New Technologies for Dark Matter Detection

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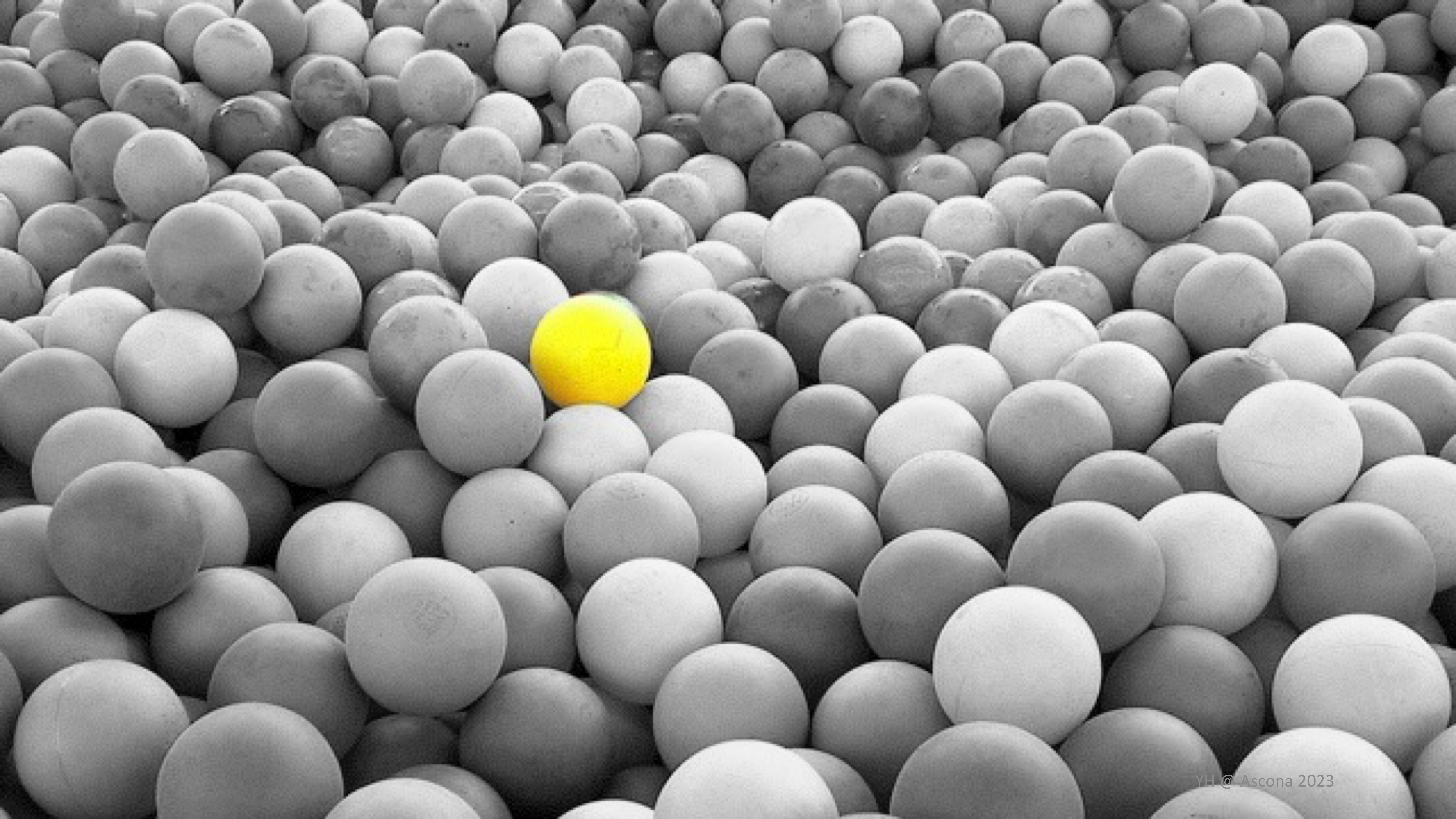
of Physics



Hi!

Theoretical particle physicist.

Work on dark matter.

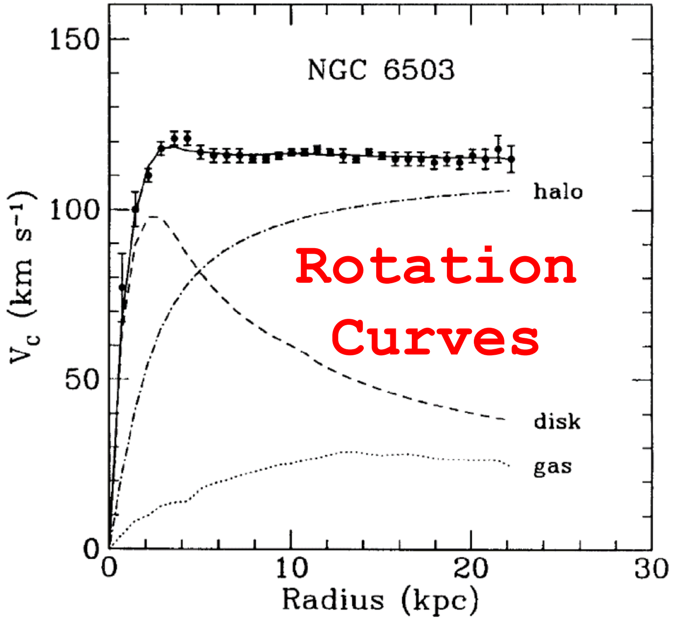
You can too!

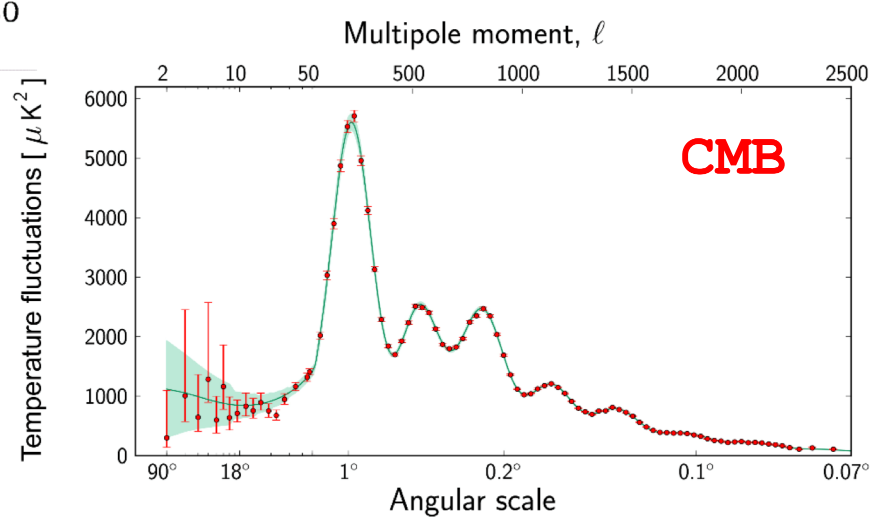
Hi!

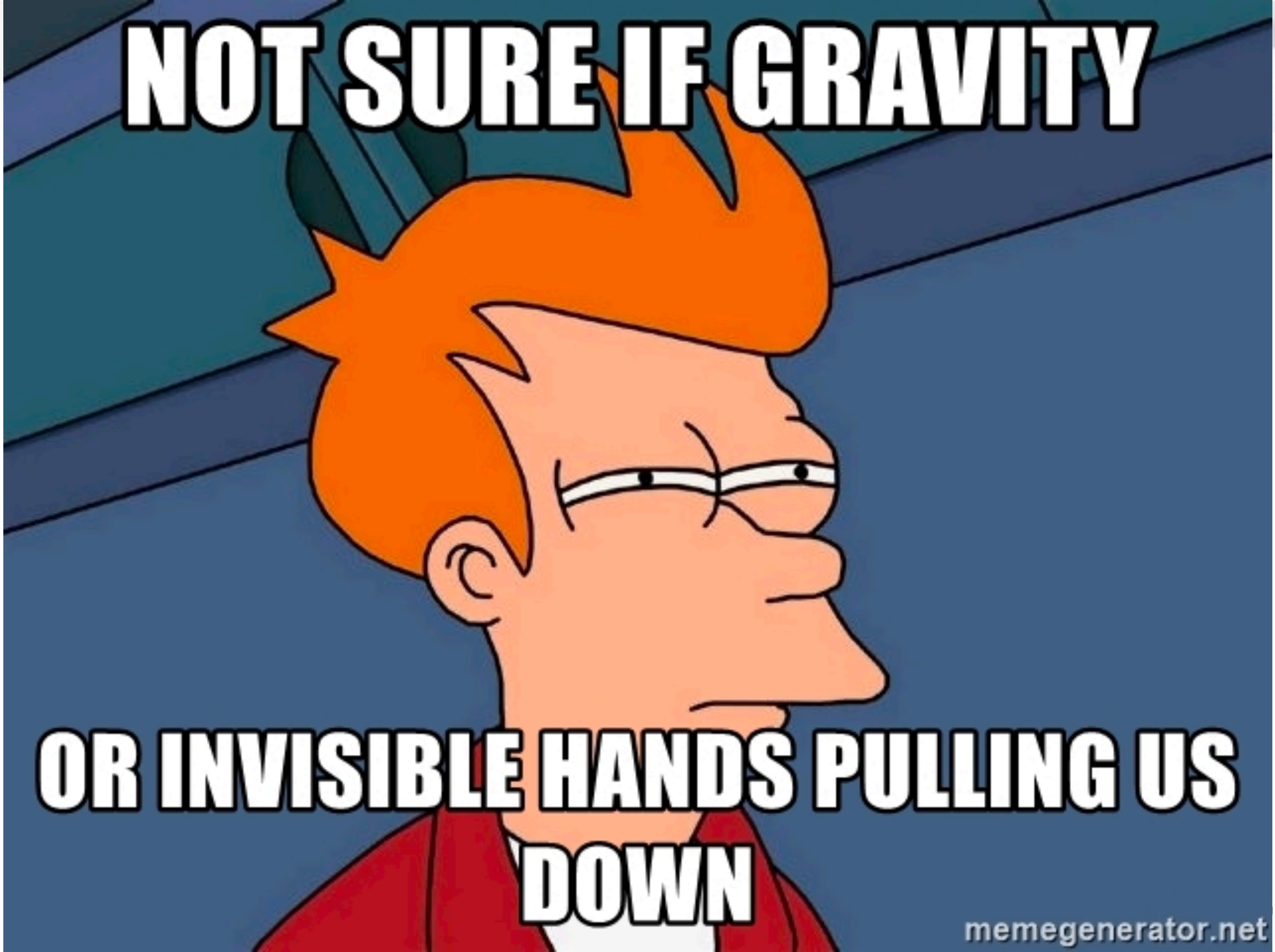
- Dark matter 101
- How to detect?
- New technologies for detection

Dark Matter 101

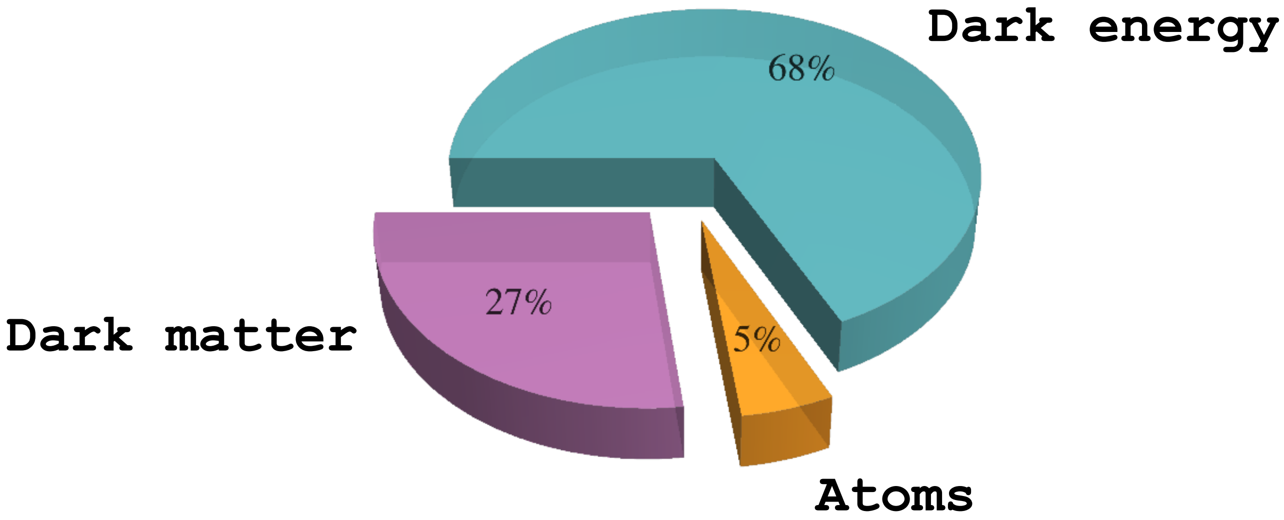
Evidence for Dark Matter

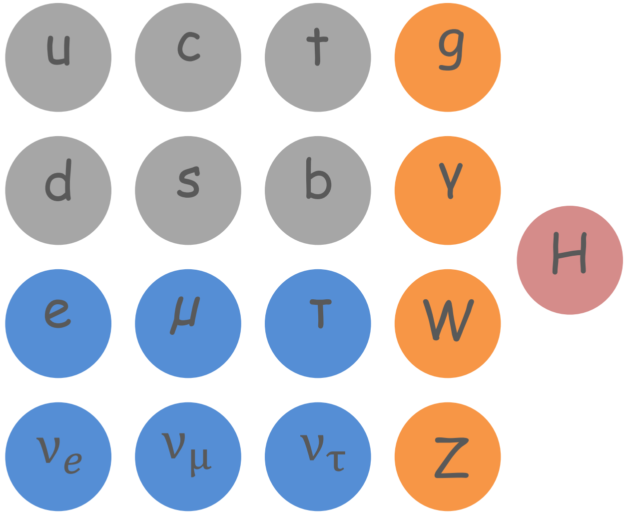





NOT SURE IF GRAVITY
OR INVISIBLE HANDS PULLING US DOWN
memegenerator.net

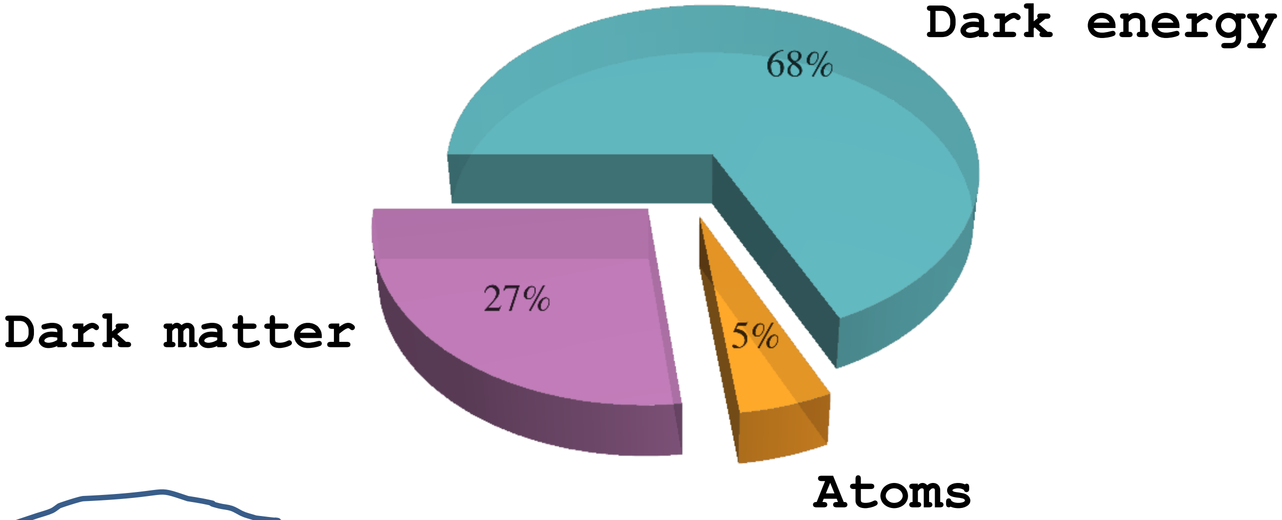
The Universe is Dark

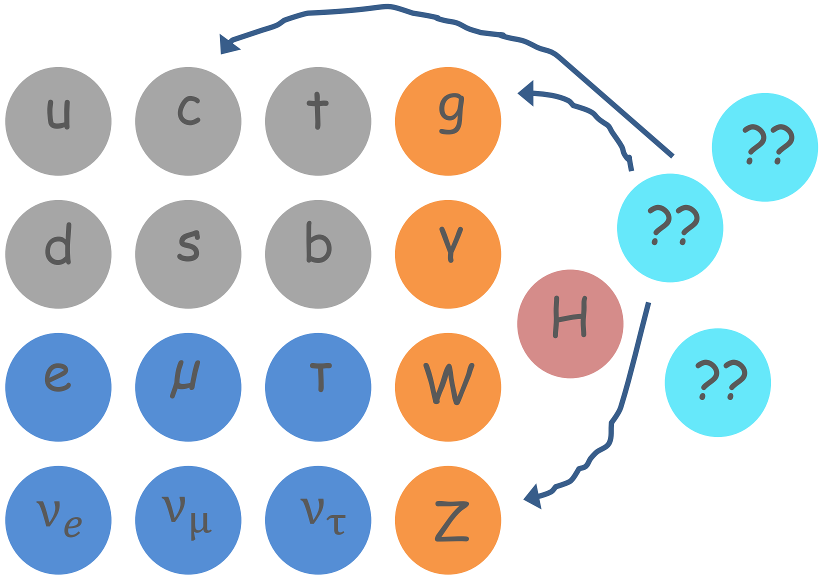




No suitable candidate within the Standard Model of particle physics

The Universe is Dark





What is it?

How does it interact?

What do we know?

- Dark matter has 5 times the mass density of baryons
- Massive (m=???)
- Can’t interact too strongly with QED and QCD
- Doesn’t interact too strongly with itself

Dark matter in a halo; we’re in a disk

Relative velocity of dark matter wind $v \sim 10^{-3} c$

Past 40 years

WIMP, glorious WIMP*

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

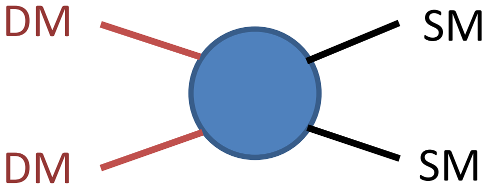
Past 40 years

Correct thermal relic abundance:

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

For weak coupling, weak scale emerges.

Weakly Interacting Massive Particle (WIMP)

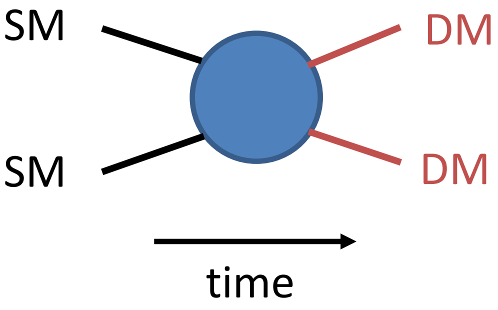


annihilation

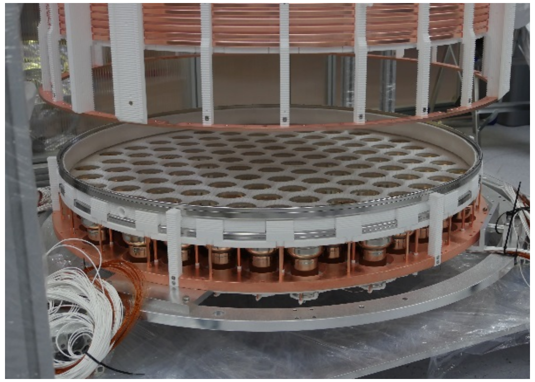
$$\langle \sigma_{\rm ann} v \rangle = \frac{\alpha^2}{m_{\rm DM}^2}$$

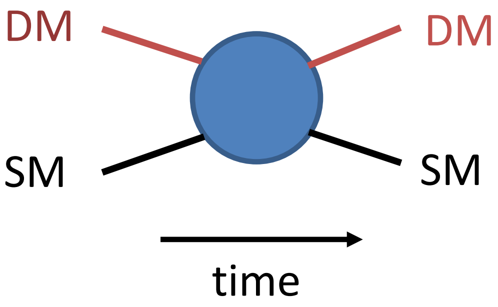
Searching for WIMPs

Colliders

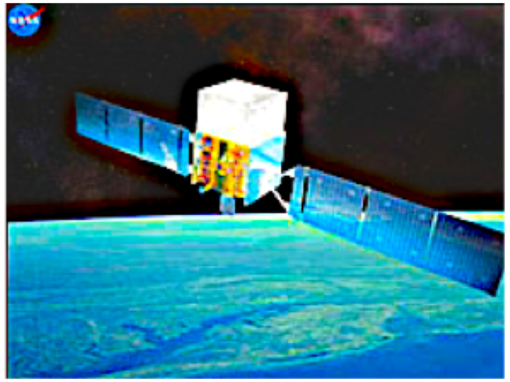


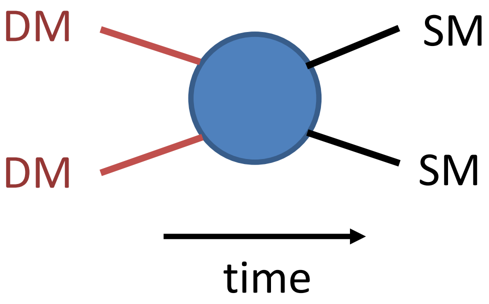
In the lab





Telescopes

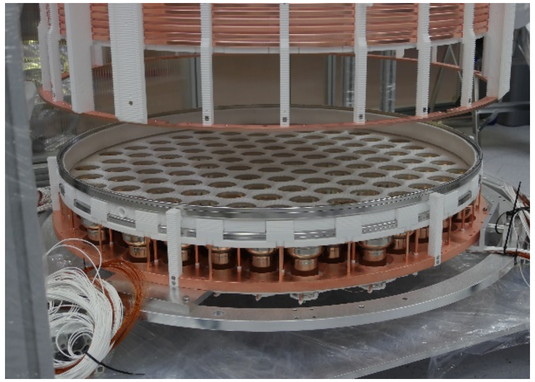




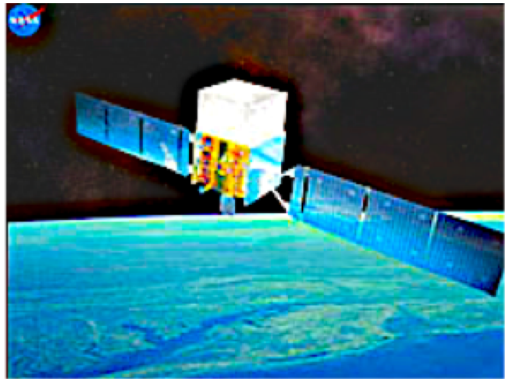
Searching for WIMPs

Colliders

In the lab



Telescopes

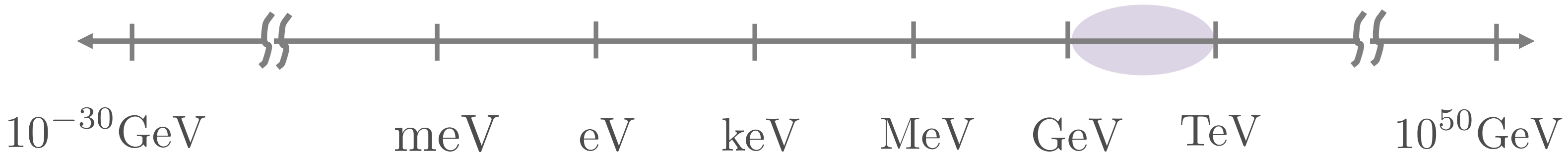


Experiments getting increasingly sensitive

Haven't yet detected dark matter

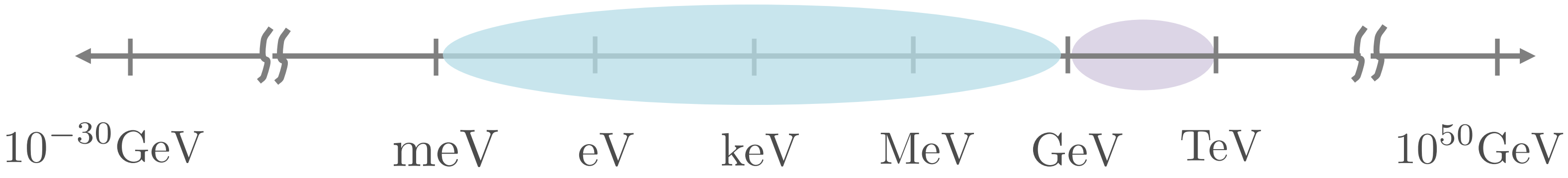
Great opportunity for new ideas.

Beyond the WIMP

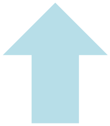


Possible dark matter mass

Beyond the WIMP

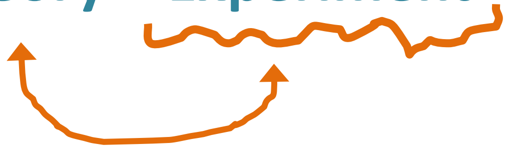


Possible dark matter mass



New Frontier: Light Dark Matter

Theory + Experiment



How to Detect?

Detection Blueprints

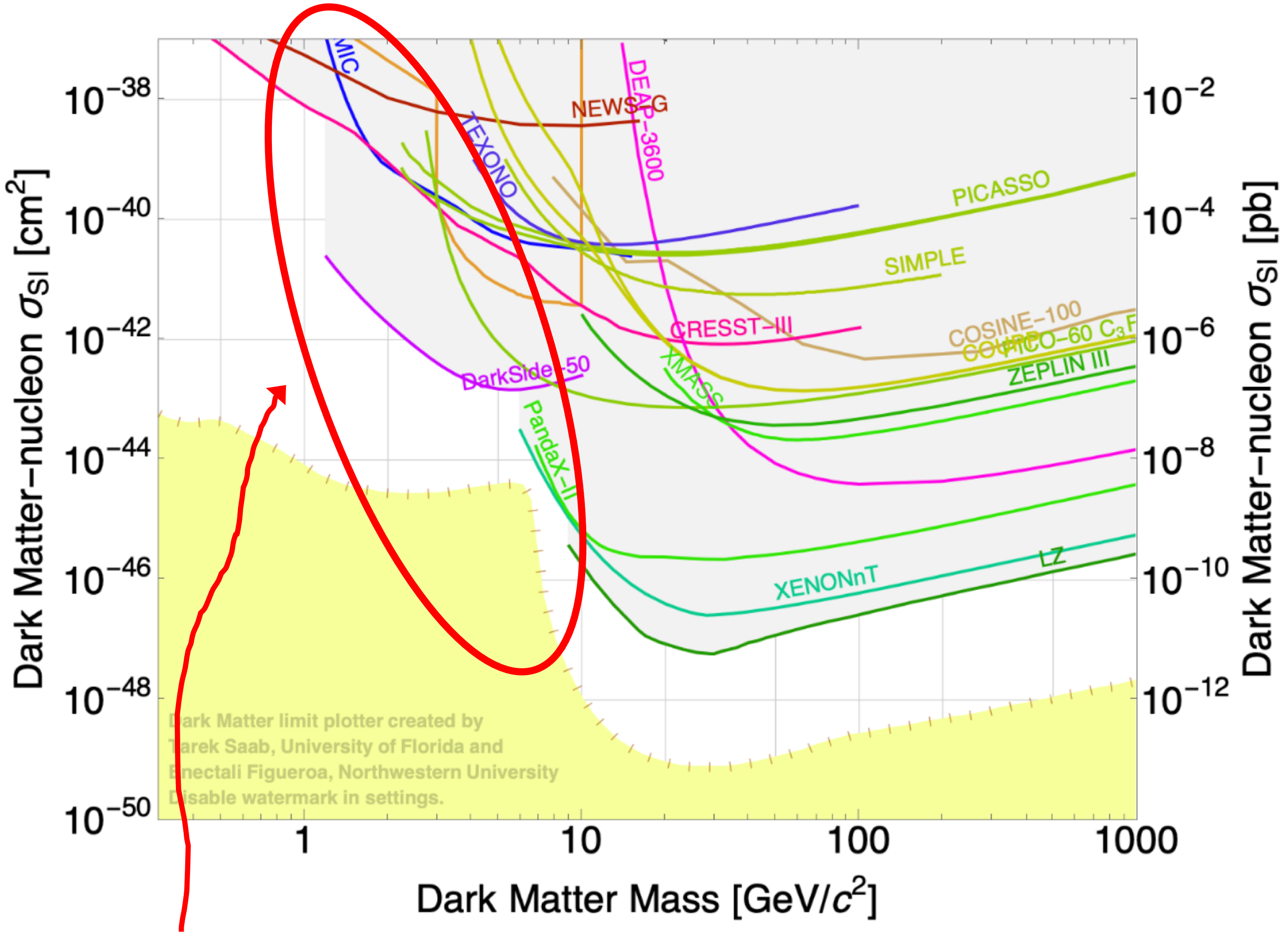
Dark matter particle comes in

Hits a target in the lab

System reacts

Measure the reaction

Direct Detection



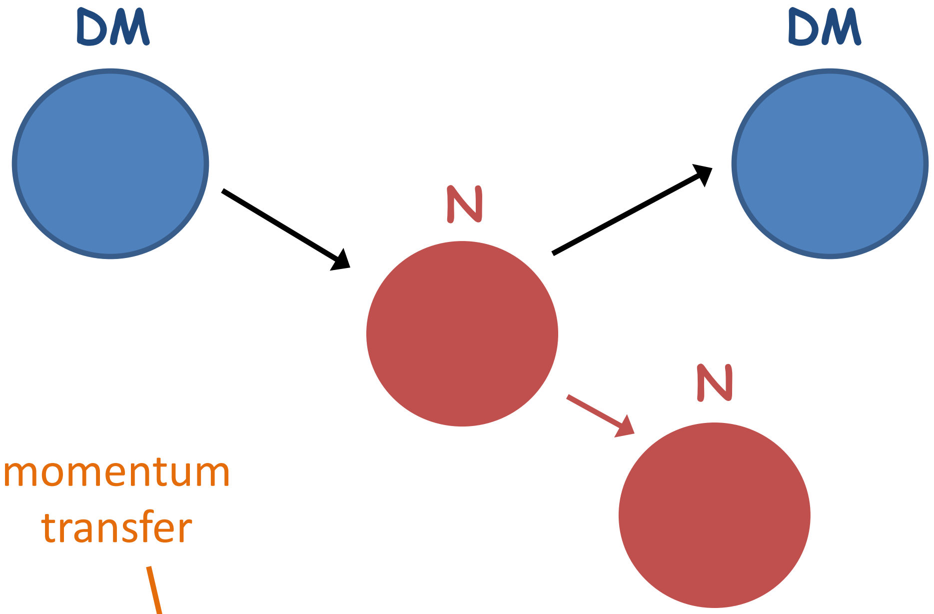
What's going on?

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

Current Experiments

Looking for nuclear recoils:

think billiard balls

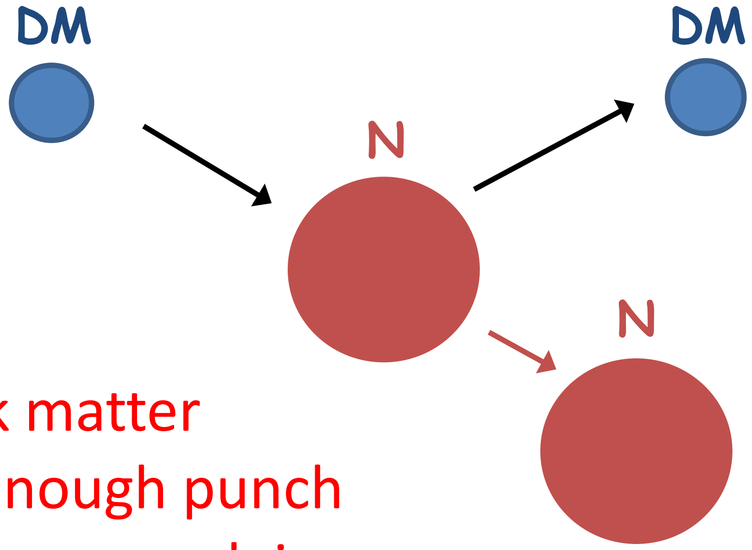


momentum transfer

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

Current Experiments

Looking for nuclear recoils:
think billiard balls

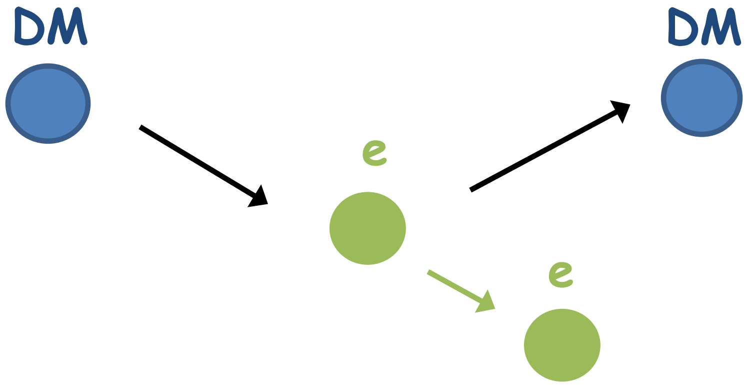


light dark matter
doesn’t have enough punch
to kick the heavy nuclei

Lose sensitivity @ O(GeV) masses

New Avenues

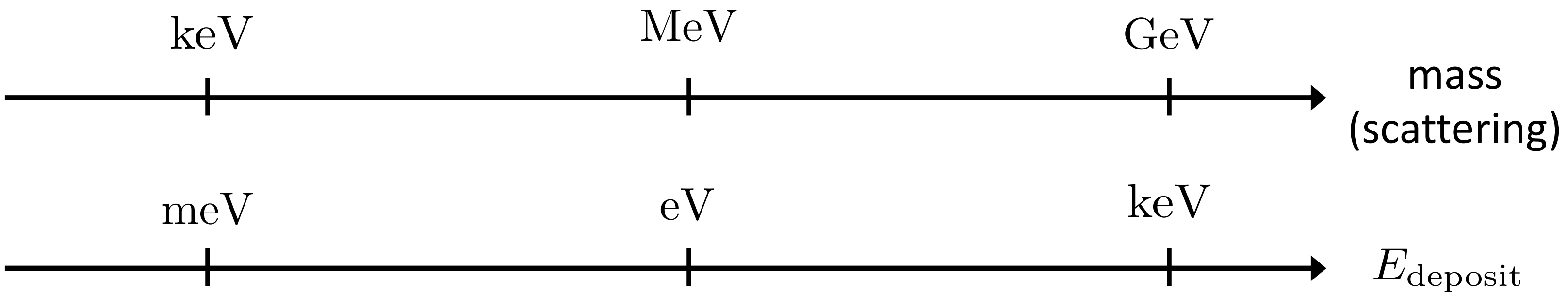
Light dark matter: scatter off electrons!



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

Energy guideline

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

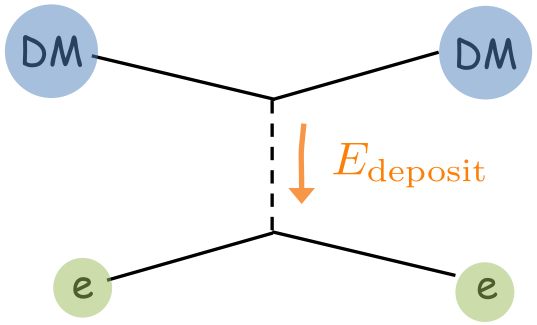


keV MeV GeV

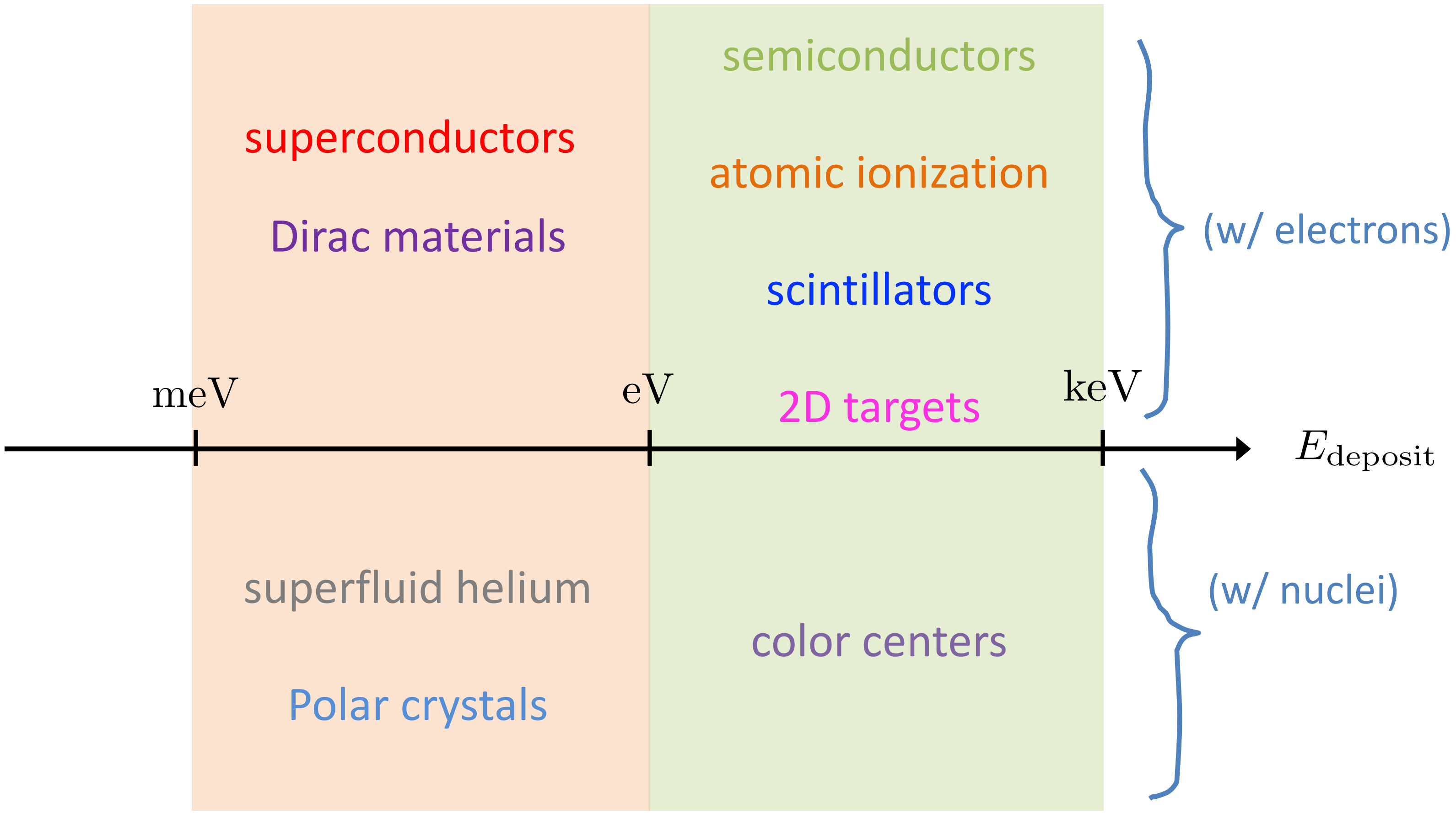
mass (scattering)

meV eV keV

E_{deposit}



New proposals

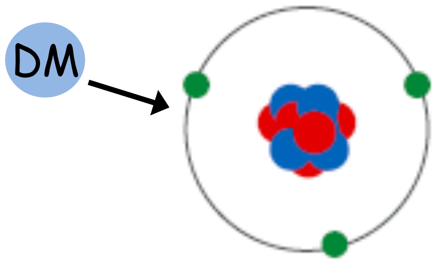


Explosion of interest and ideas in recent times

New Technologies

Ex. #1: First ideas

Atomic ionization

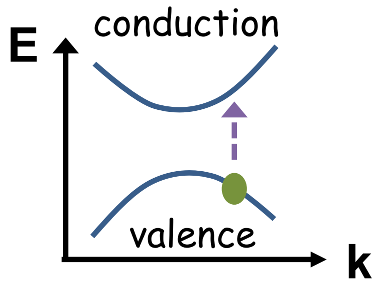


Xenon: ~12 eV

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

Essig, Mardon, Volansky, 2012

Semiconductors



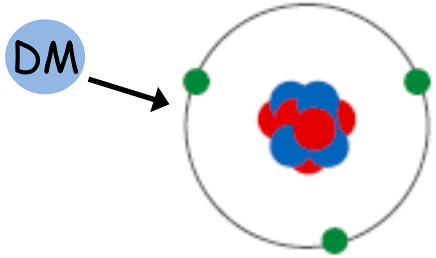
Ge, Si, Diamond, SiC: ~eV

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

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

Ex. #1: First ideas

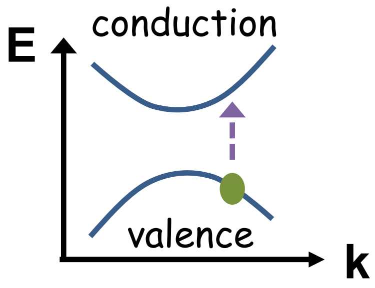
Atomic ionization



Xenon10/100/1T

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

Semiconductors



SuperCDMS, SENSEI, DAMIC-M

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

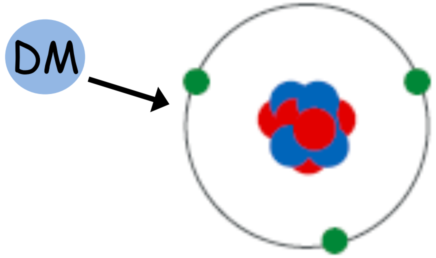
Are being experimentally realized

Essig et al 2012 | Xenon100 2016 | Xenon1T 2020

SuperCDMS 2020 | SENSEI 2020 | DAMIC-M 2023

Ex. #1: First ideas

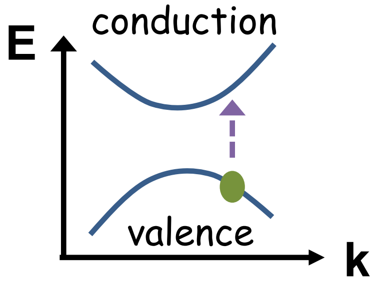
Atomic ionization



Xenon10/100/1T

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

Semiconductors



SuperCDMS,
SENSEI, DAMIC-M

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

Smaller masses?

Ex. #2: Superconductors

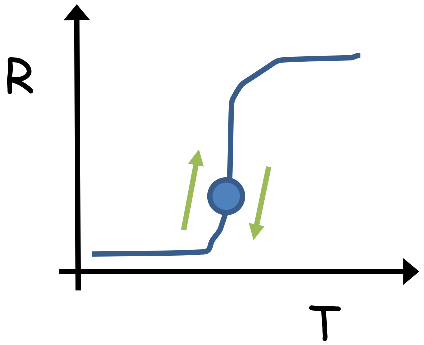
- Ground state = Cooper pairs;
  Binding energy (gap) $\sim \mathrm{meV}$ ⇒ $m_{\mathrm{DM}} \sim \mathrm{keV}$
- <u>The idea:</u>
  DM scatters with Cooper pairs, deposits enough energy, breaks Cooper pairs → detect

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)



Excitation concentration philosophy

YH, Zhao, Zurek, PRL 2015
YH, Pyle, Zhao, Zurek, JHEP 2015

Heat calorimeter

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

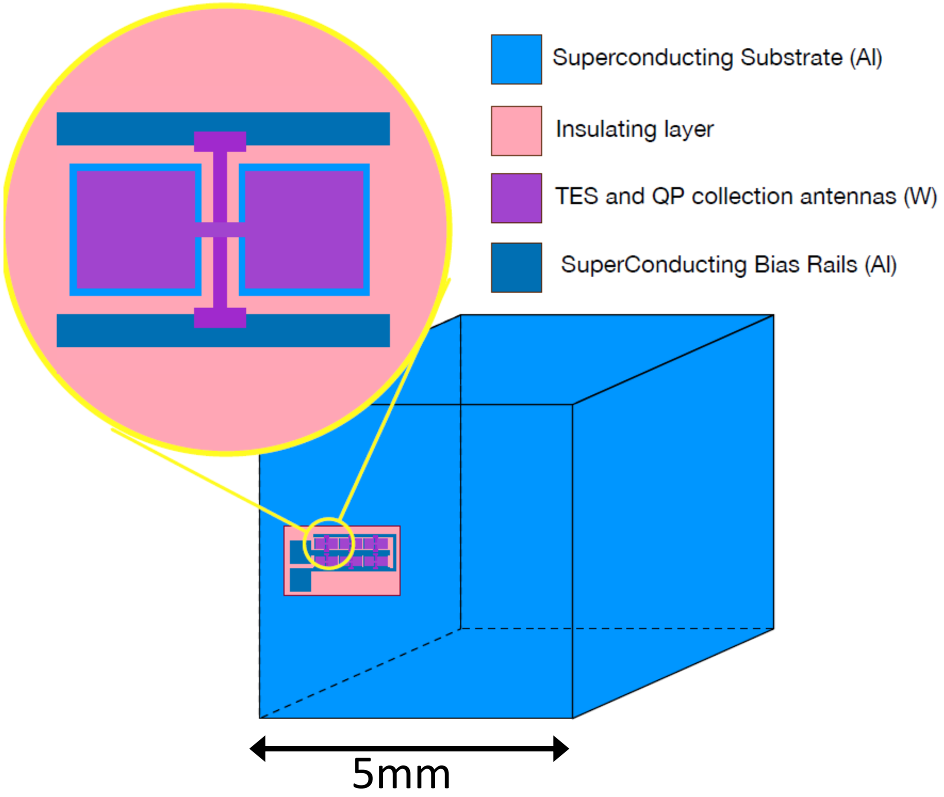
Ex. #2A: Superconductors

Absorber →
Collection fins→
sensitive bolometer

(& multiplex)

Excitation concentration philosophy

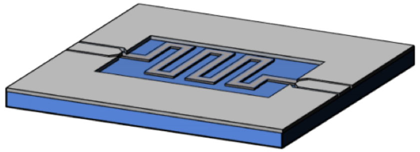
YH, Zhao, Zurek, PRL 2015
YH, Pyle, Zhao, Zurek, JHEP 2015



Current challenge:
To achieve low threshold
low noise sensors

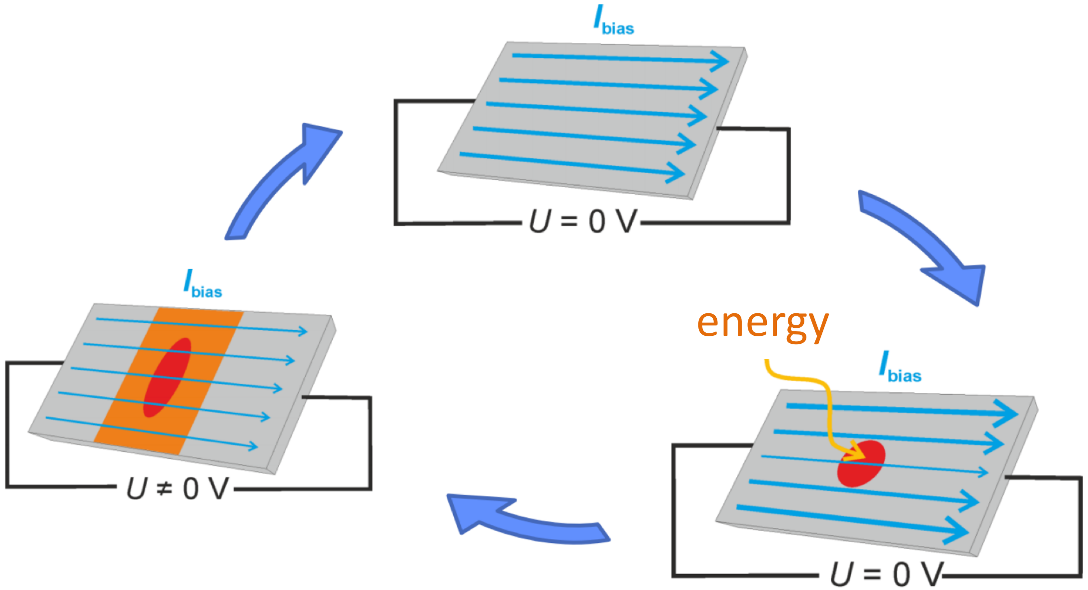
Ex. #2B: Superconductors

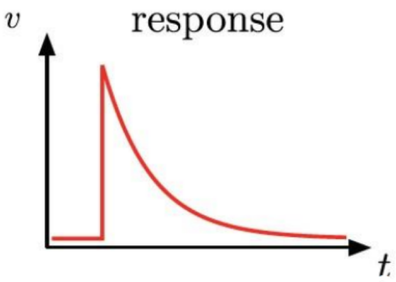
- Superconducting Nanowire Single Photon Detectors (SNSPDs)



Broadly used in quantum information science

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



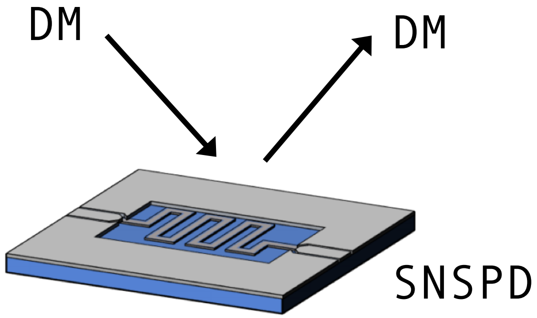


Sensor + target philosophy

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

Ex. #2B: Superconductors

Use as simultaneous target + sensor (& multiplex)



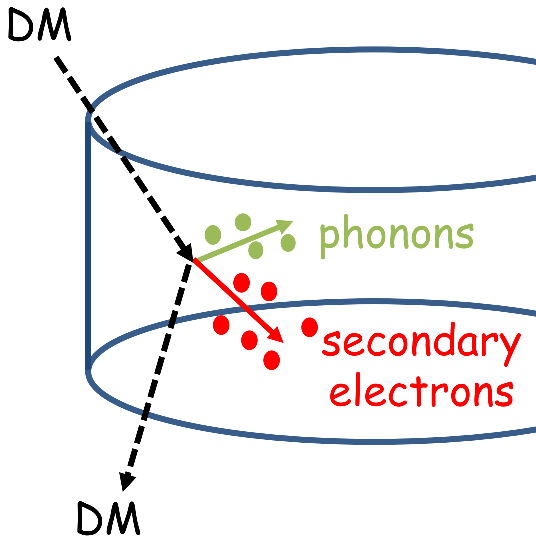
[Existing prototype]

Sensor + target philosophy

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

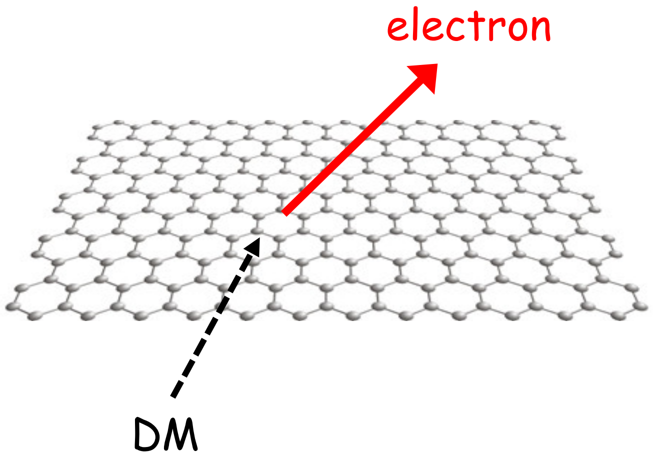
Directional Info?

Lose directional information
if detecting secondaries



e.g. semiconductors, bulk superconductors

Retain directional information
if observe primary!

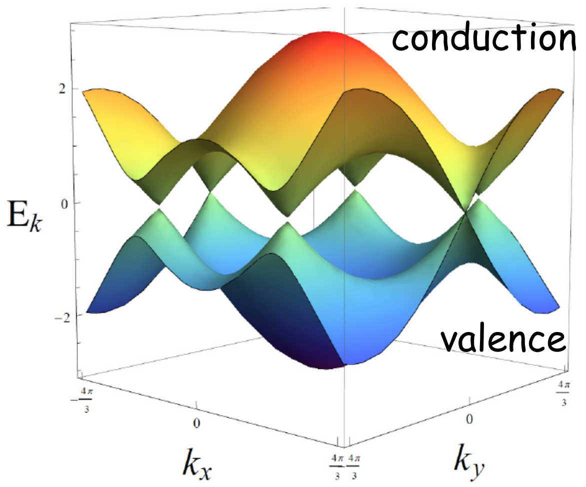


2D targets; graphene (& SNSPDs)

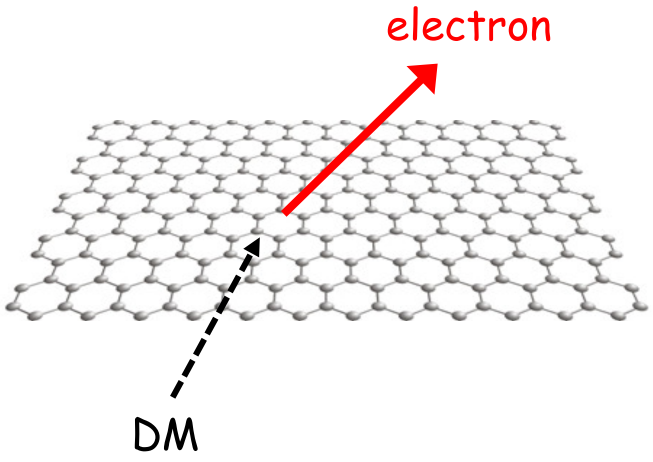
But see **YH**, Kramer, Kurinsky, Lehmann, PRD 2023

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

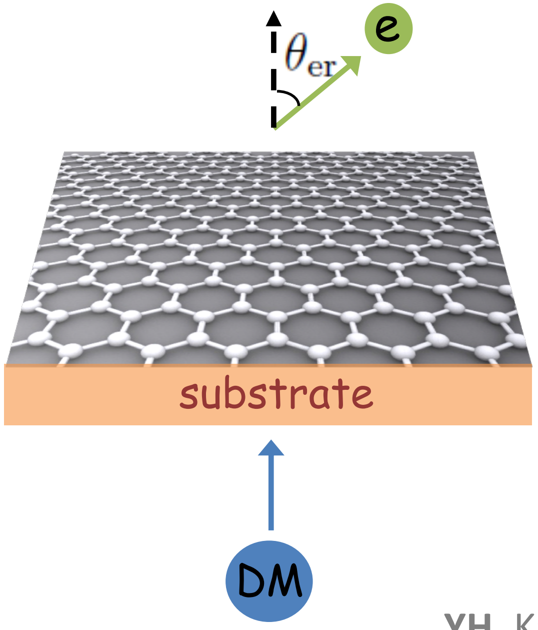
Ex. #3: Graphene

Electron follows incoming dark matter direction.

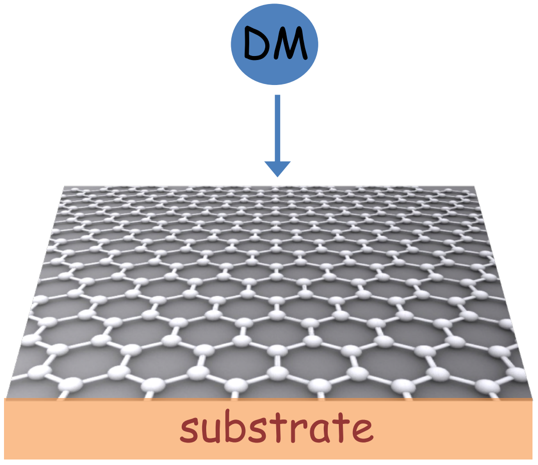
Naturally gives forward/backward discrimination

(separates signal from background)

Electron detected



electron not detected



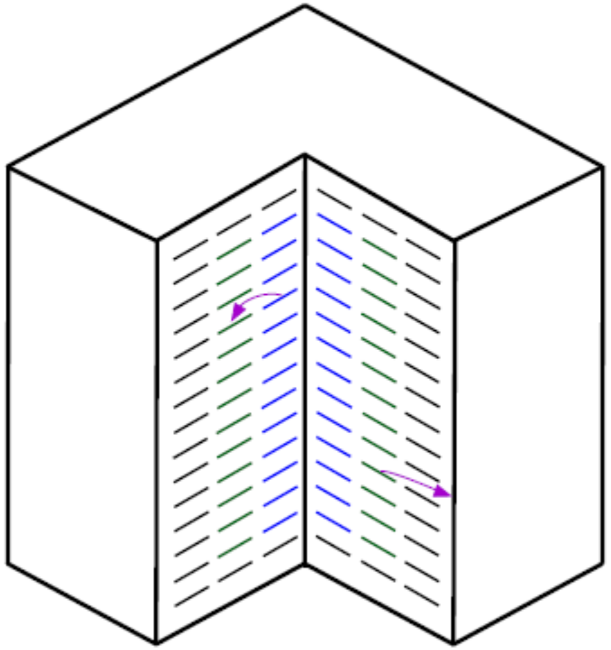
12 hours later

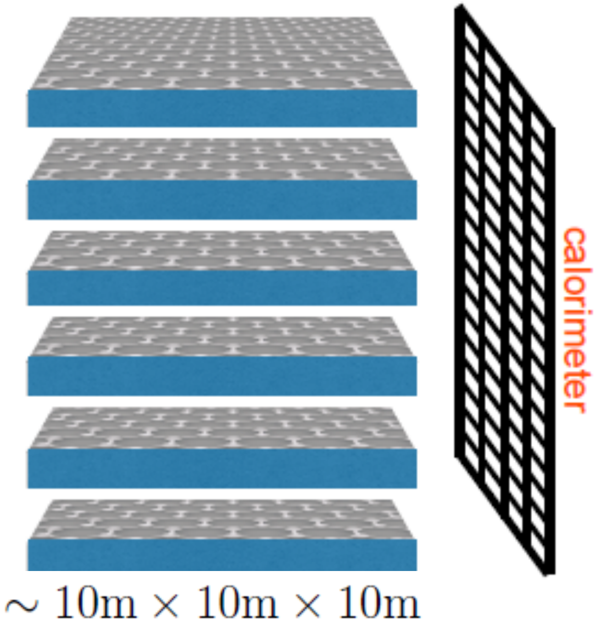
YH, Kahn, Lisanti, Tully, Zurek, 2017

Ex. #3: Design Concept

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

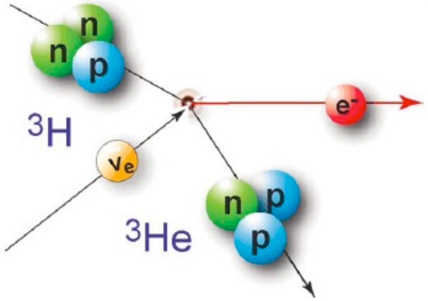
- Compact geometry: large mass via many stacks





Implement in PTOLEMY

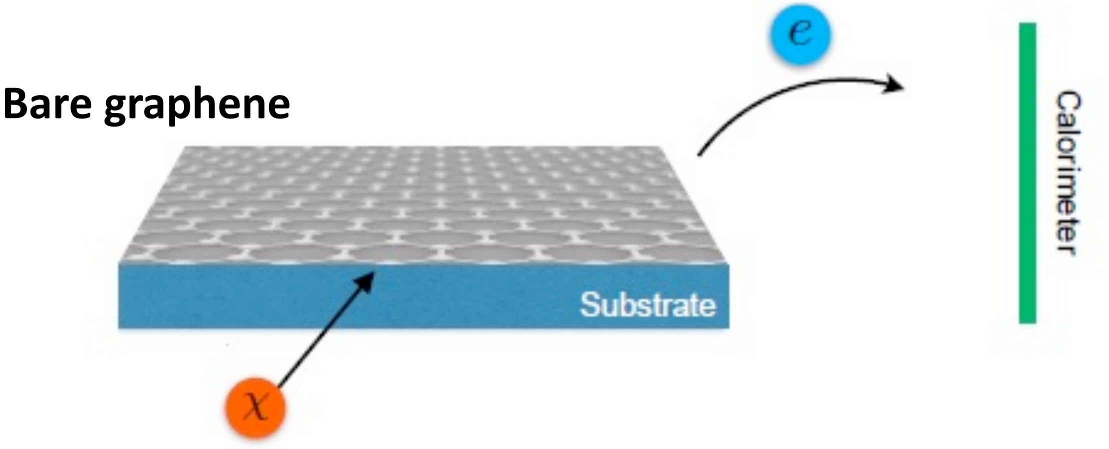
Experiment to detect relic neutrinos via capture on tritium.



Betts et al, 2013

Will use tritiated graphene (~0.5 kg).

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



PTOLEMY World-Wide Collaboration

טלסקופ ניטרינים קוסמיים

Telescopio di neutrini cosmologici

Kosmische neutrinotelescoop

Telescopio de neutrinos cósmicos

Kosmisk neutrinoteleskop

Cosmic neutrino telescope

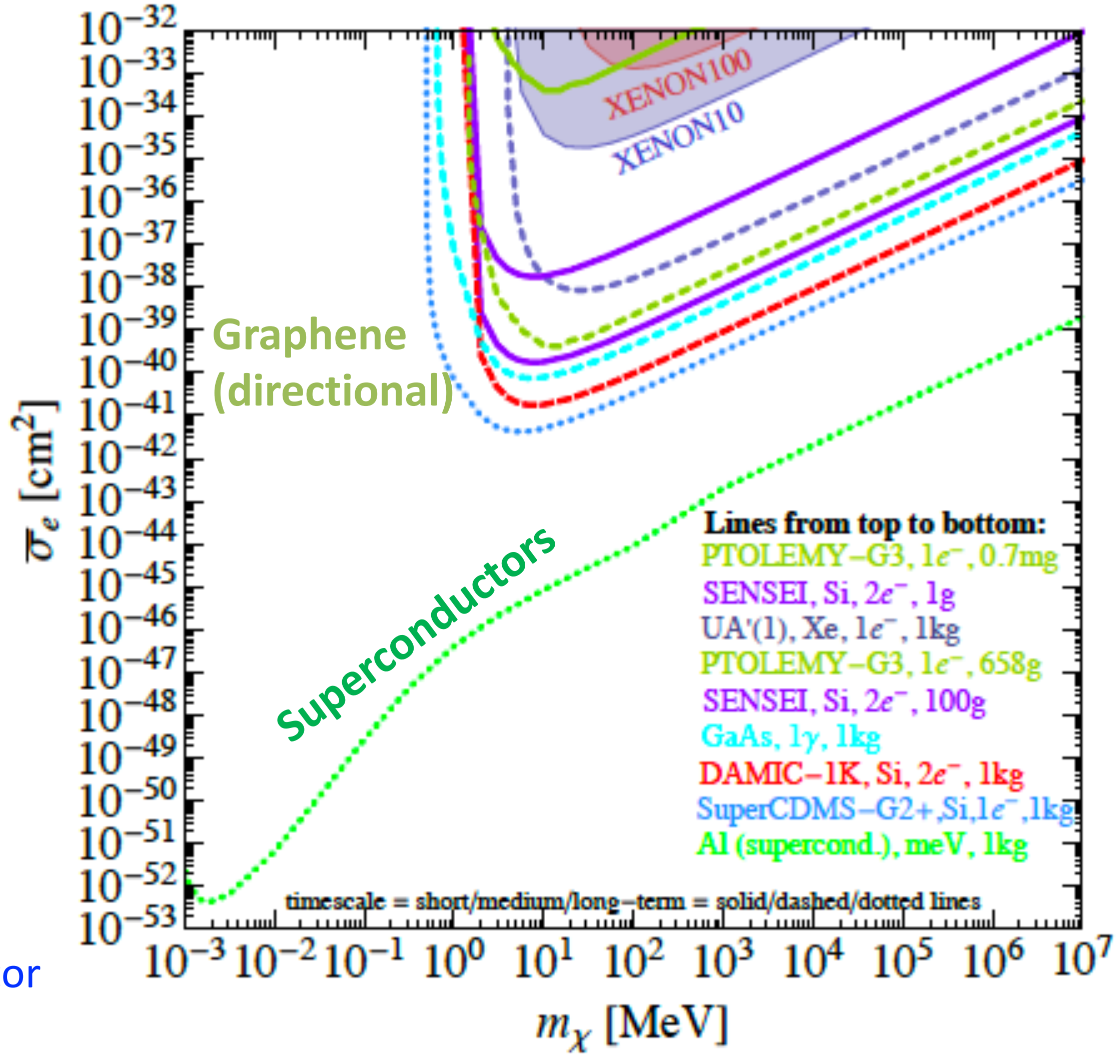
PTOLEMY: A Proposal for Thermal Relic Detection of Massive Neutrinos and Directional Detection of MeV Dark Matter

Compute Event Rate

$$\overset{\text{[Events/unit time/unit mass]}}{\downarrow}$$

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

Scattering Reach



[a few events in kg-year exposure]

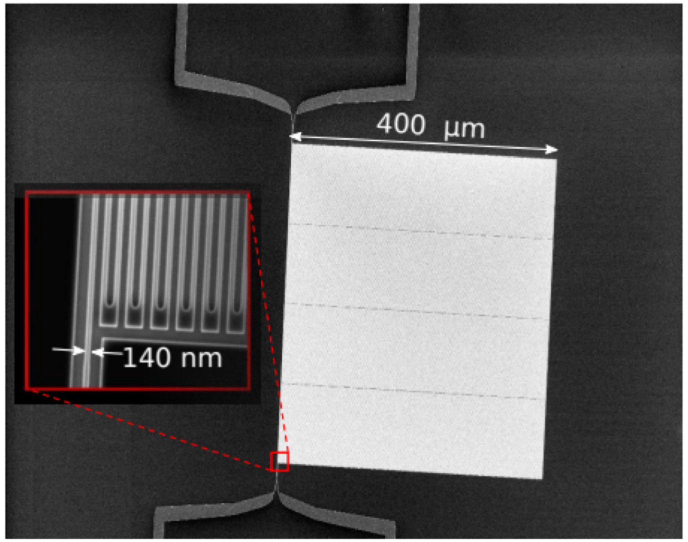
Amazing reach!

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

Community report, 2017

Existing Prototype Device

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

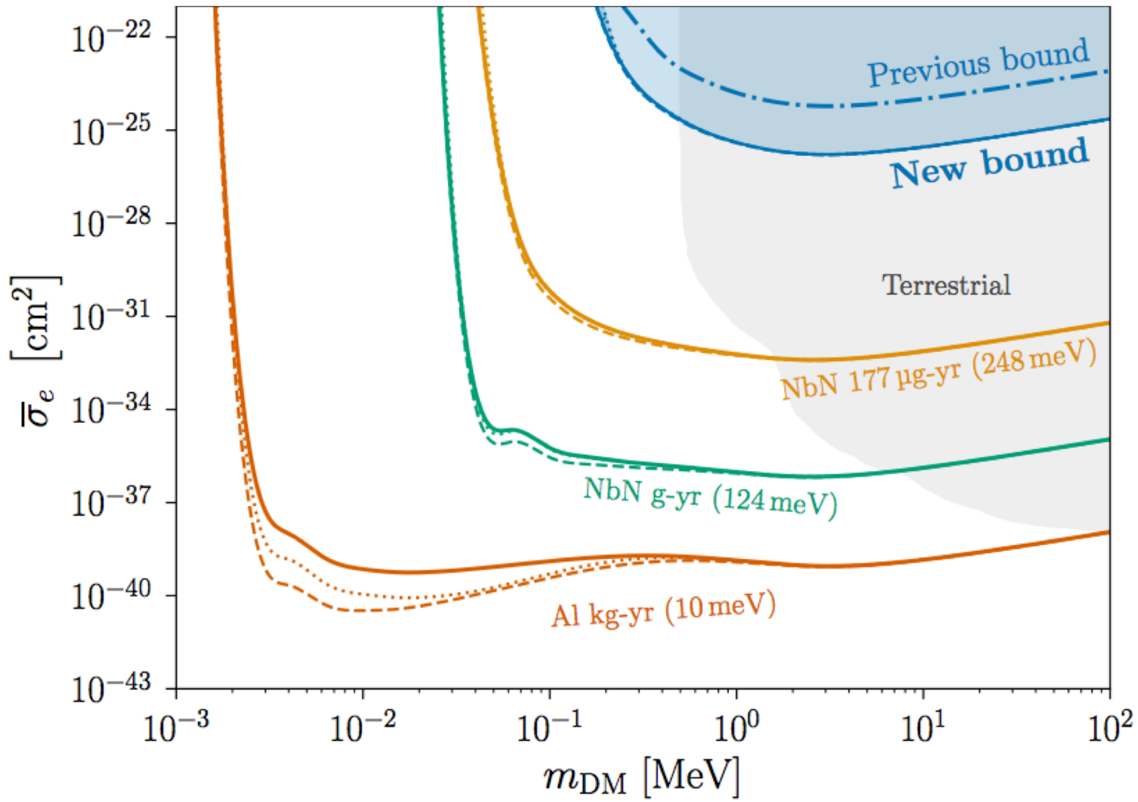


By now have 180 hours of data

YH, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019 + w/ Lehmann, PRD Editor’s Choice 2022

Scattering Reach

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



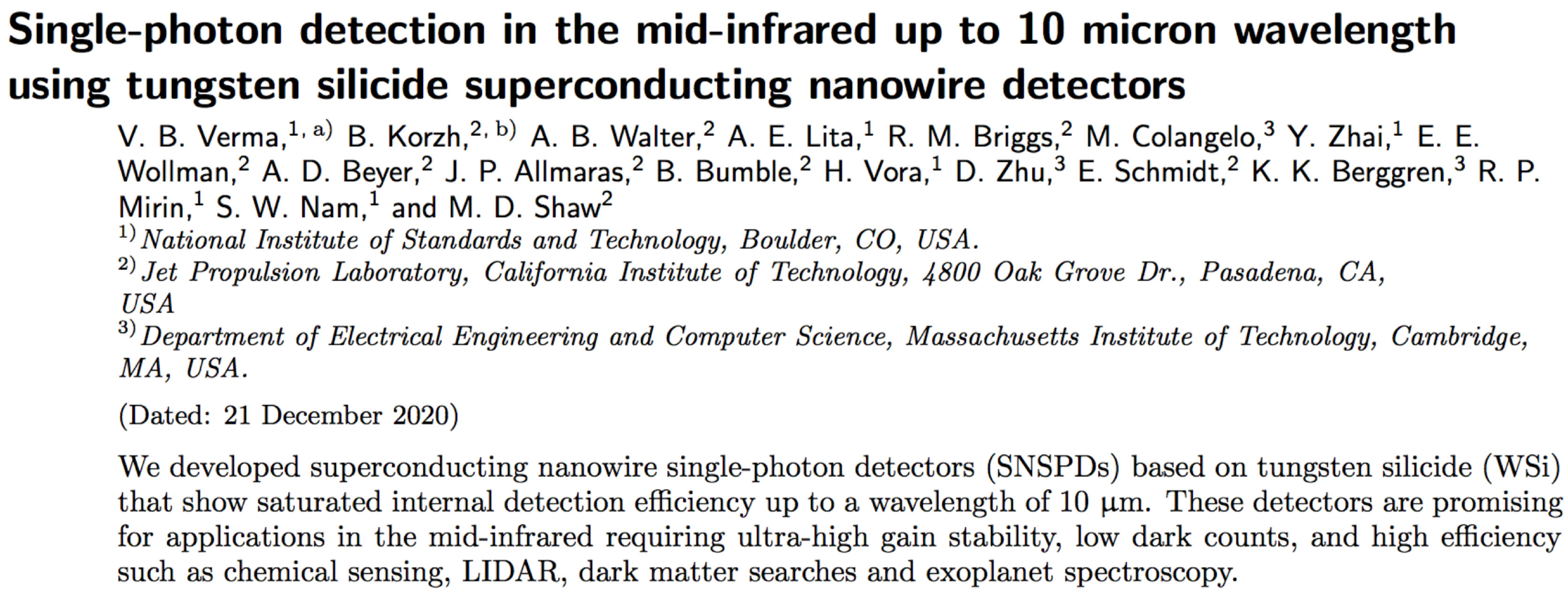
Non-solid curves: geometry effects

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 2022

Pushing Thresholds Lower



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

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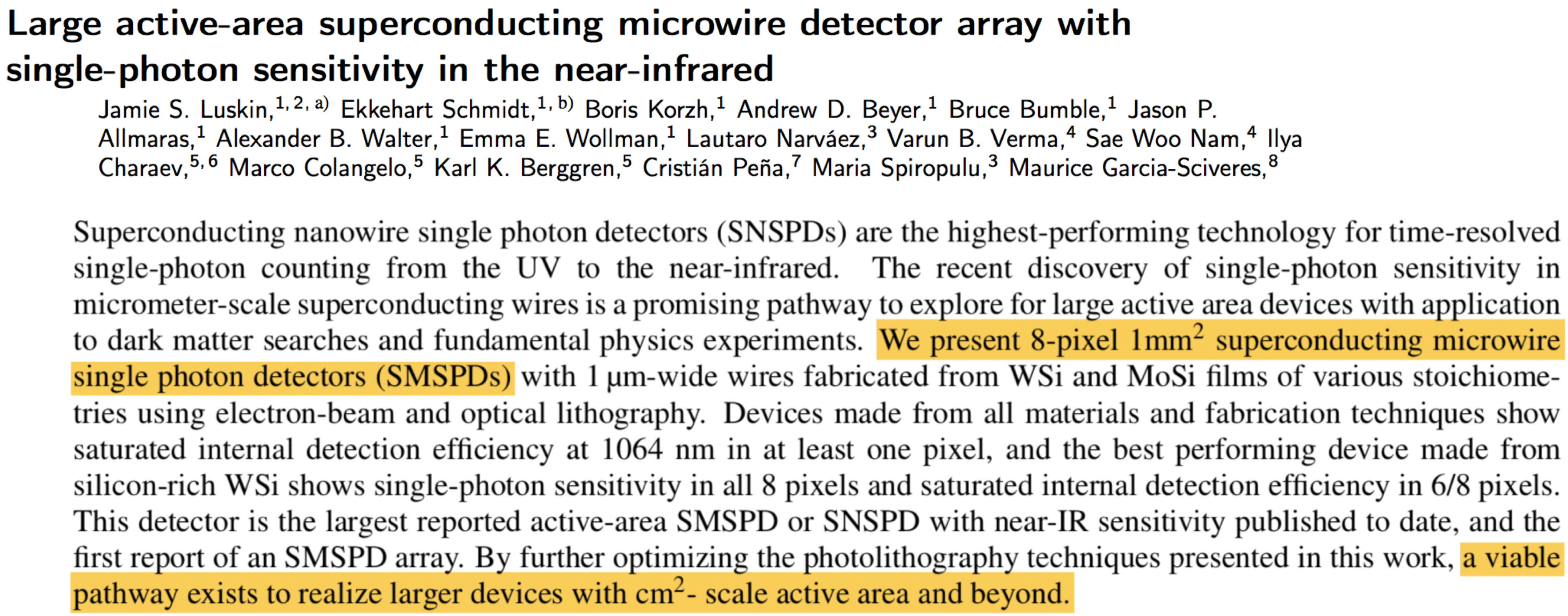
(Dated: 21 December 2020)

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

Pushing Areas Larger



Large active-area superconducting microwire detector array with single-photon sensitivity in the near-infrared

Jamie S. Luskin,[1,2,a)] Ekkehart Schmidt,[1,b)] Boris Korzh,[1] Andrew D. Beyer,[1] Bruce Bumble,[1] Jason P. Allmaras,[1] Alexander B. Walter,[1] Emma E. Wollman,[1] Lautaro Narváez,[3] Varun B. Verma,[4] Sae Woo Nam,[4] Ilya Charaev,[5,6] Marco Colangelo,[5] Karl K. Berggren,[5] Cristián Peña,[7] Maria Spiropulu,[3] Maurice Garcia-Sciveres,[8]

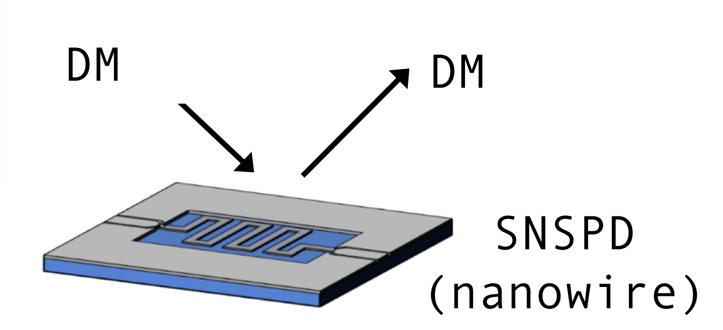
Superconducting nanowire single photon detectors (SNSPDs) are the highest-performing technology for time-resolved single-photon counting from the UV to the near-infrared. The recent discovery of single-photon sensitivity in micrometer-scale superconducting wires is a promising pathway to explore for large active area devices with application to dark matter searches and fundamental physics experiments. We present 8-pixel 1mm^2 superconducting microwire single photon detectors (SMSPDs) with 1 μm-wide wires fabricated from WSi and MoSi films of various stoichiometries using electron-beam and optical lithography. Devices made from all materials and fabrication techniques show saturated internal detection efficiency at 1064 nm in at least one pixel, and the best performing device made from silicon-rich WSi shows single-photon sensitivity in all 8 pixels and saturated internal detection efficiency in 6/8 pixels. This detector is the largest reported active-area SMSPD or SNSPD with near-IR sensitivity published to date, and the first report of an SMSPD array. By further optimizing the photolithography techniques presented in this work, a viable pathway exists to realize larger devices with cm^2- scale active area and beyond.

Demonstrated 1 mm^2 area detectors

arXiv:2303.10739

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

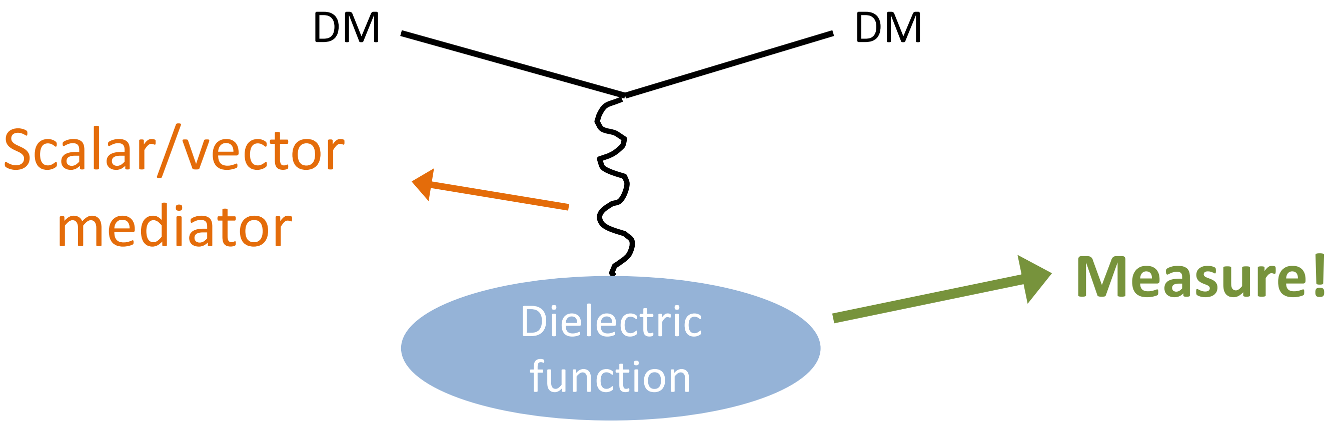
האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

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



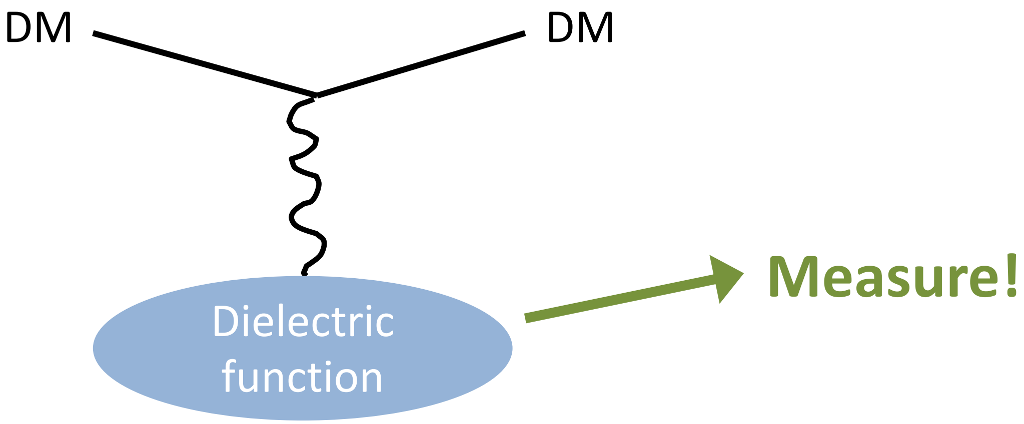
YH, Kahn, Kurinsky, Lehmann, Yu, Berggren, PRL 2021

[See also arXiv: 2101.08275]

New Formalism

Automatically includes many-body effects of the material

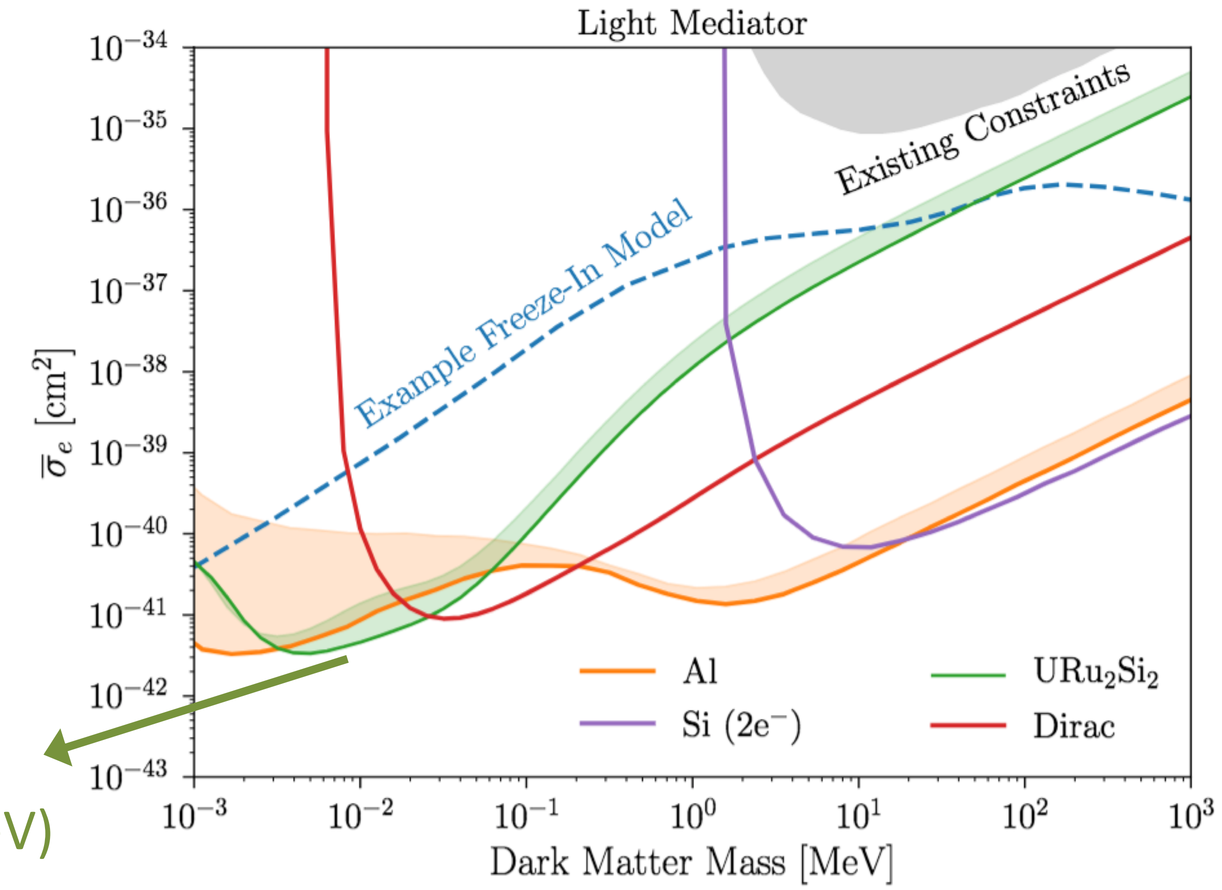
Collective modes (e.g. plasmon),
not just single particle excitations



Identify promising materials for DM detection

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

Ex. #4: Heavy Fermions



Plasmon
@ O(10meV)

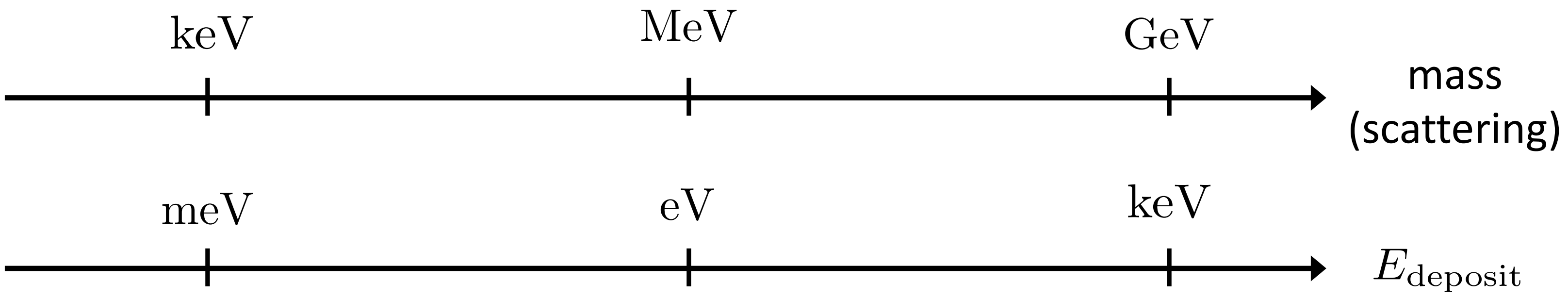
Identify promising materials for DM detection

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

Any given target material can go even further.

Absorption vs. Scattering

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

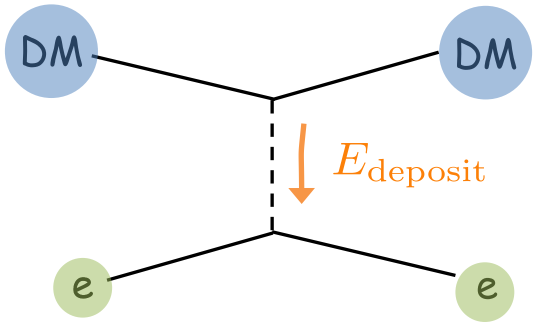


keV MeV GeV

mass (scattering)

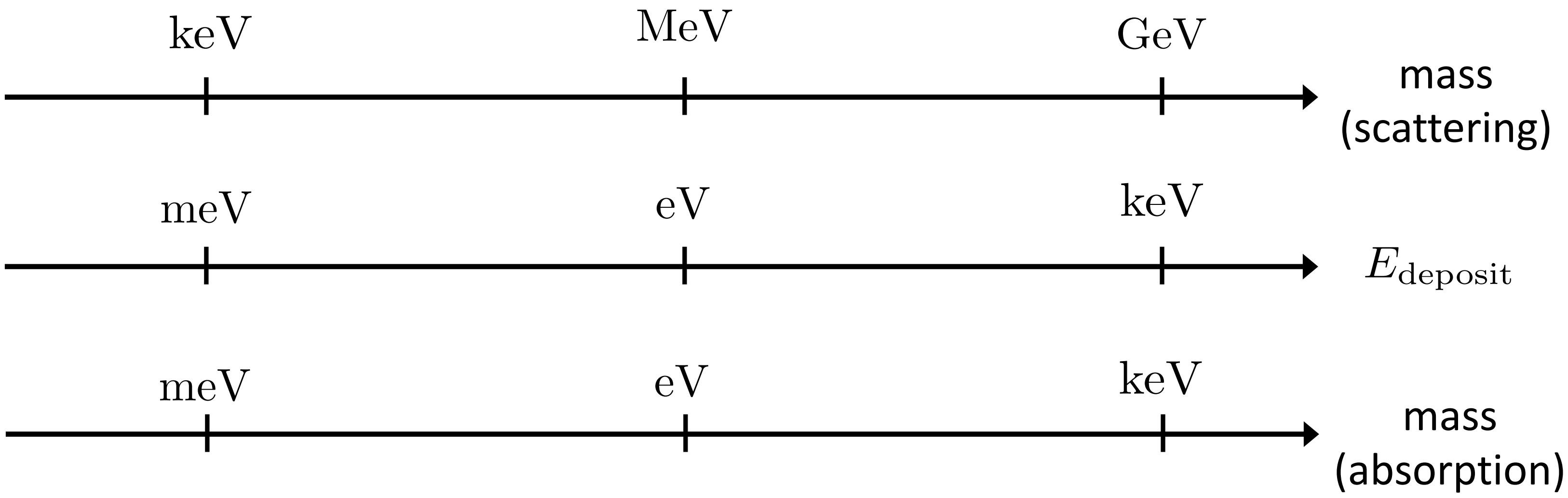
meV eV keV

E_{deposit}



Absorption vs. Scattering

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


keV MeV GeV

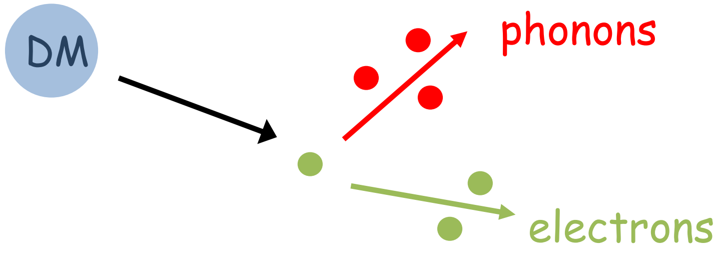
mass (scattering)

meV eV keV

$E_{\rm deposit}$

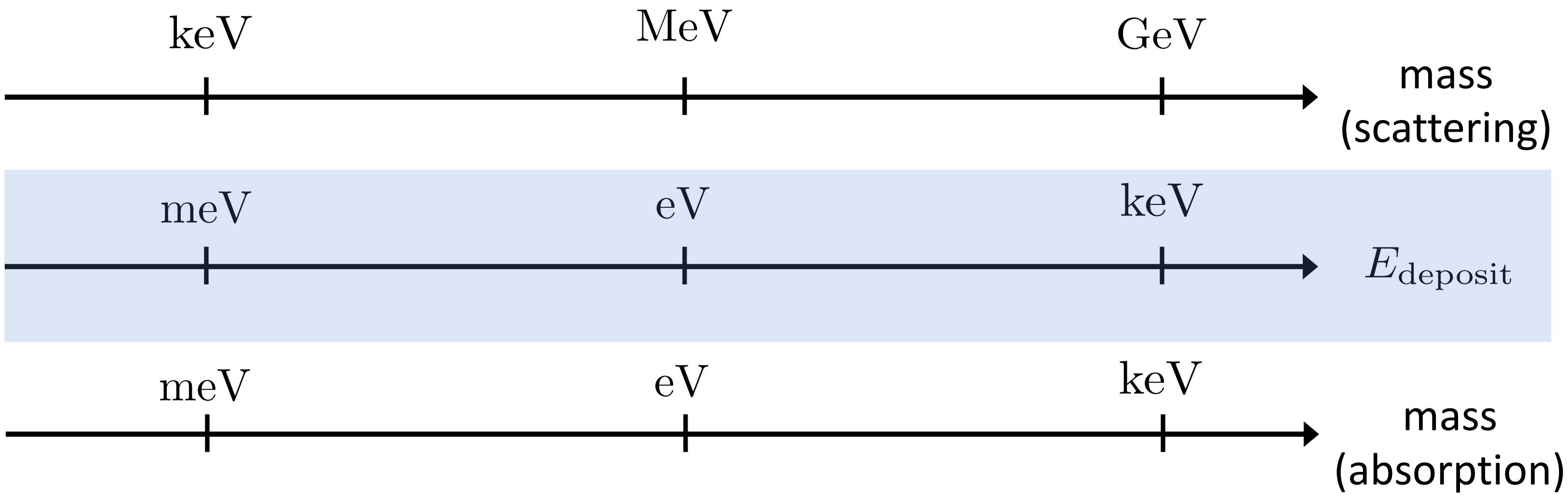
meV eV keV

mass (absorption)



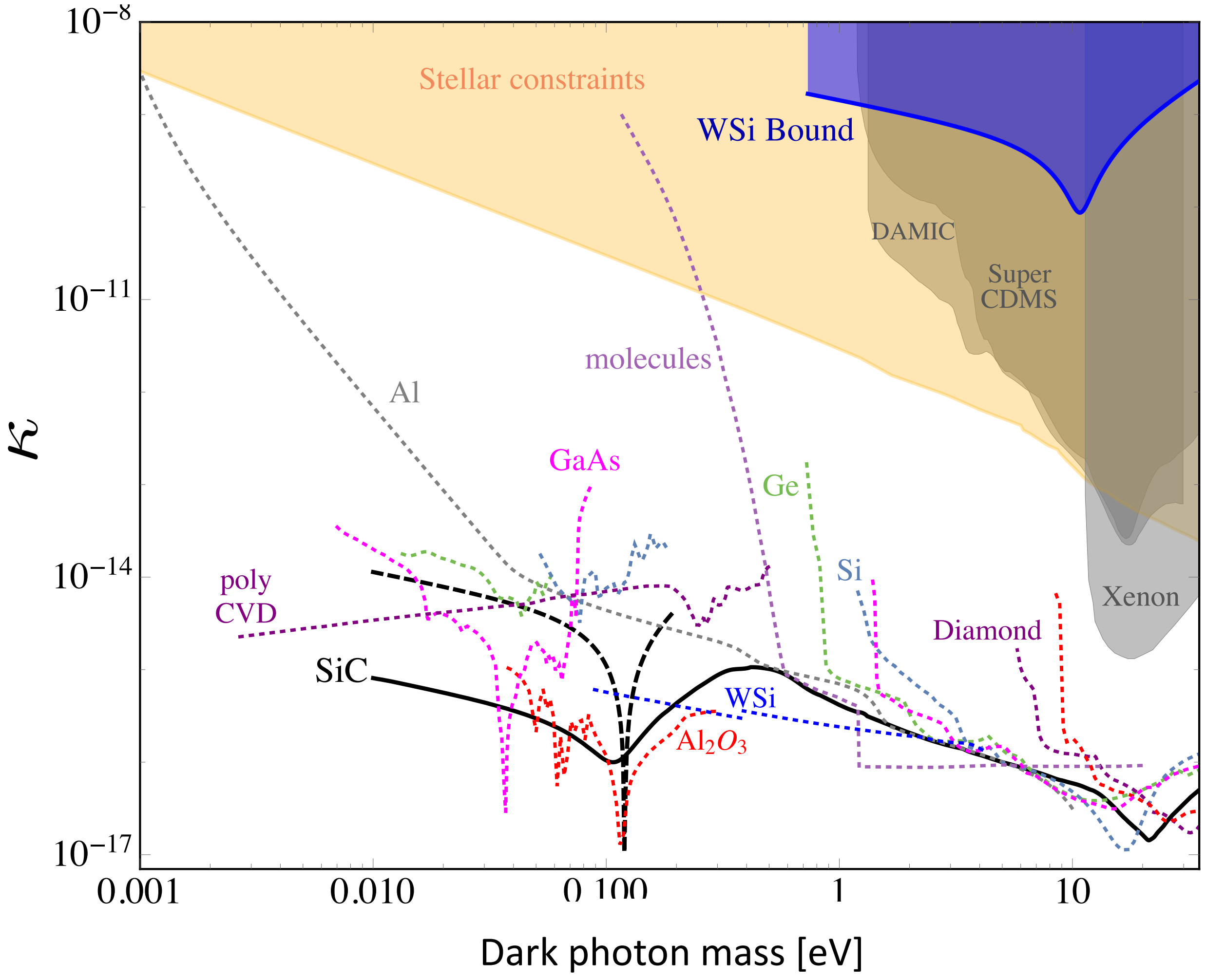
Absorption vs. Scattering

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

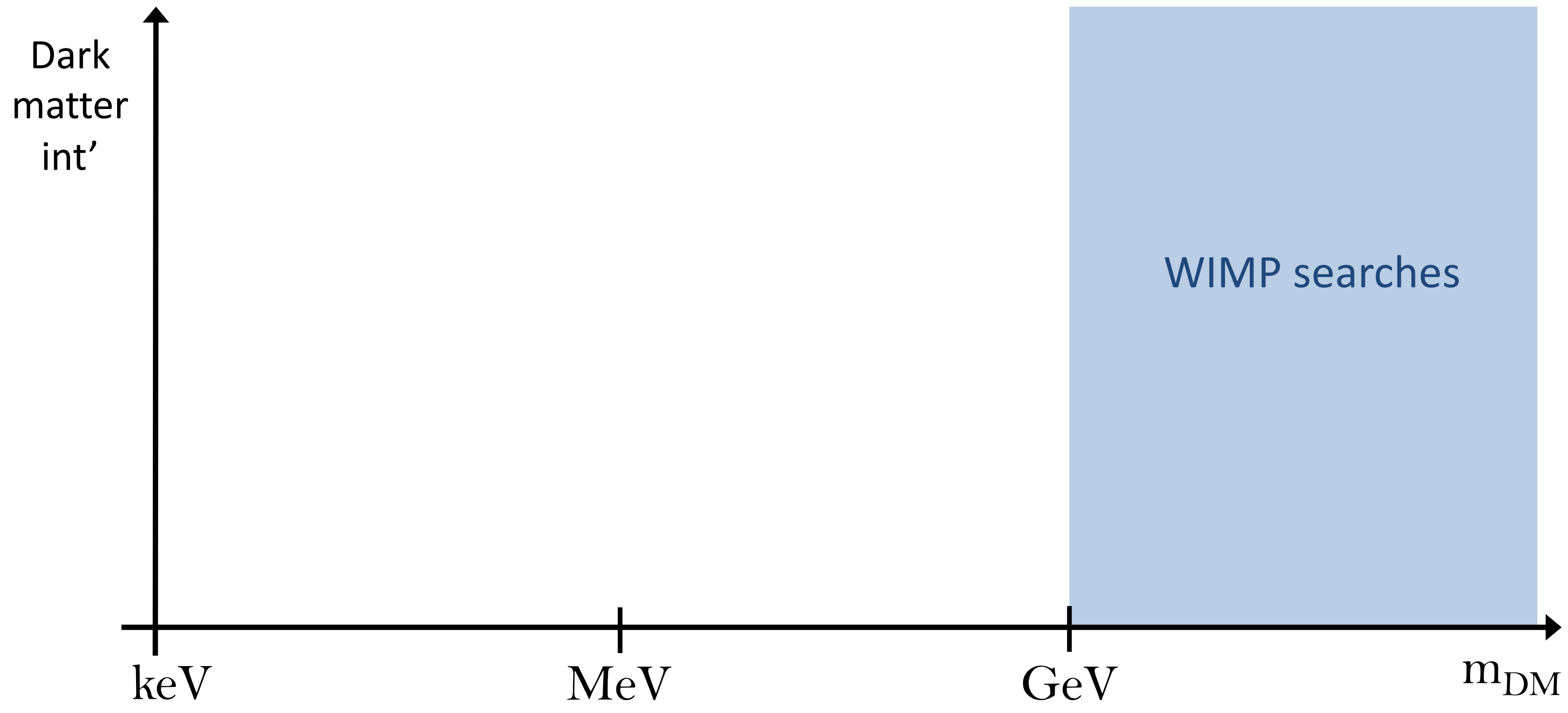
- Single/rare-event sensitivity
- Build up to large target mass: many small units ok & multiplex
- Target can/cannot be the sensitive sensor itself
- Small gap and low thresholds
- Low dark counts ideally
- Directionality a major plus
- Data

Think detection philosophy & target & sensor

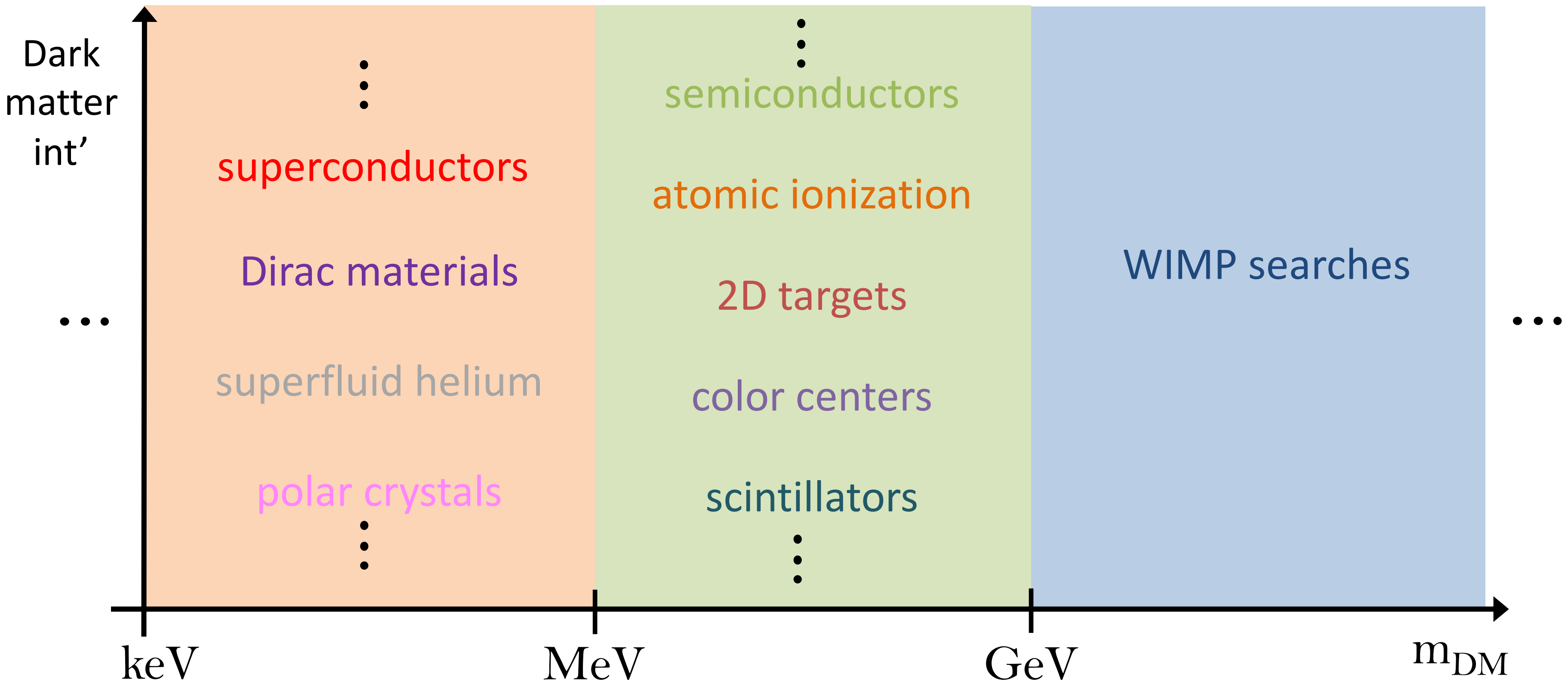
Outlook

- 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



Dark matter int’

…

⋮

superconductors

Dirac materials

superfluid helium

polar crystals

⋮

⋮

semiconductors

atomic ionization

2D targets

color centers

scintillators

⋮

WIMP searches

…

keV

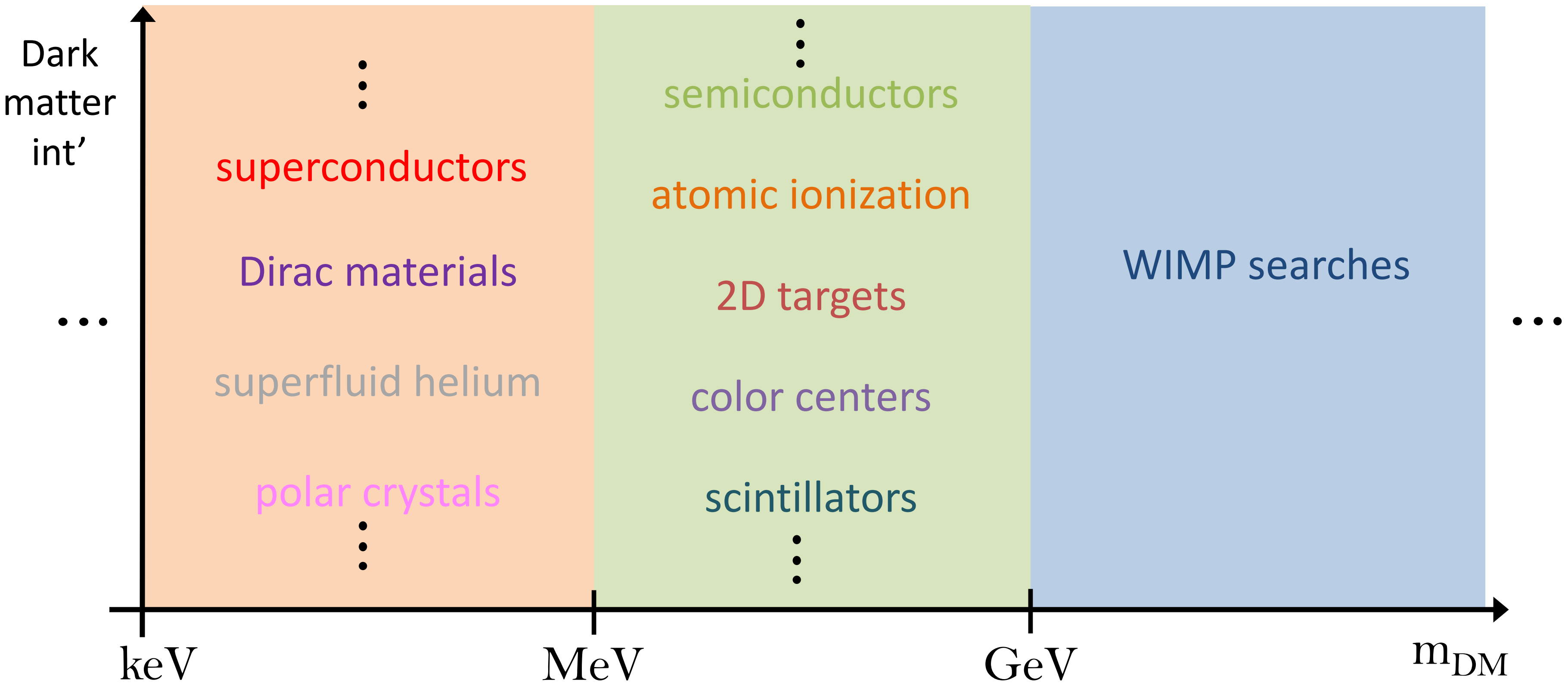
MeV

GeV

m_{DM}

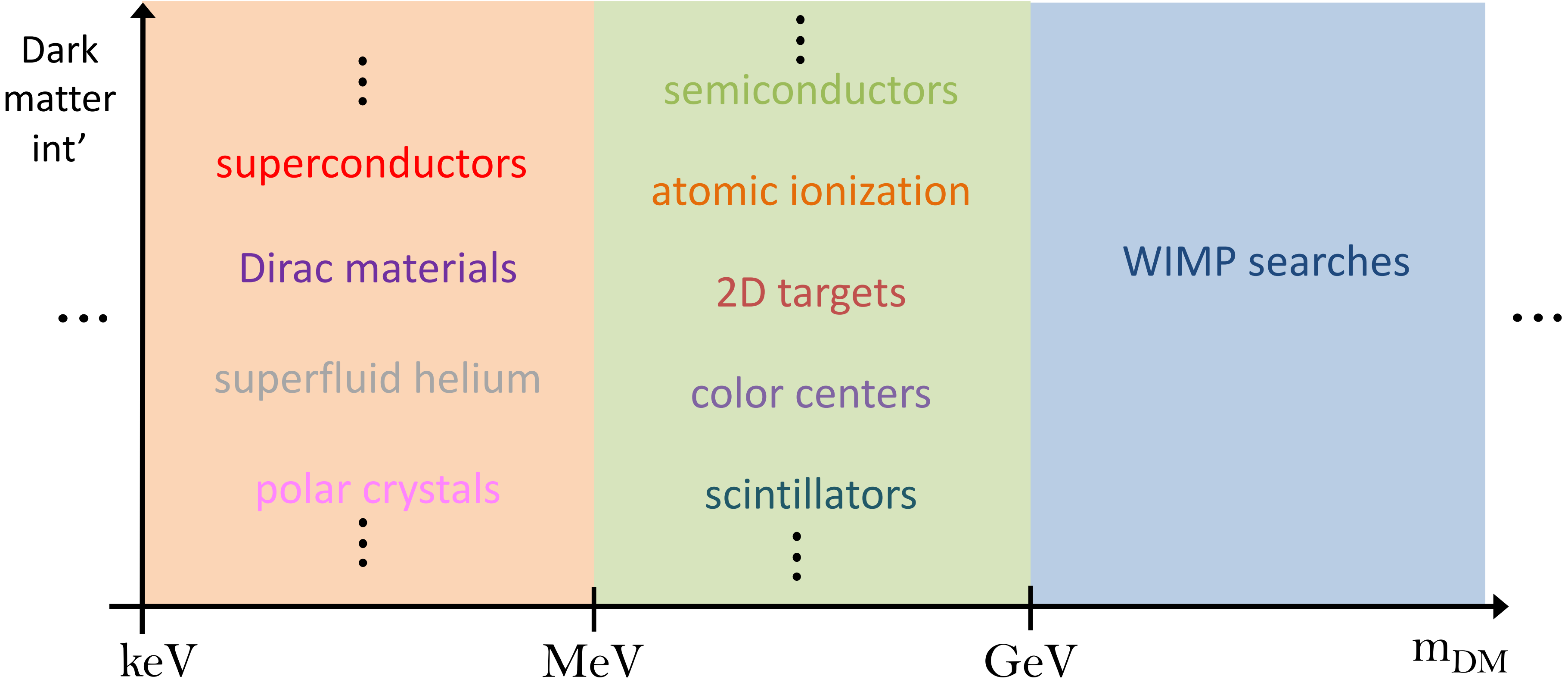
Burgeoning field in recent years

Prospects



Experimentalists are going after these ideas now!

Prospects



Dark matter int’

⋮

superconductors

Dirac materials

superfluid helium

polar crystals

⋮

⋮

semiconductors

atomic ionization

2D targets

color centers

scintillators

⋮

WIMP searches

…

…

keV

MeV

GeV

m_{DM}

Interface particle physics/condensed matter physics/ quantum sensing/precision measurements

If you have any (crazy) new ideas,

please be in touch :-)

Thanks!