

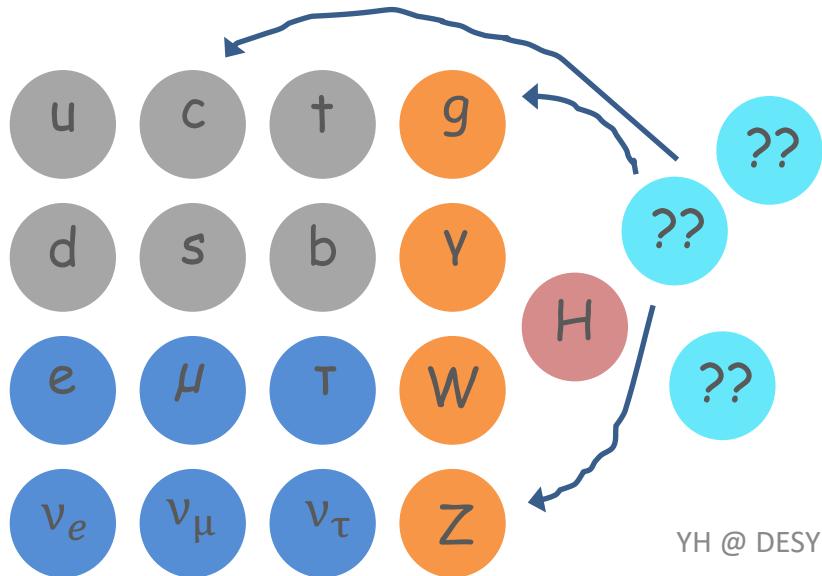
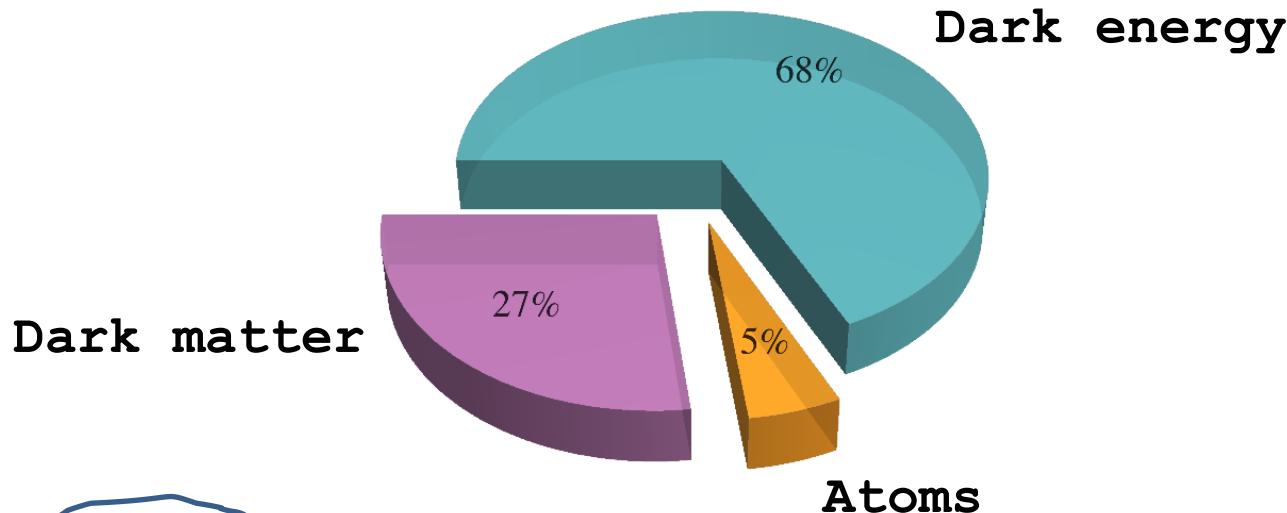
Recent Ideas for (Light) Dark Matter Detection

Yonit Hochberg



האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

The Universe is Dark



What is it?
How does it interact?

Past 40 years

WIMP, glorious WIMP^{*}

*Also axions, of
course also axions :-)

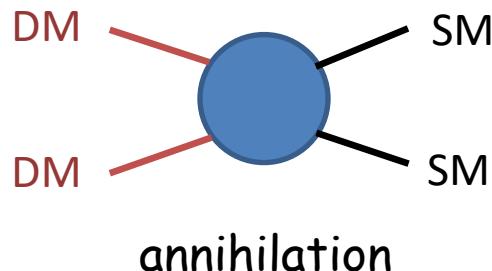
The WIMP

Correct thermal relic abundance:

$$m_{\text{DM}} \sim \alpha \times 30 \text{ TeV}$$

For weak coupling, weak scale emerges.

The dominant paradigm for ~ 40 years.



$$\langle \sigma_{\text{ann}} v \rangle = \frac{\alpha^2}{m_{\text{DM}}^2}$$

Searching for WIMPs

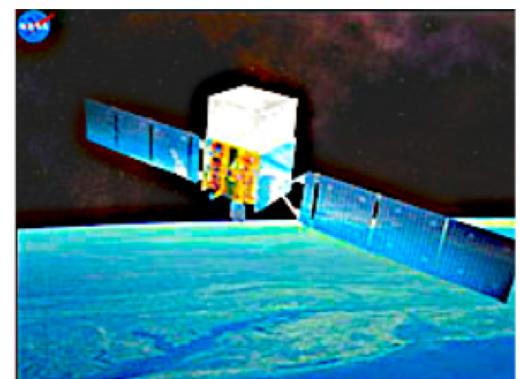
Direct production



Direct detection



Indirect detection

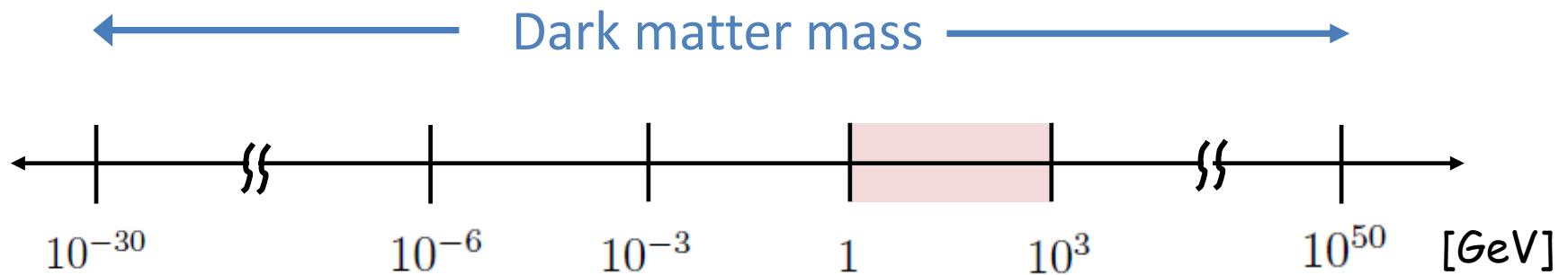


Experiments getting increasingly sensitive

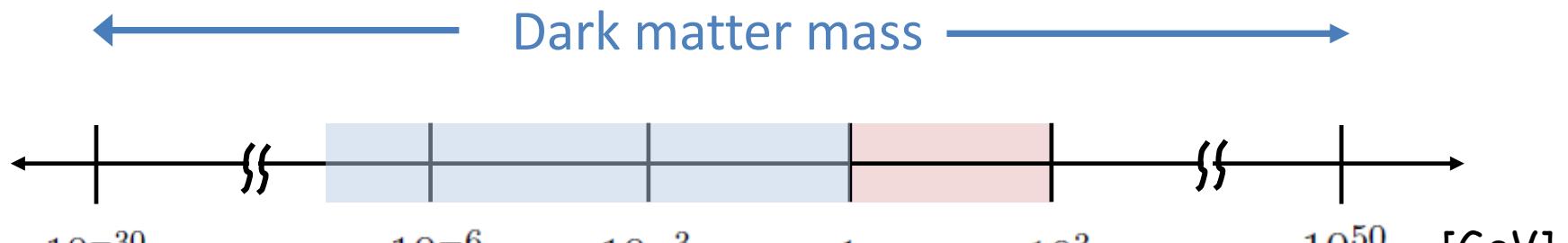
Haven't yet detected dark matter

Great opportunity for new ideas!

Beyond the WIMP



Beyond the WIMP



Lots of activity in recent years:

Theory & Experiment



New Theory Ideas

-
- Weakly coupled WIMPs [Pospelov, Ritz, Voloshin 2007; Feng, Kumar 2008]
- Asymmetric dark matter [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

How to detect?

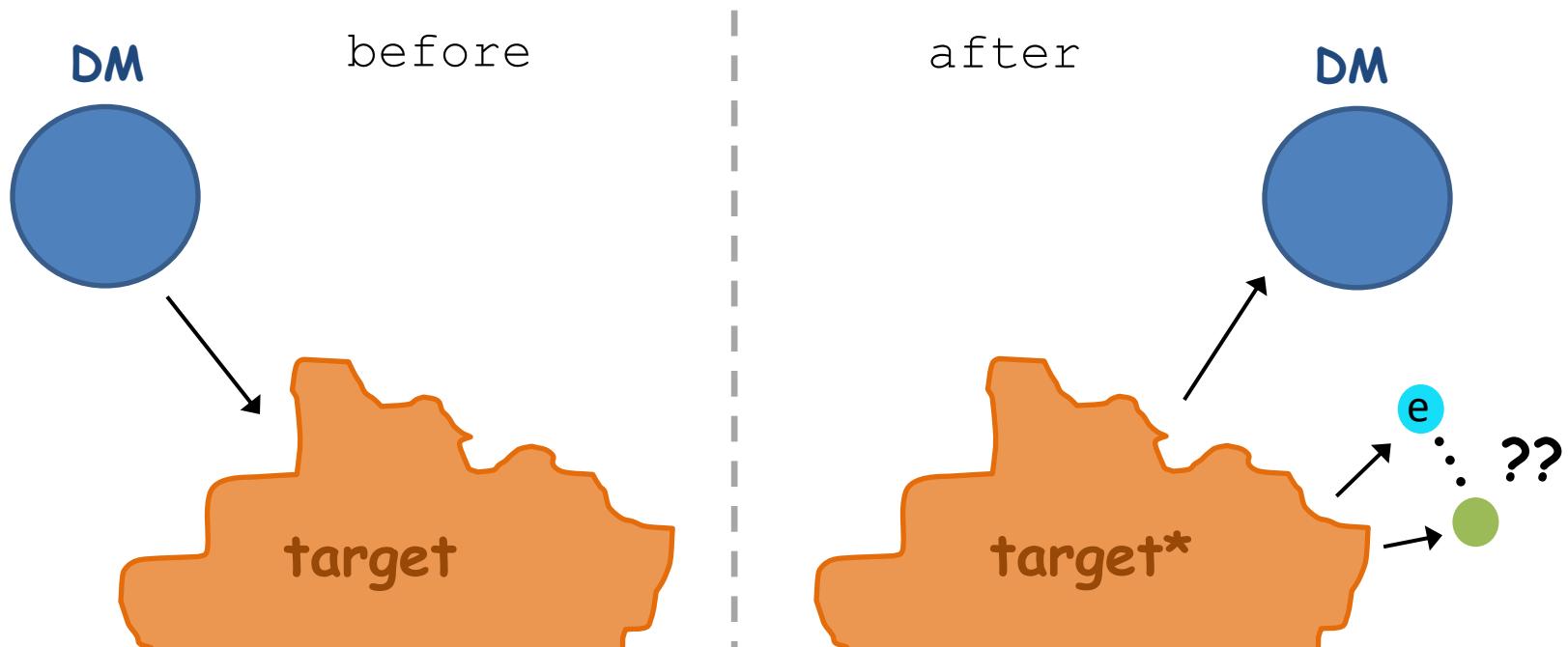
Detection Blueprints

Dark matter particle comes in

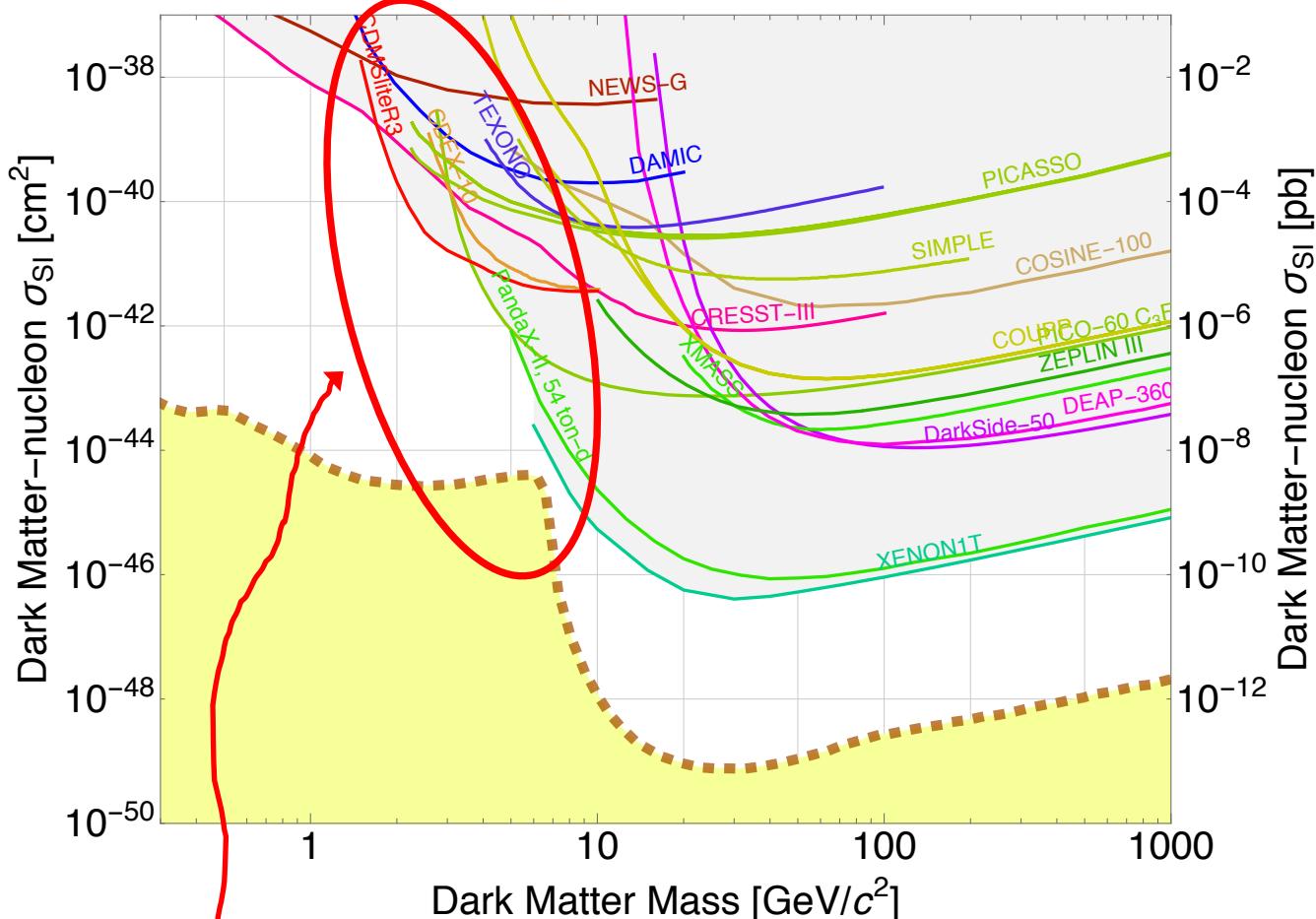
Hits a target in the lab

System reacts

Measure the reaction



Direct Detection

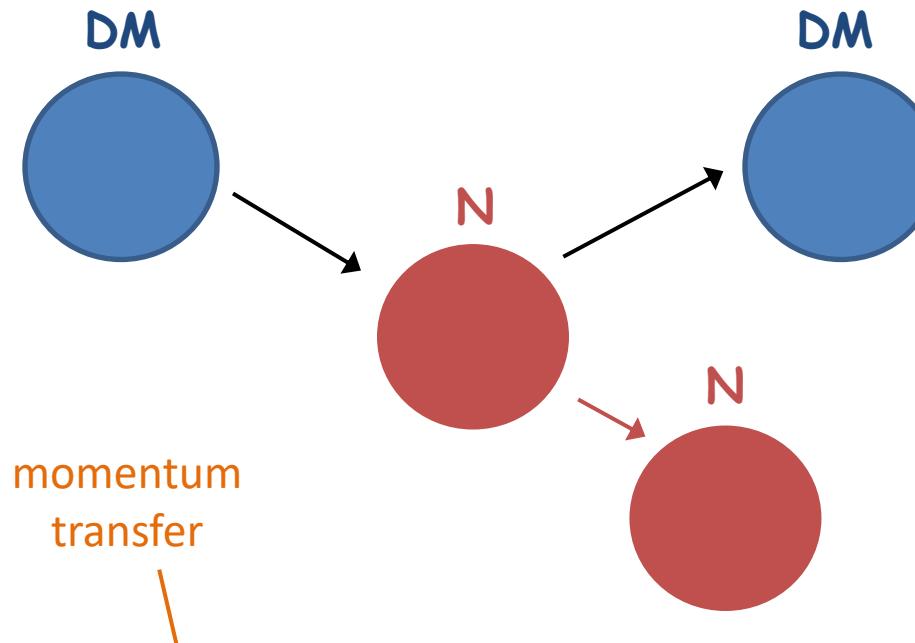


What's going on?

[website: supercdms.slac.stanford.edu/dark-matter-limit-plotter]

Current Experiments

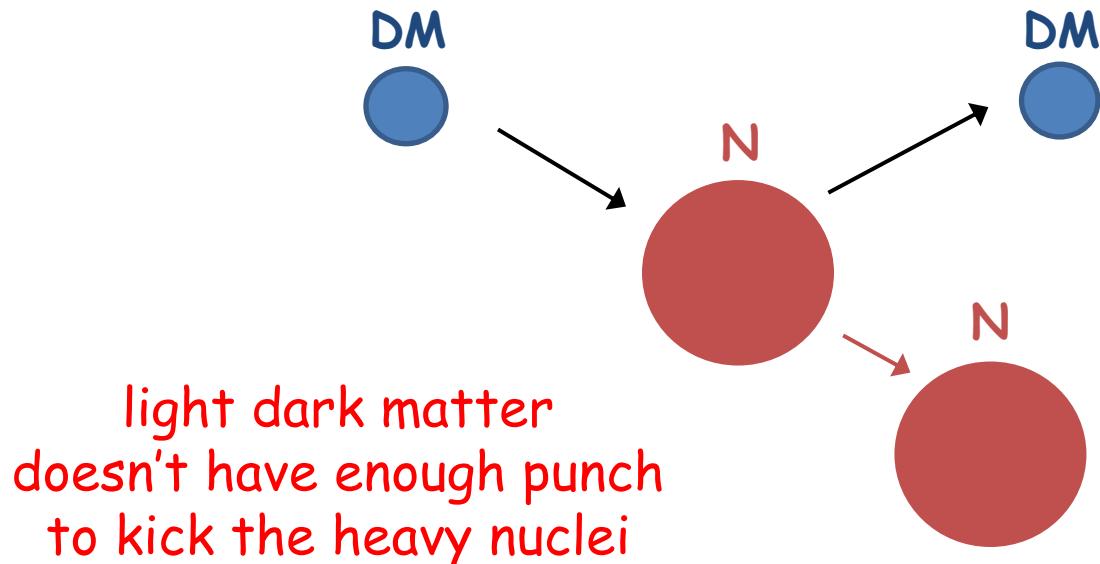
Looking for nuclear recoils:
think billiard balls



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

Current Experiments

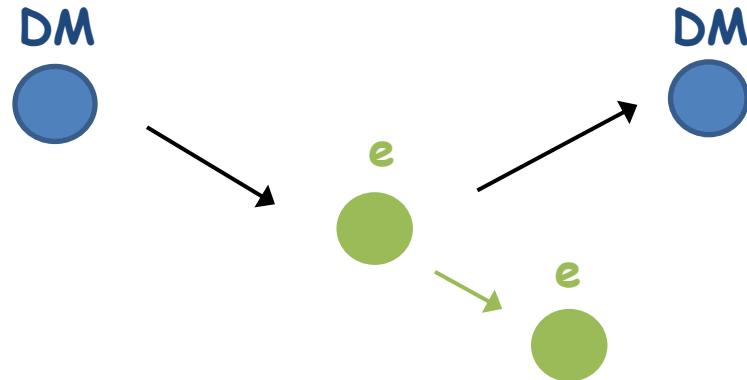
Looking for nuclear recoils:
think billiard balls



Lose sensitivity @ $O(\text{GeV})$ masses

New Avenues

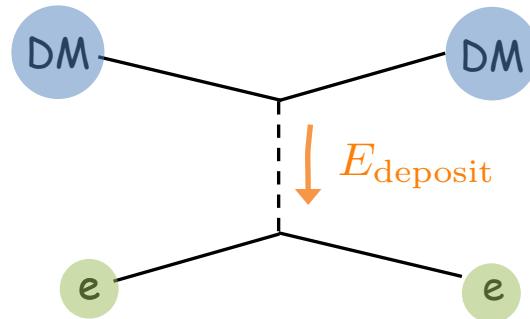
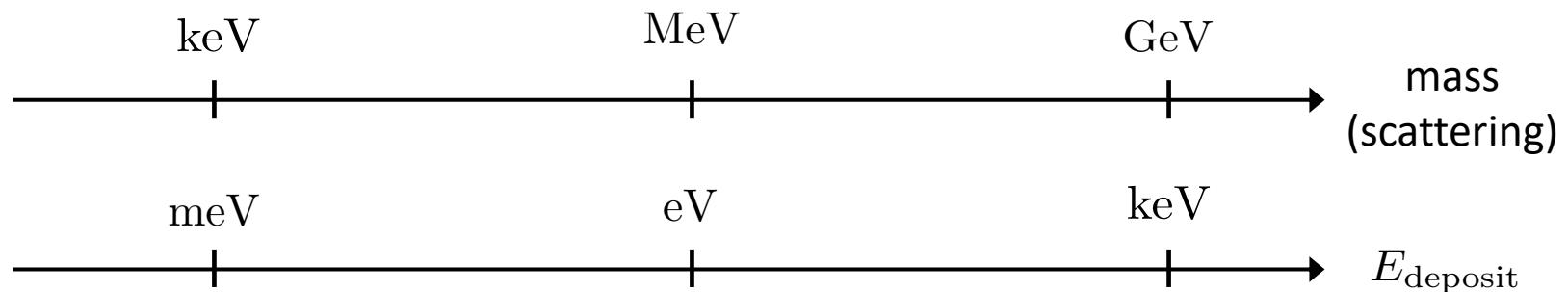
Light dark matter: scatter off electrons!



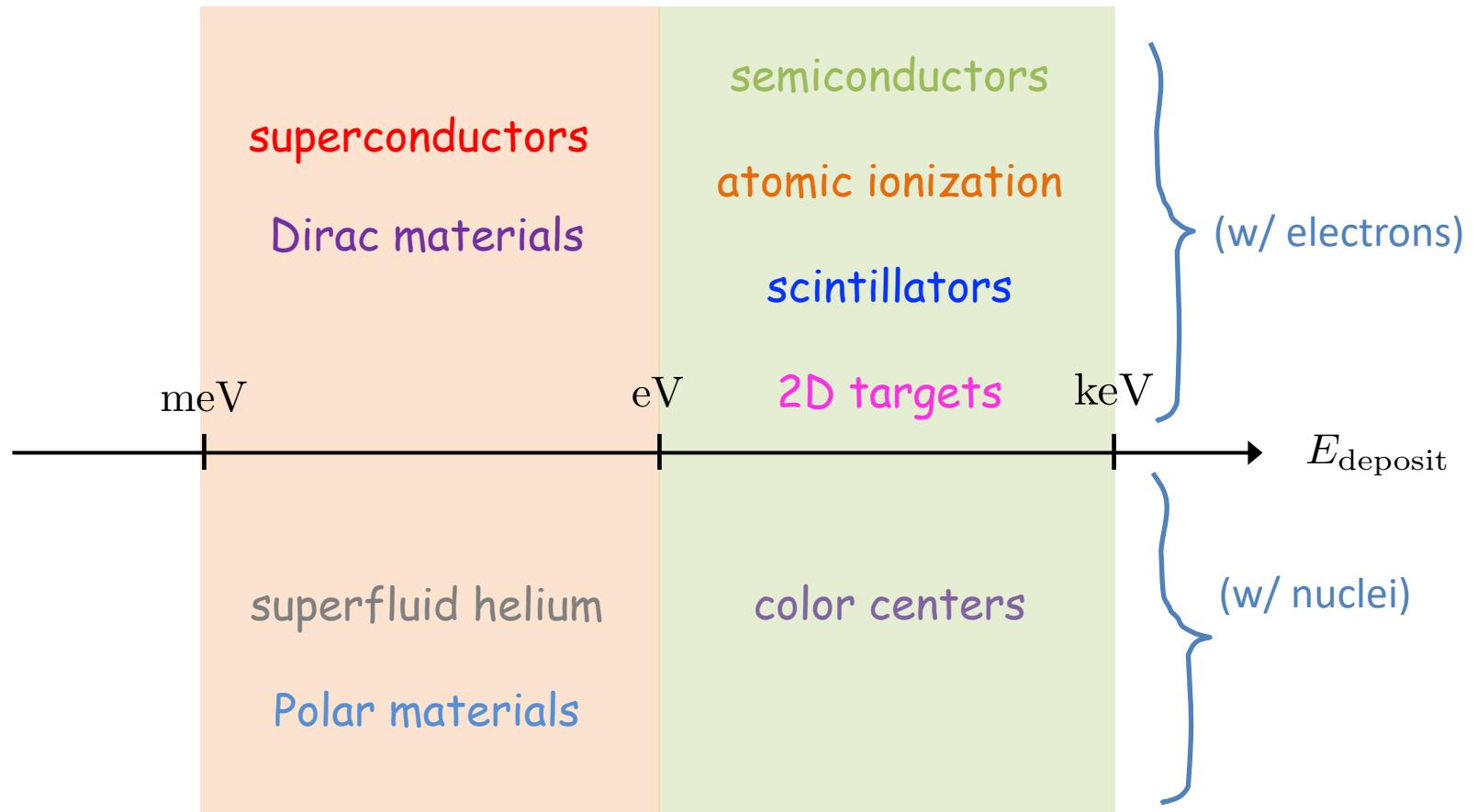
light dark matter
can give enough punch
to kick the light electrons

Energy guideline

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



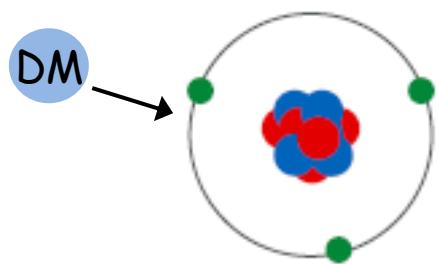
New proposals



Explosion of interest and ideas in recent times

Ex. #1: First ideas

Atomic ionization

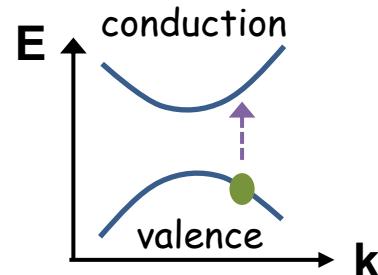


Xenon: ~12 eV

$$m_{\text{DM}} \gtrsim 10 \text{ MeV}$$

[Essig, Mardon, Volansky, 2012]

Semiconductors



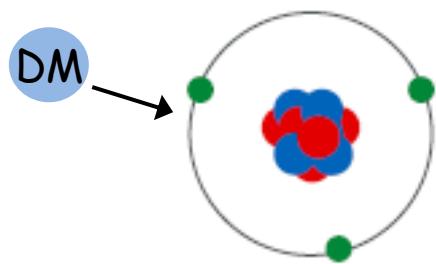
Ge, Si, Diamond, SiC: ~eV

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

[Essig , Mardon, Volansky, 2012;
Graham, Kaplan, Rajendran, Walters, 2012;
Kurinsky, Yu, **YH**, Blas, 2019;
Griffin, **YH**, et al, 2020]

Ex. #1: First ideas

Atomic ionization



Xenon10/100/1T

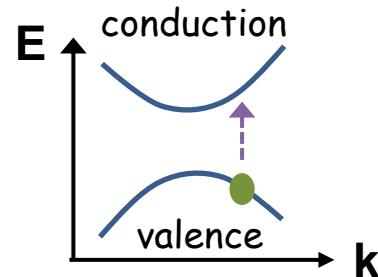
$$m_{\text{DM}} \gtrsim 10 \text{ MeV}$$

[Essig, Mardon, Volansky, 2012]

[Essig et al, 2012]

[Xenon100, 2016 & Xenon1T 2020]

Semiconductors



SuperCDMS,
SENSEI

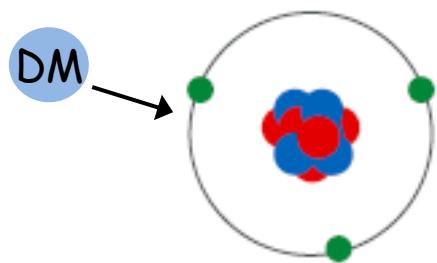
$$m_{\text{DM}} \gtrsim \text{MeV}$$

Are being experimentally realized

[Essig , Mardon, Volansky, 2012;
Graham, Kaplan, Rajendran, Walters, 2012;
Kurinsky, Yu, **YH**, Blas, 2019;
Griffin, **YH**, et al, 2020]
[SuperCDMS 2020 & SENSEI 2020]

Ex. #1: First ideas

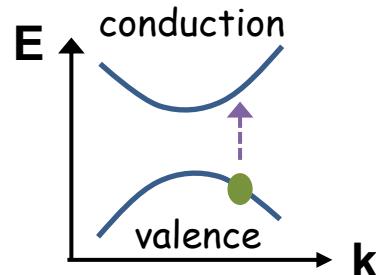
Atomic ionization



Xenon 10/100/1T

$$m_{\text{DM}} \gtrsim 10 \text{ MeV}$$

Semiconductors



SuperCDMS,
SENSEI

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

Smaller masses?

Ex. #2: Superconductors

- Ground state = Cooper pairs;
Binding energy (gap) \sim meV $\longrightarrow m_{\text{DM}} \sim \text{keV}$
- The idea:
DM scatters with Cooper pairs, deposits enough energy,
breaks Cooper pairs \rightarrow detect

Excitations

Excitation concentration
philosophy

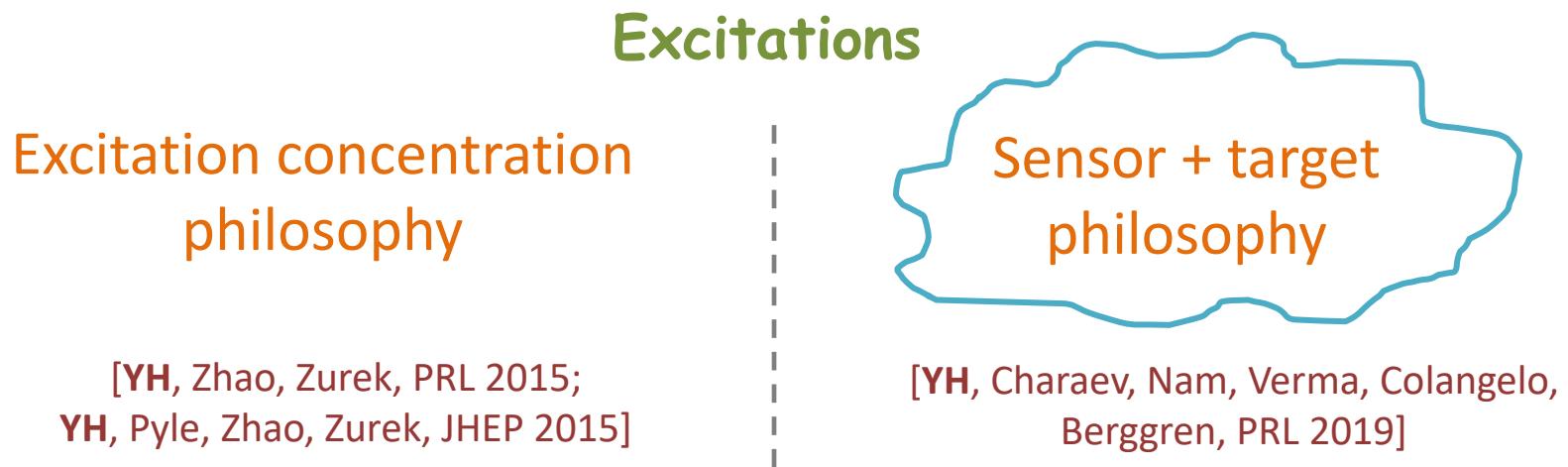
[YH, Zhao, Zurek, PRL 2015;
YH, Pyle, Zhao, Zurek, JHEP 2015]

Sensor + target
philosophy

[YH, Charaev, Nam, Verma, Colangelo,
Berggren, PRL 2019]

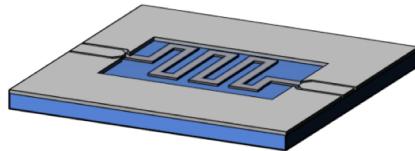
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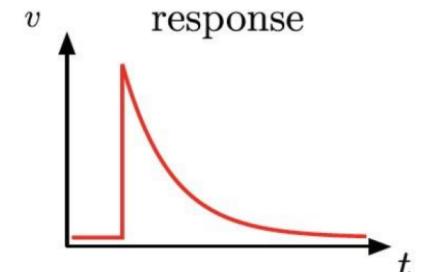
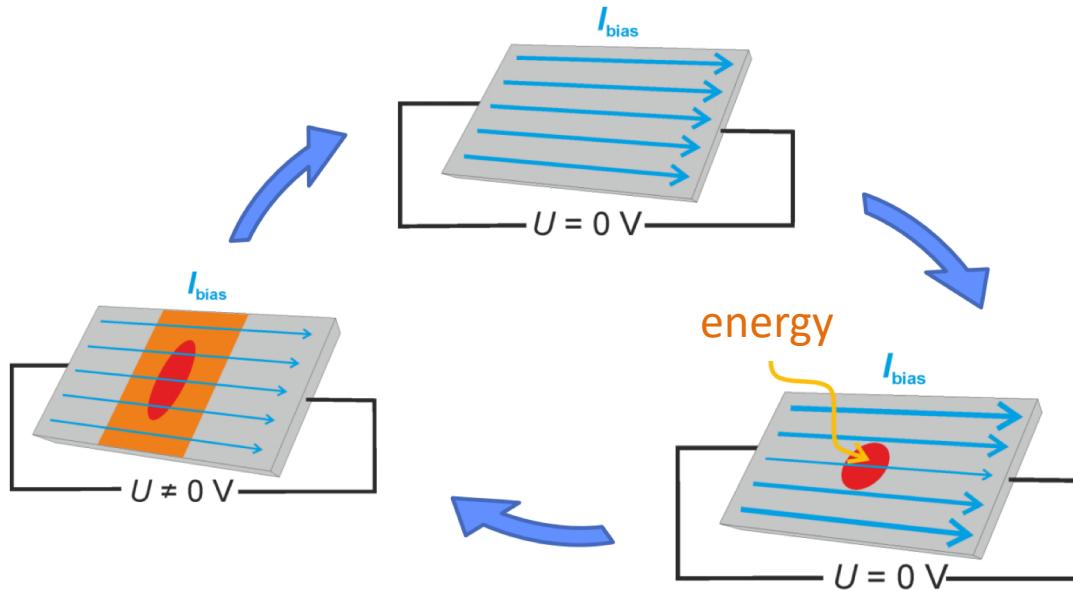
Ex. #2: Superconductors

- Superconducting Nanowire Single Photon Detectors (SNSPDs)



Broadly used in quantum information science

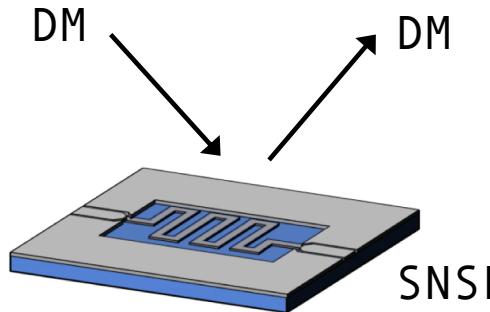
- Ram an electron, create a hotspot, electrons diffuse away, resistive region across the nanowire → voltage pulse



[YH, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019]

Ex. #2: Superconductors

Use as simultaneous target + sensor (& multiplex)

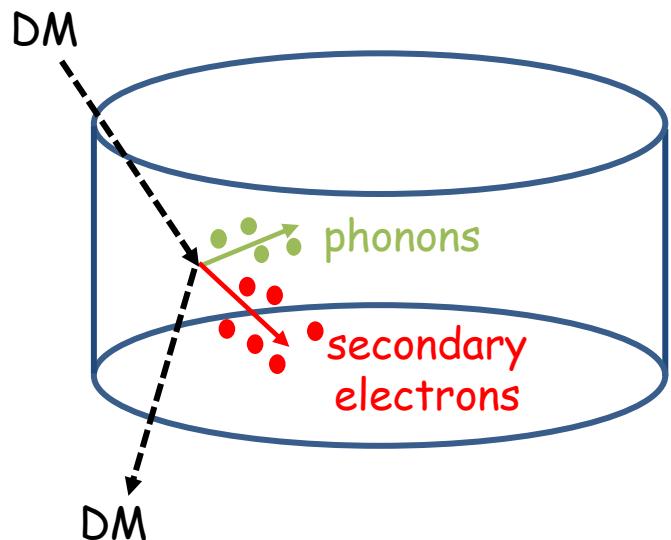


[Existing prototype]

[YH, Charaev, Nam, Verma,
Colangelo, Berggren, PRL 2019]

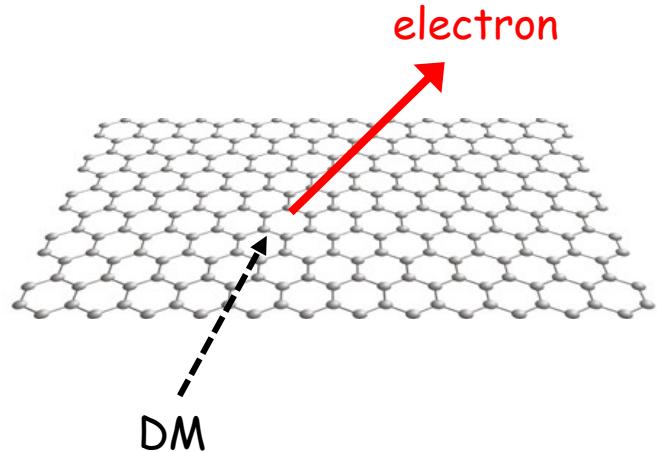
Directional Info?

Lose directional information
if detecting secondaries



e.g. semiconductors,
bulk superconductors

Retain directional information
if observe primary!



2D targets;
graphene (& SNSPDs)

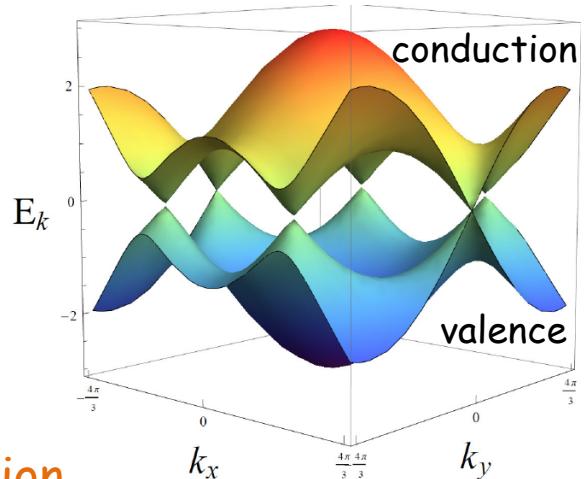
Ex. #3: Graphene

- 2D material with vanishing bandgap
- To eject electron: $E_{\text{eject}} = E_b + \Phi \sim \text{eV}$

Binding energy Work function,
 $O(\text{eV})$

→ Sensitivity to $m_{\text{DM}} \sim \text{MeV}$

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



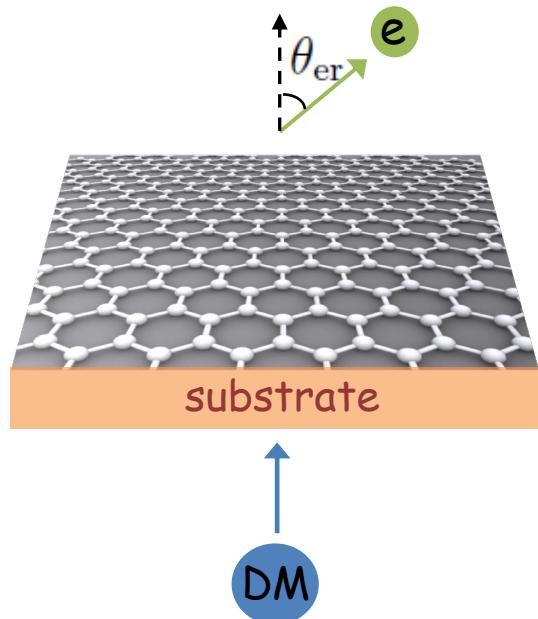
[YH, Kahn, Lisanti, Tully, Zurek, 2017]

Ex. #3: Graphene

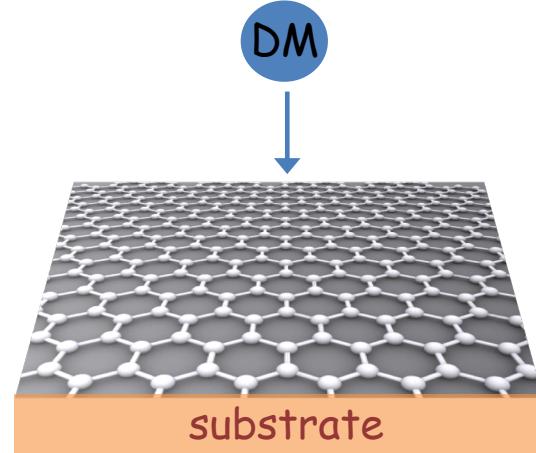
Electron follows incoming dark matter direction.

Naturally gives forward/backward discrimination
(separates signal from background)

Electron detected



electron not detected

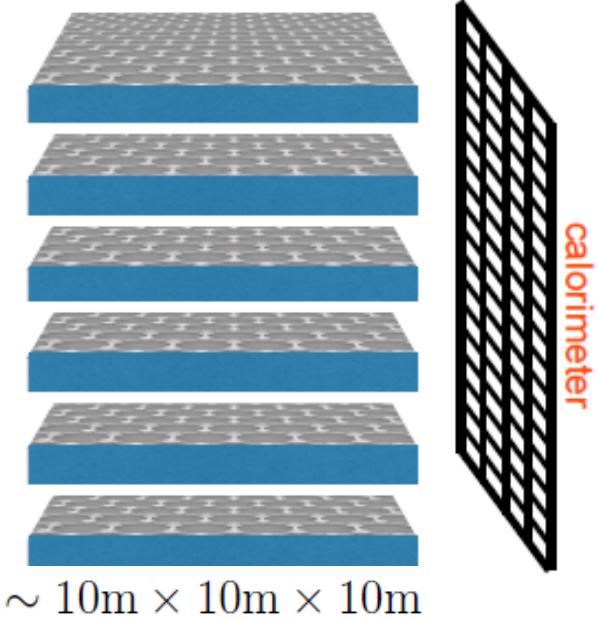
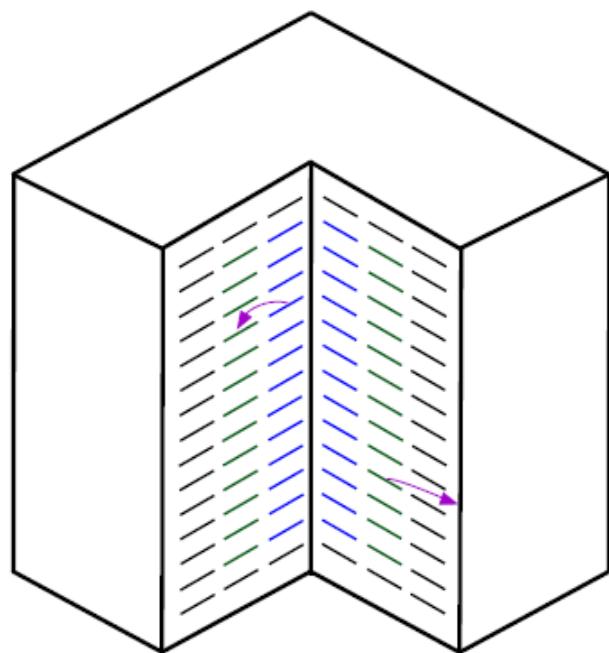


12 hours later

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

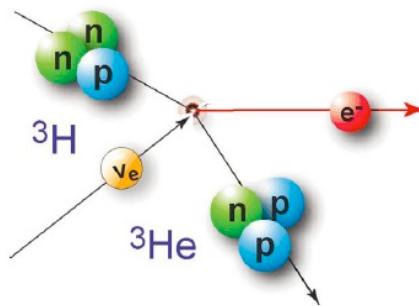
Ex. #3: Design Concept

- $\sim 0.5 \text{ kg graphene} = \text{area of Jerusalem old city} = \text{billions of cm}^2 \text{ crystals}$
- Compact geometry: large mass via many stacks



Implement in PTOLEMY

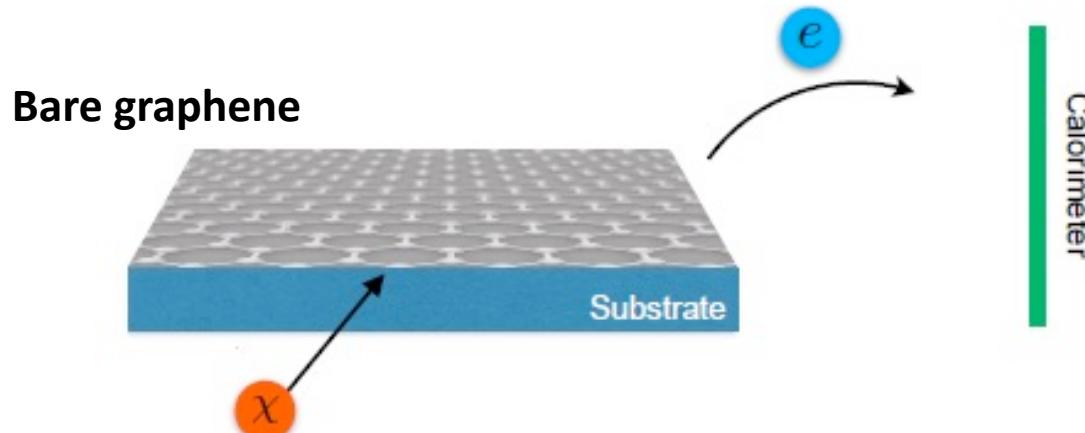
Experiment to detect relic neutrinos via capture on tritium.



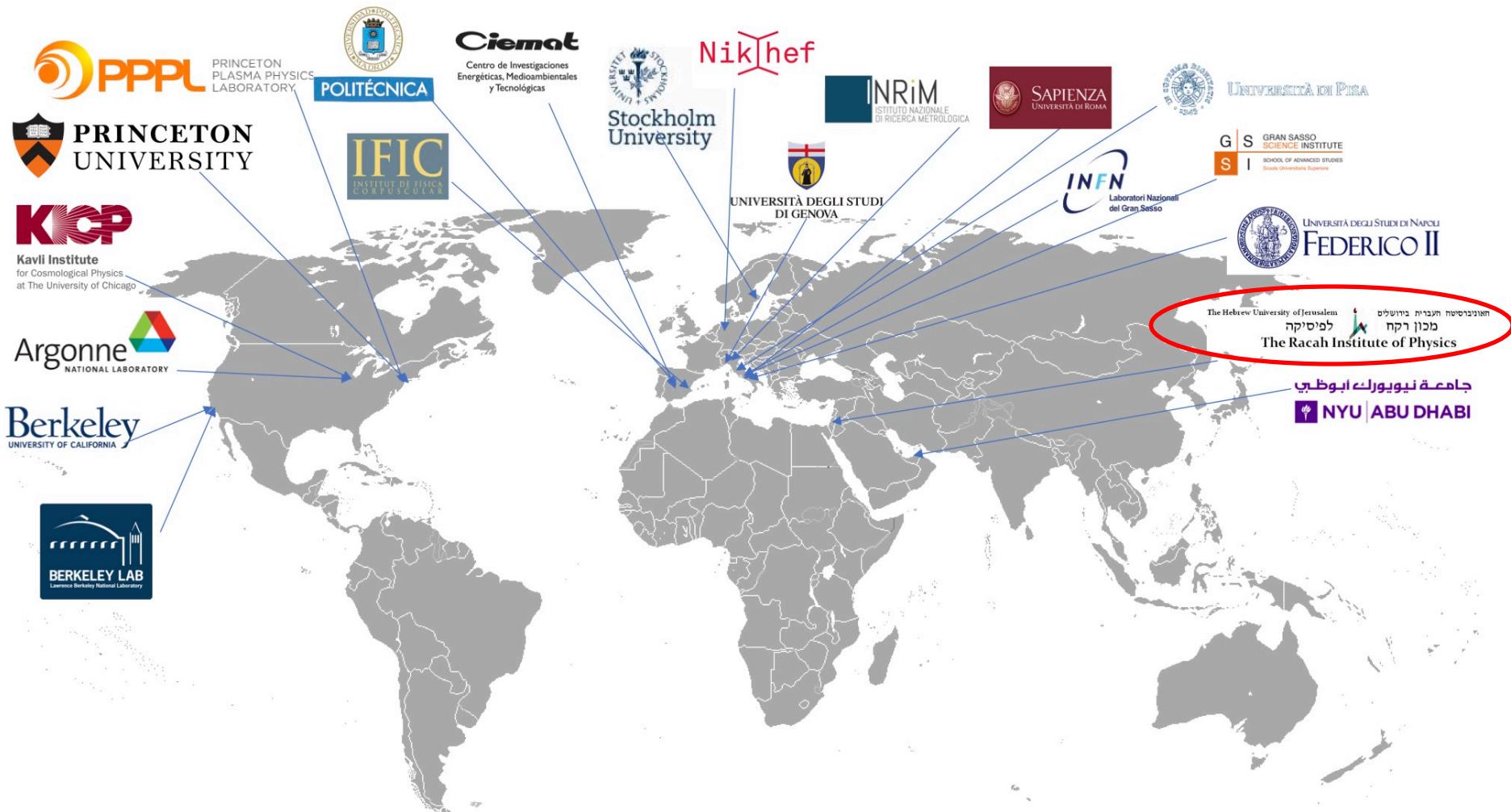
[Betts et al, 2013]

Will use tritiated graphene (~ 0.5 kg).

Borrow pure (un-tritiated) graphene for dark matter experiment!



PTOLEMY world map



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

Compute Event Rate

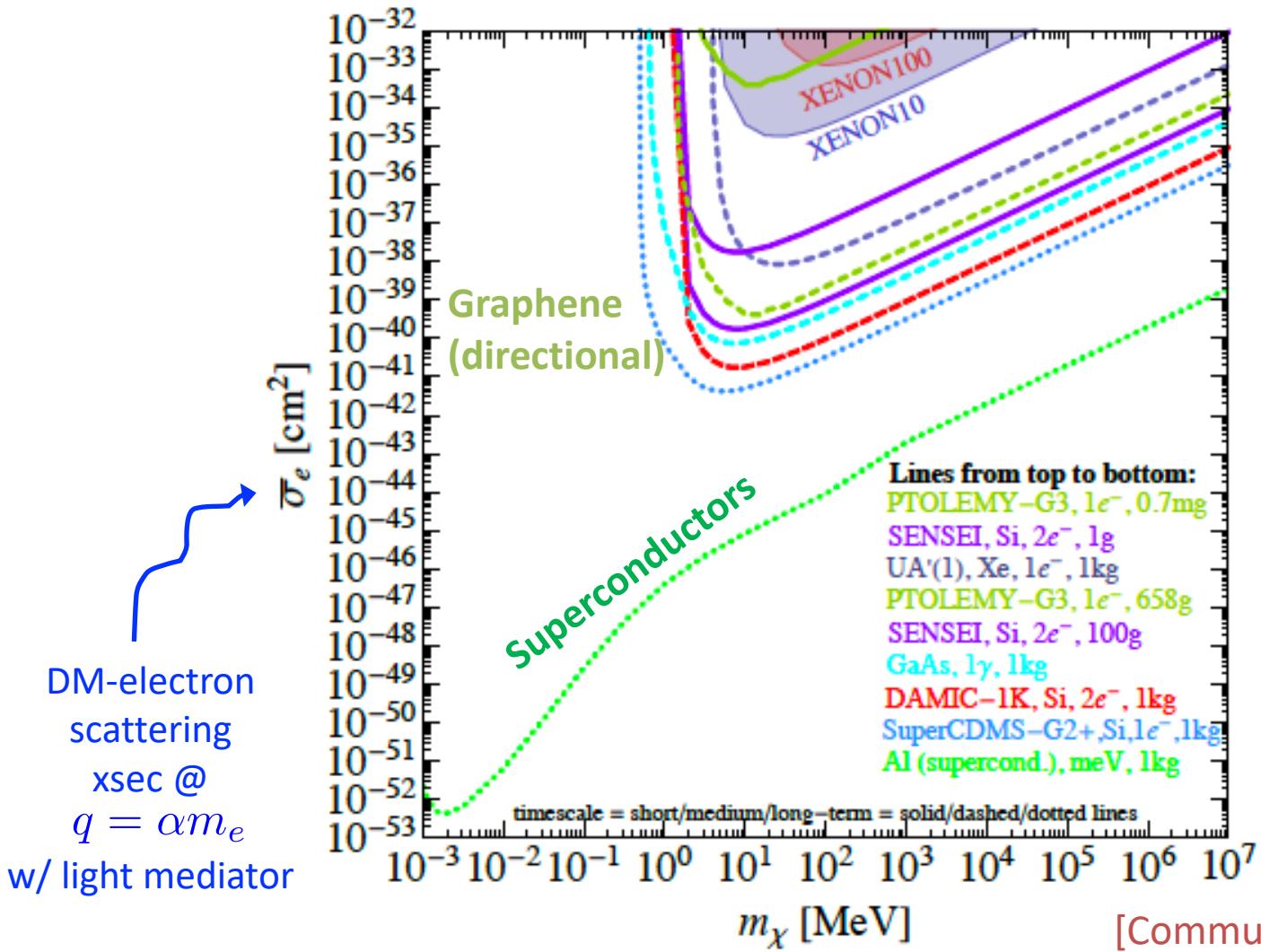
[Events/unit time/unit mass]

$$\text{Rate} \propto \frac{1}{\rho_{\text{target}}} \times \frac{\rho_{\text{DM}}}{m_{\text{DM}}} \times v_{\text{DM}} \times \underbrace{\text{target properties}}_{\substack{\text{condensed matter} \\ \text{physics}}} \times \underbrace{\sigma_{\text{int}}}_{\substack{\text{particle physics}}}$$

Target density dark matter flux (astrophysics) condensed matter physics particle physics

Target density dark matter flux (astrophysics) condensed matter physics particle physics

Scattering Reach

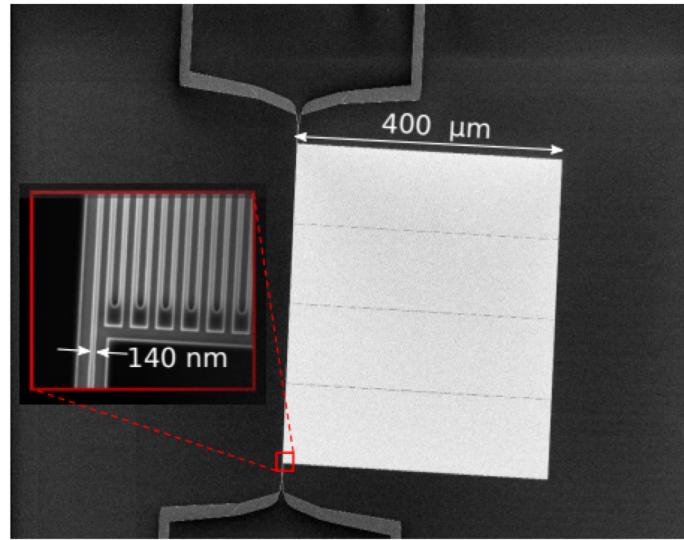


[a few events in kg-year exposure]

Amazing reach!

Existing Prototype Device

WSi SNSPD, 4.3 nanogram, 0.8 eV threshold,
no dark counts in 10000 seconds (~3 hours)



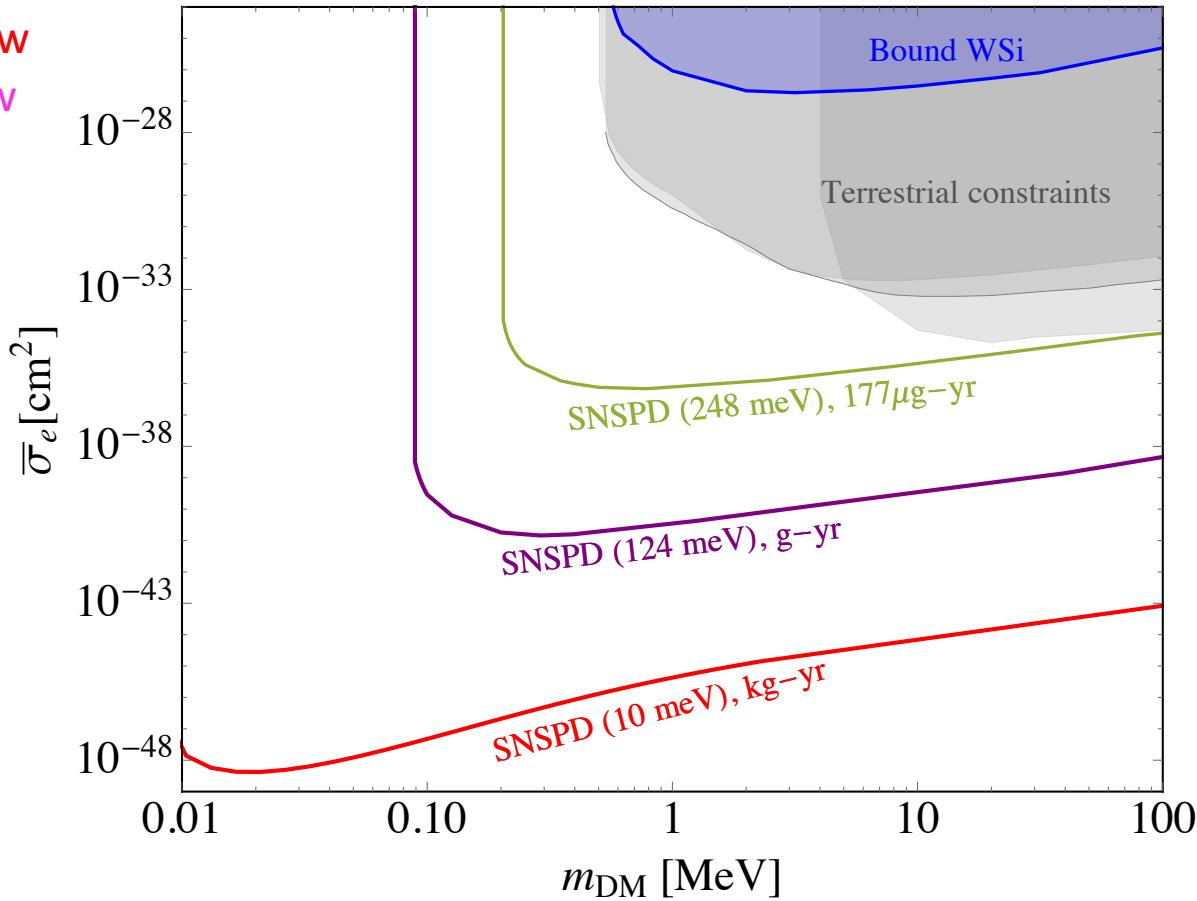
[YH, Charaev, Nam,
Verma, Colangelo,
Berggren,
PRL 2019]

Scattering Reach

Colored curves:

Large array, low
threshold, low
dark count
SNSPDs

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



New bound:
WSi SNSPD
prototype
4.3ng in 3 hours

[YH, Charaev, Nam,
Verma, Colangelo,
Berggren,
PRL 2019]

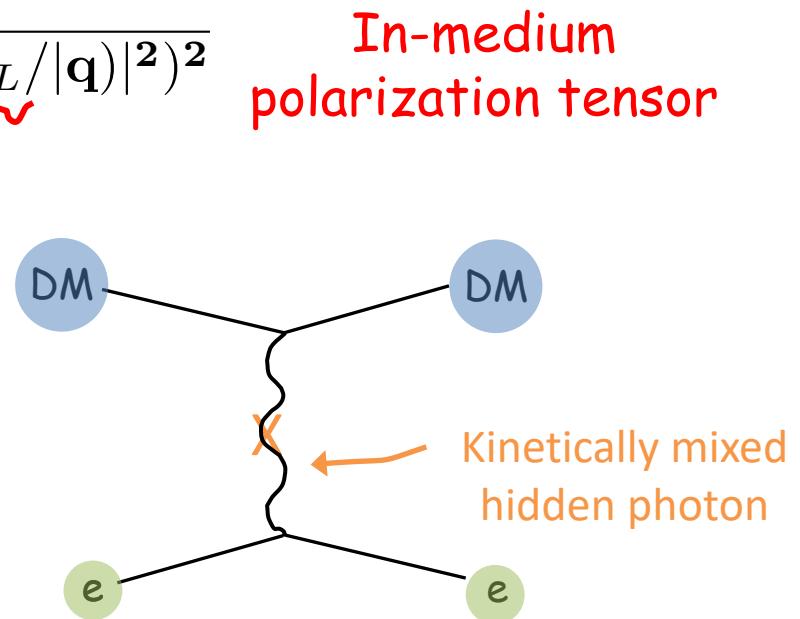
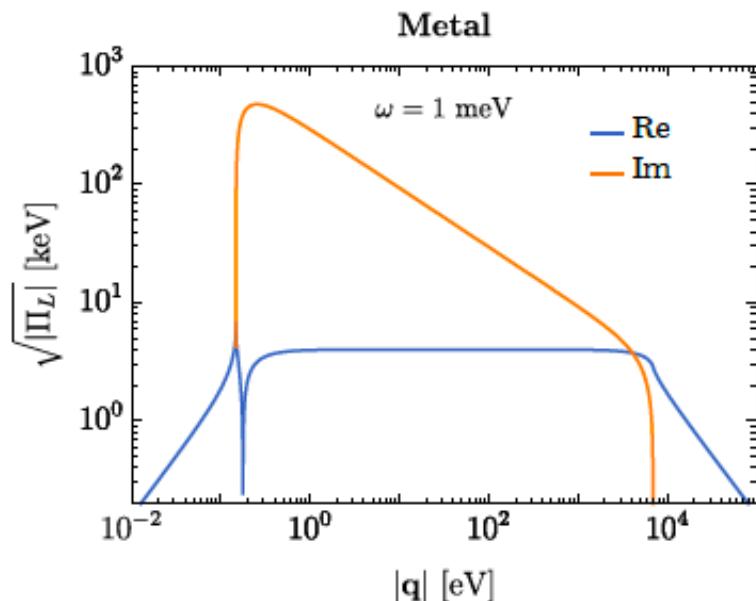
Downside?

Metals are shiny

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

If kinetically-mixed hidden photon mediator:

$$\sigma_{\text{scatter}} \propto \frac{1}{(q^2 - m_V^2)^2 (1 - \underbrace{\Pi_L / |\mathbf{q}|^2}_\text{In-medium polarization tensor})^2}$$

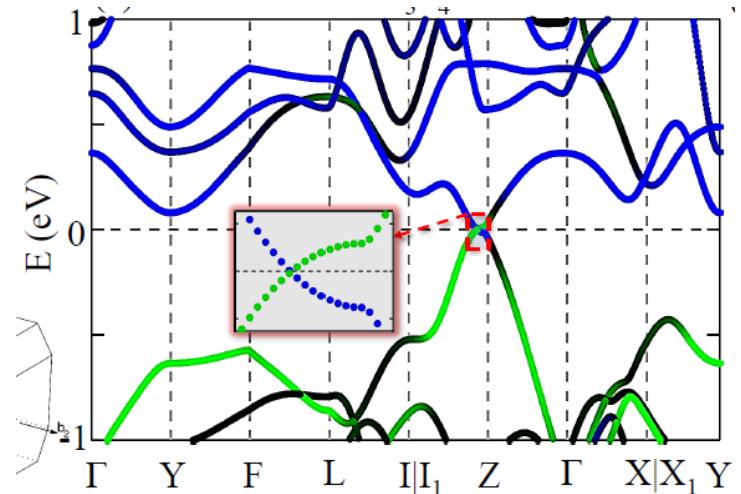
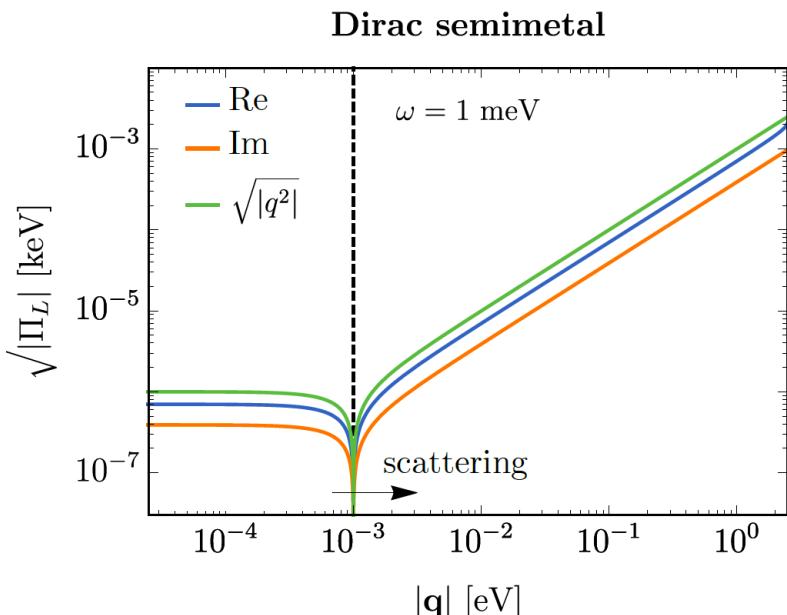


Superconductors take a hit :-(

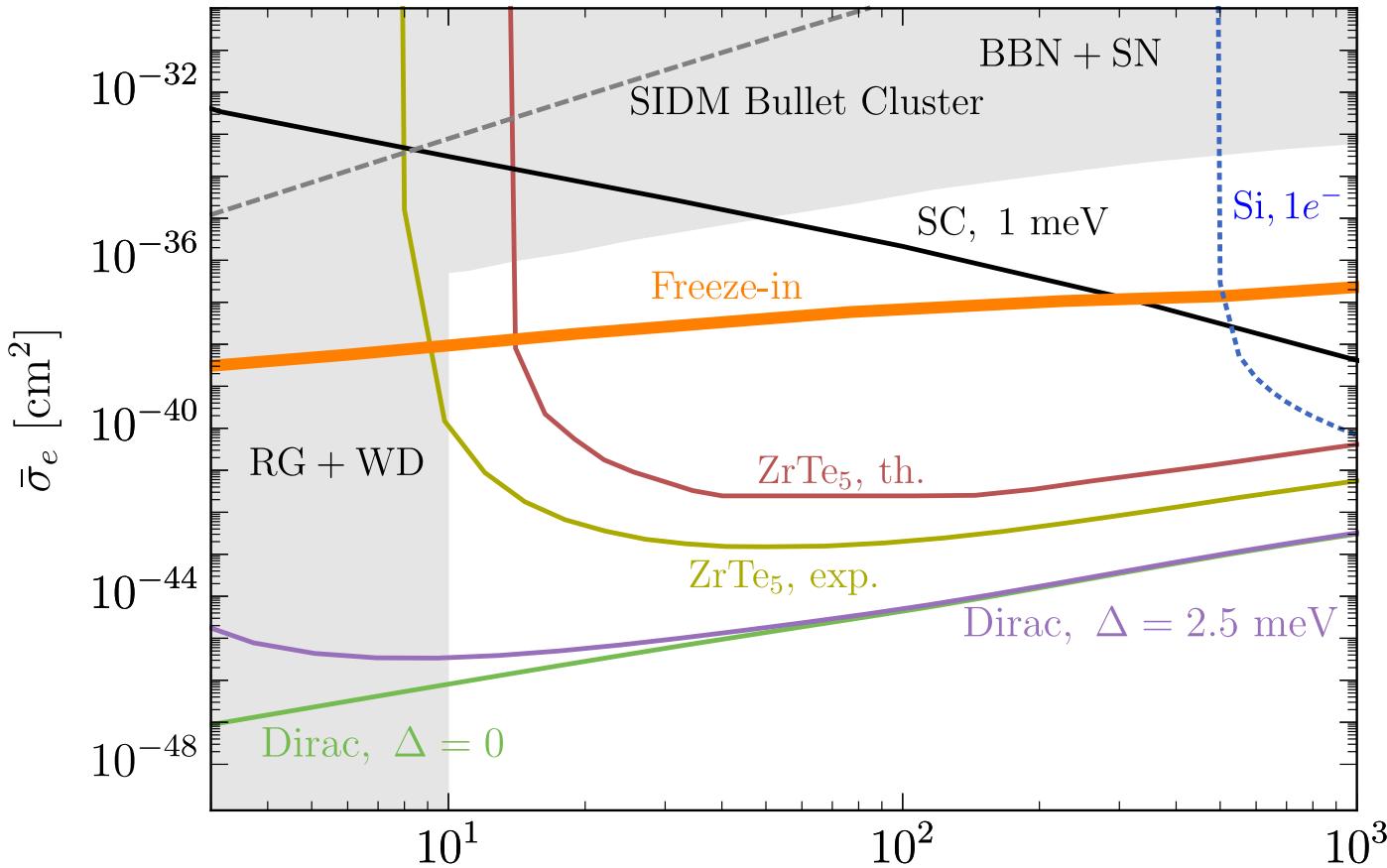
Ex. #4: Dirac materials

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

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



Scattering Reach



Kinetically mixed hidden
photon mediator

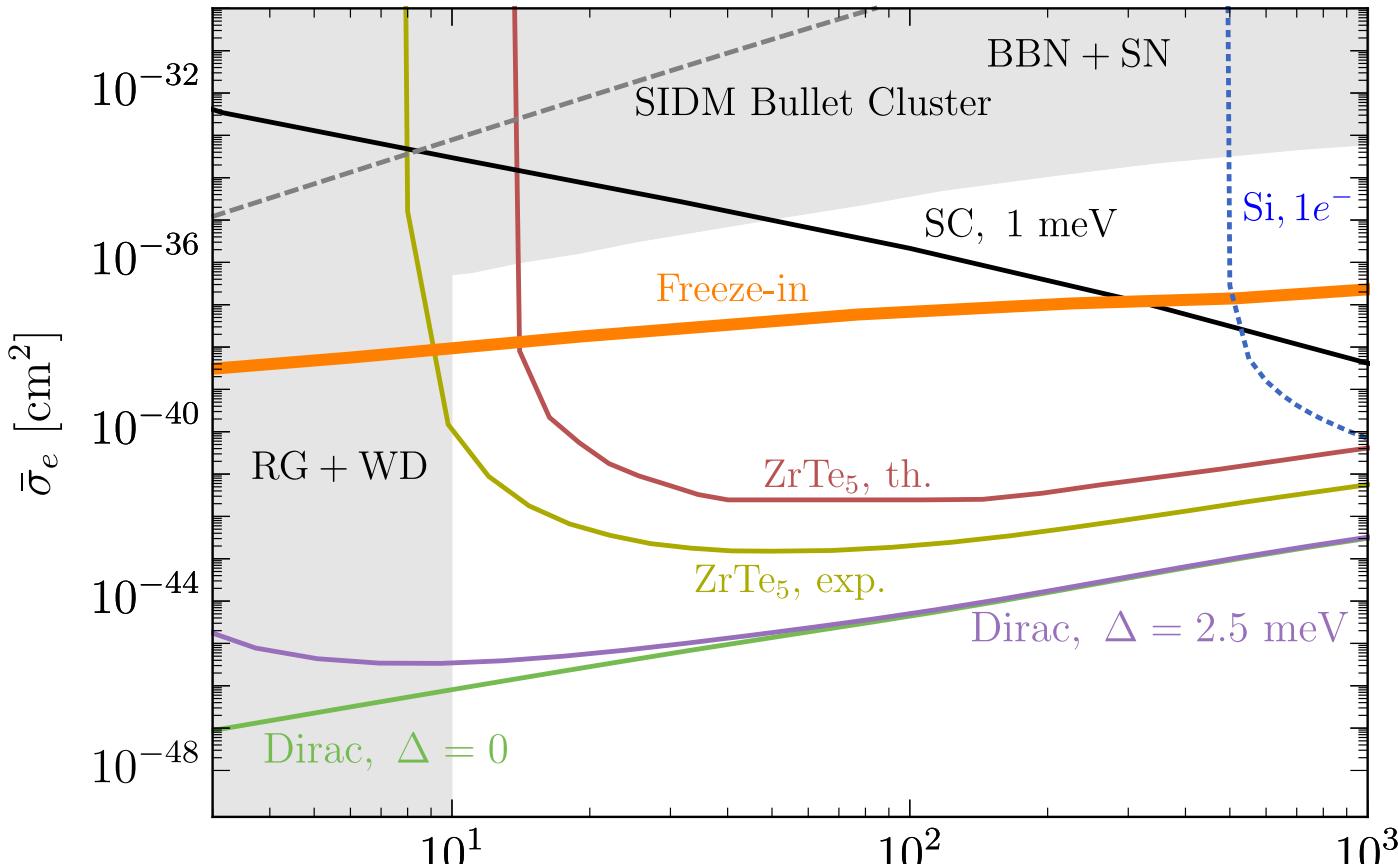
m_χ [keV]

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

[a few events in
kg-year
exposure]

Amazing
reach!

Scattering Reach



Kinetically mixed hidden
photon mediator

m_χ [keV]

[YH, Kahn, Lisanti, Zurek,
Grushin, Ilan, Griffin, Liu,
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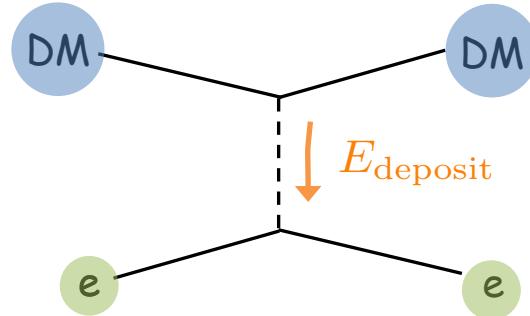
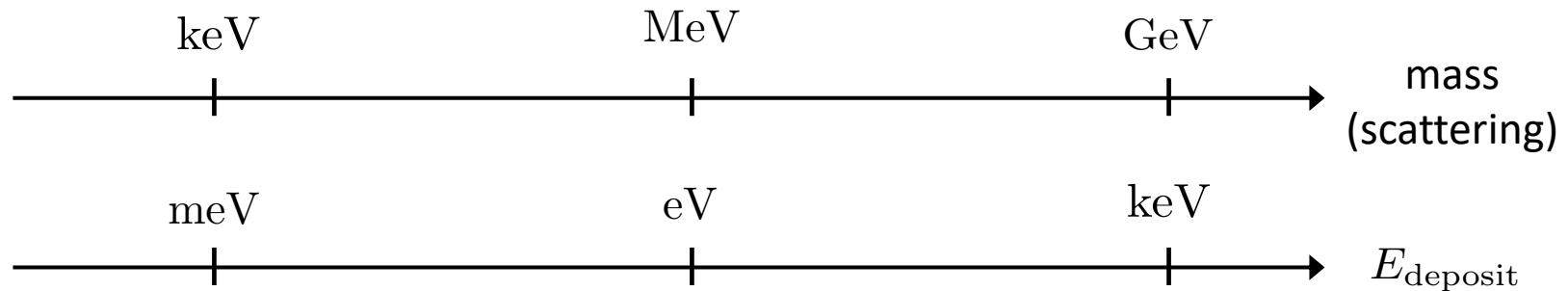
Directional
detection

[Geilhuff et al;
Coskuner et al;
2019]

Any given target material can go even further.

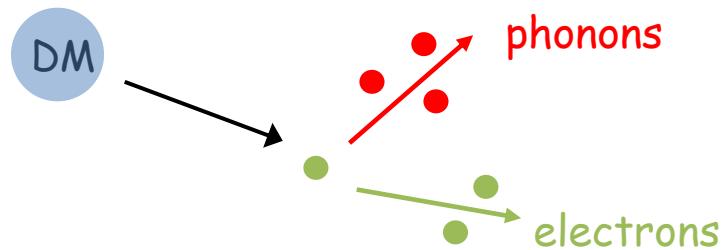
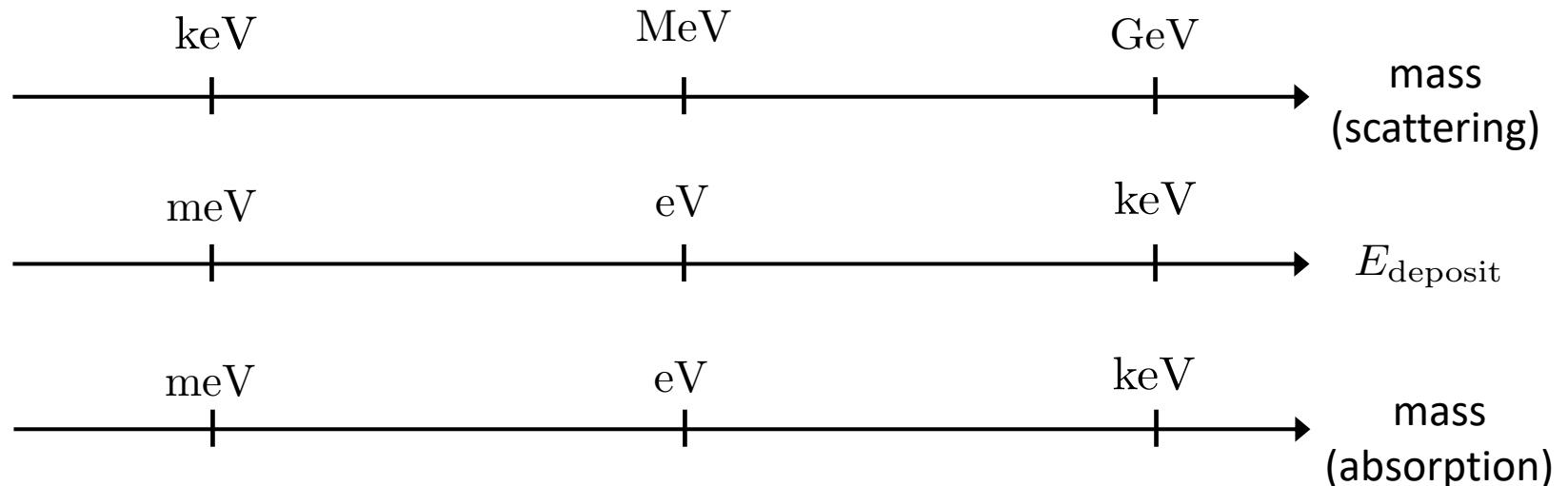
Absorption vs. Scattering

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



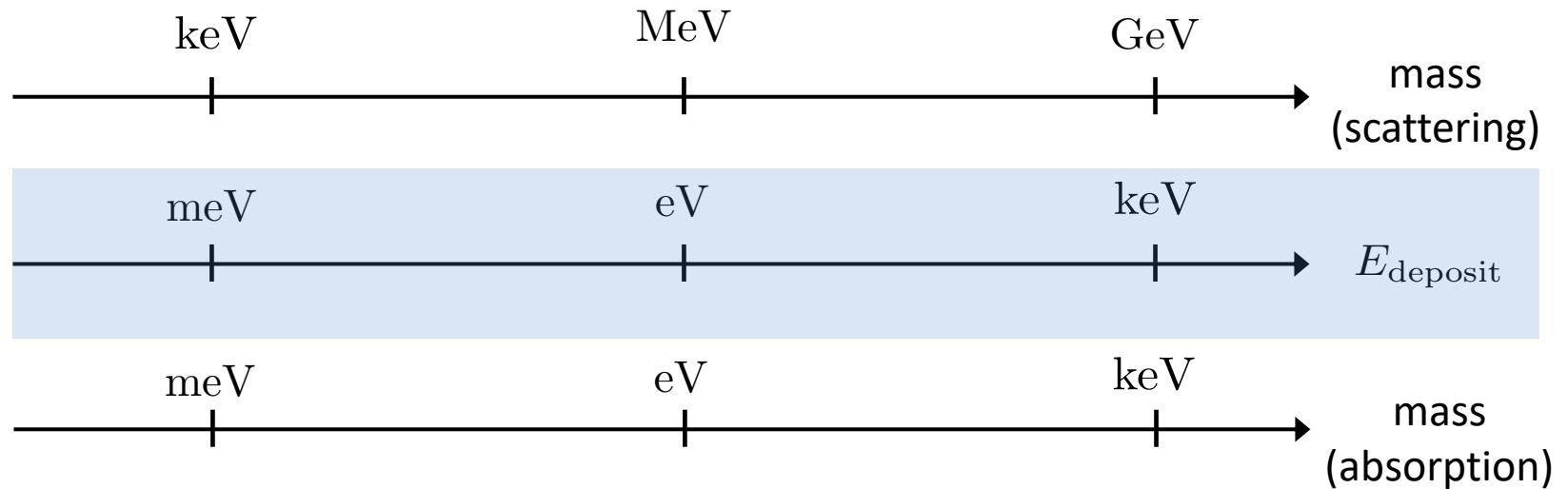
Absorption vs. Scattering

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



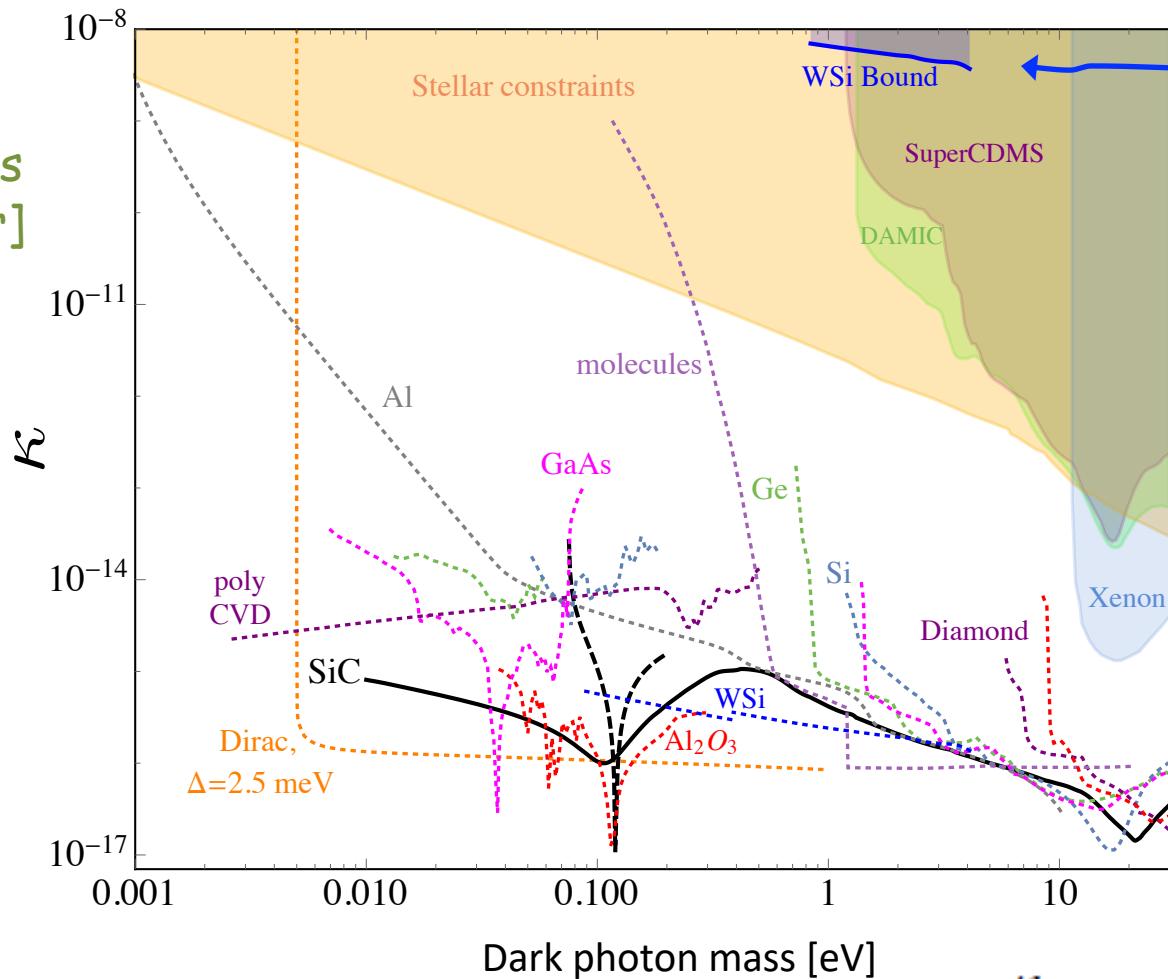
Absorption vs. Scattering

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



Absorption Reach

[projections
for kg-year]



Kinetically mixed dark photon

$$V^\mu \text{---} \kappa \text{---} X \text{---} A^\mu$$

New bound:
WSi SNSPD
prototype
4.3ng in 3 hours

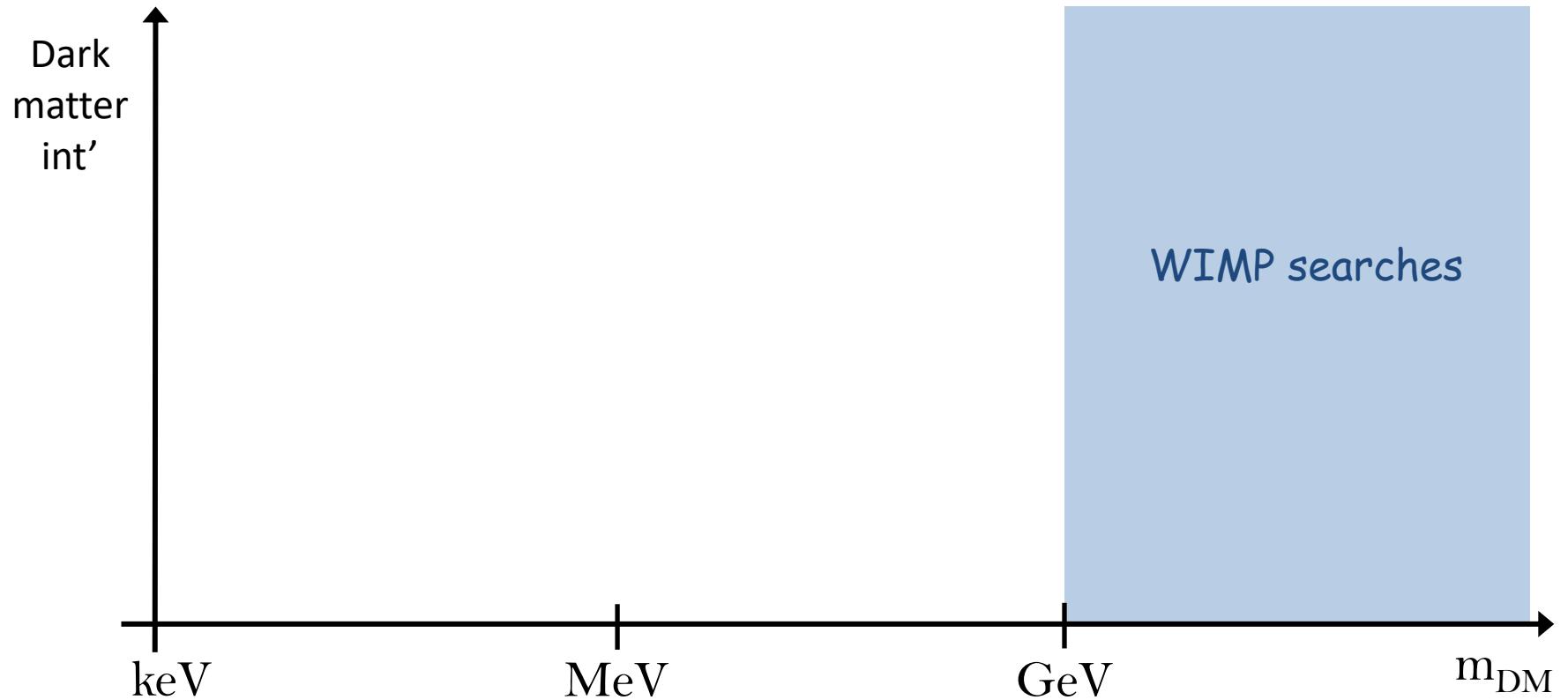
[Kurinsky, Yu,
YH, Blas,
PRD 2019;
YH et al,
PRL 2019;
Griffin, **YH**, et al,
2020]

Take aways

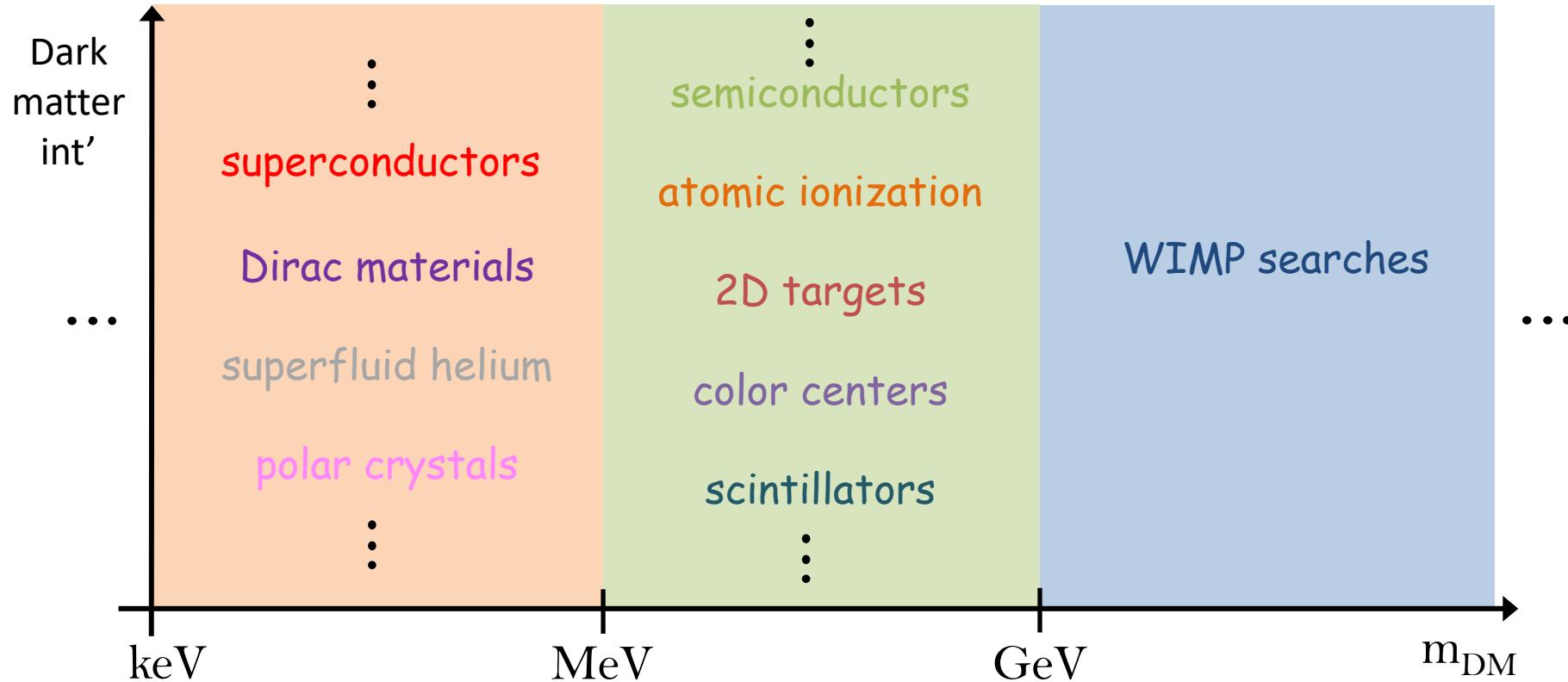
Outlook

- Lots of activity for light dark matter
- Different targets/processes/detection methods
- By no means exhausted...
- It's ok for an idea to seem crazy at first
- The best ideas might still be ahead

Prospects

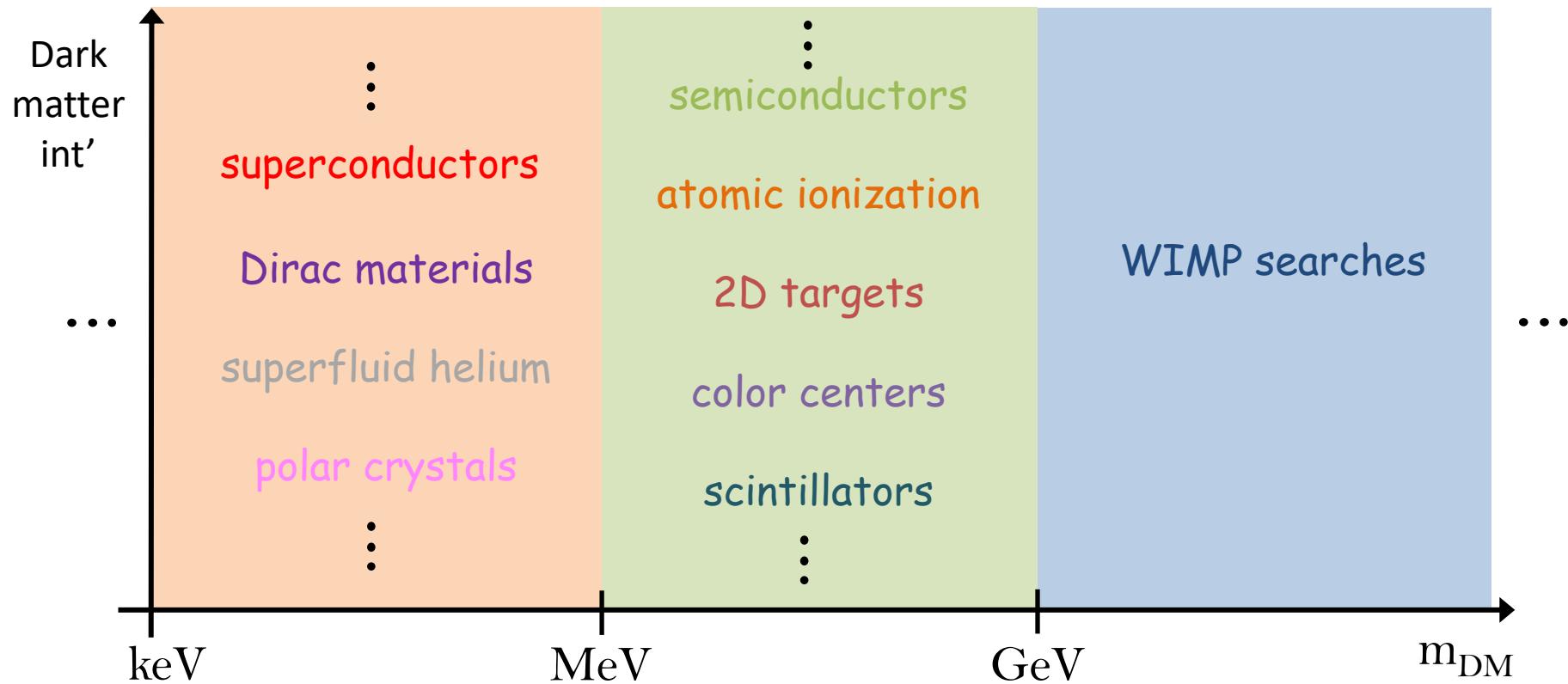


Prospects



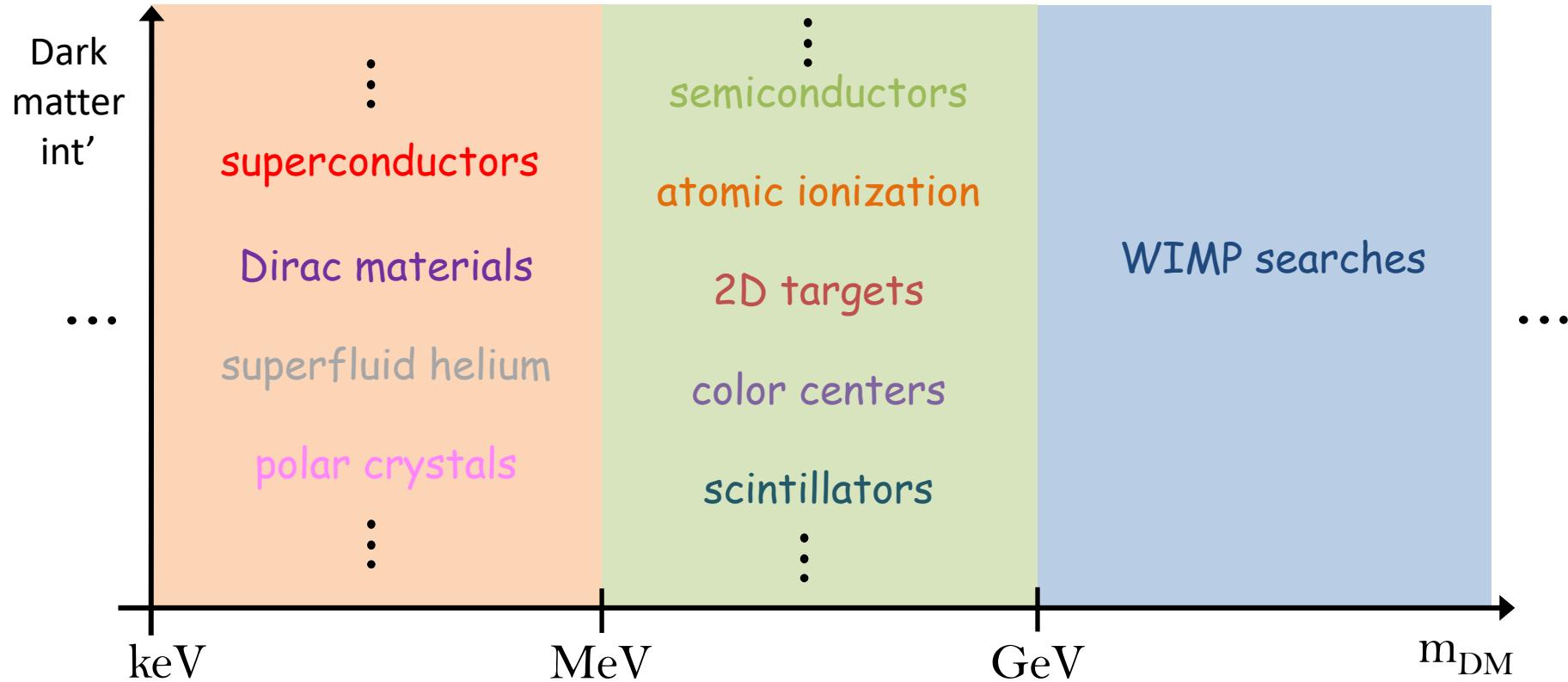
Burgeoning field in recent years

Prospects



Experimentalists are going after these ideas now!

Prospects



Interface particle physics/condensed matter physics/
quantum information science/precision measurements

If you have any (crazy) new ideas,
please be in touch :-)

Thanks!

