Direct Detection of Dark Matter

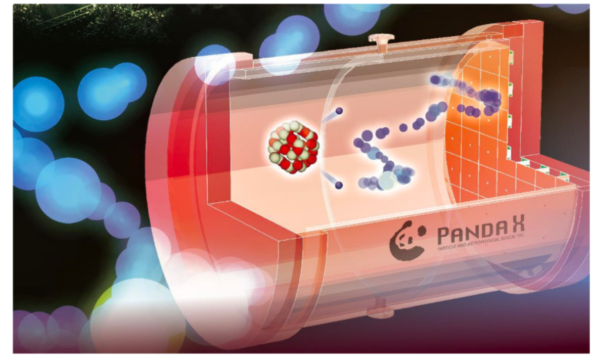
Yonit Hochberg

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

The Obvious Big Ones

LZ

Xe
XENON
Dark Matter Project



CRESST

darkside
two-phase argon TPC for Dark Matter Direct Detection

Edelweiss
Expérience pour DEtecter Les WIMPs En Site Souterrain

(Etc etc etc...)

SUPER CRYOGENIC DARK MATTER SEARCH

DAMIC-M

The Less Obvious Ones

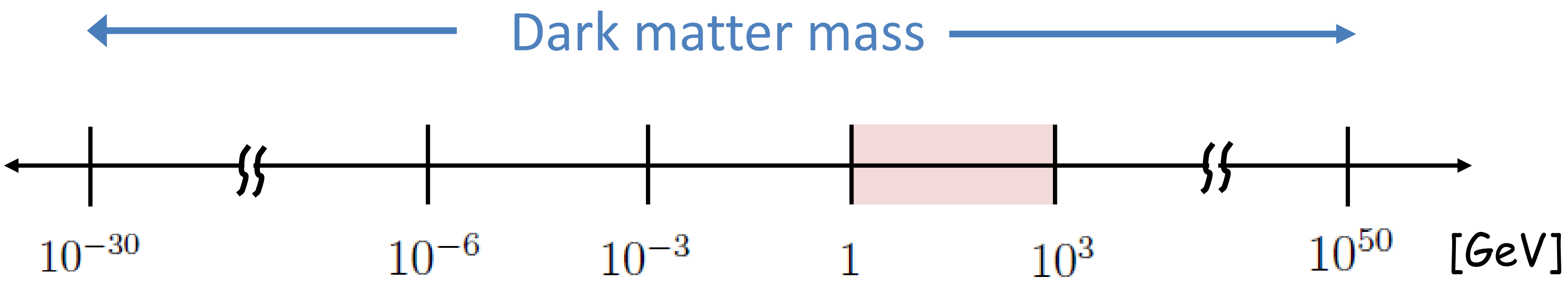
Not the classical WIMP searches.

Diverse efforts.

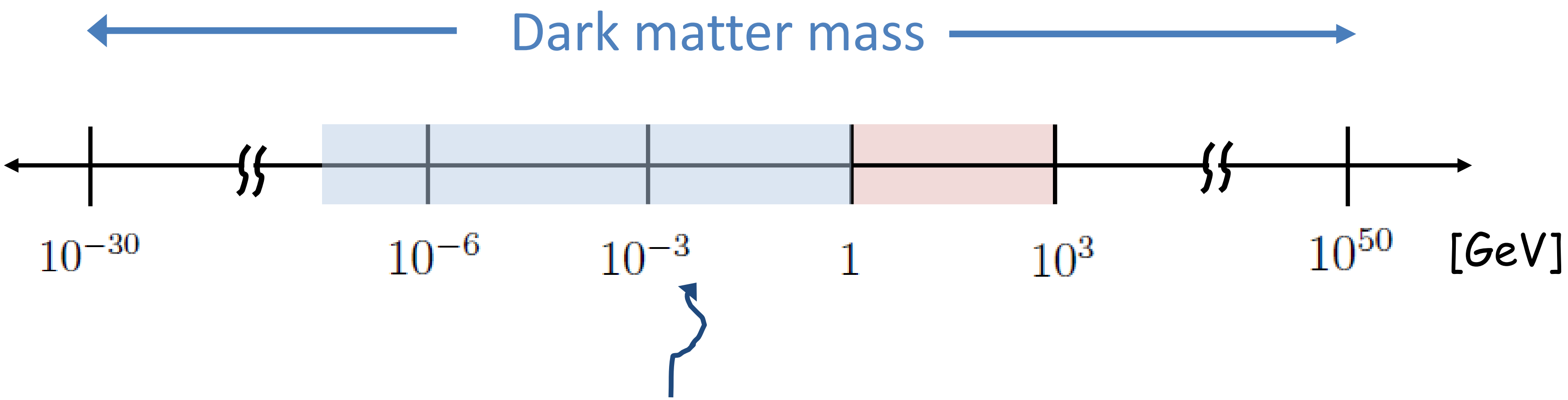
Gaining traction.

Israel involvement.

Beyond the WIMP



Beyond the WIMP



Sub-GeV dark matter.

Lots of activity in recent years:

Theory & Experiment.

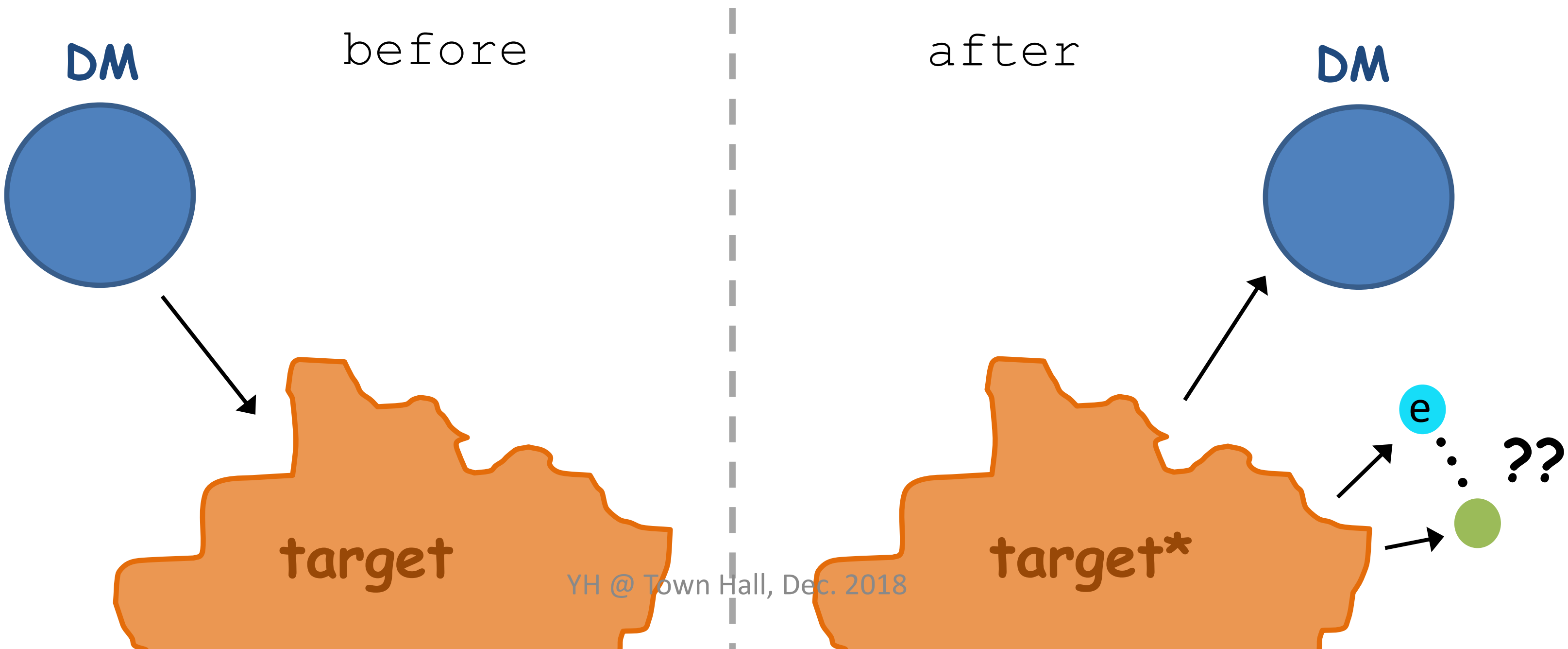
Detection Blueprints

Dark matter particle comes in

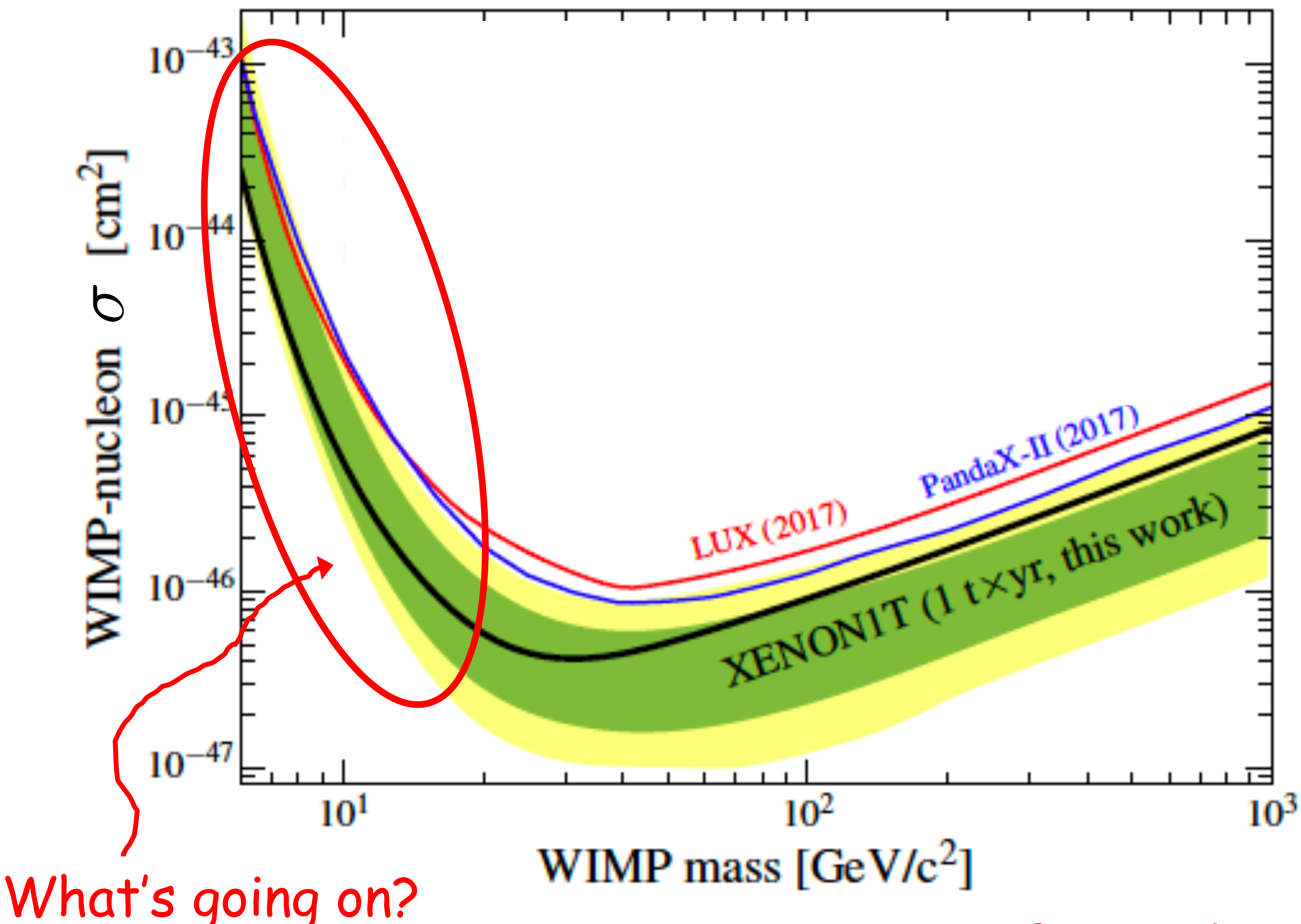
Hits a target in the lab

System reacts

Measure the reaction



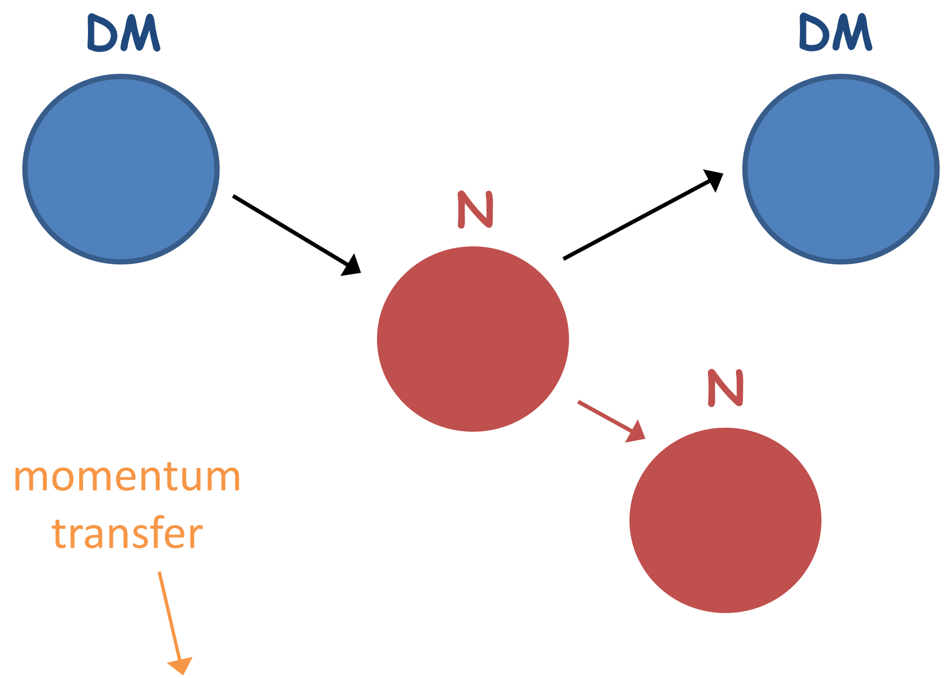
Direct Detection



[Xenon1T latest results, 2018]

Current Experiments

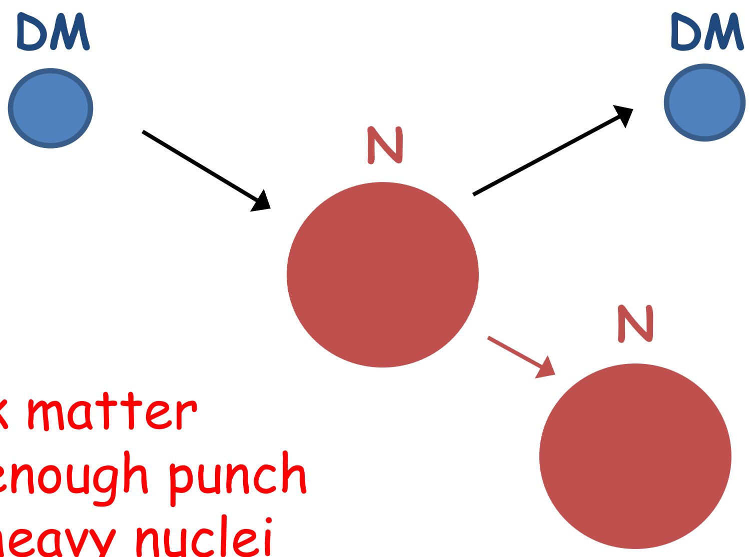
Looking for nuclear recoils:
think billiard balls



$$E_{\rm NR} = \frac{q^2}{2m_N} = \frac{(m_{\rm DM} v)^2}{2m_N} \gtrsim E_{\rm threshold} \sim {\rm keV}$$

Current Experiments

Looking for nuclear recoils:
think billiard balls

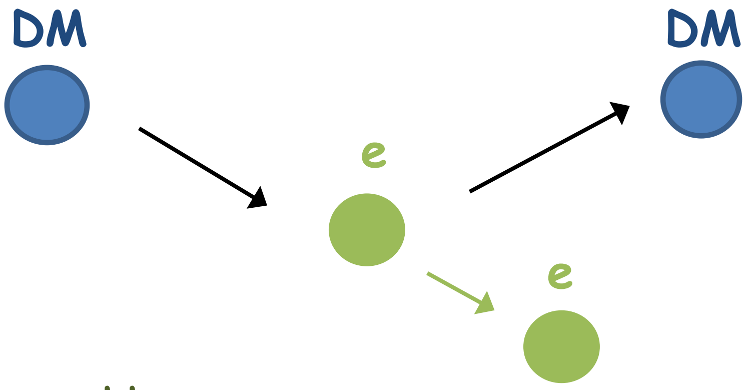


light dark matter
doesn't have enough punch
to kick the heavy nuclei

Lose sensitivity @ O(GeV) masses

New Avenues

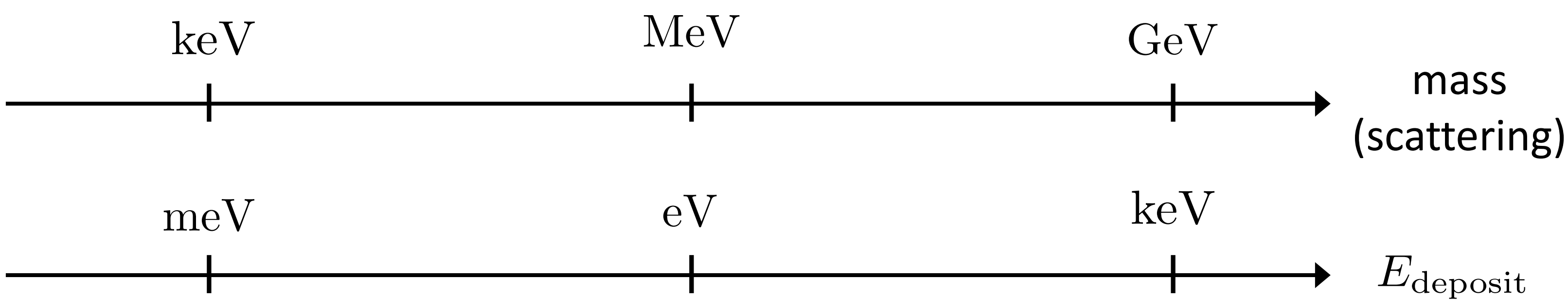
Light dark matter: scatter off electrons!

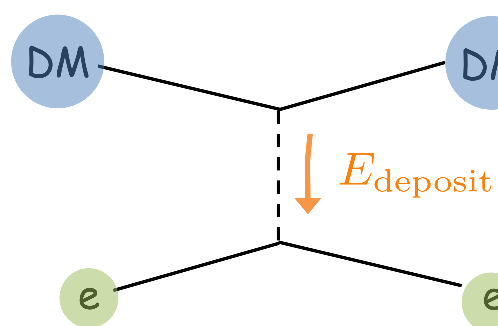


light dark matter
can give enough punch
to kick the light electrons

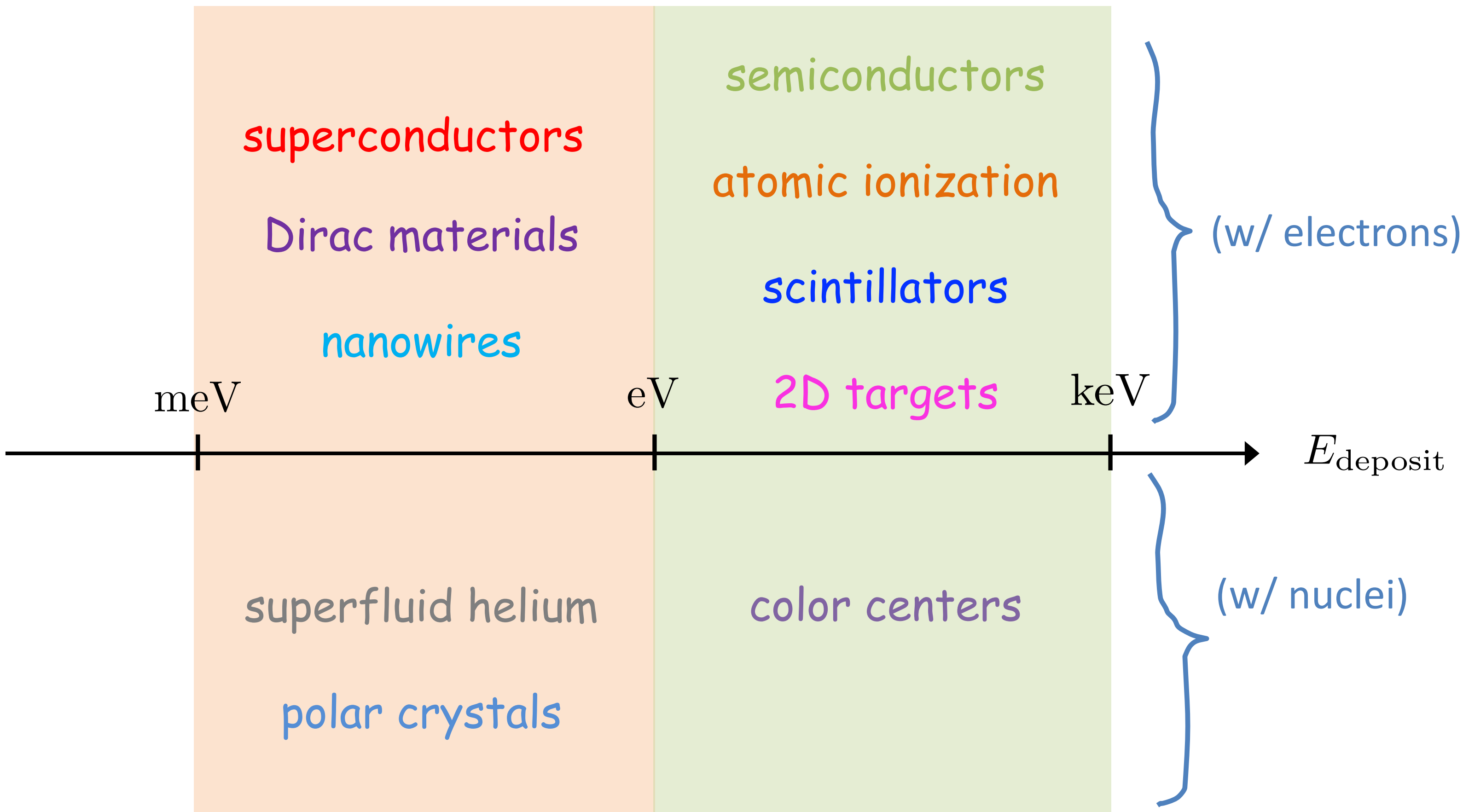
Energy guideline

Dark matter scattering: kinetic energy $m_{\rm DM} v^2 \sim 10^{-6} m_{\rm DM}$



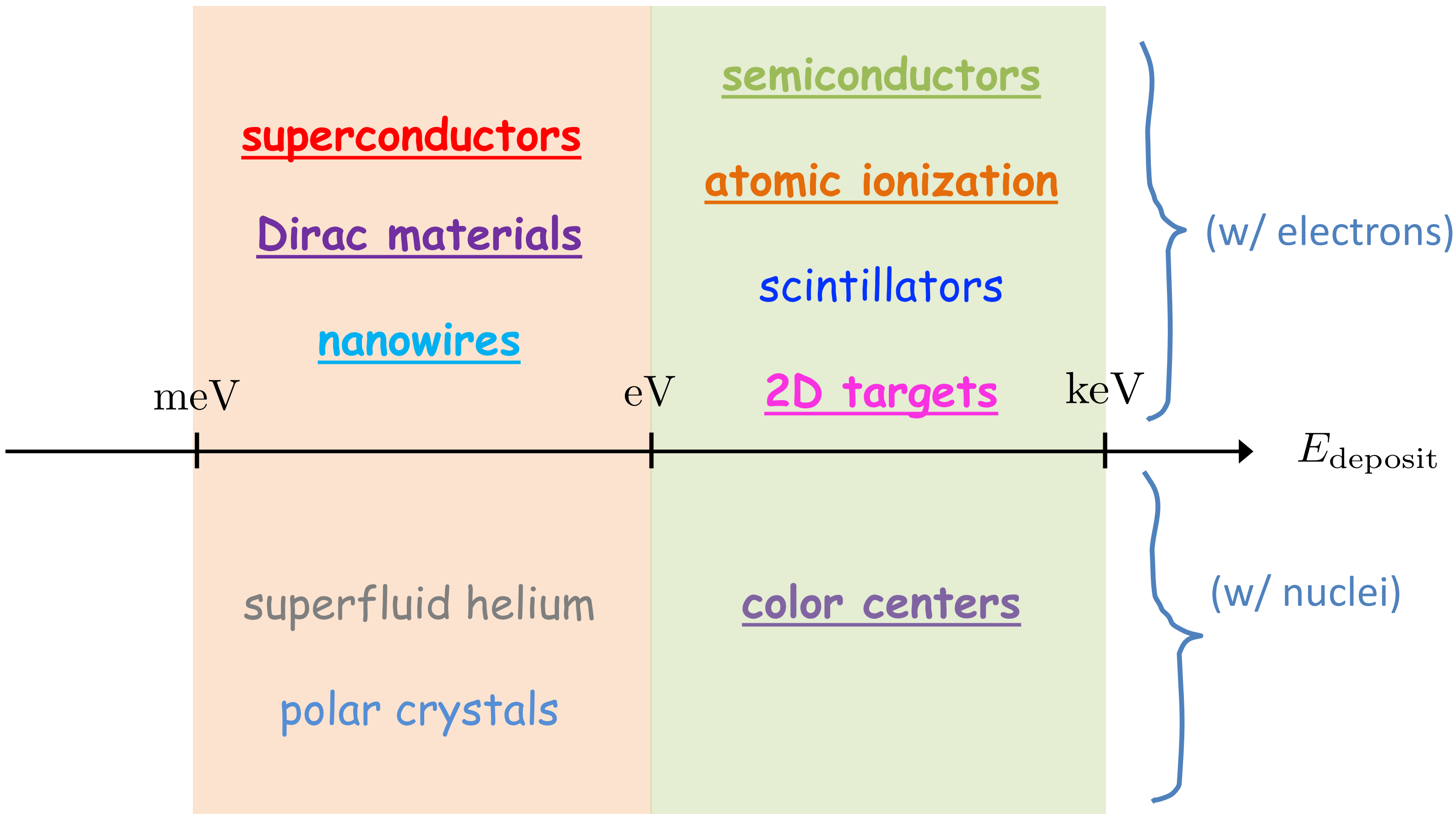


New proposals



Lots of activity

New proposals

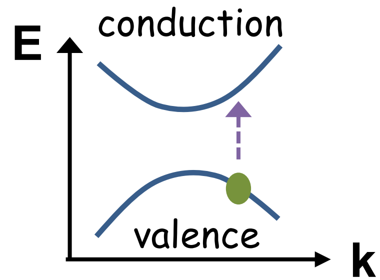


Highlight the ones Israel is involved in

#1: Semiconductors

- **Idea:** DM excites an electron from the valence to conduction band

[Essig, Mardon, Volansky, PRL 2012]



Ge, Si: ~eV

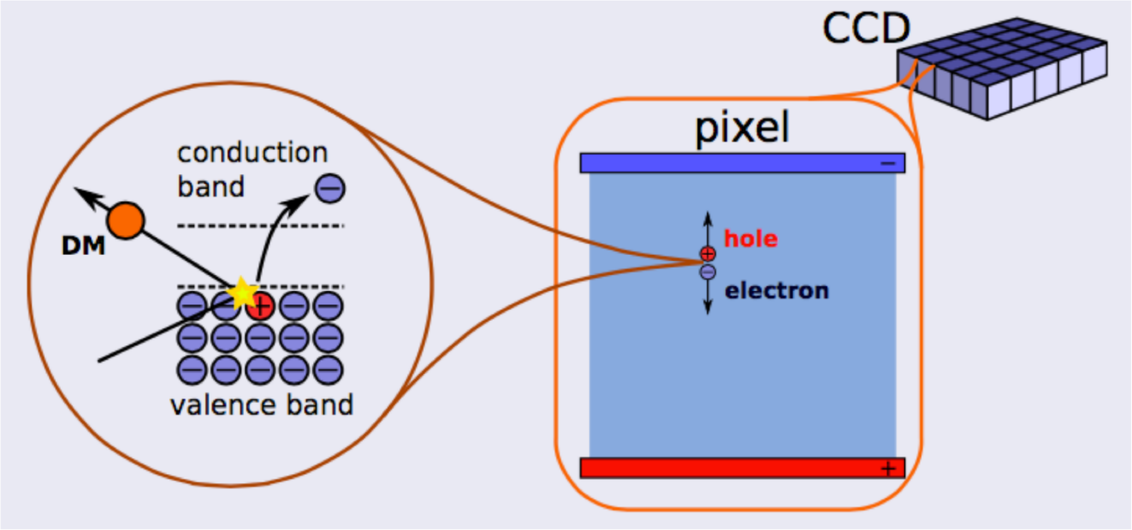
$$m_{\mathrm{DM}} \gtrsim \mathrm{MeV}$$

- E.g. SuperCDMS, DAMIC, TEXONO, SENSEI executing

SENSEI

(Sub-Electron Noise Skipper-CCD Experimental Instrument)

Silicon charge-coupled device (CCD)



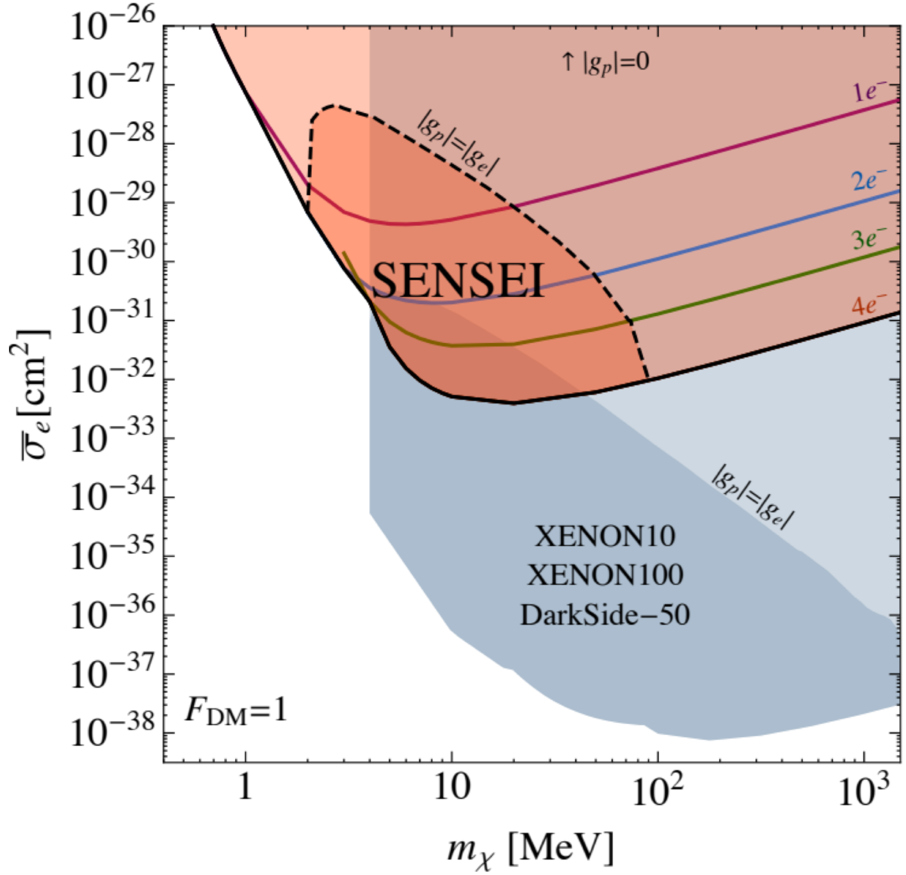
Multiple measurement of the charge in the pixel

Low electronic noise

Can resolve individual electrons

SENSEI

First results from surface run @ Fermilab: 0.02 gram-days exposure



[PRL 2018, arXiv:1804.00088]

SENSEI

- Currently: 0.09 grams installed @ MINOS (results soon).
- Next step: 10 gram @ SNOLAB in early 2019, run for a year.
- Final phase: 100 gram phase, will likely run for around a year.

~20 people from 4 institutions.

Locally @ TAU:
Tomer Volansky, Erez Etzion, Liron Barak

Experiment fully funded.

TEL AVIV UNIVERSITY
Stony Brook University
UNIVERSITY OF OREGON
Fermilab
HEISING-SIMONS FOUNDATION

Diamond

- Diamond is a semiconductor too!
- IR-induced dark counts expected to be lower than in Ge, Si
- First paper to appear shortly [Yu, **YH**, Kurinsky, Cabrera, 1812:sooon]
- Ongoing R&D in SuperCDMS; prototype planned to be built

Locally @ HUJI:
YH

Stanford University

Fermilab

THE UNIVERSITY OF CHICAGO

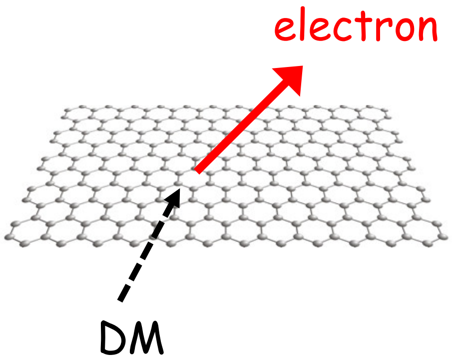
THE HEBREW UNIVERSITY OF JERUSALEM

Super CDMS

#2: 2D Targets (Graphene)

- **Idea:** DM scatters with valence electrons, deposits enough energy, ejects electron → detect

$$E_{\text{eject}} \sim \mathcal{O}(\text{few eV})$$
$$\Rightarrow \quad m_{\text{DM}} \gtrsim \text{MeV}$$



- Electron follows incoming dark matter direction. Naturally gives forward/backward discrimination (separates signal from background)

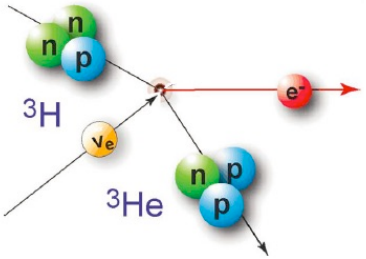
Directional info!

[**YH**, Kahn, Lisanti, Tully, Zurek, PLB 2017]

Implement in PTOLEMY

(Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield)

Experiment to detect relic neutrinos via capture on tritium.



[Betts et al, 2013]

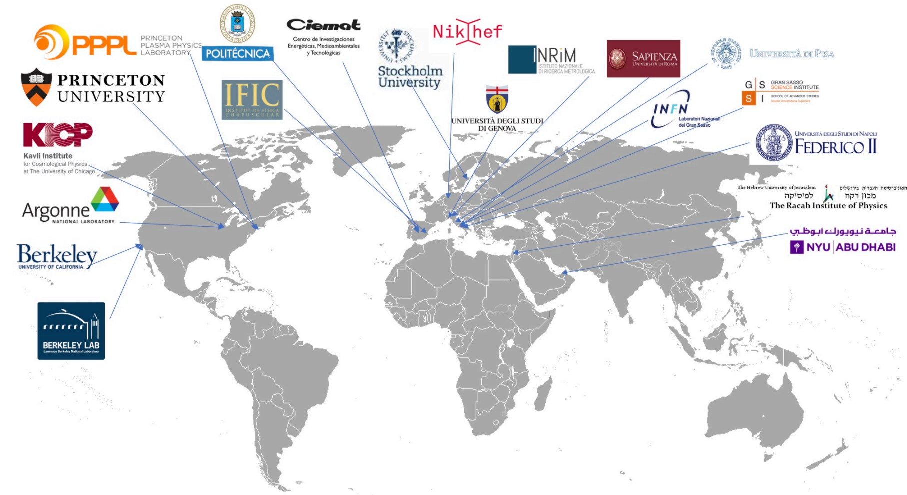
Use their (un-tritiated) graphene (~0.5 kg).

PTOLEMY: A Proposal for Thermal Relic Detection of Massive Neutrinos and Directional Detection of MeV Dark Matter

[PTOLEMY collaboration, arXiv:1808.01892]

PTOLEMY

- O(50) people, O(20) institutions



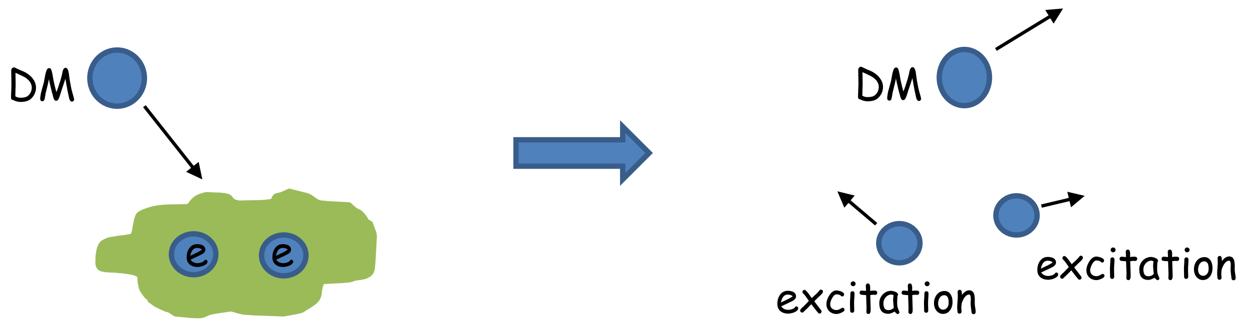
Locally @ HUJI:
YH

- Will sit in LNGS
- R&D Prototype @ Princeton
- EU synergy proposal planned for next year

Supported by: SIMONS FOUNDATION JOHN TEMPLETON FOUNDATION

#3: Superconductors

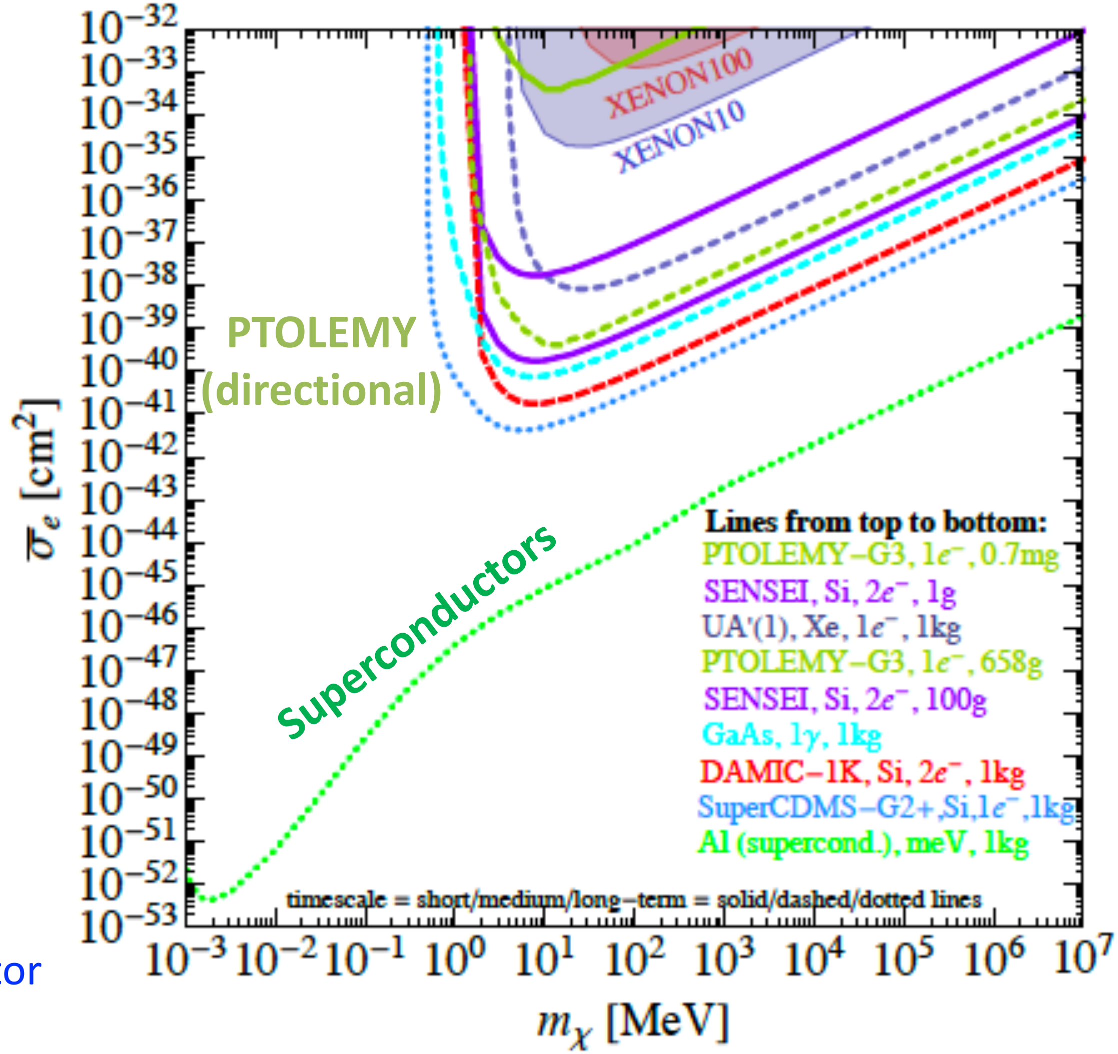
- Ground state = Cooper pairs;
  Binding energy (gap) $\sim \mathrm{meV}$ $\Longrightarrow$ $m_{\mathrm{DM}} \sim \mathrm{keV}$
- **<u>The idea:</u>**
  DM scatters with Cooper pairs, deposits enough energy, breaks Cooper pairs, creating excitations → detect



- Current challenge: to achieve low threshold O(meV) sensors

[**YH**, Zhao, Zurek, PRL 2015; +w/ Pyle, JHEP 2015]

Scattering Reach



DM-electron scattering xsec @ $q = \alpha m_e$ w/ light mediator

[a few events in kg-year exposure]

Amazing reach!

[US Cosmic Visions: Community report, 2017]

Superconductors

- Best reach but more futuristic (low thresholds)
- DoE HEP-Quantum Information Science (QIS) grant awarded this year for R&D of low threshold TESs @ LBNL
- Directional detection? (work in progress)

Locally @ HUJI:
YH

Superconducting Nanowires

- QIS: single-photon detectors
- Demonstrated low dark counts and low thresholds (sub-eV)
- Use as target + sensor for DM detection
- Tiny devices can already play meaningful role

Toy prototype @ Berggren lab, MIT

4.3 nanogram, 10K seconds:
places strongest terrestrial bounds for sub-eV dark photon absorption!

Superconducting Nanowires

- Extend to lower energy thresholds and large area nanowires

[**YH**, Charev, Naam, Berggren, 1812.sooon]

- DoE HEP-QIS grant to Berggren @ MIT for development of nanowires for another purpose

- Recently submitted dedicated grant w/ BNL

Locally @ HUJI:
YH

BROOKHAVEN NATIONAL LABORATORY
Massachusetts Institute of Technology
NIST National Institute of Standards and Technology
האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

Quantum Sensing meets HEP

Quantum Sensing for High Energy Physics

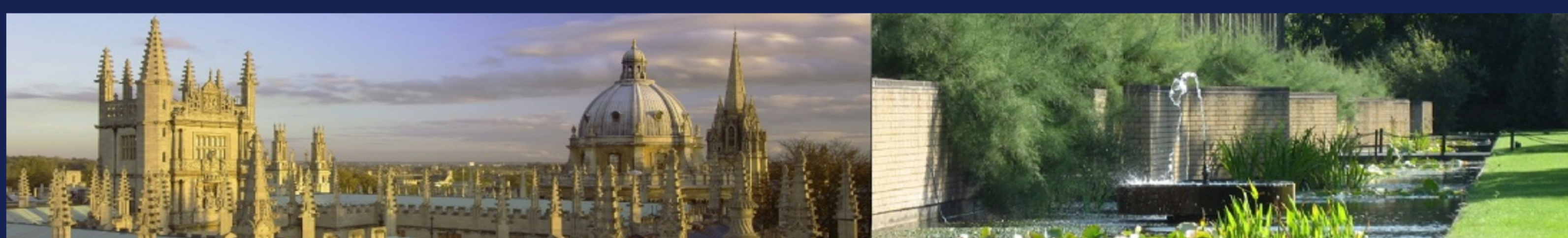
Report of the first workshop to identify approaches and techniques in the domain of quantum sensing that can be utilized by future High Energy Physics applications to further the scientific goals of High Energy Physics.

Organized by the Coordinating Panel for Advanced Detectors of the Division of Particles and Fields of the American Physical Society

March 27, 2018

Activity in the USA and starting in Europe

What about Israel??



Quantum Sensors for Fundamental Physics, St. Catherine's College, Oxford, UK

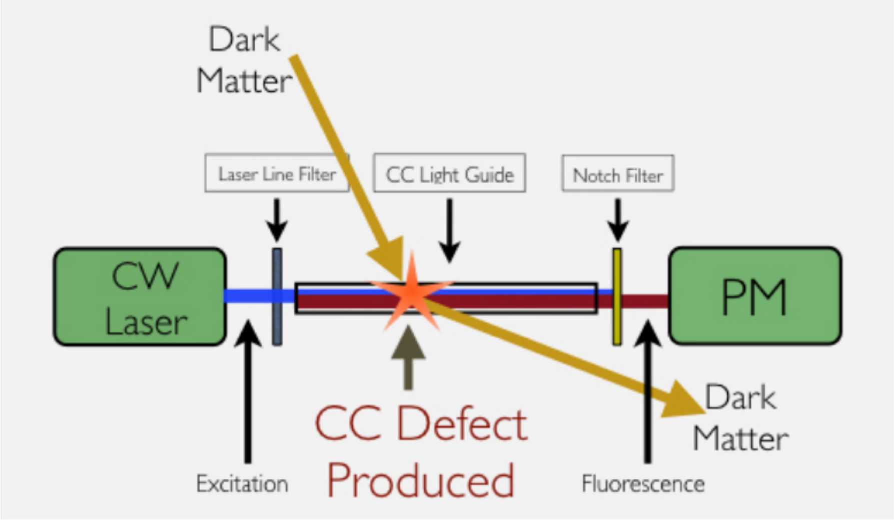
16 October - 17 October 2018
Oxford, UK

#4: Color Centers

- **Idea:** DM knocks an ion in a crystal and creates a color-center defect which can be detected

$$E_{\text{threshold}} \sim \mathcal{O}(10 \text{ eV})$$

$$\Rightarrow \quad m_{\text{DM}} \gtrsim 10\text{'s of MeV}$$



[Budnik, Chesnovsky, Slone, Volansky, 2017]

Color Centers

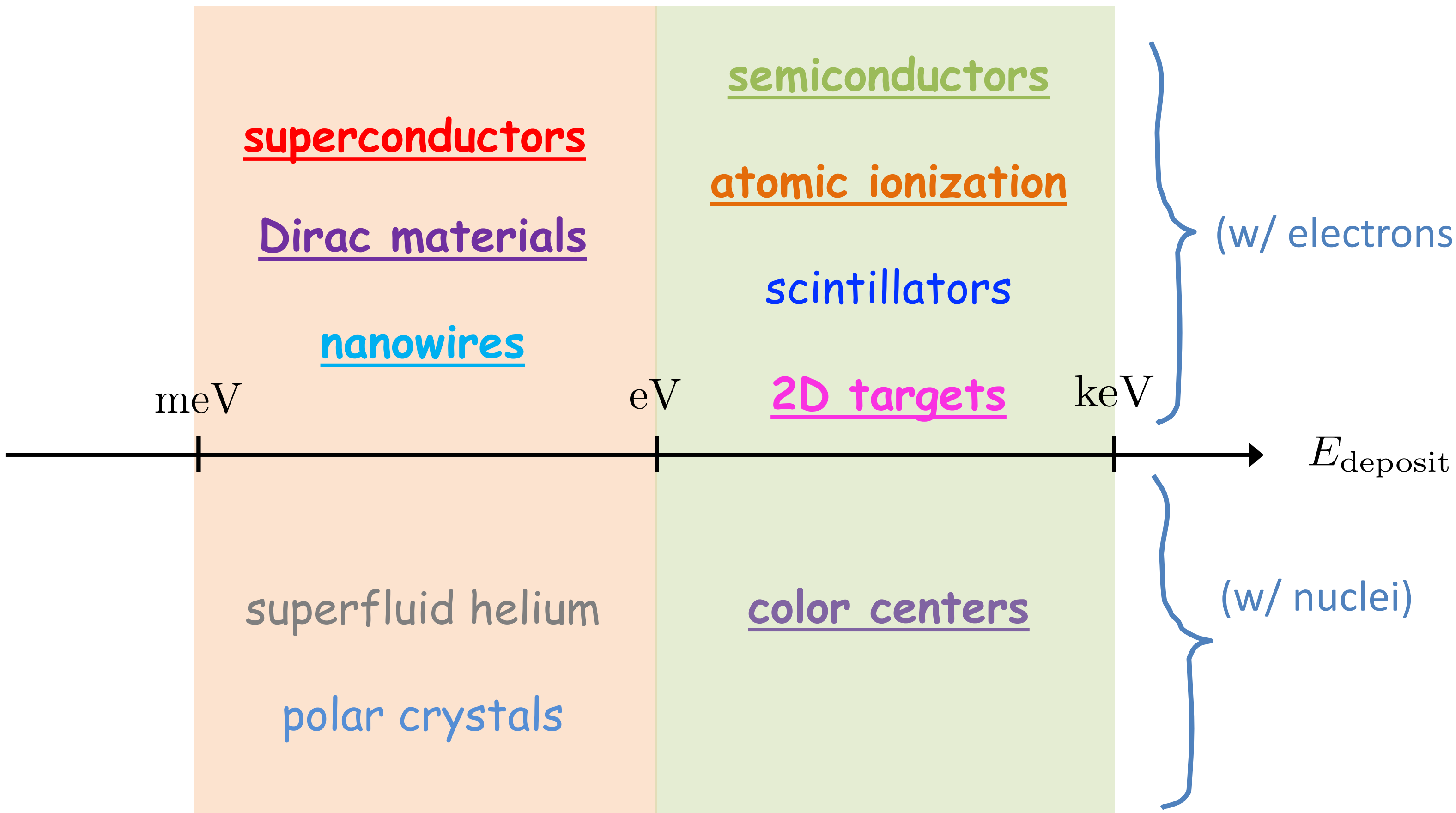
- In R&D phase
- Zoom in on number of defects in specific crystals (end of 2019).
- Prototype several years away.

Locally @ TAU & WIS:
Tomer Volansky, Ori Chesnovsky & Ranny Budnik

TEL AVIV UNIVERSITY

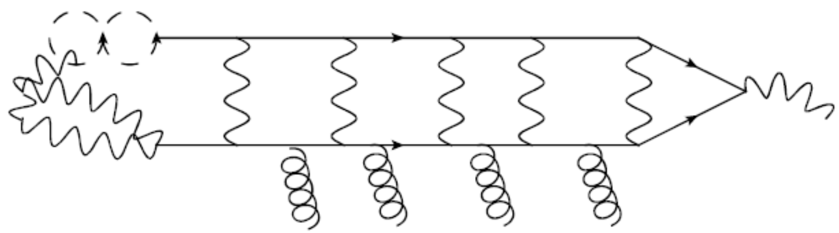
מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

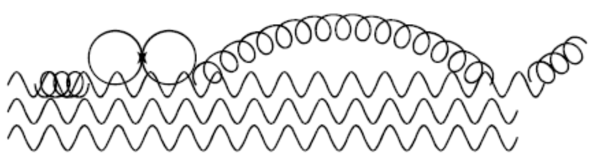
In Short

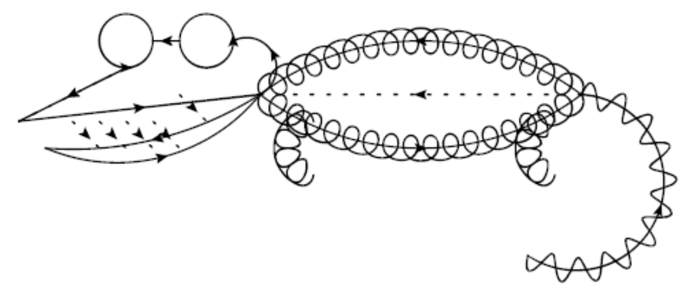


Israel highly involved in diverse efforts.

Thanks!







Backup

New theory ideas

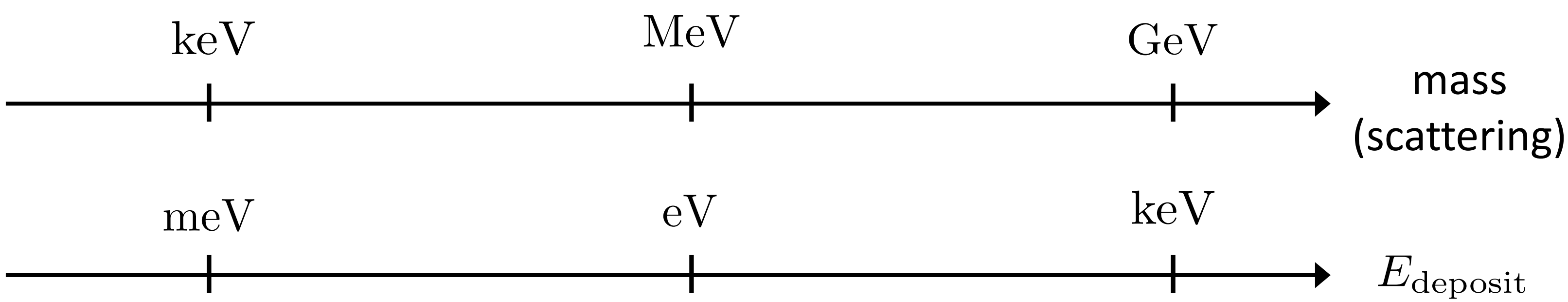
- ……
- Weakly coupled WIMPs [Pospelov, Ritz, Voloshin 2007; Feng, Kumar 2008]
- Asymmetric dark matter [Nussinov, 1985; Kaplan, Luty, Zurek, 2009]
- Freeze-in dark matter [Hall, Jedamzik, March-Russell, West, 2009]
- SIMPs [**YH**, Kuflik, Volansky, Wacker, 2014 ; **YH**, Kuflik, Murayama, Volansky, Wacker, 2015]
- ELDERs [Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2016 & 2017]
- Forbidden dark matter [Griest, Seckall, 1991; D'Agnolo, Ruderman, 2015]
- Co-Decaying dark matter [Dror, Kuflik, Ng, 2016]
- Co-scattering dark matter [D'Agnolo, Pappadopulo, Ruderman, 2017]
- ……

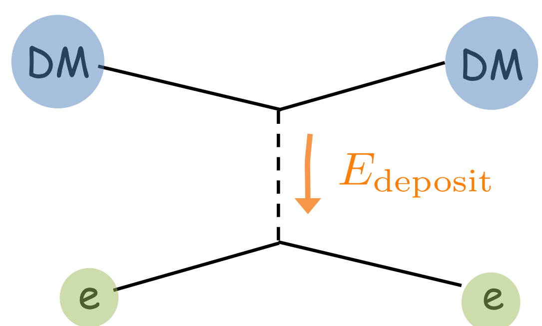
… Are abundant

By no means a comprehensive list

Energy guidelines

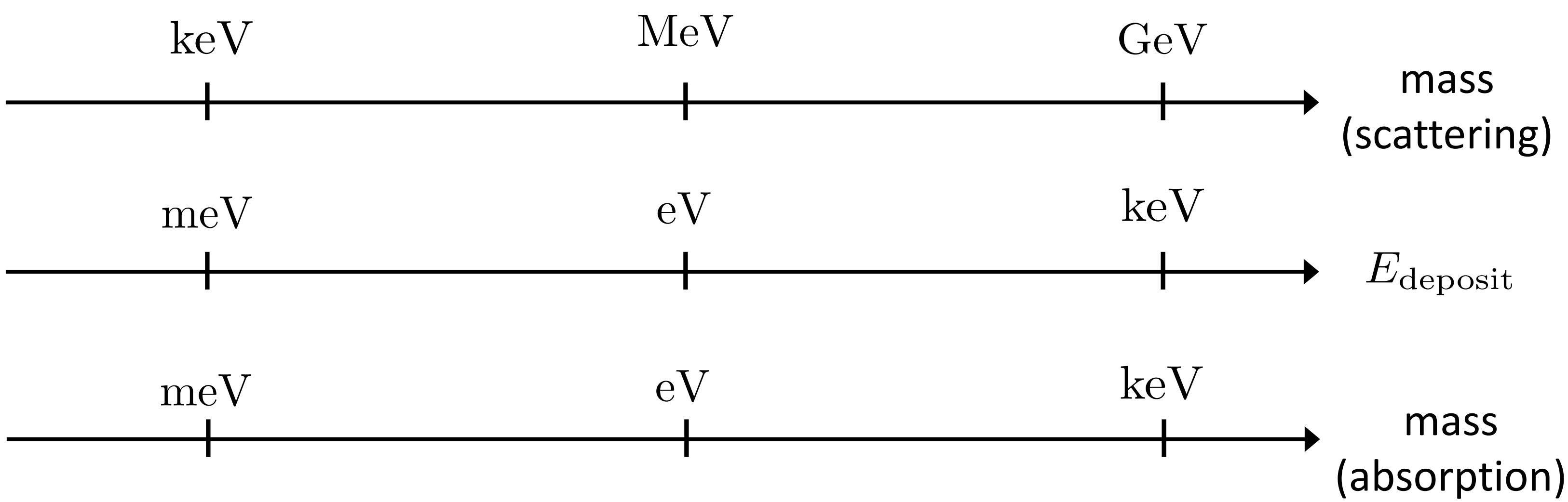
Dark matter scattering: kinetic energy $m_{\mathrm{DM}} v^2 \sim 10^{-6} m_{\mathrm{DM}}$

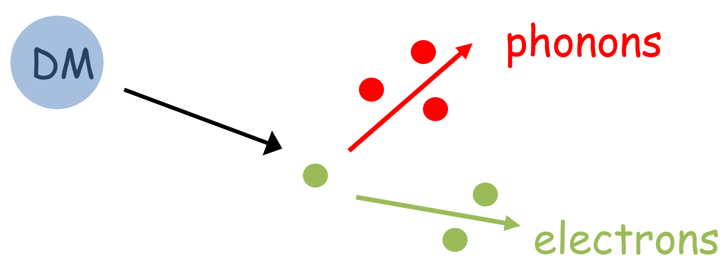




Energy guidelines

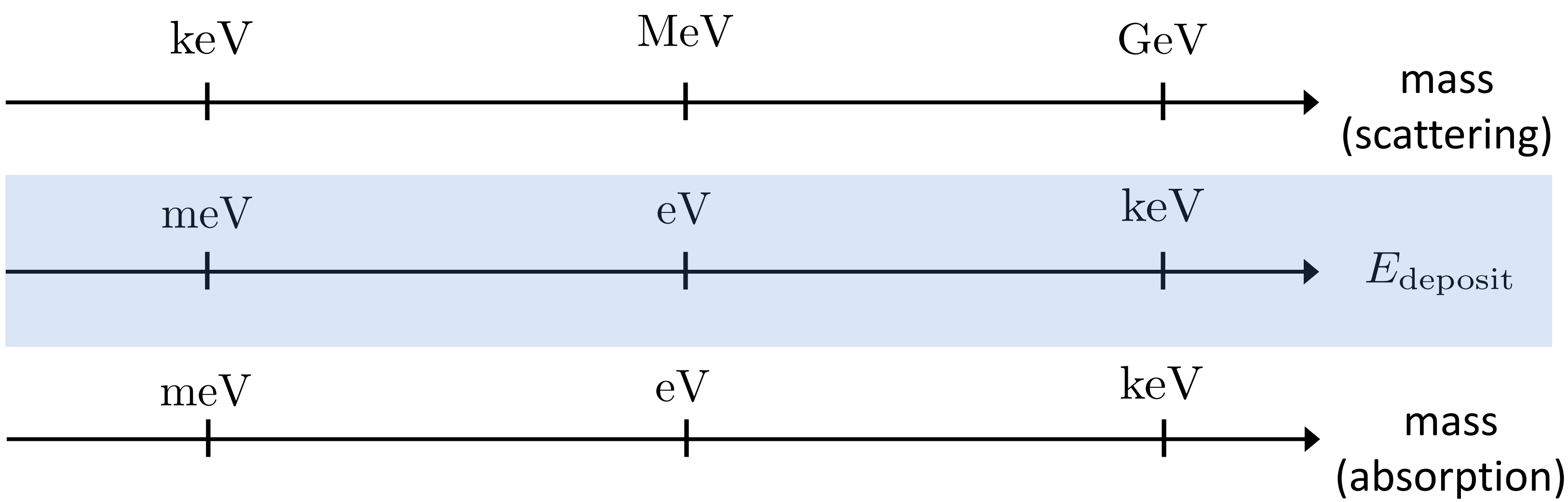
Dark matter absorption: all the mass-energy m_{DM}



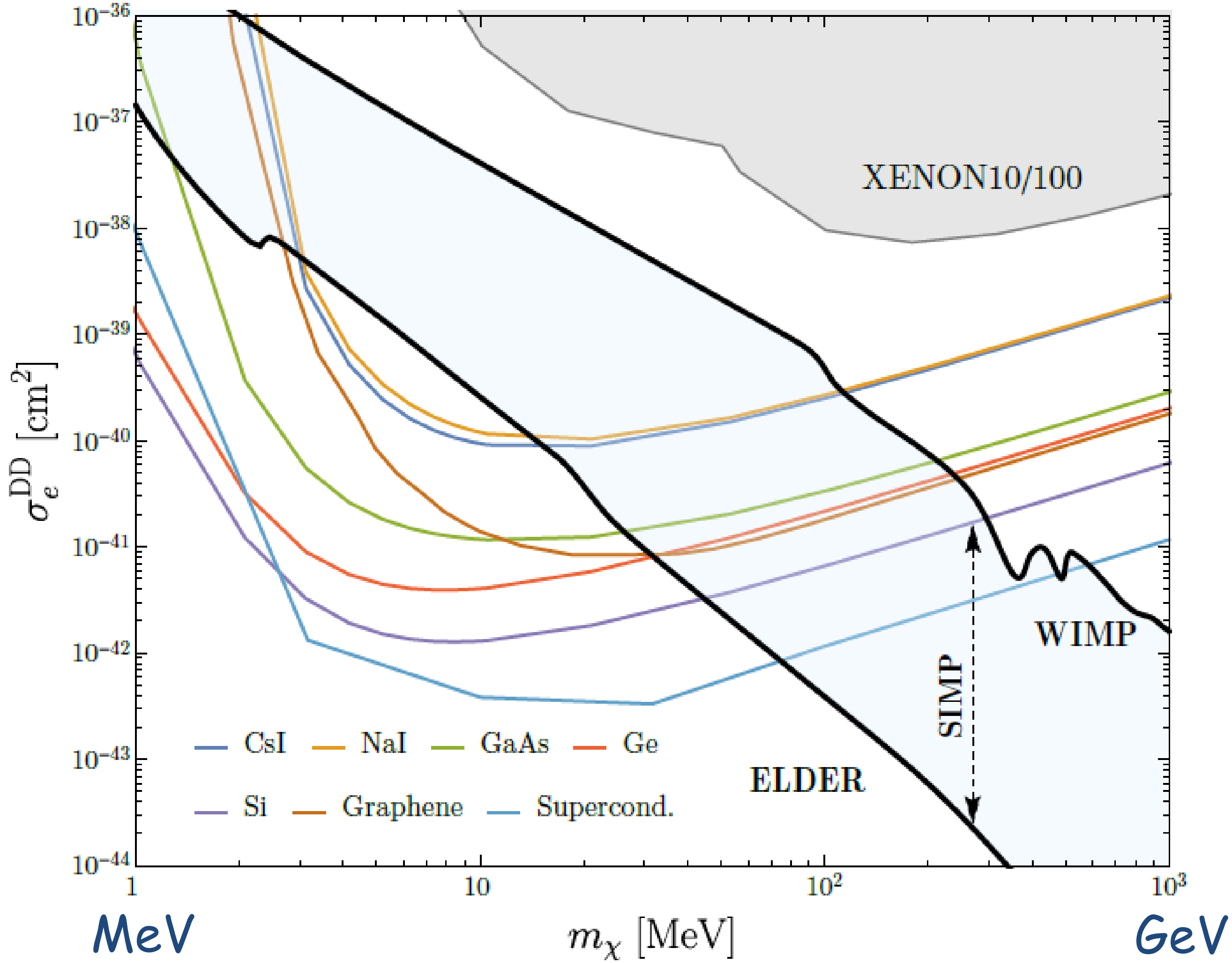


Energy guidelines

Two (mass ranges) for the price of one :-)



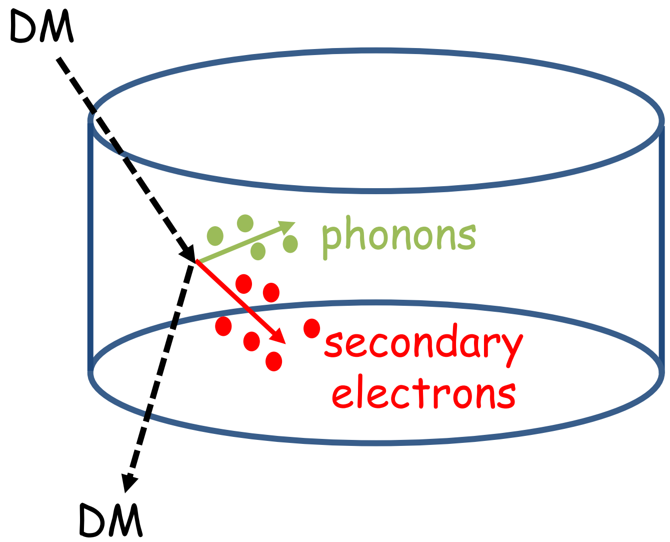
Direct Detection



[Plot: Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2017]

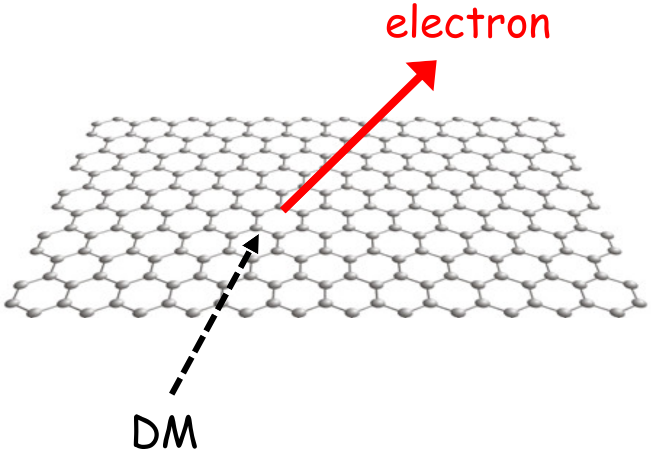
Directional Info?

Lose directional information
if detecting secondaries



e.g. semiconductors, superconductors

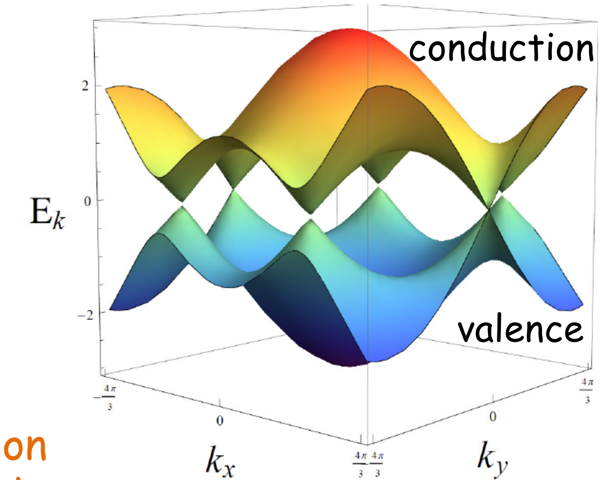
Retain directional information
if observe primary!



2D targets; graphene

Graphene

- 2D material with vanishing bandgap



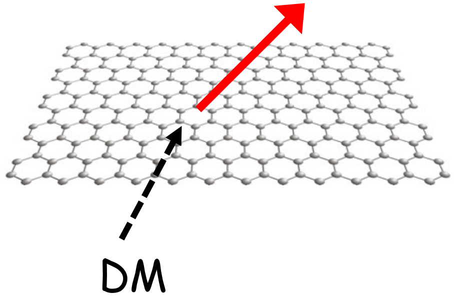
- To eject electron: $E_{\text{eject}} = E_b + \Phi \sim \text{eV}$

Binding energy

Work function
O(eV), tunable

⇒ **Sensitivity to m_{DM}~ MeV**

- The idea: DM scatters with valence electrons, deposits enough energy, ejects electron → detect



[**YH**, Kahn, Lisanti, Tully, Zurek, PLB 2017]

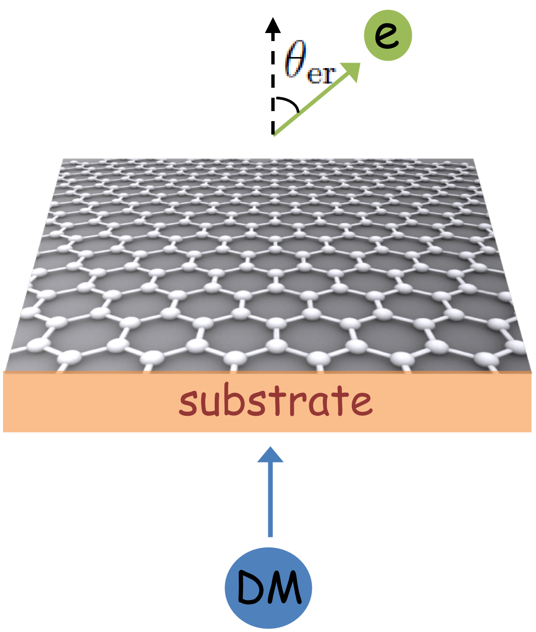
Directional info

Electron follows incoming dark matter direction.

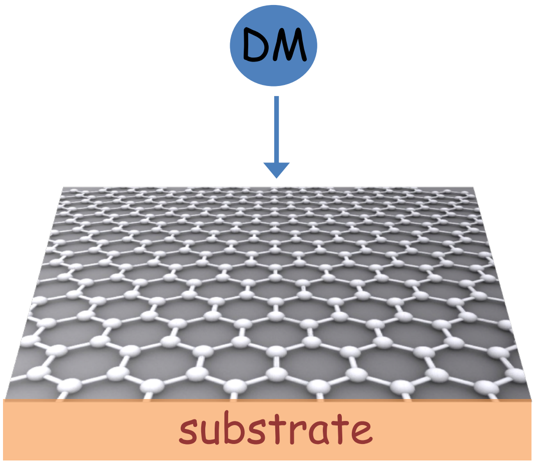
Naturally gives forward/backward discrimination

(separates signal from background)

Electron detected



electron not detected



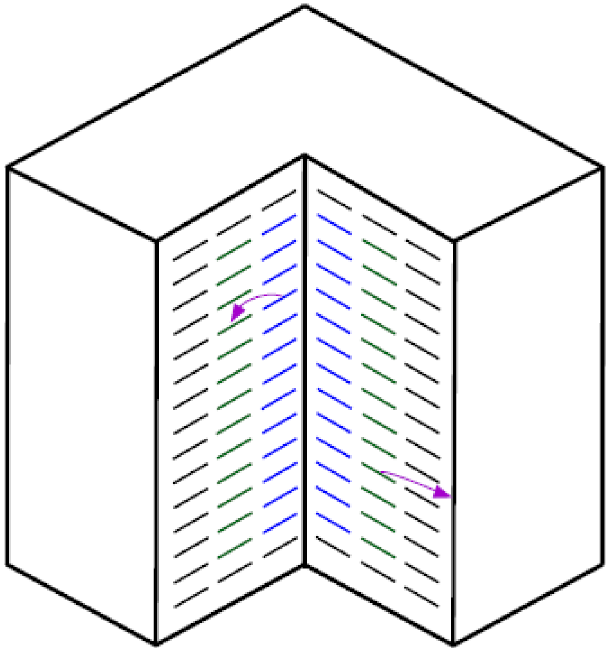
12 hours later

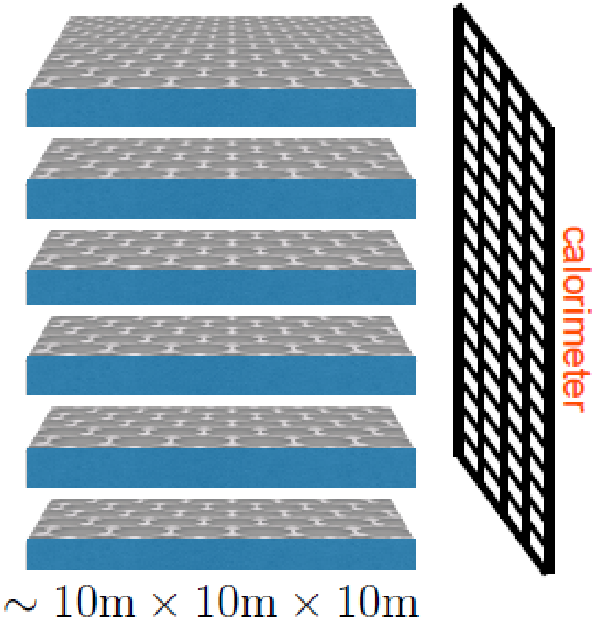
[**YH**, Kahn, Lisanti, Tully, Zurek, PLB 2017]

Design Concept

- ~0.5 kg graphene = area of Jerusalem old city = billions of cm^2 crystals

- Compact geometry: large mass via many stacks

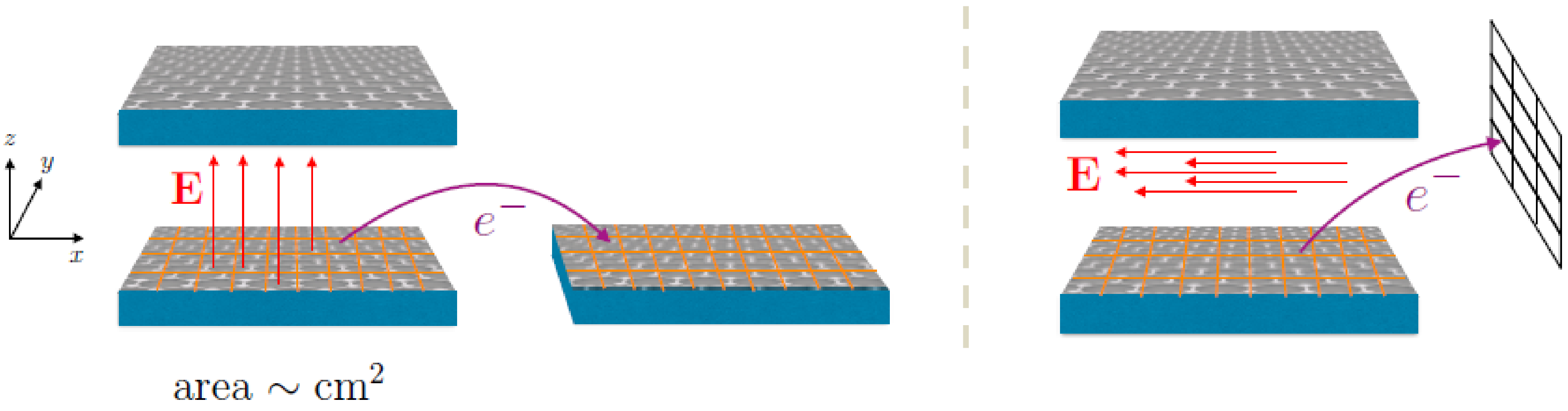




Design Concept

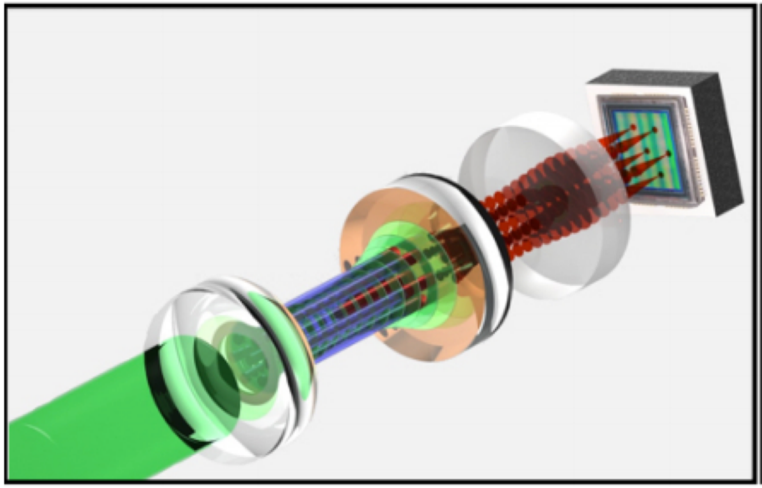
- Electron ejected from plane into vacuum, electric fields drift it to FET/calorimeter, detected

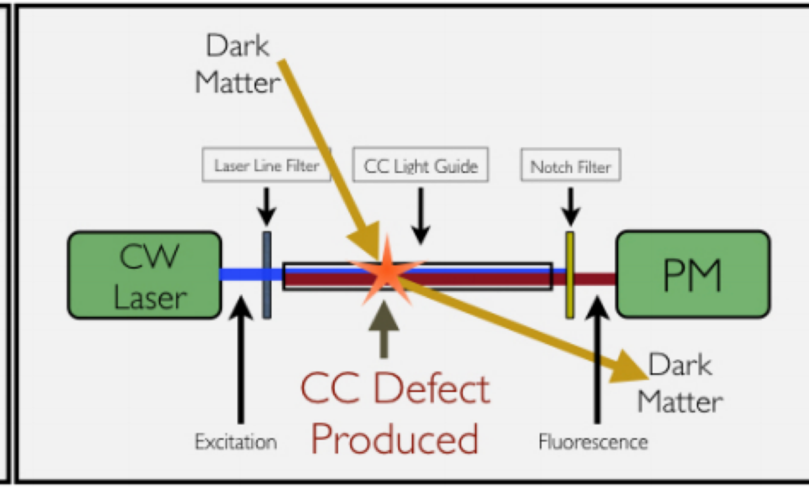
- Velocity reconstructed from time-of-flight; monitor conductivity of graphene to determine when electron ejected → directionality

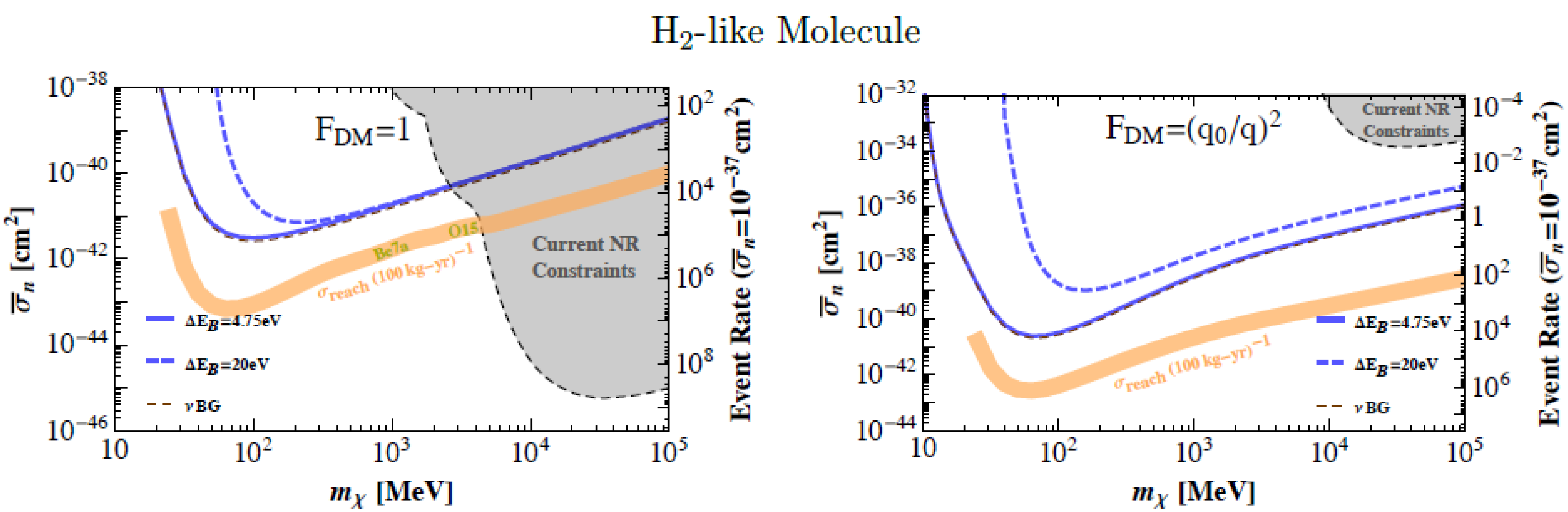


[Essig, Mardon, Slone, Volansky , 1608.02940]

Color Centers

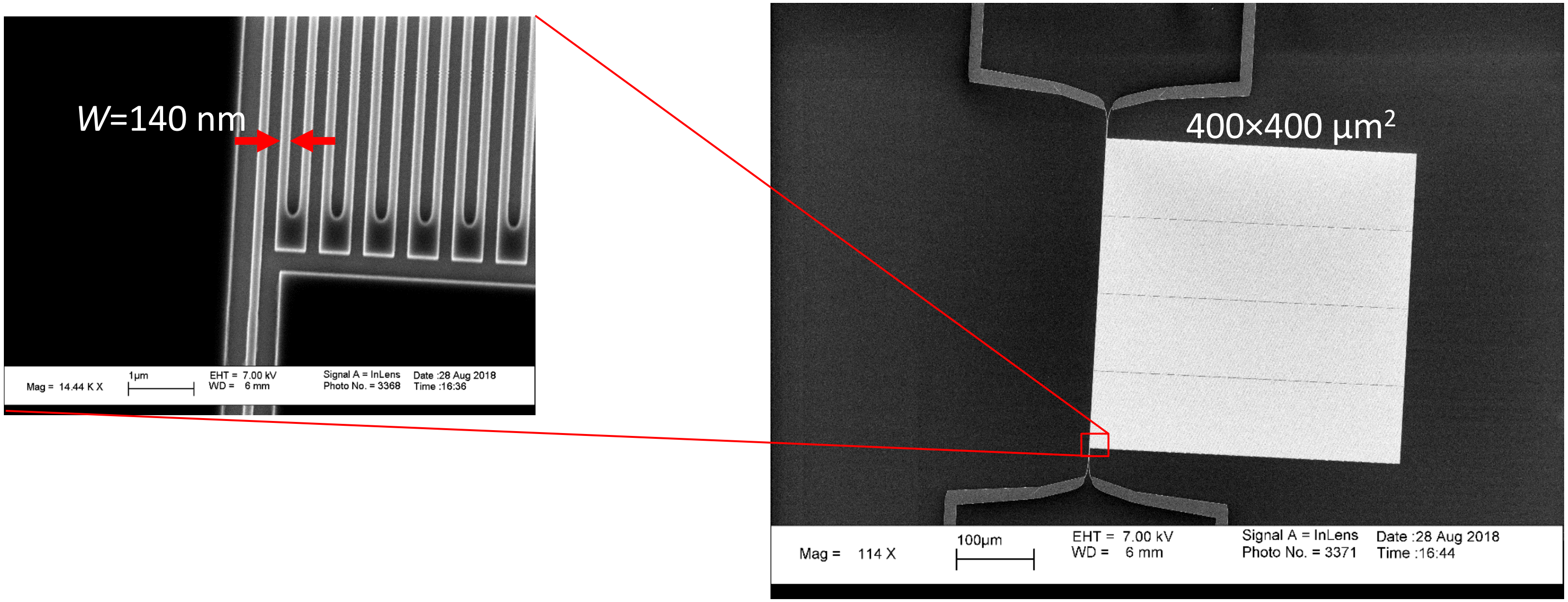






Superconducting Nanowires

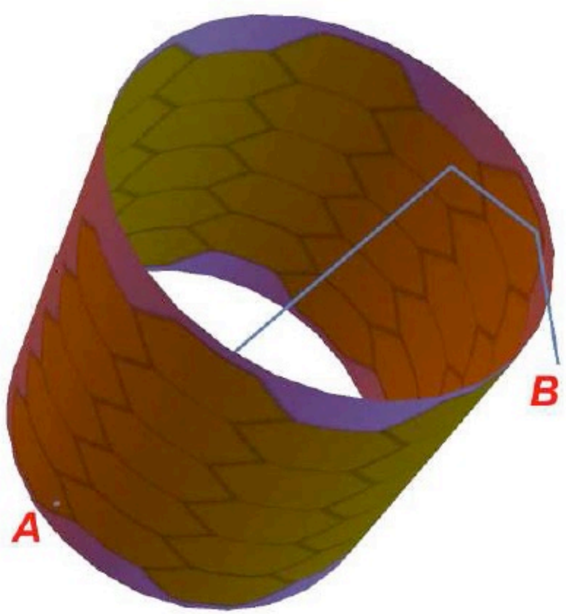
Toy prototype @ Berggren lab, MIT



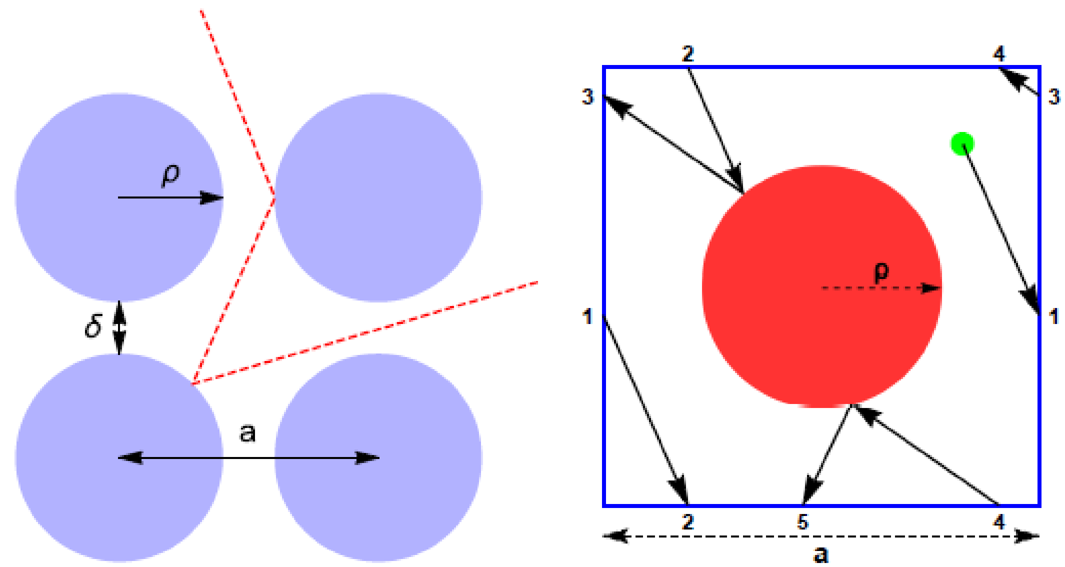
4.3 nanogram, 10K seconds (WSi):

places strongest terrestrial bounds for sub-eV dark photon absorption!

Carbon Nanotubes for WIMPs

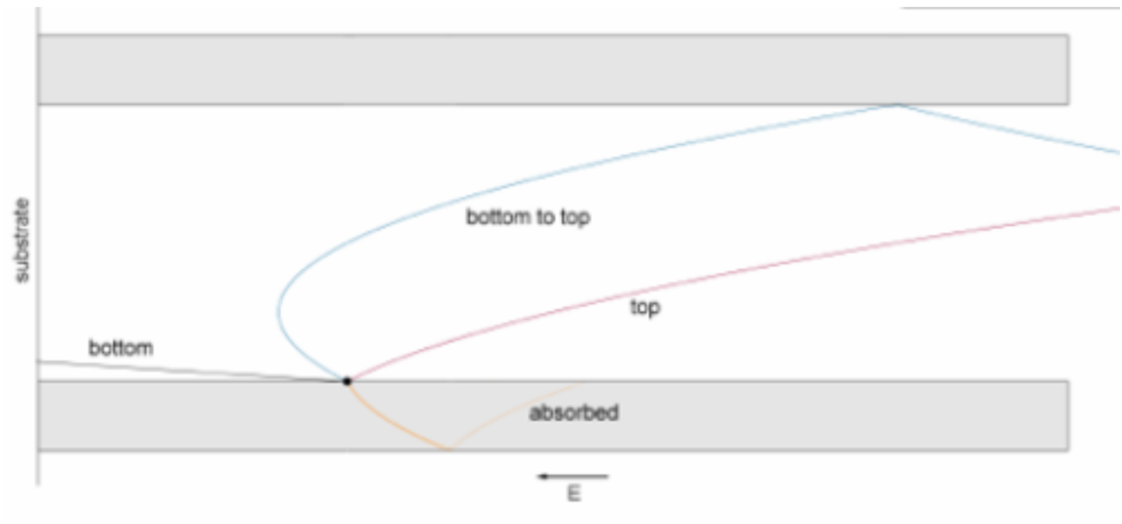


[Capparelli et al, 1412.8213]



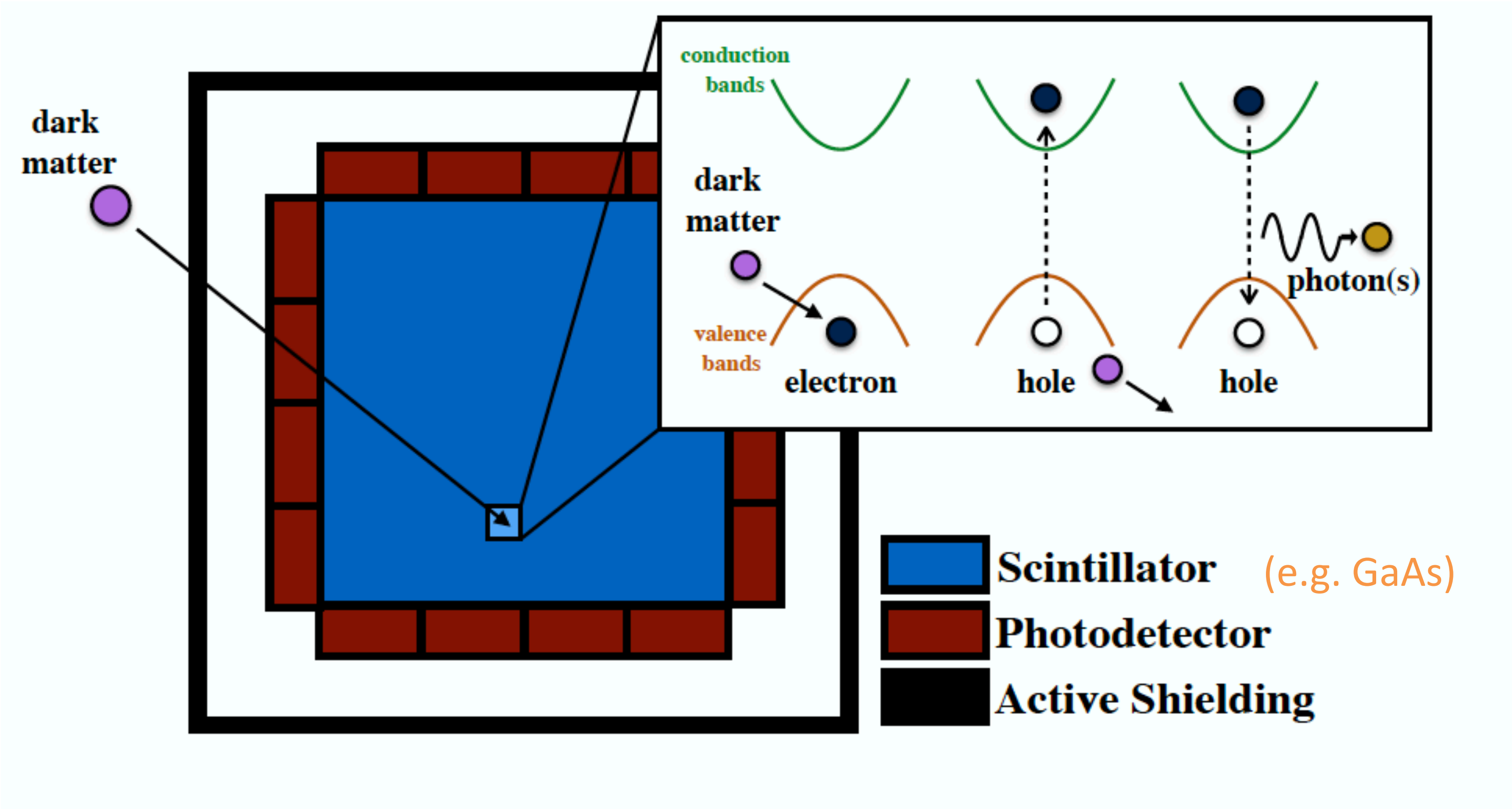
[Cavoto et al, 1602.03216]

Carbon Nanotubes (e)



[Cavota, Luchetta, Polosa, 1706.02487]

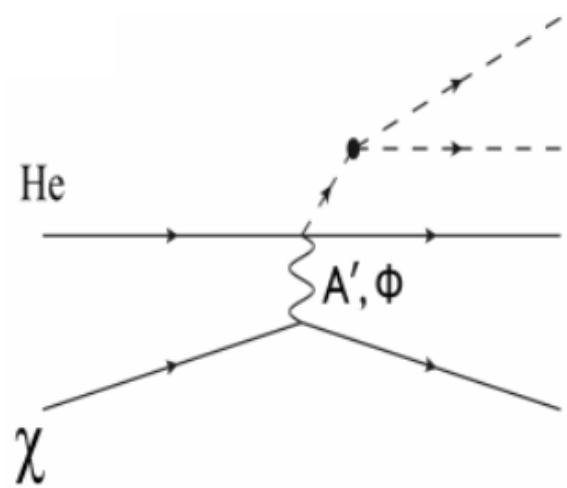
Scintillators

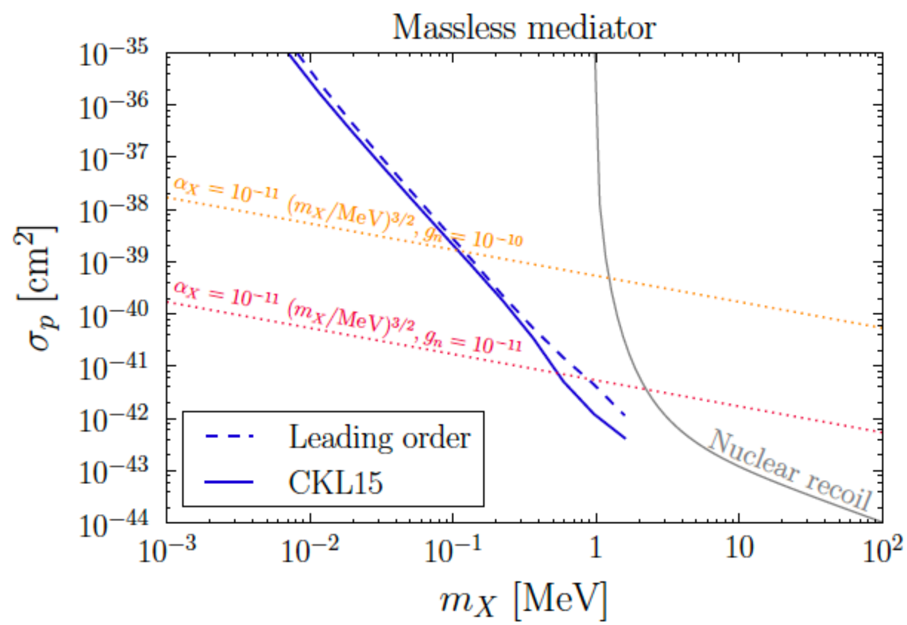


[Derenzo, Essig, Massari, Soto, Yu, 1607.01009]

Superfluid helium

Dark matter couples to collective modes
(phonons, rotons, maxons)





Not great for hidden photons

[Schutz, Zurek, 2016; Knapen, Lin, Zurek, 2016]

Downside?

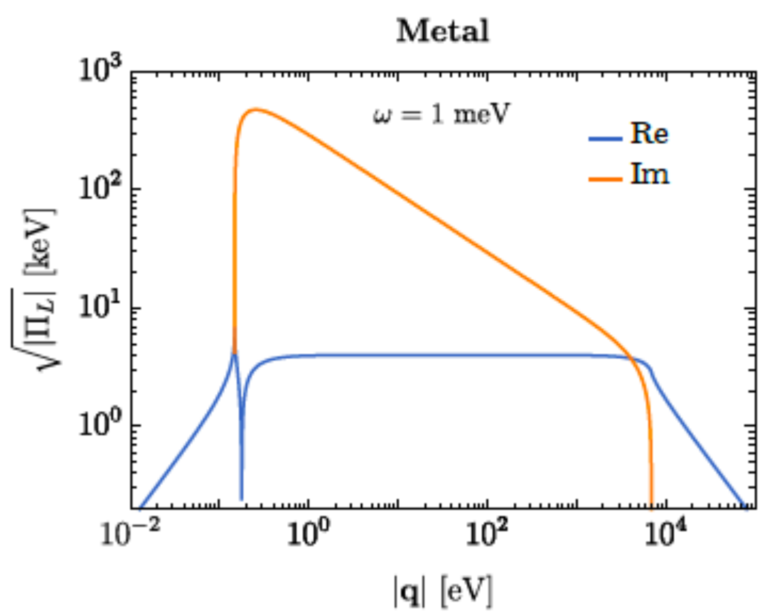
Metals are shiny

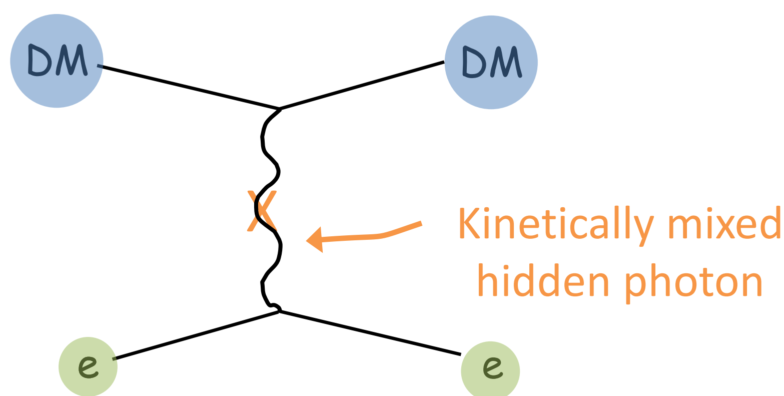
In-medium effects are substantial – photon picks up mass.

If kinetically-mixed hidden photon mediator:

$$\sigma_{\text{scatter}} \propto \frac{1}{(q^2 - m_V^2)^2 (1 - \Pi_L / |\mathbf{q}|^2)^2}$$

In-medium polarization tensor



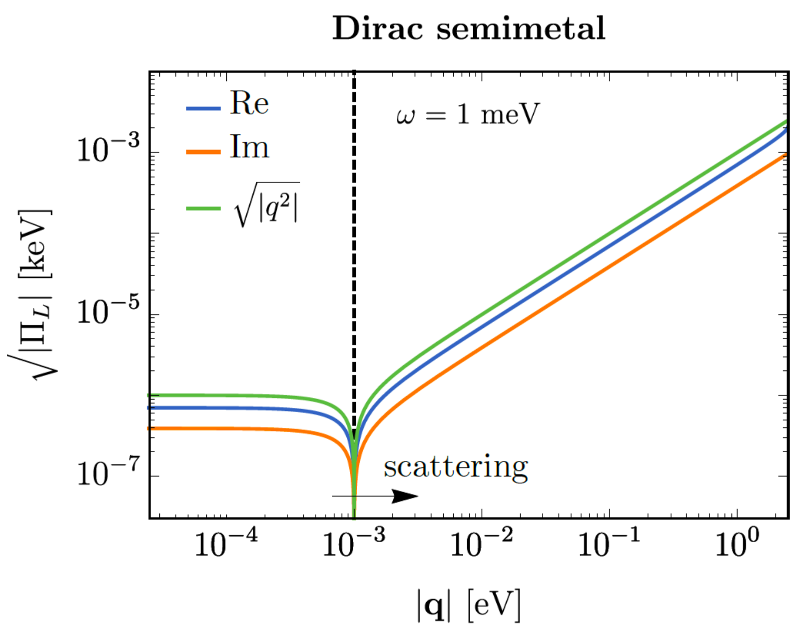


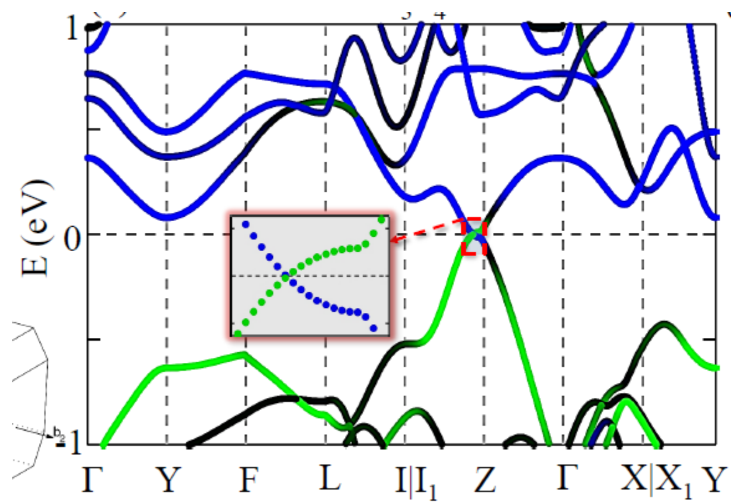
Superconductors take a hit :-(

Dirac materials

- Think of as 3D bulk graphene
- Complementary to superconductors
- Photon remains massless

[**YH,** Kahn, Lisanti, Zurek, Grushin, Ilan, Griffin, Liu, Weber, Neaton, PRD 2017]

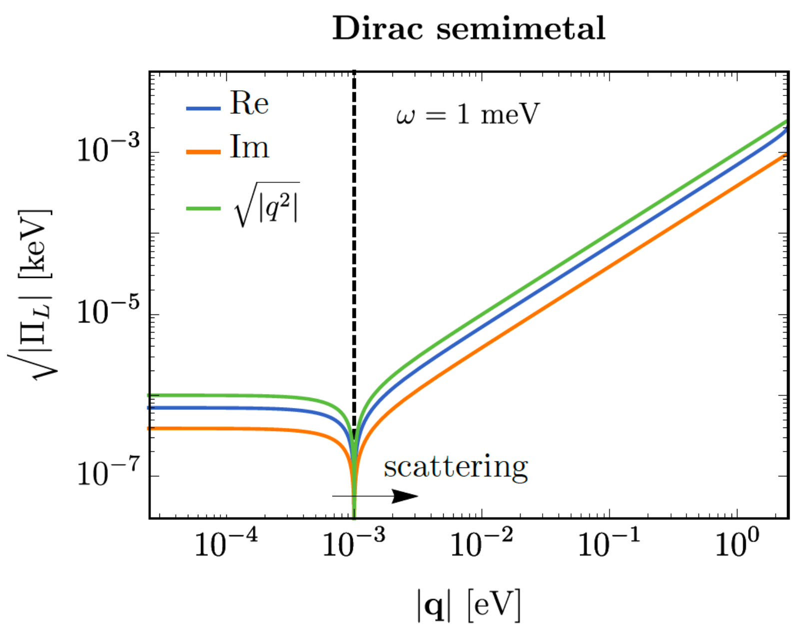


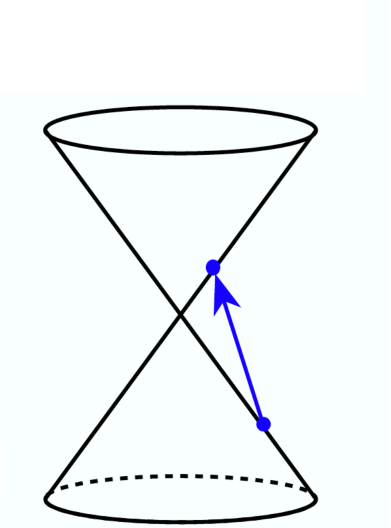


Dirac materials

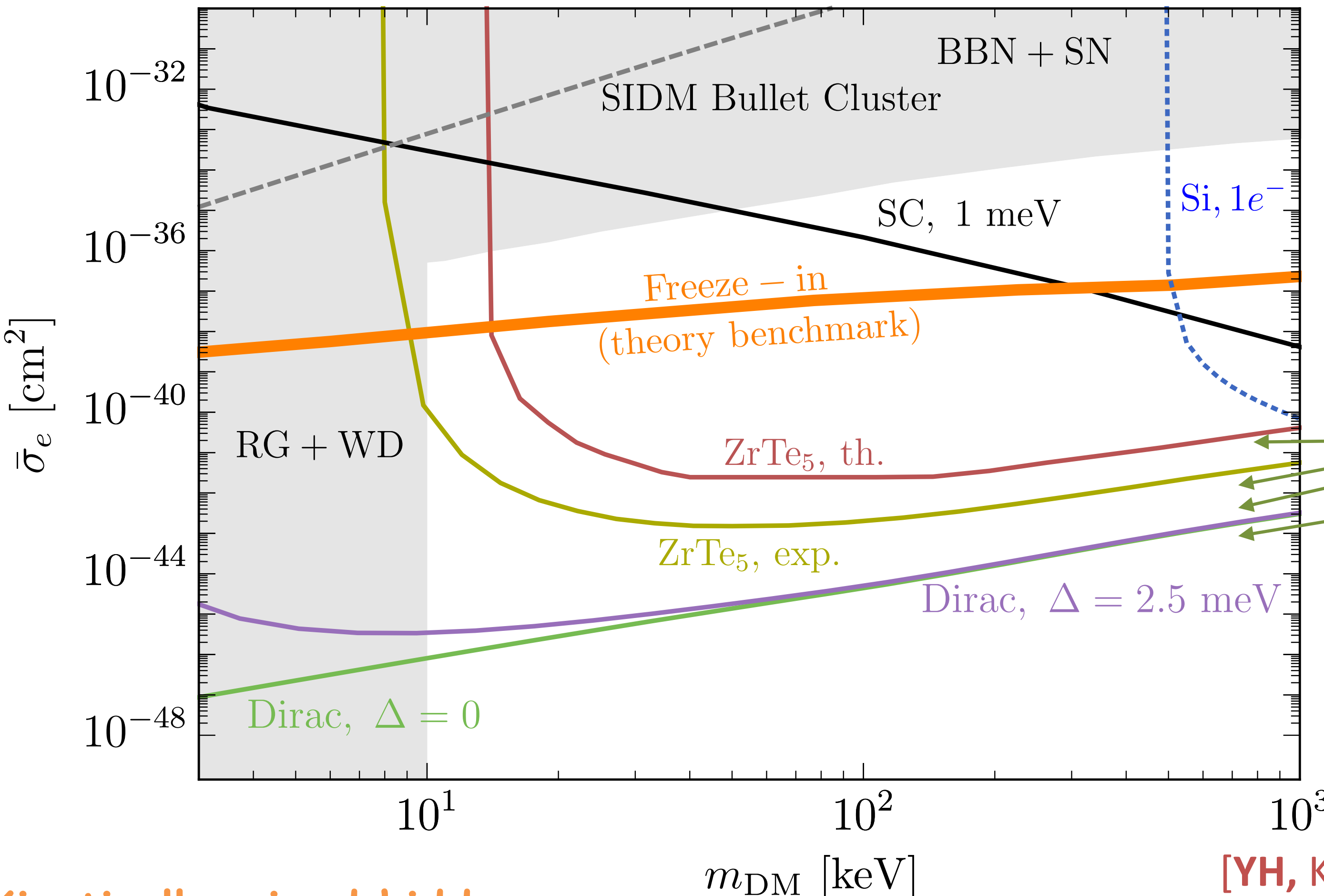
Competing effects:

Lose in phase space, win with reduced optical response





Scattering Reach



[a few events in kg-year exposure]

Amazing reach!

Kinetically mixed hidden photon mediator

[**YH,** Kahn, Lisanti, Zurek, Grushin, Ilan, Griffin,Liu, Weber, Neaton, PRD 2017]

Dirac materials

Experimental setup -- work in progress :-)

Topological properties?
Collect charge/phonons?
Excitation concentration?

[**YH,** Kahn, Lisanti, Zurek……]