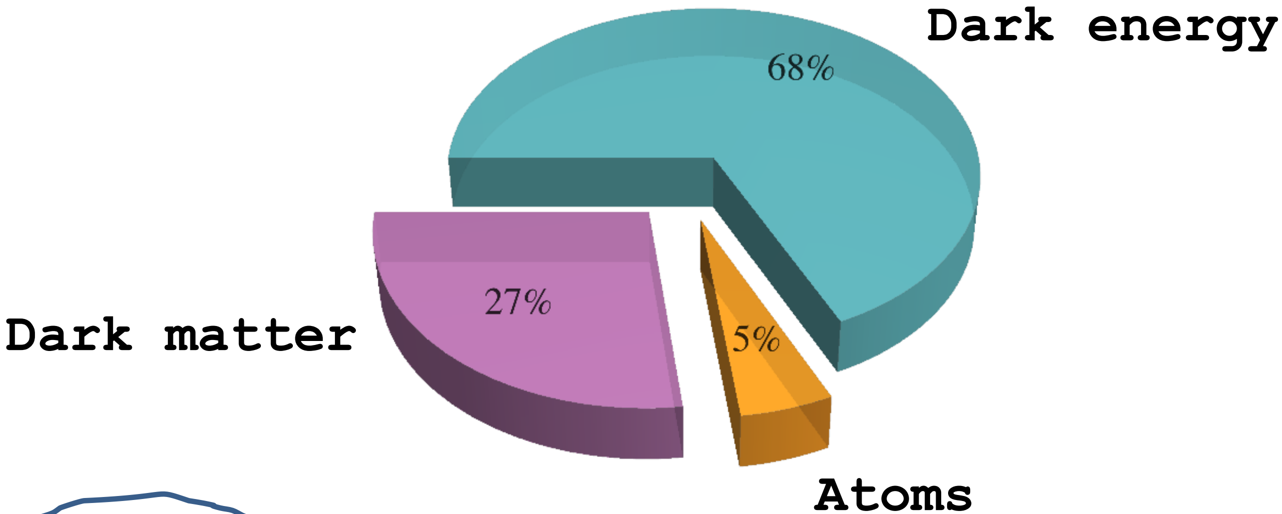
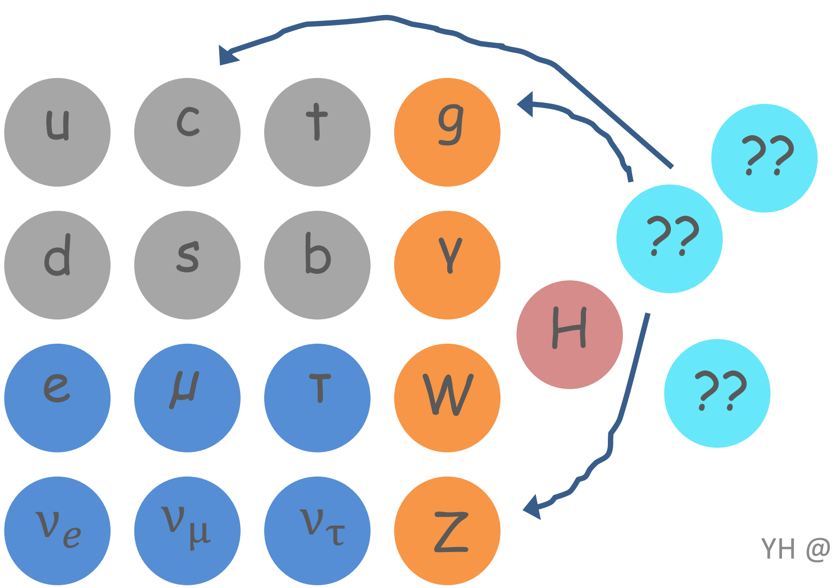
New Technologies for Dark Matter Detection

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 :-)

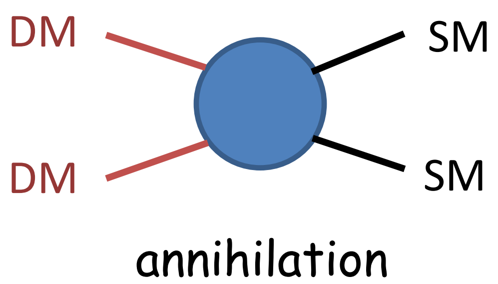
Past 40 years

Correct thermal relic abundance:

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

For weak coupling, weak scale emerges.

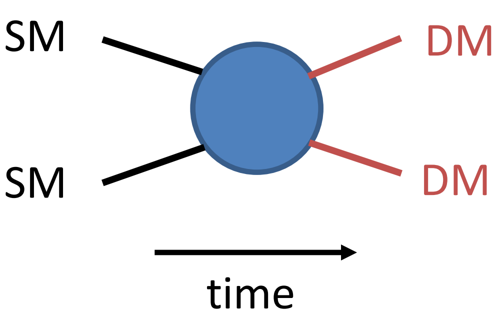
"Weakly Interacting Massive Particle (WIMP)"



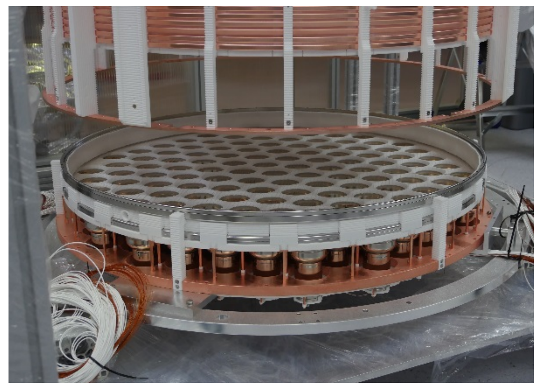
$$\langle \sigma_{\mathrm{ann}} v \rangle = \frac{\alpha^2}{m_{\mathrm{DM}}^2}$$

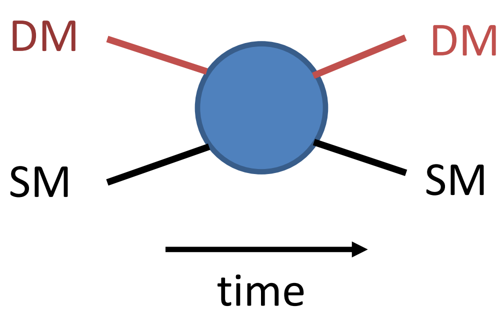
Searching for WIMPs

Direct production

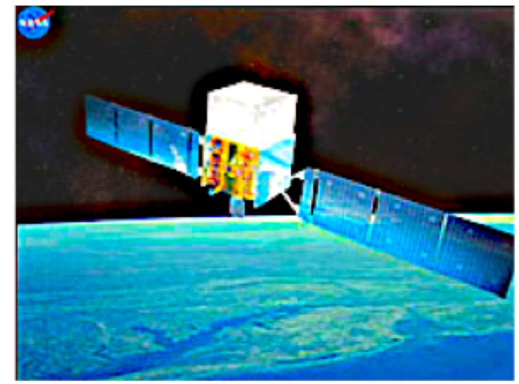


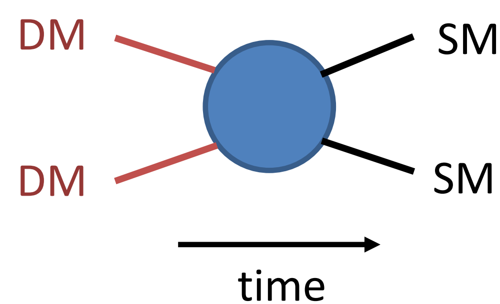
Direct detection





Indirect detection

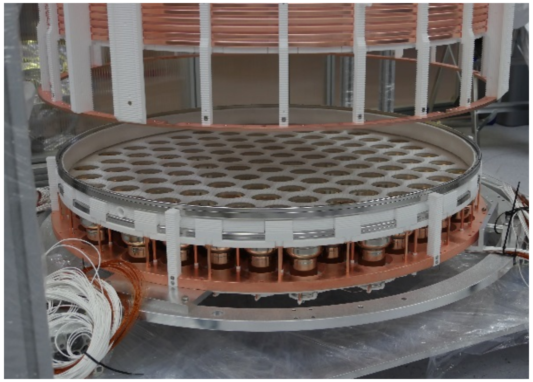




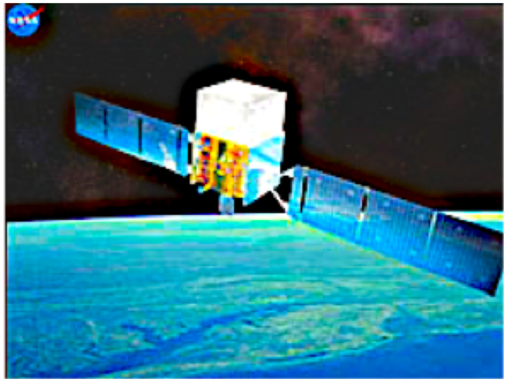
Searching for WIMPs

Direct production

Direct detection



Indirect detection

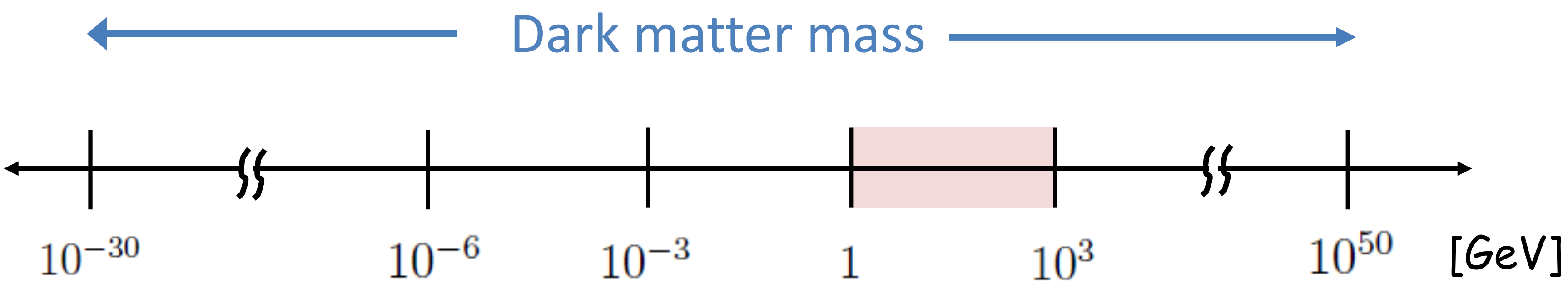


Experiments getting increasingly sensitive

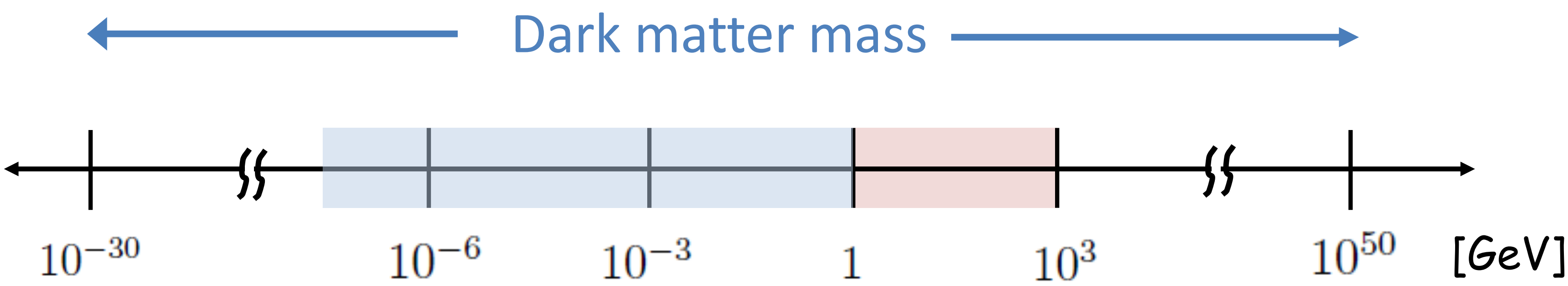
Haven't yet detected dark matter

Great opportunity for new ideas!

Beyond the WIMP



Beyond the WIMP



Lots of activity in recent years:

(Theory &) Experiment

[lower masses:
see Safronova talk]

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

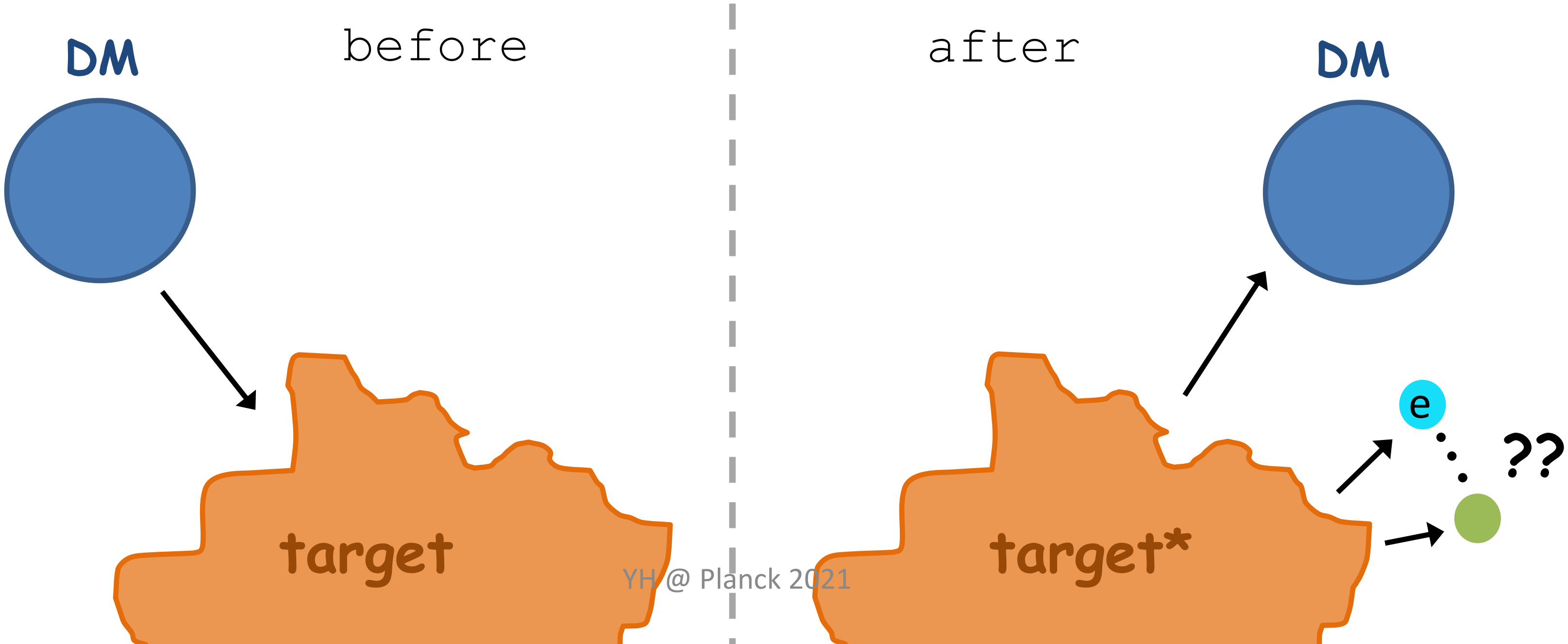
Detection Blueprints

Dark matter particle comes in

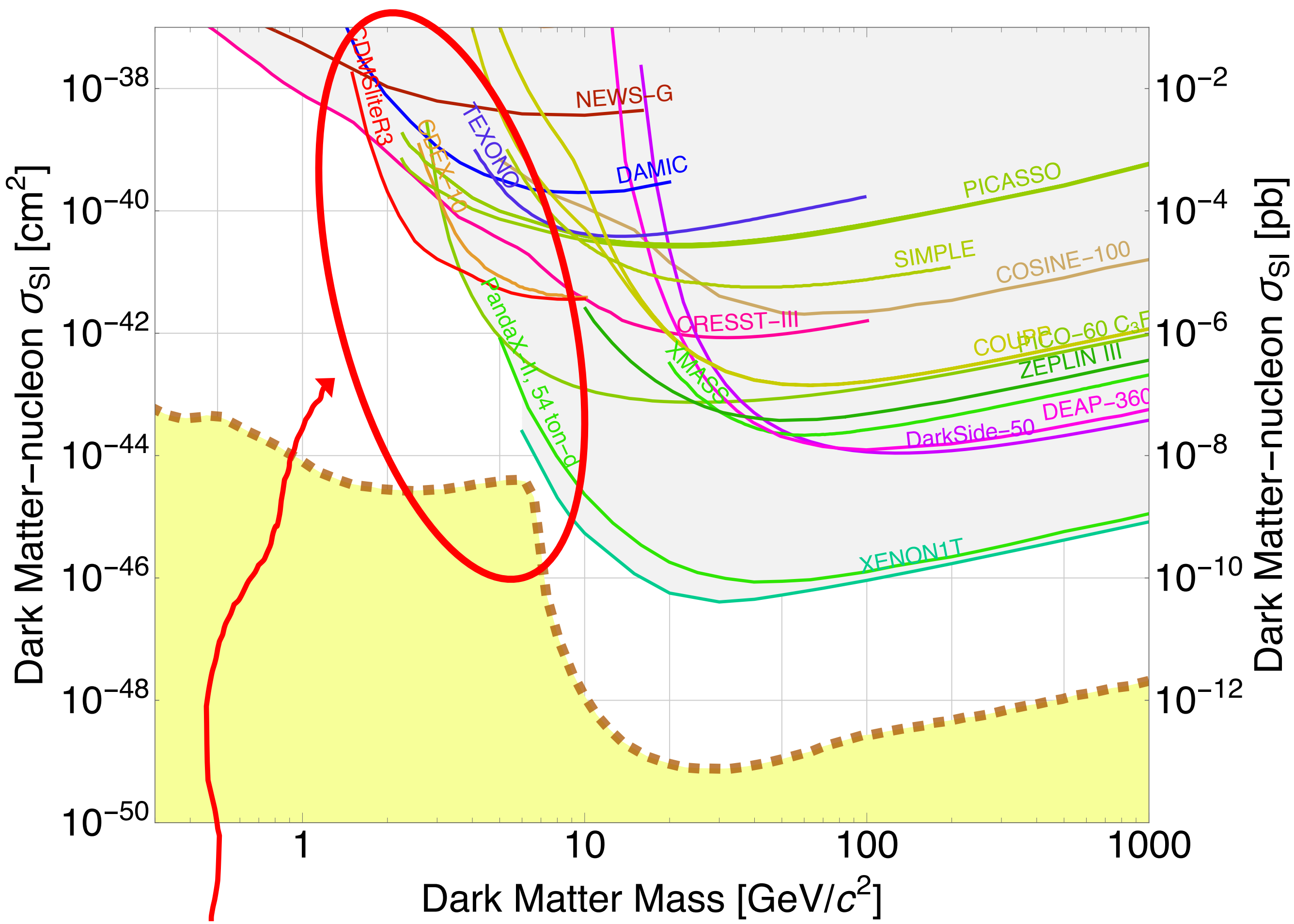
Hits a target in the lab

System reacts

Measure the reaction



Direct Detection

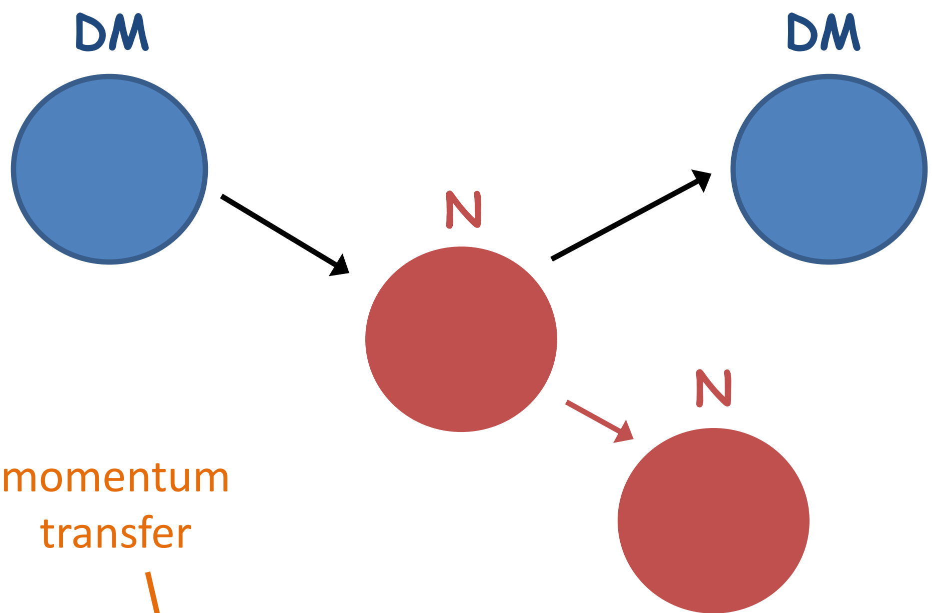


What's going on?

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

Current Experiments

Looking for nuclear recoils:
think billiard balls



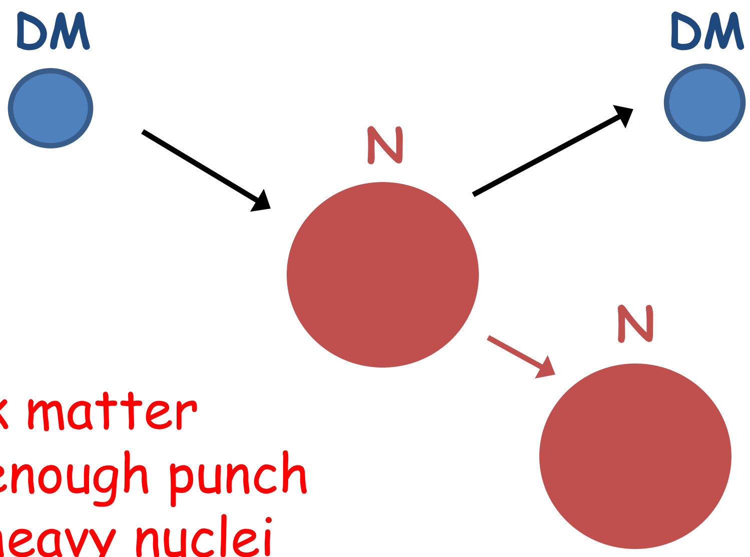
momentum transfer

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

Current Experiments

Looking for nuclear recoils:

think billiard balls

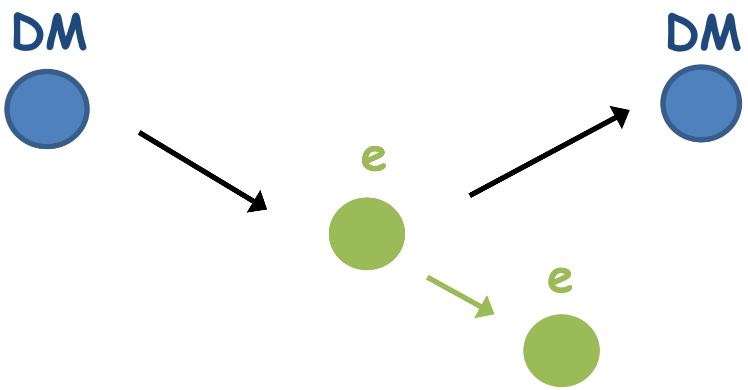


light dark matter
doesn't have enough punch
to kick the heavy nuclei

Lose sensitivity @ O(GeV) masses

New Avenues

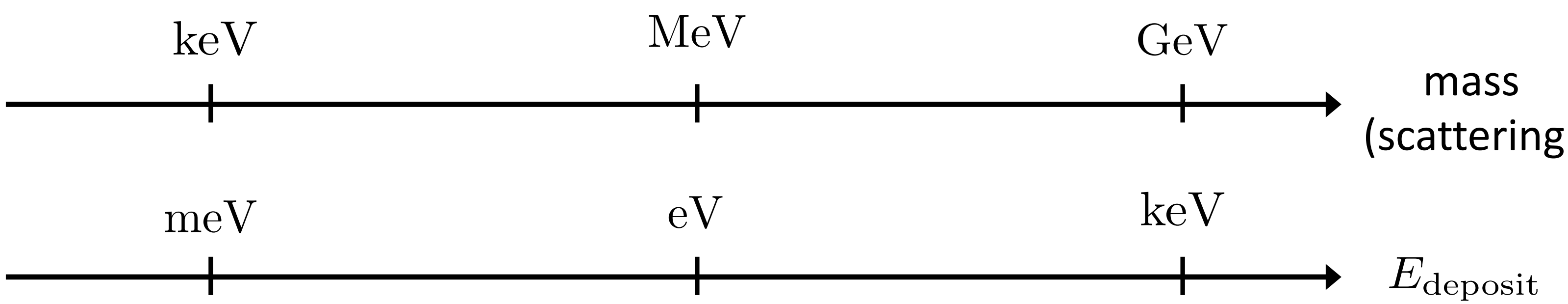
Light dark matter: scatter off electrons!

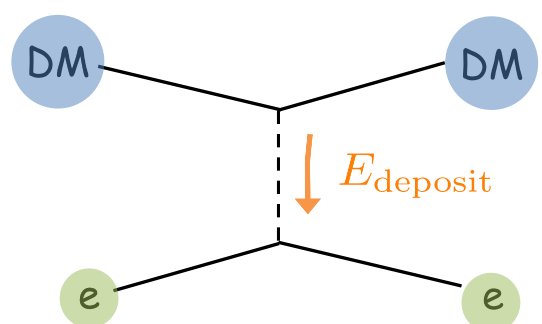


light dark matter
can give enough punch
to kick the light electrons

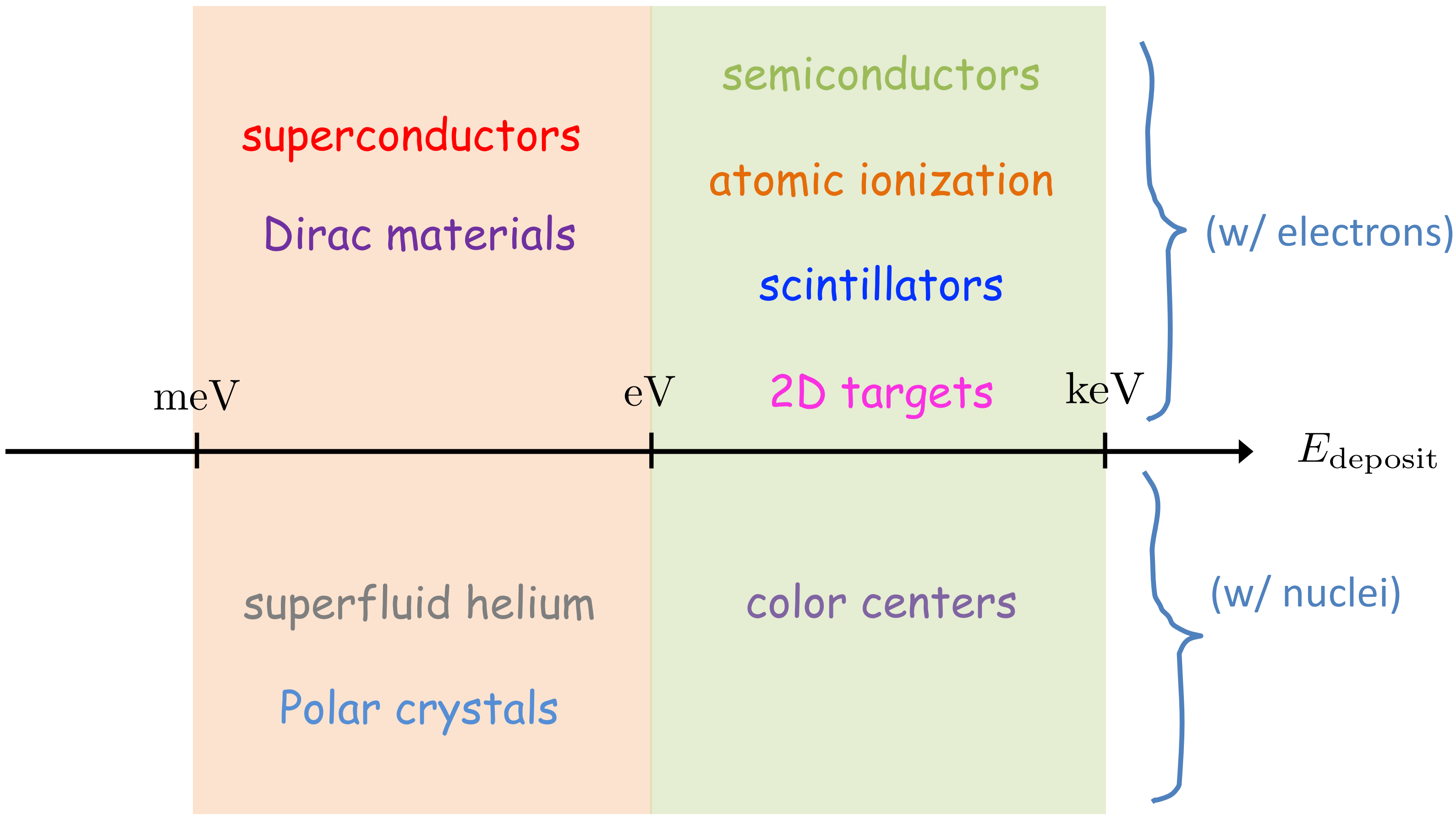
Energy guideline

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





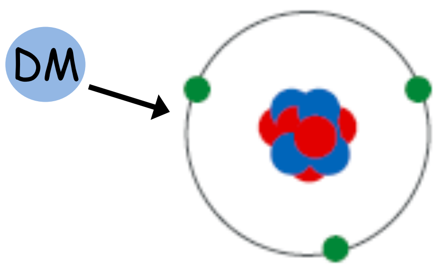
New proposals



Explosion of interest and ideas in recent times

Ex. #1: First ideas

Atomic ionization

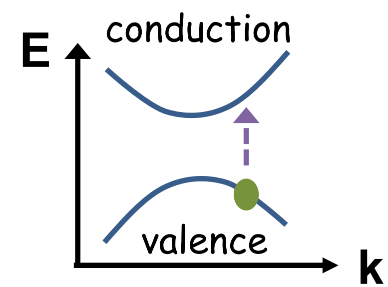


Xenon: ~12 eV

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

[Essig, Mardon, Volansky, 2012]

Semiconductors



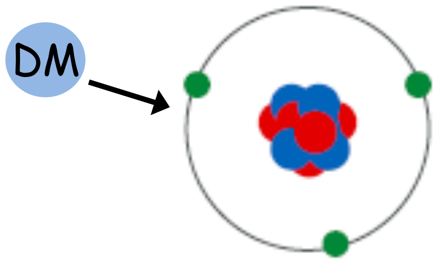
Ge, Si, Diamond, SiC: ~eV

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

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

Ex. #1: First ideas

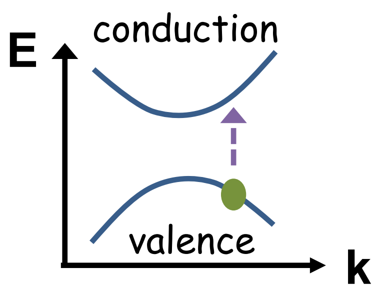
Atomic ionization



Xenon10/100/1T

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

Semiconductors



SuperCDMS, SENSEI

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

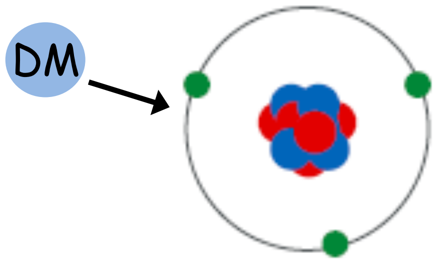
Are being experimentally realized

[Essig et al, 2012]
[Xenon100, 2016 & Xenon1T 2020]

[SuperCDMS 2020 & SENSEI 2020]

Ex. #1: First ideas

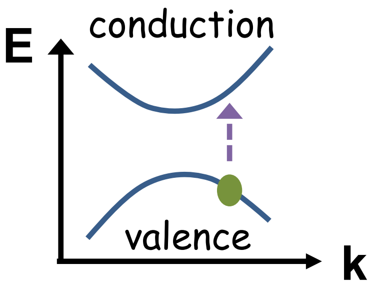
Atomic ionization



Xenon10/100/1T

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

Semiconductors



SuperCDMS, SENSEI

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

Smaller masses?

Ex. #2: Superconductors

- Ground state = Cooper pairs;

  Binding energy (gap) $\sim \mathrm{meV}$ ⇒ $m_{\mathrm{DM}} \sim \mathrm{keV}$
- <u>The idea:</u>

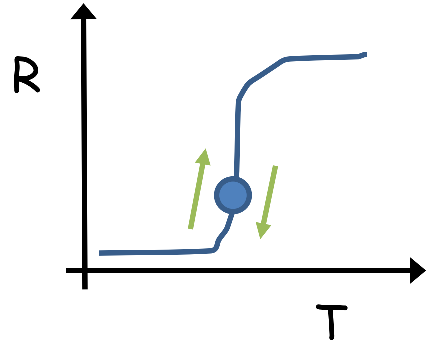
  Dark matter scatters with Cooper pairs, deposits enough energy, breaks Cooper pairs → detect

Excitations

Excitation concentration philosophy	Sensor + target philosophy
[**YH**, Zhao, Zurek, PRL 2015; **YH**, Pyle, Zhao, Zurek, JHEP 2015]	[**YH**, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019]

Ex. #2A: Superconductors

Ram an electron, create excitations which random walk until collected by e.g. a Transition Edge Sensor (TES)



Heat calorimeter

TESs used to detect microwaves and x-rays in astro applications (e.g. ACT, SPT, SuperCDMS)

Excitation concentration philosophy

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

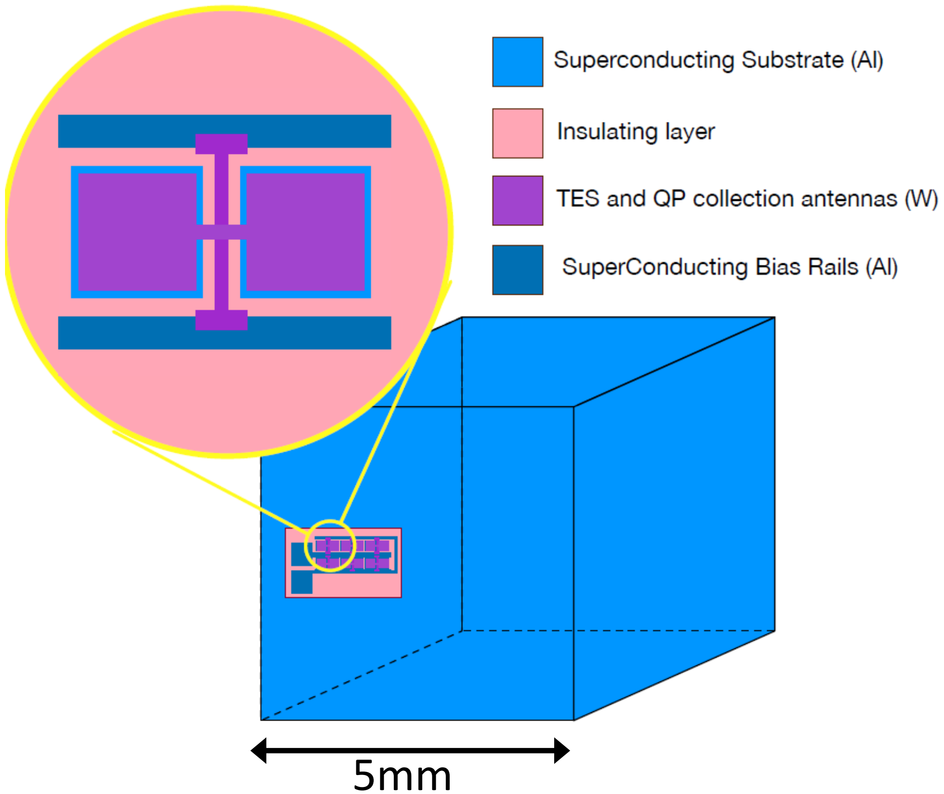
Ex. #2A: Superconductors

Absorber →
Collection fins→
sensitive bolometer

(& multiplex)

Excitation concentration philosophy

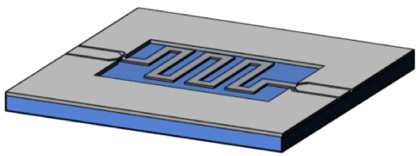
[**YH**, Zhao, Zurek, PRL 2015;
YH, Pyle, Zhao, Zurek, JHEP 2015]



Current challenge:
To achieve low threshold low noise sensors

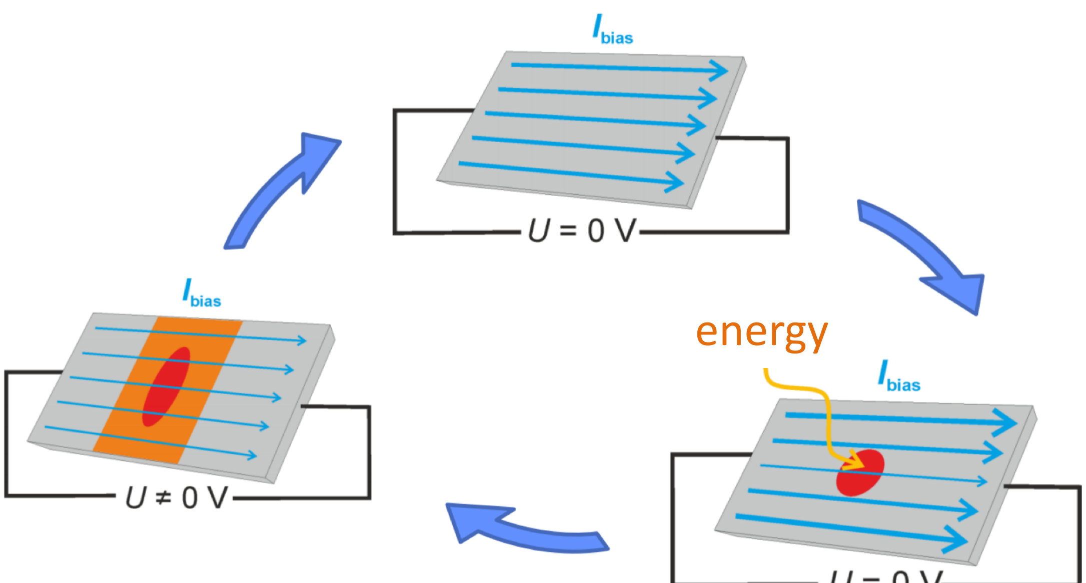
Ex. #2B: Superconductors

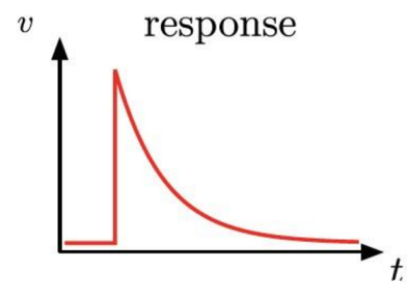
- Superconducting Nanowire Single Photon Detectors (SNSPDs)



Broadly used in quantum information science

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



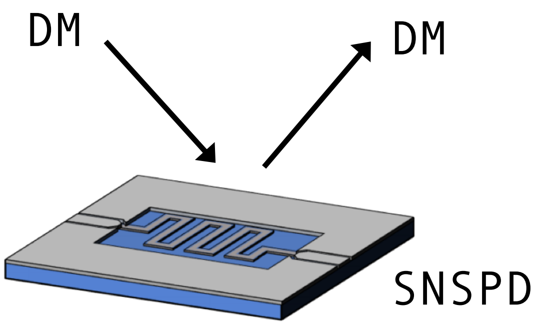


Sensor + target philosophy

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

Ex. #2B: Superconductors

Use as simultaneous target + sensor (& multiplex)



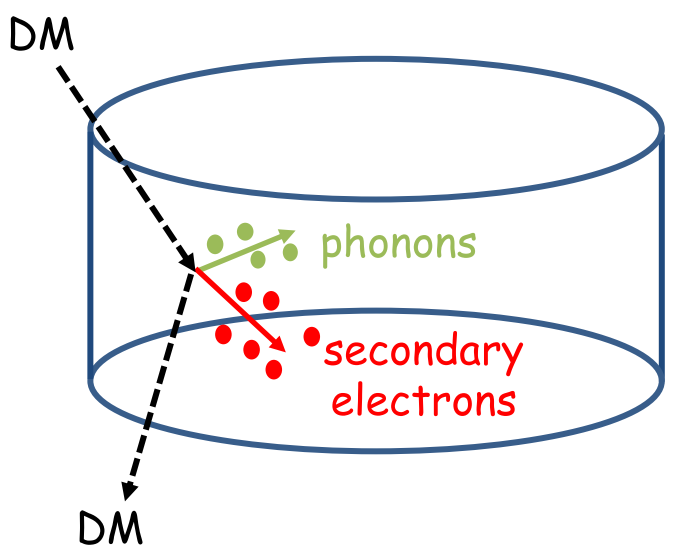
[Existing prototype]

Sensor + target philosophy

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

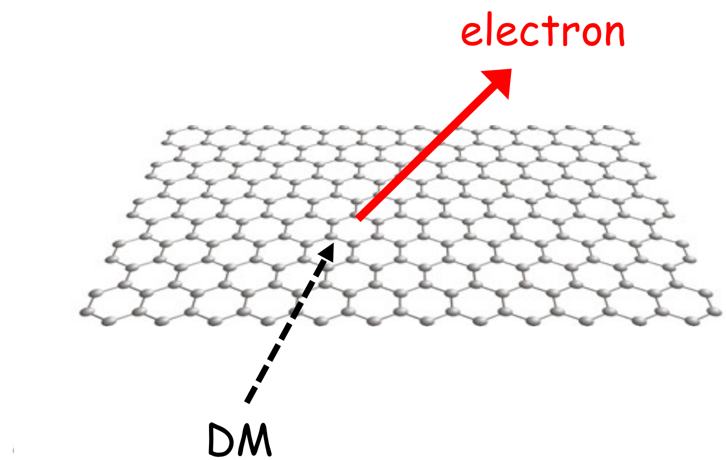
Directional Info?

Lose directional information if detecting secondaries



e.g. semiconductors, bulk superconductors

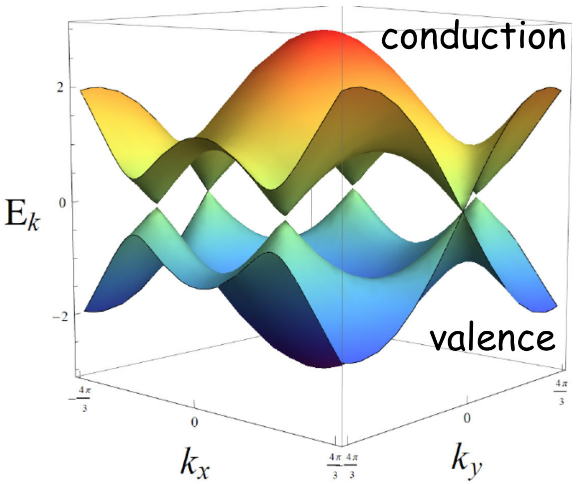
Retain directional information if observe primary!



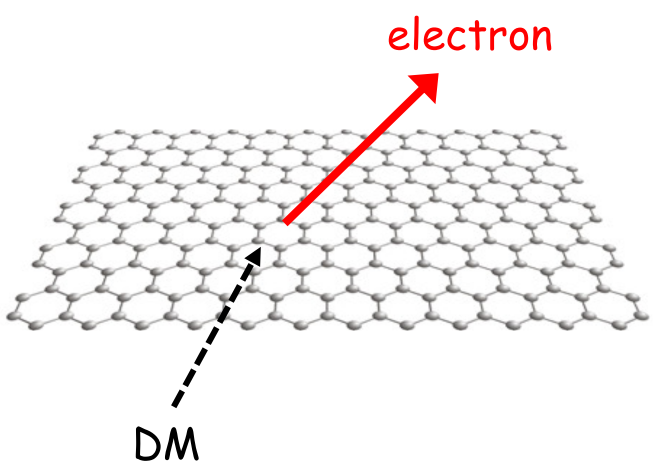
2D targets; graphene (& SNSPDs)

Ex. #3: Graphene

Dark matter scatters with valence electrons, deposits enough energy, ejects electron → detect



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



Eject and detect philosophy

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

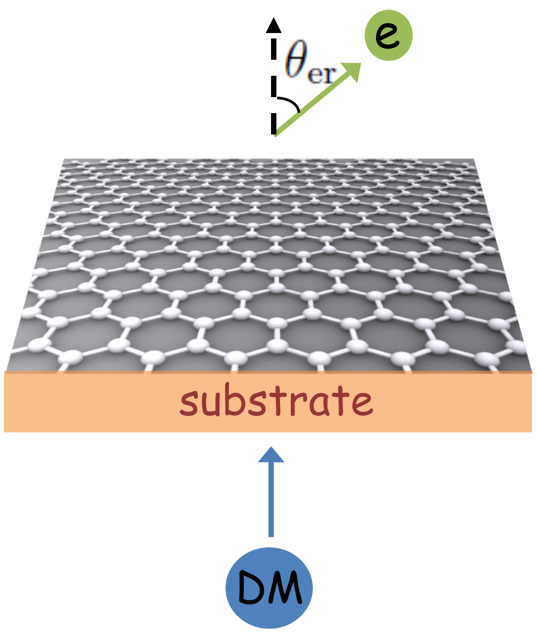
Ex. #3: Graphene

Electron follows incoming dark matter direction.

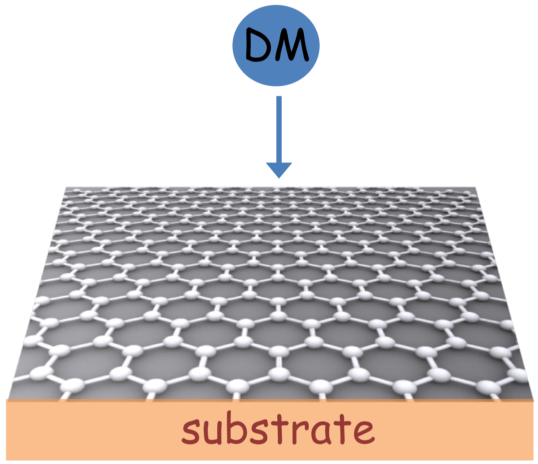
Naturally gives forward/backward discrimination

(separates signal from background)

electron detected



electron not detected



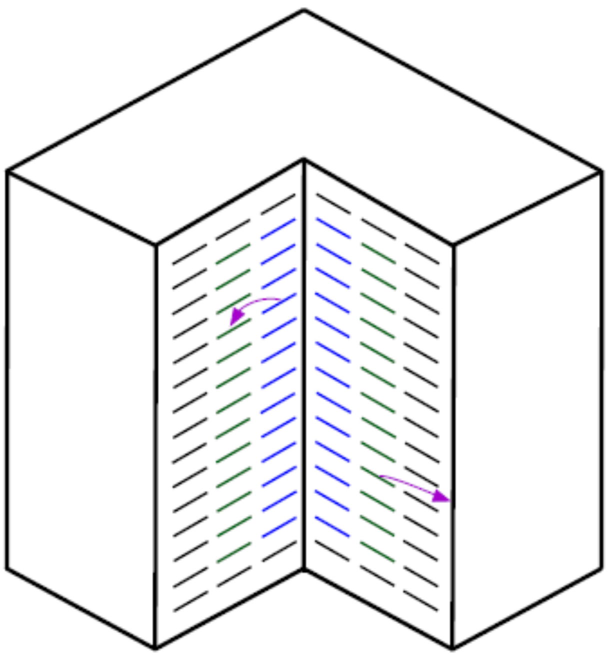
12 hours later

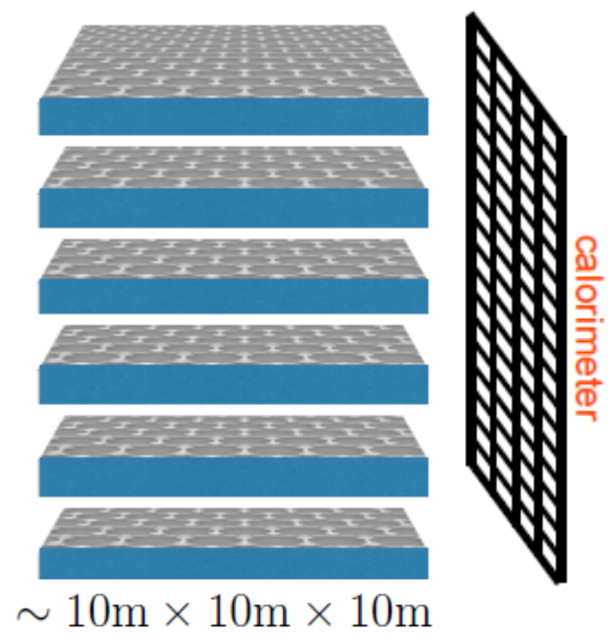
[**YH**, Kahn, Lisanti, Tully, Zurek, 2017]

Ex. #3: Graphene

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

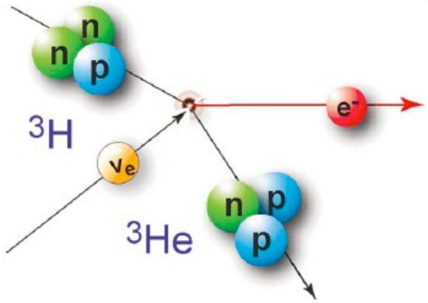
- Compact geometry: large mass via many stacks





Implement in PTOLEMY

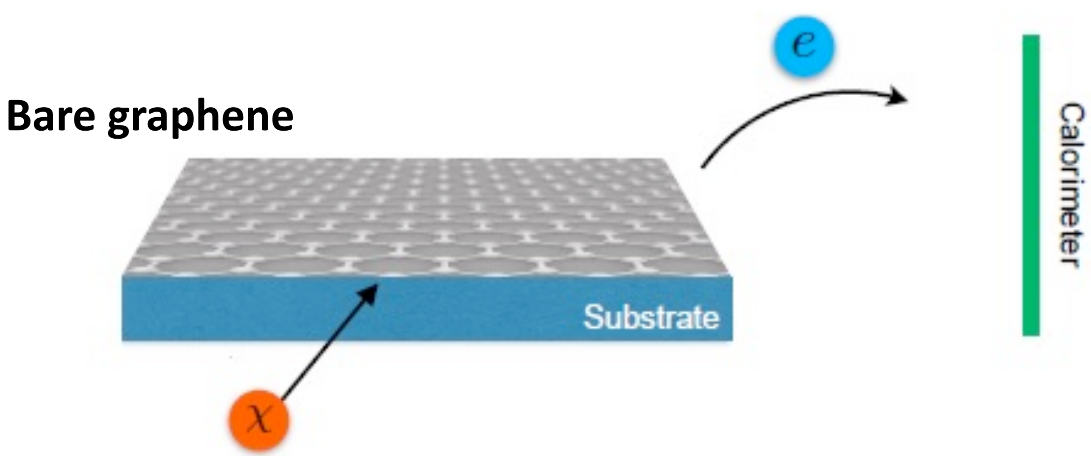
Experiment to detect relic neutrinos via capture on tritium.



[Betts et al, 2013]

Will use tritiated graphene (~0.5 kg).

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



PTOLEMY World-Wide Collaboration

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]

$$\text{Rate} \propto \underbrace{\frac{1}{\rho_{\text{target}}}}_{\text{Target density}} \times \underbrace{\frac{\rho_{\text{DM}}}{m_{\text{DM}}} \times v_{\text{DM}}}_{\text{dark matter flux (astrophysics)}} \times \underbrace{\text{target properties}}_{\text{condensed matter physics}} \times \underbrace{\sigma_{\text{int}}}_{\text{particle physics}}$$

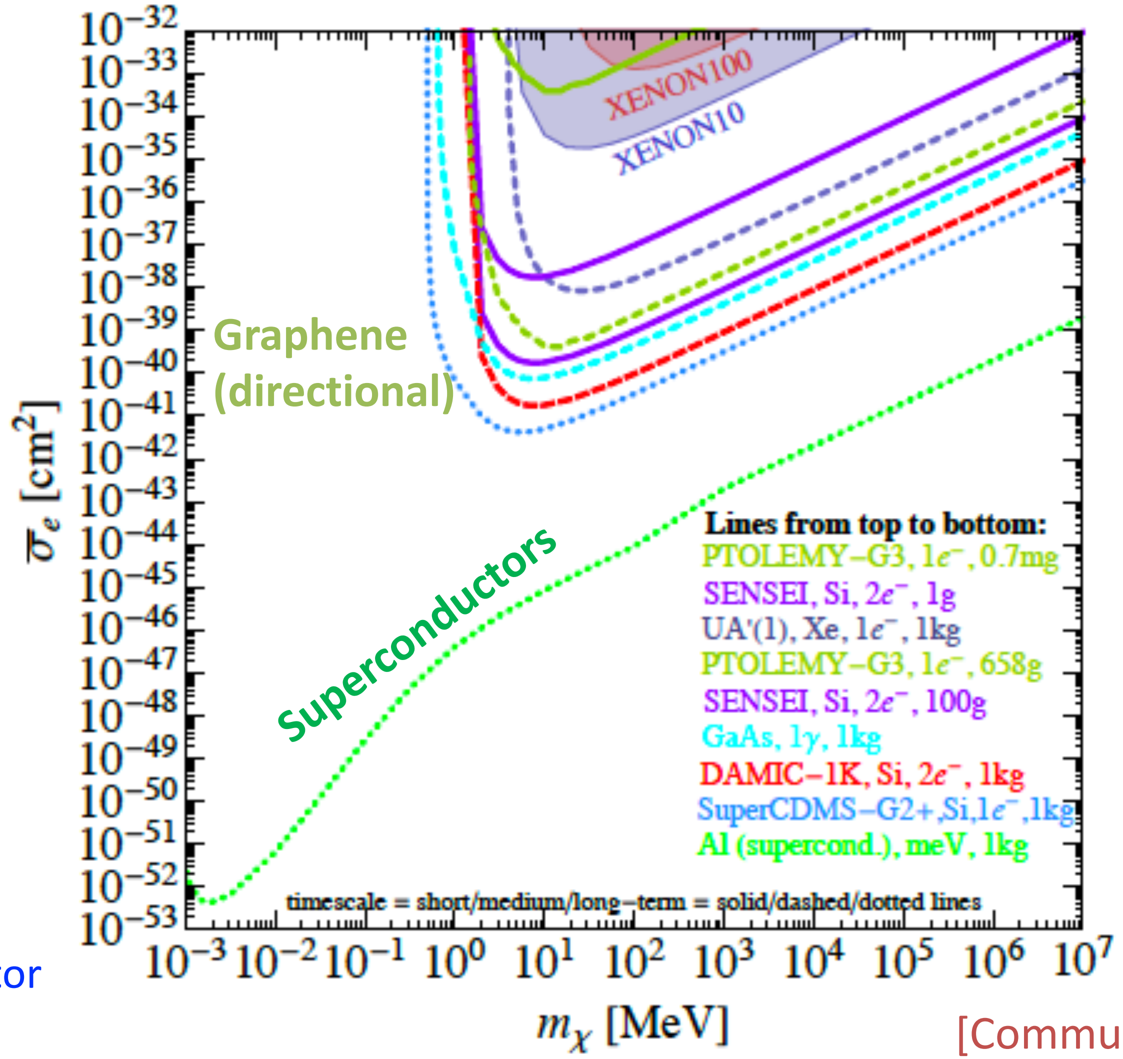
Target density

dark matter flux (astrophysics)

condensed matter physics

particle physics

Scattering Reach



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

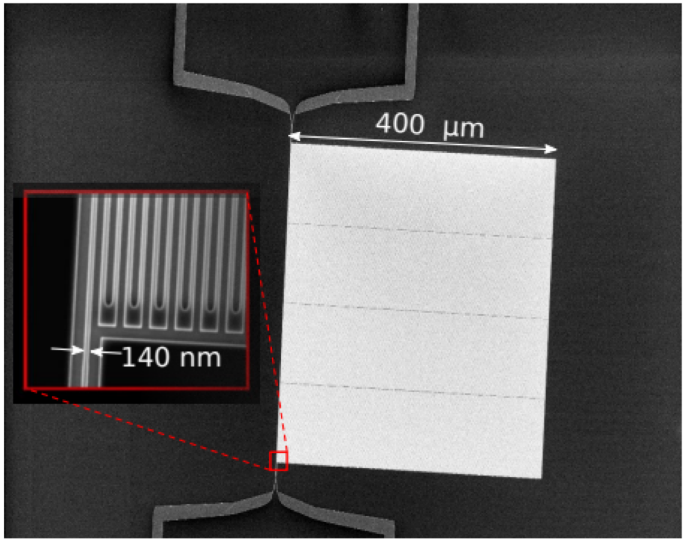
[a few events in kg-year exposure]

Amazing reach!

[Community report, 2017]

Existing Prototype Device

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

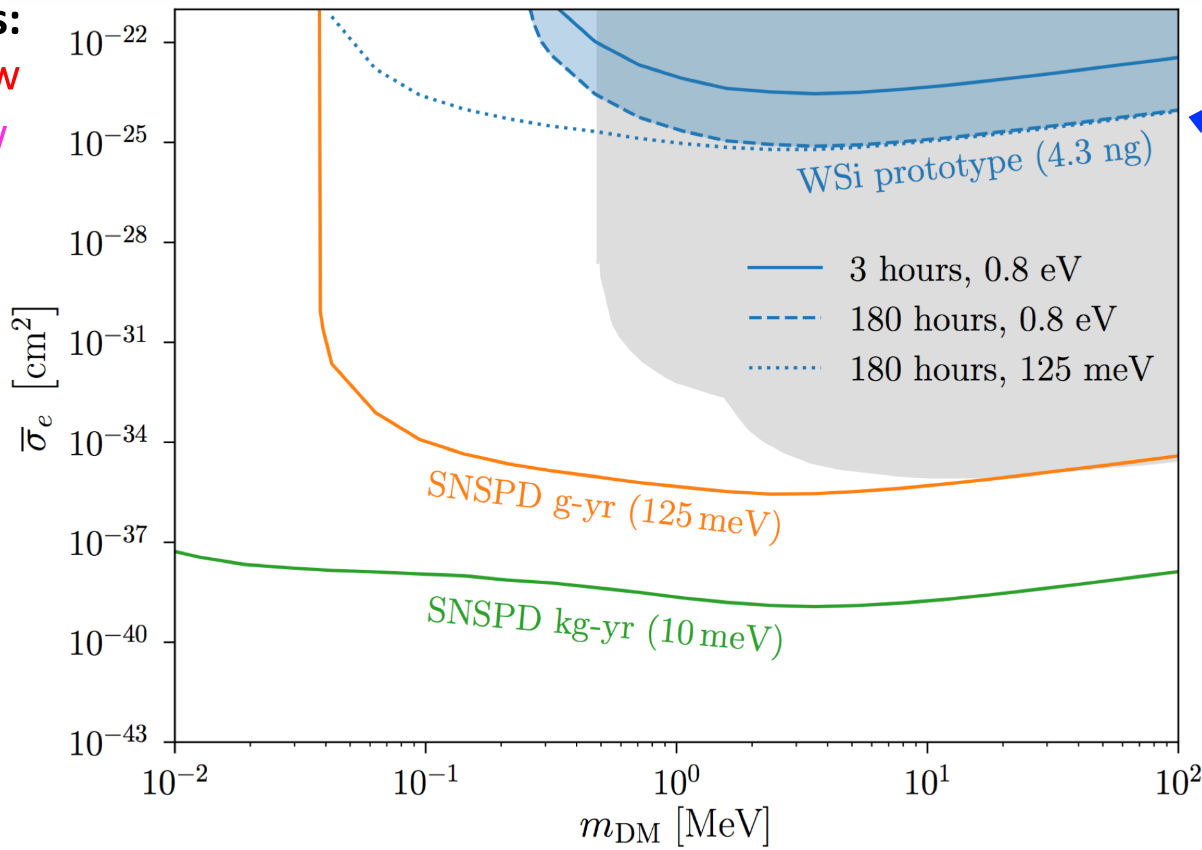


By now have 180 hours of data

[**YH**, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019 + to appear (w/ Lehmann)]

Scattering Reach

Colored curves:
Large array, low threshold, low dark count SNSPDs



New bound (Preliminary)

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

[**YH**, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019 + to appear (w/ Lehmann)]

Pushing Thresholds Lower

Single-photon detection in the mid-infrared up to 10 micron wavelength using tungsten silicide superconducting nanowire detectors

V. B. Verma,[1,a)] B. Korzh,[2,b)] A. B. Walter,[2] A. E. Lita,[1] R. M. Briggs,[2] M. Colangelo,[3] Y. Zhai,[1] E. E. Wollman,[2] A. D. Beyer,[2] J. P. Allmaras,[2] B. Bumble,[2] H. Vora,[1] D. Zhu,[3] E. Schmidt,[2] K. K. Berggren,[3] R. P. Mirin,[1] S. W. Nam,[1] and M. D. Shaw[2]
[1)] *National Institute of Standards and Technology, Boulder, CO, USA.*
[2)] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA, USA*
[3)] *Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA, USA.*

(Dated: 21 December 2020)

We developed superconducting nanowire single-photon detectors (SNSPDs) based on tungsten silicide (WSi) that show saturated internal detection efficiency up to a wavelength of 10 µm. These detectors are promising for applications in the mid-infrared requiring ultra-high gain stability, low dark counts, and high efficiency such as chemical sensing, LIDAR, dark matter searches and exoplanet spectroscopy.

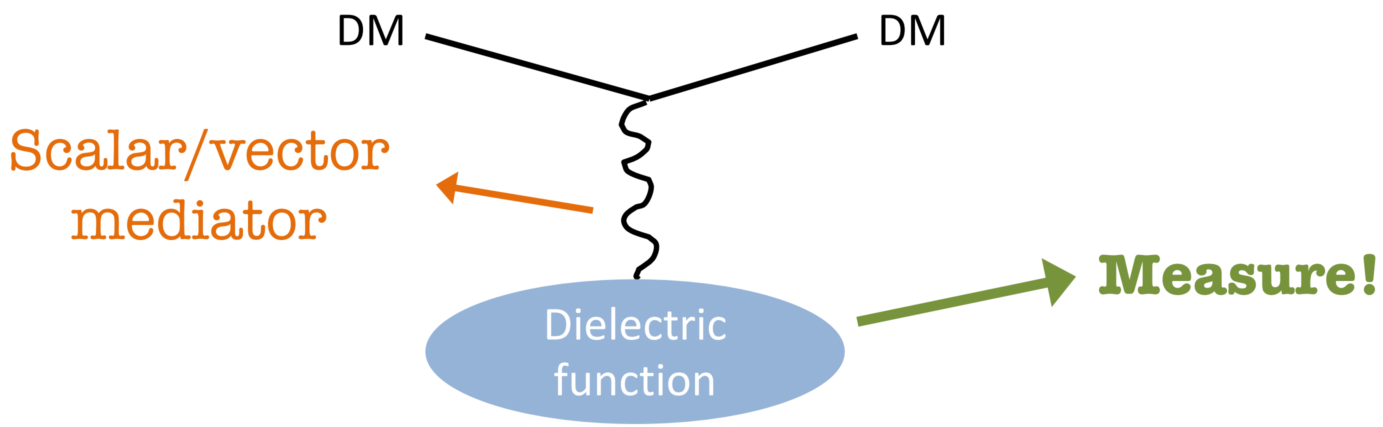
Demonstrated WSi SNSPDs w/ 125meV energy threshold

[arXiv:2012.09979]

New Formalism

Dark matter-electron scattering in any material
is determined by the dielectric function.

For any dark matter interaction that couples to electron density



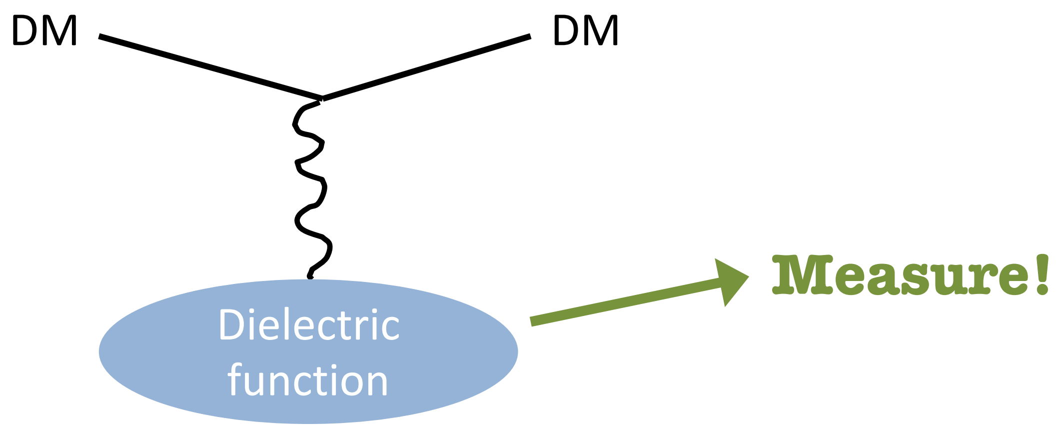
[**YH**, Kahn, Kurinsky, Lehmann, Yu, Berggren, arXiv:2101.08263]

[See also arXiv: 2101.08275]

New Formalism

Automatically includes many-body effects of the material

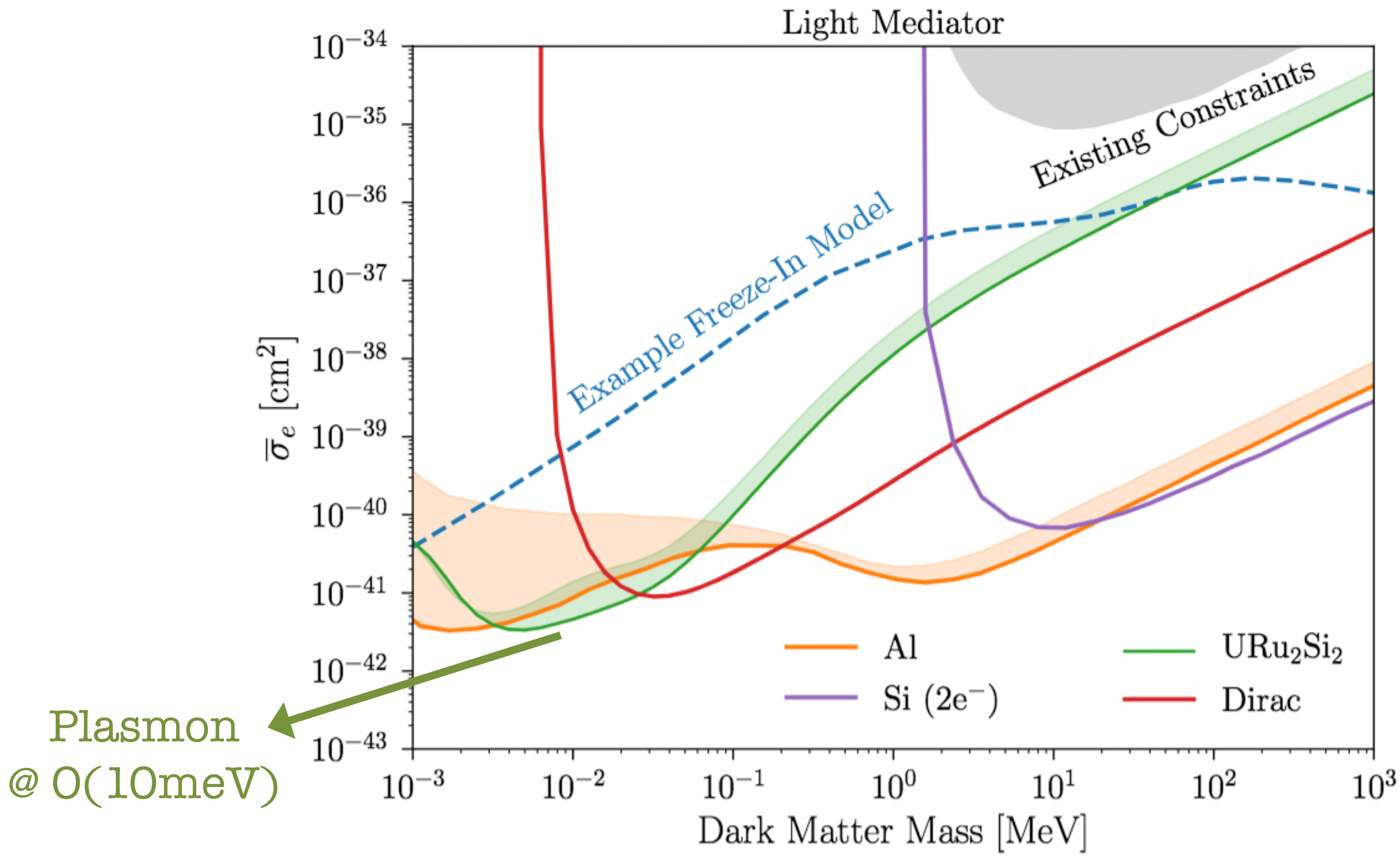
Collective modes (e.g. plasmon),
not just single particle excitations



Identify promising materials for dark matter detection

[**YH**, Kahn, Kurinsky, Lehmann, Yu, Berggren, arXiv:2101.08263]

E.g. Heavy Fermions



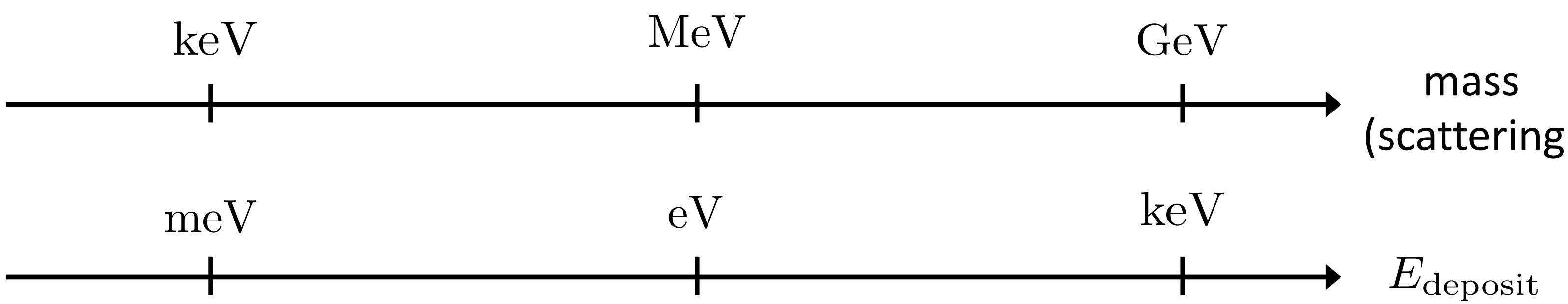
Identify promising materials for dark matter detection

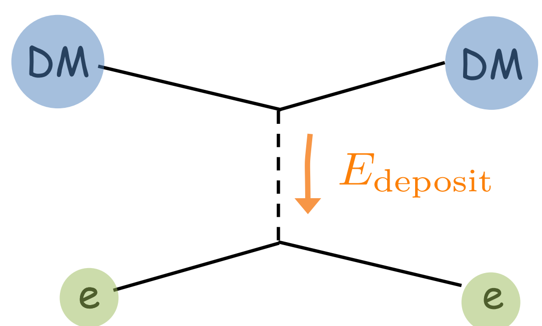
[**YH**, Kahn, Kurinsky, Lehmann, Yu, Berggren, arXiv:2101.08263]

Any given target material can go even further.

Absorption vs. Scattering

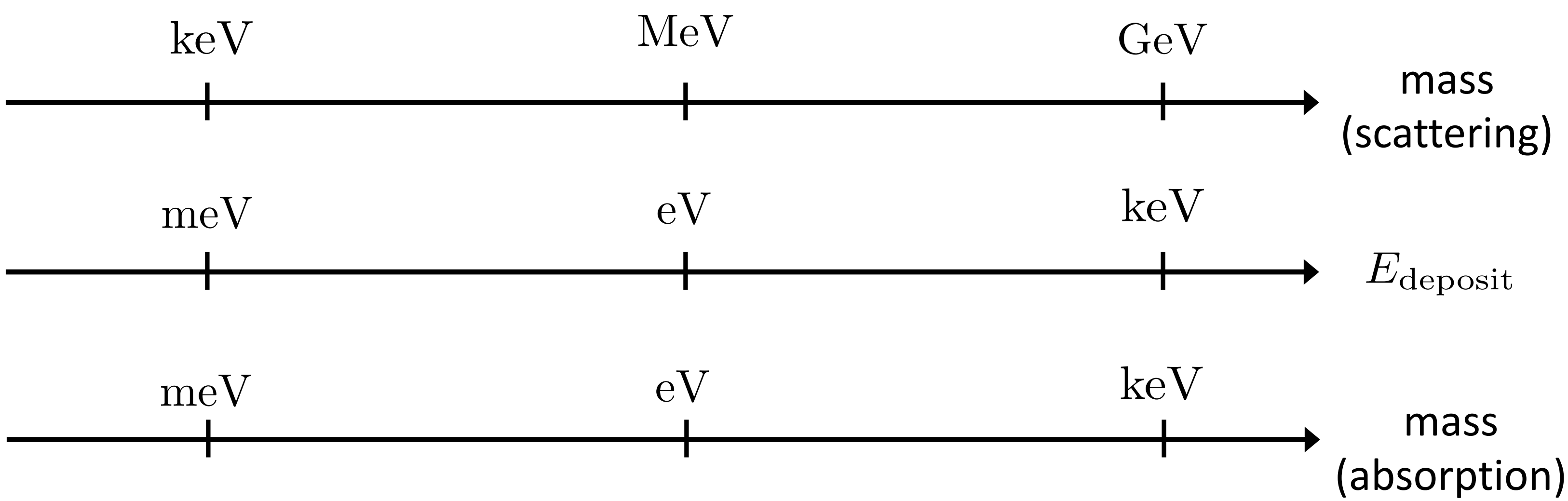
Dark matter scattering: kinetic energy $m_{\rm DM} v^2 \sim 10^{-6} m_{\rm DM}$

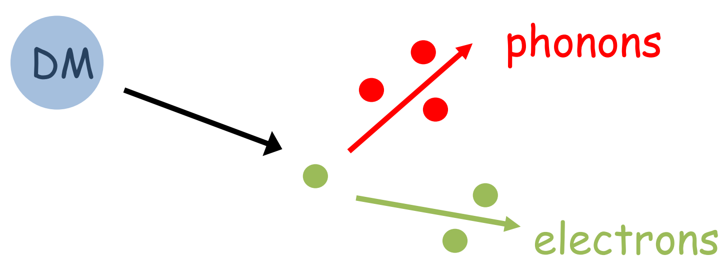




Absorption vs. Scattering

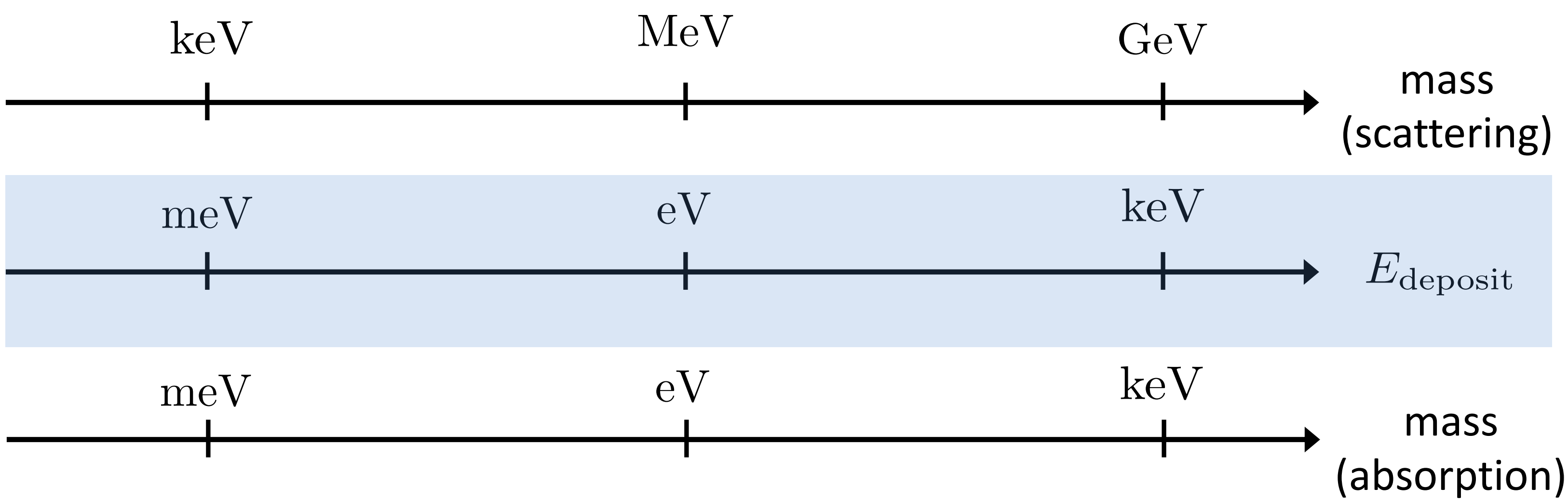
Dark matter absorption: all the mass-energy $m_{\rm DM}$





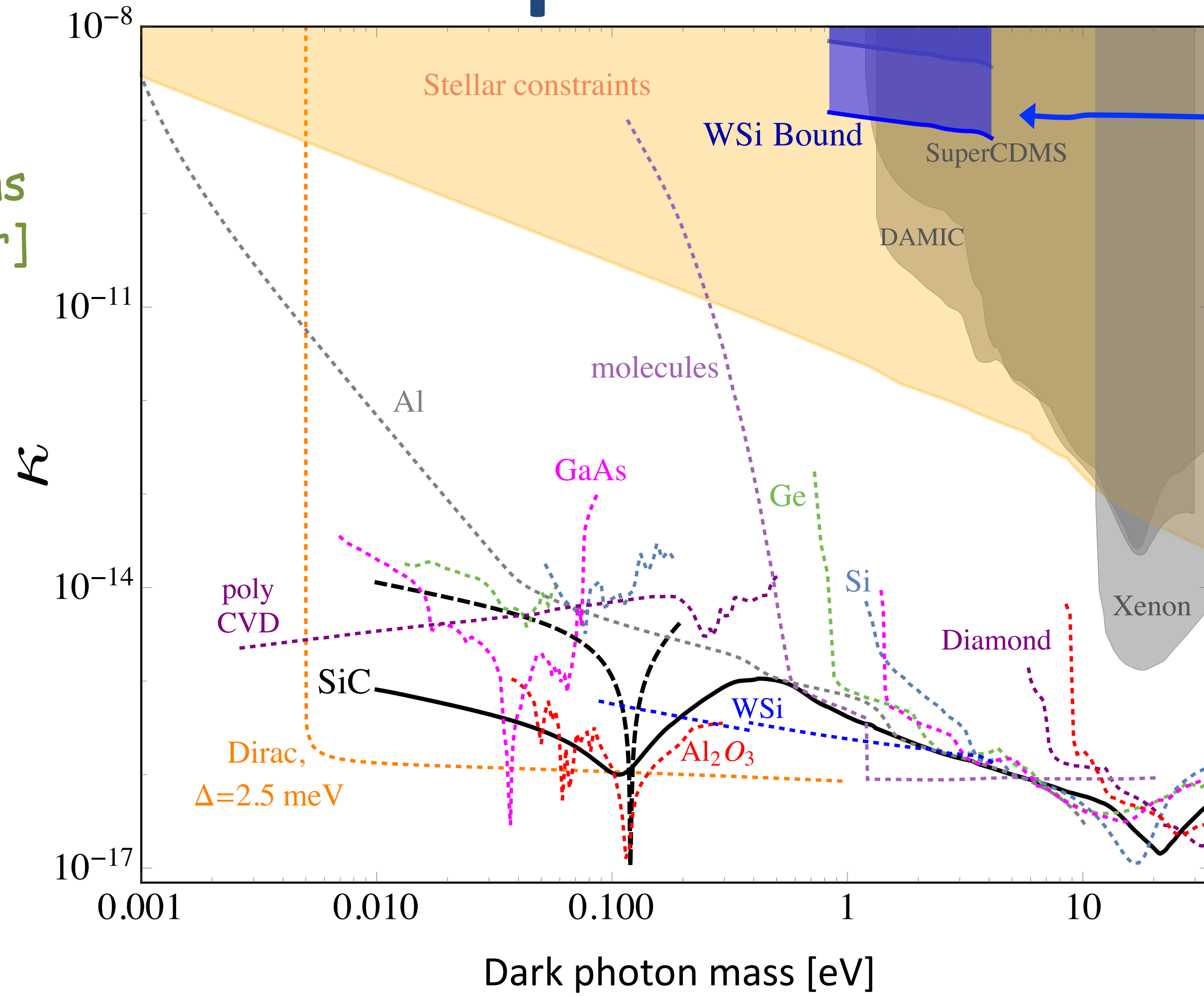
Absorption vs. Scattering

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



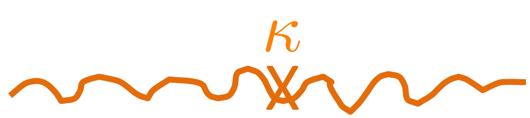
Absorption Reach

[projections for kg-year]



New prelim' bound:
WSi SNSPD prototype 4.3ng in 180 hours

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



Wish List

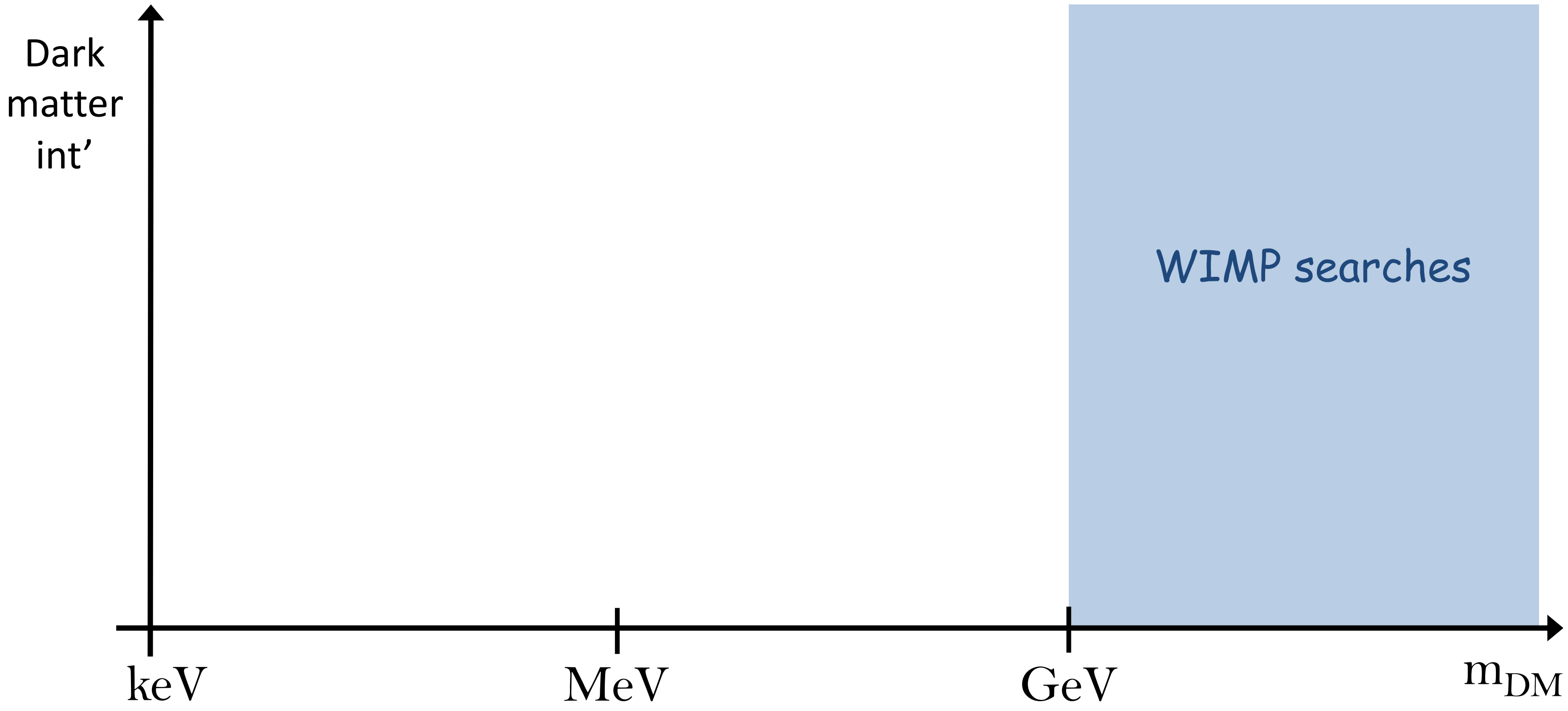
- Single/rare-event sensitivity
- Build up to large target mass: many small units ok & multiplex
- Target can/cannot be the sensitive sensor itself
- Small gap and low thresholds
- Low dark counts ideally
- Directionality a major plus
- Data

Think detection philosophy & target & sensor

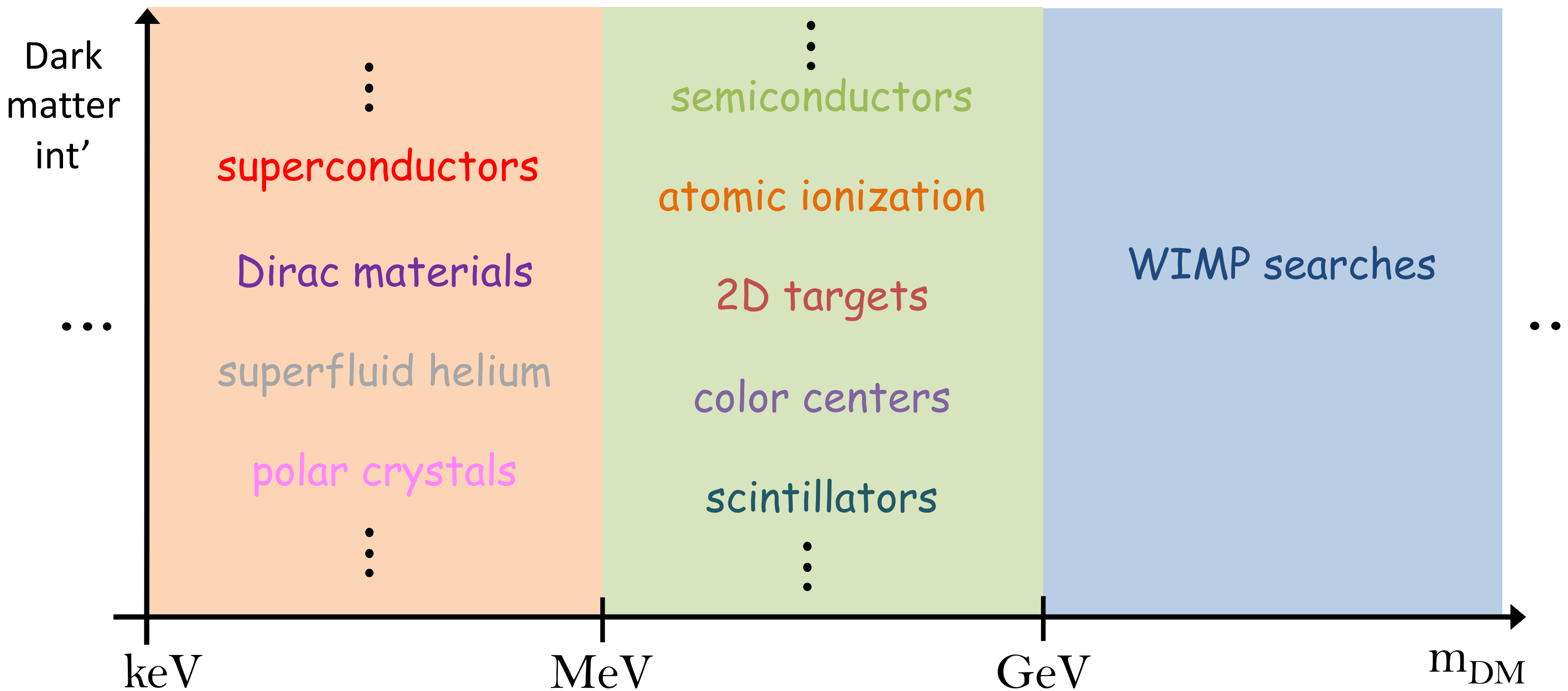
Outlook

- Lots of activity for light dark matter
- Theory ←→ experiment
- By no means exhausted…
- It’s ok for an idea to seem crazy at first
- The best ideas might still be ahead

Prospects

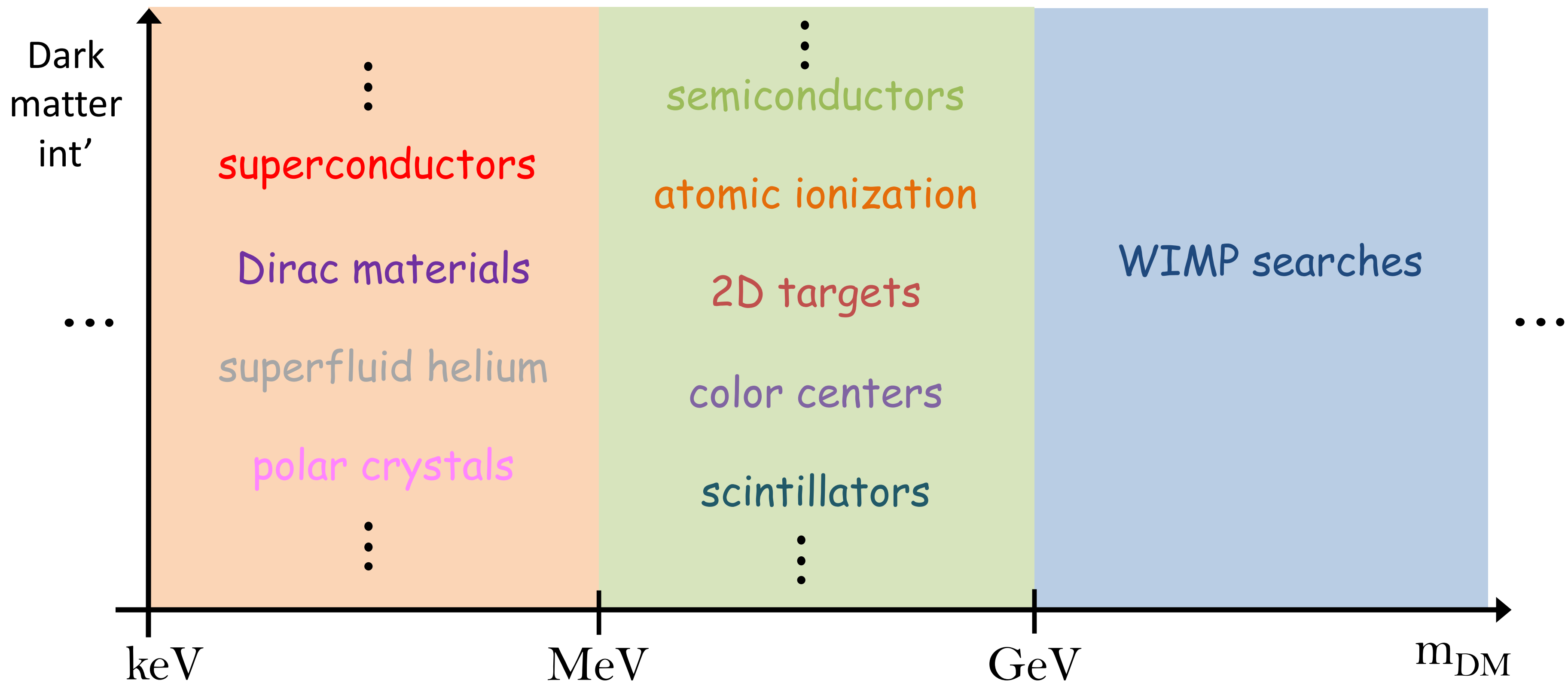


Prospects



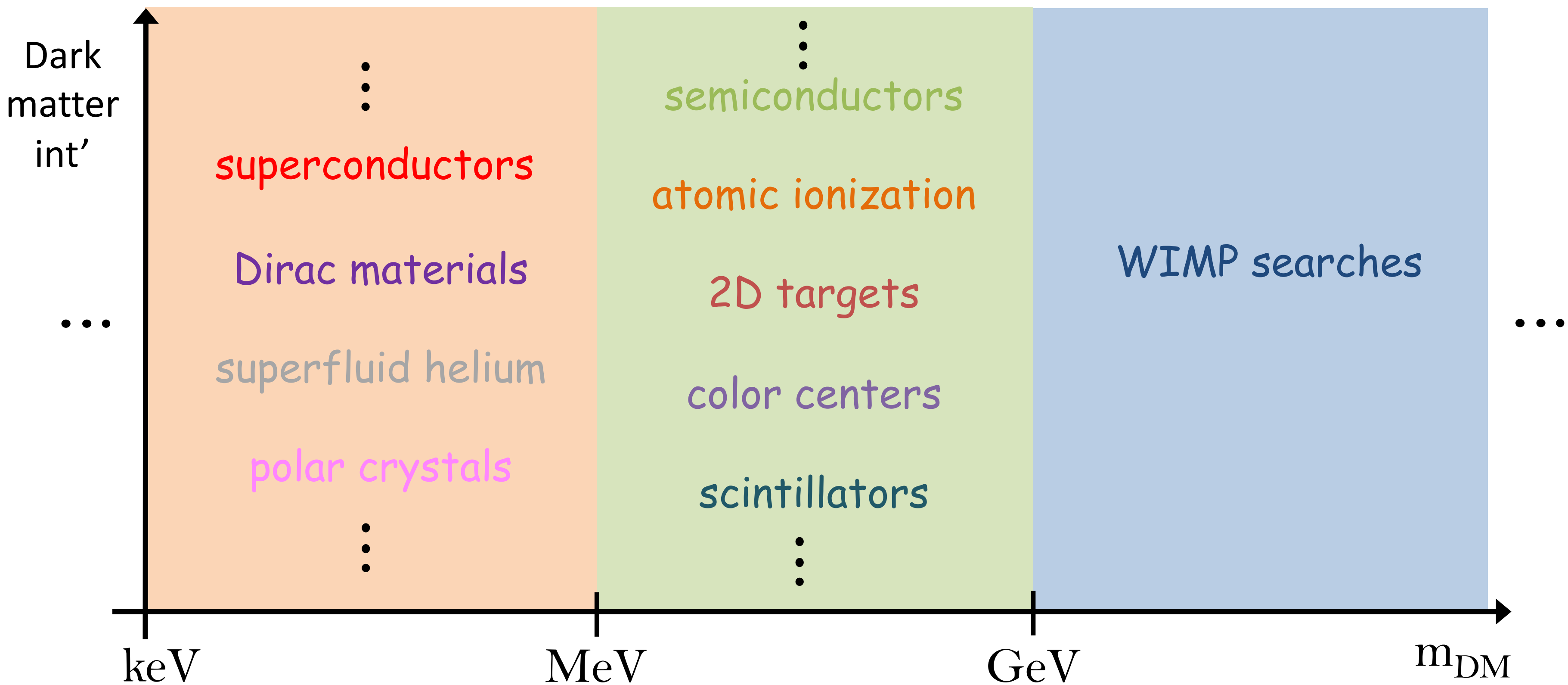
Burgeoning field in recent years

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!