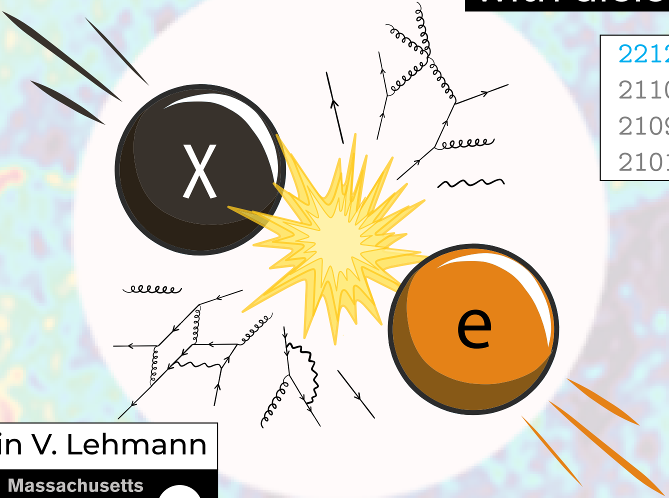
New **directions** for direct detection with dielectrics

2212.04505
2110.01586
2109.04473
2101.08263



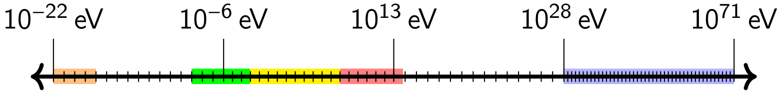
Benjamin V. Lehmann

Massachusetts Institute of Technology

CTP

with Christian Boyd, Yonit Hochberg, Yoni Kahn, Eric David Kramer, Noah Kurinsky & To Chin Yu

This talk in one slide



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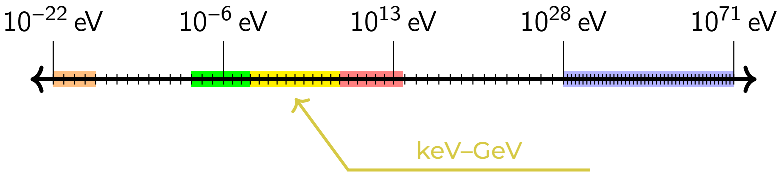
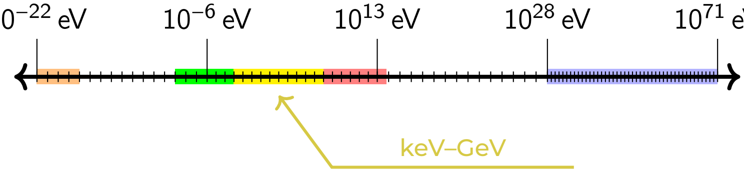
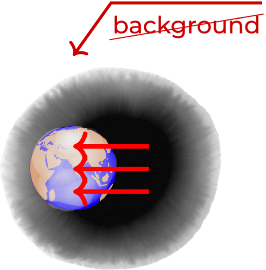


Search for light dark matter,

This talk in one slide



Search for light dark matter, directionally,



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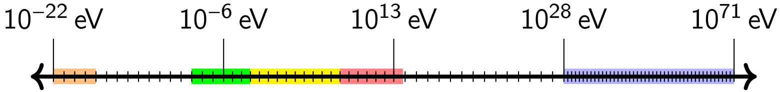
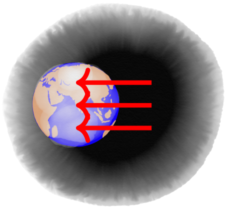


keV–GeV

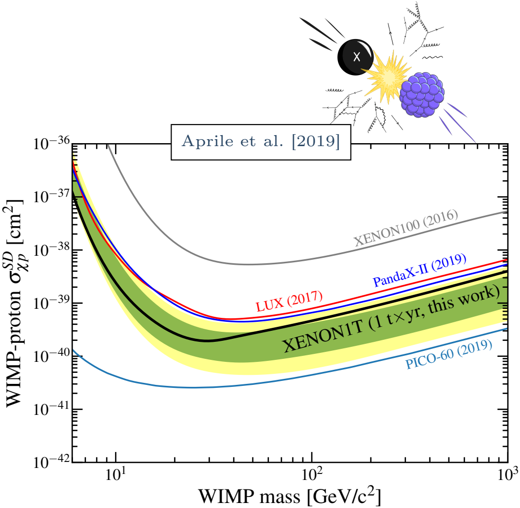
Search for light dark matter,
directionally, with anisotropic dielectrics.

~~background~~

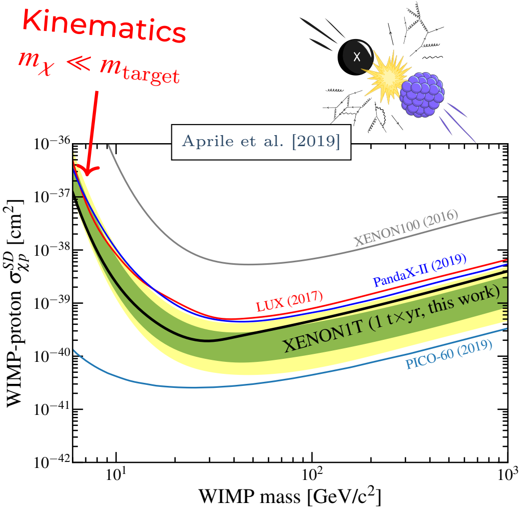
common stuff



Sub-GeV DM



Aprile et al. [2019]
X
XENON100 (2016)
PandaX-II (2019)
LUX (2017)
XENON1T (1 t×yr, this work)
PICO-60 (2019)
WIMP-proton $\sigma^{SD}_{\chi p}$ [cm^2]
WIMP mass [GeV/c^2]


Kinematics
$m_\chi \ll m_{\mathrm{target}}$
X
Aprile et al. [2019]
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
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10^1
10^2
10^3
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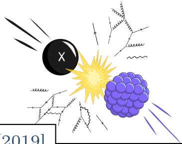

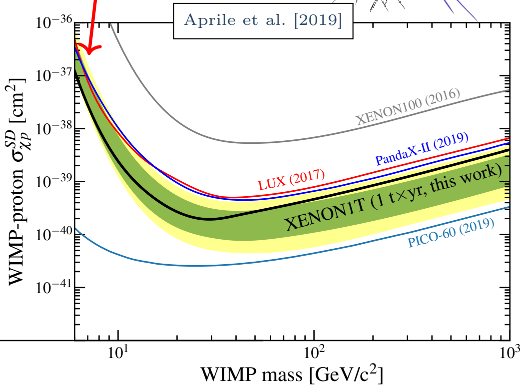

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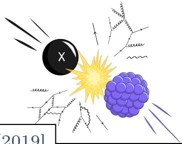
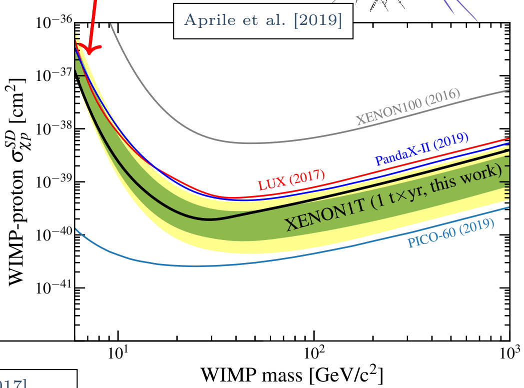
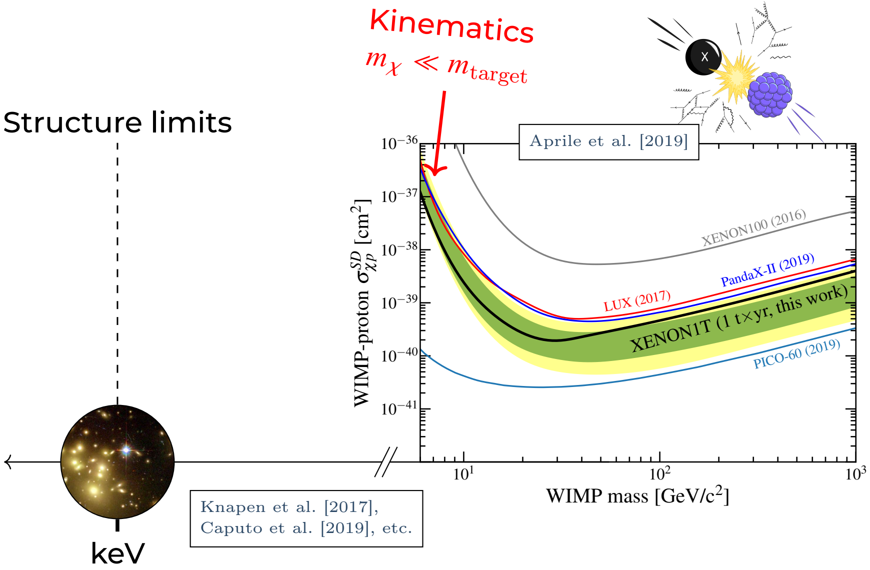




Knapen et al. [2017],
Caputo et al. [2019], etc.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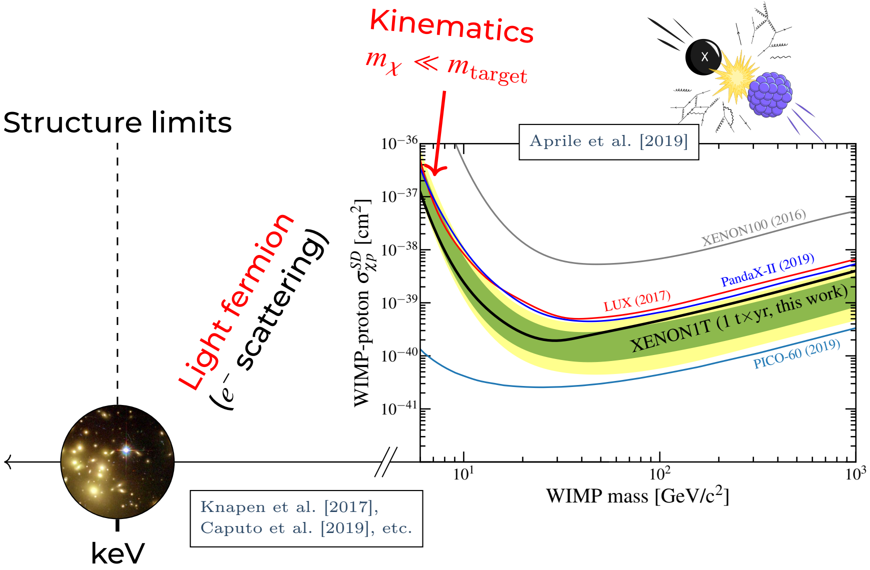
Kinematics
$m_\chi \ll m_{\mathrm{target}}$
Structure limits
Light fermion
(e^- scattering)
keV
Knapen et al. [2017],
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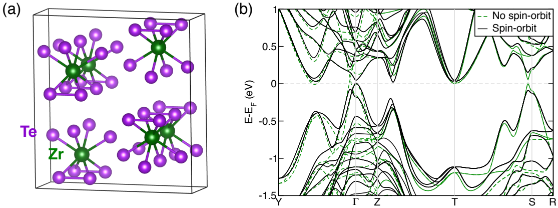
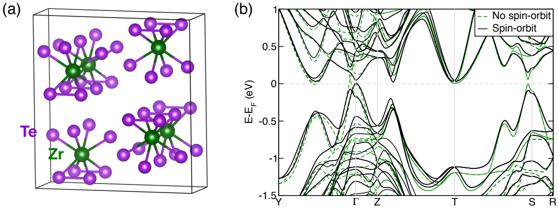


Hochberg et al. [2018]

DM does not interact with just one particle.



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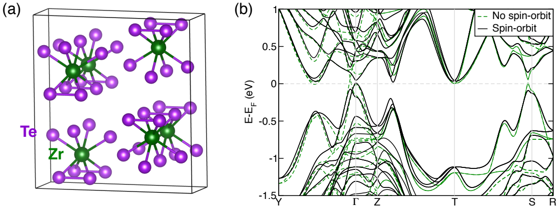

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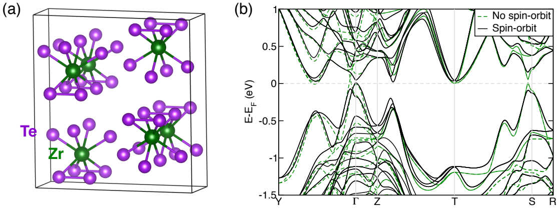

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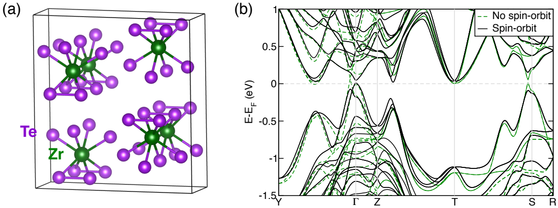
$$|\chi\rangle|\Psi\rangle_{\text{detector}} \longrightarrow |\chi'\rangle|\Psi'\rangle_{\text{detector}}$$

Ψ and Ψ' from material physics

All is not well with 1-particle language



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Ψ and Ψ' from material physics *(opportunity)*

DM scattering in dielectrics

Electrons are not free: **condensed matter matters**

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Hochberg+ & **BVL** 2101.08263; Lin, Knapen & Kozaczuk 2101.08275

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Predict scattering rate from **response function**

$$\Gamma = \int \frac{\mathrm{d}^3\mathbf{q}}{(2\pi)^3}|V(q)|^2\left[2\frac{q^2}{e^2}\underbrace{\mathrm{Im}\left(-\frac{1}{\epsilon(\mathbf{q},\omega_\mathbf{q})}\right)}_{\text{“Loss function” } \mathcal{W}}\right]$$

Hochberg+ & **BVL** 2101.08263; Lin, Knapen & Kozaczuk 2101.08275

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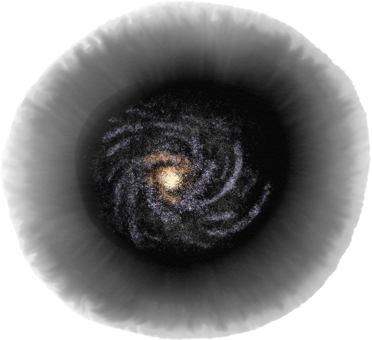
3. **Flexible:** works for many targets, DM models
4. **Inclusive:** ϵ contains **all** collective modes

 Hochberg+ & **BVL** 2101.08263; Lin, Knapen & Kozaczuk 2101.08275

Directional sensitivity



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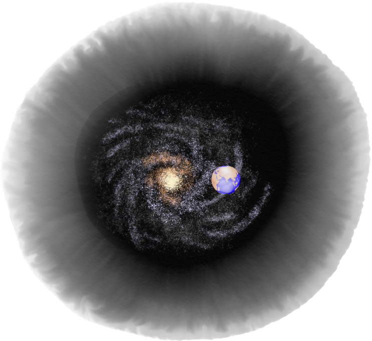

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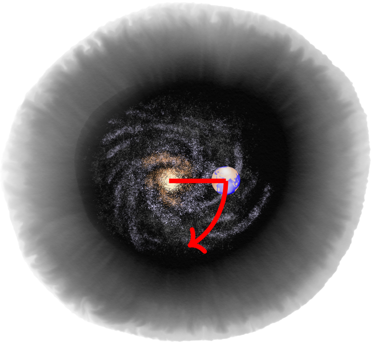

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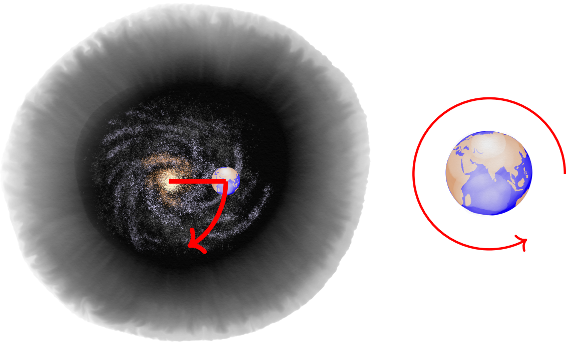

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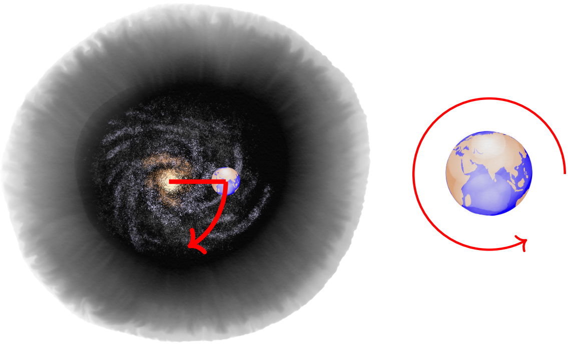
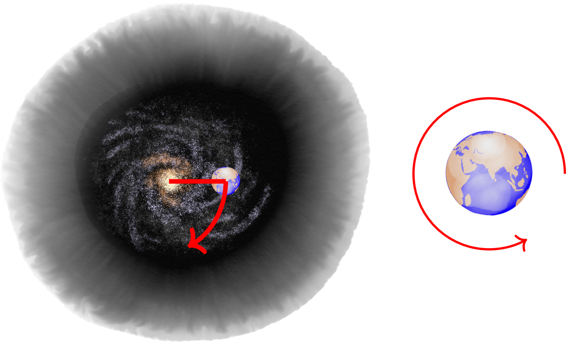


Anisotropic sensitivity ⟶ daily modulation in rate

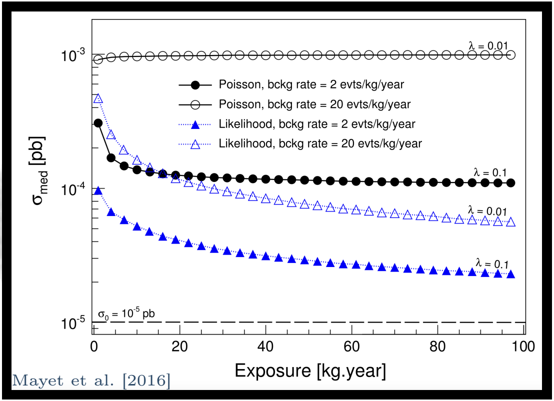
Directional sensitivity



Anisotropic sensitivity ⟶ daily modulation in rate

Cut through background: scale with exposure

Directional sensitivity



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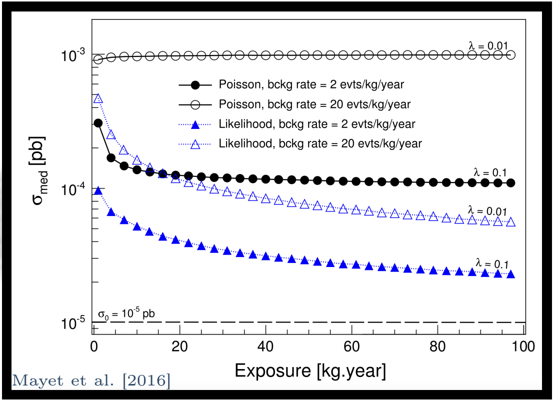

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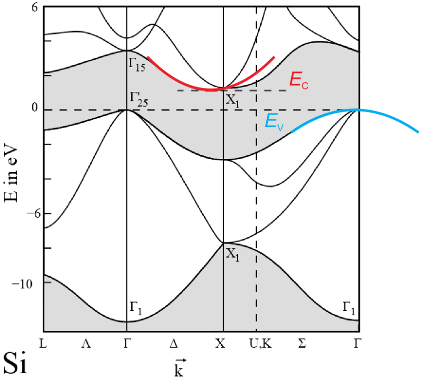
An experimental challenge?

 Boyd+ & **BVL** 2212.04505

New approach: anisotropic mass



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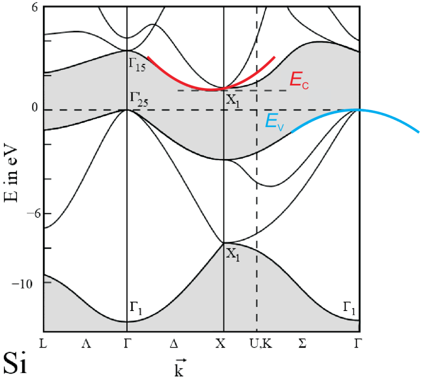

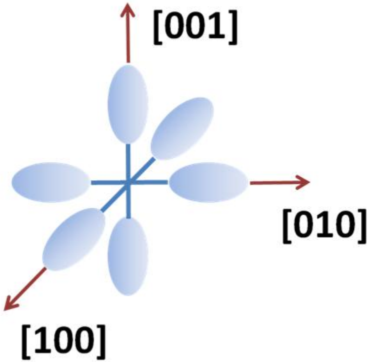

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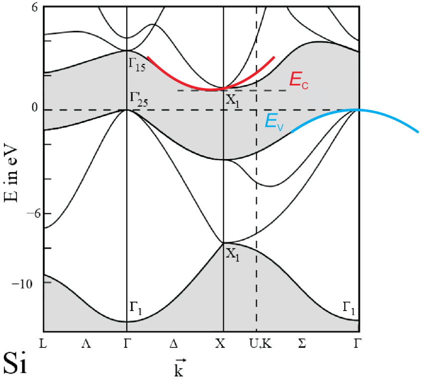

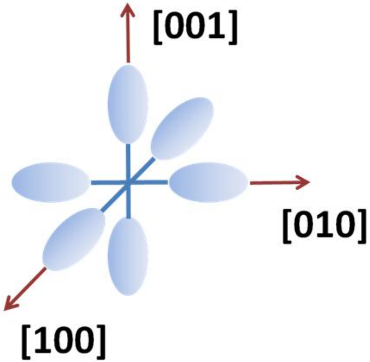

Toy model: anisotropic m_e^*

$$E_{\mathbf{q}} = \frac{q_x^2}{2m_x} + \frac{q_y^2}{2m_y} + \frac{q_z^2}{2m_z}$$

Boyd+ & **BVL** 2212.04505

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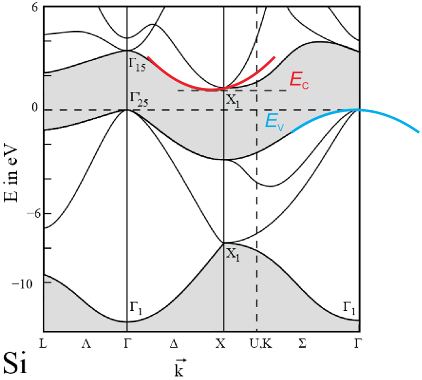

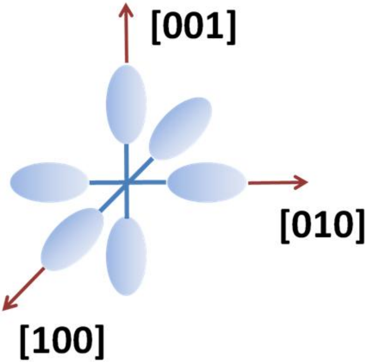

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What happens to $\mathcal{W} = \mathrm{Im}\left(-\frac{1}{\epsilon}\right)$?

Technicalities

Where did $\mathrm{Im}(-1/\epsilon)$ come from?

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Material physics enters Golden Rule via dynamic structure factor

$$S(\mathbf{q}, \omega) = \frac{2\pi}{\mathrm{vol}} \sum_f |\langle f| \hat{n}_{e^-}(-\mathbf{q}) |0\rangle|^2 \, \delta(\omega - [E_f - E_0])$$

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 Boyd+ & **BVL** 2212.04505

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 Boyd+ & **BVL** 2212.04505

Computing χ

See e.g. Mahan [2013]

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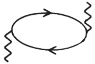

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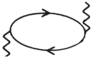
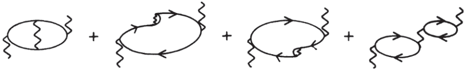
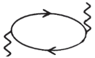
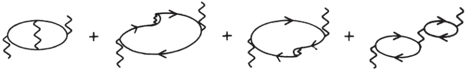
$P^{(1)}$ = 

$P^{(2)}$ = 

See e.g. Mahan [2013]

$$\chi(\mathbf{r},\ \mathbf{r}';\ t) = -i\Theta(t)\Big\langle\Big[\hat{n}_{e^-}(\mathbf{r}, t),\ \hat{n}_{e^-}(\mathbf{r}', t)\Big]\Big\rangle$$

$P^{(1)} =$ 

$P^{(2)} =$ 

$$\chi(\mathbf{q},\ \omega) = \sum_{\text{(geom.)}} P_{\text{1PI}}(\mathbf{q},\ \omega)$$

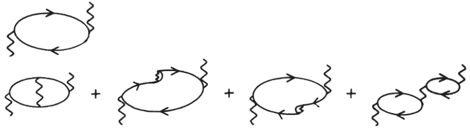
Computing χ

See e.g. Mahan [2013]

$$\chi(\mathbf{r},\, \mathbf{r}';\, t) = -i\Theta(t)\left\langle\left[\hat{n}_{e^-}(\mathbf{r},t),\, \hat{n}_{e^-}(\mathbf{r}',t)\right]\right\rangle$$

$P^{(1)} =$

$P^{(2)} =$



$$\chi(\mathbf{q},\, \omega) = \sum_{\text{(geom.)}} P_{\text{1PI}}(\mathbf{q},\, \omega)$$

Random phase approximation (RPA)

$$\chi_{\text{RPA}}(\mathbf{q},\, \omega) = \sum_{\text{(geom.)}} P^{(1)}(\mathbf{q},\, \omega)$$

The Lindhard function

$$P^{(1)}(\mathbf{q},\ \omega) = \chi_0(\mathbf{q},\omega) = 2\int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3}\frac{n_{\mathrm{FD}}(E_{\mathbf{p+q}}) - n_{\mathrm{FD}}(E_{\mathbf{p}})}{E_{\mathbf{p+q}} - E_{\mathbf{p}} - \omega - i\Gamma}$$

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$\longrightarrow$ Lindhard dielectric function

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$\longrightarrow$ Lindhard dielectric function

$$\epsilon_{\mathrm{RPA}} \overset{T\to 0}{=} 1 + \frac{3\omega_{\mathrm{p}}}{q^2 v_{\mathrm{F}}}\left\{\frac{1}{2} + \frac{k_{\mathrm{F}}}{4q}\left[1 - \left(\frac{q}{2k_{\mathrm{F}}} - \frac{\omega + i\Gamma}{q v_{\mathrm{F}}}\right)^2\right]\mathrm{Log}\left(\frac{\frac{q}{2k_{\mathrm{F}}} - \frac{\omega+i\Gamma}{q v_{\mathrm{F}}} + 1}{\frac{q}{2k_{\mathrm{F}}} - \frac{\omega+i\Gamma}{q v_{\mathrm{F}}} - 1}\right)\right.$$

$$\left. + \frac{k_{\mathrm{F}}}{4q}\left[1 - \left(\frac{q}{2k_{\mathrm{F}}} + \frac{\omega + i\Gamma}{q v_{\mathrm{F}}}\right)^2\right]\mathrm{Log}\left(\frac{\frac{q}{2k_{\mathrm{F}}} + \frac{\omega+i\Gamma}{q v_{\mathrm{F}}} + 1}{\frac{q}{2k_{\mathrm{F}}} + \frac{\omega+i\Gamma}{q v_{\mathrm{F}}} - 1}\right)\right\}$$

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$$\left. + \frac{k_{\rm F}}{4q}\left[1 - \left(\frac{q}{2k_{\rm F}} + \frac{\omega+i\Gamma}{q v_{\rm F}}\right)^2\right]{\rm Log}\left(\frac{\frac{q}{2k_{\rm F}} + \frac{\omega+i\Gamma}{q v_{\rm F}} + 1}{\frac{q}{2k_{\rm F}} + \frac{\omega+i\Gamma}{q v_{\rm F}} - 1}\right)\right\}$$

Material parameters:

The Lindhard function

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$$\left. + \frac{k_{\mathrm{F}}}{4q}\left[1 - \left(\frac{q}{2k_{\mathrm{F}}} + \frac{\omega + i\Gamma}{q v_{\mathrm{F}}}\right)^2\right]\mathrm{Log}\left(\frac{\frac{q}{2k_{\mathrm{F}}} + \frac{\omega+i\Gamma}{q v_{\mathrm{F}}} + 1}{\frac{q}{2k_{\mathrm{F}}} + \frac{\omega+i\Gamma}{q v_{\mathrm{F}}} - 1}\right)\right\}$$

Material parameters:

plasma frequency $\omega_p \sim \mathcal{O}(1) \times E_{\mathrm{F}}$,

The Lindhard function

$$P^{(1)}(\mathbf{q},\,\omega) = \chi_0(\mathbf{q},\omega) = 2\int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3}\frac{n_{\mathrm{FD}}(E_{\mathbf{p+q}}) - n_{\mathrm{FD}}(E_{\mathbf{p}})}{E_{\mathbf{p+q}} - E_{\mathbf{p}} - \omega - i\Gamma}$$

$\longrightarrow$ Lindhard dielectric function

$$\epsilon_{\mathrm{RPA}} \overset{T\to 0}{=} 1 + \frac{3\omega_{\mathrm{p}}}{q^2 v_{\mathrm{F}}}\left\{\frac{1}{2} + \frac{k_{\mathrm{F}}}{4q}\left[1 - \left(\frac{q}{2k_{\mathrm{F}}} - \frac{\omega + i\Gamma}{q v_{\mathrm{F}}}\right)^2\right]\mathrm{Log}\left(\frac{\frac{q}{2k_{\mathrm{F}}} - \frac{\omega+i\Gamma}{q v_{\mathrm{F}}} + 1}{\frac{q}{2k_{\mathrm{F}}} - \frac{\omega+i\Gamma}{q v_{\mathrm{F}}} - 1}\right) + \frac{k_{\mathrm{F}}}{4q}\left[1 - \left(\frac{q}{2k_{\mathrm{F}}} + \frac{\omega + i\Gamma}{q v_{\mathrm{F}}}\right)^2\right]\mathrm{Log}\left(\frac{\frac{q}{2k_{\mathrm{F}}} + \frac{\omega+i\Gamma}{q v_{\mathrm{F}}} + 1}{\frac{q}{2k_{\mathrm{F}}} + \frac{\omega+i\Gamma}{q v_{\mathrm{F}}} - 1}\right)\right\}$$

Material parameters:

plasma frequency $\omega_p \sim \mathcal{O}(1) \times E_{\mathrm{F}}$,

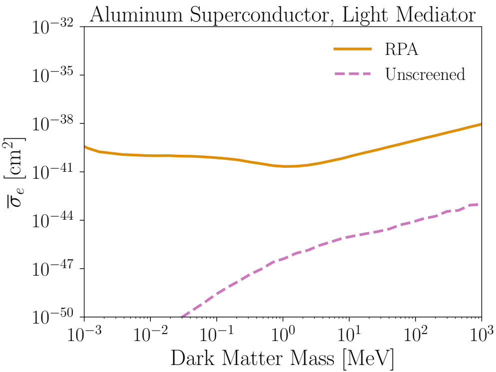
plasmon width $\Gamma \sim \mathcal{O}(0.01\text{–}0.1) \times \omega_p$

Understanding χ — screening

Heuristically identical to E&M

Understanding χ — screening

Heuristically identical to E&M



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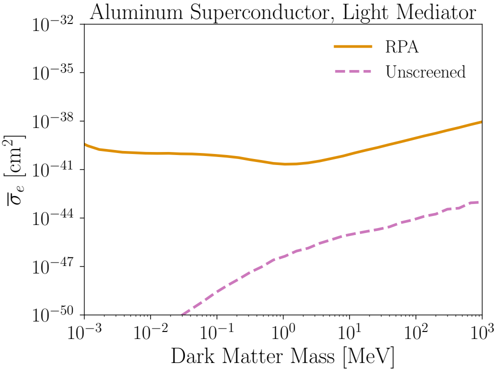
Understanding χ — screening

Heuristically identical to E&M



Screening is a property of material response

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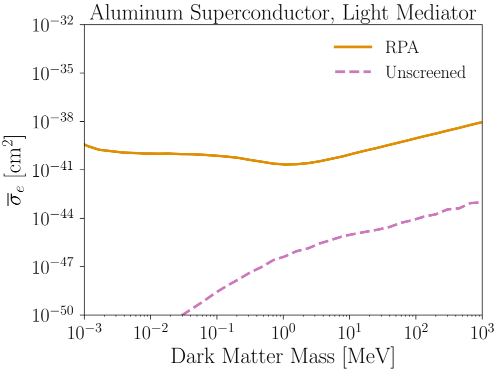
Heuristically identical to E&M



Screening is a property of material response

Scalar and vector interactions are screened identically

Understanding χ — plasmons

Understanding χ — plasmons

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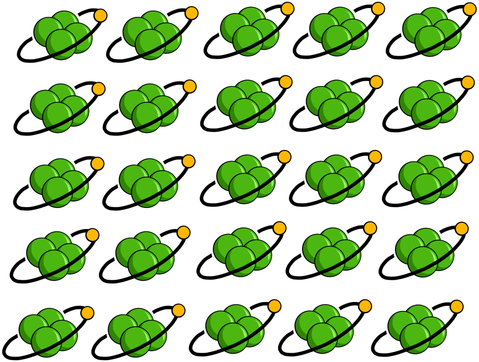
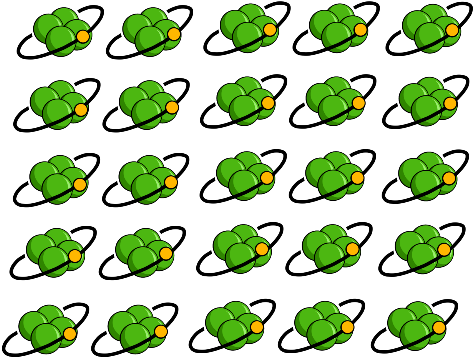
Understanding χ — plasmons



A **collective oscillation** of electrons

Understanding χ — plasmons



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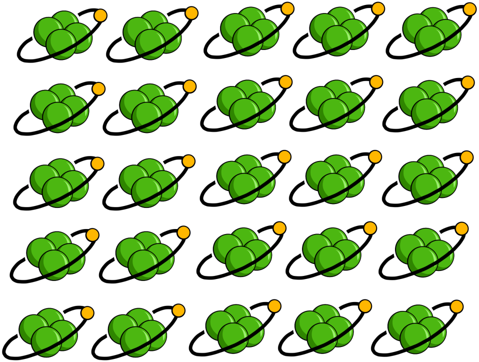

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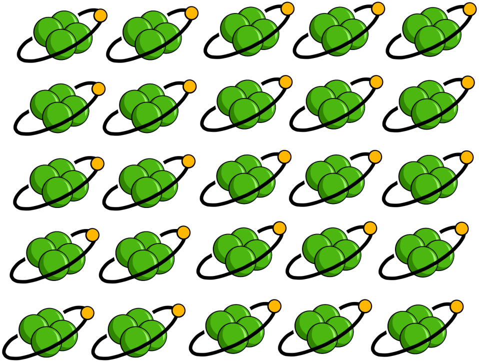
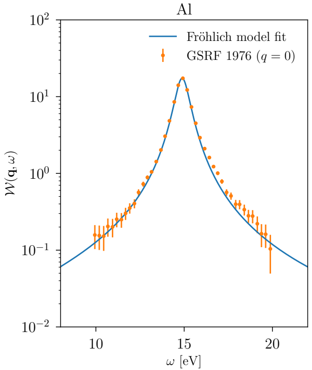


A **collective oscillation** of electrons

Shows up as a resonance in the **loss function**

Understanding χ — plasmons



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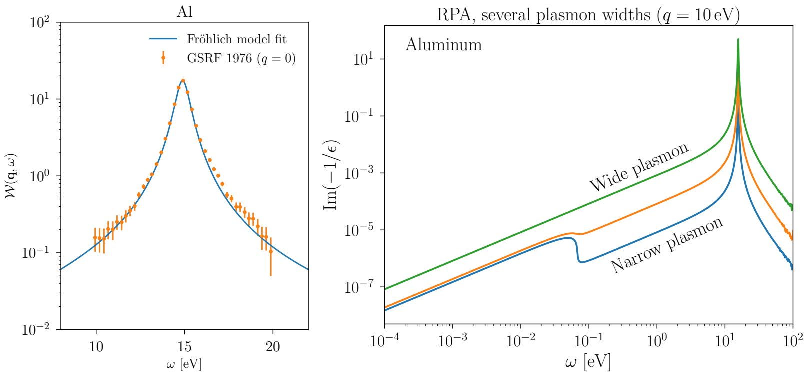
Understanding χ — plasmons



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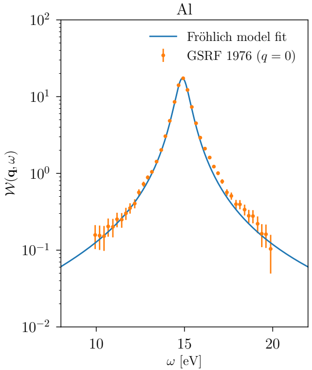

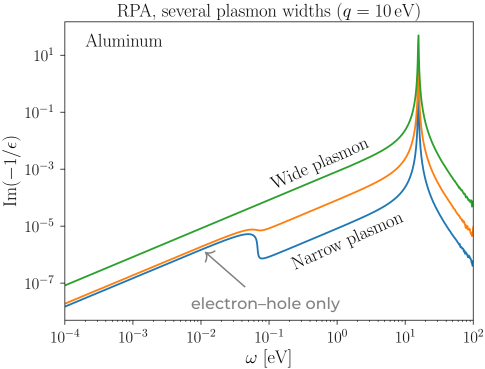

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Understanding χ — Lindhard's lessons

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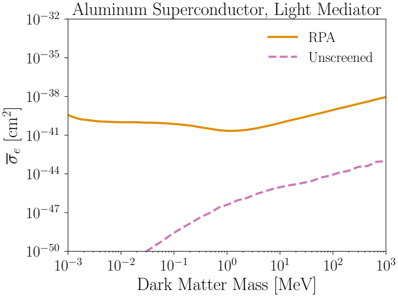
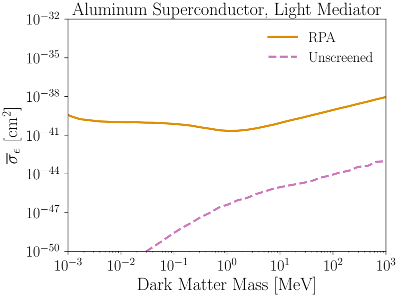
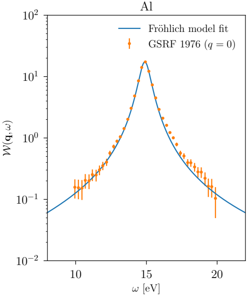


❶ Screening is generic, not model-dependent

Understanding χ — Lindhard's lessons





1. Screening is generic, not model-dependent
2. Resonances (plasmons) enhance the scattering rate

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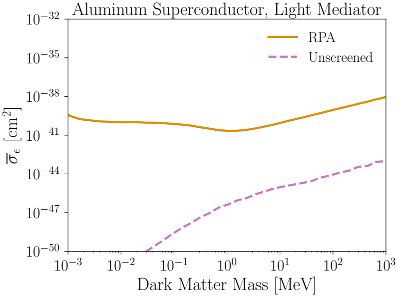
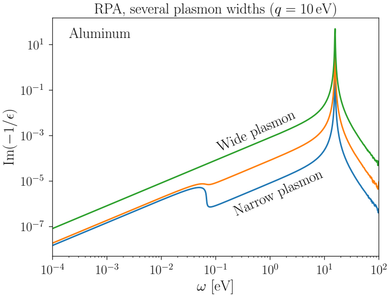
Understanding χ — Lindhard's lessons





1. Screening is generic, not model-dependent
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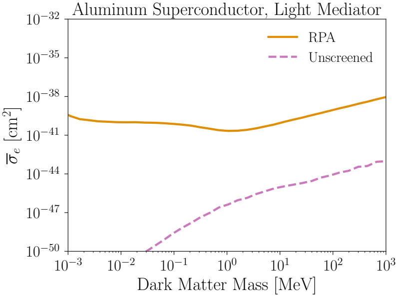
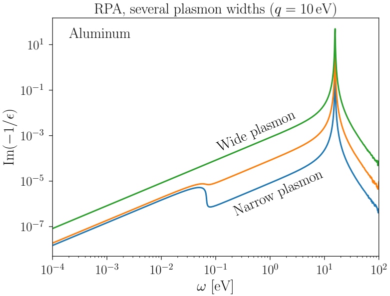
3. Plasmon width is important

 Hochberg+ & **BVL** 2101.08263

Understanding χ — Lindhard's lessons





1. Screening is generic, not model-dependent
2. Resonances (plasmons) enhance the scattering rate
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We can use analytical forms of ϵ for heuristics

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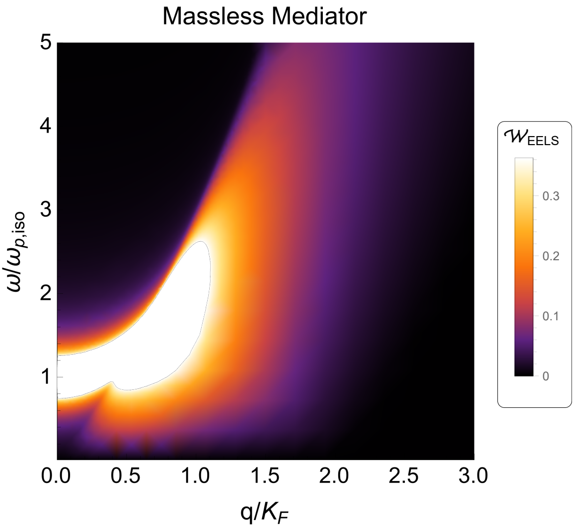
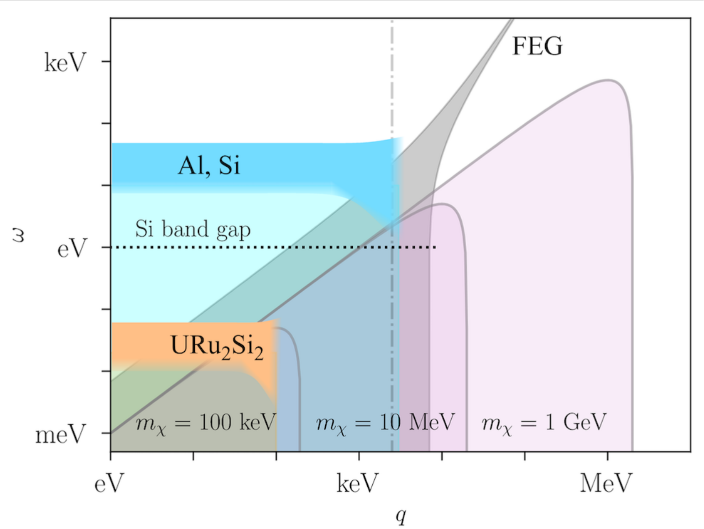
Visualizing the loss function



Visualizing the loss function



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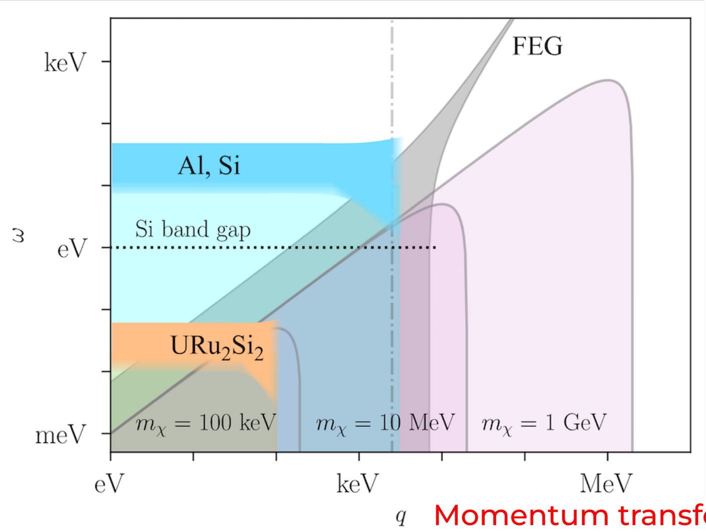
Visualizing the loss function



Momentum transfer

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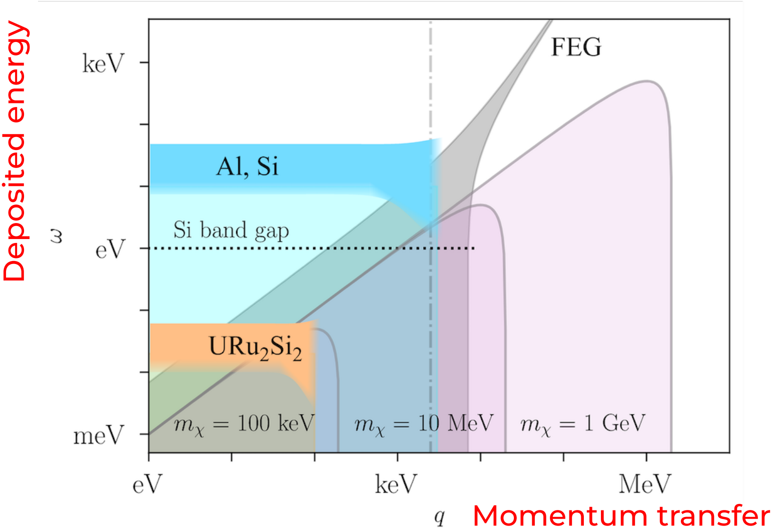
Visualizing the loss function



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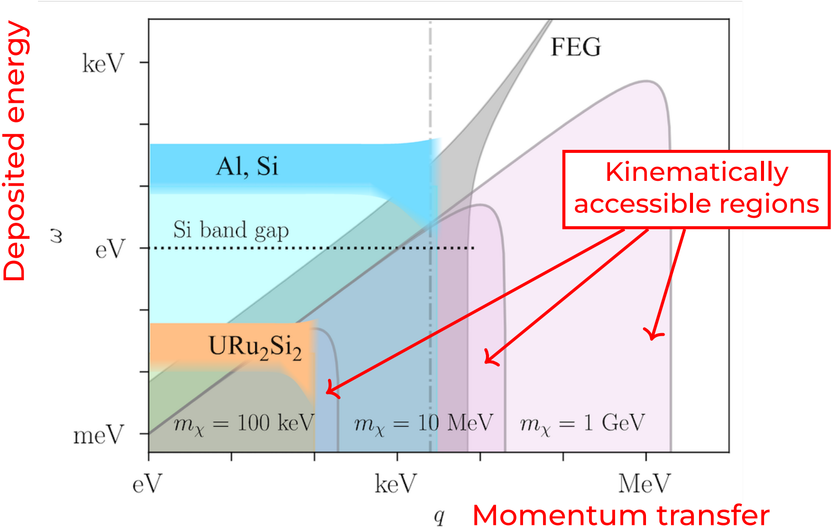
Visualizing the loss function



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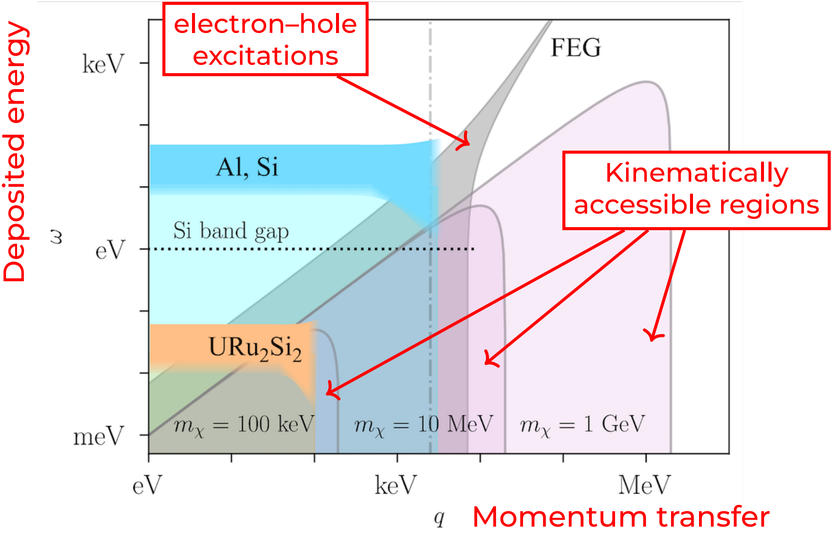

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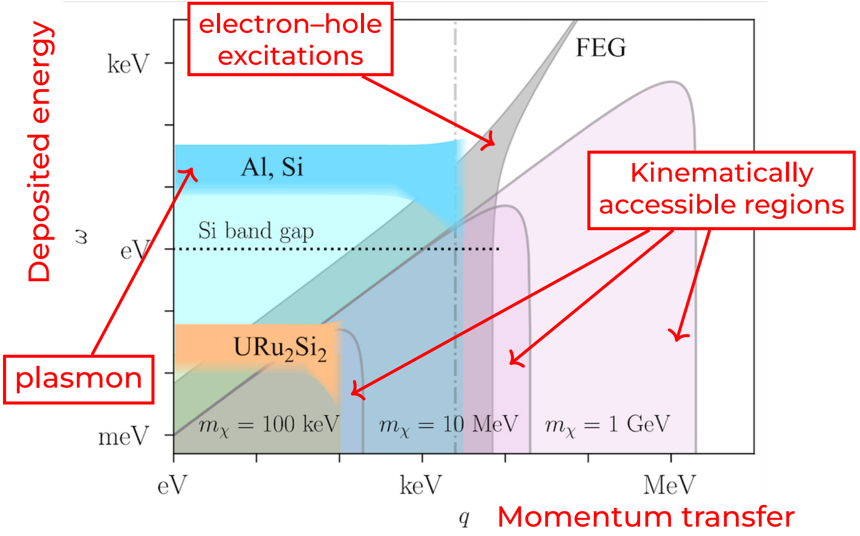

Hochberg+ & **BVL** 2101.08263

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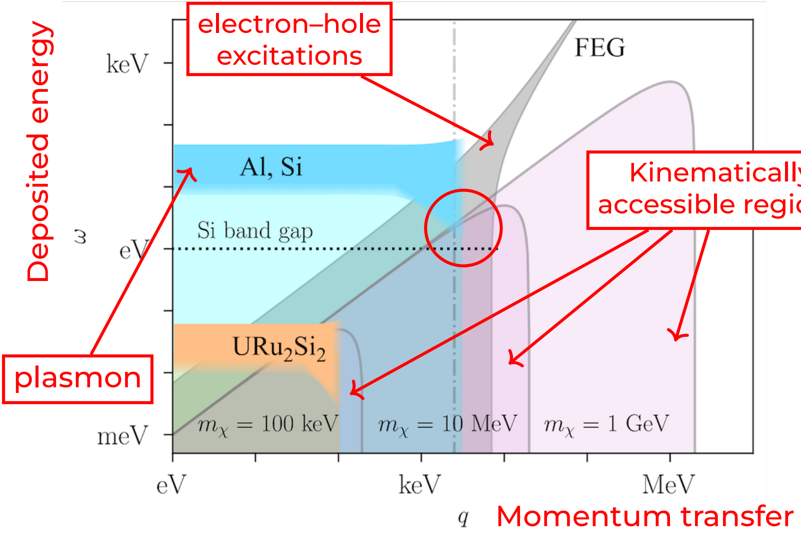

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Maximizing the rate

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Small q: Can DM hit the plasmon peak? $(\omega \sim \omega_{\mathrm{p}})$

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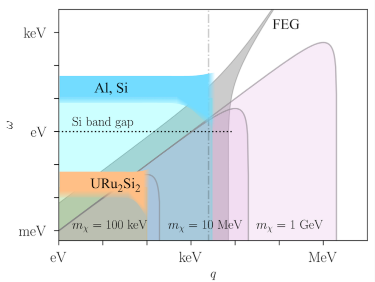

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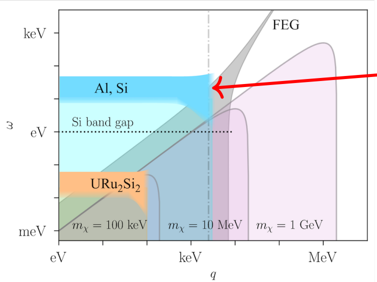

plasmon trails off

$q_c \simeq \omega_{\mathrm{p}}/v_{\mathrm{F}}$

Hochberg+ & **BVL** 2101.08263

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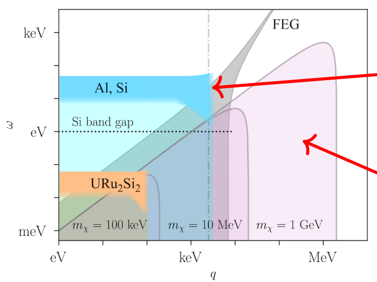

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$q_c \simeq \omega_{\rm p}/v_{\rm F}$

$\omega < q v_\chi$

kinematics

 Hochberg+ & **BVL** 2101.08263

Maximizing the rate

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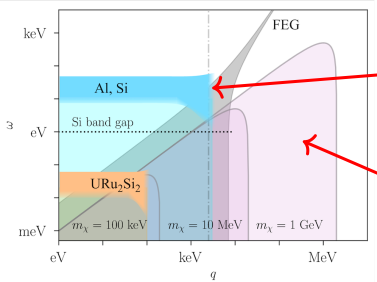


plasmon trails off

$q_c \simeq \omega_\mathrm{p}/v_\mathrm{F}$

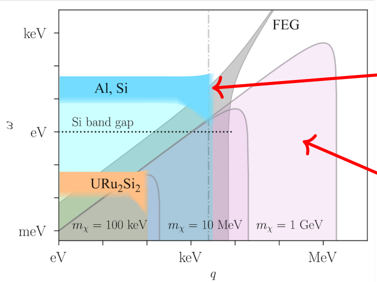
Only possible if $v_\mathrm{F} \lesssim v_\chi$

$\omega < q v_\chi$

kinematics

Maximizing the rate

Small q: Can DM hit the plasmon peak? $(\omega \sim \omega_p)$



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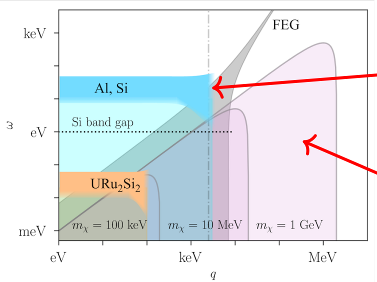
kinematics

Large q: Can DM reach the maximum value of $\mathcal{W}$?

 Hochberg+ & **BVL** 2101.08263

Maximizing the rate

Small q: Can DM hit the plasmon peak? $(\omega \sim \omega_\mathrm{p})$



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$q_c \simeq \omega_\mathrm{p}/v_\mathrm{F}$

Only possible if $v_\mathrm{F} \lesssim v_\chi$

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kinematics

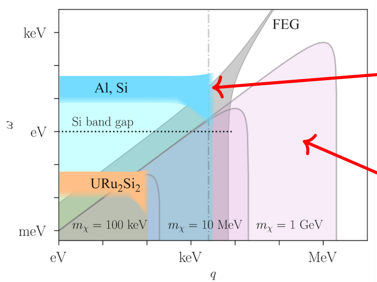
Large q: Can DM reach the maximum value of $\mathcal{W}$?

FEG: $\omega_\mathrm{max} \simeq q v_\mathrm{F}$

Hochberg+ & **BVL** 2101.08263

Maximizing the rate

Small q: Can DM hit the plasmon peak? $(\omega \sim \omega_\mathrm{p})$



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Only possible if $v_\mathrm{F} \lesssim v_\chi$

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kinematics

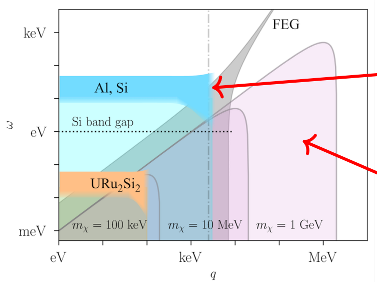
Large q: Can DM reach the maximum value of $\mathcal{W}$?

FEG: $\omega_\mathrm{max} \simeq q v_\mathrm{F}$

Also requires $v_\mathrm{F} \lesssim v_\chi$

Maximizing the rate

Small q: Can DM hit the plasmon peak? $(\omega \sim \omega_p)$



plasmon trails off

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kinematics

Large q: Can DM reach the maximum value of $\mathcal{W}$?

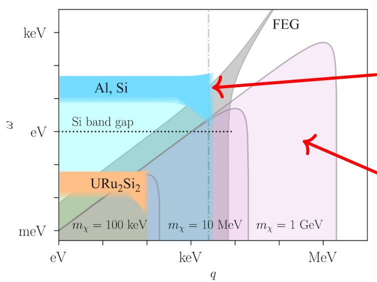
FEG: $\omega_{\max} \simeq q v_F$

Also requires $v_F \lesssim v_\chi$

Find a target with a low Fermi velocity

Maximizing the rate

Small q: Can DM hit the plasmon peak? $(\omega \sim \omega_{\mathrm{p}})$



plasmon trails off

$q_c \simeq \omega_{\mathrm{p}}/v_{\mathrm{F}}$

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$\omega < q v_\chi$

kinematics

Large q: Can DM reach the maximum value of $\mathcal{W}$?

FEG: $\omega_{\max} \simeq q v_{\mathrm{F}}$

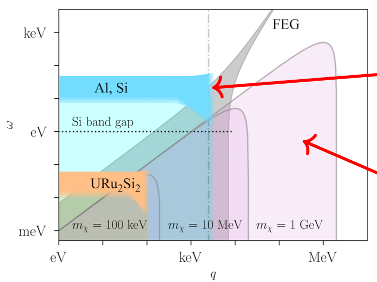
Also requires $v_{\mathrm{F}} \lesssim v_\chi$

Find a target with a low Fermi velocity

Dirac materials

Maximizing the rate

Small q: Can DM hit the plasmon peak? $(\omega \sim \omega_\mathrm{p})$



plasmon trails off

$q_c \simeq \omega_\mathrm{p}/v_\mathrm{F}$

Only possible if $v_\mathrm{F} \lesssim v_\chi$

$\omega < q v_\chi$

kinematics

Large q: Can DM reach the maximum value of $\mathcal{W}$?

FEG: $\omega_\mathrm{max} \simeq q v_\mathrm{F}$

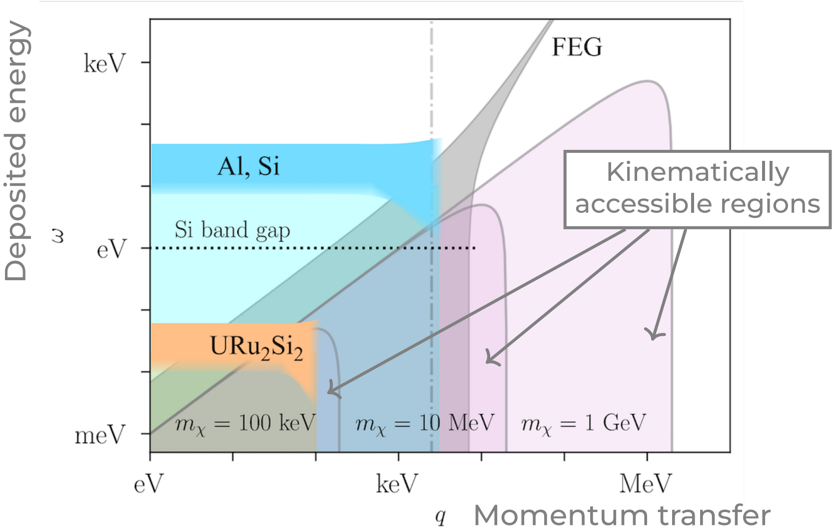
Also requires $v_\mathrm{F} \lesssim v_\chi$

Find a target with a low Fermi velocity

Dirac materials

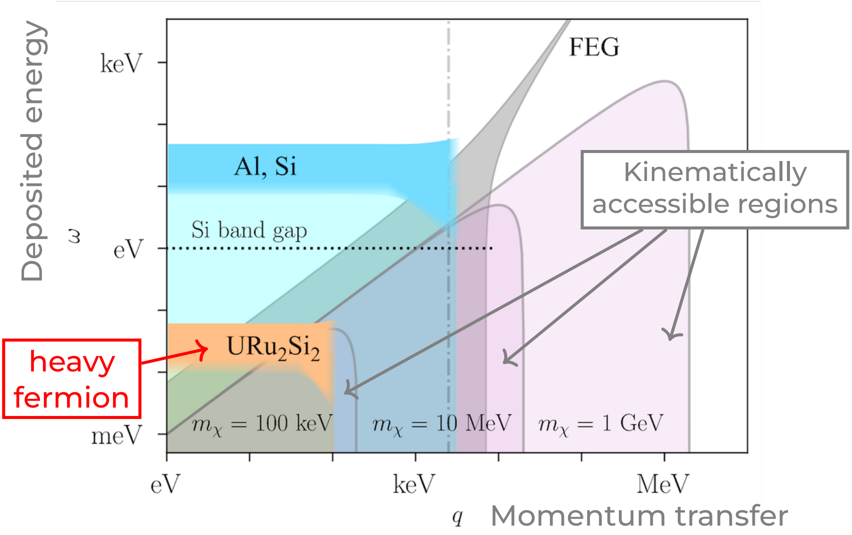
Heavy-fermion materials

Heavy fermion materials

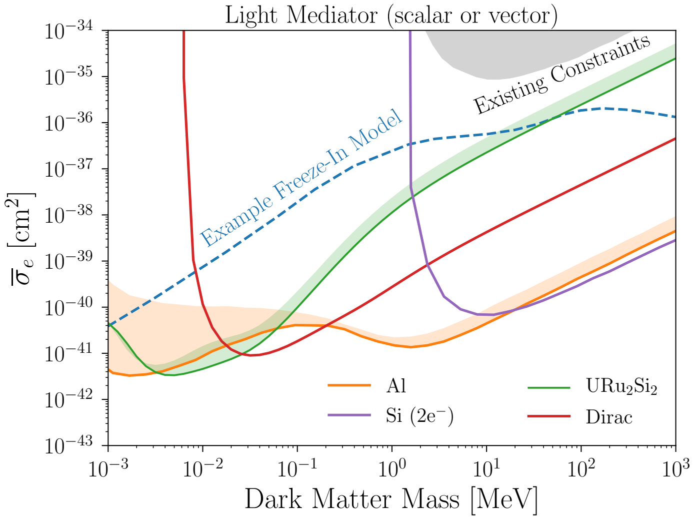


Hochberg+ & **BVL** 2101.08263

Heavy fermion materials



Projected reach



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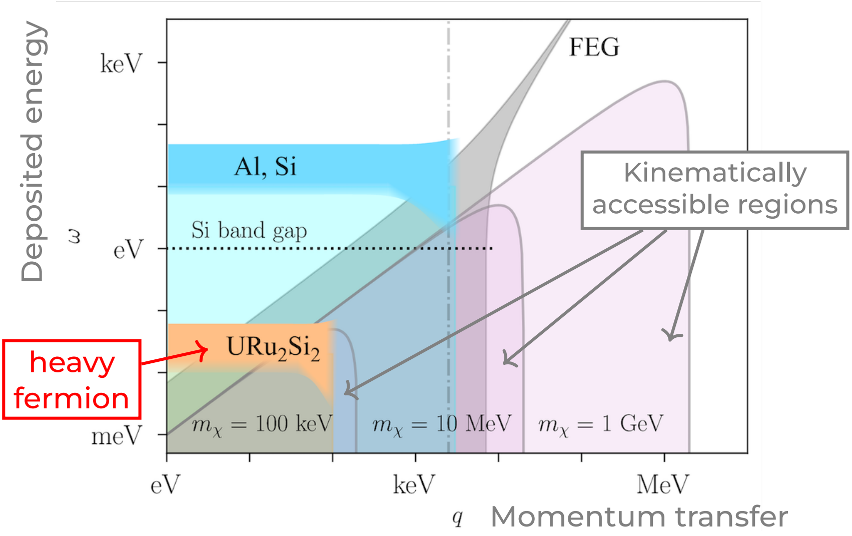
Back to anisotropy

An anisotropic plasmon?



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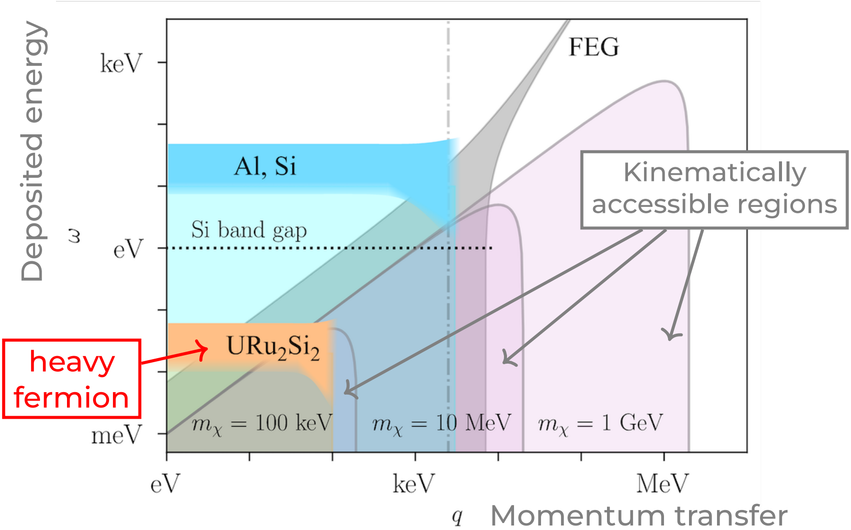
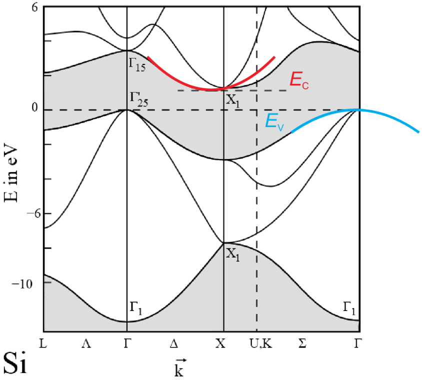
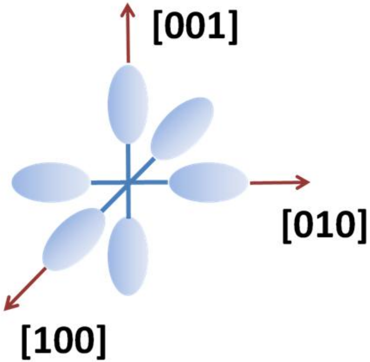


Heavy fermion in only one direction?

Boyd+ & **BVL** 2212.04505

New approach: anisotropic mass





Toy model: anisotropic m_e^*

$$E_{\mathbf{q}} = \frac{q_x^2}{2m_x} + \frac{q_y^2}{2m_y} + \frac{q_z^2}{2m_z}$$

What happens to $\mathcal{W} = \mathrm{Im}\left(-\frac{1}{\epsilon}\right)$?

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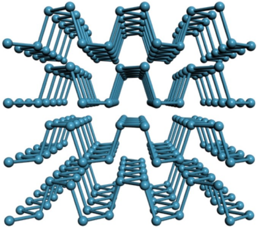
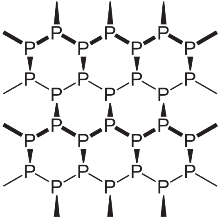
Real materials

Real materials

Black phosphorus

$m_{\mathrm{heavy}}/m_{\mathrm{light}} \approx 9$





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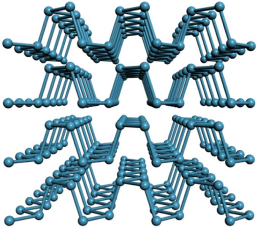
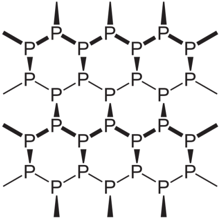
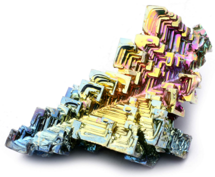
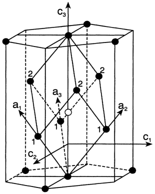


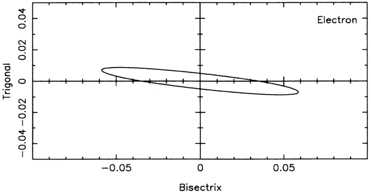


Bismuth

$m_{\text{heavy}}/m_{\text{light}} \approx 230$







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Anisotropic response function

Isotropic case.

Anisotropic response function

Isotropic case. $\chi^{\mathrm{iso}}_{\mathrm{RPA}} = \sum_{\text{(geom.)}} P^{(1)} = \dfrac{\chi_0^{\mathrm{iso}}(\mathbf{q},\omega)}{1-(e^2/q^2)\chi_0^{\mathrm{iso}}(\mathbf{q},\omega)}$

 Boyd+ & **BVL** 2212.04505

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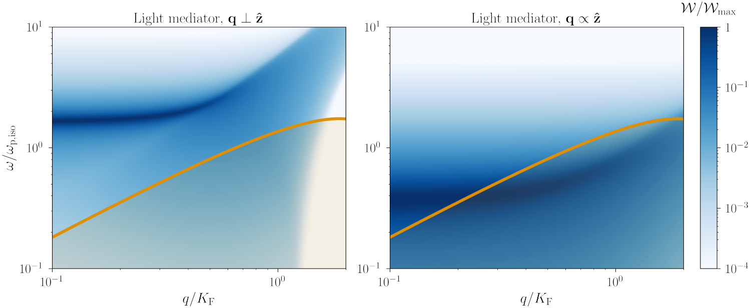
Anisotropic loss function

$$m_z/m_{xy} = 20, \qquad m_x m_y m_z = m_e^3$$



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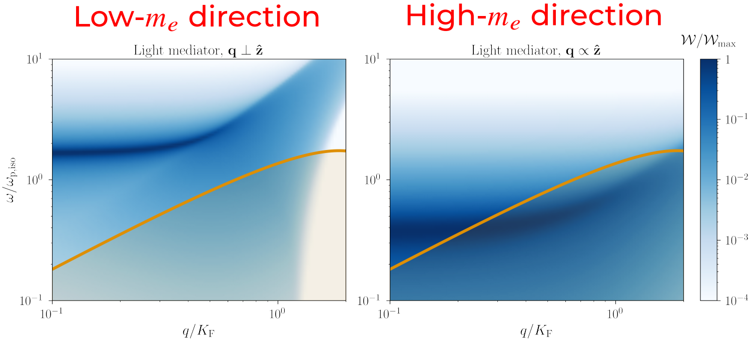

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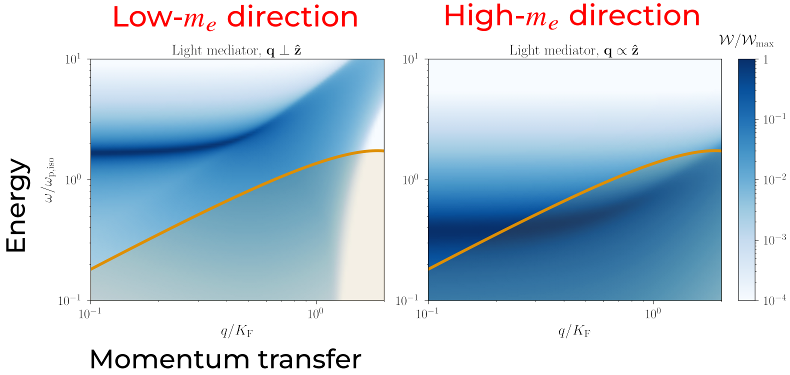

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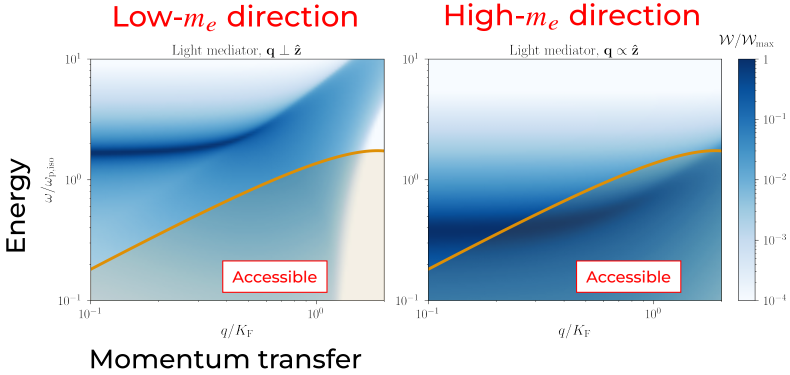

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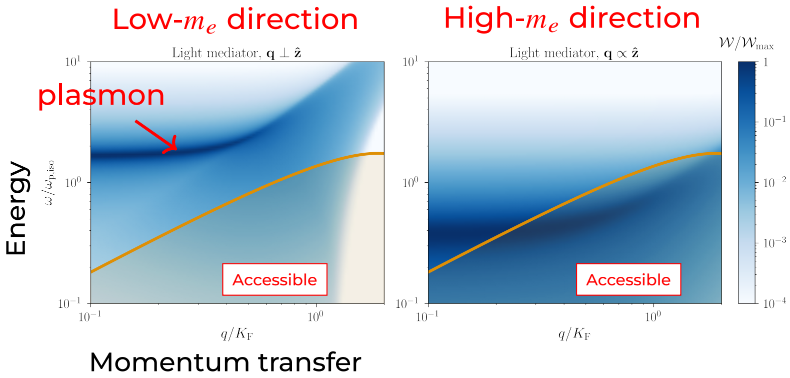

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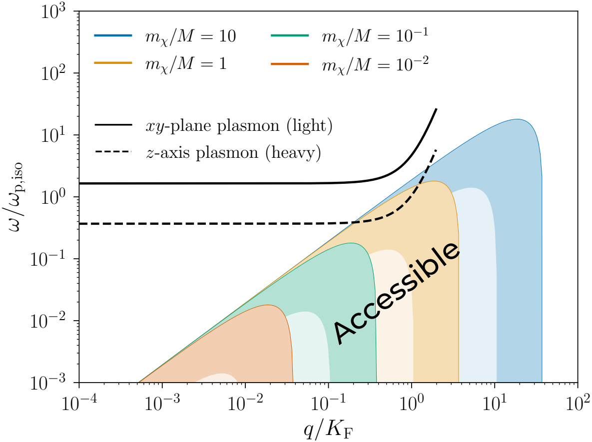
Anisotropic plasmon threshold



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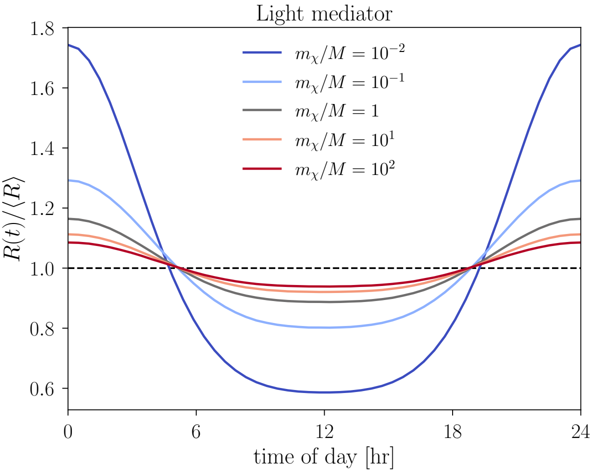
Daily modulation in the rate



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Modulation features

$$\Delta_R = \frac{R(\mathrm{midnight}) - R(\mathrm{noon})}{\langle R \rangle}$$

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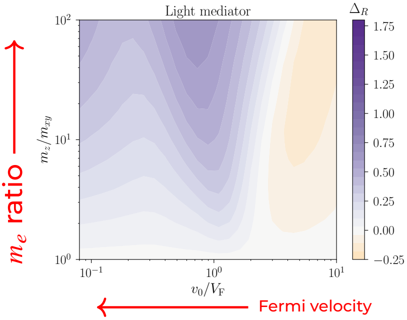

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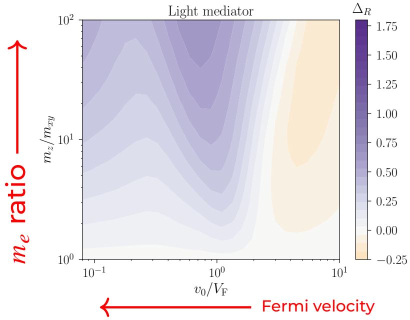

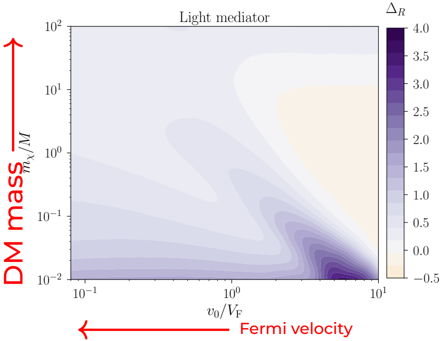

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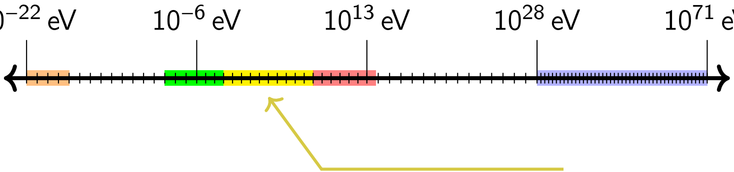
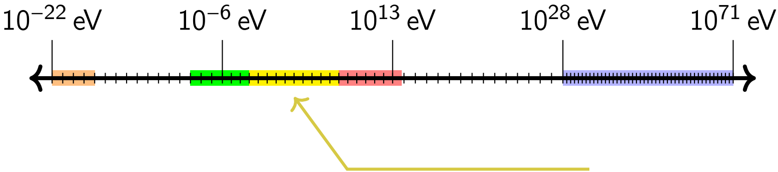


Search for light dark matter, directionally, with anisotropic dielectrics.

Conclusions



Search for light dark matter,
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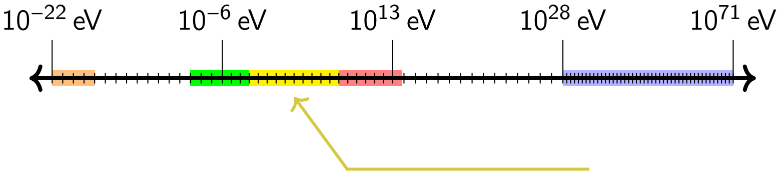
1. Dielectric formalism with anisotropy [m_e^*]

Conclusions



Search for light dark matter, directionally, with anisotropic dielectrics.

1. Dielectric formalism with anisotropy [m_e^*]
2. Tunable plasmon threshold controls modulation

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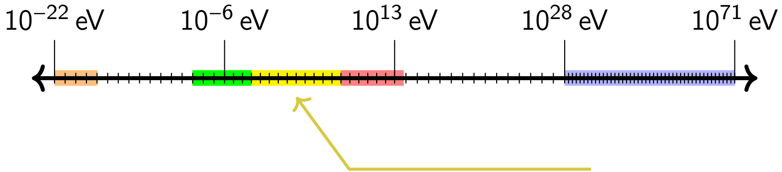

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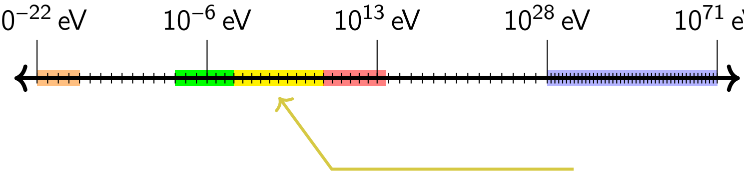
Conclusions



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References I

E. Aprile et al. Constraining the spin-dependent WIMP-nucleon cross sections with XENON1T. *Phys. Rev. Lett.*, 122(14):141301, 2019. doi: 10.1103/PhysRevLett.122.141301.

R. Caputo, T. Linden, J. Tomsick, C. Prescod-Weinstein, M. Meyer, C. Kierans, Z. Wadiasingh, J. P. Harding, and J. Kopp. Looking Under a Better Lamppost: MeV-scale Dark Matter Candidates. 3 2019.

Y. Hochberg, Y. Kahn, M. Lisanti, K. M. Zurek, A. G. Grushin, R. Ilan, S. M. Griffin, Z.-F. Liu, S. F. Weber, and J. B. Neaton. Detection of sub-MeV Dark Matter with Three-Dimensional Dirac Materials. *Phys. Rev. D*, 97(1): 015004, 2018. doi: 10.1103/PhysRevD.97.015004.

S. Knapen, T. Lin, and K. M. Zurek. Light Dark Matter: Models and Constraints. *Phys. Rev. D*, 96(11):115021, 2017. doi: 10.1103/PhysRevD.96.115021.

G. D. Mahan. *Many-particle physics.* Springer Science & Business Media, 2013.

F. Mayet et al. A review of the discovery reach of directional Dark Matter detection. *Phys. Rept.*, 627:1–49, 2016. doi: 10.1016/j.physrep.2016.02.007.