# New Avenues in Dark Matter Detection

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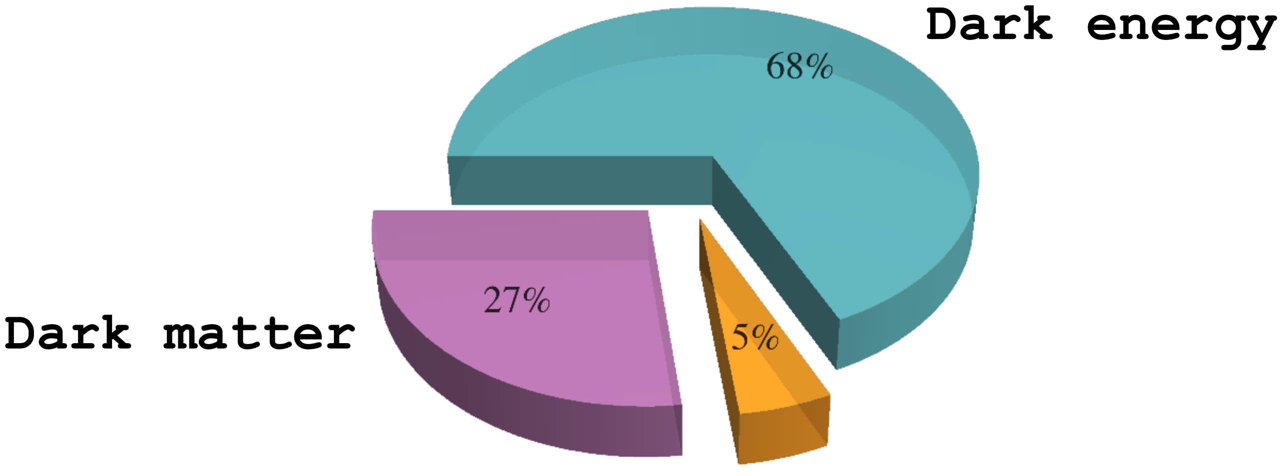
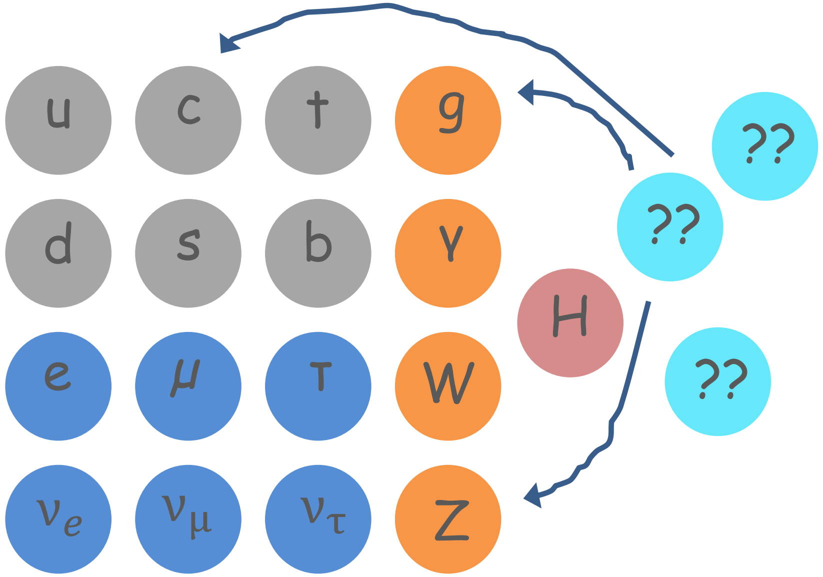
מכון רקח
The Racah Institute
לפיסיקה
of Physics

# The Universe is Dark





What is it?
How does it interact?

# Past 40 years

WIMP, glorious WIMP*

{ *Also axions, of course
also axions :-) }

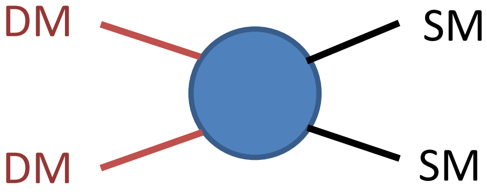
# Past 40 years

Correct thermal relic abundance:

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

For weak coupling, weak scale emerges.

Weakly Interacting Massive Particle (WIMP)

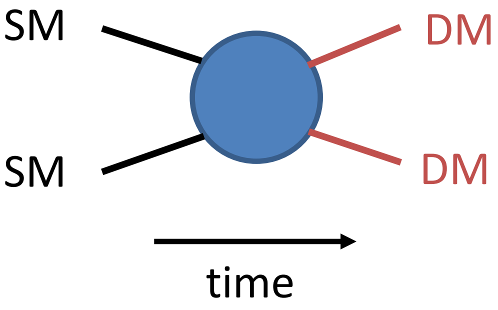


annihilation

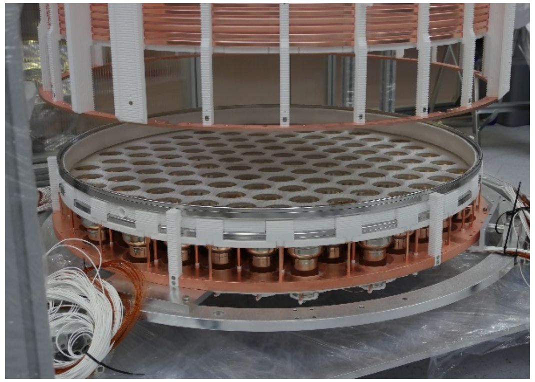
$$\langle \sigma_{\rm ann} v \rangle = \frac{\alpha^2}{m_{\rm DM}^2}$$

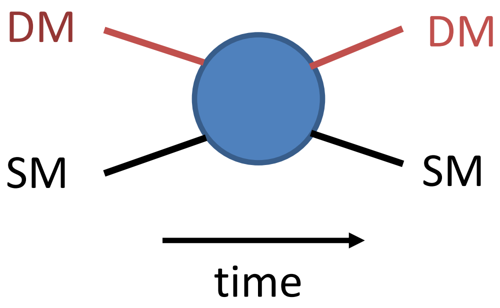
# Searching for WIMPs

## Direct production

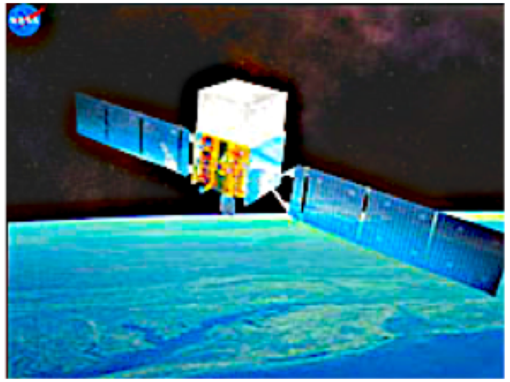


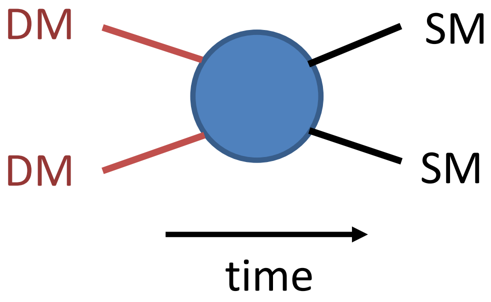
## Direct detection





## Indirect detection

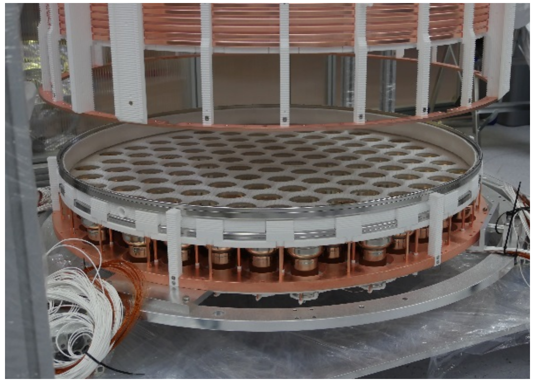




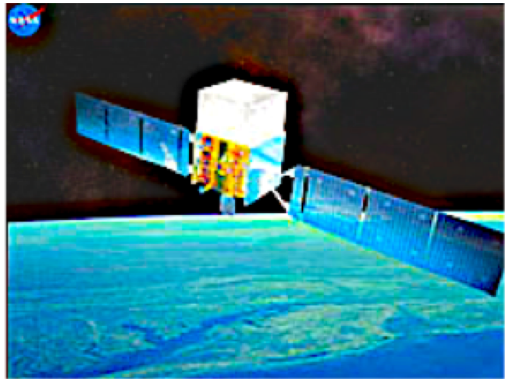
# Searching for WIMPs

**Direct production**

**Direct detection**



**Indirect detection**

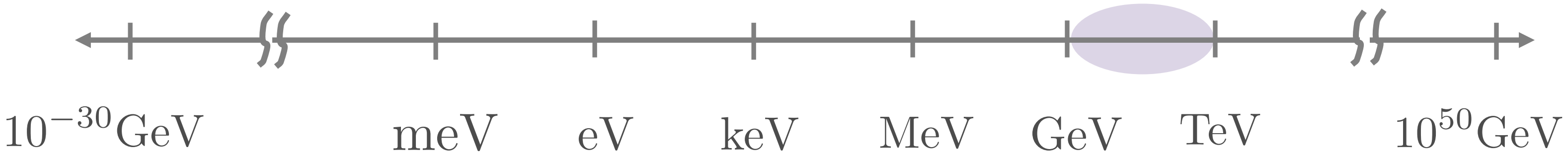


**Experiments getting increasingly sensitive**

**Haven’t yet detected dark matter**

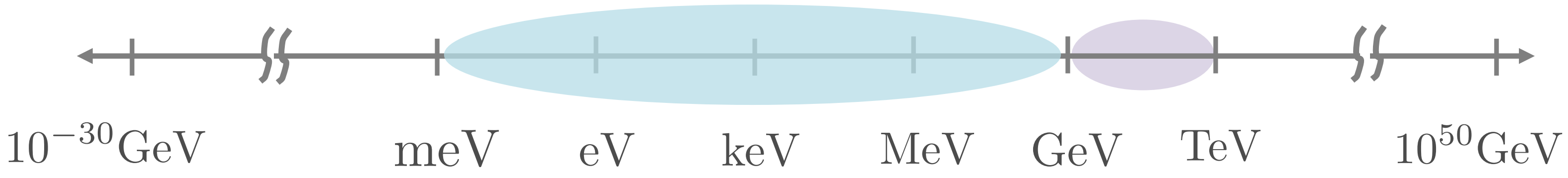
Great opportunity for new ideas.

# Beyond the WIMP



Possible dark matter mass

# Beyond the WIMP



Possible dark matter mass

**New Frontier: Light Dark Matter**
**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**

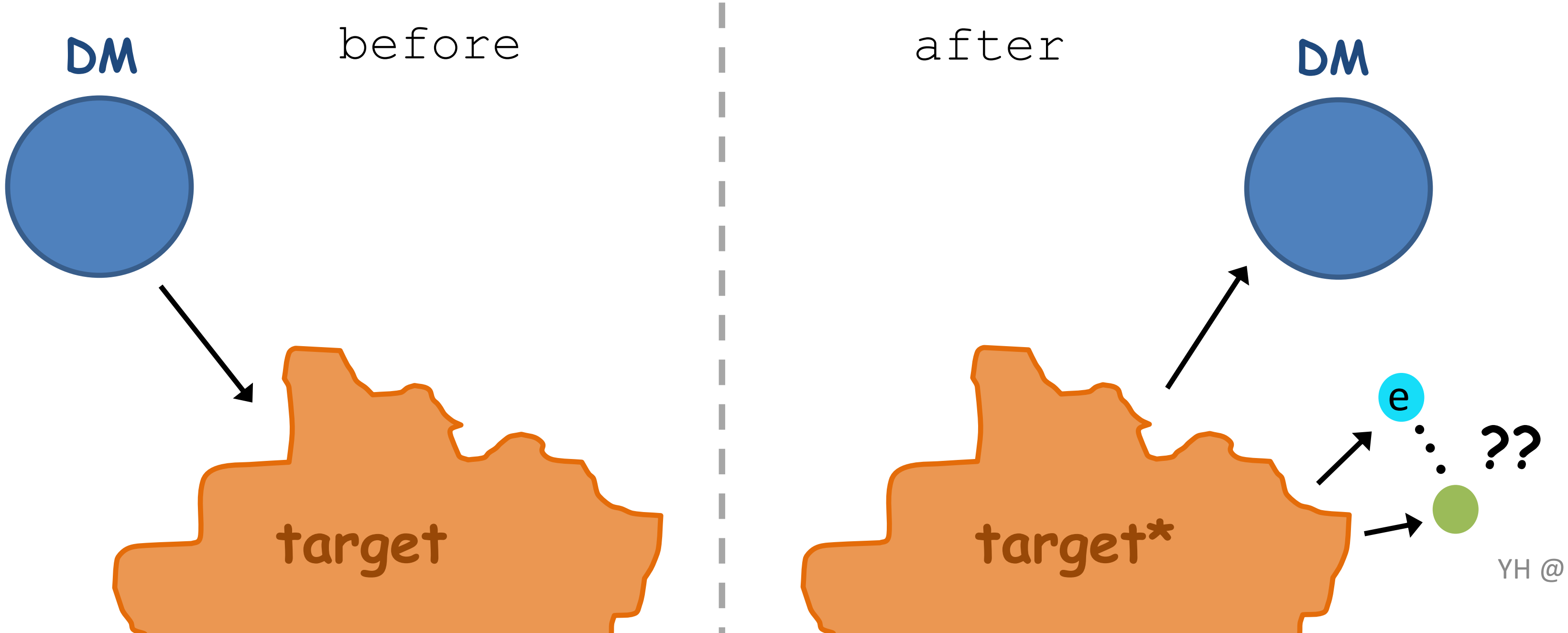
# Detection Blueprints

Dark matter particle comes in

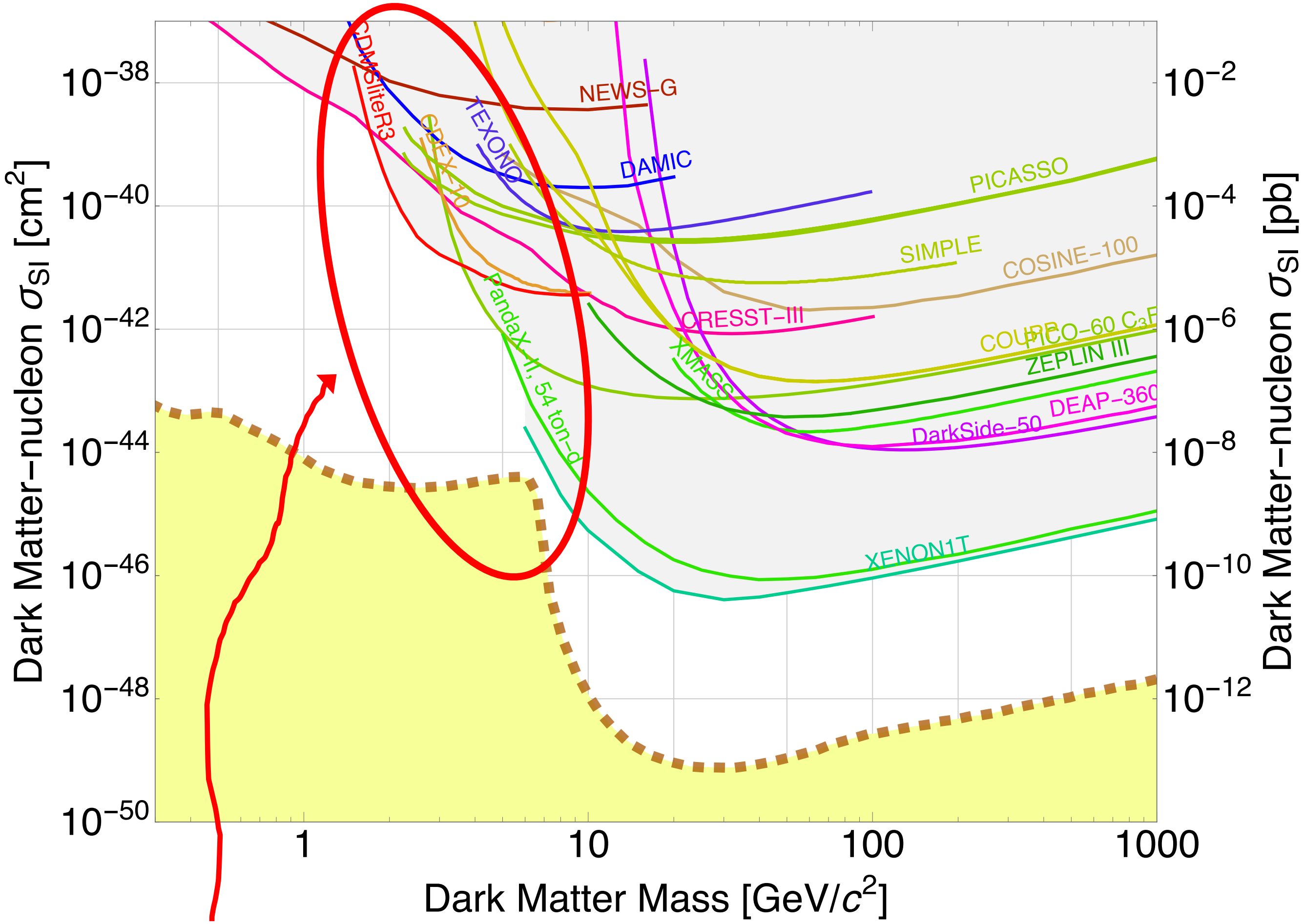
Hits a target in the lab

System reacts

Measure the reaction



# Direct Detection



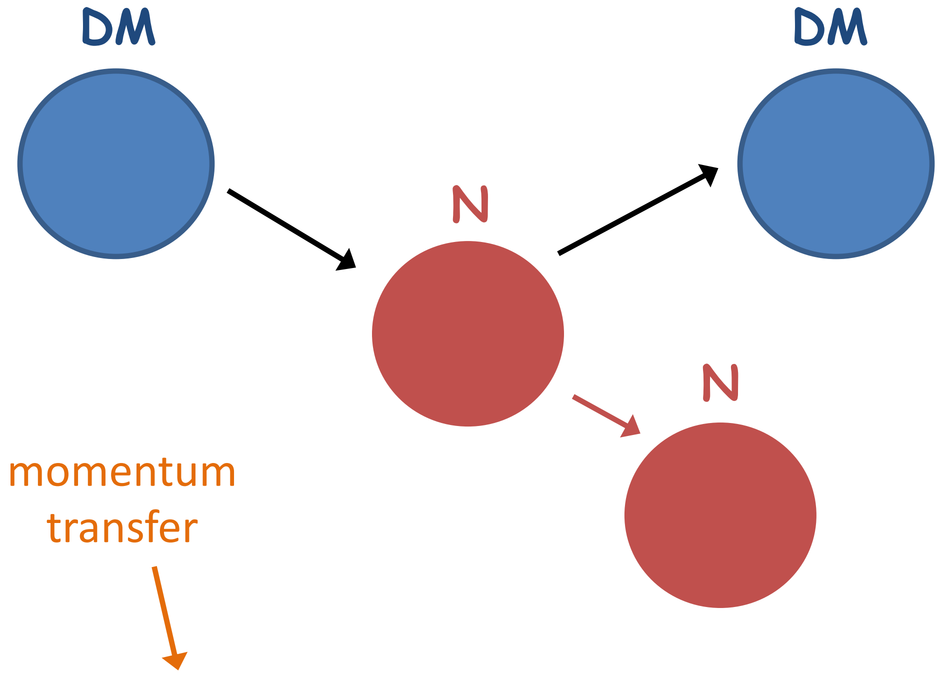
What's going on?

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

# Current Experiments

Looking for nuclear recoils:

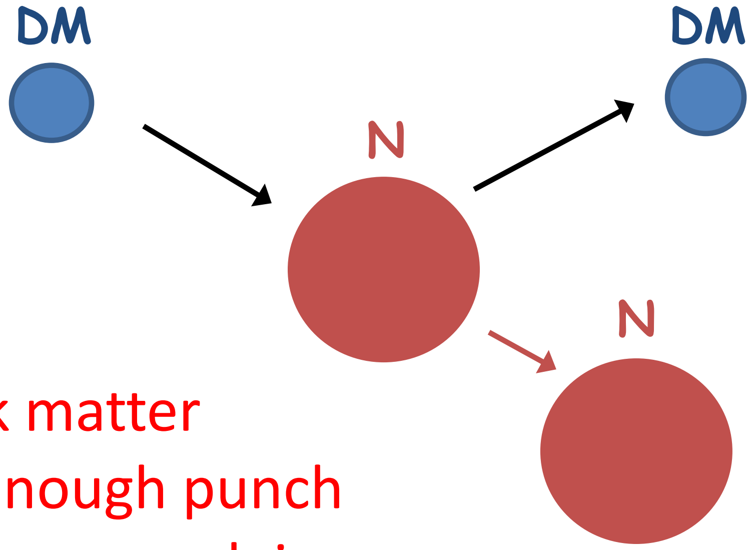
think billiard balls



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

# Current Experiments

Looking for nuclear recoils:
think billiard balls

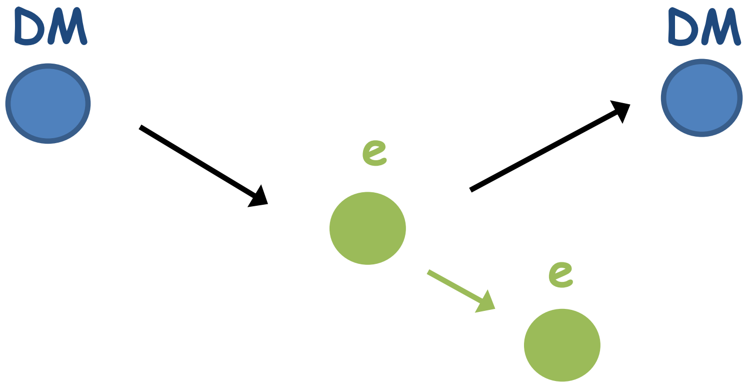


light dark matter
doesn't have enough punch
to kick the heavy nuclei

Lose sensitivity @ O(GeV) masses

# New Avenues

Light dark matter: scatter off electrons!



light dark matter
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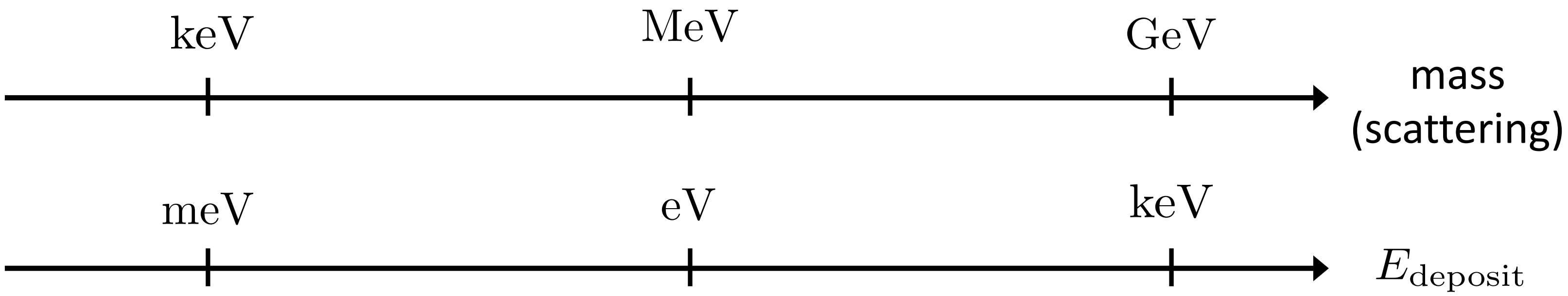
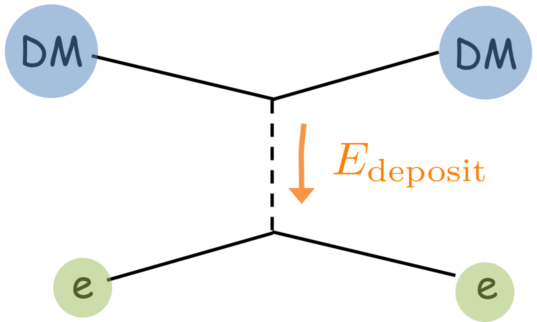
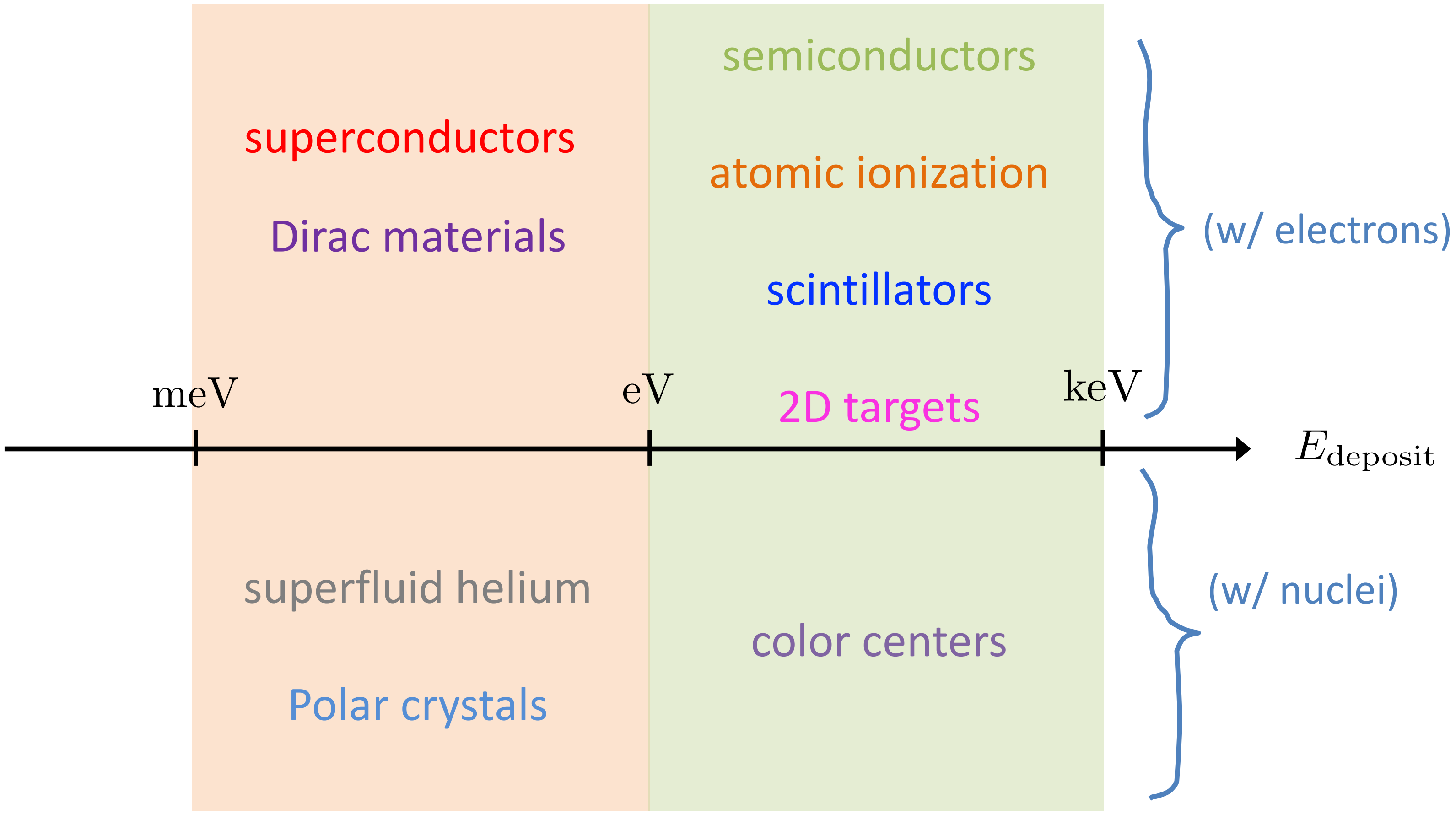
# Energy guideline

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





# New proposals



superconductors

Dirac materials

semiconductors

atomic ionization

scintillators

2D targets

(w/ electrons)

meV

eV

keV

$E_{\text{deposit}}$

superfluid helium

Polar crystals

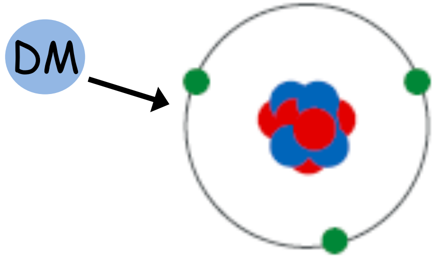
color centers

(w/ nuclei)

Explosion of interest and ideas in recent times

# Ex. #1: First ideas

## Atomic ionization

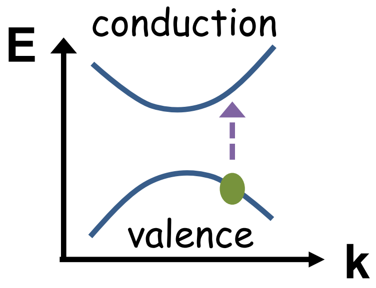


Xenon: ~12 eV

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

Essig, Mardon, Volansky, 2012

## Semiconductors



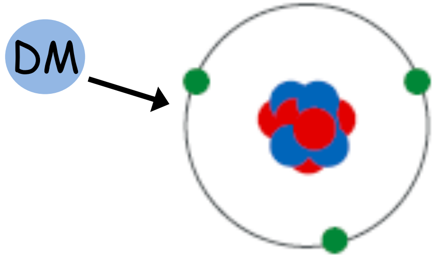
Ge, Si, Diamond, SiC: ~eV

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

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

# Ex. #1: First ideas

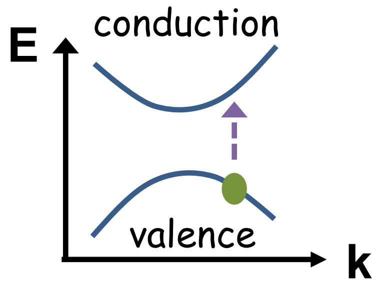
**Atomic ionization**



**Xenon10/100/1T**

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

**Semiconductors**



**SuperCDMS, SENSEI**

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

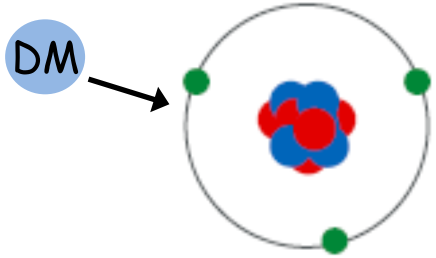
**Are being experimentally realized**

Essig et al 2012 | Xenon100 2016 | Xenon1T 2020

SuperCDMS 2020 | SENSEI 2020

# Ex. #1: First ideas

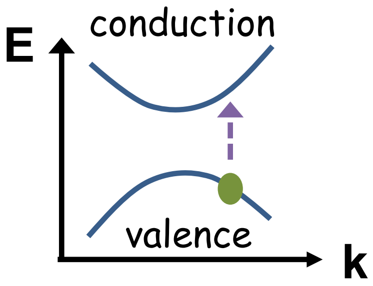
## Atomic ionization



**Xenon10/100/1T**

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

## Semiconductors



**SuperCDMS, SENSEI**

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

**Smaller masses?**

# Ex. #2: Superconductors

- Ground state = Cooper pairs;

  Binding energy (gap) $\sim \mathrm{meV}$ ➡ $m_{\rm DM} \sim \mathrm{keV}$
- The idea:

  DM scatters with Cooper pairs, deposits enough energy, breaks Cooper pairs → 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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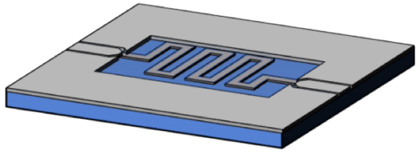
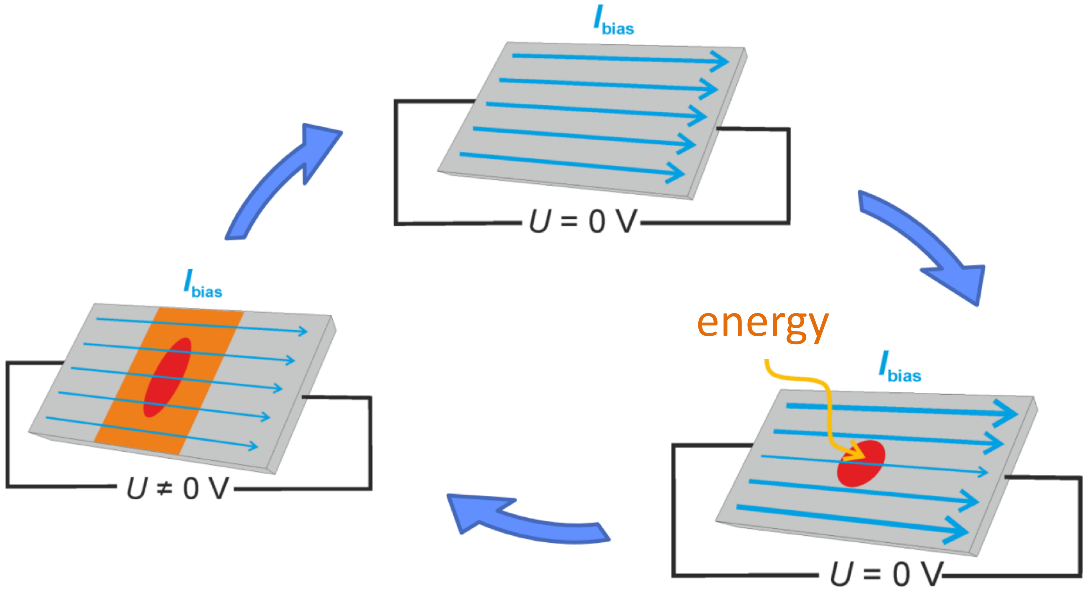
# Ex. #2: Superconductors

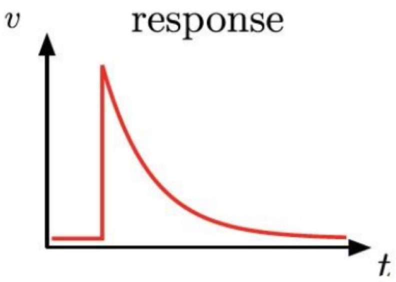
- Superconducting Nanowire Single Photon Detectors (SNSPDs)



Broadly used in quantum information science

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

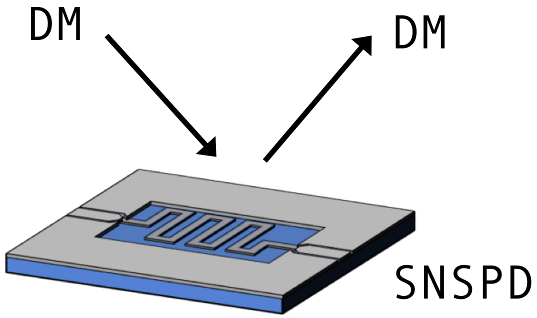




**YH**, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019

# Ex. #2: Superconductors

Use as simultaneous target + sensor (& multiplex)

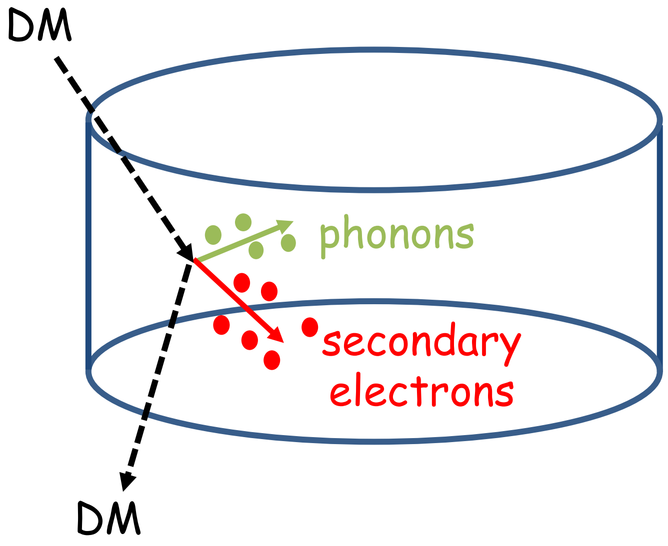


[Existing prototype]

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

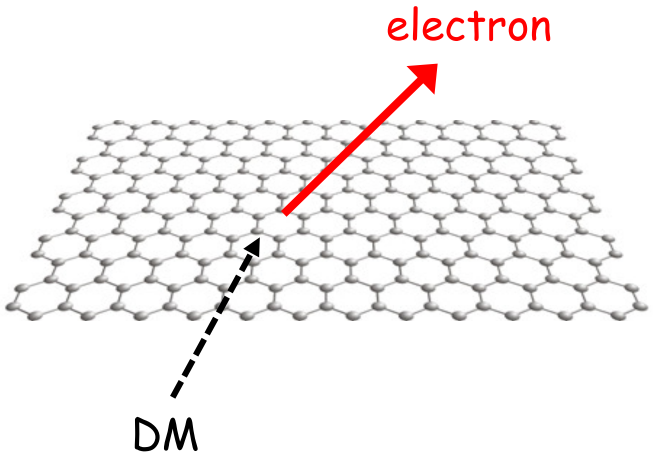
# Directional Info?

Lose directional information
if detecting secondaries



**e.g. semiconductors,
bulk superconductors**

Retain directional information
if observe primary!

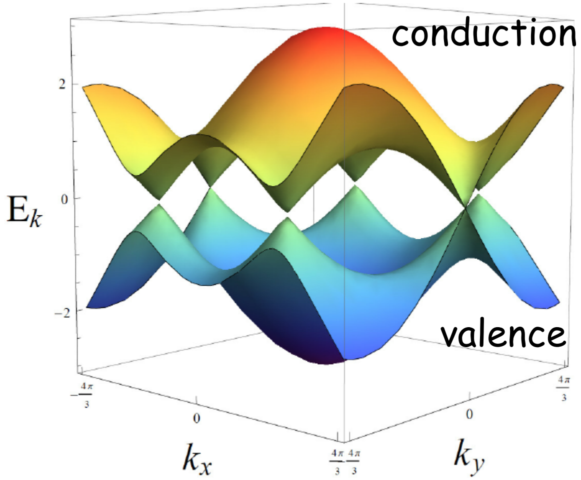


**2D targets;
graphene (& SNSPDs)**

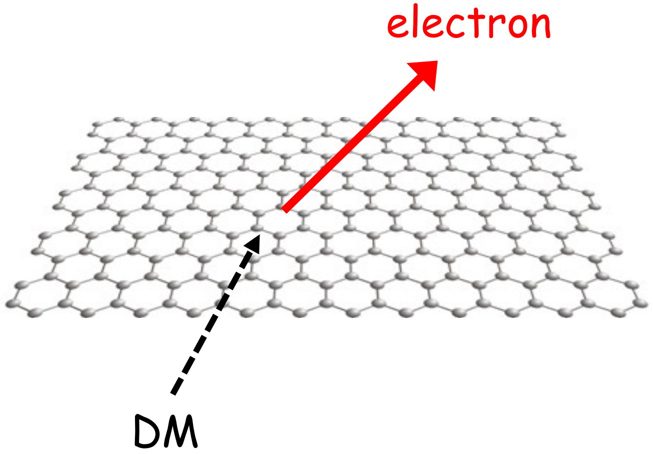
But see **YH**, Kramer, Kurinsky, Lehmann 2109.04473

# Ex. #3: Graphene

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



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



Eject and detect philosophy

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

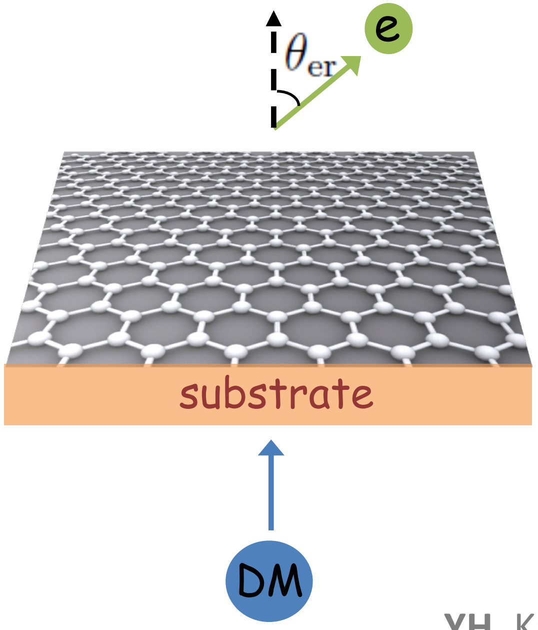
# Ex. #3: Graphene

Electron follows incoming dark matter direction.

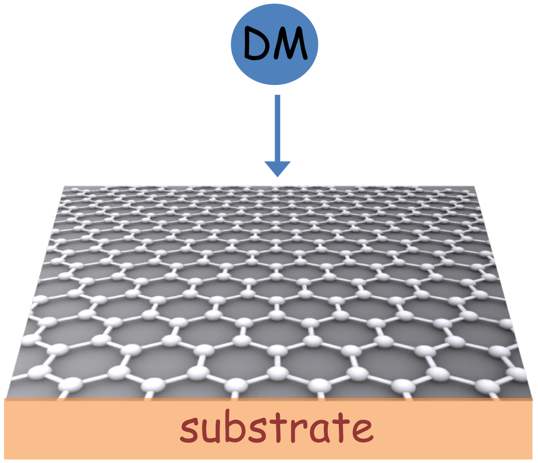
Naturally gives forward/backward discrimination

(separates signal from background)

**Electron detected**



**electron not detected**



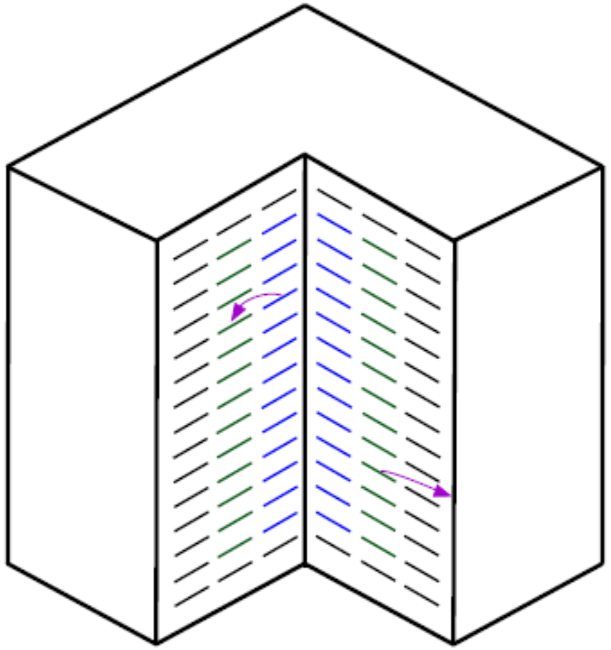
12 hours later

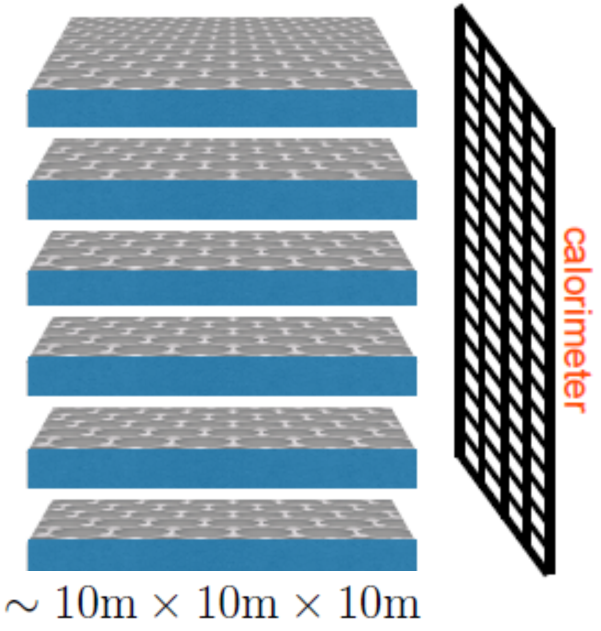
**YH**, Kahn, Lisanti, Tully, Zurek, 2017

# Ex. #3: Design Concept

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

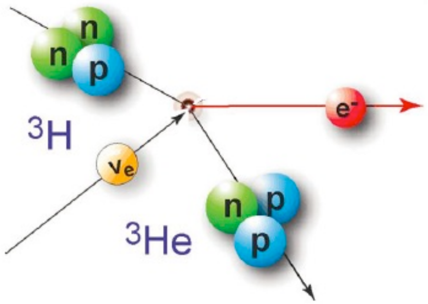
- Compact geometry: large mass via many stacks





# Implement in PTOLEMY

Experiment to detect relic neutrinos via capture on tritium.

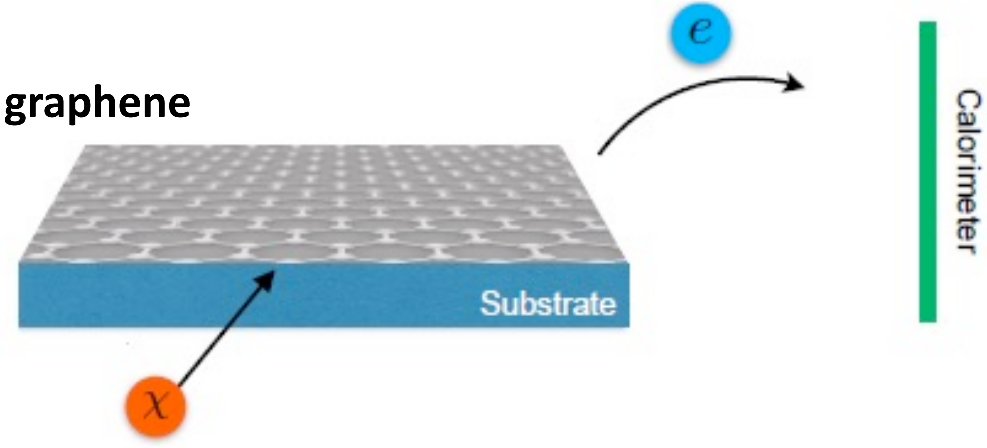


Betts et al, 2013

Will use tritiated graphene (~0.5 kg).

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

**Bare graphene**



# PTOLEMY World-Wide Collaboration

**טלסקופ ניטרינים קוסמיים**

**Telescopio di neutrini cosmologici**

**Kosmische neutrinotelescoop**

**Telescopio de neutrinos cósmicos**

**Kosmisk neutrinoteleskop**

**Cosmic neutrino telescope**

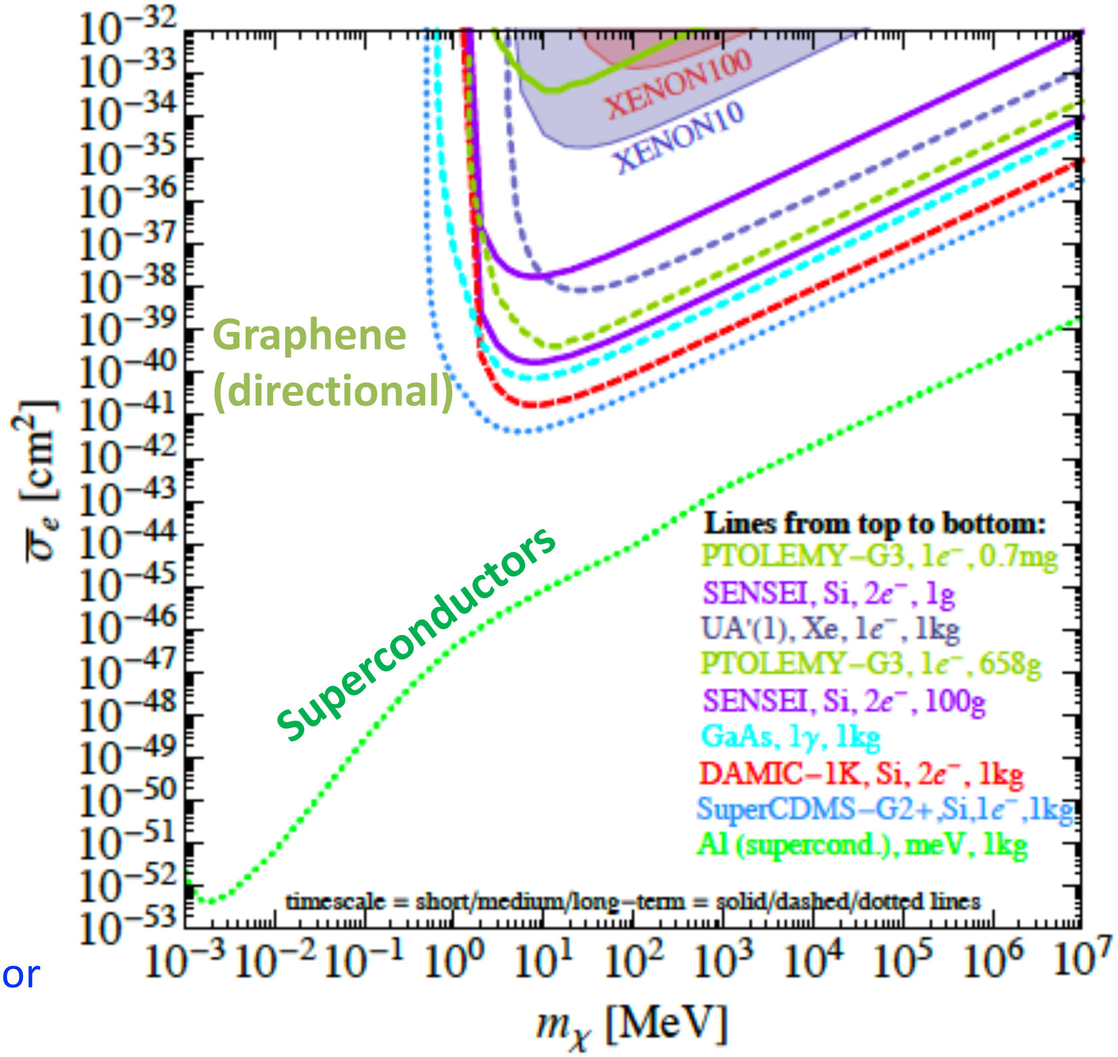
PTOLEMY: A Proposal for Thermal Relic Detection of Massive Neutrinos and Directional Detection of MeV Dark Matter

# Compute Event Rate

$$\overset{\text{[Events/unit time/unit mass]}}{\overset{\downarrow}{\text{Rate}}} \propto \underbrace{\frac{1}{\rho_{\text{target}}}}_{\uparrow \atop \text{Target density}} \times \underbrace{\frac{\rho_{\text{DM}}}{m_{\text{DM}}} \times v_{\text{DM}}}_{\uparrow \atop \text{dark matter flux (astrophysics)}} \times \underbrace{\text{target properties}}_{\uparrow \atop \text{condensed matter physics}} \times \underbrace{\sigma_{\text{int}}}_{\uparrow \atop \text{particle physics}}$$

# Scattering Reach

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



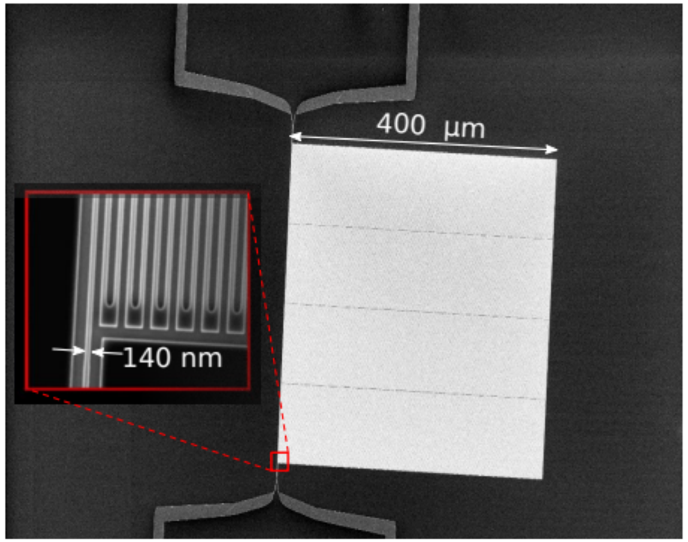
Community report, 2017

[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)

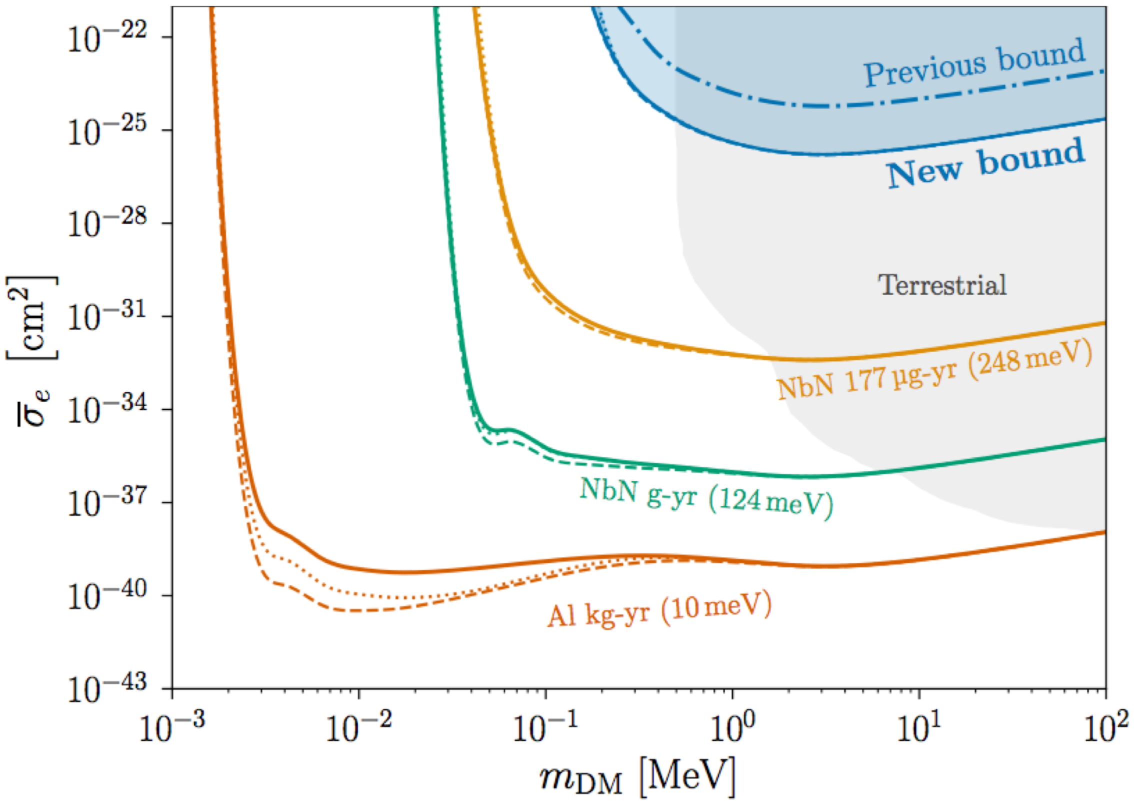


By now have 180 hours of data

**YH**, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019 + w/ Lehmann, PRD Editor's Choice 2021

# Scattering Reach

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



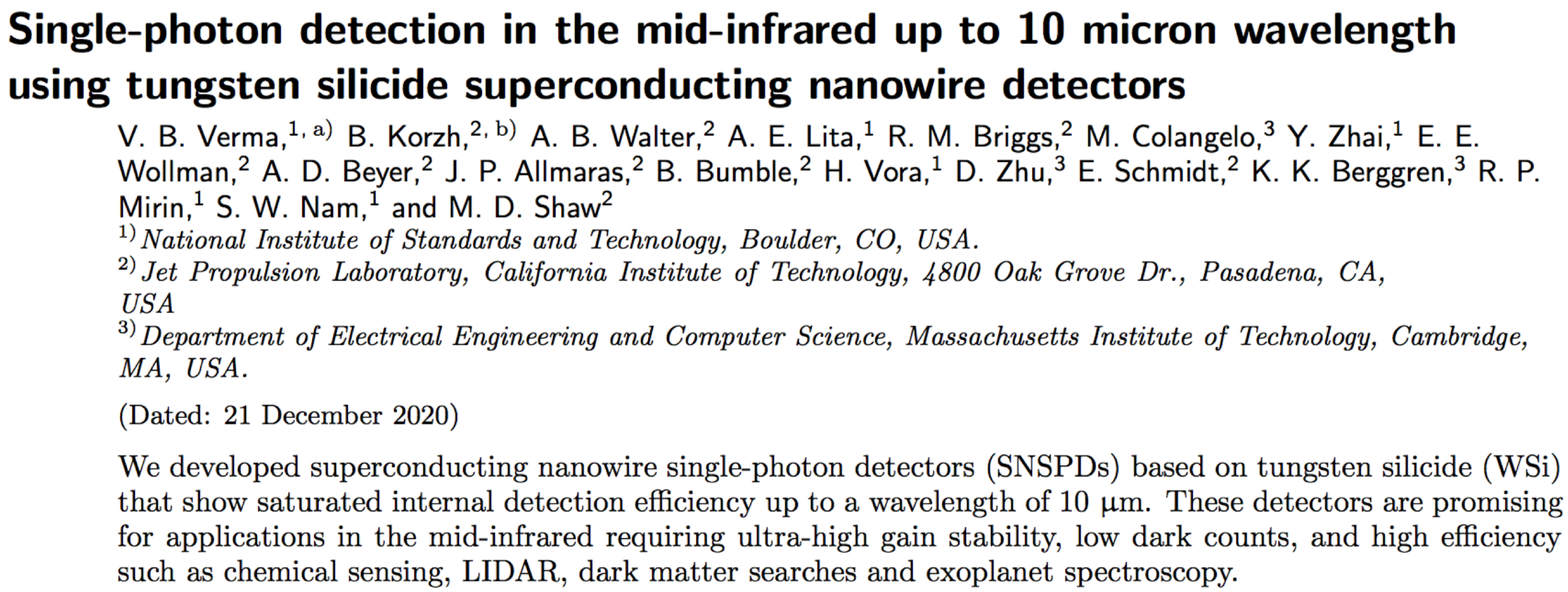
Non-solid curves: geometry effects

Lasenby, Prabhu 2021

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

**YH**, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019 + w/ Lehmann, PRD Editor's Choice 2021

# 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)

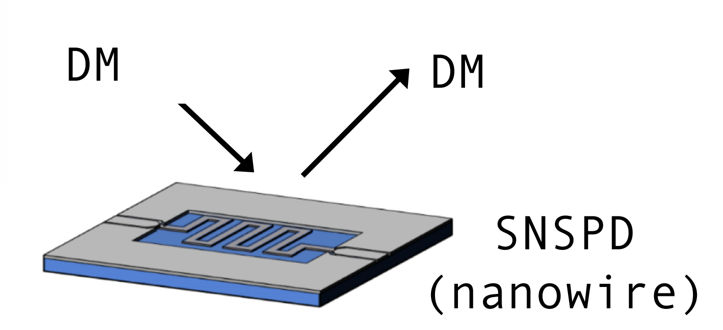
We developed superconducting nanowire single-photon detectors (SNSPDs) based on tungsten silicide (WSi) that show saturated internal detection efficiency up to a wavelength of 10 µm. These detectors are promising for applications in the mid-infrared requiring ultra-high gain stability, low dark counts,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

**Demonstrated WSi SNSPDs w/ 125meV energy threshold**

arXiv:2012.09979

# Quantum sensoR cryOgeniC search fOr Dark matter In Light mass rangE

Crocodile



Newly forming interdisciplinary collaboration
(particle theory | condensed matter | DM experiment | quantum sensing)

Massachusetts Institute of Technology

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

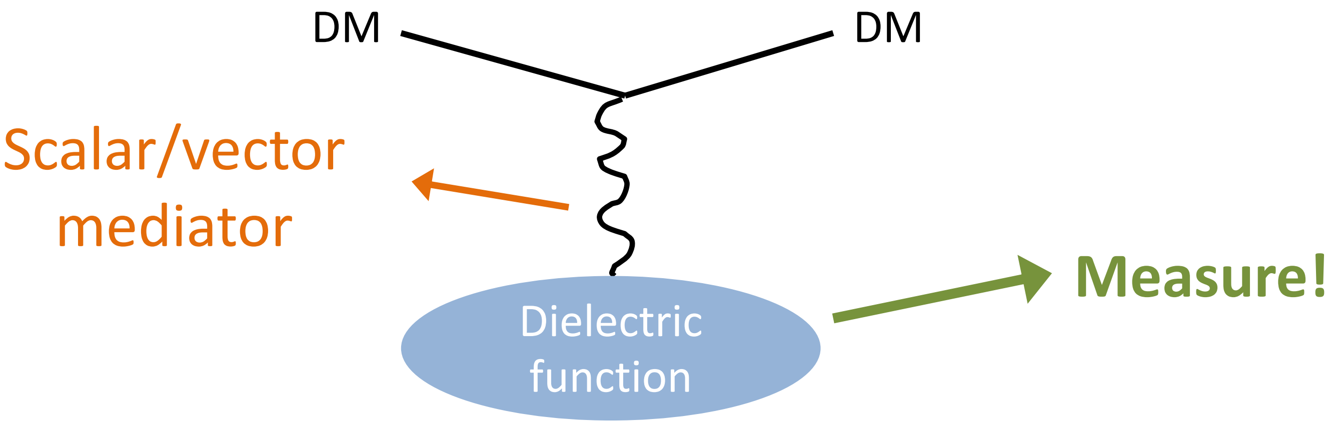
Universität Zürich UZH

# New Formalism

DM-electron scattering in any material

is determined by the dielectric function.

For any DM interaction that couples to electron density



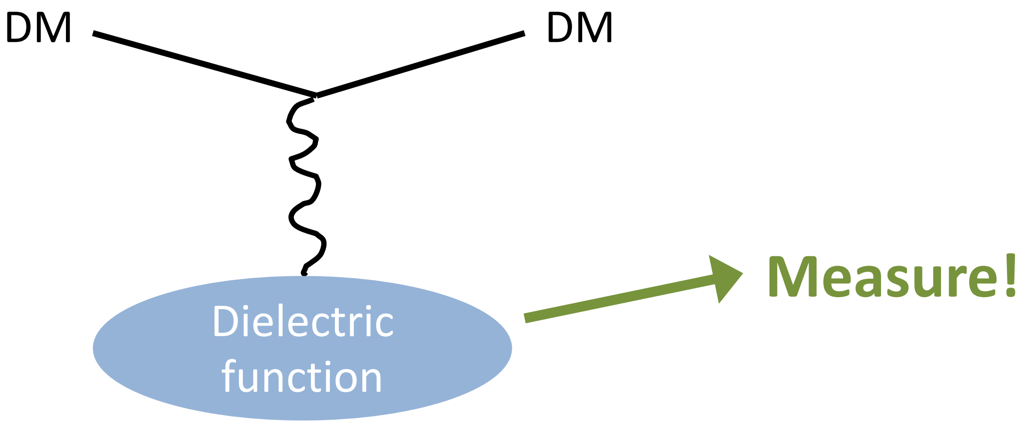
**YH**, Kahn, Kurinsky, Lehmann, Yu, Berggren, PRL 2021

[See also arXiv: 2101.08275]

# New Formalism

Automatically includes many-body effects of the material

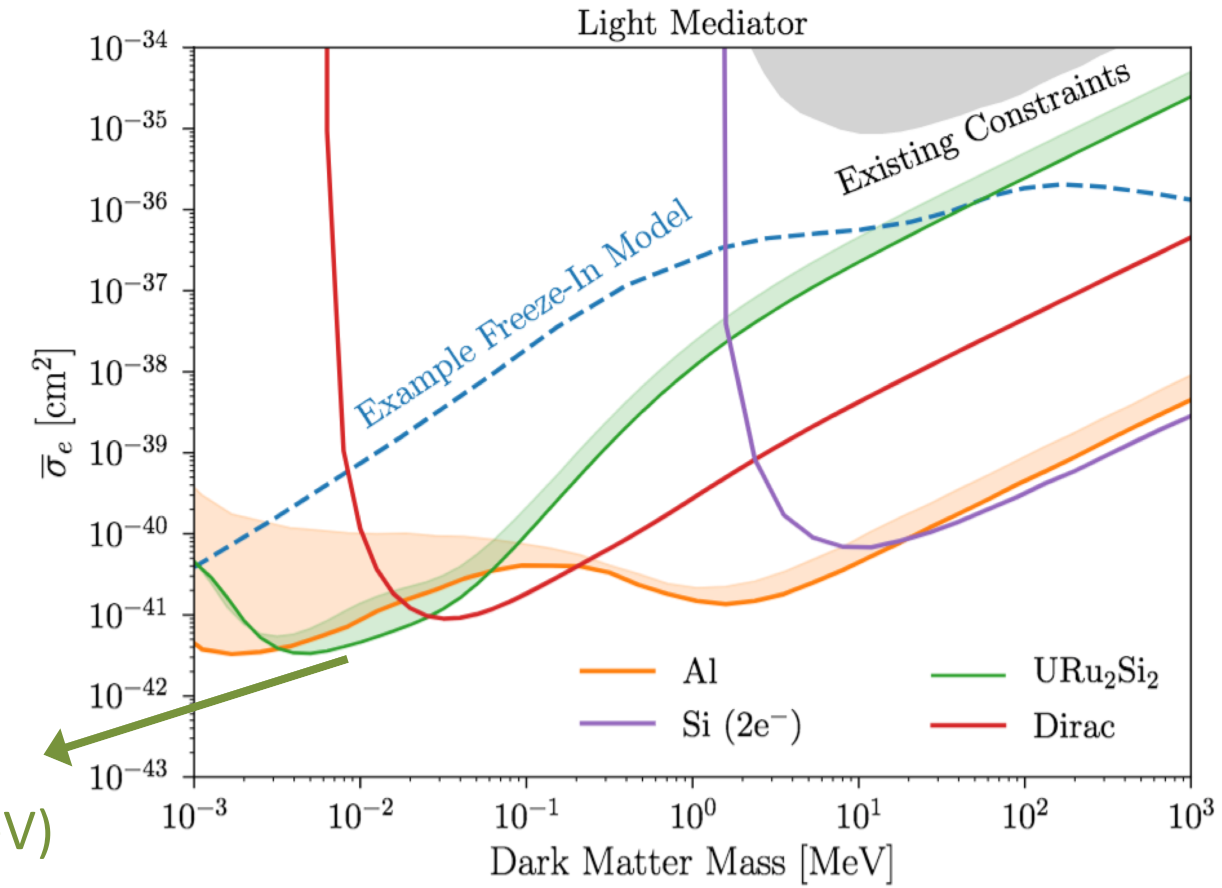
Collective modes (e.g. plasmon),
not just single particle excitations



**Identify promising materials for DM detection**

**YH**, Kahn, Kurinsky, Lehmann, Yu, Berggren, PRL 2021

# Ex. #4: Heavy Fermions



Plasmon
@ O(10meV)

**Identify promising materials for DM detection**

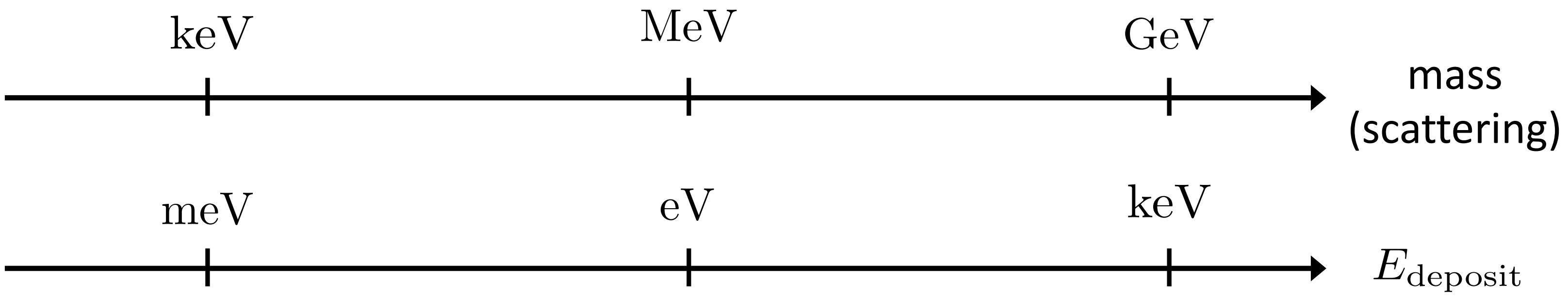
**YH**, Kahn, Kurinsky, Lehmann, Yu, Berggren, PRL 2021

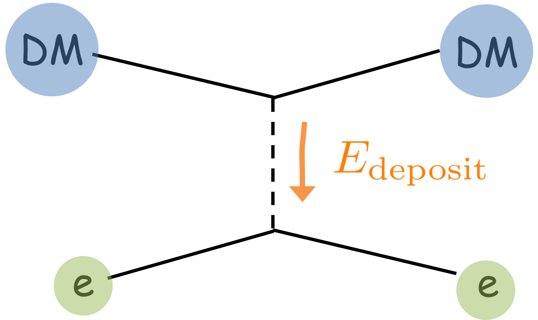
(+ Boyd, **YH**, Kahn, Kramer, Kurinsky, Lehmann, Yu, 2011.nextweek)

Any given target material can go even further.

# Absorption vs. Scattering

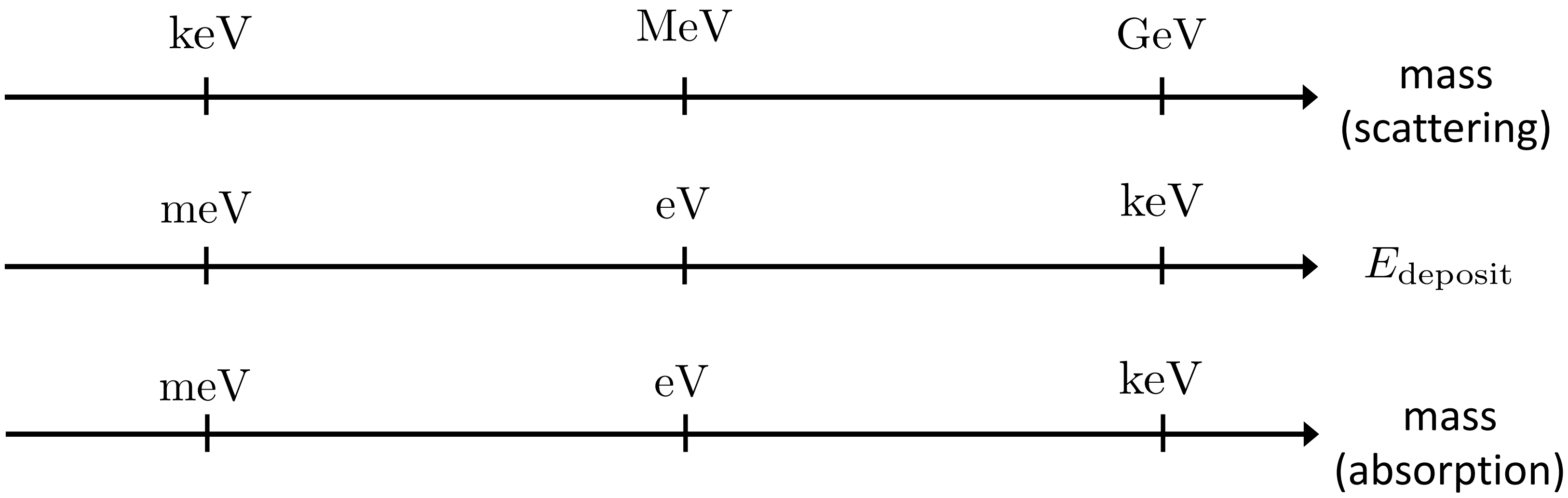
Dark matter scattering: kinetic energy $m_{\mathrm{DM}} v^2 \sim 10^{-6} m_{\mathrm{DM}}$

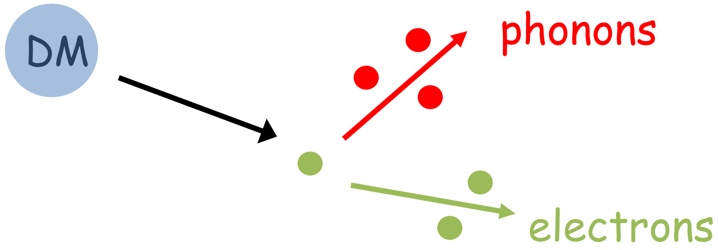




# Absorption vs. Scattering

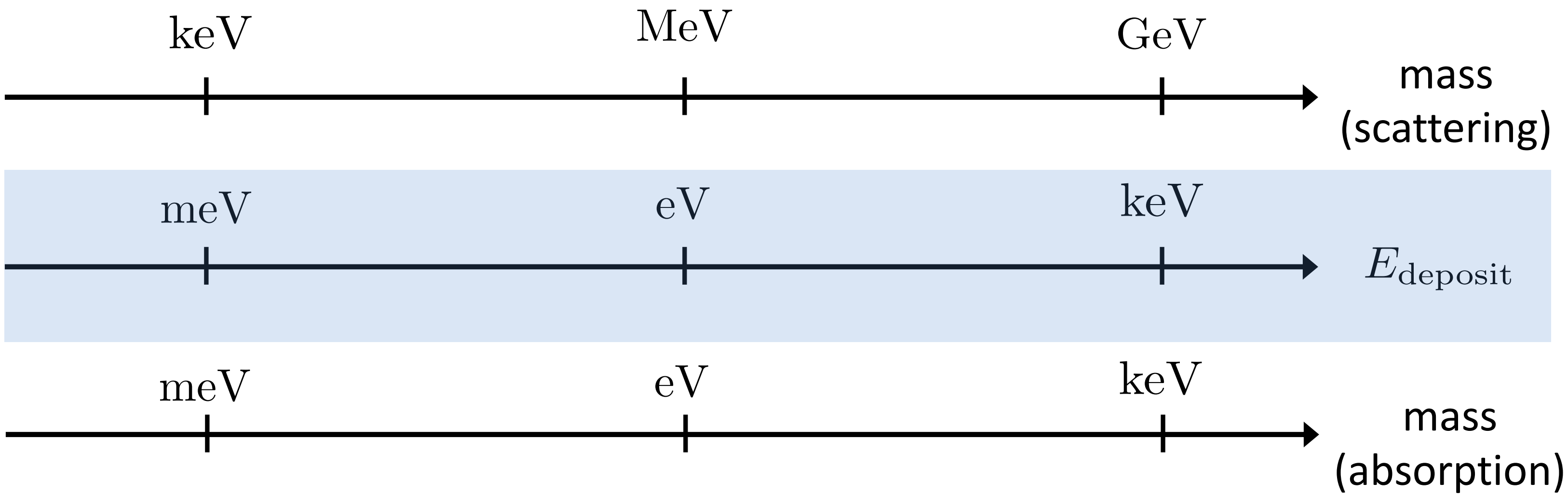
Dark matter absorption: all the mass-energy $m_{\mathrm{DM}}$





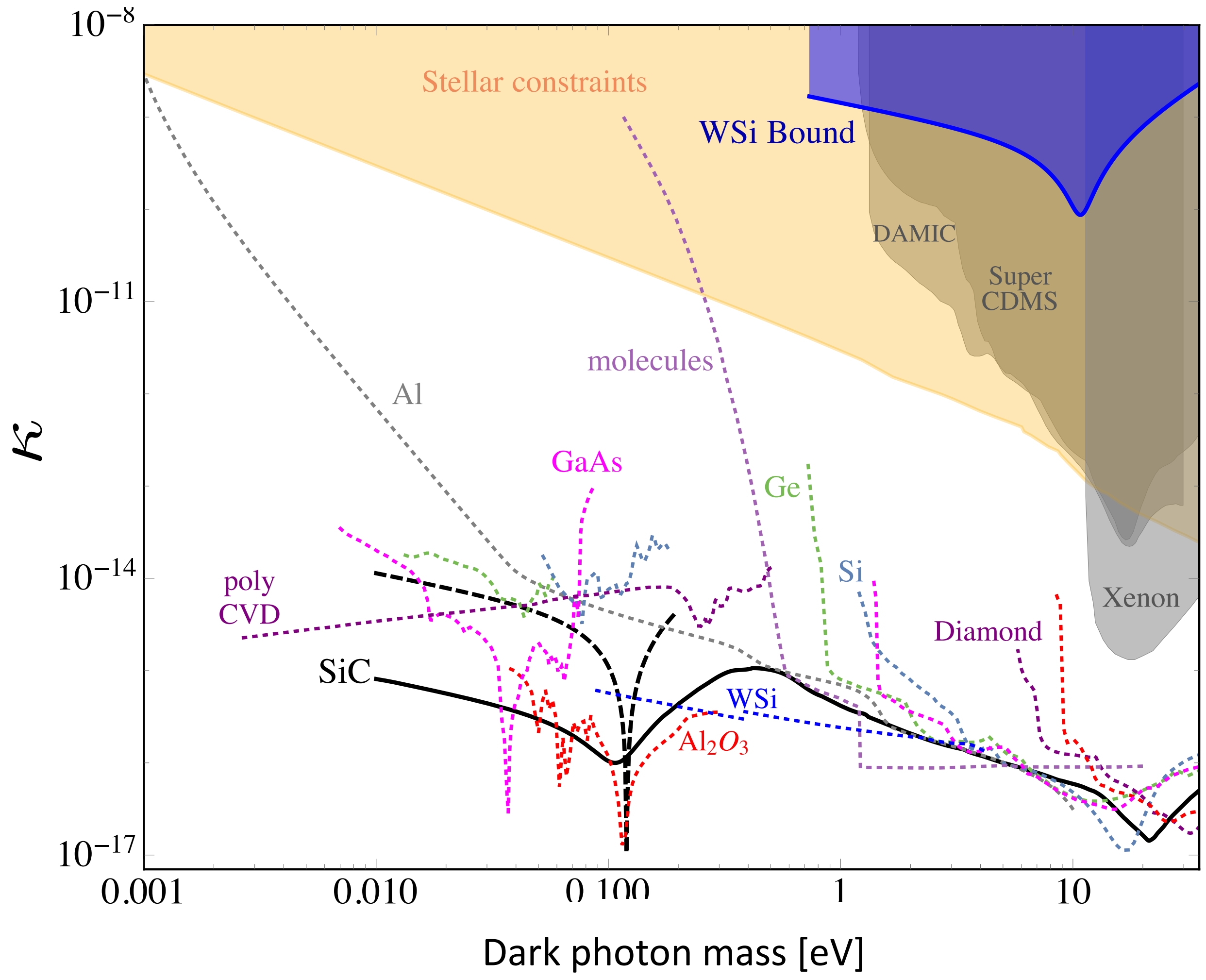
# Absorption vs. Scattering

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



# Absorption Reach

[projections for kg-year]



**New bound:**
WSi SNSPD
prototype
4.3ng in 180
hours

Kurinsky, Yu, **YH,** Blas, PRD 2019
Griffin, **YH**, et al, 2020
**YH** et al, 2021

# Wish List

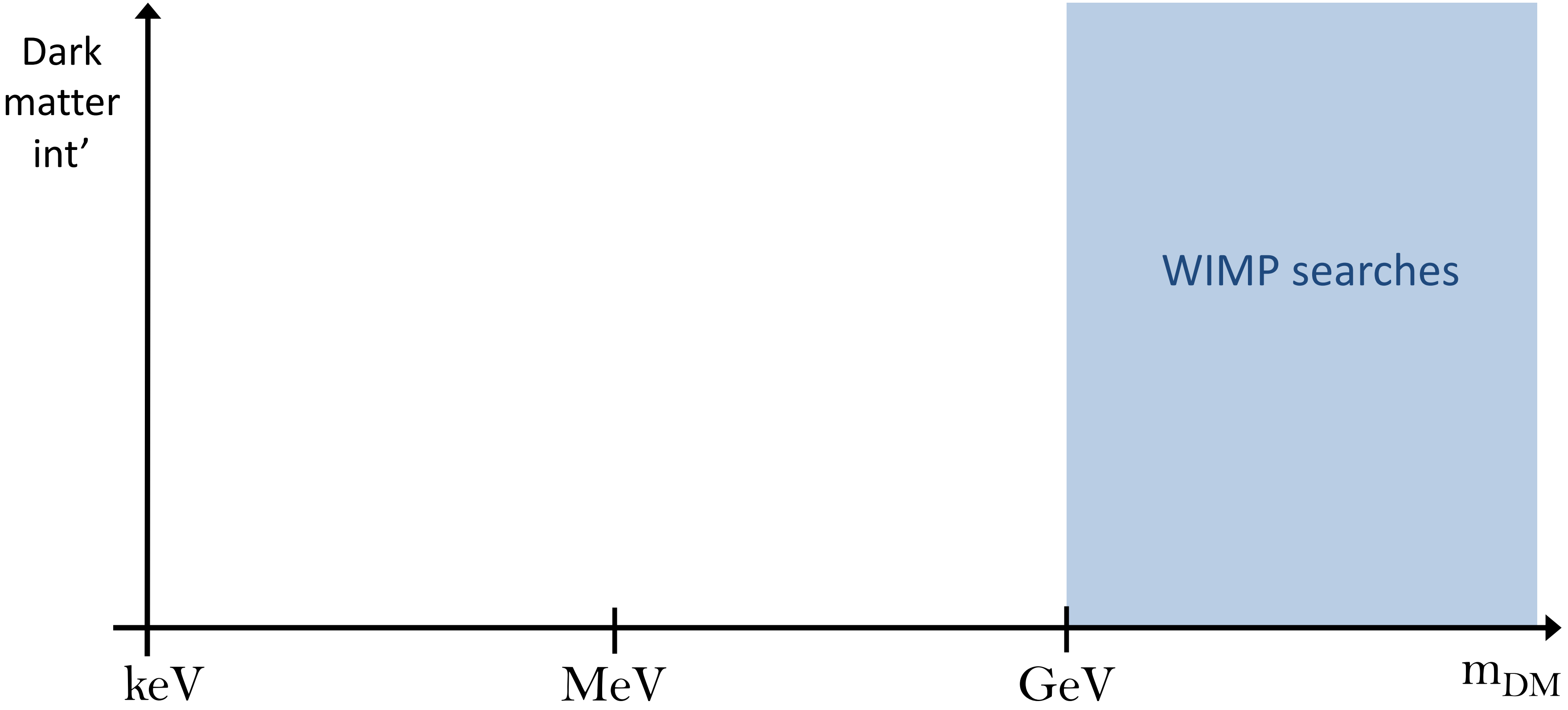
- Single/rare-event sensitivity
- Build up to large target mass: many small units ok & multiplex
- Target can/cannot be the sensitive sensor itself
- Small gap and low thresholds
- Low dark counts ideally
- Directionality a major plus
- Data

**Think detection philosophy & target & sensor**

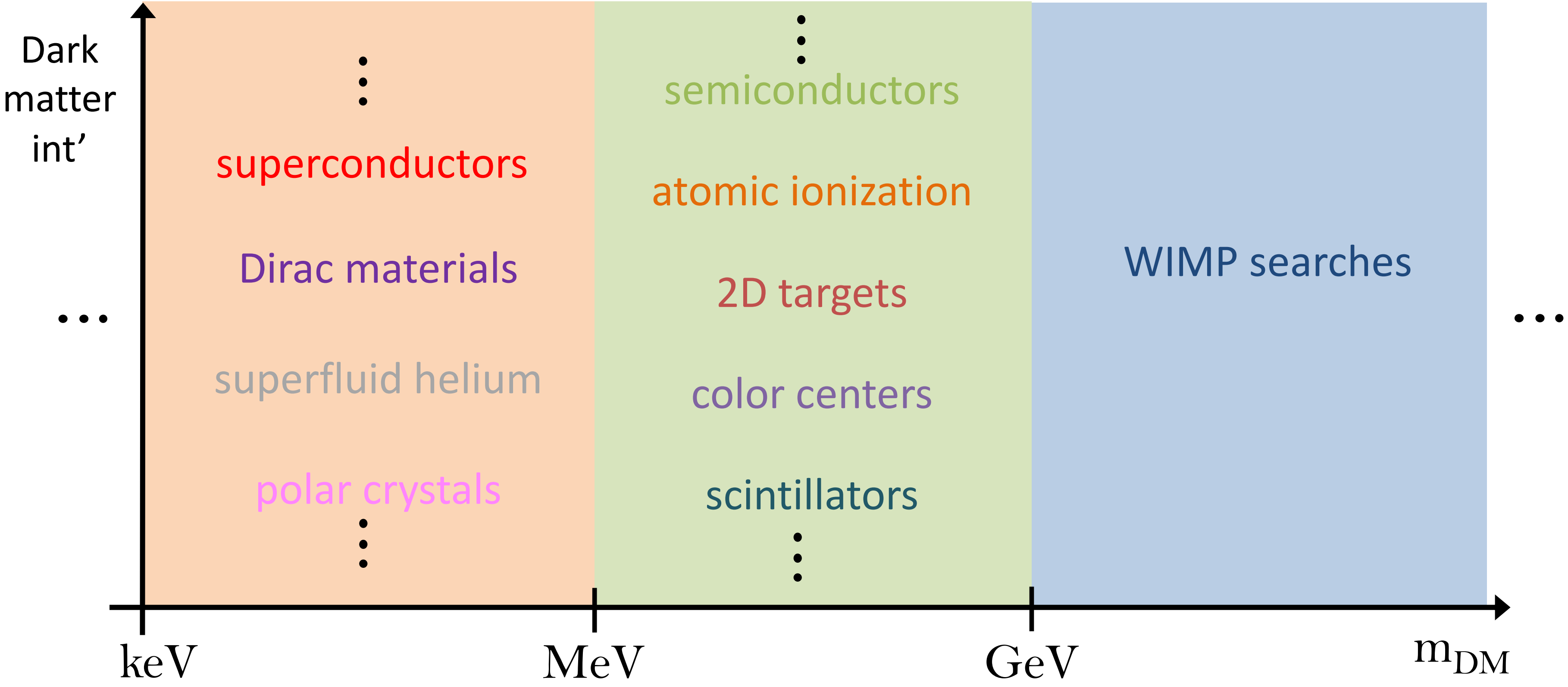
# Outlook

- 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

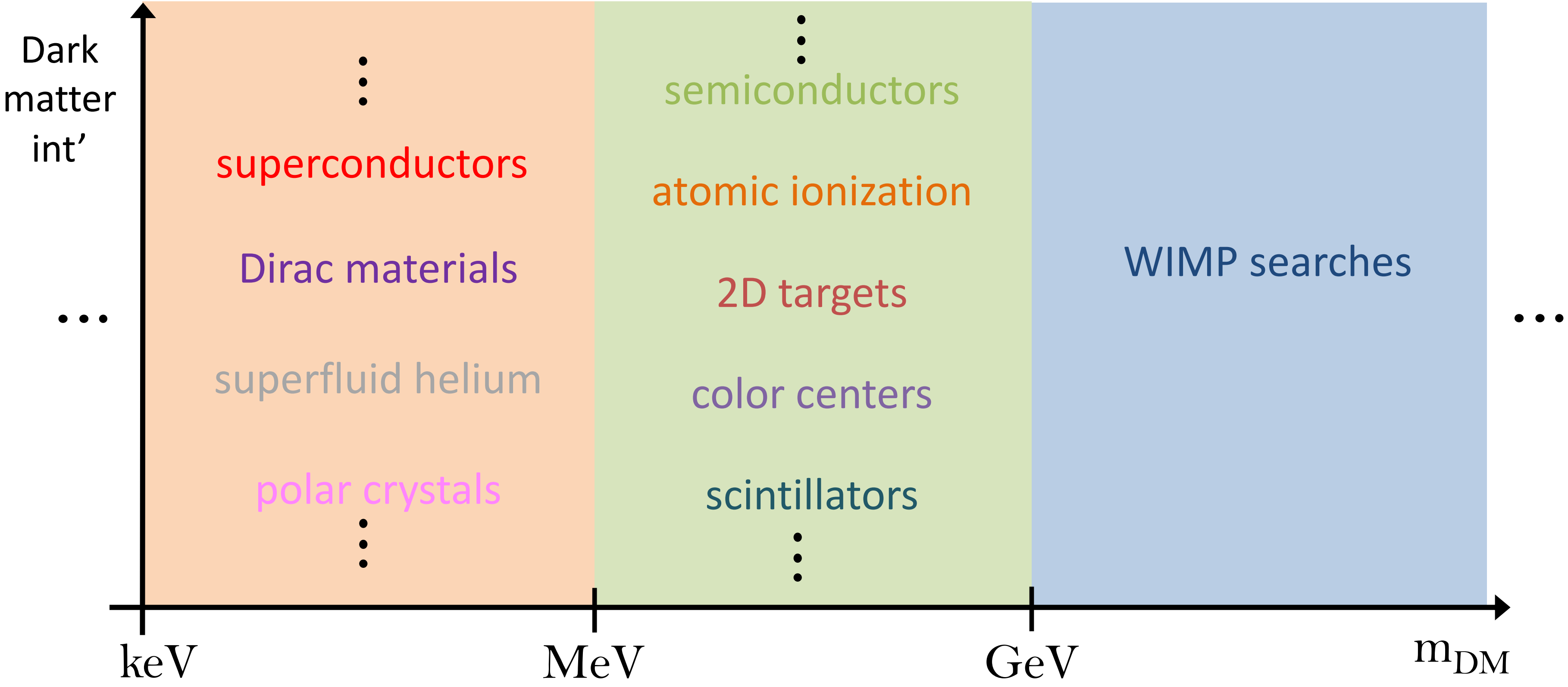


# Prospects



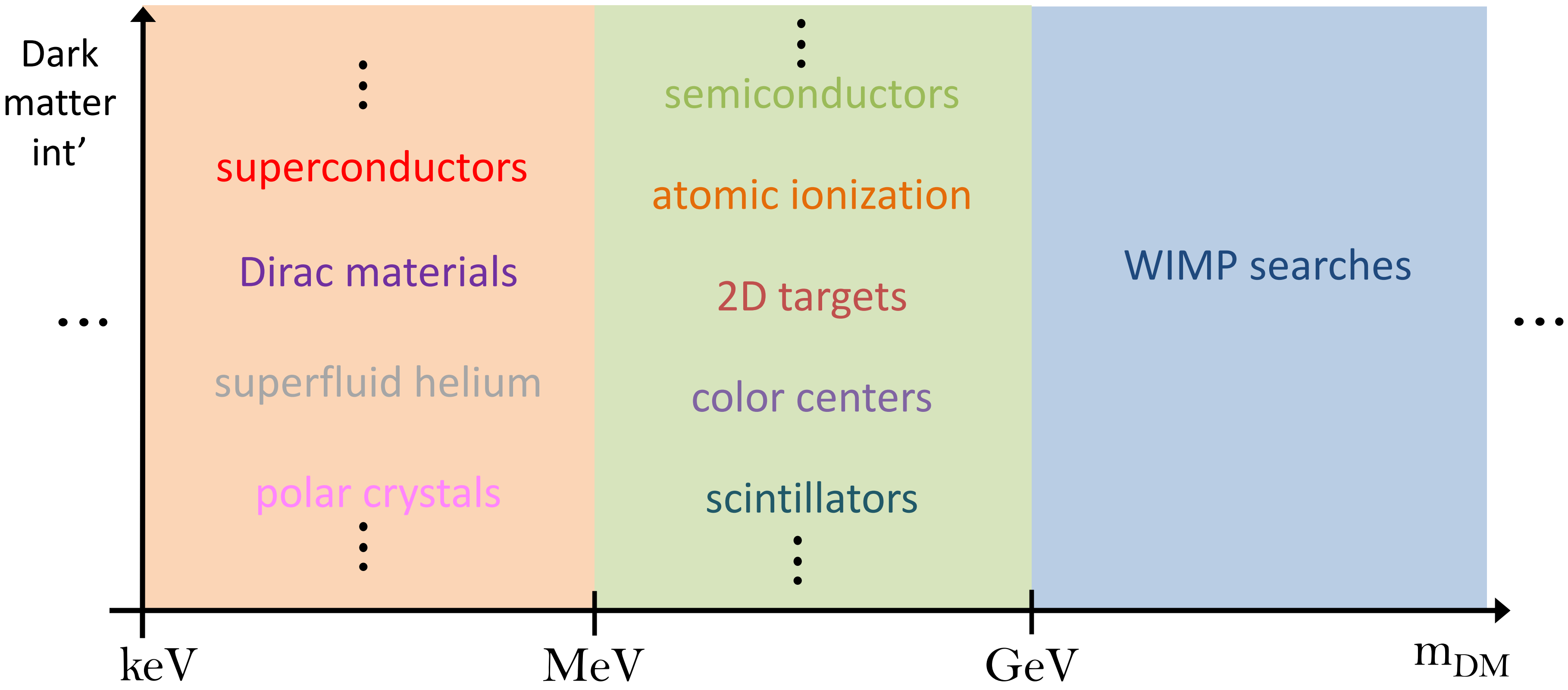
Burgeoning field in recent years

# 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!