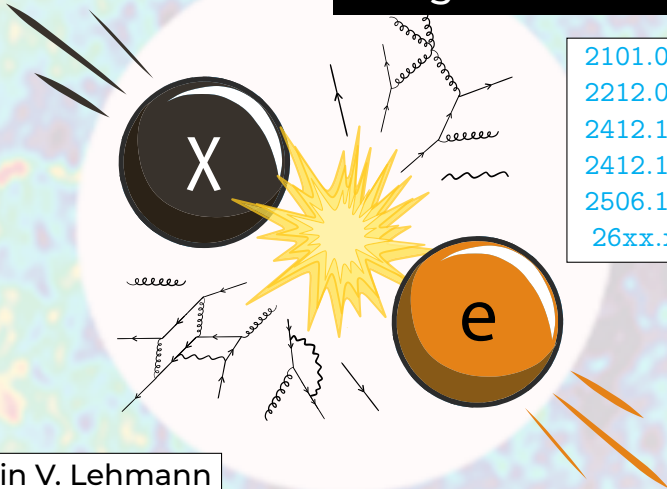


Broadening direct searches for light dark matter



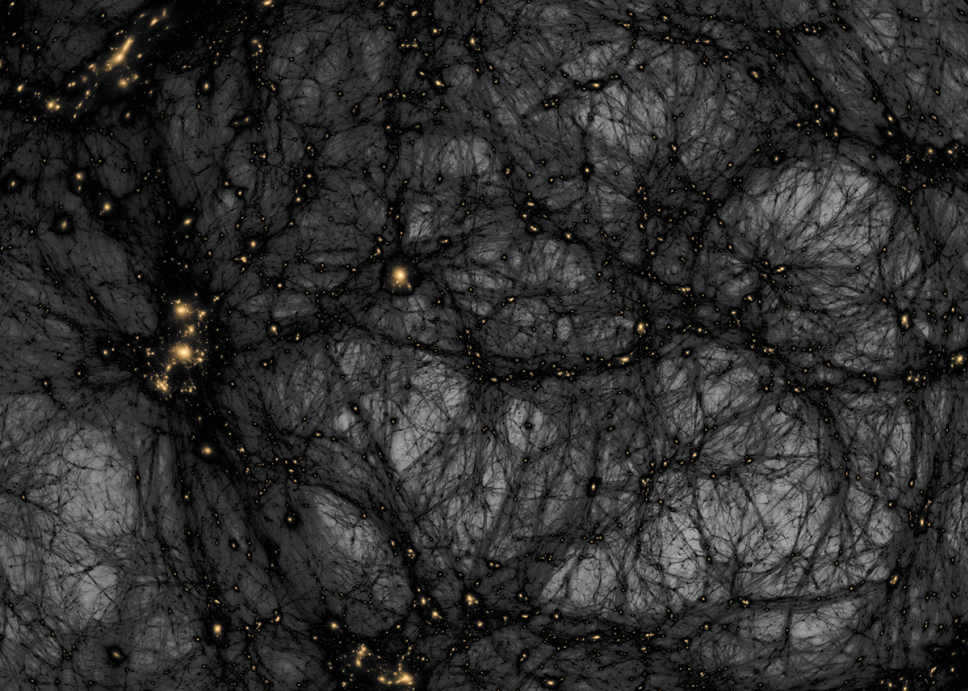
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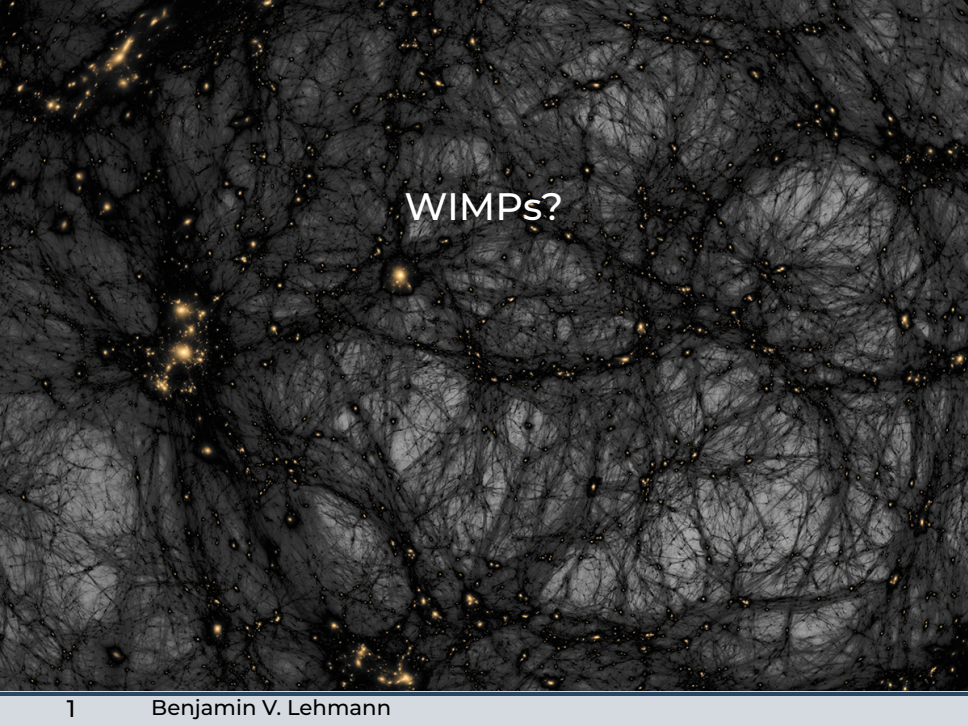
Benjamin V. Lehmann



Massachusetts
Institute of
Technology





A visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. The filaments are represented by a dense, interconnected web of thin, dark lines, while the galaxy clusters are shown as bright, yellowish-orange points of light. The overall structure is highly irregular and fractal-like, with many smaller clusters and filaments branching off from the main network.

WIMPs?

The moment of truth for WIMP dark matter

Gianfranco Bertone^{1,2}

We know that dark matter constitutes 85 per cent of all the matter in the Universe, but we do not know of what it is made. Amongst the many dark matter candidates proposed, WIMPs (weakly interacting massive particles) occupy a special place, because they arise naturally from new theories that seek to extend the standard model of particle physics. With the advent of the Large Hadron Collider at CERN, and a new generation of astroparticle experiments, the moment of truth has come for WIMPs: either we will discover them in the next five to ten years, or we will witness their inevitable decline.

The waning of the WIMP: endgame?

Giorgio Arcadi^{1,2,a}, David Cabo-Almeida^{1,2,3,b}, Maíra Dutra^{4,5,c}, Pradipta Ghosh^{6,d}, Manfred Lindner^{7,e}, Yann Mambrini^{8,f}, Jacinto P. Neto^{1,9,10,g}, Mathias Pierre^{11,h}, Stefano Profumo^{12,13,i}, Farinaldo S. Queiroz^{9,10,14,j}

¹ Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra, Università degli Studi di Messina, Via Ferdinando Stagno d'Alcontres 31, 98166 Messina, Italy

² INFN Sezione di Catania, Via Santa Sofia 64, 95123 Catania, Italy

³ Departament de Física Quàntica i Astrofísica, Universitat de Barcelona, Martí i Franquès 1, 08028 Barcelona, Spain

⁴ Astroparticle Physics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

⁵ Center for Cosmology and Particle Physics, Harvard University, Cambridge, MA 02138, USA

⁶ School of Physics and Astronomy, University of Southampton, Highfield, Southampton SO9 5NH, UK
⁷ Institut d'Astropartícules de Barcelona, Universitat de Barcelona, Martí i Franquès 1, 08028 Barcelona, Spain
⁸ Institut de Física d'Altes Energies, Universitat de Barcelona, Martí i Franquès 1, 08028 Barcelona, Spain
⁹ Instituto de Física de São Carlos, Universidade de São Carlos, São Carlos, Minas Gerais, 13560-970, Brazil
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¹² Department of Physics, University of Wisconsin-Madison, 480 Lincoln Drive, Madison, WI 53706, USA
¹³ Department of Physics, University of Wisconsin-Madison, 480 Lincoln Drive, Madison, WI 53706, USA
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REVIEW

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1. Model-driven

Find and invest in other lampposts

REVIEW

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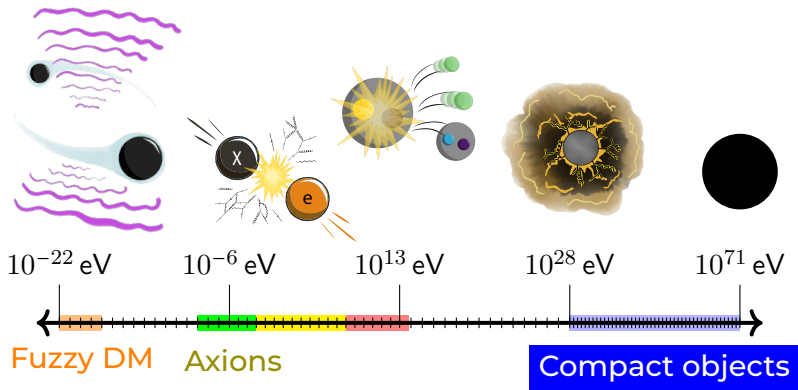
1. Model-driven

Find and invest in other lampposts

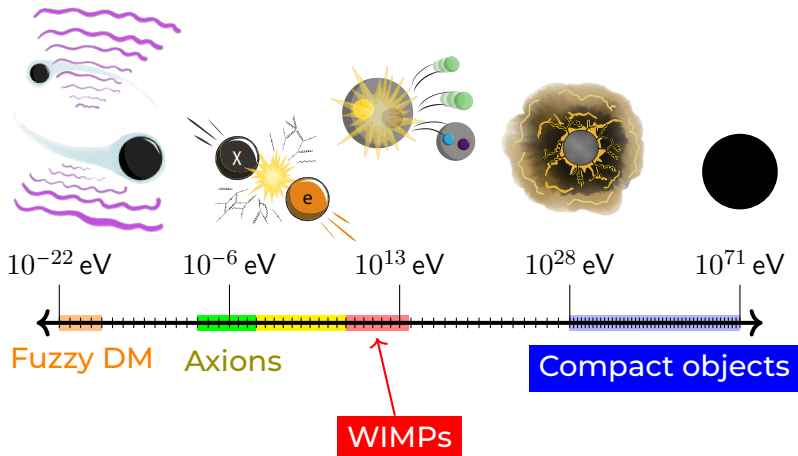
2. Model-independent

Systematic, widely-applicable probes

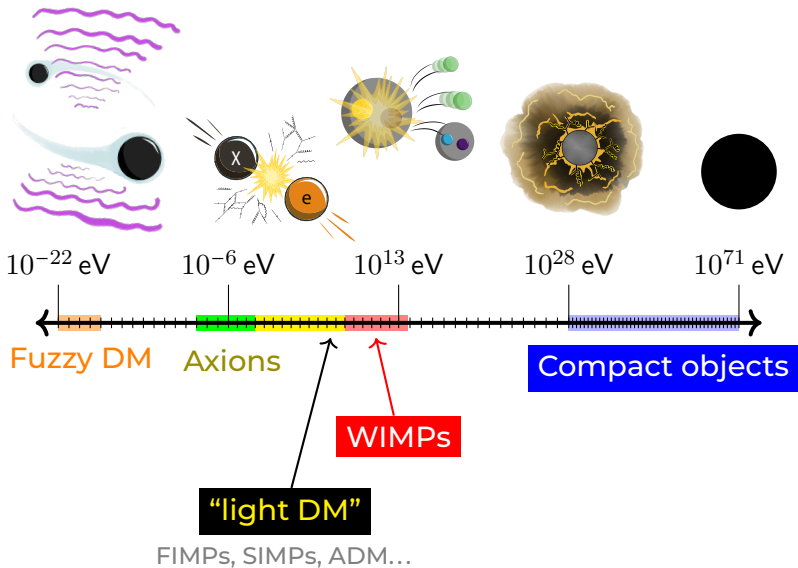
The dark matter parameter space



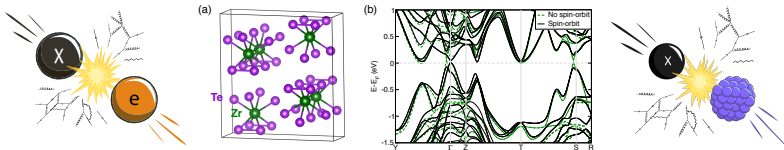
The dark matter parameter space



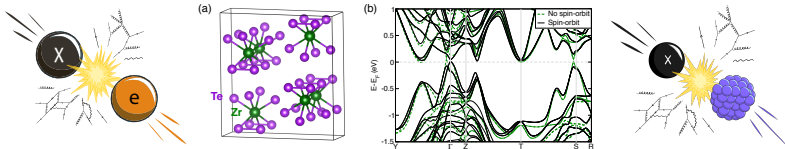
The dark matter parameter space



This talk in one slide



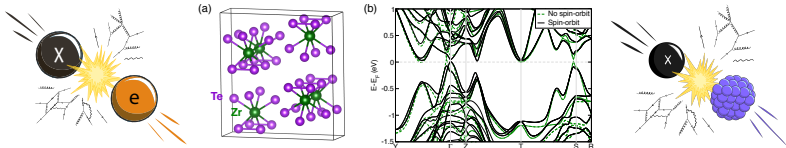
This talk in one slide



1. DM in condensed matter systems

Capabilities and control handles

This talk in one slide



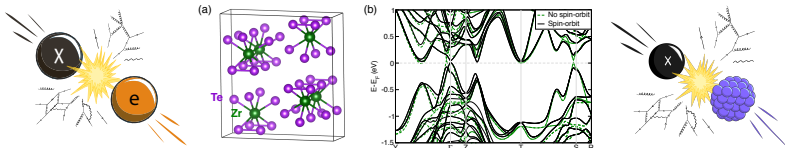
1. DM in condensed matter systems

Capabilities and control handles

2. Data-driven detector design

Materials physics for sensitive experiments

This talk in one slide



1. DM in condensed matter systems

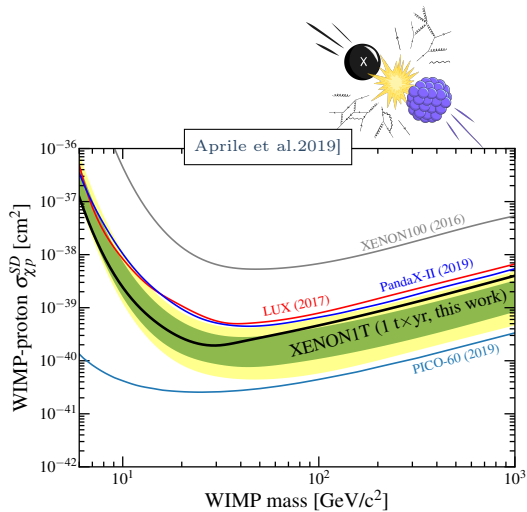
Capabilities and control handles

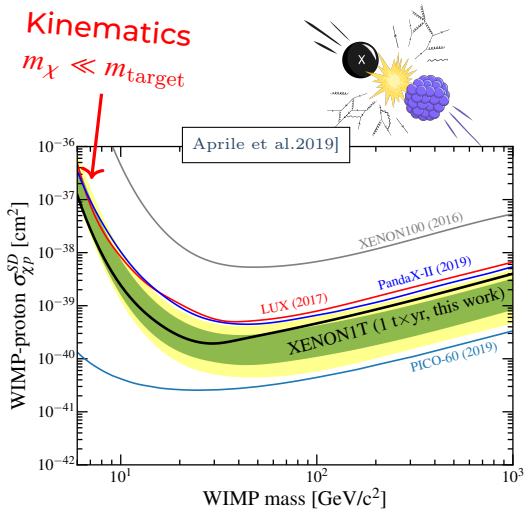
2. Data-driven detector design

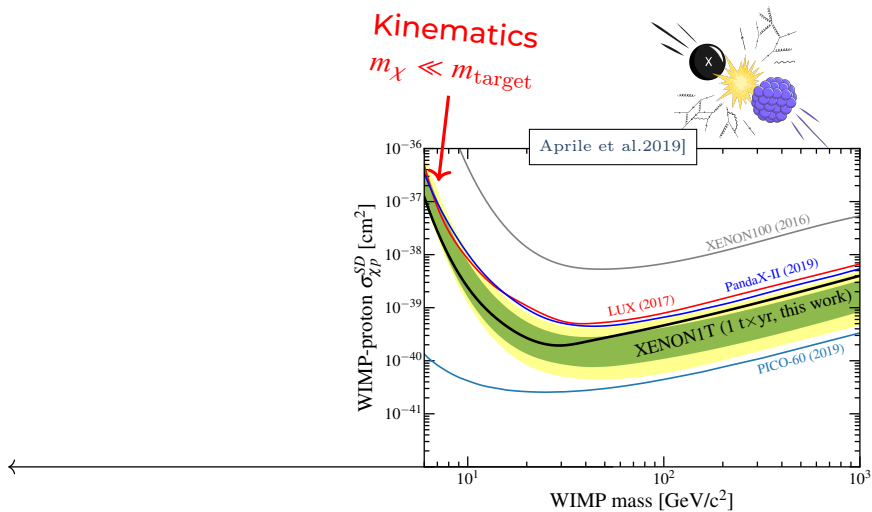
Materials physics for sensitive experiments

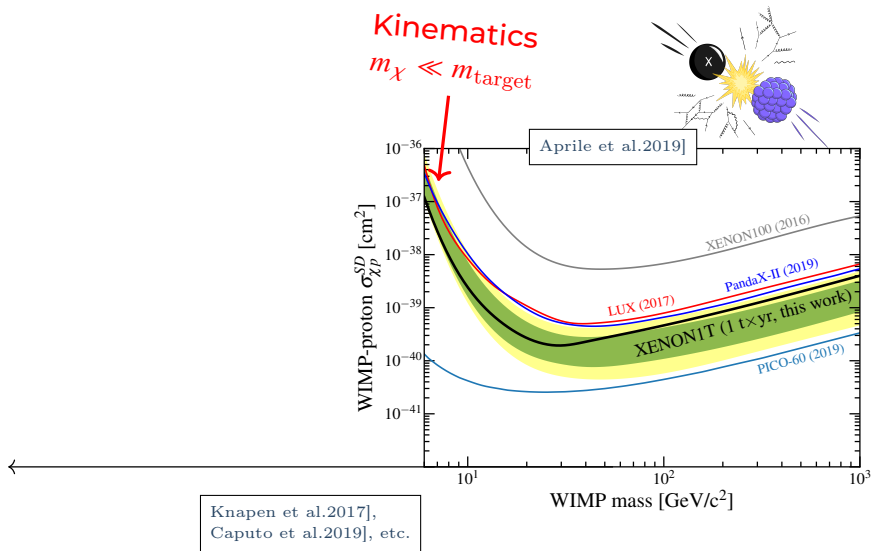
3. Real detectors: challenges and rewards

Prototypes, geometric effects, and nuclear sensitivity

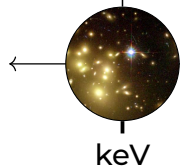




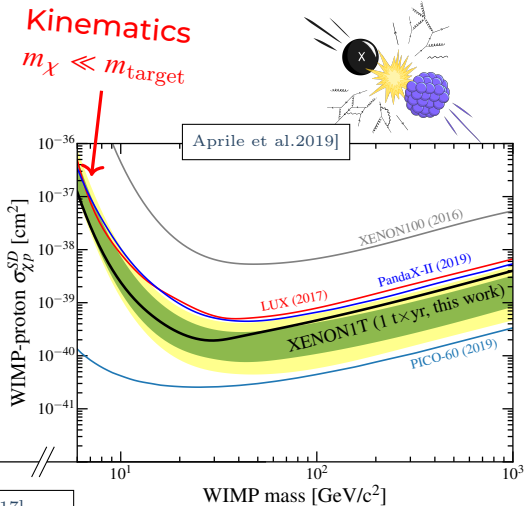




Structure limits

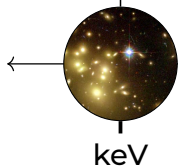


Knapen et al.2017],
Caputo et al.2019], etc.



Sub-GeV DM

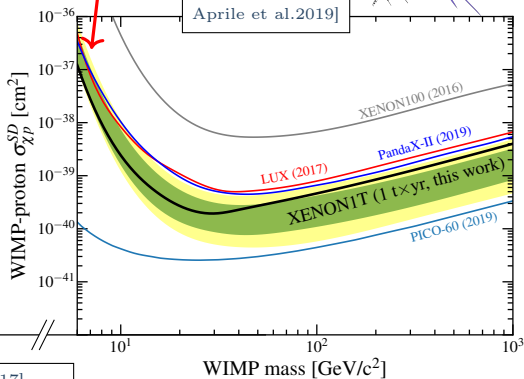
Structure limits



Light fermion

Knapen et al.2017],
Caputo et al.2019], etc.

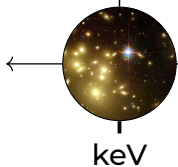
Kinematics
 $m_\chi \ll m_{\text{target}}$



Sub-GeV DM

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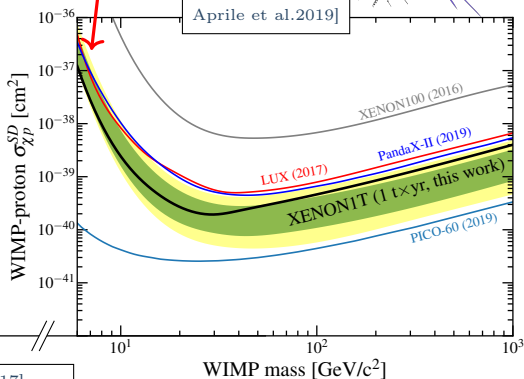
Light boson



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Knapen et al.2017],
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Kinematics
 $m_\chi \ll m_{\text{target}}$

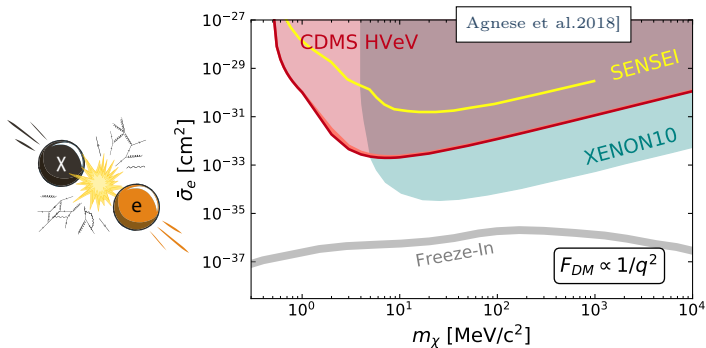


Electron recoils for light DM

Match DM mass to target mass

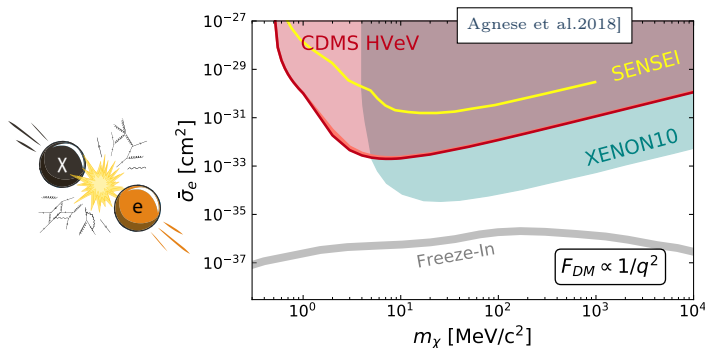
Electron recoils for light DM

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Electron recoils for light DM

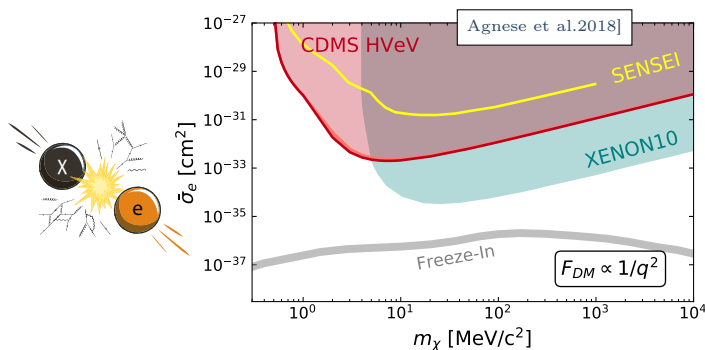
Match DM mass to target mass



At lower masses, free-particle scattering breaks down

Electron recoils for light DM

Match DM mass to target mass

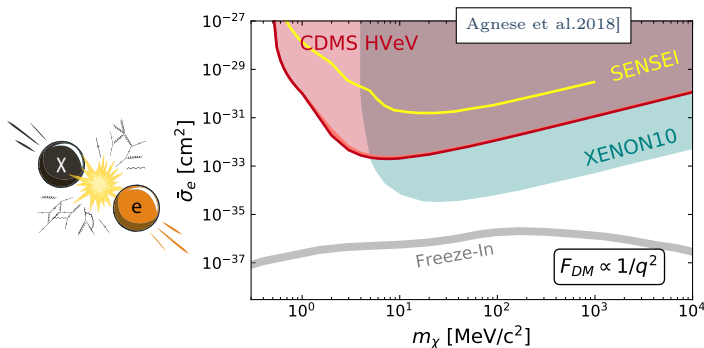


At lower masses, free-particle scattering breaks down

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

Electron recoils for light DM

Match DM mass to target mass



At lower masses, free-particle scattering breaks down

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

[1/3] Dark matter in condensed matter

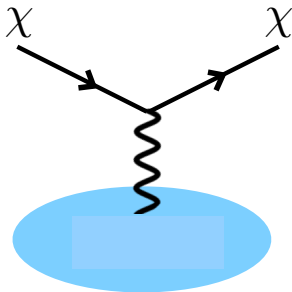
Yonit Hochberg, Yoni Kahn, Noah Kurinsky,
BVL, To Chin Yu & Karl Berggren

2101.08263, PRL

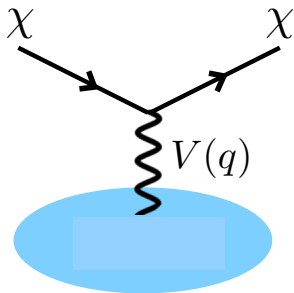
Christian Boyd, Yonit Hochberg, Yoni Kahn,
Eric David Kramer, Noah Kurinsky, **BVL** & To Chin Yu

2212.04505, PRD

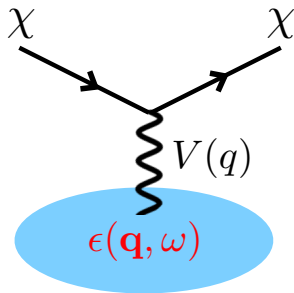
Idea: separate *probe* and *response*



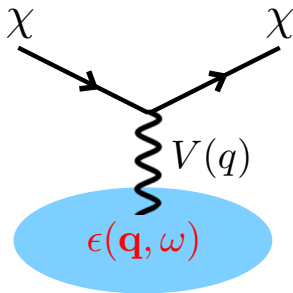
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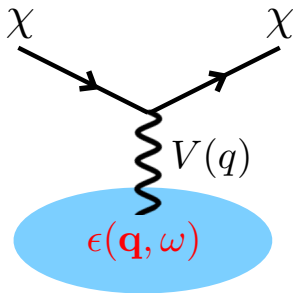


Response described by **complex dielectric function**,

$$\epsilon(\mathbf{q}, \omega) = \frac{V_{\text{applied}}}{V_{\text{applied}} + V_{\text{induced}}}$$

$$\begin{cases} \mathbf{q} = \text{momentum transfer} \\ \omega = \text{deposited energy} \end{cases}$$

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Response described by **complex dielectric function**,

$$\epsilon(\mathbf{q}, \omega) = \frac{V_{\text{applied}}}{V_{\text{applied}} + V_{\text{induced}}} \quad \left\{ \begin{array}{l} \mathbf{q} = \text{momentum transfer} \\ \omega = \text{deposited energy} \end{array} \right.$$

Same quantity as in ordinary **screening**

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

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- 1 Predictable: ϵ admits analytical approximations

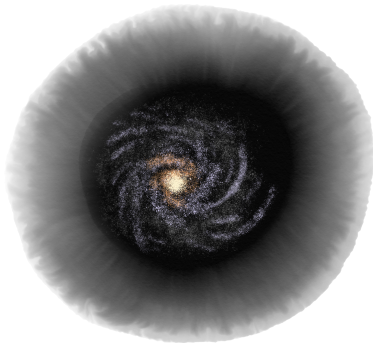
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- 1 **Predictable:** ϵ admits analytical approximations
- 2 **Empirical:** ϵ is directly measurable / computable

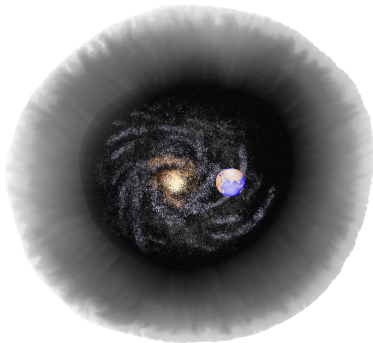
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- ① **Predictable:** ϵ admits analytical approximations
- ② **Empirical:** ϵ is directly measurable / computable
- ③ **Anisotropic:** ϵ is tensorial (directional sensitivity)

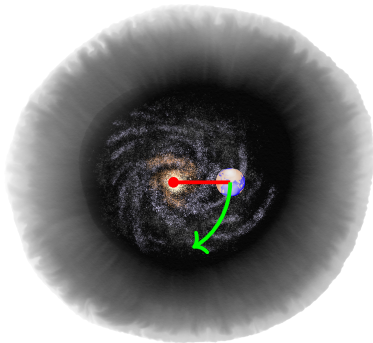
Directional sensitivity



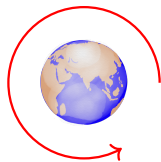
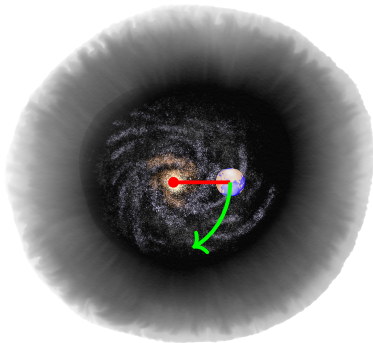
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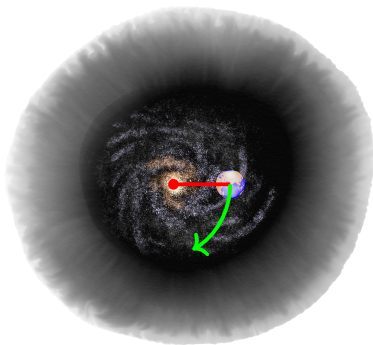


Directional sensitivity



Daily modulation
from DM "wind"

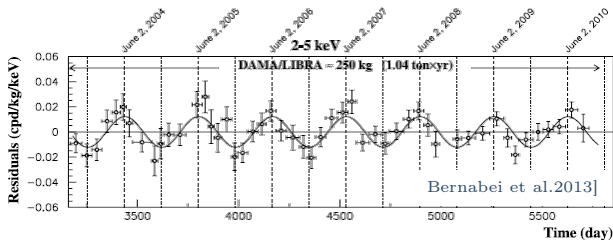
Directional sensitivity



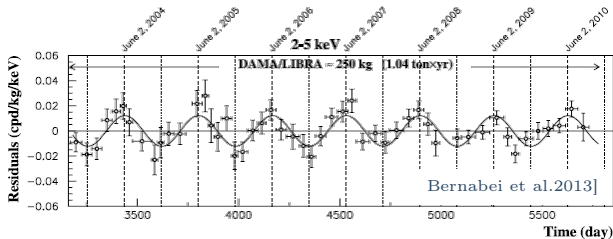
Daily modulation
from DM “wind”

Detecting wind is **crucial** for background rejection

Annual vs. daily

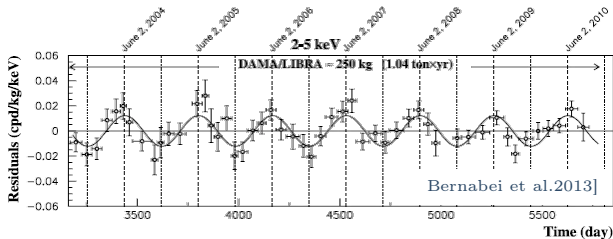


Annual vs. daily

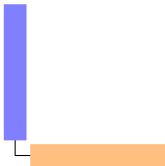


“Daily modulation” is really “angular modulation”

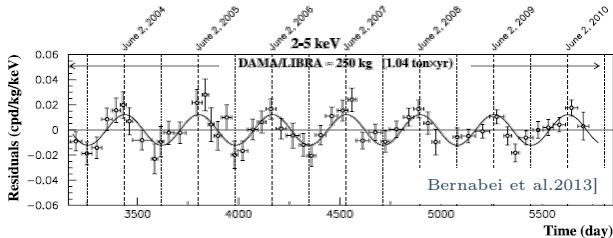
Annual vs. daily



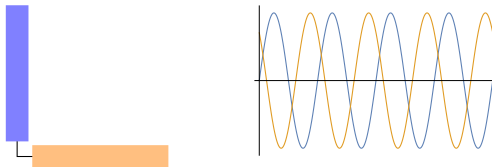
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Annual vs. daily



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The response function — explicit

See e.g. Mahan2013]

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$$\chi(\mathbf{q}, \omega) = V_{\text{Coul.}}^{-1}(\mathbf{q}) \epsilon^{-1}(\mathbf{q}, \omega)$$

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

The response function — explicit

See e.g. Mahan2013]

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$$P^{(1)} = \text{diagram}$$

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$$P^{(1)} = \text{diagram 1}$$

$$P^{(2)} = \text{diagram 2} + \text{diagram 3} + \text{diagram 4} + \text{diagram 5}$$

The response function — explicit

See e.g. Mahan2013]

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

The response function — explicit

See e.g. Mahan2013]

$$\chi(\mathbf{q}, \omega) = V_{\text{Coul.}}^{-1}(\mathbf{q}) \epsilon^{-1}(\mathbf{q}, \omega)$$

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

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See e.g. Mahan2013]

$$\chi(\mathbf{q}, \omega) = V_{\text{Coul.}}^{-1}(\mathbf{q}) \epsilon^{-1}(\mathbf{q}, \omega)$$

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$$P^{(1)} = \text{diagram: a bubble with two wavy external lines and a single internal wavy line}$$

$$P^{(2)} = \text{diagram: a bubble with two wavy external lines and two internal wavy lines} + \text{diagram: a bubble with two wavy external lines and two internal wavy lines} + \text{diagram: a bubble with two wavy external lines and two internal wavy lines} + \text{diagram: a bubble with two wavy external lines and two internal wavy lines}$$

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Random phase approximation (RPA)

The Lindhard function

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

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Lindhard dielectric function

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

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Material parameters:

The Lindhard function

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plasma frequency $\omega_p \sim O(1) \times E_F$,

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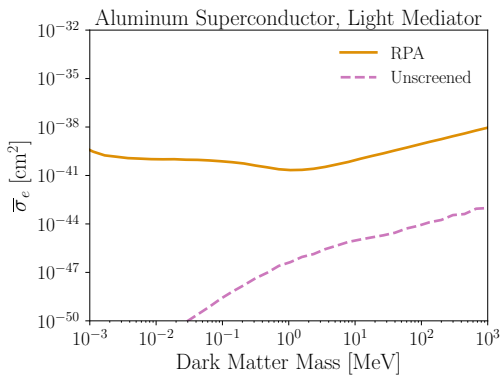
plasmon width $\Gamma \sim O(0.01-0.1) \times \omega_p$

Understanding χ — screening

Heuristically identical to E&M

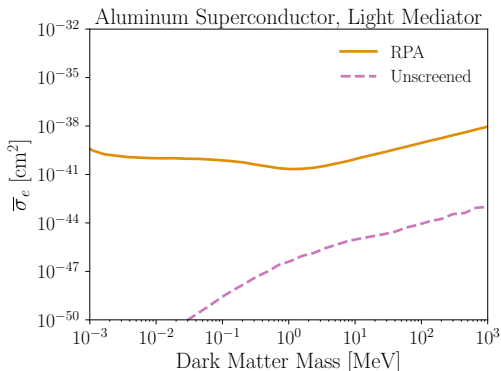
Understanding χ — screening

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Understanding χ — screening

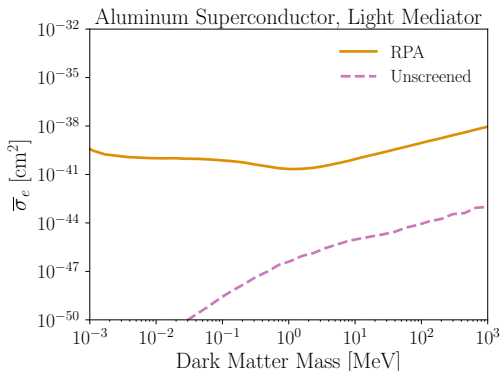
Heuristically identical to E&M



Screening is a property of material response

Understanding χ — screening

Heuristically identical to E&M



Screening is a property of material response

Scalar and vector interactions are screened identically

Understanding χ — plasmons

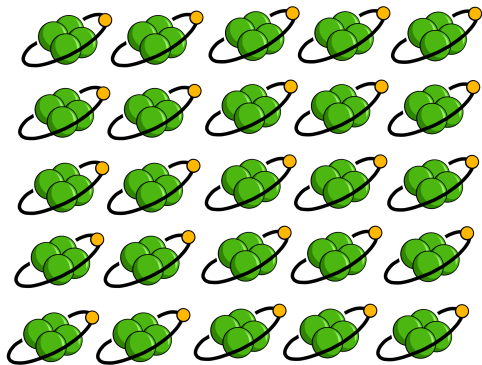
Understanding χ — plasmons



Understanding χ — plasmons

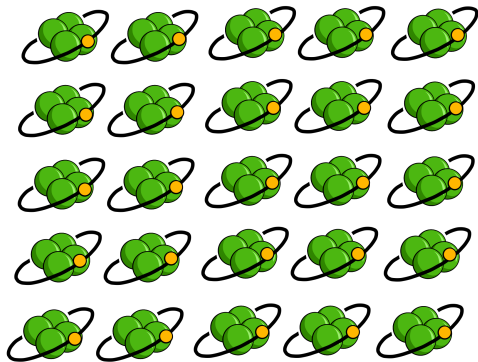


Understanding χ — plasmons



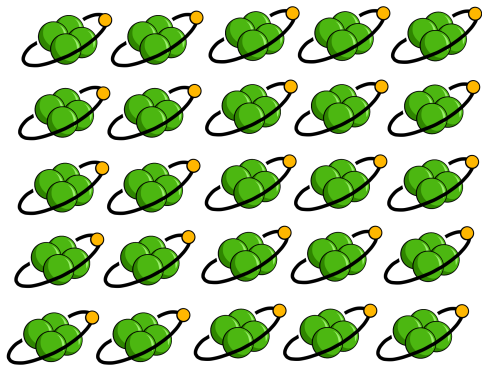
A **collective oscillation** of electrons

Understanding χ — plasmons



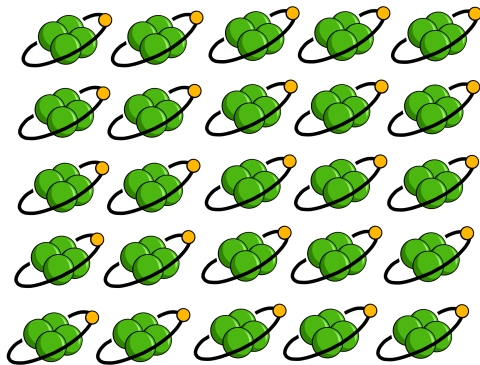
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Understanding χ — plasmons



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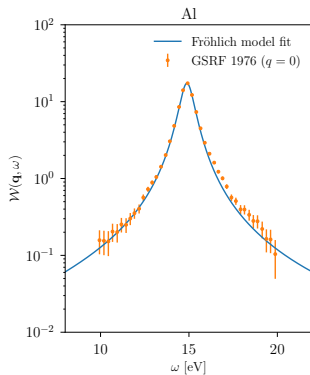
Understanding χ — plasmons



A **collective oscillation** of electrons

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

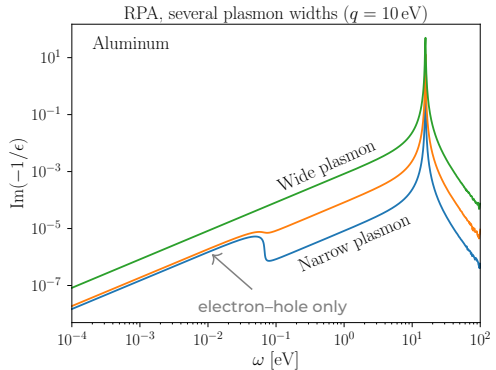
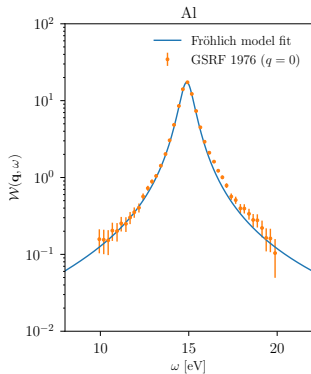
Understanding χ — plasmons



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Understanding χ — plasmons

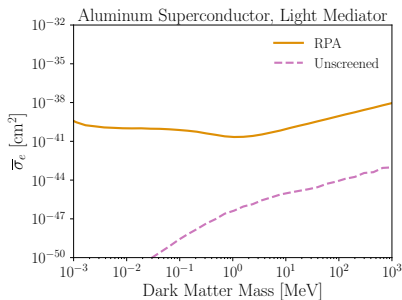


A collective oscillation of electrons

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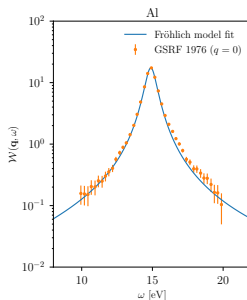
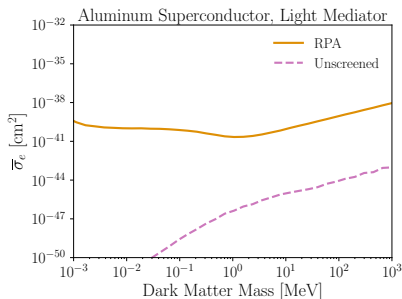
Understanding χ — Lindhard lessons

Understanding χ — Lindhard lessons



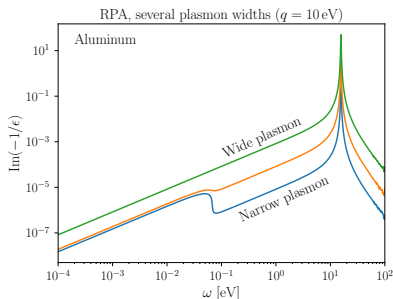
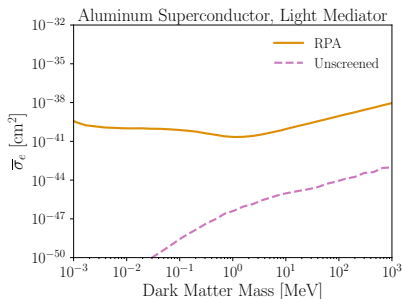
- 1 Screening is generic, not model-dependent

Understanding χ — Lindhard lessons



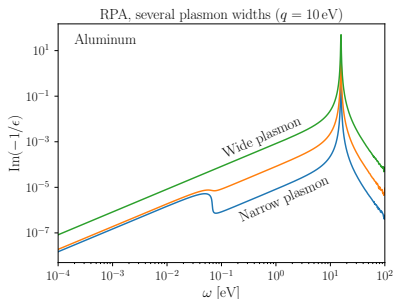
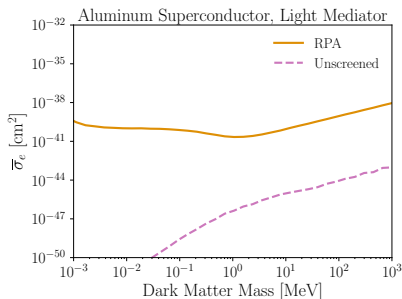
- 1 Screening is generic, not model-dependent
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Understanding χ — Lindhard lessons



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- 3 Plasmon width is important

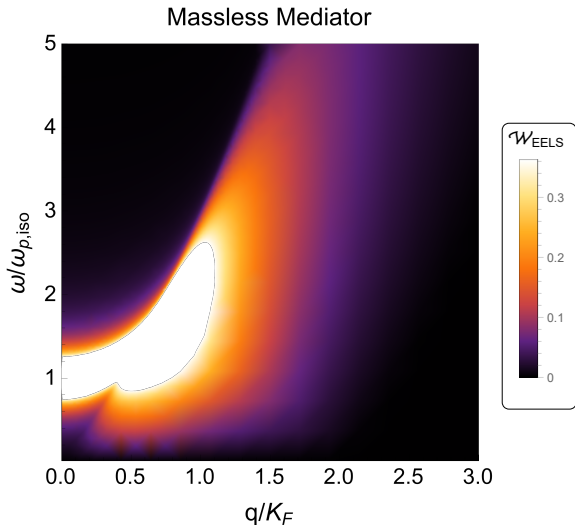
Understanding χ — Lindhard lessons



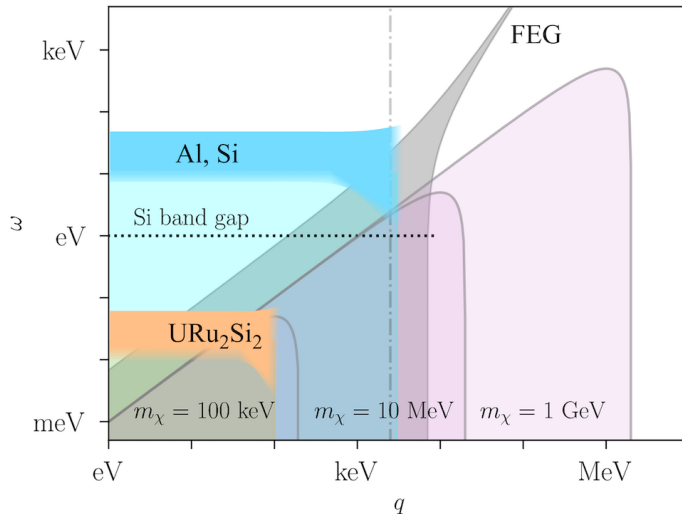
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We can use analytical forms of ϵ for heuristics

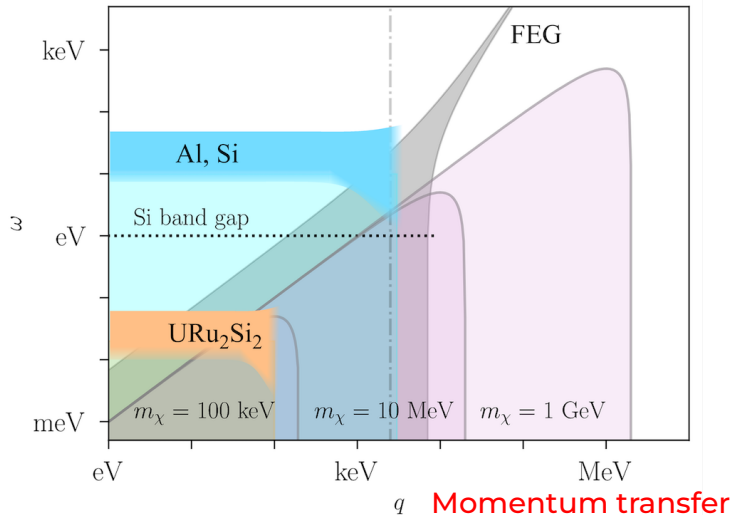
Visualizing the loss function



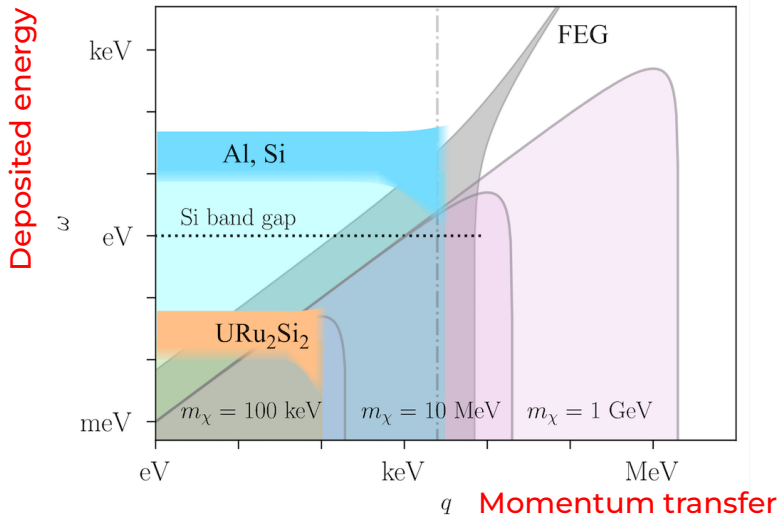
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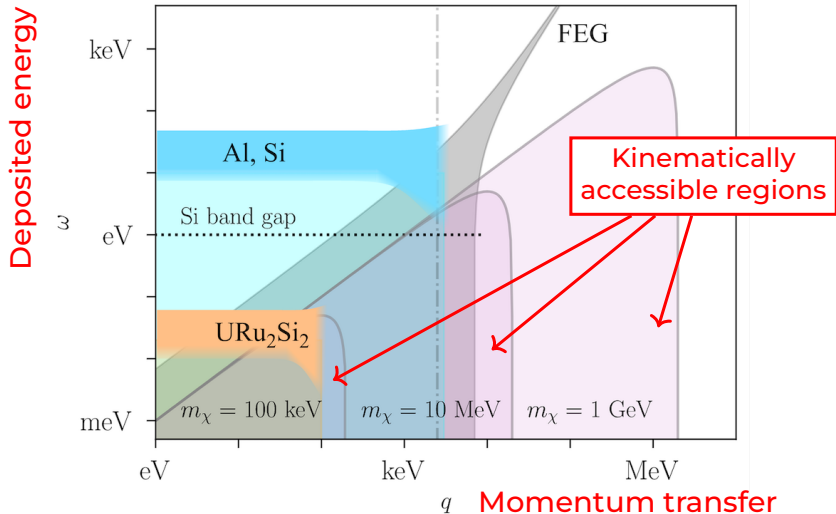
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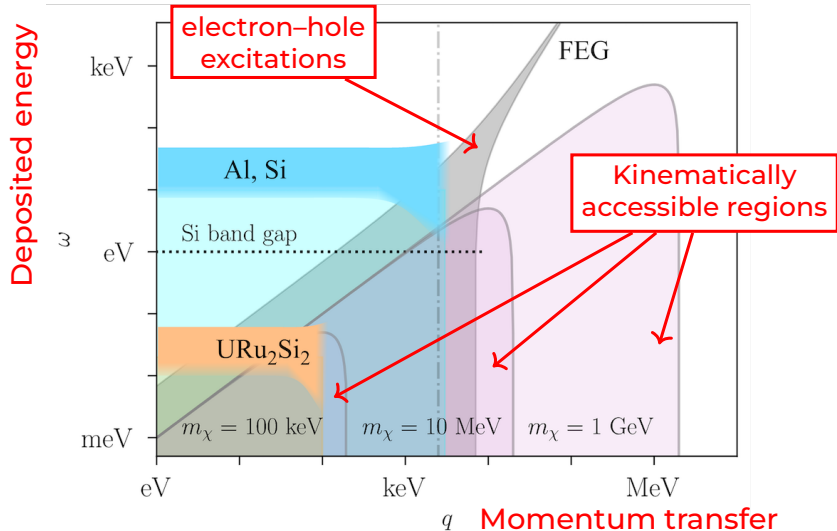
Visualizing the loss function



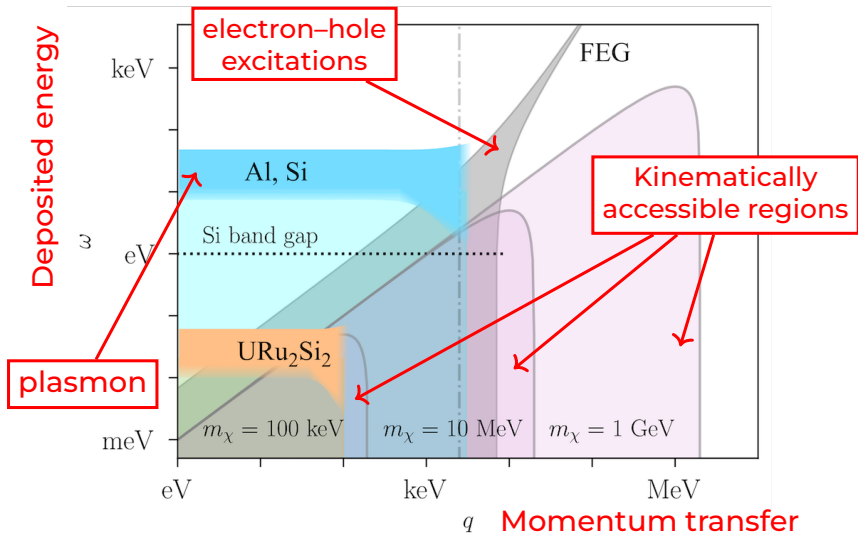
Visualizing the loss function



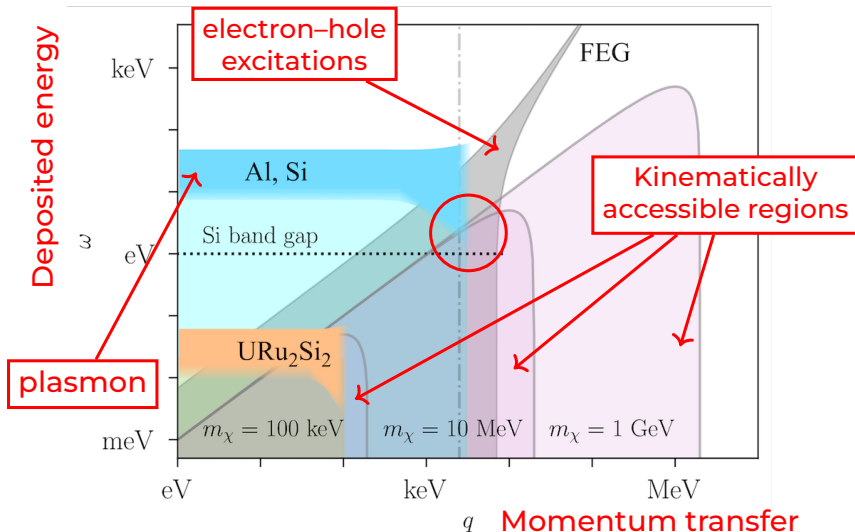
Visualizing the loss function



Visualizing the loss function



Visualizing the loss function



Identifying new targets

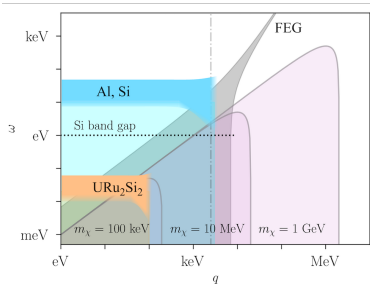
When can DM access the plasmon peak?

$$(\omega \sim \omega_p)$$

Identifying new targets

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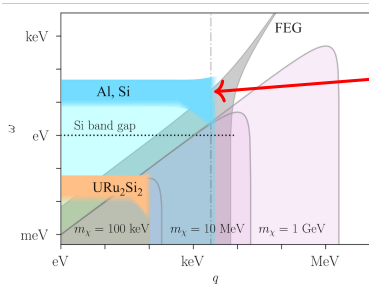
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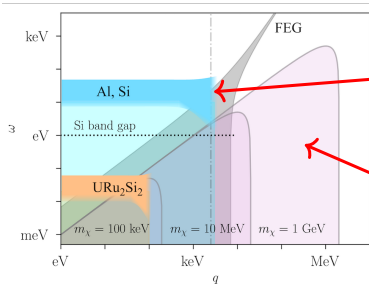
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plasmon trails off

$$q_c \simeq \omega_p / v_F$$

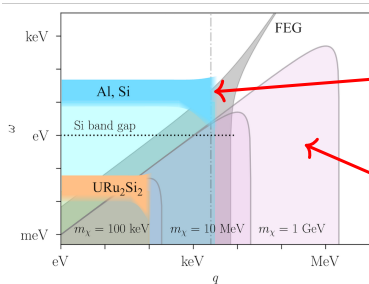
$$\omega < qv_\chi$$

kinematics

Identifying new targets

When can DM access the plasmon peak?

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Only possible if $v_F \lesssim v_\chi$

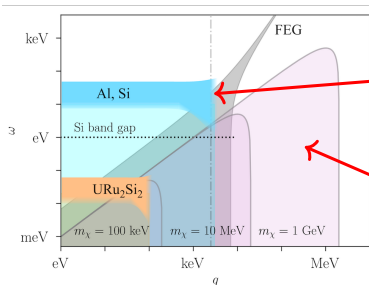
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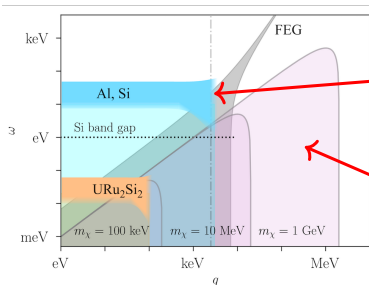
kinematics

Find a target with a low Fermi velocity

Identifying new targets

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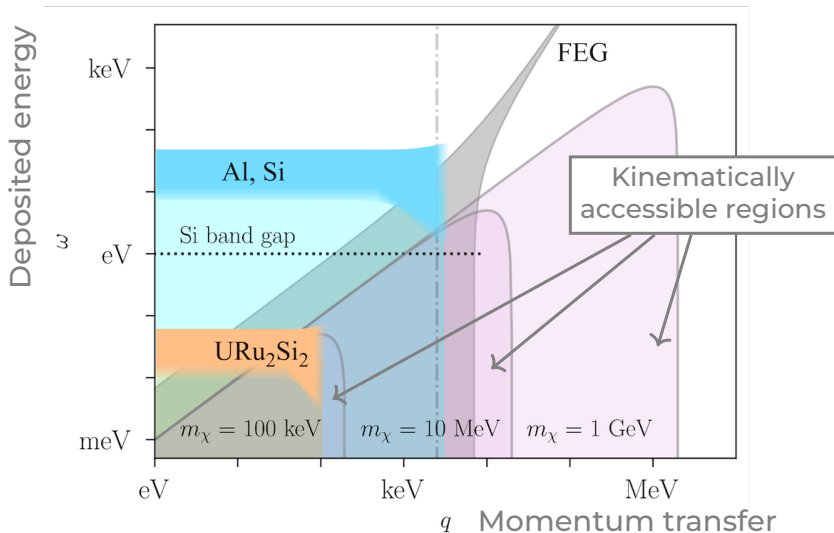
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kinematics

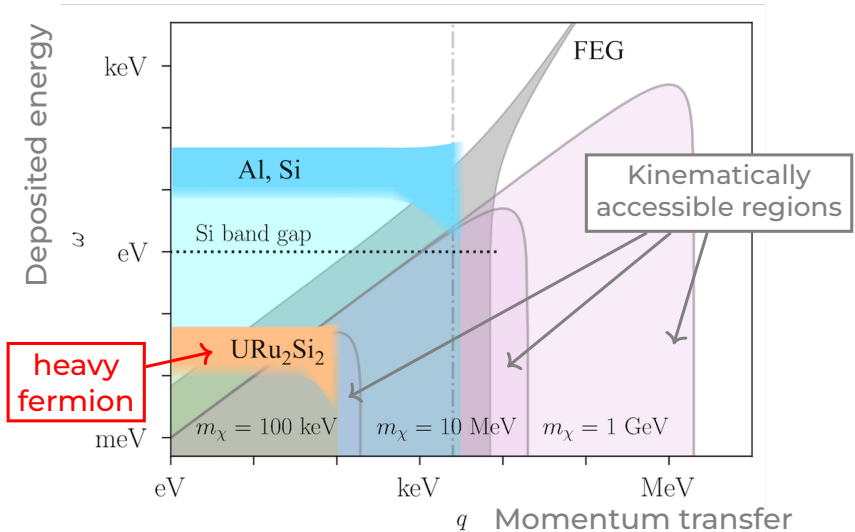
Find a target with a low Fermi velocity

Heavy-fermion materials?

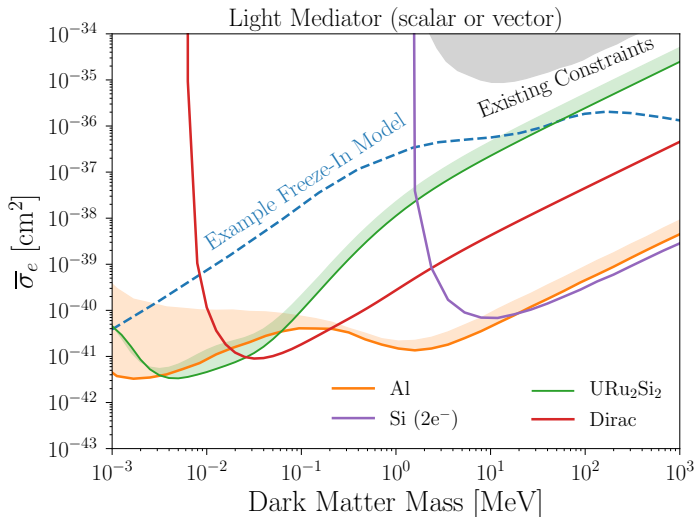
Heavy-fermion materials



Heavy-fermion materials



Heavy-fermion reach

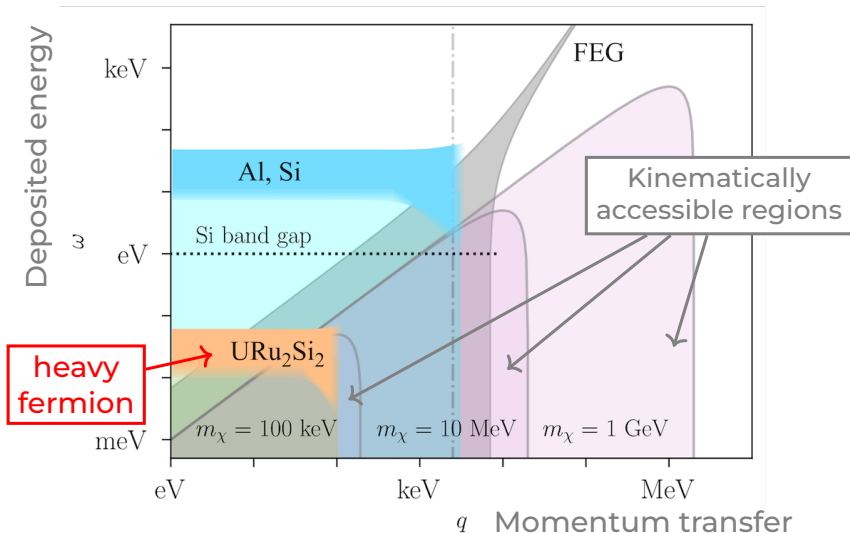


[2/3] Data-driven detector design

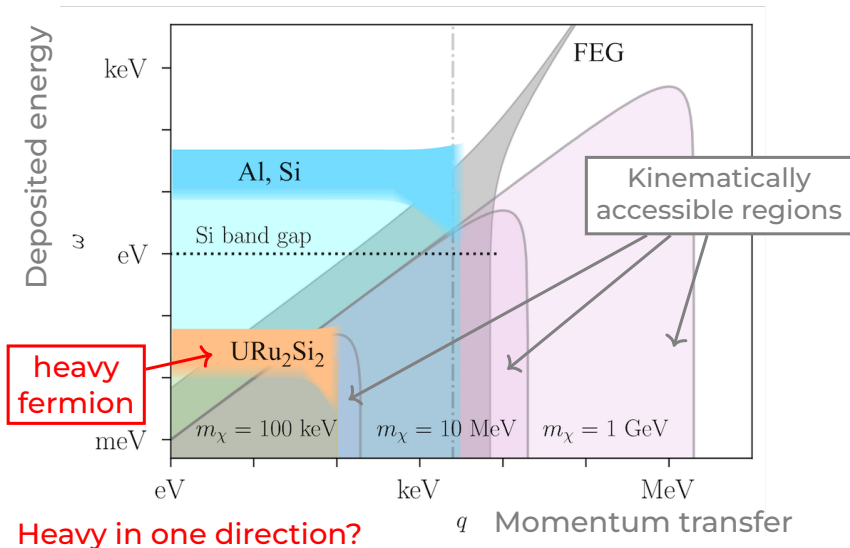
Sinéad M. Griffin, Yonit Hochberg, **BVL**, Rotem Ovadia,
Bethany A. Suter, Ruo Xi Yang, Wayne Zhao

2506.19905, PRL

Anisotropic “heavy fermion”



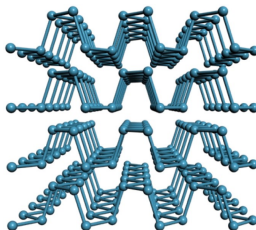
Anisotropic “heavy fermion”



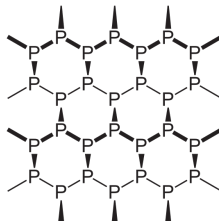
Model system: anisotropic mass

Model system: anisotropic mass

Black phosphorus

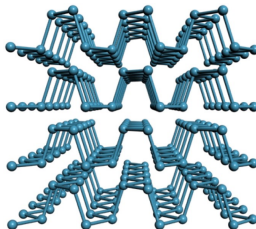


$$m_{\text{heavy}}/m_{\text{light}} \approx 9$$

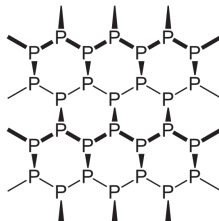


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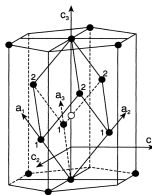
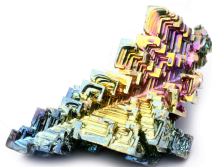
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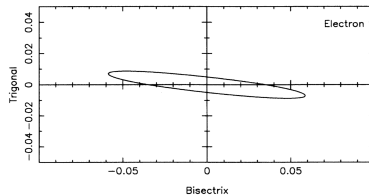
$$m_{\text{heavy}}/m_{\text{light}} \approx 9$$



Bismuth



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



Isotropic case.

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

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Anisotropic response function

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

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Anisotropic case. $E_{\mathbf{q}}^{\text{iso}} = \frac{q^2}{2m} \longrightarrow E_{\mathbf{q}}^{\text{ani}} = \frac{q_x^2}{2m_x} + \frac{q_y^2}{2m_y} + \frac{q_z^2}{2m_z}$

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Transform back to isotropic in k -space

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Transform back to isotropic in k -space

$$Q_i(\mathbf{q}) = q_i \sqrt{\frac{M}{m_i}}, \quad M = (m_x m_y m_z)^{1/3}$$

Anisotropic response function

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Anisotropic case. $E_{\mathbf{q}}^{\text{iso}} = \frac{q^2}{2m} \longrightarrow E_{\mathbf{q}}^{\text{ani}} = \frac{q_x^2}{2m_x} + \frac{q_y^2}{2m_y} + \frac{q_z^2}{2m_z}$

Transform back to isotropic in k -space

$$Q_i(\mathbf{q}) = q_i \sqrt{\frac{M}{m_i}}, \quad M = (m_x m_y m_z)^{1/3} \implies E_{\mathbf{q}}^{\text{ani}} = \frac{Q^2}{2M} = E_{\mathbf{q}}^{\text{iso}}$$

Anisotropic response function

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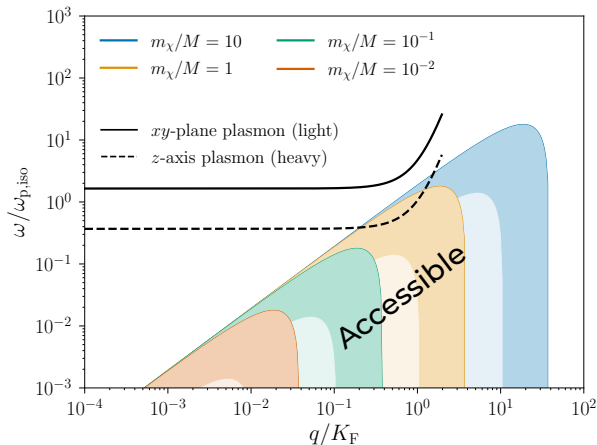
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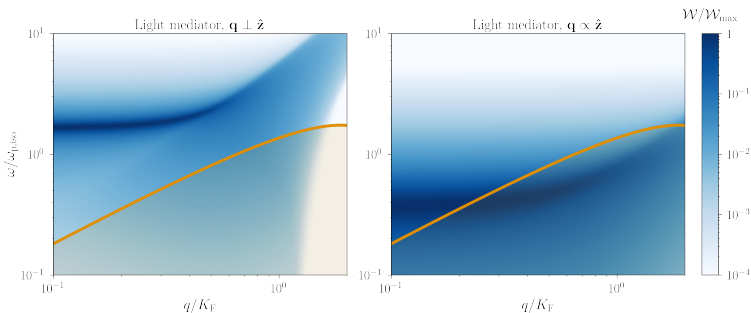
$$\chi_0^{\text{iso}}(\mathbf{q}, \omega) \longrightarrow \chi_0^{\text{ani}}(\mathbf{q}, \omega) = \chi_0^{\text{iso}}(\mathbf{Q}(\mathbf{q}), \omega)$$

Anisotropic plasmon threshold



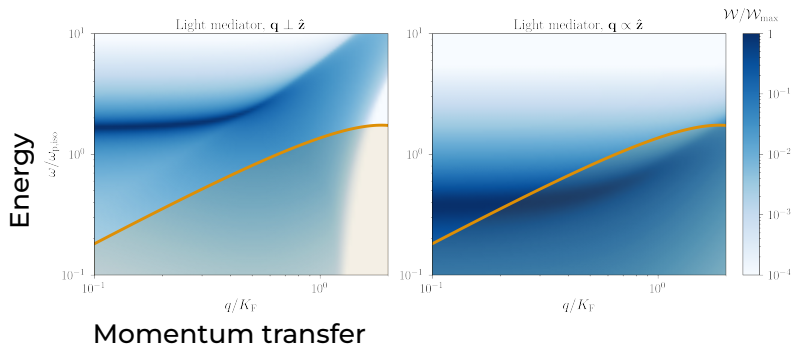
Anisotropic loss function

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



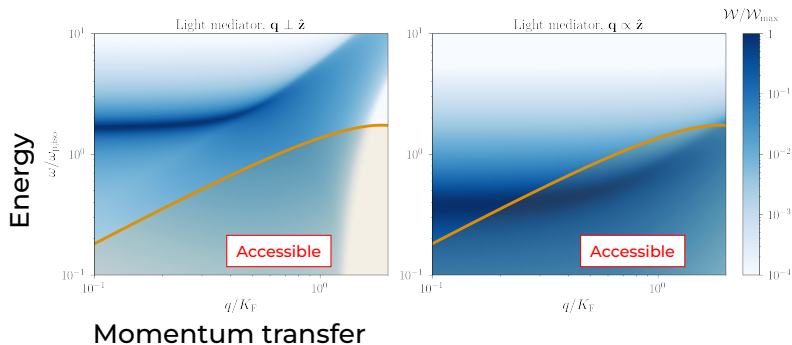
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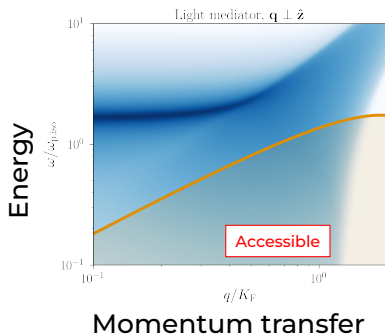


Anisotropic loss function

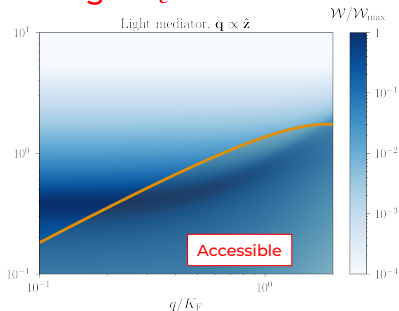
$$m_z/m_{xy} = 20,$$

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Low- m_e direction



High- m_e direction

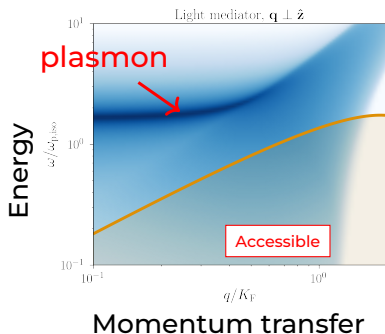


Anisotropic loss function

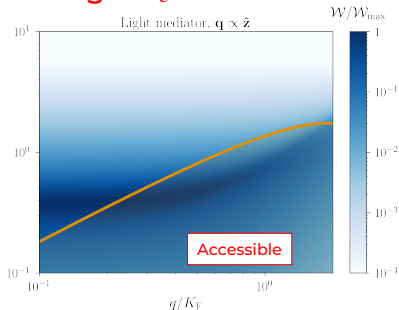
$$m_z/m_{xy} = 20,$$

$$m_x m_y m_z = m_e^3$$

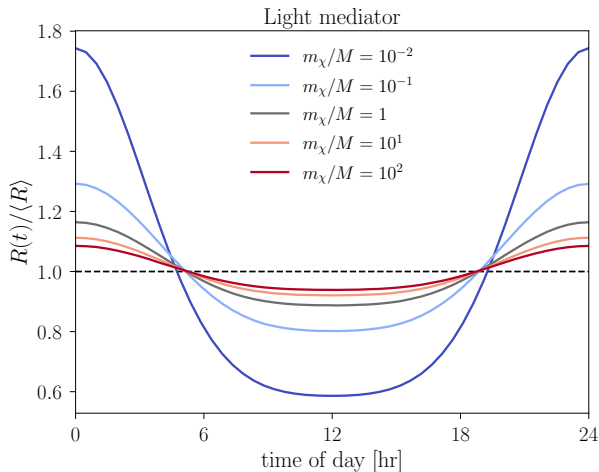
Low- m_e direction



High- m_e direction



Substantial daily modulation



Super-broad material exploration

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

- ② **Empirical:** ϵ is directly measurable / computable

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The Materials Project

Harnessing the power of supercomputing and state-of-the-art methods, the Materials Project provides open web-based access to computed information on known and predicted materials as well as powerful analysis tools to inspire and design novel materials.

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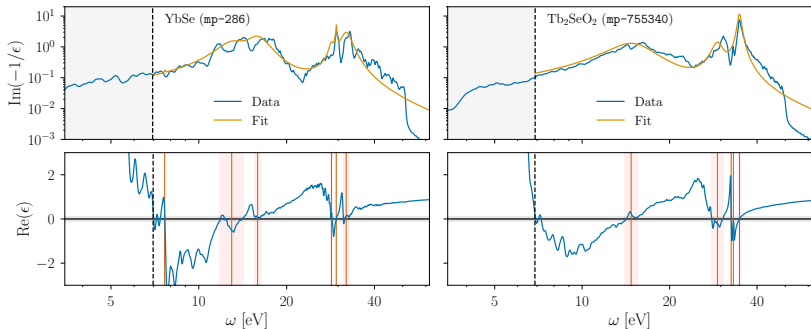
$\epsilon|_{\mathbf{q}=0}$ via DFT for **1,019 materials** (out of 154,718!)

Recovering $\epsilon(q > 0)$

Materials Project only computes $\epsilon^{\leftrightarrow}|_{q=0}$

Recovering $\epsilon(q > 0)$

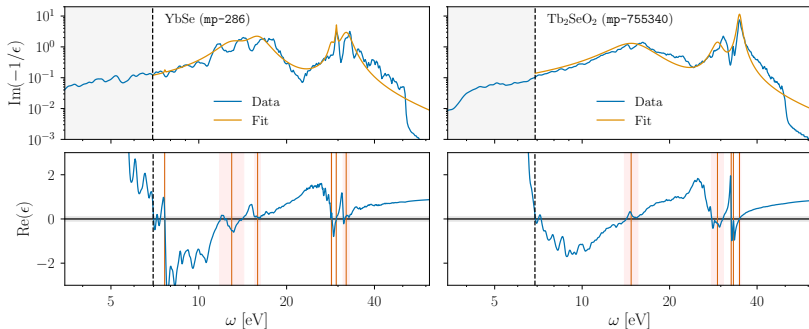
Materials Project only computes $\epsilon^{\leftrightarrow}|_{q=0}$



Locate features in $\text{Re}(\epsilon)$ and fit analytical Lindhard functions

Recovering $\epsilon(q > 0)$

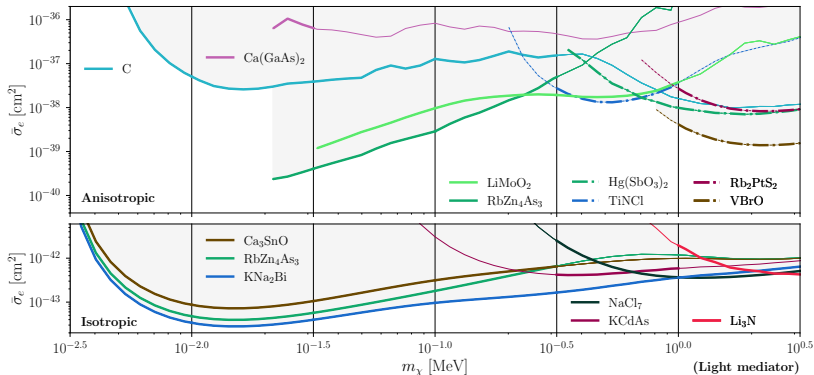
Materials Project only computes $\epsilon^{\leftrightarrow}|_{\mathbf{q}=0}$



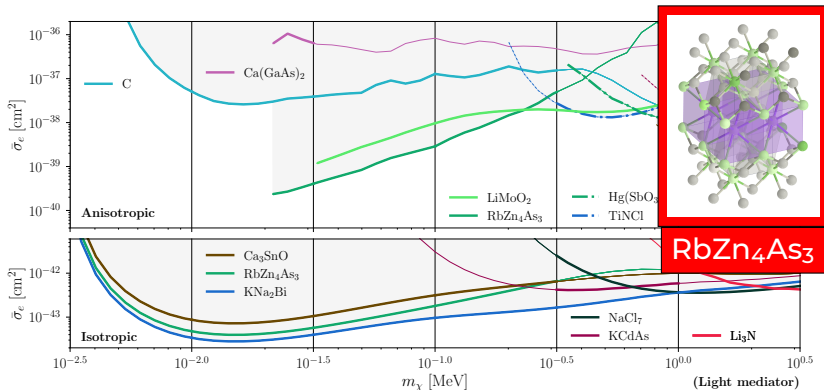
Locate features in $\text{Re}(\epsilon)$ and fit analytical Lindhard functions

$$\epsilon_{\text{fit}}(\mathbf{q}, \omega) = \frac{1}{\sum_k h_k} \sum_{k=1}^{n_{\text{peaks}}} h_k \epsilon_L(\omega_{\text{p},k}, \Gamma_{\text{p},k}, E_{\text{F}}; \mathbf{q}, \omega)$$

Three optimal systems per half-decade

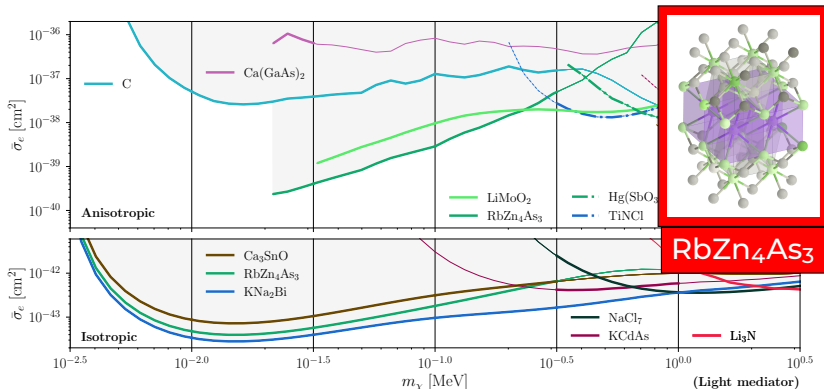


Three optimal systems per half-decade



Scattering sensitivity

Three optimal systems per half-decade



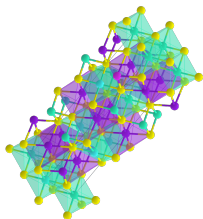
Now evaluating these new materials for use

Broadening with machine learning

Materials Project has $\epsilon(\hat{\mathbf{q}}, \omega)$ for 10^3 of 10^5 materials

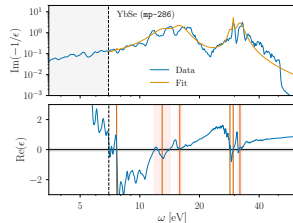
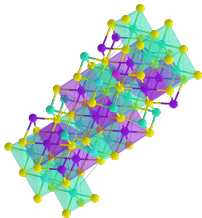
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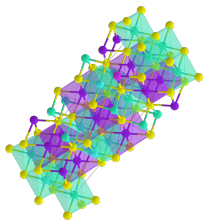
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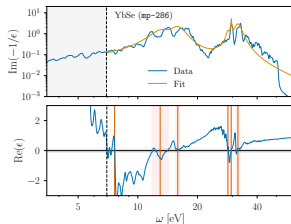
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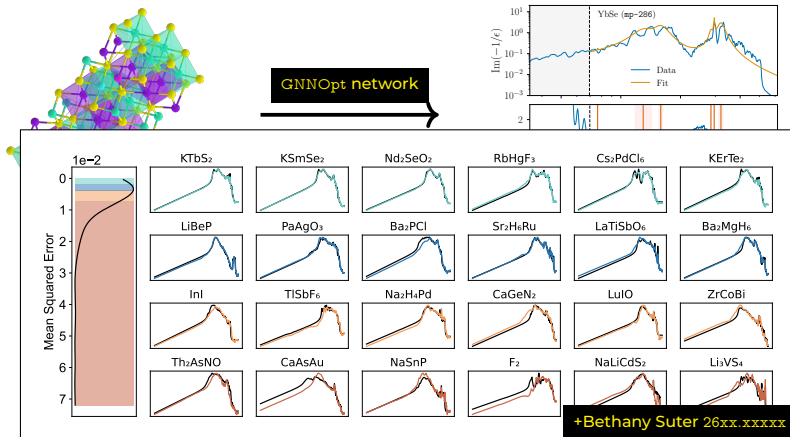
GNNOpt network

Hung+ 2406.16654



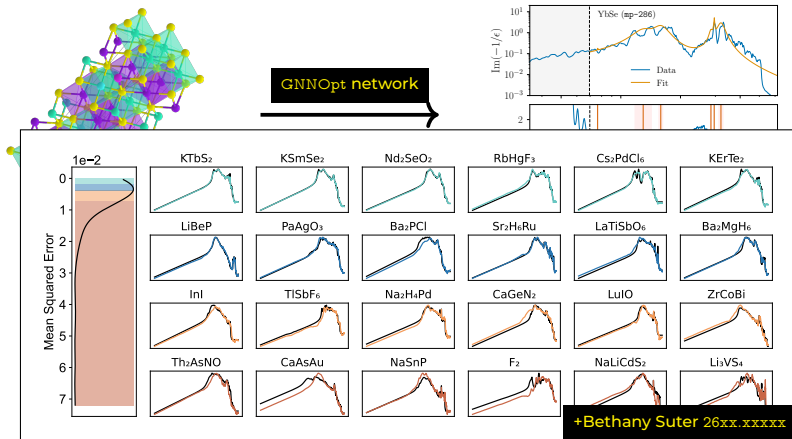
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Broadening with machine learning

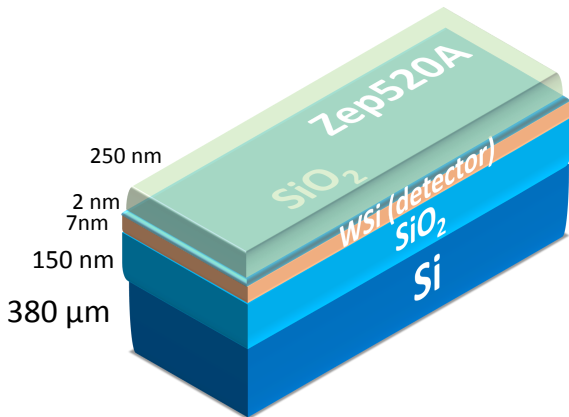
Materials Project has $\epsilon(\hat{\mathbf{q}}, \omega)$ for 10^3 of 10^5 materials



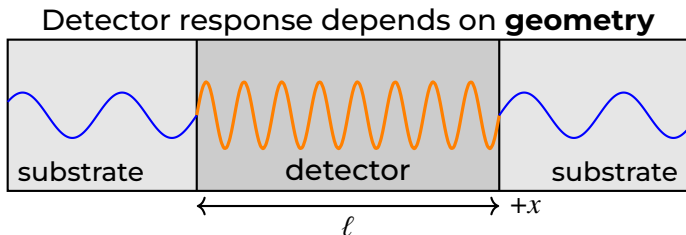
ML will rapidly expand results to entire MP database

Targets may not be bulk volumes

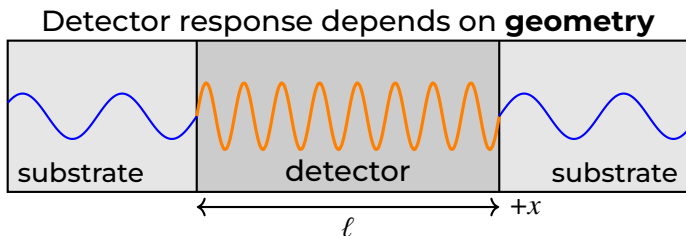
Targets may not be bulk volumes



DM scattering in a thin layer

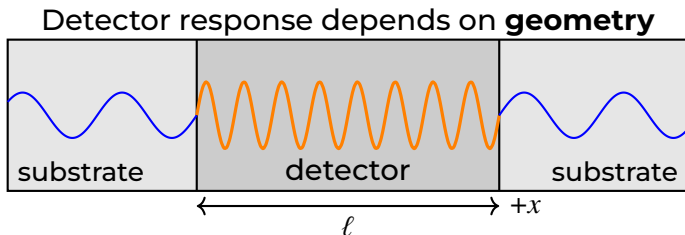


DM scattering in a thin layer



Study energy loss classically

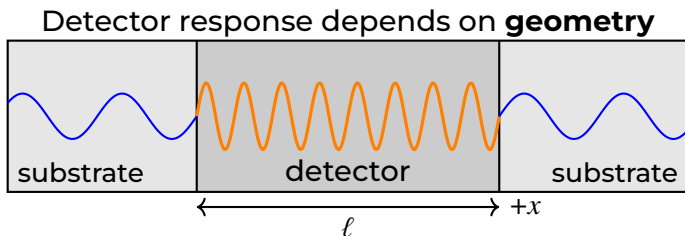
DM scattering in a thin layer



Study energy loss classically

$$\epsilon(x) \nabla^2 \phi(x) = \phi_0 e^{i(\mathbf{q} \cdot \mathbf{x} - \omega t)}$$

DM scattering in a thin layer

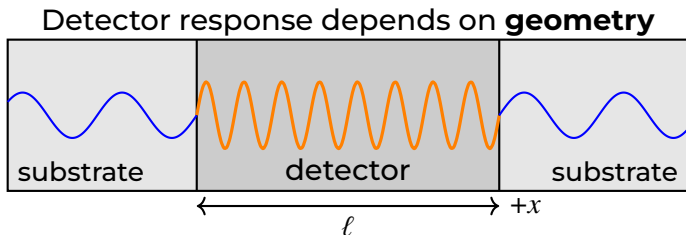


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Solve with BCs and compute average power dissipation

DM scattering in a thin layer



Study energy loss classically

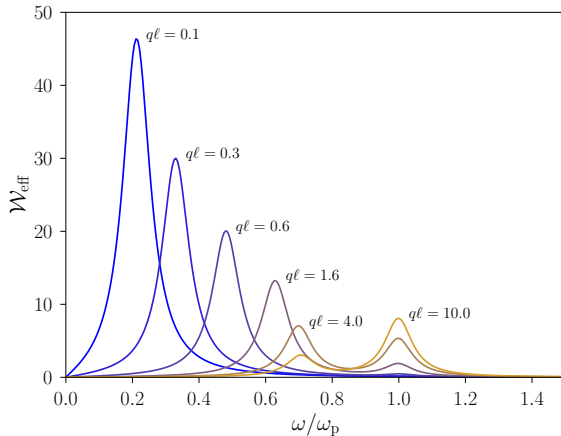
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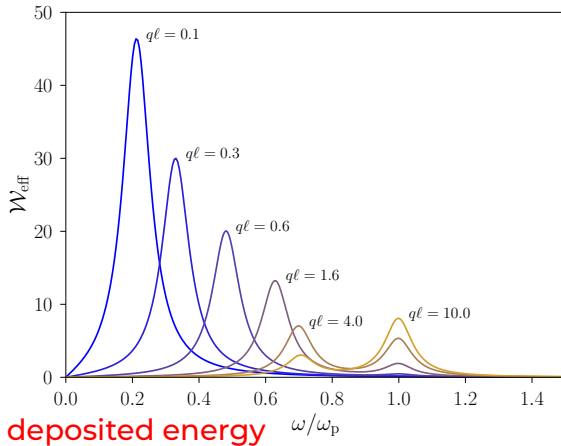
Effective loss function

$$\mathcal{W}_{\text{eff}} \equiv \frac{q^2}{\ell} \text{Re} \left[-i \frac{1}{\rho} \int dx e^{-i(\mathbf{q} \cdot \mathbf{x} - \omega t)} \left(\phi(x) - \frac{q_x}{q} i \phi(x) + \frac{q_x}{q^2} \phi'(x) \right) \right]$$

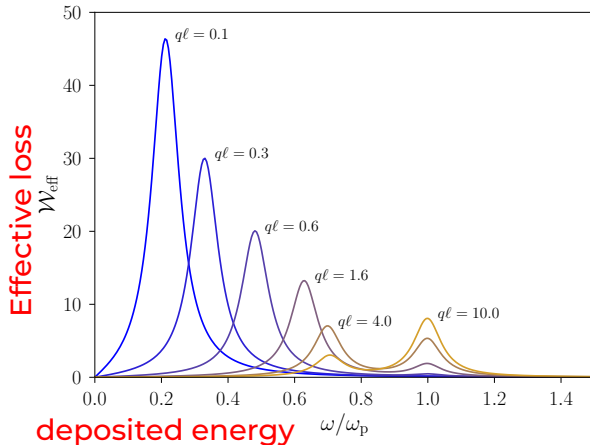
Thin-layer response function



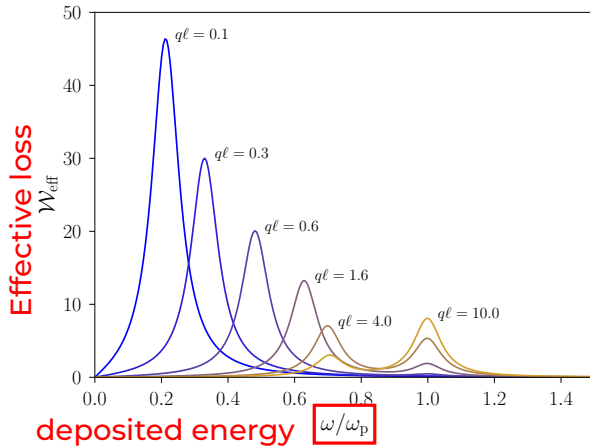
Thin-layer response function



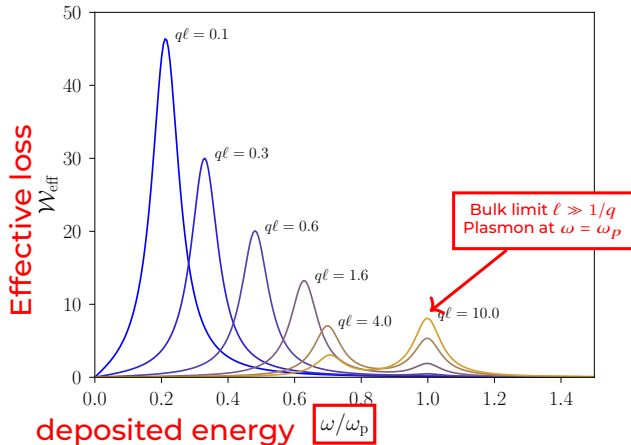
Thin-layer response function



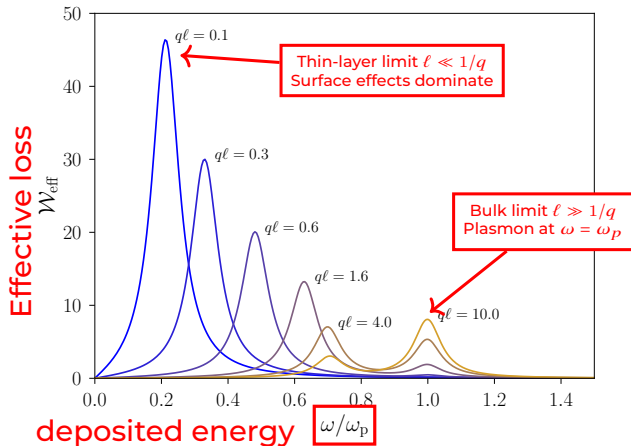
Thin-layer response function



Thin-layer response function



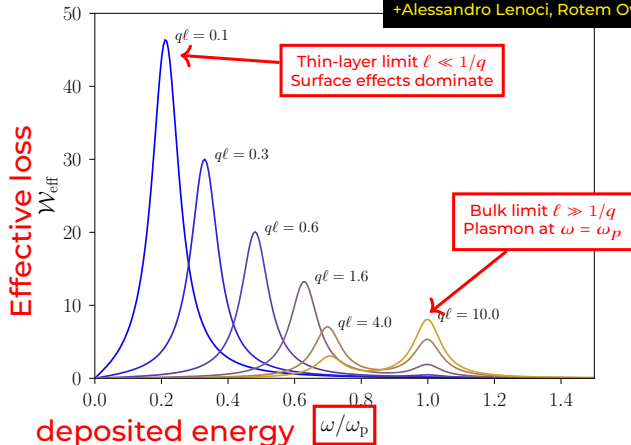
Thin-layer response function



Thin-layer response function

26yy.yyyy: targeted layering

+Alessandro Lenoci, Rotem Ovadia



Key points for detectors

Key points for detectors

- 1 Strong dielectric response for light DM

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- ① Strong dielectric response for light DM
- ② Geometric enhancement

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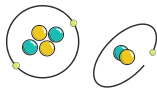
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Central idea of direct detection:
DM induces measurable transitions

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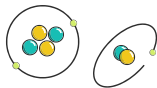


e.g. ionization for atomic targets

Key points for detectors

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Central idea of direct detection:
DM induces measurable transitions



e.g. ionization for atomic targets

But there are many other possibilities

[3/3] Real detectors

Yonit Hochberg, **BVL**, Ilya Charaev, Jeff Chiles,
Marco Colangelo, Sae Woo Nam & Karl Berggren
2110.01586, PRD

Yonit Hochberg, Eric David Kramer, Noah Kurinsky & **BVL**
2109.04473, PRD

Jiansong Gao, Yonit Hochberg, **BVL**, Sae Woo Nam,
Paul Szypryt, Michael R. Vissers & Tao Xu
2403.19739

Sinéad M. Griffin, Guy Daniel Hadas, Yonit Hochberg, Katherine Inzani, **BVL**
2412.16283, PRL

Laura Baudis & **BVL**+ (QROCODILE Collaboration)
2412.16279, PRL

Superconductors as detectors

“Cooper-pair breaking”

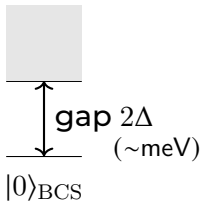
Superconductors as detectors

“Cooper-pair breaking”

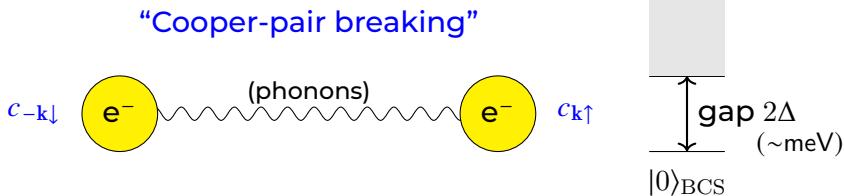


Superconductors as detectors

“Cooper-pair breaking”

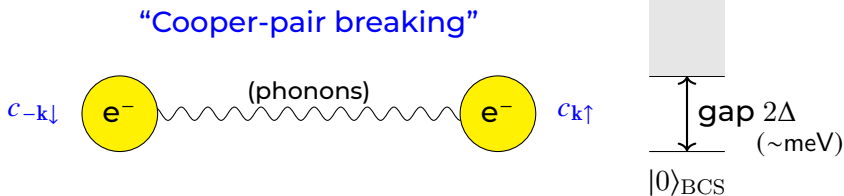


Superconductors as detectors



Vacuum $|0_{\text{BCS}}\rangle$ has **CP condensate**: $\langle c_{-k\downarrow} c_{k\uparrow} \rangle \neq 0$.

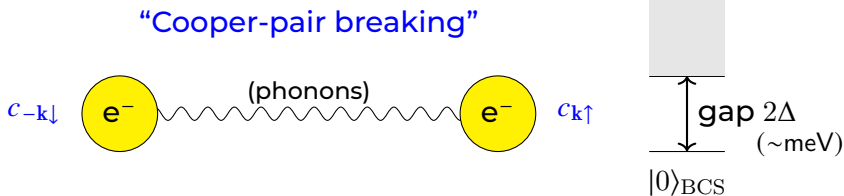
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Superconductors as detectors



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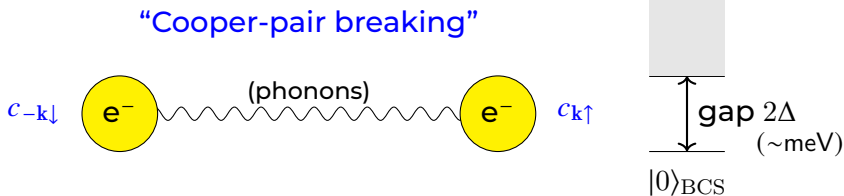
Diagonalize

$\mathcal{H}$

with

$$\begin{cases} c_{\mathbf{k}\uparrow} = u_{\mathbf{k}}^* \gamma_{\mathbf{k}0} + v_{\mathbf{k}} \gamma_{\mathbf{k}1} \\ c_{-\mathbf{k}\downarrow}^* = -v_{\mathbf{k}}^* \gamma_{\mathbf{k}0} + u_{\mathbf{k}} \gamma_{\mathbf{k}1}^* \end{cases}$$

Superconductors as detectors



Vacuum $|0_{\text{BCS}}\rangle$ has **CP condensate**: $\langle c_{-k\downarrow} c_{k\uparrow} \rangle \neq 0$.

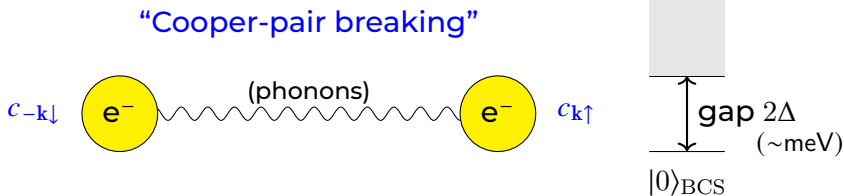
$$\mathcal{H} = \sum_{\mathbf{k}\sigma} \xi_{\mathbf{k}} c_{\mathbf{k}\sigma}^* c_{\mathbf{k}\sigma} + \sum_{\mathbf{k}\ell} V_{\mathbf{k}\ell} \left(c_{\mathbf{k}\uparrow}^* c_{-\mathbf{k}\downarrow}^* b_{\ell} + b_{\mathbf{k}}^* c_{-\ell\downarrow} c_{\ell\uparrow} - b_{\mathbf{k}}^* b_{\ell} \right)$$

Diagonalize $\mathcal{H}$ with

$$\begin{cases} c_{\mathbf{k}\uparrow} = u_{\mathbf{k}}^* \gamma_{\mathbf{k}0} + v_{\mathbf{k}} \gamma_{\mathbf{k}1} \\ c_{-\mathbf{k}\downarrow}^* = -v_{\mathbf{k}}^* \gamma_{\mathbf{k}0} + u_{\mathbf{k}} \gamma_{\mathbf{k}1}^* \end{cases}$$

Bogoliubov quasiparticles

Superconductors as detectors



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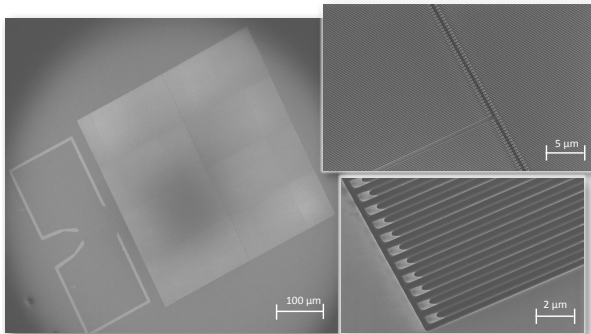
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Bogoliubov quasiparticles

$$|\chi\rangle |0_{\text{BCS}}\rangle \longrightarrow |\chi\rangle |\text{QP}_1, \text{QP}_2\rangle$$

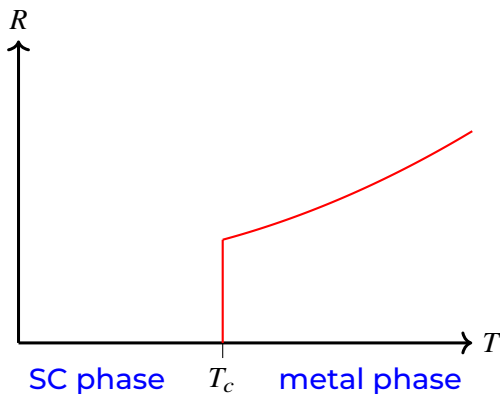
Real detectors: SNSPDs

Superconducting Nanowire Single-Photon Detector



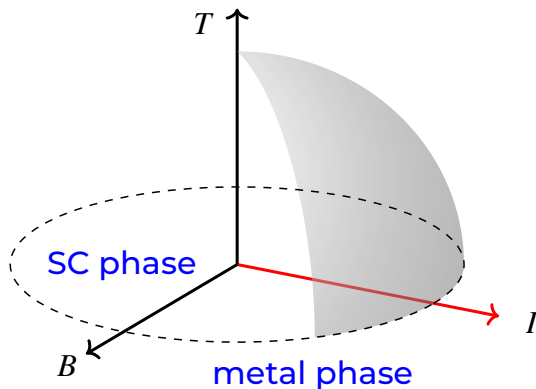
Real detectors: SNSPDs

Superconducting Nanowire Single-Photon Detector



Real detectors: SNSPDs

Superconducting Nanowire Single-Photon Detector



Superconducting wire **current-biased** near transition

The QROCODILE experiment

Quantum Resolution-Optimized Cryogenic Observatory for Dark matter Incident at Low Energy

Next-generation SNSPD demonstrator (11 μm threshold)

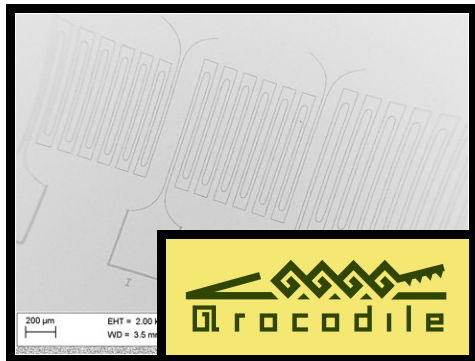
[Laura Baudis, Ilya Charaev, BVL, +]

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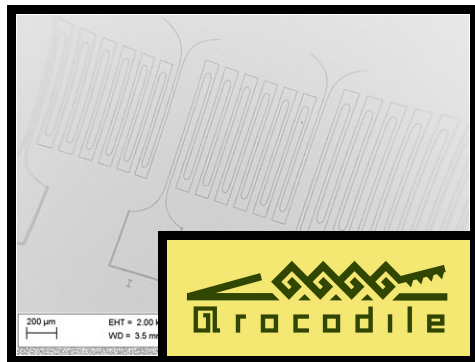


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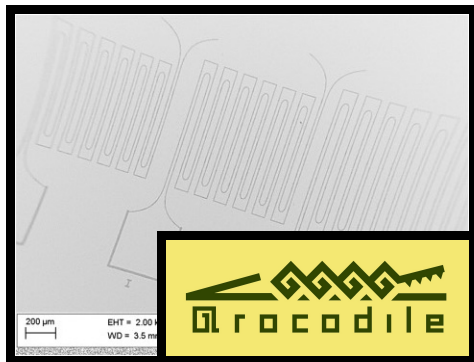
Prototype-scale, 720 μm^3

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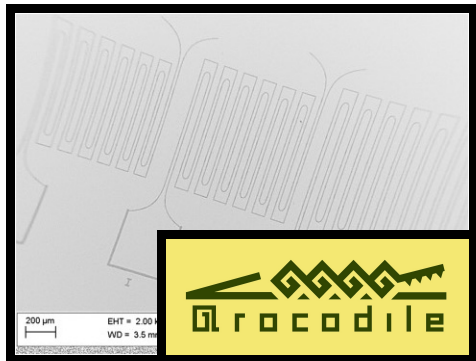
Prototype-scale, 720 μm^3
415 hours with 15 counts

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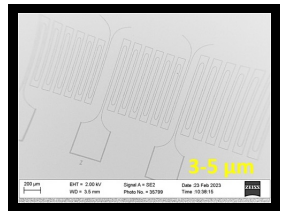


Prototype-scale, 720 μm^3

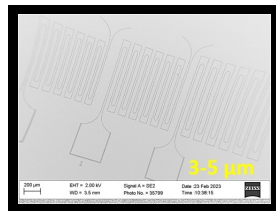
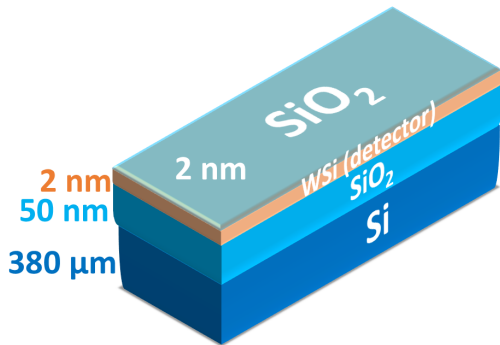
415 hours with 15 counts

World-leading limits

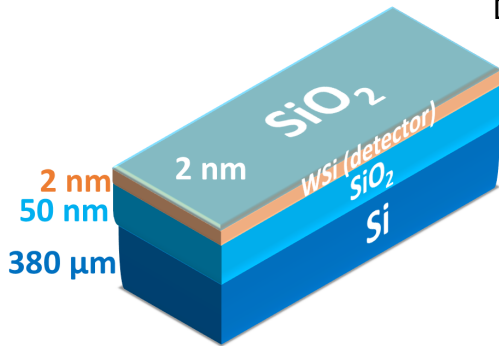
QROCODILE nanowire structure



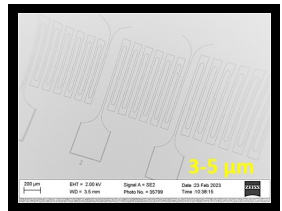
QROCODILE nanowire structure



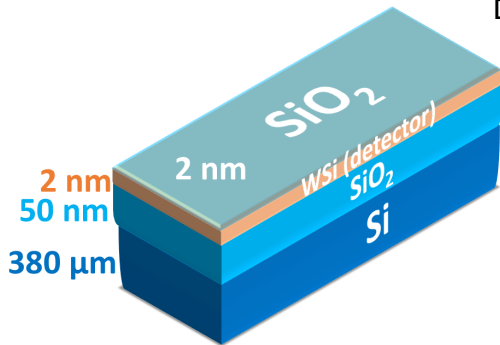
QROCODILE nanowire structure



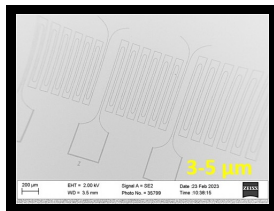
Detector depth $\ell = 2 \text{ nm}$



QROCODILE nanowire structure

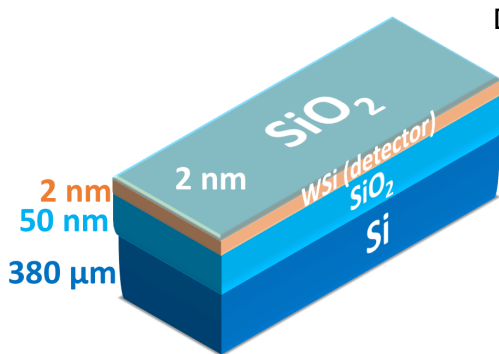


Detector depth $\ell = 2 \text{ nm}$

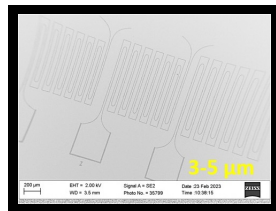


Geometric corrections for $q \lesssim O(\text{few}) \times \ell \approx 1 \text{ keV}$

QROCODILE nanowire structure



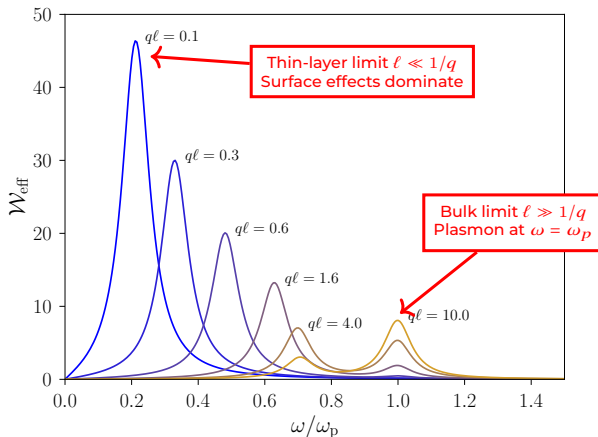
Detector depth $\ell = 2 \text{ nm}$



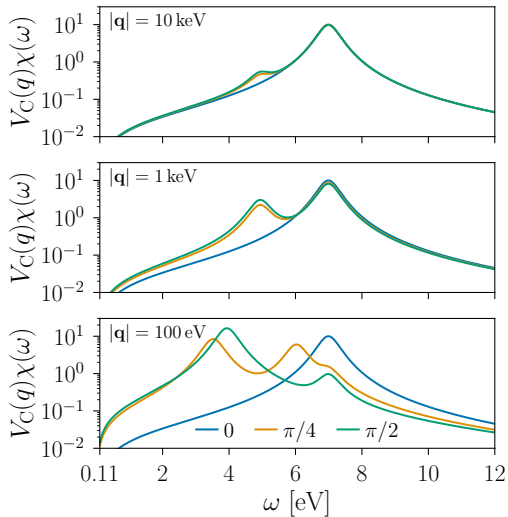
Geometric corrections for $q \lesssim O(\text{few}) \times \ell \approx 1 \text{ keV}$

Nontrivial effect for $m_{\text{DM}} \lesssim 1 \text{ MeV}$

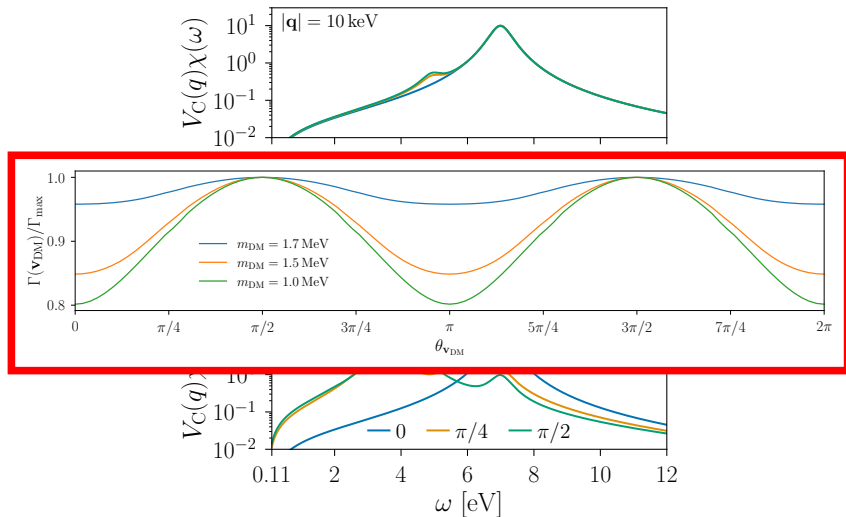
Anisotropy from geometry



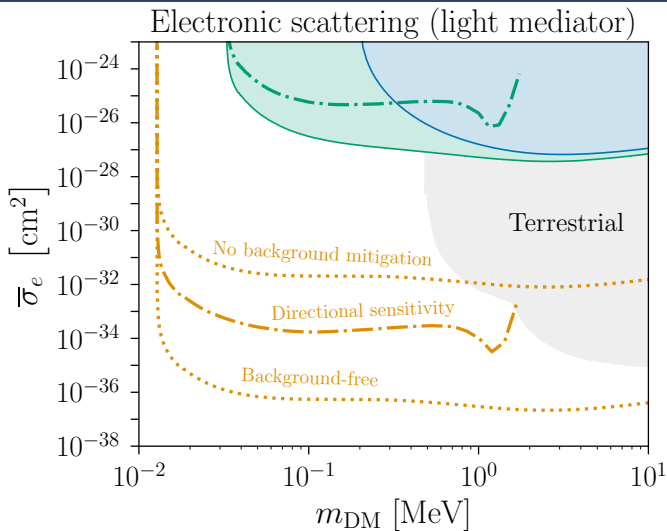
Anisotropy from geometry



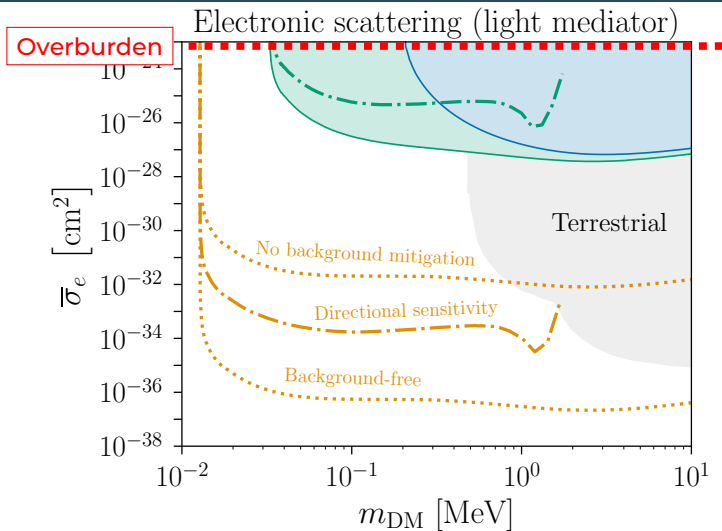
Anisotropy from geometry



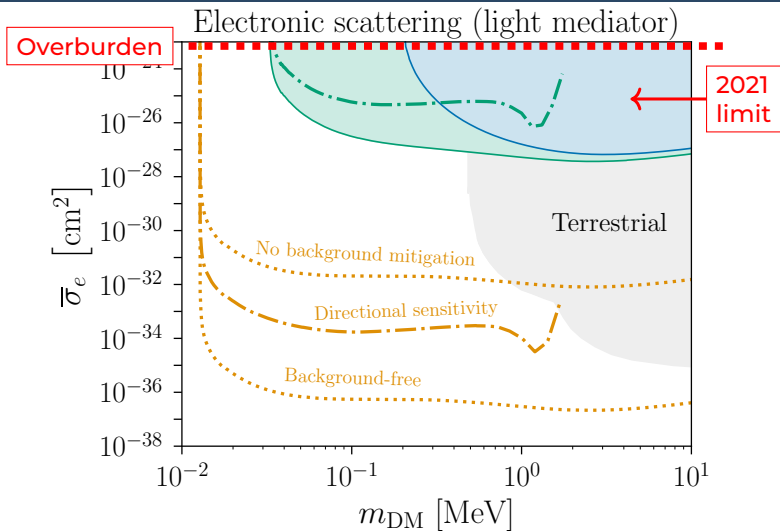
QROCODILE constraints



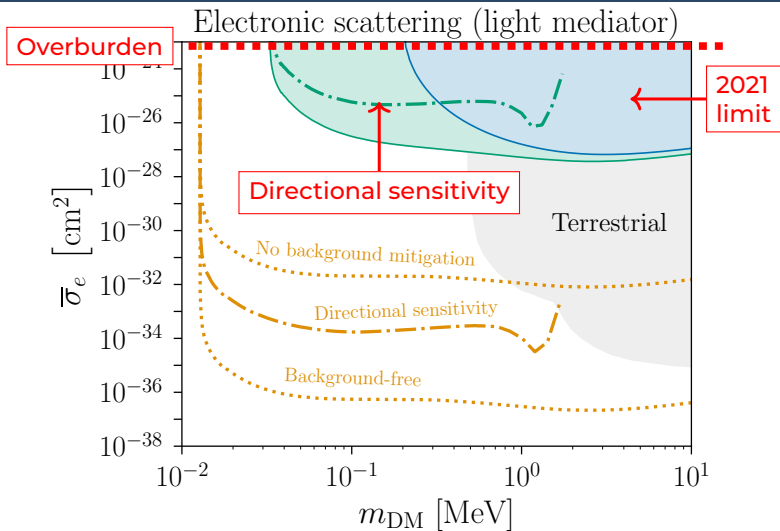
QROCODILE constraints



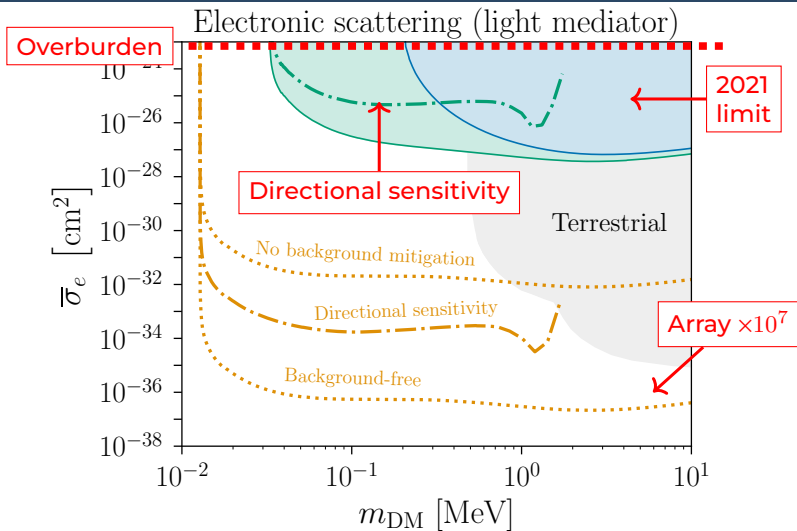
QROCODILE constraints



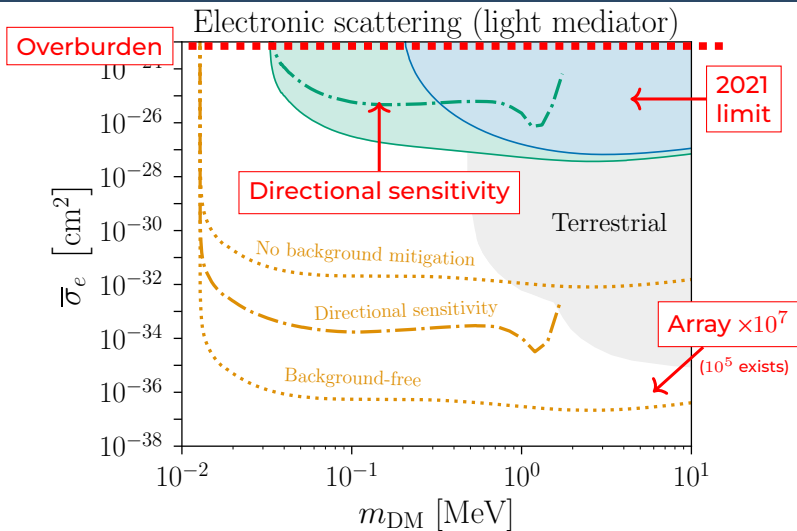
QROCODILE constraints



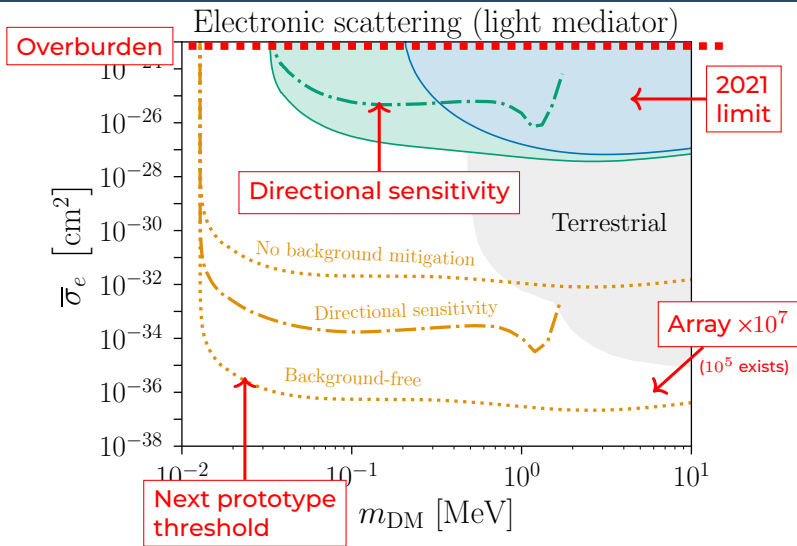
QROCODILE constraints



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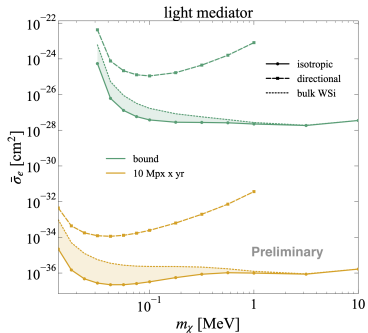


QROCODILE constraints

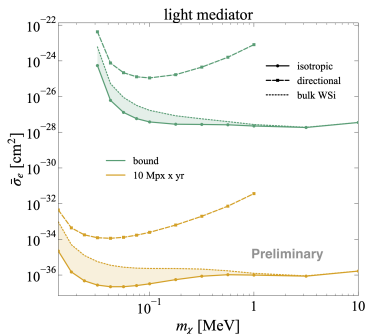


The heterostructure viewpoint

The heterostructure viewpoint

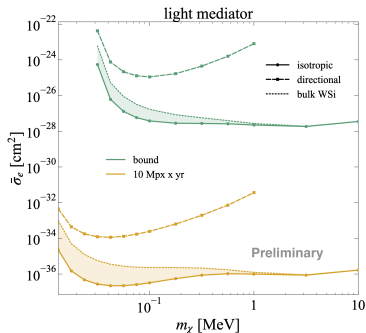


The heterostructure viewpoint



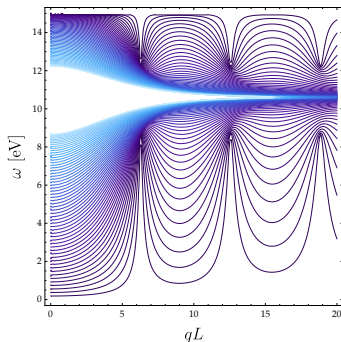
QROCODILE gains ~ 2 dex!

The heterostructure viewpoint



QROCODILE gains ~ 2 dex!

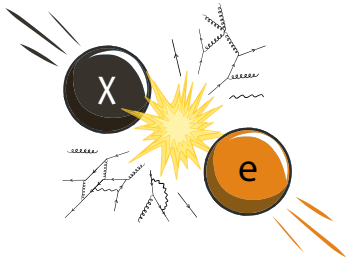
Al-vacuum stack



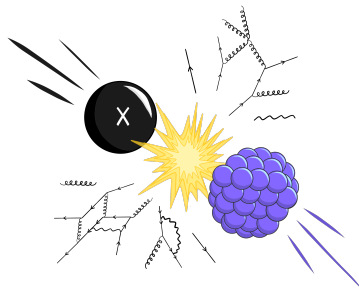
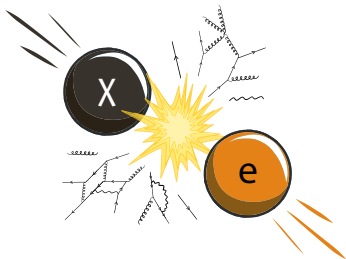
Plasmons by angle

And one more thing...

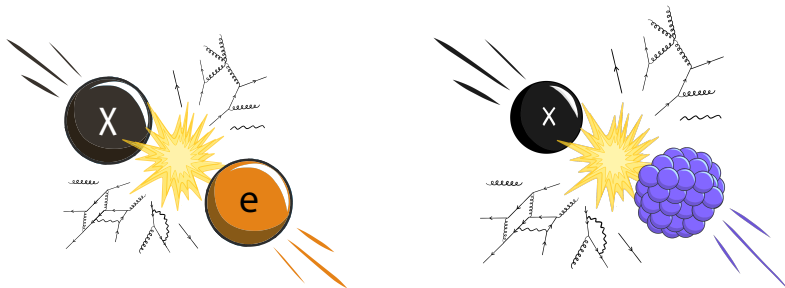
And one more thing...



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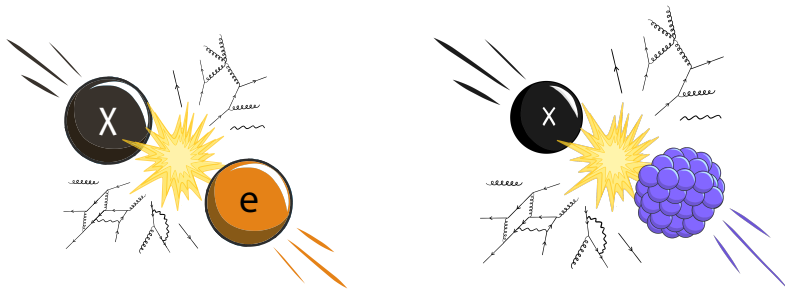


And one more thing...



Nuclear scattering?

And one more thing...



Nuclear scattering?

Superconducting detectors probe this as well

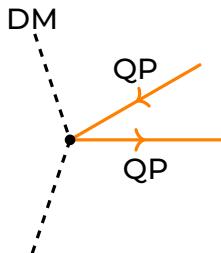
Down-conversion

What does the final state look like?

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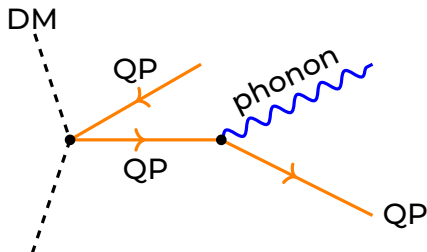
- 1 DM scattering produces a QP pair



Down-conversion

What does the final state look like?

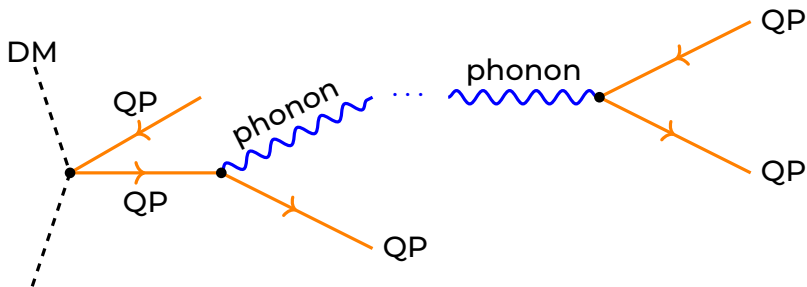
- 1 DM scattering produces a QP pair
- 2 Energetic QPs relax by emission of phonons



Down-conversion

What does the final state look like?

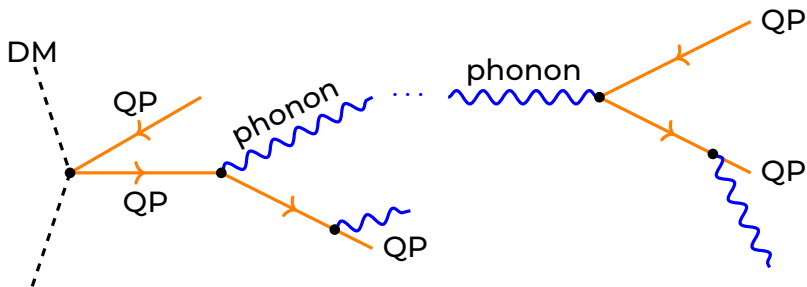
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Down-conversion

What does the final state look like?

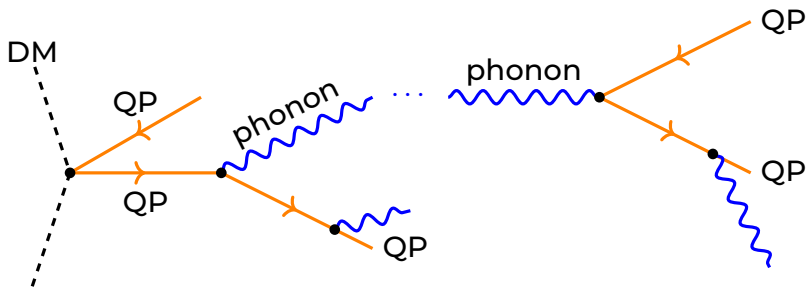
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Down-conversion

What does the final state look like?

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Final state is insensitive to initial excitation

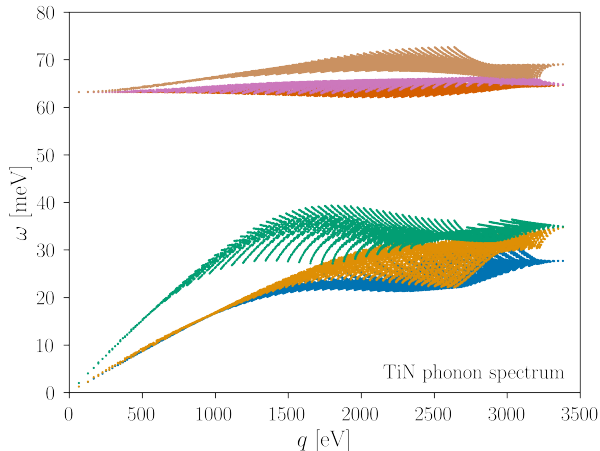
Phonon excitation rate

Phonon excitation rate

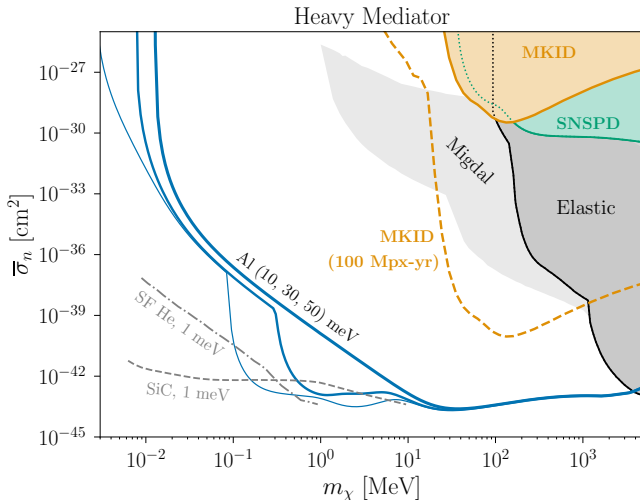
$$S(\mathbf{q}, \omega) = \frac{\pi}{\Omega} \sum_{\nu} \frac{\delta(\omega - \omega_{\nu, \mathbf{k}})}{\omega_{\nu, \mathbf{k}}} \left| \sum_j \frac{e^{-W_j(\mathbf{q})}}{\sqrt{m_j}} e^{i\mathbf{G} \cdot \mathbf{x}_j^0} \times \left(\frac{f_{N_j}}{f_n} \right) F_{N_j}(\mathbf{q}) \mathbf{q} \cdot \boldsymbol{\epsilon}_{\nu, \mathbf{k}, j}^* \right|^2$$

Phonon excitation rate

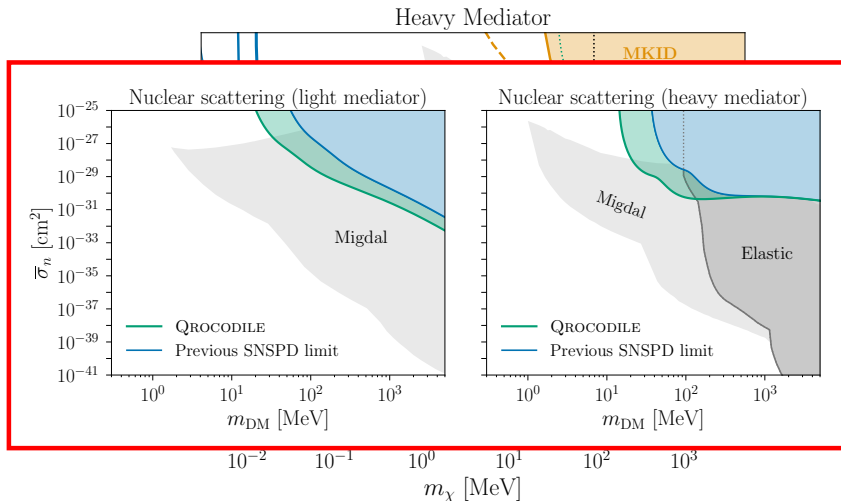
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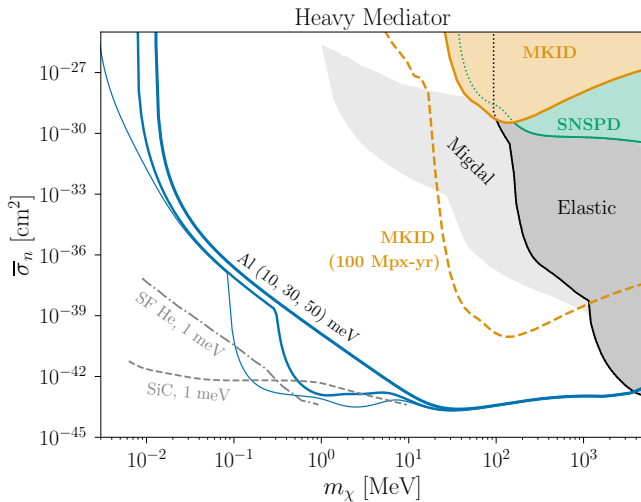
Constraints on nuclear scattering



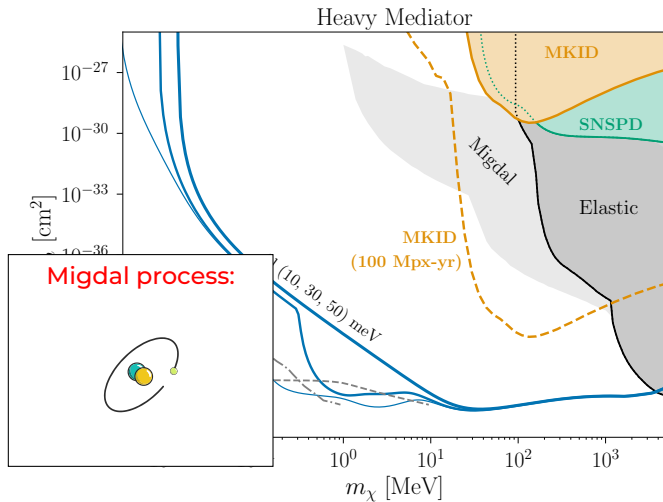
Constraints on nuclear scattering



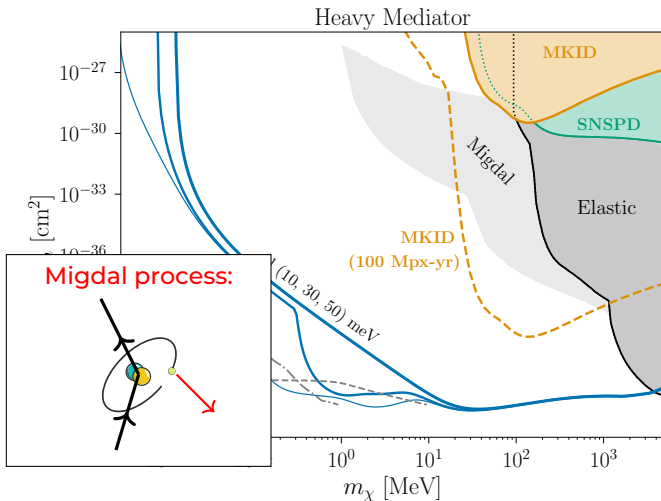
The Migdal effect



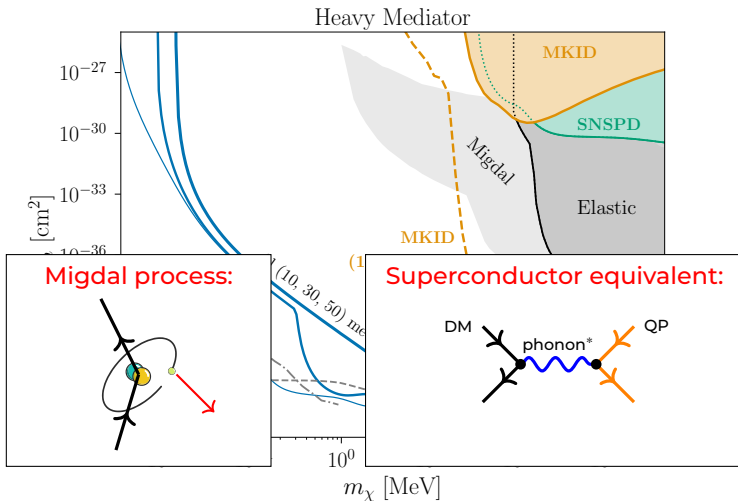
The Migdal effect



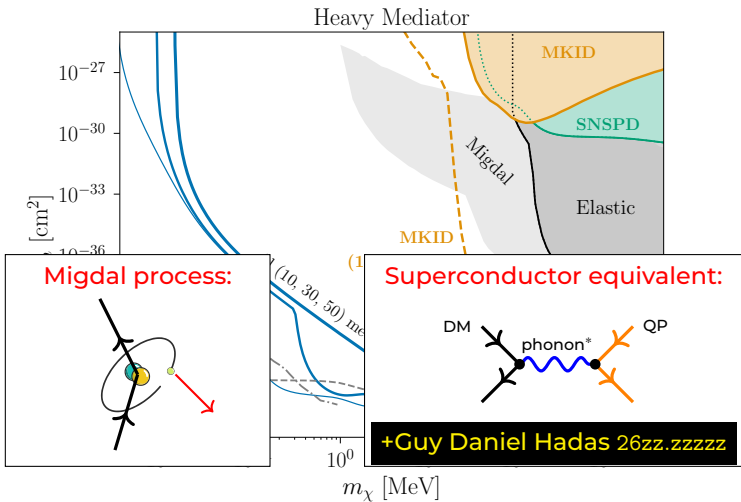
The Migdal effect



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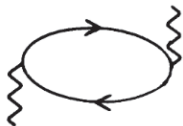


The Migdal effect



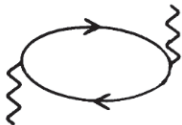
New approaches to broaden light DM detection

New approaches to broaden light DM detection

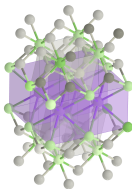


Dark matter in
condensed matter

New approaches to broaden light DM detection

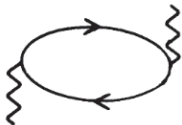


Dark matter in
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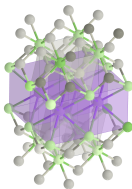


Data-driven
detector design

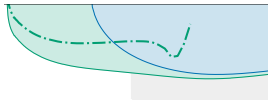
New approaches to broaden light DM detection



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Data-driven
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Real experiments

- R. Agnese et al. First Dark Matter Constraints from a SuperCDMS Single-Charge Sensitive Detector. *Phys. Rev. Lett.*, 121(5):051301, 2018. doi: 10.1103/PhysRevLett.121.051301. [Erratum: *Phys.Rev.Lett.* 122, 069901 (2019)].
- 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. Bernabei et al. Final model independent result of DAMA/LIBRA-phase1. *Eur. Phys. J. C*, 73:2648, 2013. doi: 10.1140/epjc/s10052-013-2648-7.
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- 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.