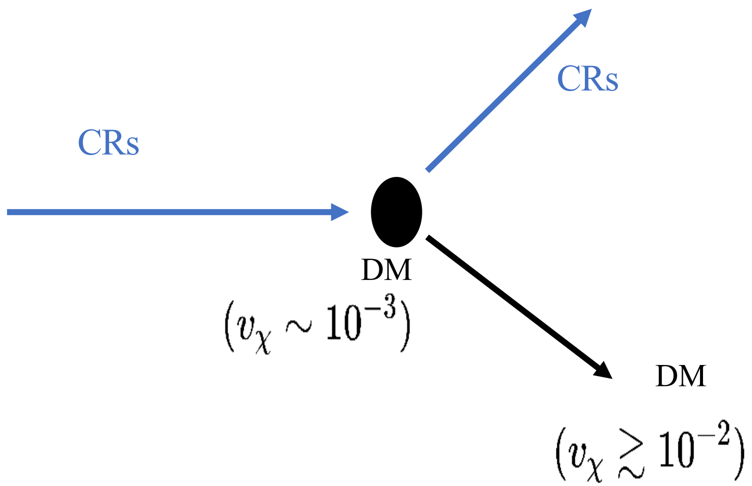
Atmospheric DM

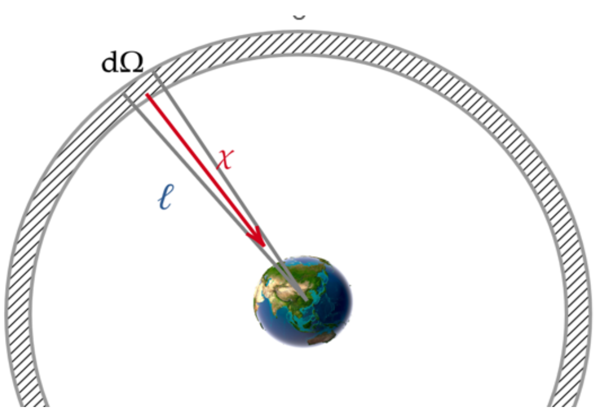


1905.05776,
2006.11837,
…

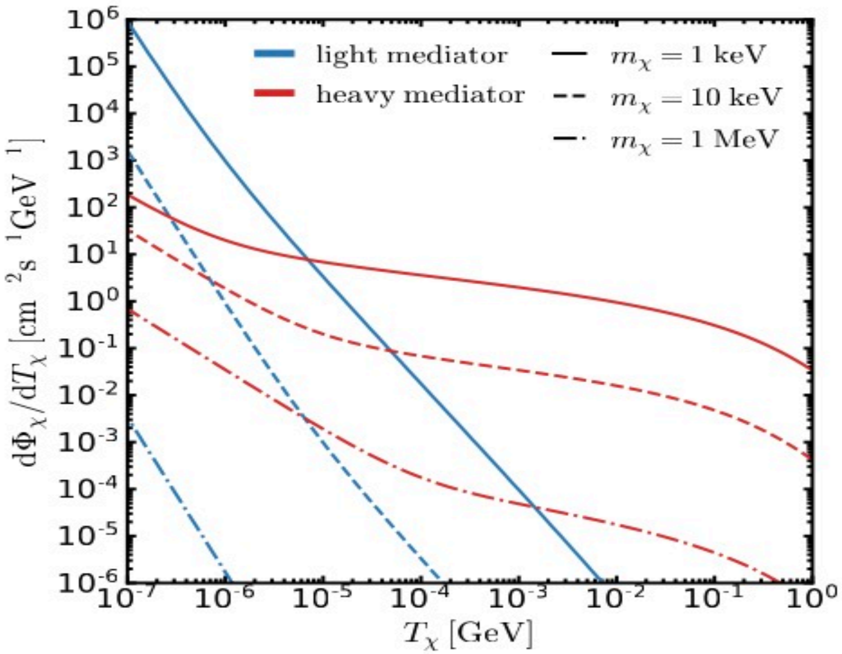
Liang, Su, LW, Zhu, 2401.11971

Cosmic Ray Boosted DM





$$\frac{\mathrm{d}\Phi_\chi}{\mathrm{d}T_\chi} = \int \frac{\mathrm{d}\Omega}{4\pi} \int_{\mathrm{l.o.s.}} \frac{\rho_\chi(\Omega,\ell)}{m_\chi} \mathrm{d}\ell \int_{T_e^{\min}}^{+\infty} \mathrm{d}T_e \frac{\mathrm{d}\sigma_{\chi e}}{\mathrm{d}T_\chi} \frac{\mathrm{d}\Phi_e}{\mathrm{d}T_e}$$



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

2. Light DM and Collective Excitations

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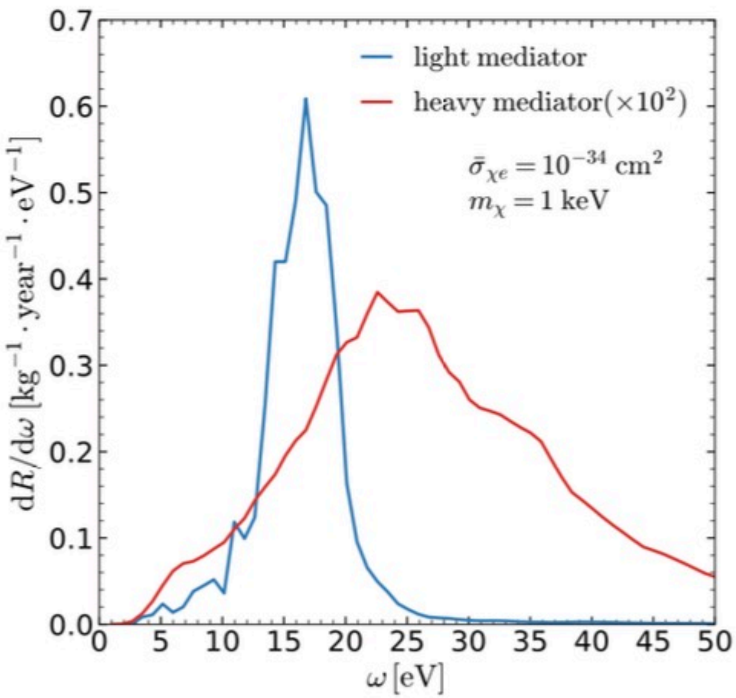
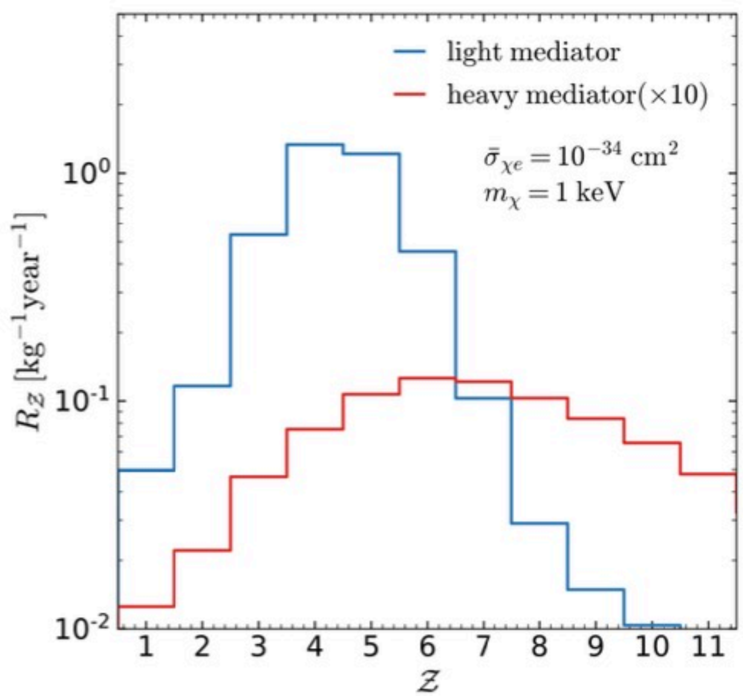
$$|F_{\rm DM}(q)|^2 = \frac{\left(\alpha^2 m_e^2 + m_{A'}^2\right)^2}{\left(q^2 + m_{A'}^2\right)^2} = \begin{cases} 1 & \text{heavy mediator} \\ \frac{(\alpha m_e)^4}{q^4} & \text{light mediator} \end{cases}$$



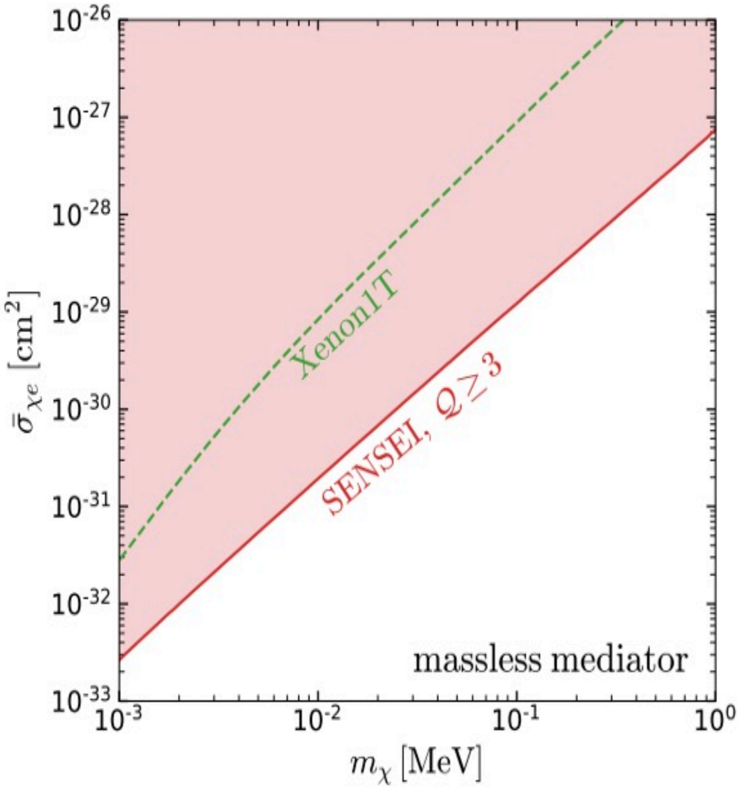


2. Sub-GeV DM and Collective Excitations

Liang, Su, WU, Zhu, 2401.11971

2312.13342 **SENSEI @ SNOLAB**

	All data		
Shape	Expo.	Ev.	Bkgd.
2e2p, h	13.58	10	10.66
2e2p, v	16.21	13	12.65
2e2p, d	17.82	32	25.31
2e, all	**46.61**	**55**	**48.62**
3e2p	30.87	3	0.01
3e3p	26.84	1	0.06
3e, all	**57.71**	**4**	**0.07**
4e2p	19.51	0	0.00
4e3p	27.60	0	0.00
4e4p	15.93	0	0.00
4e, all	**63.03**	**0**	**0.00**
5e, all	65.56	0	0.00
6e, all	67.31	0	0.00
7e, all	68.53	0	0.00
8e, all	69.52	0	0.00
9e, all	70.30	0	0.00
10e, all	70.89	0	0.00



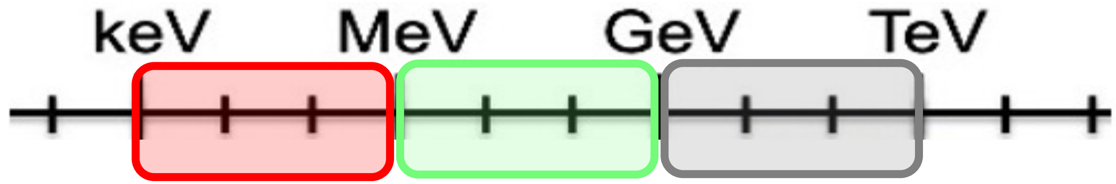
Light Dark Matter	Noble Liquid Detector (large volume, high threshold)	Solid detector (small volume, low threshold)
Non-Relativistic	√	√
Relativistic	√	Collective Excitations

Conclusions

Dark Matter Particle

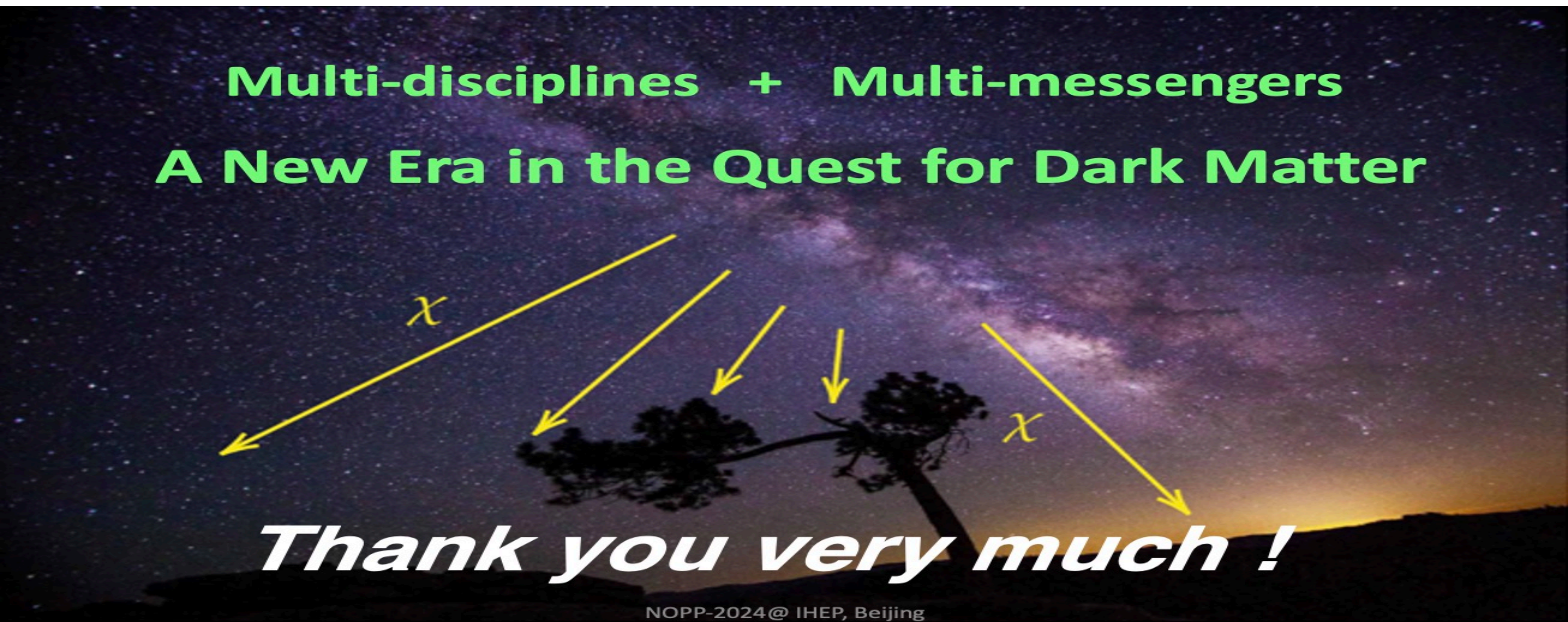
Direct Detection

(~ 40 years, 10^9 orders)



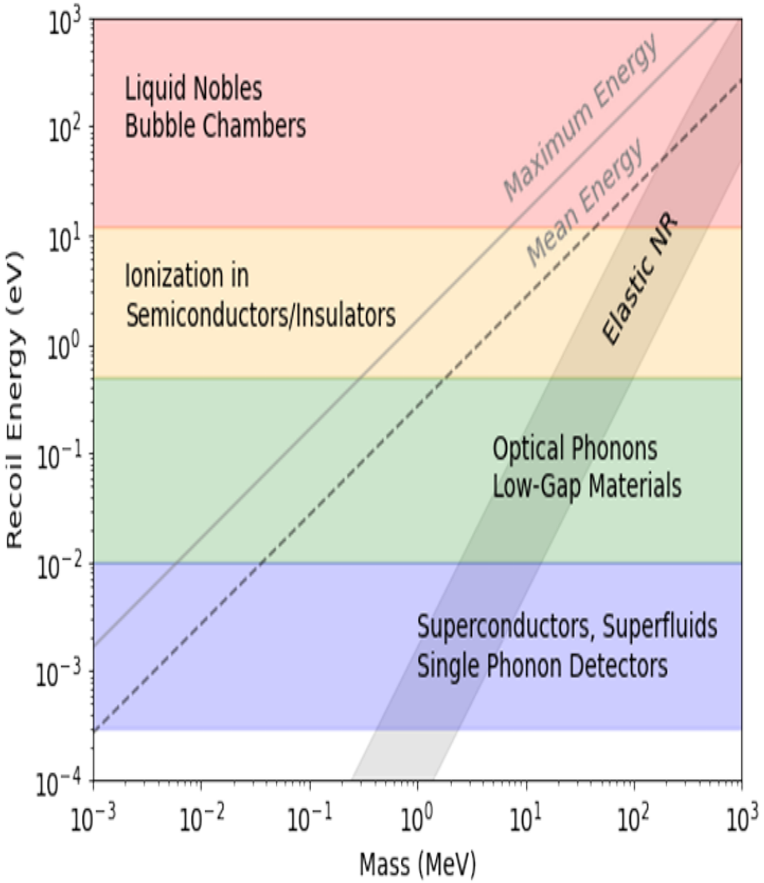
2020-Now | **2012-Now** | **1983-Now**

Collective Excitations | **DM-e** | **DM-N**



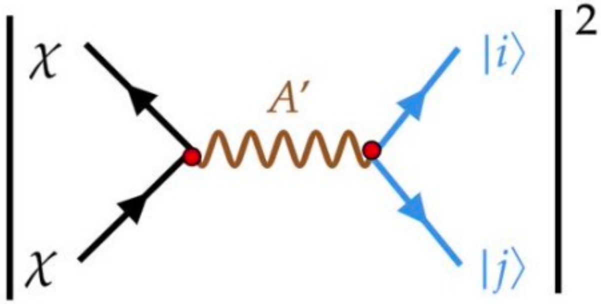
Back Up

Threshold	Lowest DM Mass Probed	Relevant Techniques, Technologies, and Materials
20 eV	20 MeV (ER) 100 MeV (NR)	Noble Elements (TPCs & SPCs) Solid-State Charge Detectors Phonon Detectors Threshold Detectors
500 meV	1 MeV (ER/NR) 500 meV (Abs.)	Semiconductor Detectors Athermal Phonon Detectors Scintillators NIR Photon Detectors
5 meV	10 keV (CE) 5 meV (Abs.)	Superconductors Low-Gap Materials Athermal Phonon Detectors Polar Materials Superfluids FIR Photon Detectors Magnetic Bubble Chambers Other new ideas



Rouven Essig, *et.al*, arxiv: 2203.08297

Back Up



$$\sum_{i,j} p_j \langle j|e^{-i\mathbf{Q}\cdot\hat{\mathbf{x}}}|i\rangle \underline{\langle i|e^{i\mathbf{Q}\cdot\hat{\mathbf{x}}}|j\rangle} \qquad \int \mathrm{d}^3x e^{i\mathbf{Q}\cdot\mathbf{x}} u_i^*(\mathbf{x})\, u_j(\mathbf{x})$$

$$\hat{\psi}(\mathbf{x}) = \sum_k \hat{a}_k u_k(\mathbf{x})$$

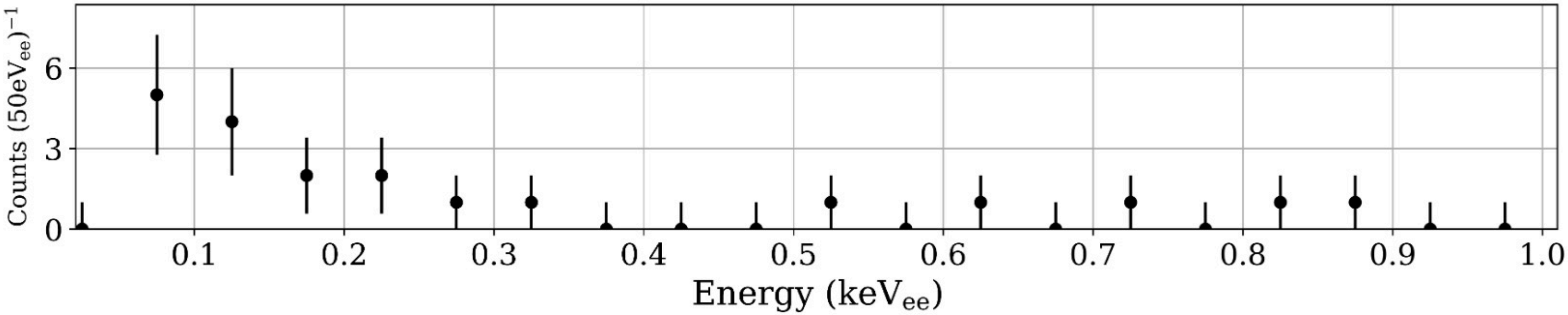
$$\langle i|e^{i\mathbf{Q}\cdot\hat{\mathbf{x}}}|j\rangle = \int \mathrm{d}^3x e^{i\mathbf{Q}\cdot\mathbf{x}} \left\langle i|\hat{\psi}^\dagger(\mathbf{x})\, \hat{\psi}(\mathbf{x})\, |j\right\rangle = \int \mathrm{d}^3x e^{i\mathbf{Q}\cdot\mathbf{x}} \langle i|\hat{\rho}(\mathbf{x})\, |j\rangle$$

$$\int \mathrm{d}^3x' \mathrm{d}^3x e^{i\mathbf{Q}\cdot(\mathbf{x}-\mathbf{x}')} \sum_j p_j \langle j|\hat{\rho}(\mathbf{x}')\, \hat{\rho}(\mathbf{x})\, |j\rangle \sim \langle \hat{\rho}\hat{\rho}\rangle$$

Back Up

FERMILAB-PUB-23-256-PPD

Confirmation of the spectral excess in DAMIC at SNOLAB with skipper CCDs



EXCESS21

EXCESS22

EXCESS22@IDM

EXCESS23@TAUP

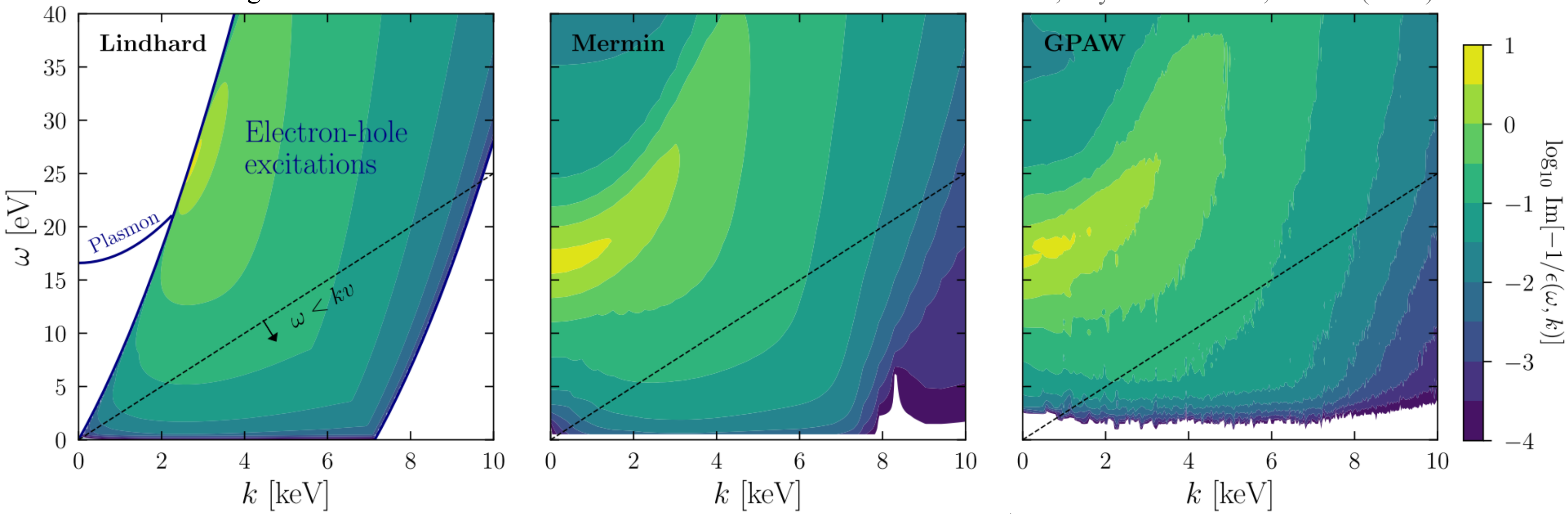
excess may corresponds to a WIMP with mass ~2.5 GeV/c^2 and a WIMP-nucleon scattering cross section ~3×10^{-40} cm^2.

Back Up

- The calculation of dielectric function:

DarkELF: Including the real and imaginary parts of the dielectric function calculated using the DFT software GPAW.

Simon Knapen, Jonathan Kozaczuk, and Tongyan Lin, Phys. Rev. D **105**, 015014(2021).



- The Lindhard method:

Assuming homogenous material and neglecting all dissipation effects.

- The Mermin method:

A generalization of the Lindhard which includes dissipation.

- The GPAW method:

It relies on a first principles calculation with package GPAW.

Back Up

e.g. Cosmic Ray DM

$$\frac{d\Phi_\chi}{dT_\chi} \equiv D_{\rm eff} \frac{\rho_\chi^{\rm local}}{m_\chi} \int_{T_{\rm CR}^{\rm min}}^{\infty} dT_{\rm CR} \frac{d\sigma}{dT_\chi} \frac{d\Phi_{\rm CR}^{\rm LIS}}{dT_{\rm CR}}$$

differential electronic excitation rate:

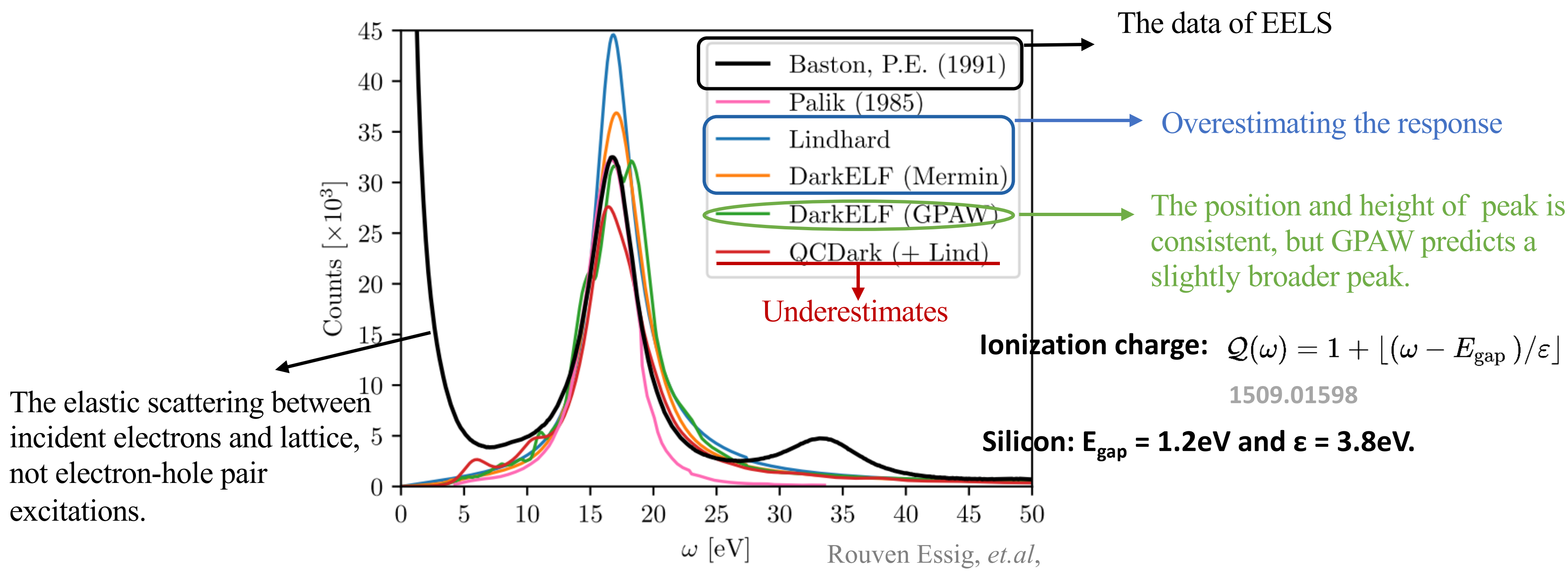
$$\begin{aligned}
\frac{dR}{d\omega} &= \frac{1}{M_{\rm target}} \int dE_\chi \int \frac{d\Omega}{4\pi} \frac{d\Phi_\chi}{dE_\chi} \frac{d\sigma}{d\omega} \\
&= \frac{1}{\rho_T} \frac{\bar{\sigma}_{\chi e}}{4\alpha\mu_{\chi e}^2} \int \frac{d^3\mathbf{Q}}{(2\pi)^3} \int dE_\chi \frac{d\Phi(E_\chi)}{dE_\chi} \left(\frac{(2E_\chi-\omega)^2 - Q^2}{4E_\chi(E_\chi-\omega)}\right) \left(\frac{\alpha^2 m_e^2 + m_{A'}^2}{Q^2-\omega^2+m_{A'}^2}\right)^2 \left(\frac{E_\chi(E_\chi-\omega)}{p_\chi^2}\right) \\
&\times Q\, \mathrm{Im}\left[\frac{-1}{\epsilon(\mathbf{Q},\omega)}\right] \Theta\left[E_\chi - \sqrt{(p_\chi - Q)^2 + m_\chi^2} - \omega\right],
\end{aligned}$$

Back Up

DM-Electron scattering in semiconductor

- Comparison with EELS data:

The results an incident electron beam kinetic energy of $T = 100$ keV



Rouven Essig, *et.al*, arxiv: 2403.00123

Ionization charge: $\mathcal{Q}(\omega) = 1 + \lfloor (\omega - E_{\text{gap}})/\varepsilon \rfloor$

1509.01598

Silicon: E_{gap} = 1.2eV and ε = 3.8eV.

在论文中，作者们使用了几种不同的方法来计算或近似介电函数，包括：

1. **Lindhard模型**：这是一个半经典的模型，用于描述低动量转移下的电子气响应。它提供了一个合理的描述，特别是在低动量转移和小能量损失的区域。

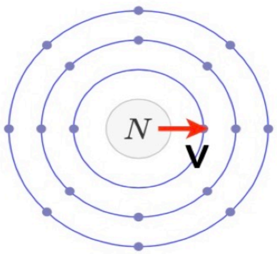
2. **密度泛函理论（DFT）和随机相近似（RPA）**：这些方法可以更精确地计算介电函数，包括电子波函数的量子力学计算。DFT结合RPA可以提供对介电函数实部和虚部的全面描述。

3. **QCDark计算**：这是一个基于第一性原理的计算工具，用于计算暗物质与电子散射的介电函数虚部。

4. **DarkELF工具**：这是一个开源软件包，它提供了使用DFT软件GPAW计算介电函数的实部和虚部的功能，并且可以选择使用Lindhard模型来拟合介电函数。

论文中还提到了如何将这些不同的计算方法结合起来，以获得更准确的介电函数表达式，特别是通过使用Lindhard模型来校正QCDark计算的介电函数虚部，从而得到一个在低能量区域表现良好的介电函数模型。这种组合模型在描述等离子体激元峰值方面特别有效，这是因为Lindhard模型在这一区域内提供了可靠的描述，并且与QCDark计算的介电函数虚部的更复杂的计算相匹配。

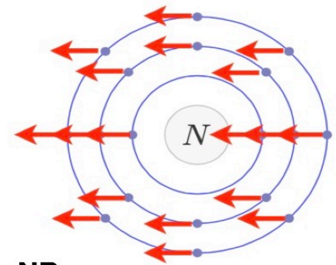
Lab frame



V: nucleus velocity after the recoil

The electron clouds are no more in the energy eigenstates

Nucleus rest frame



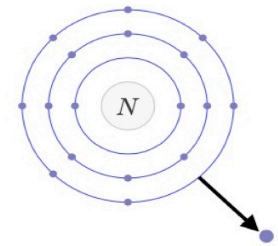
after NR before NR

$$|\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i} |\Phi_{ec}\rangle$$

Galilei transformation

x_i the position operator of the i-th electron

Ionization/excitation electron

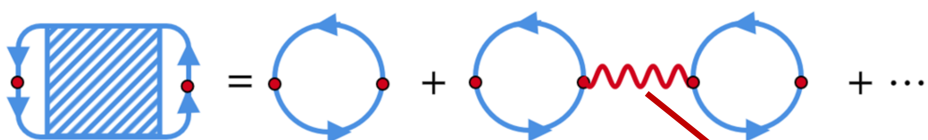


$$\mathcal{P} = |\langle \Phi^*_{ec} | \Phi'_{ec} \rangle|^2$$

ionized/excited energy eigenstate

$$\frac{1}{2} m_\chi v_\chi^2 \gtrsim E_{\text{threshold}} \quad \Rightarrow \quad m_\chi \gtrsim 6 \text{ MeV} \cdot \left(\frac{E_{\text{threshold}}}{15 \text{ eV}}\right)$$

where



$\Pi_e(Q, \omega)$

$$\frac{1}{V} \sum_{i,j} \frac{\left|\langle i | e^{i\mathbf{Q}\cdot\hat{\mathbf{x}}} | j \rangle\right|^2}{\varepsilon_i - \varepsilon_j - \omega - i0^+} (f_i - f_j)$$

Lindhard function

$$\frac{4\pi\alpha}{Q^2}$$

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

- Similar Fermi's Golden Rule, but different kinematics

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

- Scattering potential

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

- Dielectric function remains the same
- Event rate

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