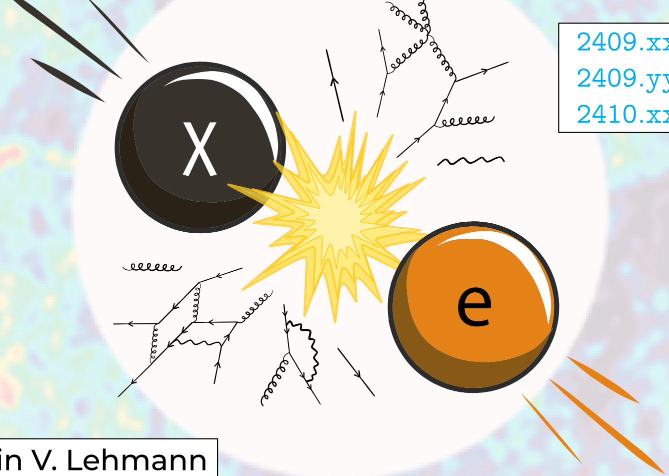
# Broadening direct searches for light dark matter

2409.xxxxx
2409.yyyyy
2410.xxxxx

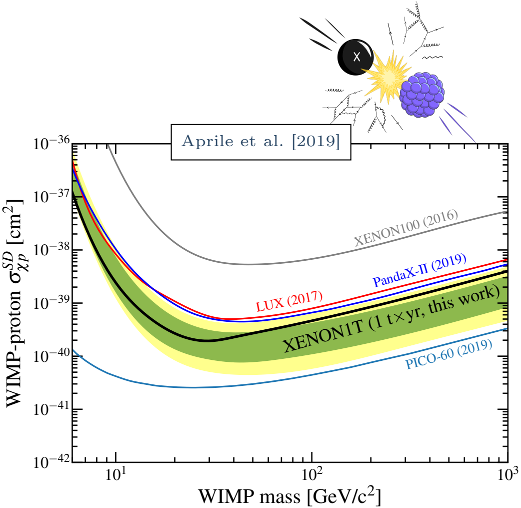




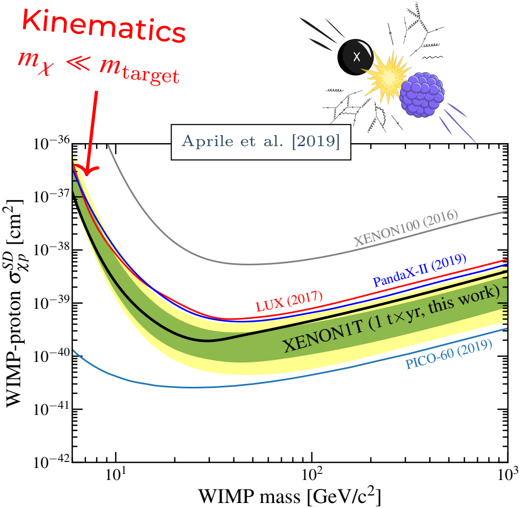
Benjamin V. Lehmann

Massachusetts Institute of Technology

# 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 $\sigma_{\chi p}^{SD}$ [cm$^2$]
WIMP mass [GeV/c$^2$]
$10^{-36}$
$10^{-37}$
$10^{-38}$
$10^{-39}$
$10^{-40}$
$10^{-41}$
$10^{-42}$
$10^{1}$
$10^{2}$
$10^{3}$


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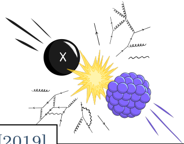

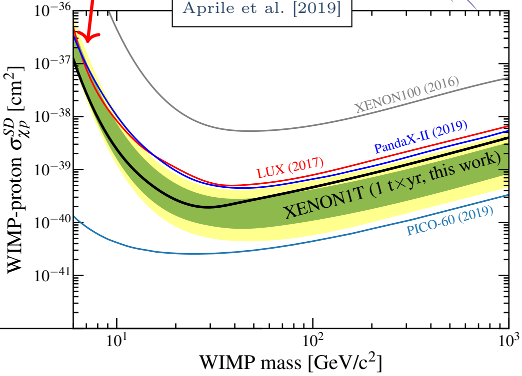

**Kinematics**

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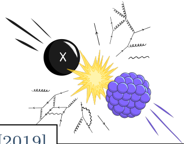
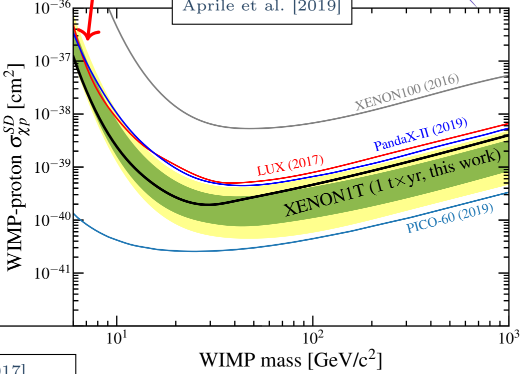


Aprile et al. [2019]




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

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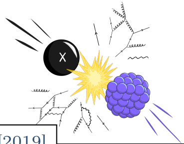

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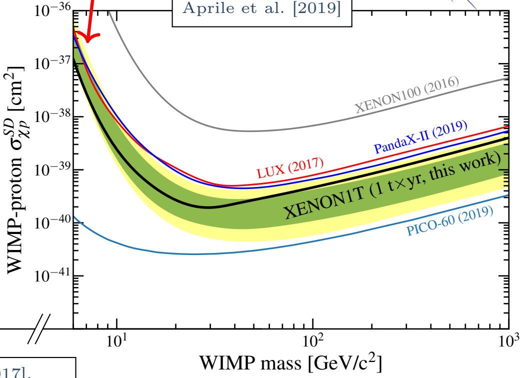
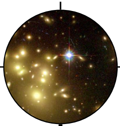



Structure limits



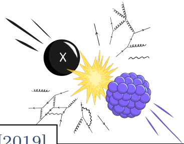
keV

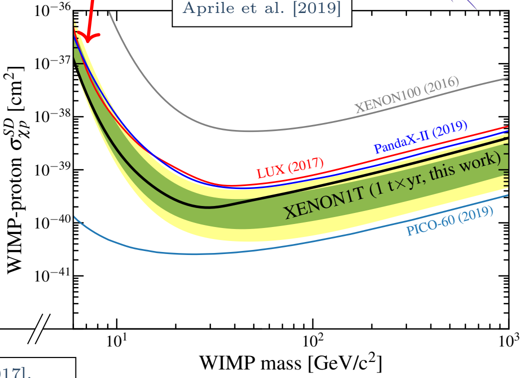
Knapen et al. [2017], Caputo et al. [2019], etc.

# Sub-GeV DM

Kinematics

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





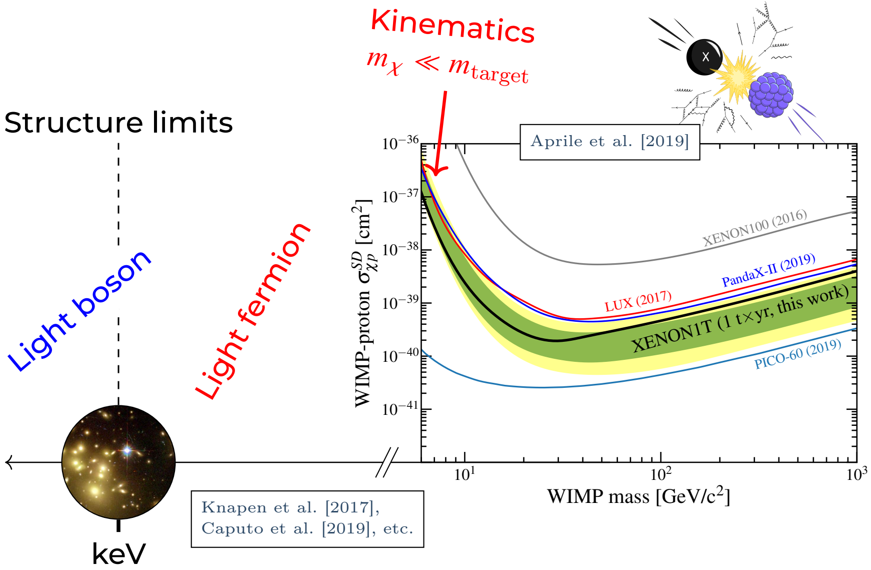

Structure limits

Light fermion

keV

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

# Sub-GeV DM


Kinematics
$m_\chi \ll m_{\rm target}$
Structure limits
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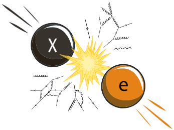
Electron recoils




Kinematics

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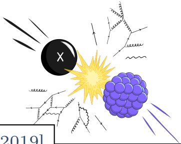


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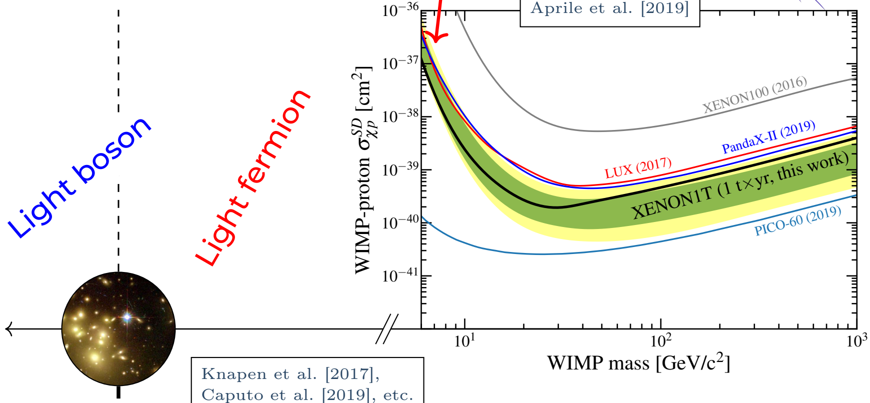
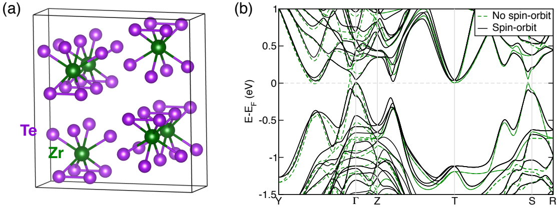



Knapen et al. [2017], Caputo et al. [2019], etc.

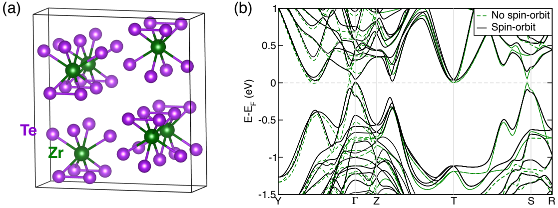
# The collective regime




Hochberg et al. [2018]

**DM does not interact with just one electron.**

# The collective regime




Hochberg et al. [2018]

**DM does not interact with just one electron.**

Response described by complex dielectric function,

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

$\mathbf{q}$ = momentum transfer
$\omega$ = deposited energy

# DM scattering rate

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

 Hochberg+ & **BVL** 2101.08263; Boyd+ & **BVL** 2212.04505

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❶ Predictable: $\epsilon$ admits analytical approximations



Hochberg+ & **BVL** 2101.08263; Boyd+ & **BVL** 2212.04505

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2. Empirical: $\epsilon$ is directly measurable / computable

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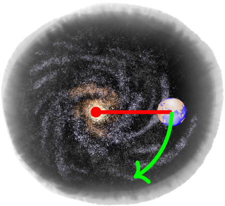
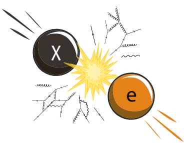
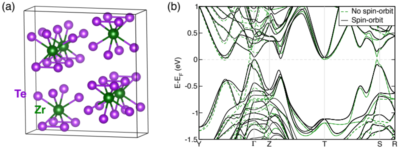


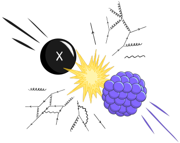
[DM wind detection]

 Hochberg+ & **BVL** 2101.08263; Boyd+ & **BVL** 2212.04505

# This talk in one slide



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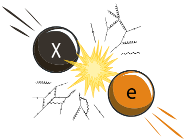
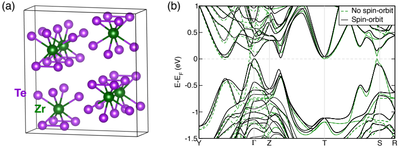
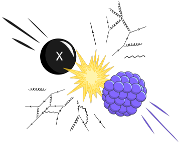


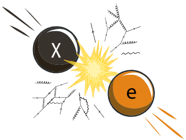



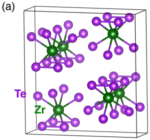



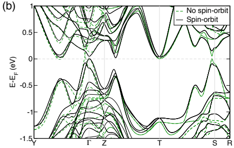

## 1. Data-driven detector design

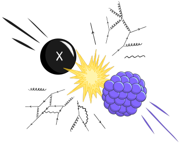
Materials physics for sensitive experiments

# This talk in one slide



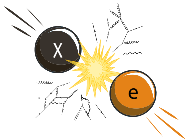

## 1. Data-driven detector design

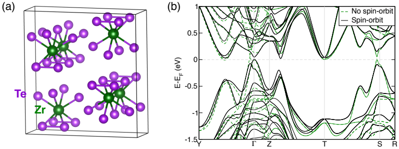
Materials physics for sensitive experiments

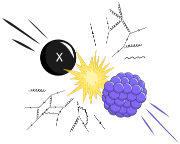
## 2. Leveraging detector geometry

Thin-layer enhancement in a real detector

# This talk in one slide




## 1. Data-driven detector design

Materials physics for sensitive experiments

## 2. Leveraging detector geometry

Thin-layer enhancement in a real detector

## 3. Recovering nuclear recoils

Electron recoil detectors do double-duty

# [1/3] Data-driven material selection

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

2409.xxxxx

# Super-broad material exploration

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

❷ Empirical: $\epsilon$ is directly measurable / computable


Jain+ 2013

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


Jain+ 2013

# Recovering $\epsilon(q > 0)$

*Materials Project* only computes $\overleftrightarrow{\epsilon}\Big|_{\mathbf{q}=0}$

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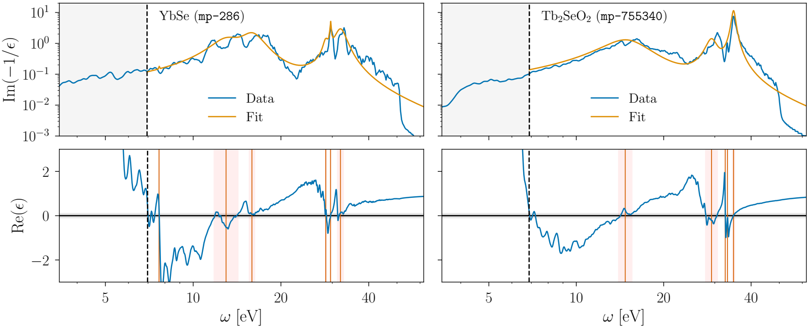
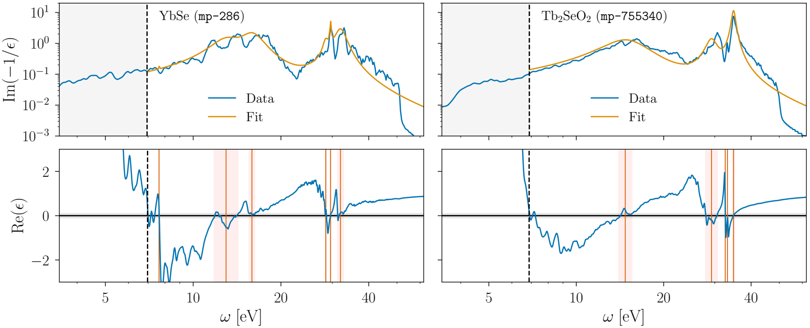
*Materials Project* only computes $\overleftrightarrow{\epsilon}\big|_{\mathbf{q}=0}$




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

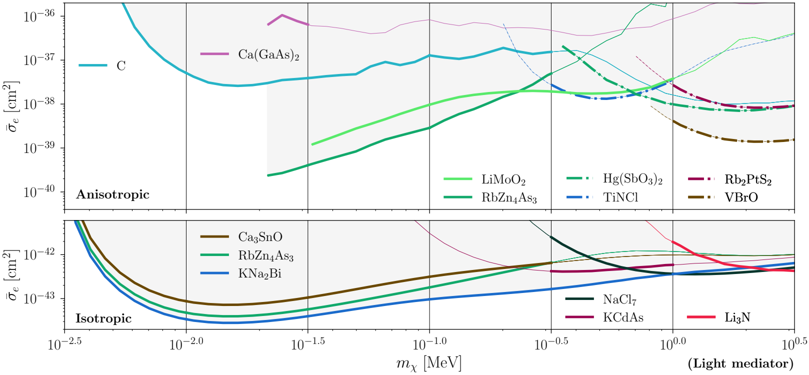
*Materials Project* only computes $\overleftrightarrow{\epsilon}\big|_{\mathbf{q}=0}$




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

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

## Three most sensitive materials per half-decade

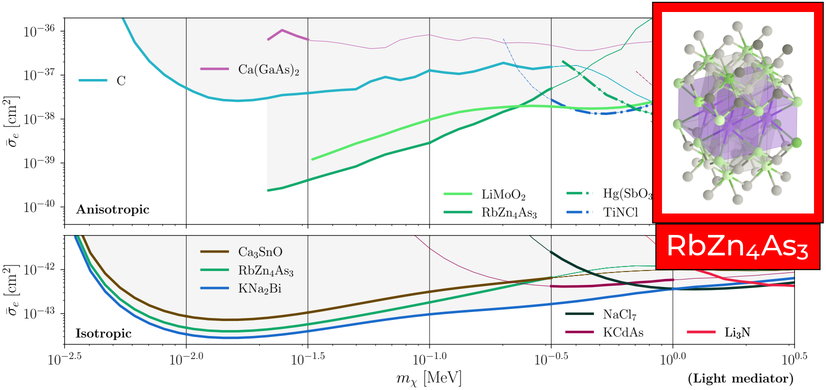




Griffin+ & **BVL** 2409.xxxxx

# Scattering sensitivity

Three most sensitive materials per half-decade




 Griffin+ & **BVL** 2409.xxxxx

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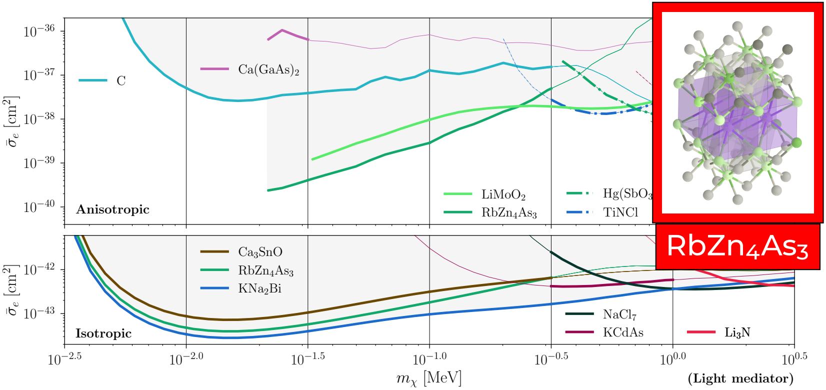



**Now evaluating** these new materials for use


Griffin+ & **BVL** 2409.xxxxx

# [2/3] Extra sensitivity from detector geometry

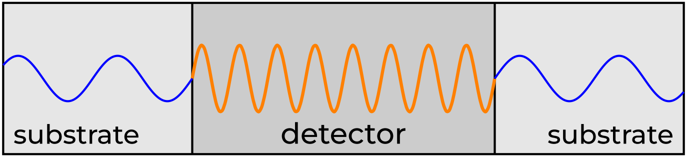
Laura Baudis, Alexander Bismark, Noah Brugger, Chiara Capelli,
Ilya Charaev, Jose Cuenca, Guy Daniel Hadas, Yonit Hochberg,
Benjamin Kilminster, **BVL,** Severin Nägeli, Titus Neupert,
Bjoern Penning, Diego Ramirez, Andreas Schilling
(QROCODILE collaboration)

2410.xxxxx

(See also: Lasenby & Prabhu 2110.01587, Hochberg+ & **BVL** 2110.01586)

# DM scattering in a thin layer

Detector response depends on **geometry**




 Lasenby & Prabhu 2110.01587; Hochberg+ & **BVL** 2110.01586

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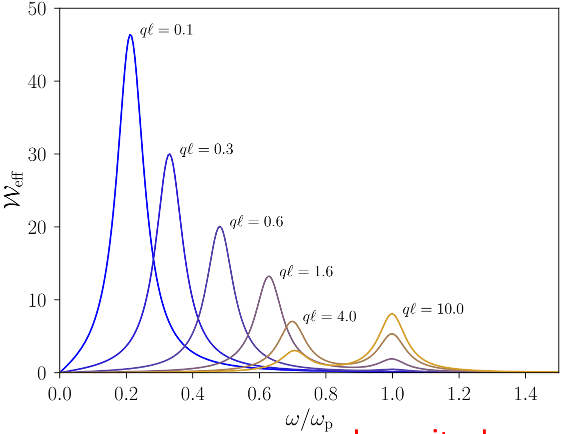


deposited energy

 Lasenby & Prabhu 2110.01587; Hochberg+ & **BVL** 2110.01586

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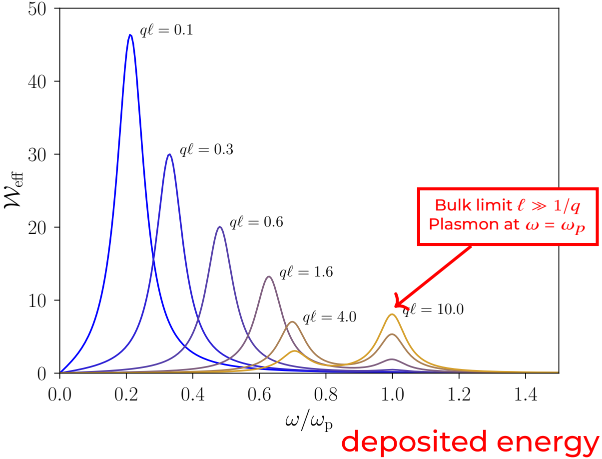


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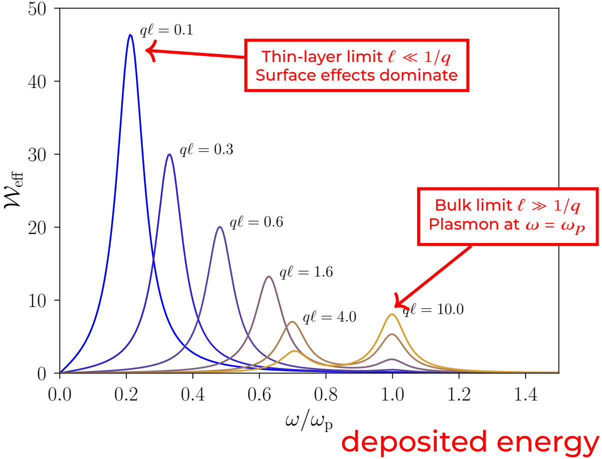



Lasenby & Prabhu 2110.01587; Hochberg+ & **BVL** 2110.01586

# Real detectors: SNSPDs


Hochberg+ & **BVL** 2110.01586

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**S**uperconducting **N**anowire **S**ingle-**P**hoton **D**etector

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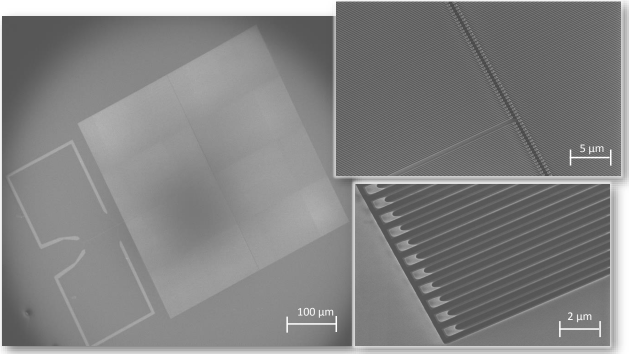


Thin-layer geometry

# The QROCODILE experiment

**Q**uantum **R**esolution-**O**ptimized **C**ryogenic **O**bservatory for **D**ark matter **I**ncident at **L**ow **E**nergy

Next-generation SNSPD demonstrator ($11\,\mu\mathrm{m}$ threshold)

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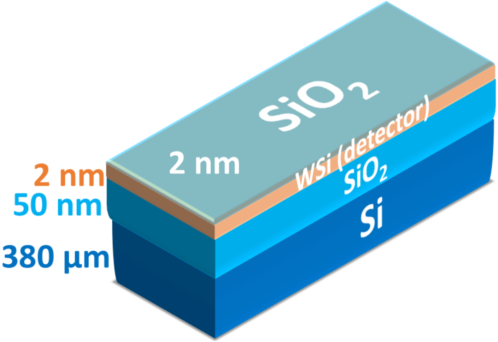


[Laura Baudis, Ilya Charaev, +]

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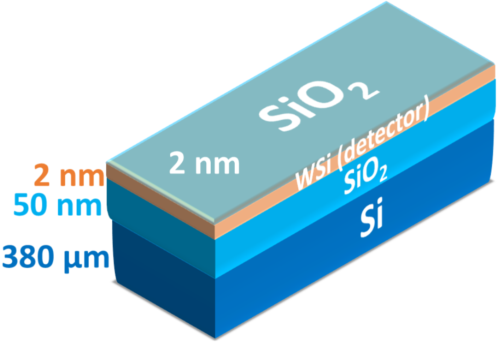
Next-generation SNSPD demonstrator ($11\,\mu$m threshold)

Geometry matters for $q \lesssim 1/(2\,\text{nm}) \approx 100\,\text{eV}$




[Laura Baudis, Ilya Charaev, +]

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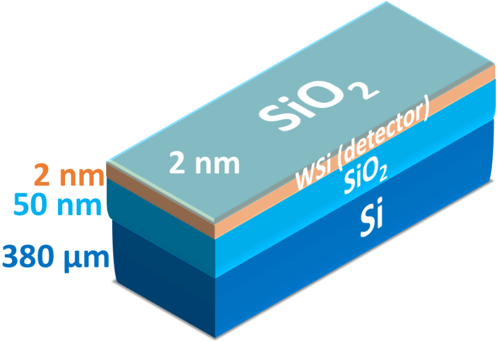
**Q**uantum **R**esolution-**O**ptimized **C**ryogenic **O**bservatory for **D**ark matter **I**ncident at **L**ow **E**nergy

Next-generation SNSPD demonstrator ($11\,\mu$m threshold)

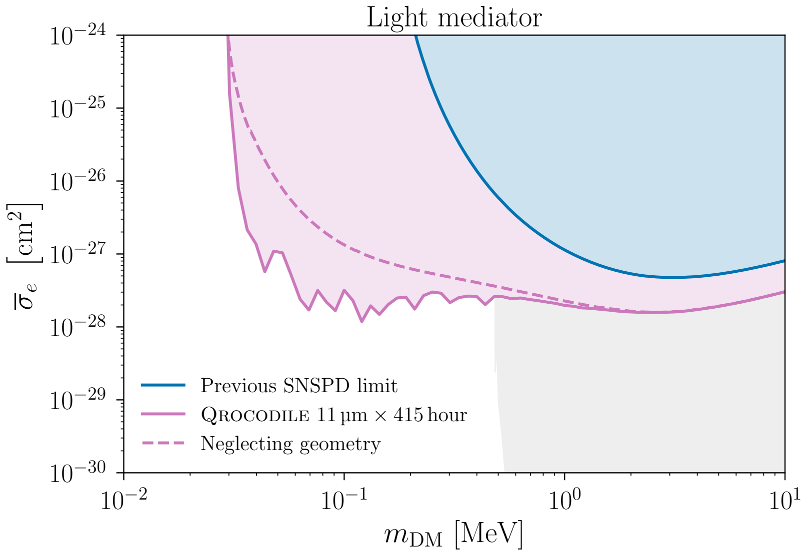
Geometry matters for $q \lesssim 1/(2\,\text{nm}) \approx 100\,\text{eV}$

$\implies$ nontrivial effect for $m_{\text{DM}} \lesssim 100\,\text{keV}$




[Laura Baudis, Ilya Charaev, +]

# Geometric enhancement



# [3/3] *Nuclear* recoils in electronic detectors

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

2409.xxxxx

# Nature of the excitations

“Broken Cooper pairs”


Griffin+ & **BVL** 2409.xxxxx; Hochberg+ & **BVL** 2109.04473

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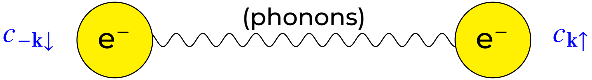
"Broken Cooper pairs"



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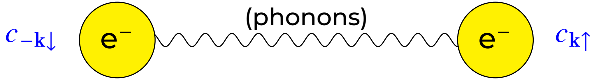


Below $T_C$, transition to superconducting vacuum $|0_{\text{BCS}}\rangle$, with a condensate of Cooper pairs: $\langle c_{-\mathbf{k}\downarrow} c_{\mathbf{k}\uparrow}\rangle \neq 0$.

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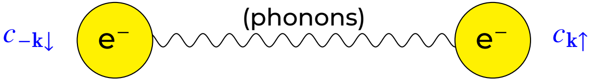


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$$\mathcal{H} = \sum_{\mathbf{k}\sigma} \xi_{\mathbf{k}} c^*_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{\mathbf{k}\boldsymbol{\ell}} V_{\mathbf{k}\boldsymbol{\ell}} \left( c^*_{\mathbf{k}\uparrow} c^*_{-\mathbf{k}\downarrow} b_{\boldsymbol{\ell}}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

 Griffin+ & **BVL** 2409.xxxxx; Hochberg+ & **BVL** 2109.04473

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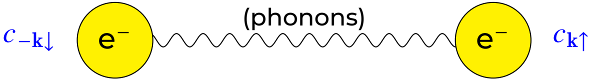


Below $T_C$, transition to superconducting vacuum $|0_{\rm BCS}\rangle$,
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$$\mathcal{H} = \sum_{\mathbf{k}\sigma} \xi_{\mathbf{k}} c^*_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{\mathbf{k}\boldsymbol{\ell}} V_{\mathbf{k}\boldsymbol{\ell}} \left( c^*_{\mathbf{k}\uparrow} c^*_{-\mathbf{k}\downarrow} b_{\boldsymbol{\ell}} + b^*_{\mathbf{k}} c_{-\boldsymbol{\ell}\downarrow} c_{\boldsymbol{\ell}\uparrow} - b^*_{\mathbf{k}} b_{\boldsymbol{\ell}} \right)$$

Diagonalize $\mathcal{H}$ with
$$\begin{cases} c_{\mathbf{k}\uparrow} = u^*_{\mathbf{k}} \gamma_{\mathbf{k}0} + v_{\mathbf{k}} \gamma_{\mathbf{k}1} \\ c^*_{-\mathbf{k}\downarrow} = -v^*_{\mathbf{k}} \gamma_{\mathbf{k}0} + u_{\mathbf{k}} \gamma^*_{\mathbf{k}1} \end{cases}$$


Griffin+ & **BVL** 2409.xxxxx; Hochberg+ & **BVL** 2109.04473

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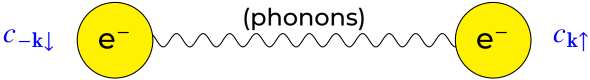


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Griffin+ & **BVL** 2409.xxxxx; Hochberg+ & **BVL** 2109.04473

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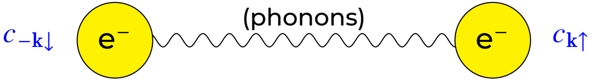


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*Bogoliubov quasiparticles*

"Electron recoils": $|\chi\rangle|0_{\mathrm{BCS}}\rangle \longrightarrow |\chi\rangle|\mathrm{QP}_1,\, \mathrm{QP}_2\rangle$

 Griffin+ & **BVL** 2409.xxxxx; Hochberg+ & **BVL** 2109.04473

# Down-conversion

**What does the final state look like?**


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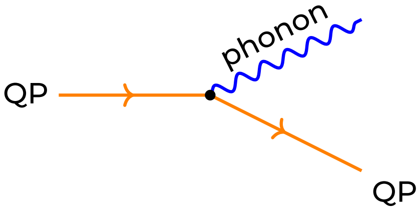
1. Energetic QPs relax by emission of phonons




 Griffin+ & **BVL** 2409.xxxxx; Hochberg+ & **BVL** 2109.04473

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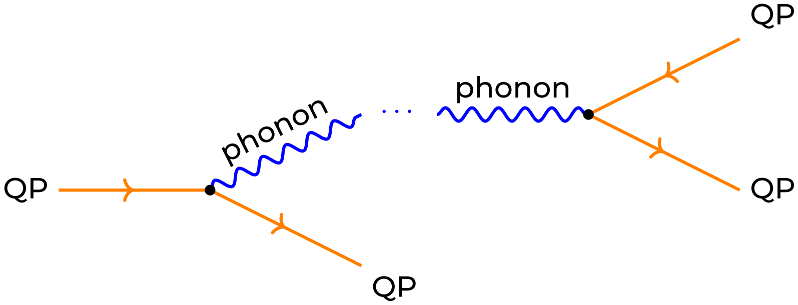
**What does the final state look like?**

1. Energetic QPs relax by emission of phonons
2. Energetic phonons relax by QP pair production



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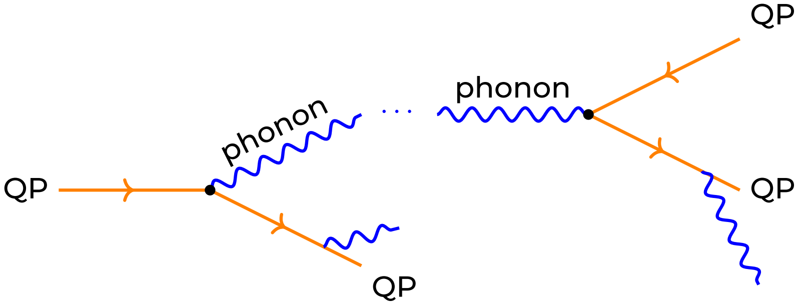


 Griffin+ & **BVL** 2409.xxxxx; Hochberg+ & **BVL** 2109.04473

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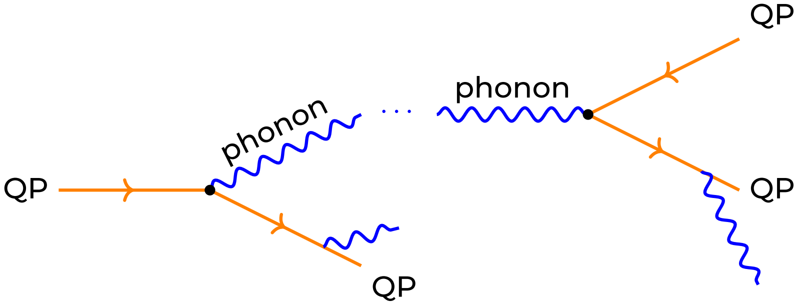


Final state is insensitive to initial excitation type

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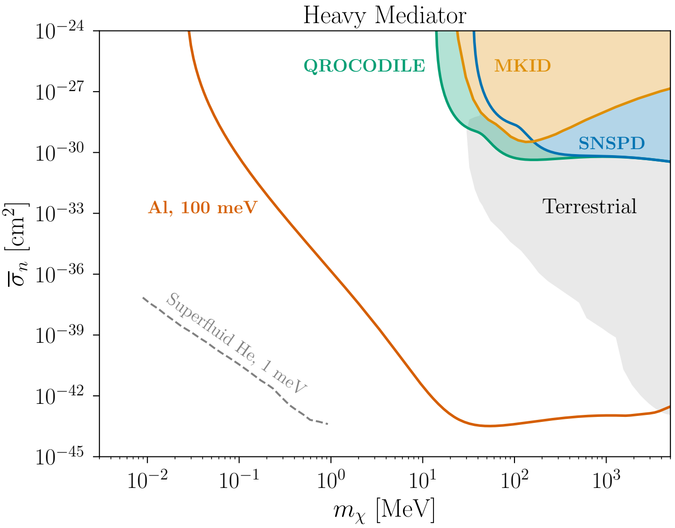
# New constraints on scattering






Griffin+ & **BVL** 2409.xxxxx

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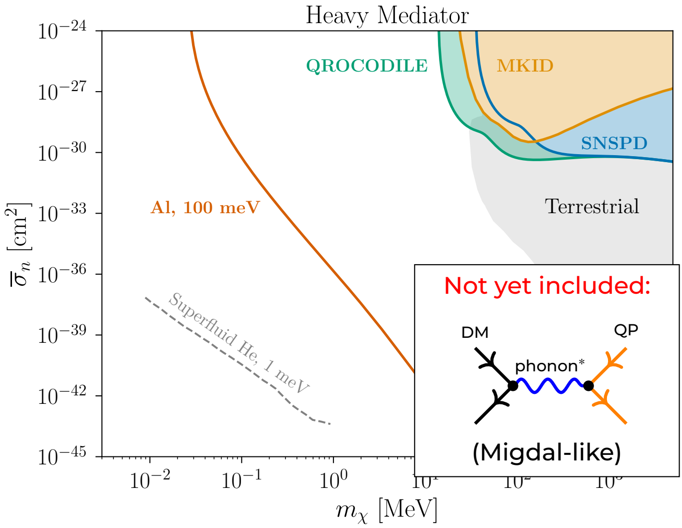



Griffin+ & **BVL** 2409.xxxxx

# Conclusions

New approaches to broaden light DM detection

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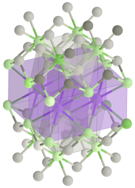
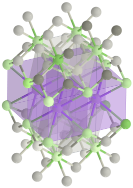


Data-driven
material discovery

New approaches to broaden light DM detection



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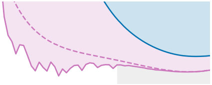
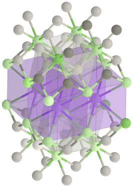


Geometric enhancement

# Conclusions

New approaches to broaden light DM detection



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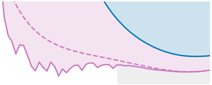
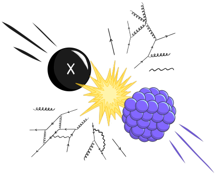


Geometric enhancement




Nuclear recoils in
superconductors

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