New Materials for Dark Matter Detection

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&

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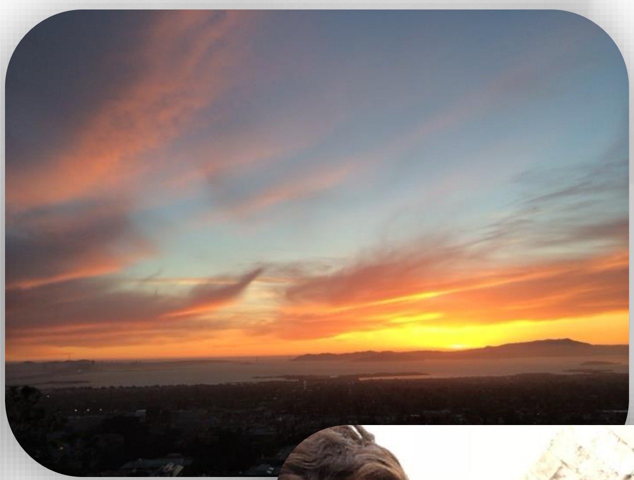
Happy

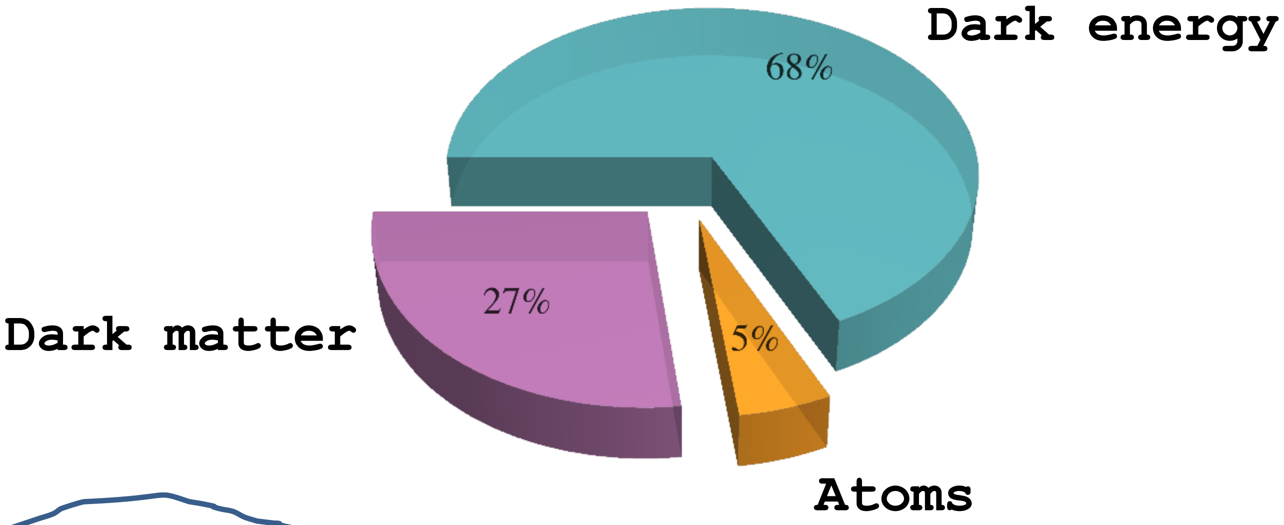


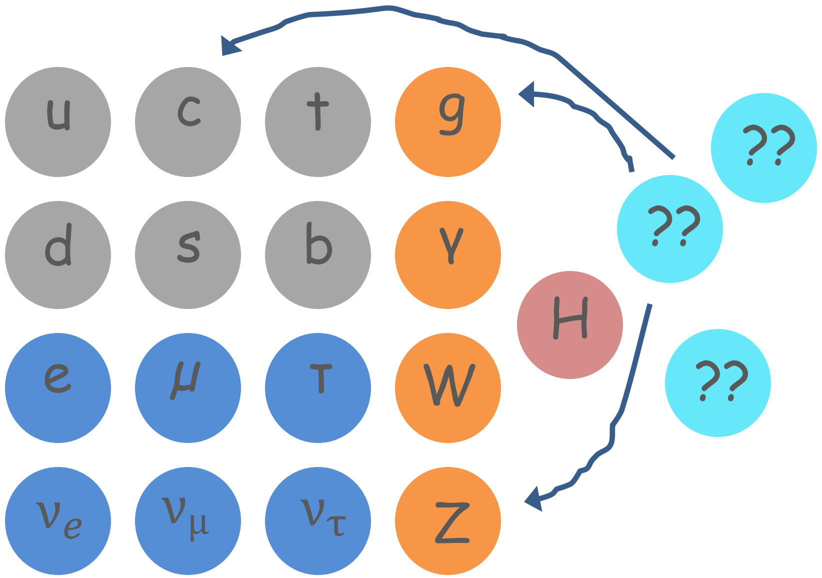



H I T O S H I

Introduction

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 Miracle

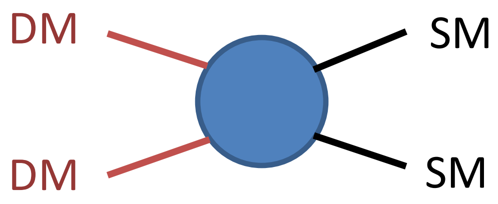
Correct thermal relic abundance:

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

For weak coupling, weak scale emerges.

Weakly Interacting Massive Particle (WIMP)

The dominant paradigm for 40+ years.

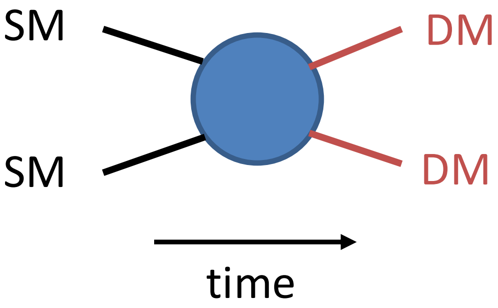


annihilation

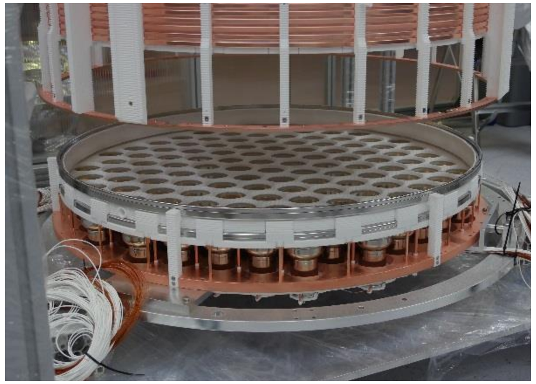
$$\langle \sigma_{\rm ann} v \rangle = \frac{\alpha^2}{m_{\rm DM}^2}$$

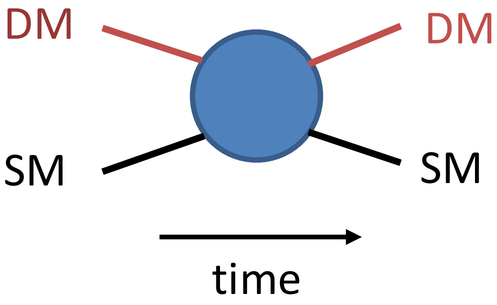
Searching for WIMPs

Direct production

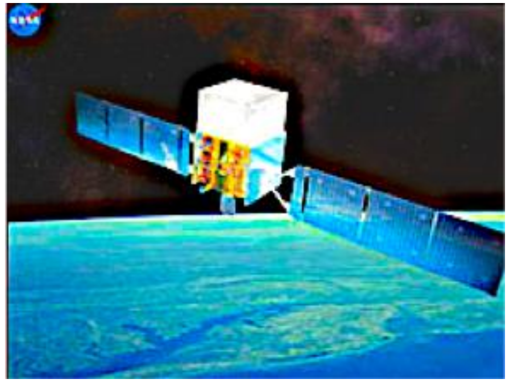


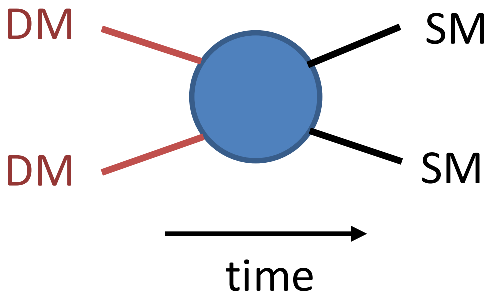
Direct detection





Indirect detection

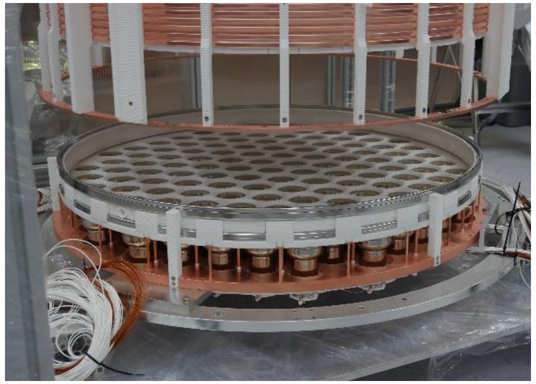




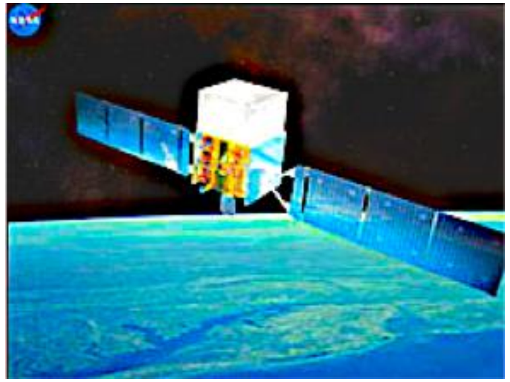
Searching for WIMPs

Direct production

Direct detection



Indirect detection

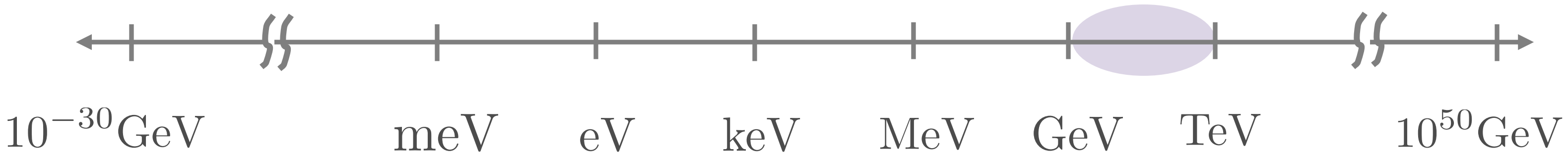


Experiments getting increasingly sensitive

Haven't yet detected dark matter

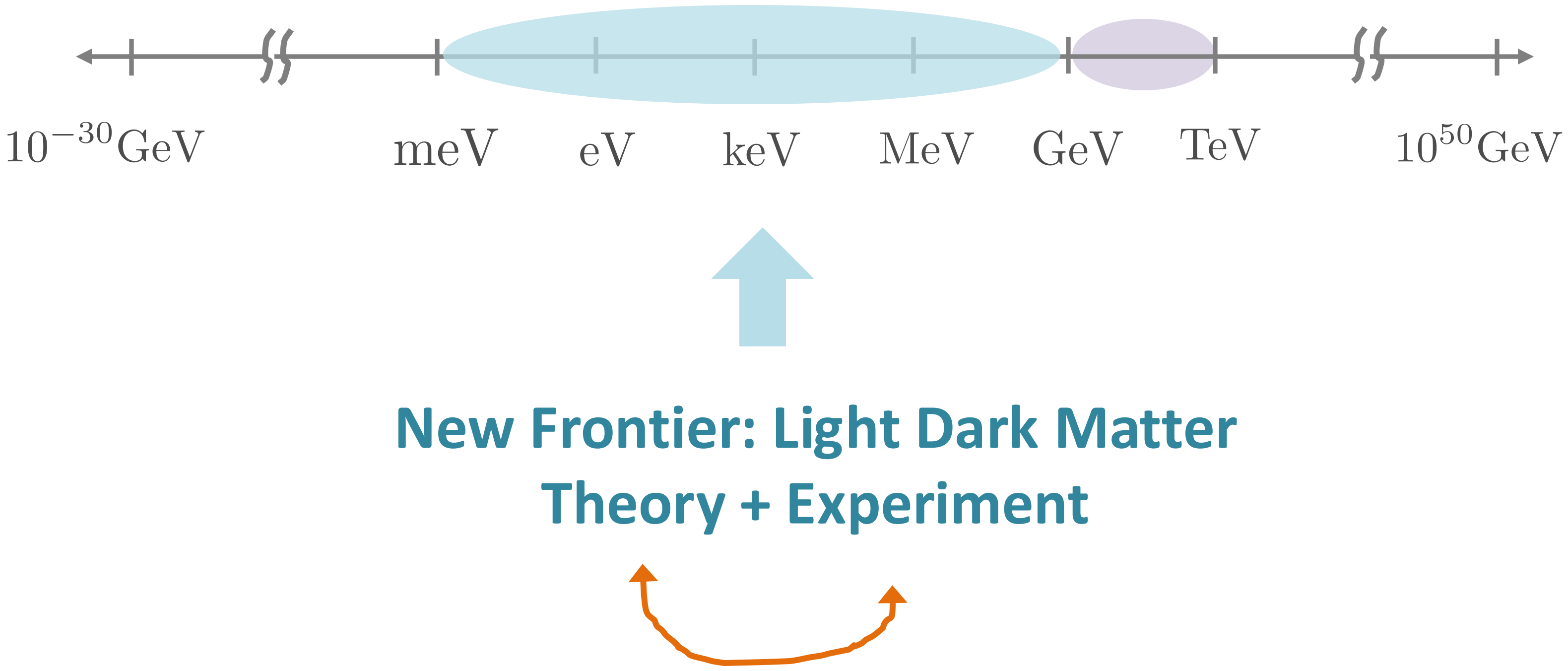
Great opportunity for new ideas.

Beyond the WIMP



Possible dark matter mass

Beyond the WIMP



Possible dark matter mass

New Frontier: Light Dark Matter
Theory + Experiment

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SIMP

New Theory Ideas

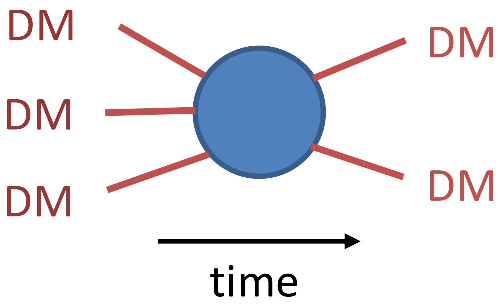
- ……
- Weakly coupled WIMPs — Pospelov, Ritz, Voloshin 2007; Feng, Kumar 2008
- Asymmetric dark matter — Kaplan, Luty, Zurek, 2009
- Freeze-in dark matter — Hall, Jedamzik, March-Russell, West, 2009
- SIMPs — **YH**, Kuflik, Volansky, Wacker, 2014 | **YH**, Kuflik, Murayama, Volansky, Wacker, 2015
- 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

SIMP

What if dark matter mostly interacted with itself?



$$\langle \sigma v^2 \rangle_{3\to 2} \equiv \frac{\alpha^3}{m_{\rm DM}^5}$$

$$m_{\rm DM} \sim \alpha \times 100\ \text{MeV}$$

3 → 2 self-annihilations

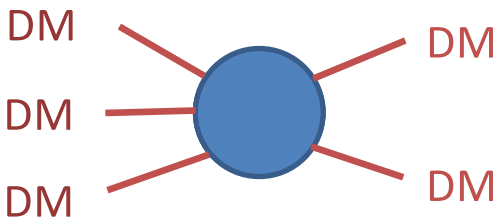
For strong coupling, the strong scale emerges.

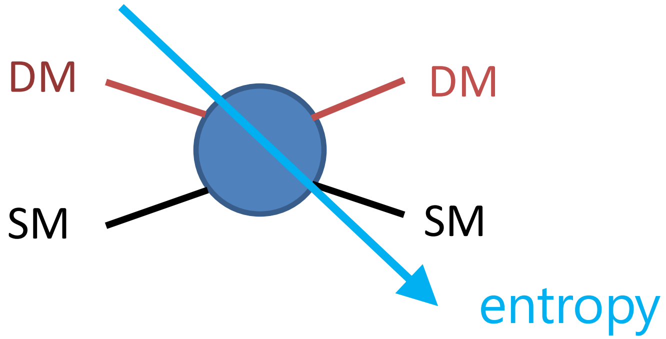
SIMP = Strongly (self) Interacting Massive Particle

Carlson, Hall, Machacek, 1992 | **YH**, Kuflik, Volansky, Wacker, 2014

SIMP

Pumps heat into the system: need to shed the heat



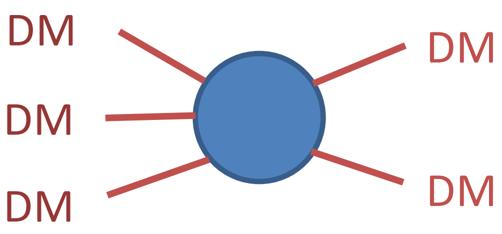


3 → 2 self-annihilations

thermalize with
light SM species
(active during freeze-out)

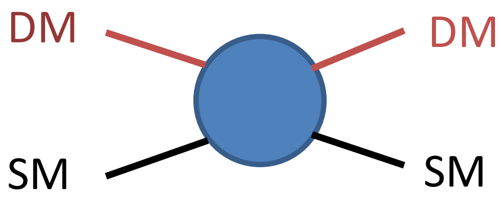
YH, Kuflik, Volansky, Wacker, 2014

SIMP



decouples 1^{st}

Determines
DM relic density

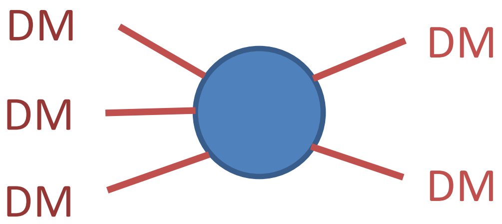


decouples 2^{nd}

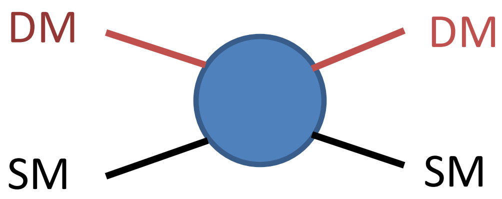
What if the order was reversed?

ELDER

ELastically DEcoupling Relic (ELDER)



decouples 2nd



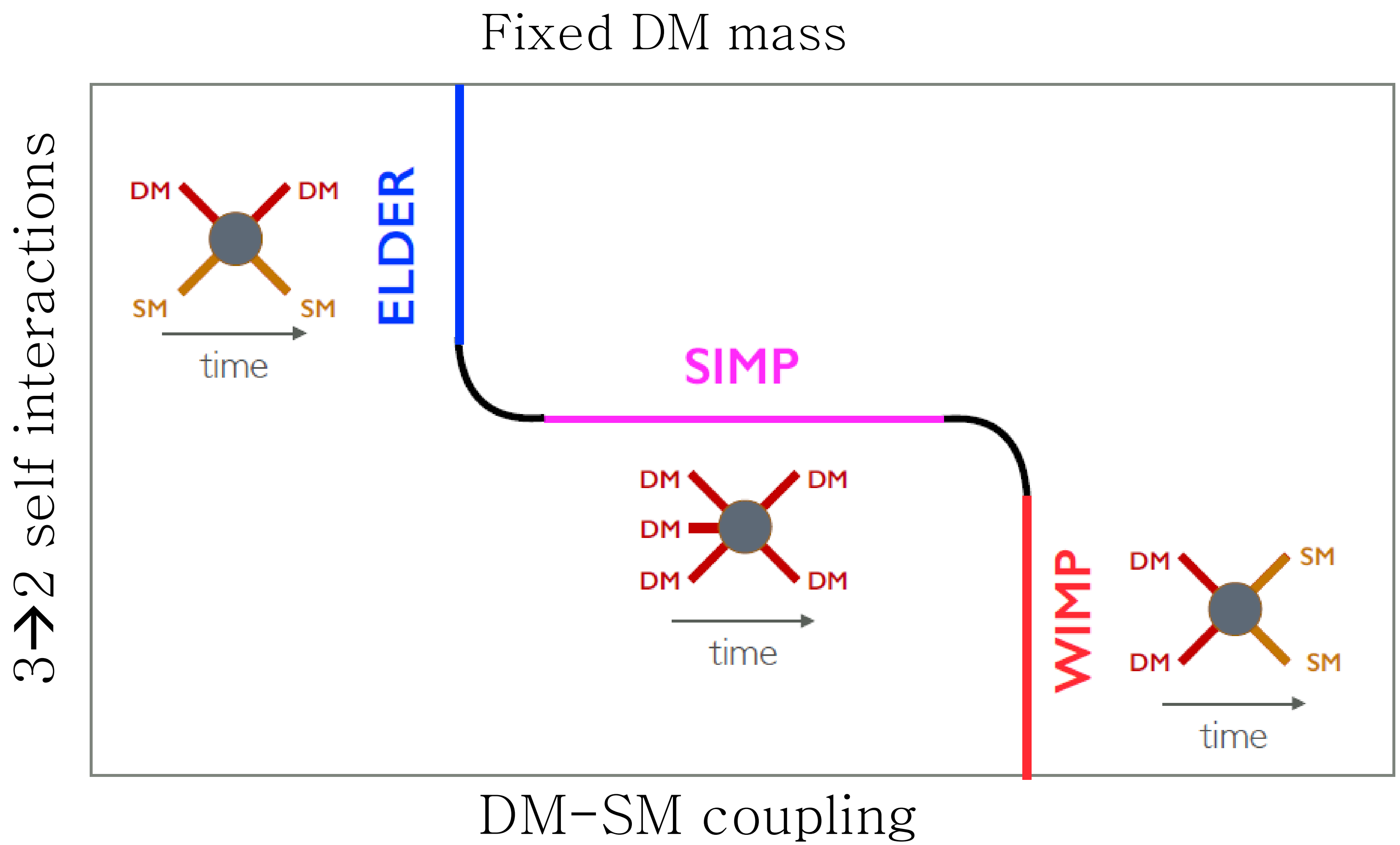
decouples 1st

Determines
DM relic density

$$\Omega_{\rm DM} \propto e^{-\langle \sigma v \rangle_{\rm el} \#}$$

Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2016 & 2017

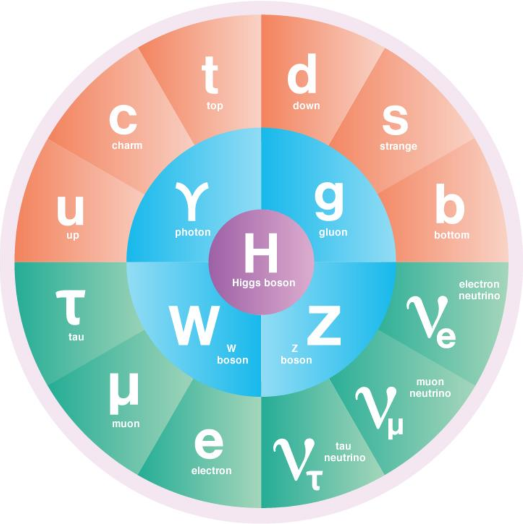
WIMP/SIMP/ELDER



Generic.

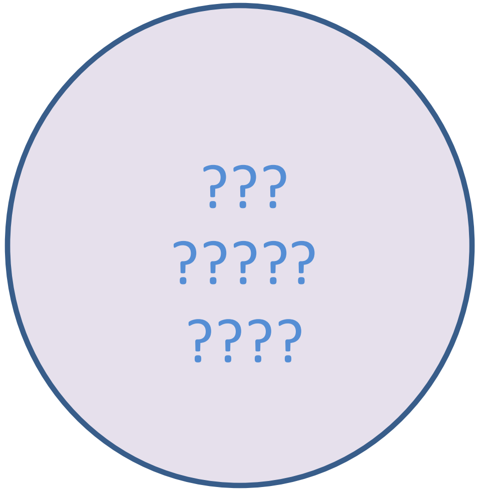
Dark Sectors

Visible sector



Zoo of particles
w/structure
$SU(3)_c x\ SU(2)_L\ x\ U(1)_Y$

Dark sector



Why not in the
dark sector too?
New gauge symmetries?

Dark Sectors

Think Standard Model!

Dark matter from strongly coupled gauge theories

E.g. $SU(3)_{dark} \times U(1)_{dark}$

$Sp(N_c)$, $SU(N_c)$, $SO(N_c)$

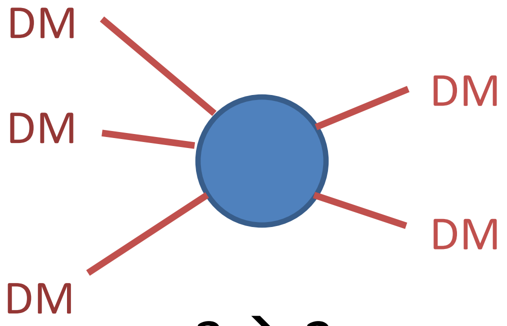
Kinetically mixed dark photon (V)

QCD-like theories, pions = dark matter

Many processes, many dark matter mechanisms.

E.g. SIMPs

Think QCD!



3→ 2

QCD has 5-point interactions! $K^+K^-\rightarrow\pi^+\pi^0\pi^-$

WZW term

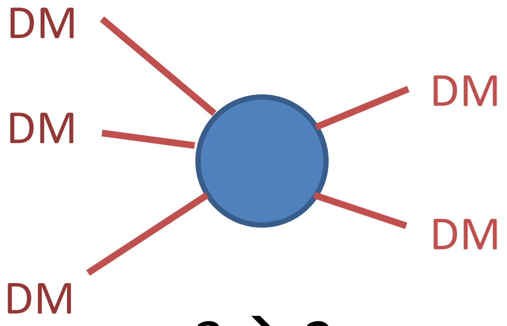
If calculate the rate, find that is just right for SIMPs with mass ~ few hundred MeV

YH, Kuflik, Murayama, Volansky, Wacker, 2015

E.g. SIMPs

Think QCD!

$Sp(N_c)$, $SU(N_c)$, $SO(N_c)$



3→ 2

$$\mathcal{L}_{\mathrm{WZW}} = \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi]$$

WZW term

pion decay constant

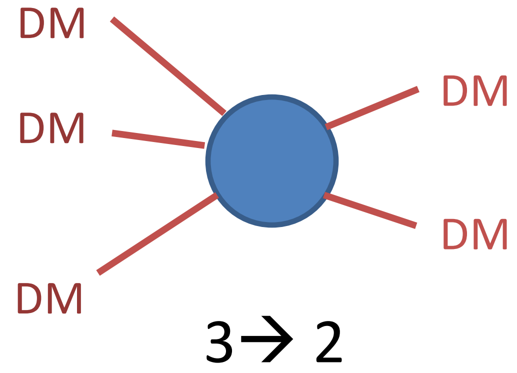
Wess and Zumino, 1971 | Witten x 2, 1983

YH, Kuflik, Murayama, Volansky, Wacker, 2015

E.g. SIMPs

Think QCD!

$Sp(N_c)$, $SU(N_c)$, $SO(N_c)$



Stable dark matter = dark pions

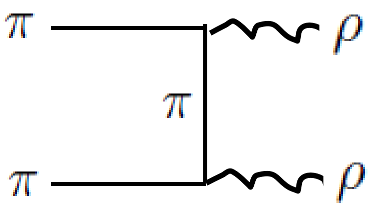
mass ~ few hundred MeV

Non-exotic!

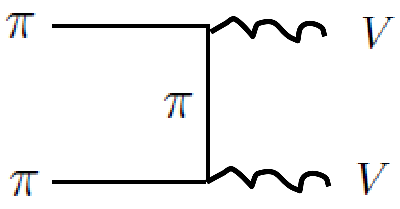
{ <u>3→ 2 dark glueballs</u>: Carelson, Hall, Machacek, 1992 | Soni, Zhang, 2016 | Forestell, Morrissey, Sigurdson, 2017 }

YH, Kuflik, Murayama, Volansky, Wacker, 2015

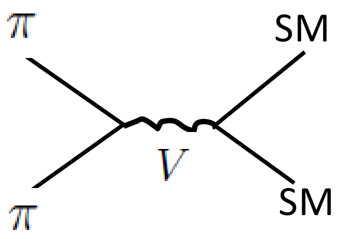
E.g. 2→2



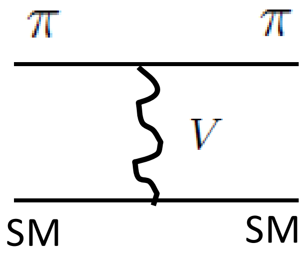
forbidden annihilations



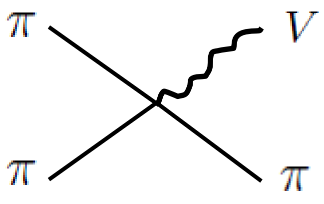
2→2 annihilations



2→ 2 annihilations



elastic scattering



semi-annihilations

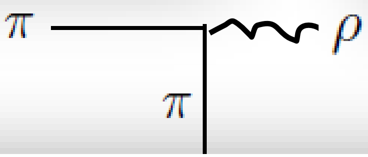
Lee, Seo, 2015 | **YH**, Kuflik, Murayama, 2016 | Harigaya, Nomura, 2016
Berlin, Blinov, Gori, Schuster, Toro, 2018

SIMP spectroscopy

Yonit Hochberg,[a,b] Eric Kuflik[c] and Hitoshi Murayama[a,b,d,e]

Vector SIMP dark matter

Soo-Min Choi,[a] Yonit Hochberg,[b,c] Eric Kuflik,[b,c] Hyun Min Lee,[a] Yann Mambrini,[d]
Hitoshi Murayama[e,f,g,h] and Mathias Pierre[d]



PHYSICAL REVIEW D **97,** 055030 (2018)

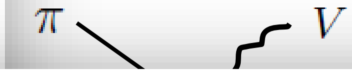
Dark spectroscopy at lepton colliders

Yonit Hochberg,[1,2,*] Eric Kuflik,[1,2,†] and Hitoshi Murayama[3,4,5,‡]

PRL **115,** 021301 (2015) PHYSICAL REVIEW LETTERS week ending 10 JULY 2015

Model for Thermal Relic Dark Matter of Strongly Interacting Massive Particles

Yonit Hochberg,[1,2,*] Eric Kuflik,[3,†] Hitoshi Murayama,[1,2,4,‡] Tomer Volansky,[5,§] and Jay G. Wacker[6,7,¶]
[1]*Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720, USA*
[2]*Department of Physics, University of California, Berkeley, California 94720, USA*
[3]*Department of Physics, LEPP, Cornell University, Ithaca, New York 14853, USA*
[4]*Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo Institutes for Advanced Study, University of Tokyo, Kashiwa 277-8583, Japan*
[5]*Department of Physics, Tel Aviv University, Tel Aviv 6997801, Israel*
[6]*Quora, Mountain View, California 94041, USA*
[7]*Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94305, USA*
(Received 8 January 2015; published 10 July 2015)



Twin SIMPs

Yonit Hochberg[1],* Eric Kuflik[1],† and Hitoshi Murayama[2,3,4,5‡]

2→ 2 annihilations elastic scattering semi-annihilations

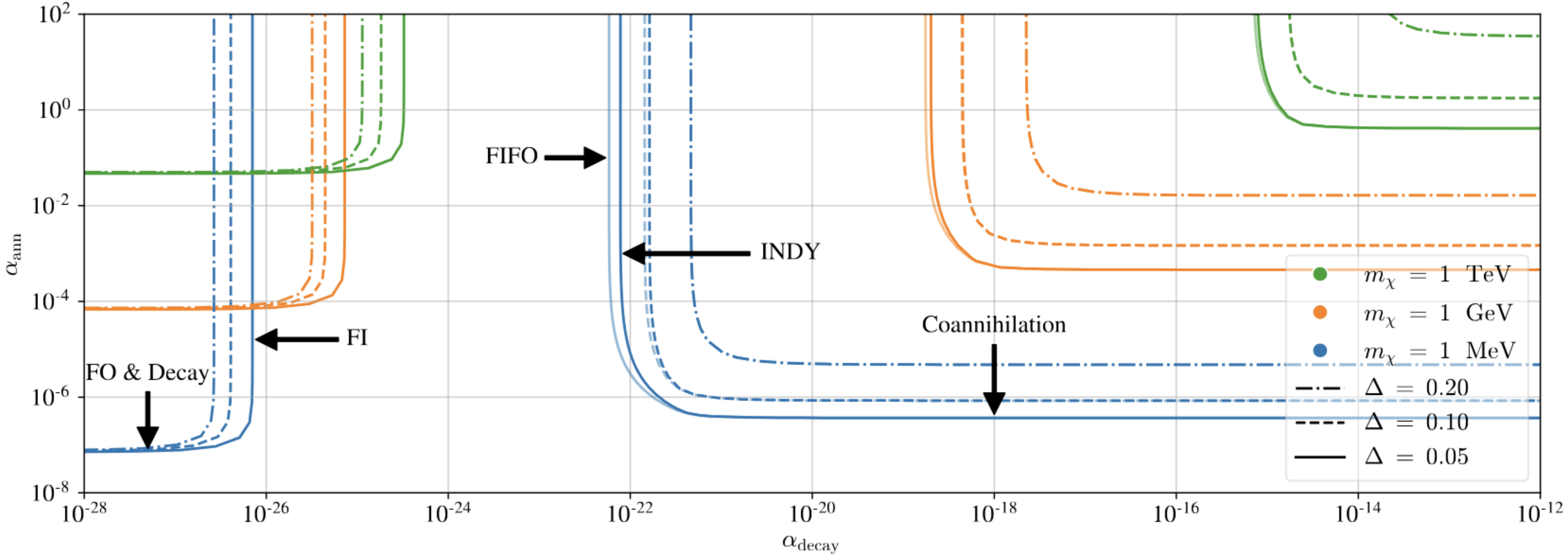
SIMPs through the axion portal

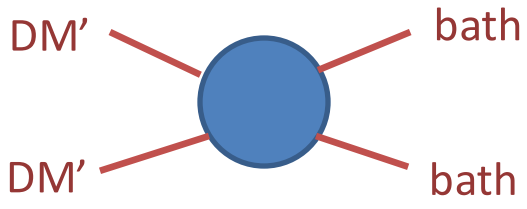
Yonit Hochberg,[1,*] Eric Kuflik,[1,†] Robert McGehee,[2,3,‡] Hitoshi Murayama,[2,3,4,5,§] and Katelin Schutz[2,3,¶]

Lee, Se

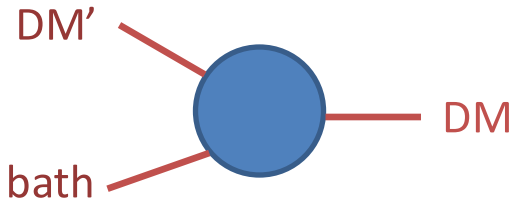
Berlin, Blinov, Gori, Schuster, Toro, 2018

INDY



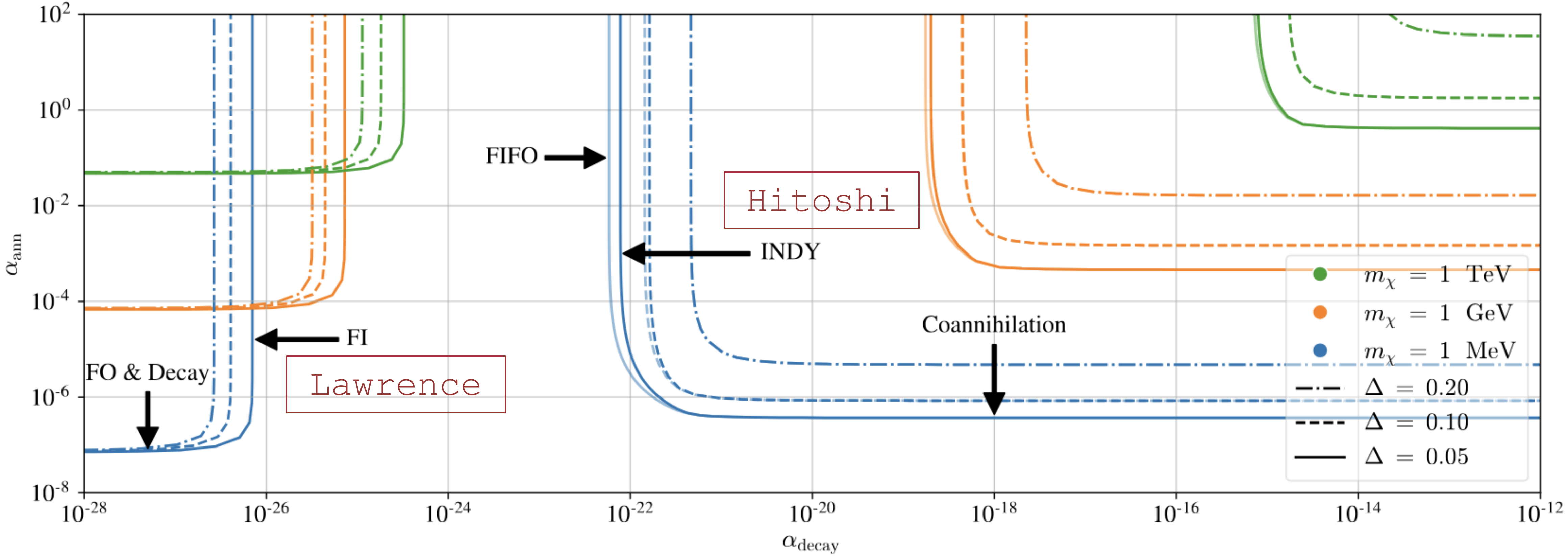


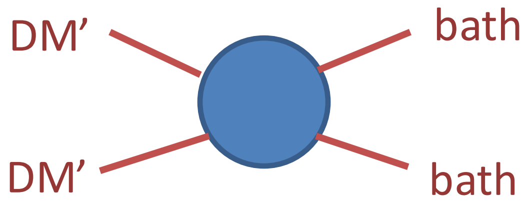
Phases of INverse DecaYs (INDY)
of dark matter



Frumkin, **YH**, Kuflik and Murayama, PRL 2023 + 2410.sooon

INDY





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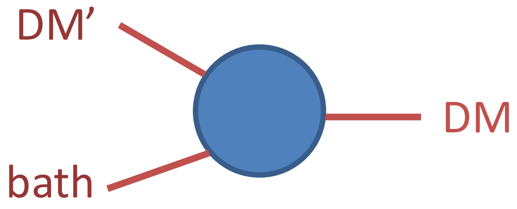


Frumkin, **YH**, Kuflik and Murayama, PRL 2023 + 2410.sooon

H I T O S **H** I

How?

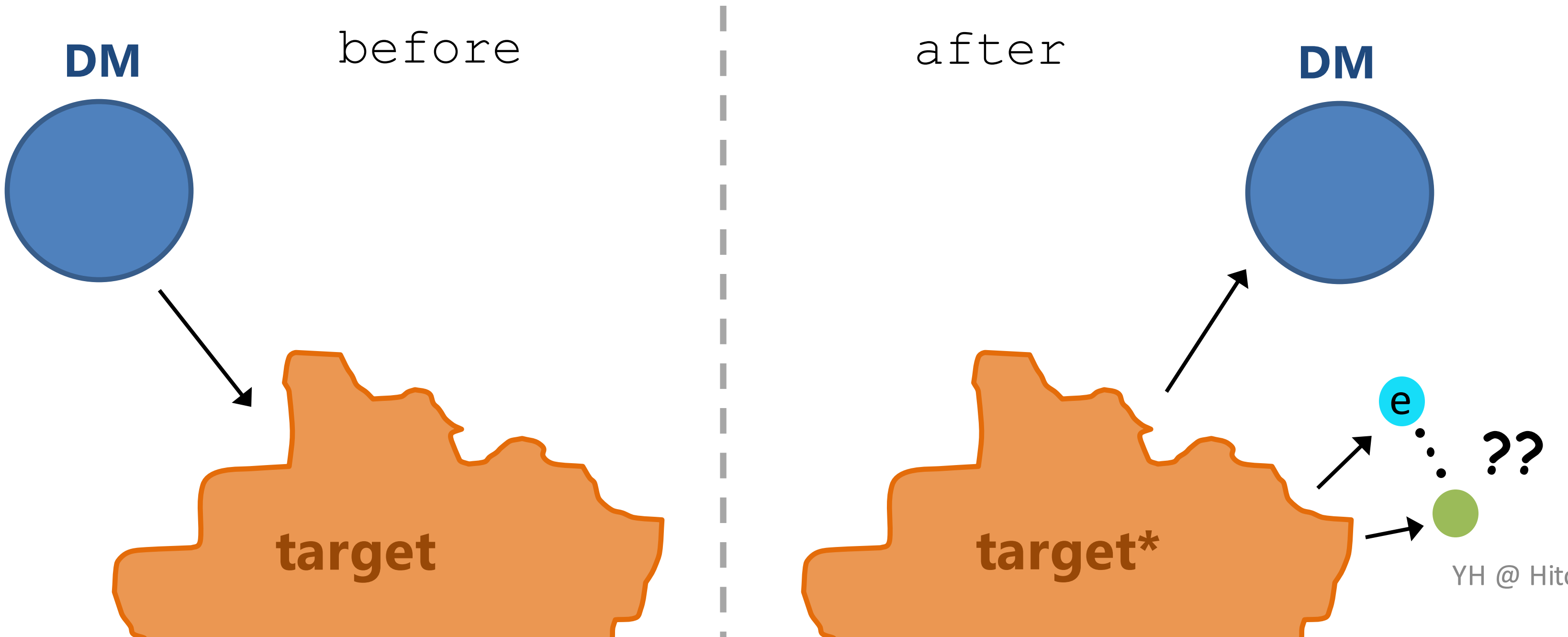
Detection Blueprints

Dark matter particle comes in

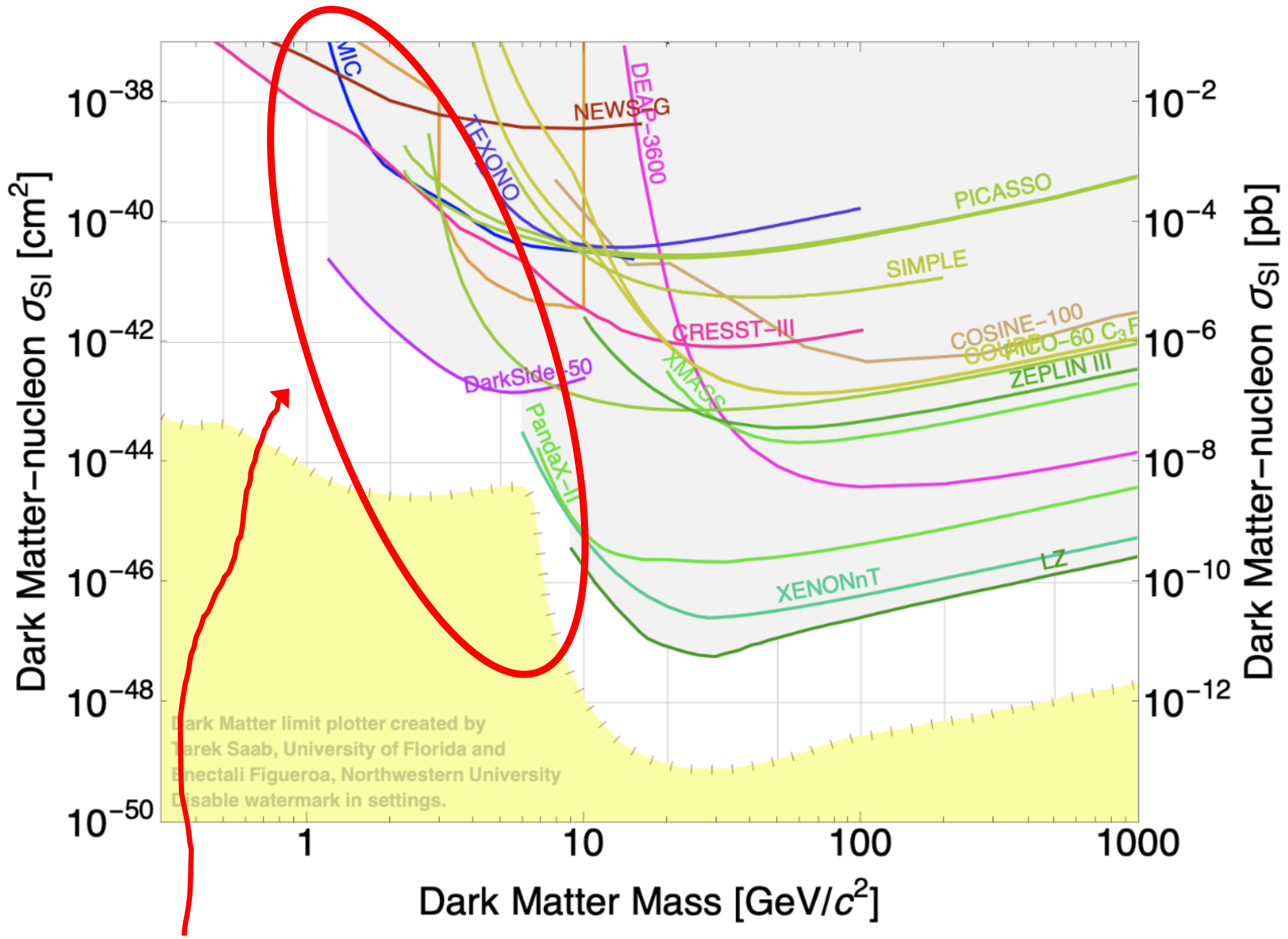
Hits a target in the lab

System reacts

Measure the reaction



Direct Detection

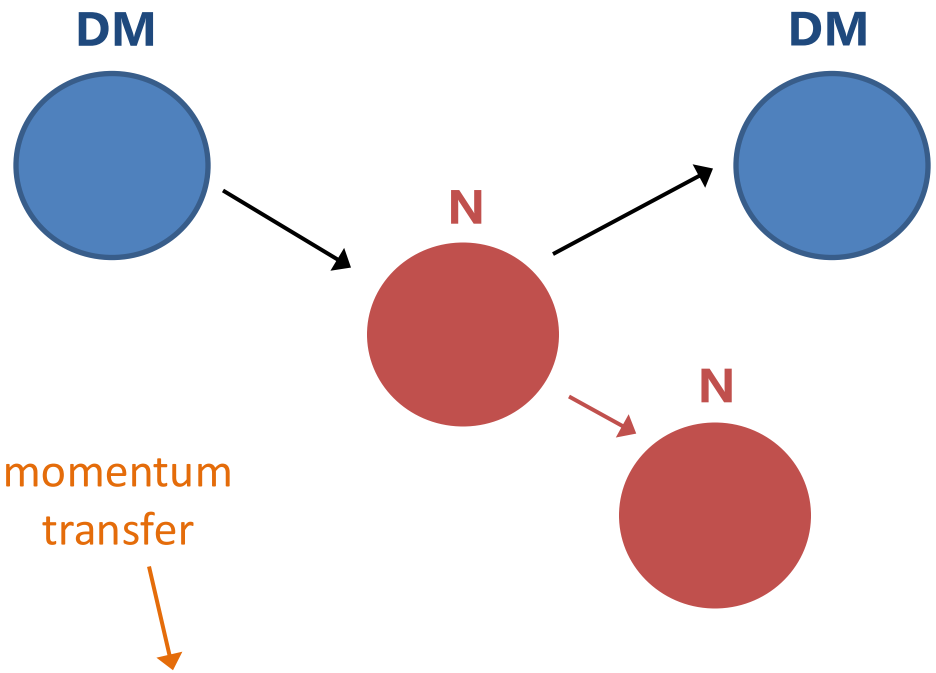


What's going on?

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

Current Experiments

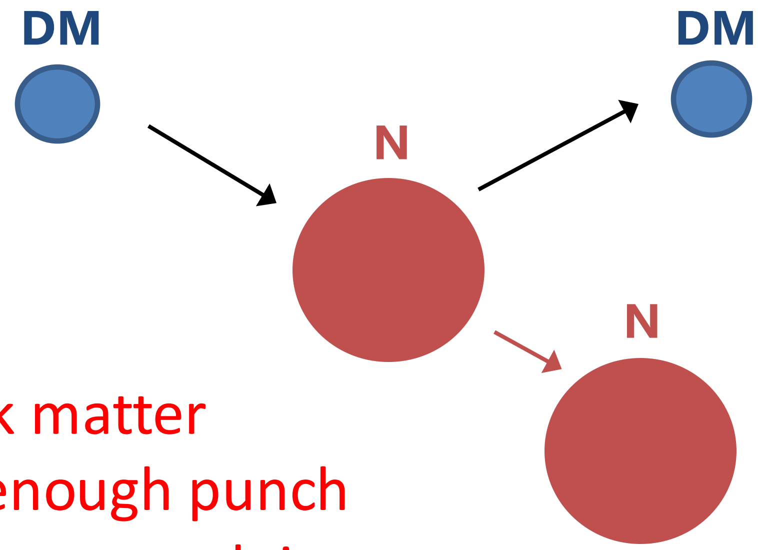
Looking for nuclear recoils:
think billiard balls



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

Current Experiments

Looking for nuclear recoils:
think billiard balls

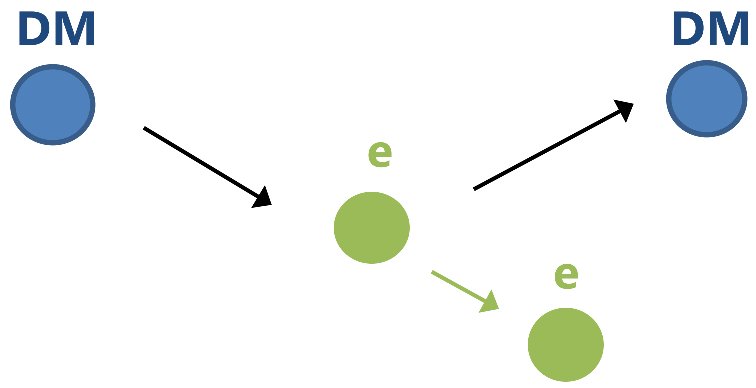


light dark matter
doesn't have enough punch
to kick the heavy nuclei

Lose sensitivity @ O(GeV) masses

New Avenues

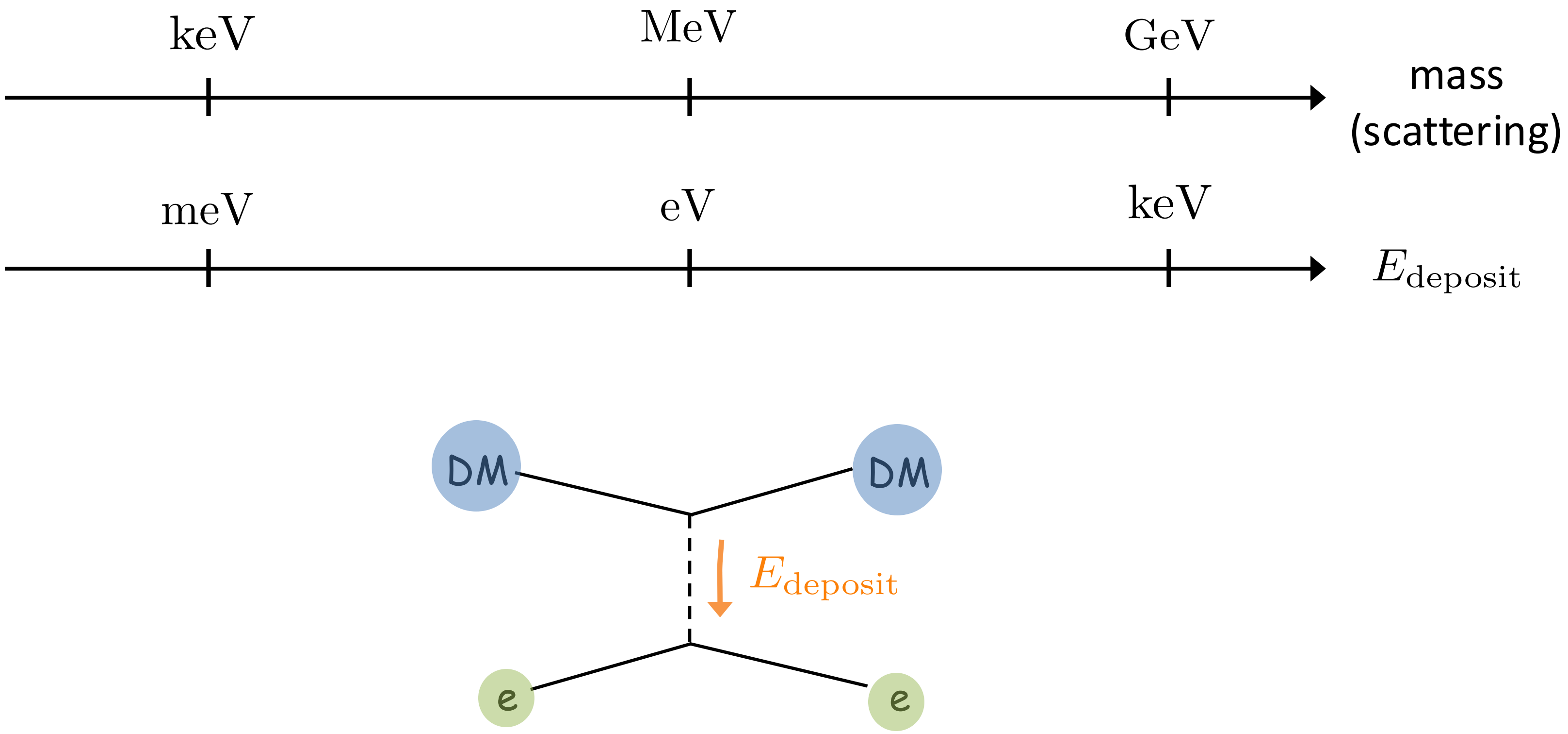
Light dark matter: scatter off electrons!



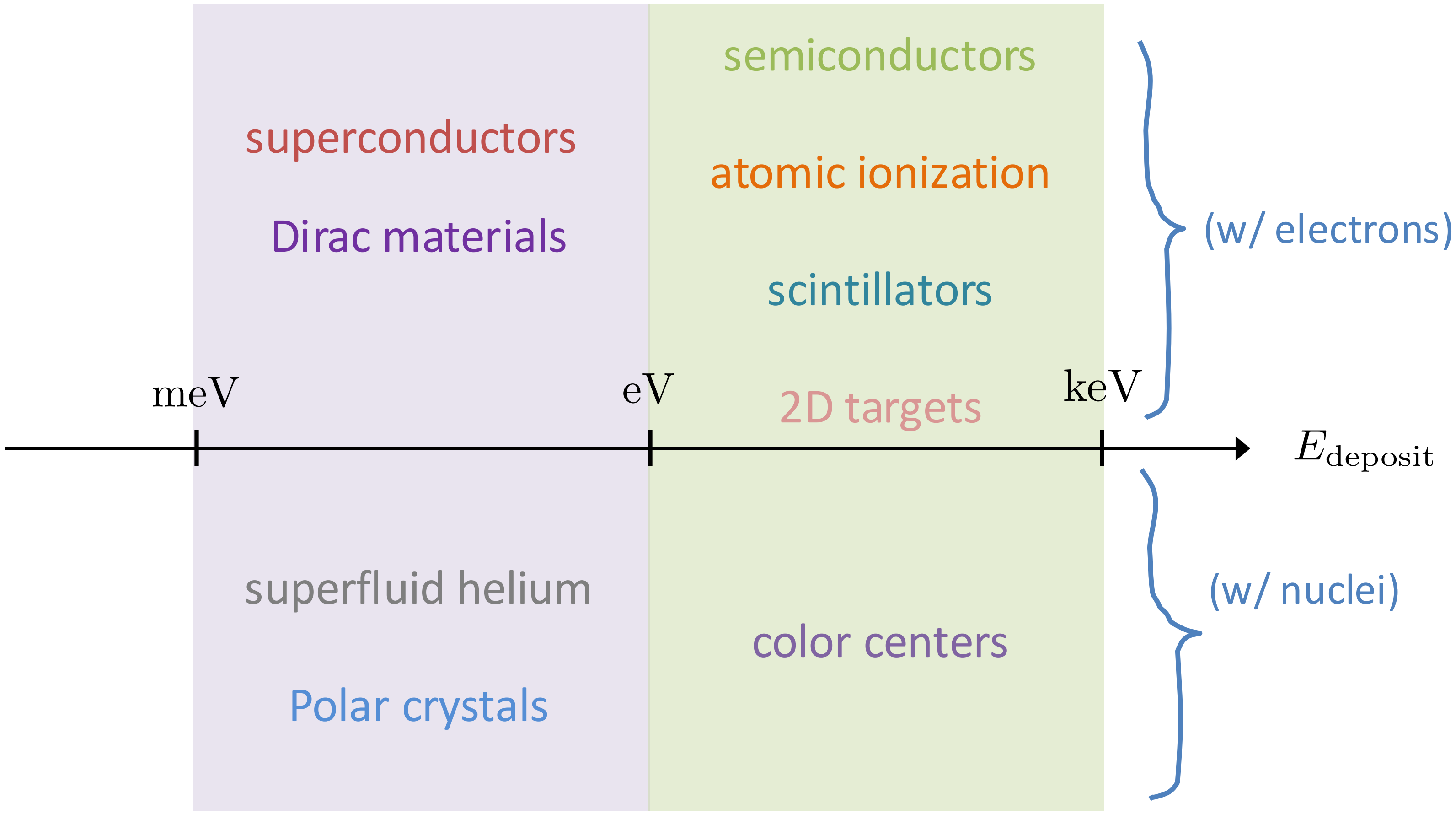
light dark matter
can give enough punch
to kick the light electrons

Energy guideline

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



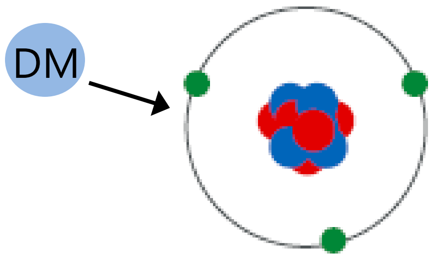
New proposals



Explosion of interest and ideas in recent times

Ex. #1: First ideas

Atomic ionization

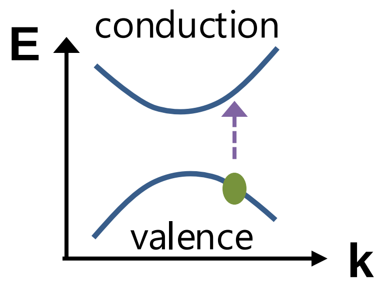


Xenon: ~12 eV

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

Essig, Mardon, Volansky, 2012

Semiconductors



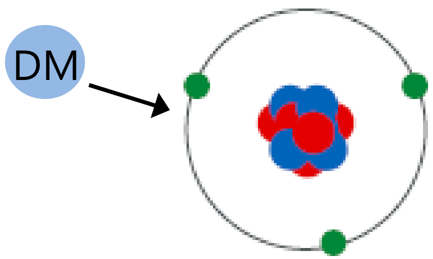
Ge, Si, Diamond, SiC: ~eV

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

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

Ex. #1: First ideas

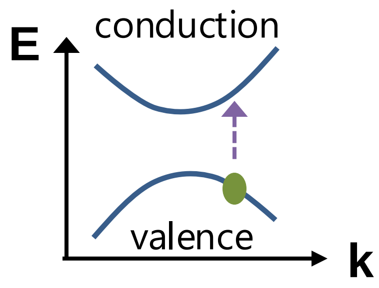
<u>Atomic ionization</u>



Xenon10/100/1T

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

<u>Semiconductors</u>



SuperCDMS, SENSEI, DAMIC-M

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

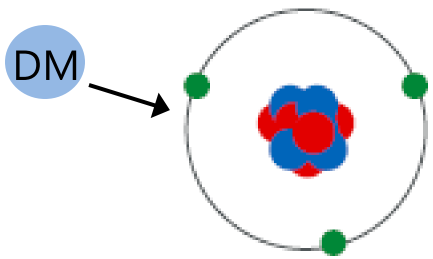
Are being experimentally realized

Essig et al 2012 | Xenon100 2016 | Xenon1T 2020

SuperCDMS 2020 | SENSEI 2023 | DAMIC-M 2023

Ex. #1: First ideas

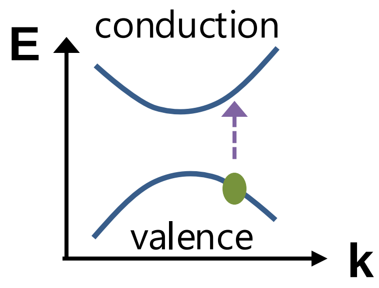
Atomic ionization



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>

  Dark matter interacts 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

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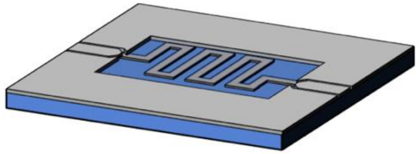
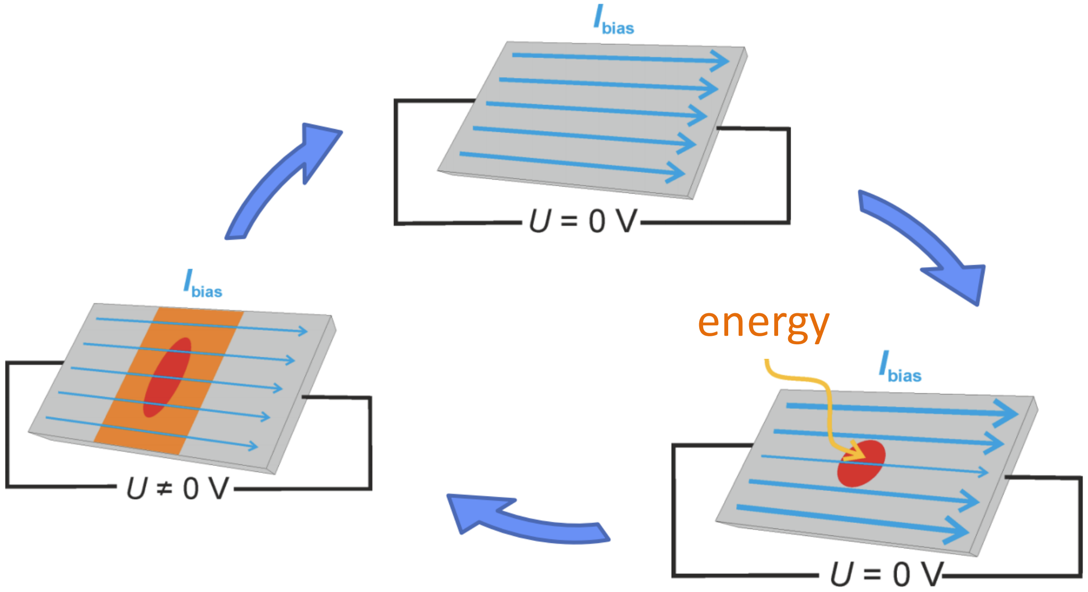
Ex. #2: Superconductors

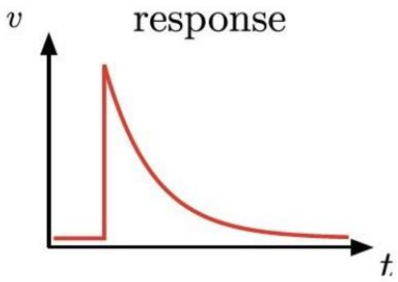
- Superconducting Nanowire Single Photon Detectors (SNSPDs)



Broadly used in quantum information science

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

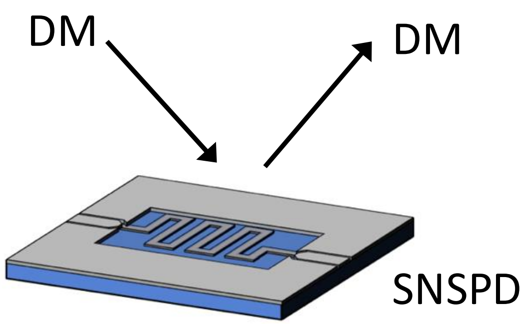




YH, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019

Ex. #2: Superconductors

Use as simultaneous target + sensor (& multiplex)



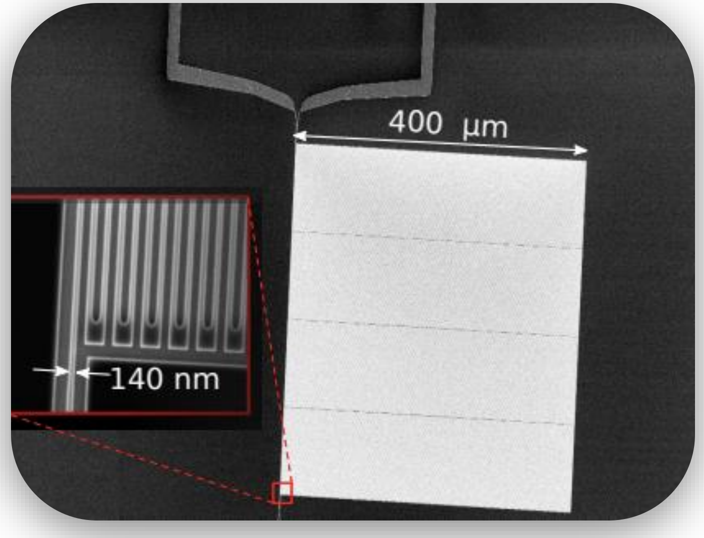
[Similarly for Kinetic Inductance Device (KID) and Transition Edge Sensor (TES)]

Gao, **YH,** Lehmann, Nam, Szypryt, Visser, Xu 2403.19739
+ **YH** et al (ALPs Collaboration), to appear

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

Existing Prototype Device

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

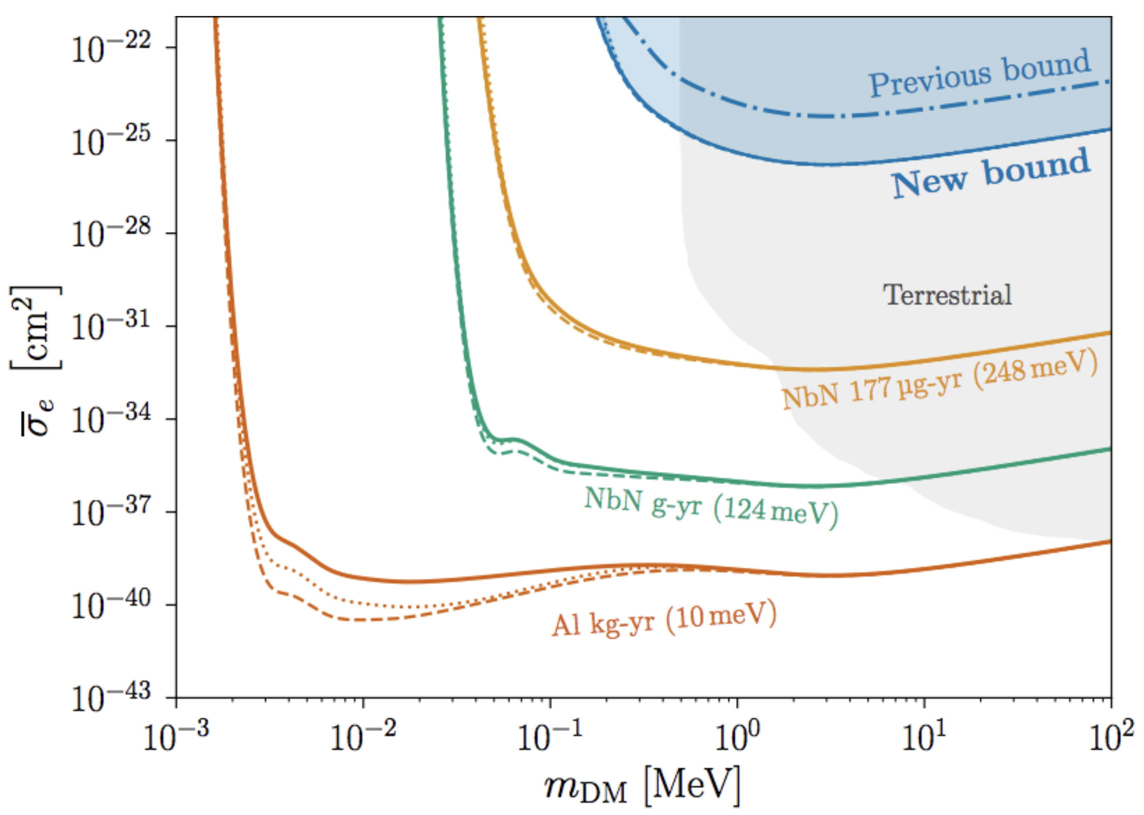


By now have 180 hours of data

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



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

Non-solid curves: geometry effects

Lasenby, Prabhu 2021

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

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

Pushing Thresholds Lower

Low-noise single-photon counting superconducting nanowire detectors at infrared wavelengths up to 29 μm

GREGOR G. TAYLOR,* ALEXANDER B. WALTER, BORIS KORZH, BRUCE BUMBLE, SAHIL R. PATEL, JASON P. ALLMARAS, ANDREW D. BEYER, ROGER O'BRIENT, MATTHEW D. SHAW, AND EMMA E. WOLLMAN

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, California 91109, USA
**gregor.g.taylor@jpl.nasa.gov*

Received 13 October 2023; revised 15 November 2023; accepted 22 November 2023; published 14 December 2023

We report on the extension of the spectral sensitivity of superconducting nanowire single-photon detectors to a wavelength of 29 μm. To our knowledge, this represents the first demonstration of a single-photon counting detector at these long infrared wavelengths. We achieve saturated internal detection efficiency from 10 to 29 μm, while maintaining dark count rates below 0.1 counts per second. Extension of superconducting nanowire single-photon detectors to this spectral range provides low-noise and high-timing-resolution photon counting detection, effectively providing a new class of single-photon sensitive detectors for these wavelengths. These detectors are important for applications such as exoplanet spectroscopy, infrared astrophysics, physical chemistry, remote sensing, and direct dark-matter detection.

And even lower @ 29 microns

Optica, Dec. 2023

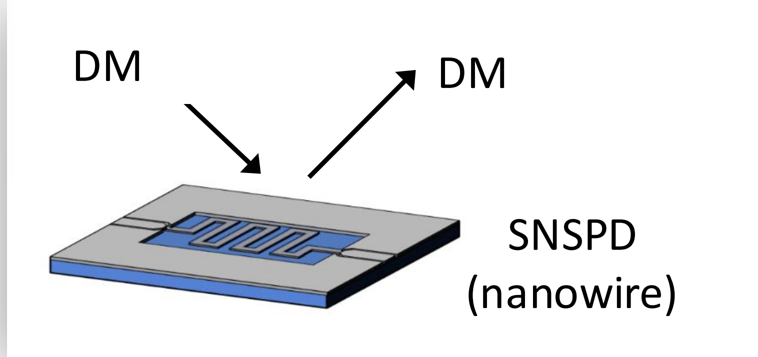
Pushing Areas Larger

Demonstrated 1 mm^2 area detectors

Appl. Phys. Lett, 2023

Quantum Resolution-Optimized Cryogenic Observatory for Dark matter Incident at Low Energy

Crocodile



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

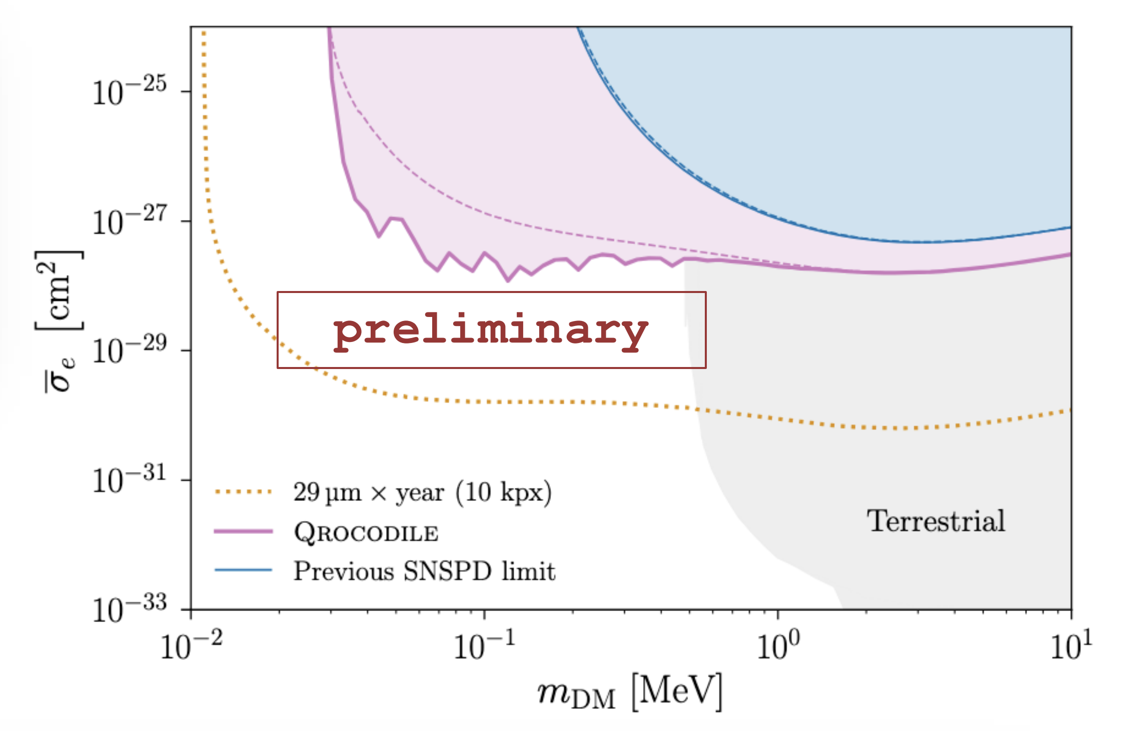
Massachusetts Institute of Technology

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

Universität Zürich UZH

Quantum Resolution-Optimized Cryogenic Observatory for Dark matter Incident at Low Energy

WSi, 0.17ng,
11 micron,
415 hours



First science results shortly [arXiv:2410.sooon]

Massachusetts Institute of Technology

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

Universität Zürich[UZH]

H I T O S H I

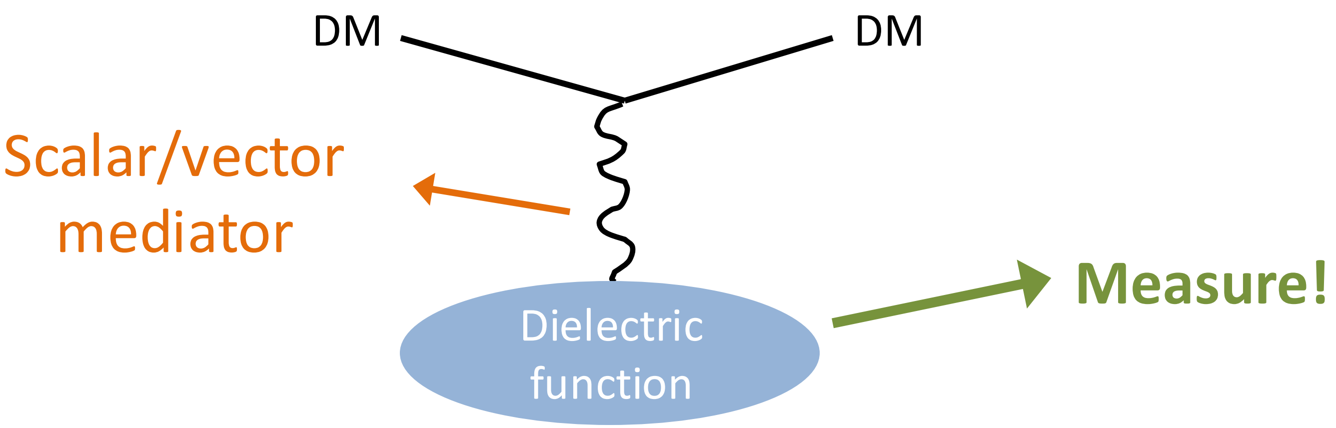
Other materials

New Formalism

DM-electron scattering in any material is determined by the dielectric function

$$\Gamma = \int \frac{d^3\mathbf{q}}{(2\pi)^3} |V(q)|^2 \left[2\frac{q^2}{e^2} \mathrm{Im}\left(-\frac{1}{\epsilon(\mathbf{q}, \omega_{\mathbf{q}})} \right) \right]$$

For any dark matter interaction that couples to electron density



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

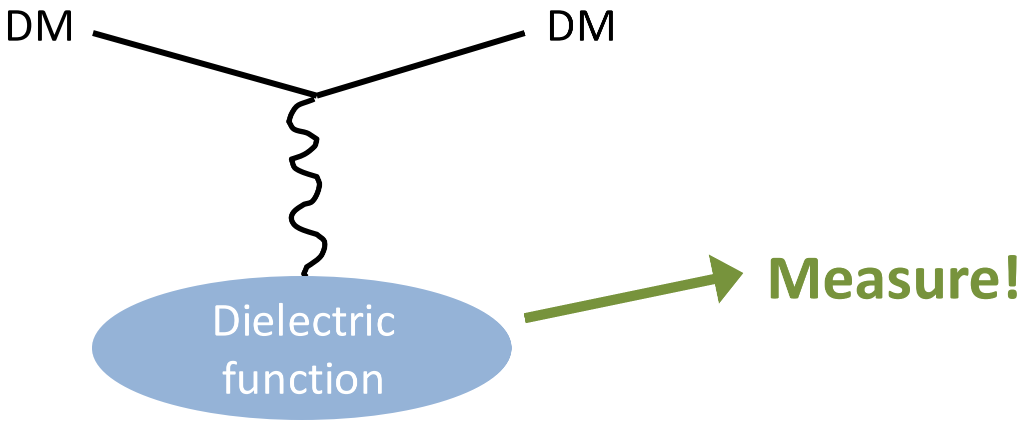
[See also arXiv: 2101.08275]

New Formalism

Automatically includes many-body effects of the material

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

Identify promising materials for dark matter detection



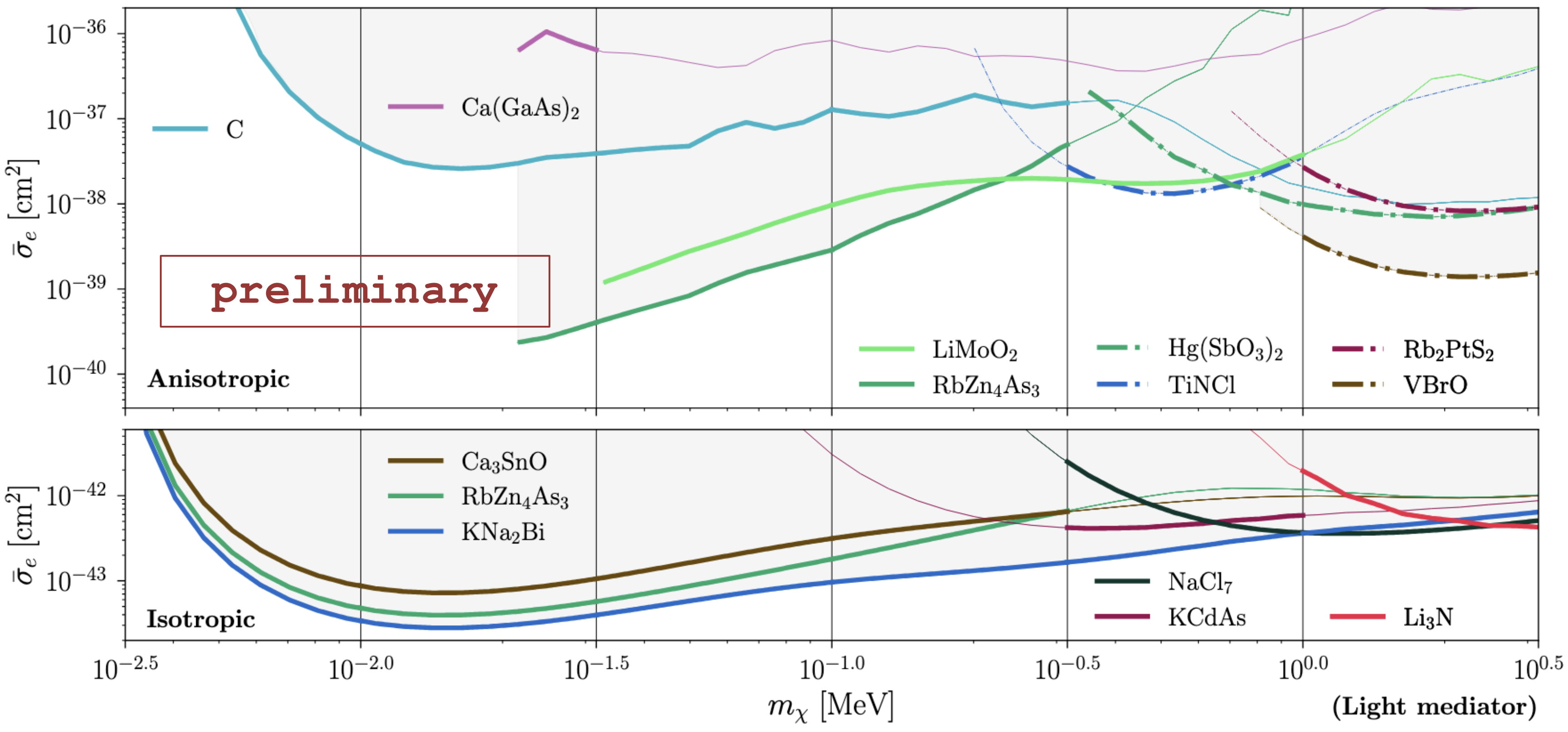
YH, Kahn, Kurinsky, Lehmann, Yu, Berggren, PRL 2021

Ex. #3: Materials Project

The Materials Project

BERKELEY LAB

Over 1000 materials with dielectric function data



First high-throughput search for dark matter detector materials

Griffin, **YH**, Lehmann, Ovadia, Suter, Yang 2410.sooon

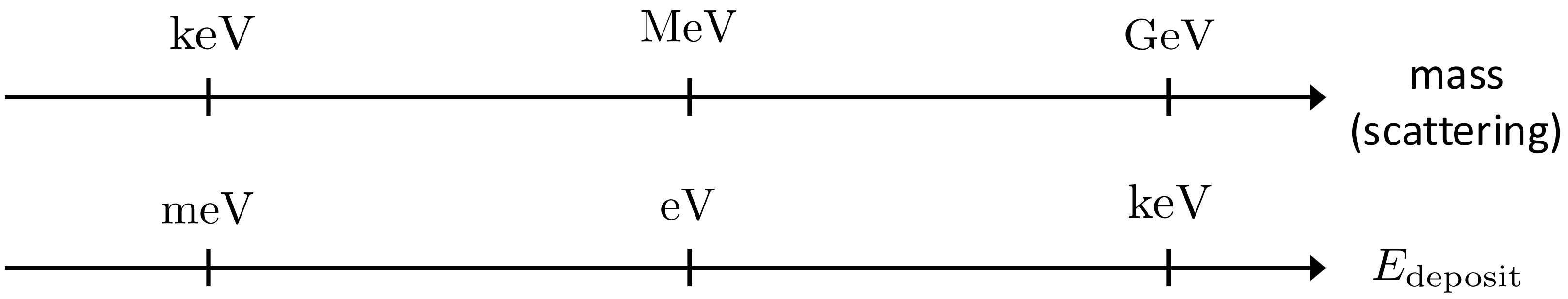
H I T O S H I

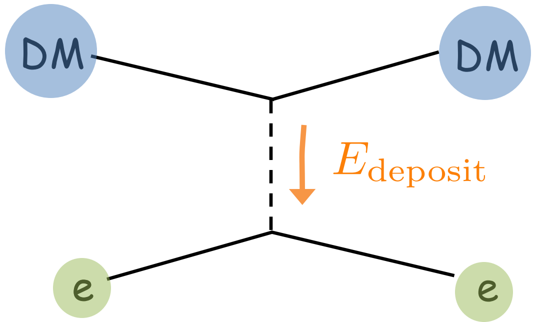
2 for the price of 1

Any given target material can go even further.

Absorption vs. Scattering

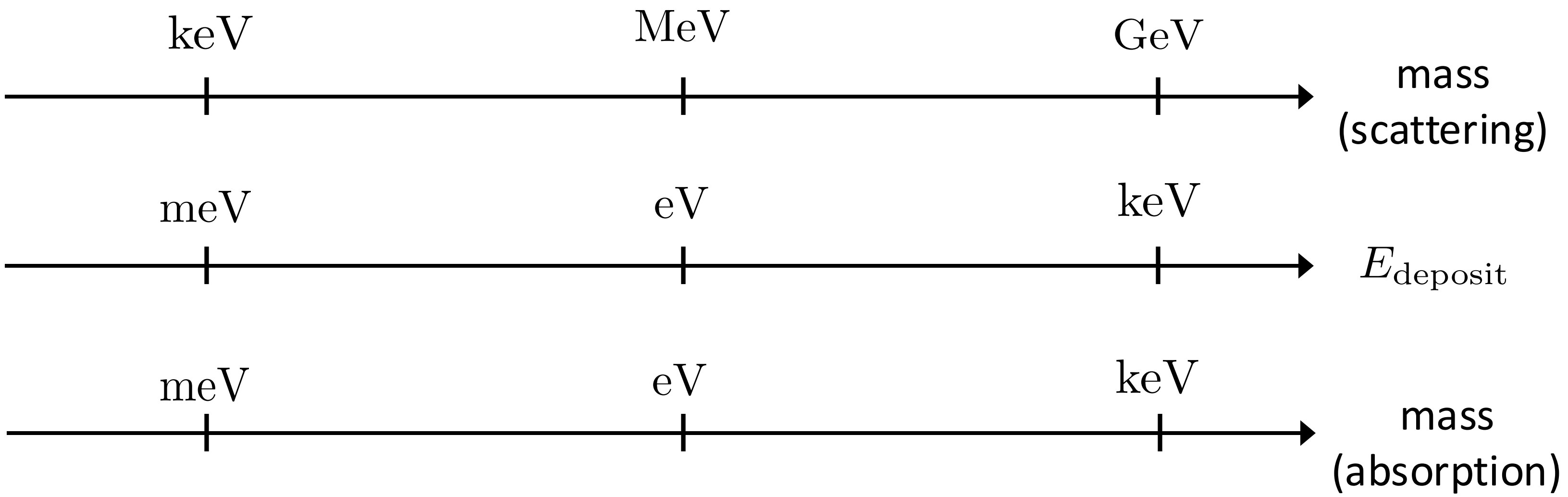
Dark matter scattering: kinetic energy $m_{\rm DM} v^2 \sim 10^{-6} m_{\rm DM}$

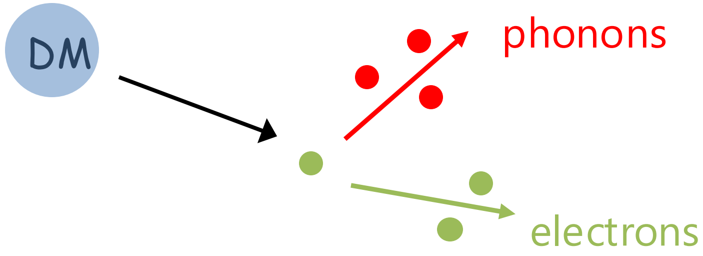




Absorption vs. Scattering

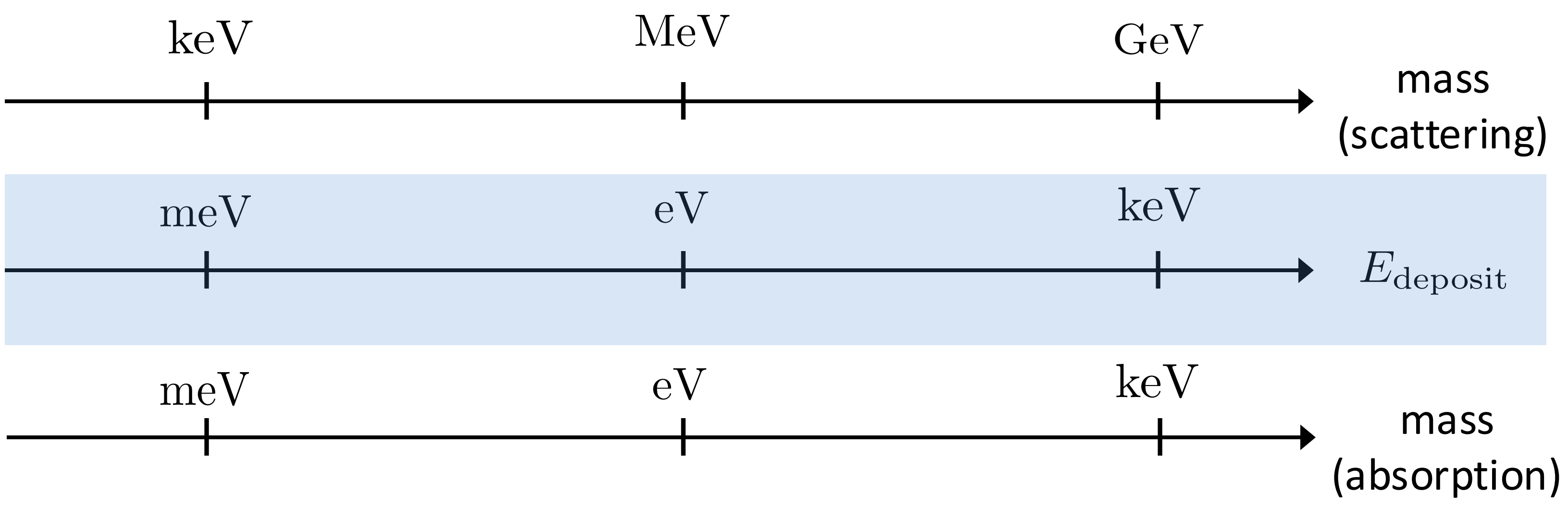
Dark matter absorption: all the mass-energy $m_{\rm DM}$





Absorption vs. Scattering

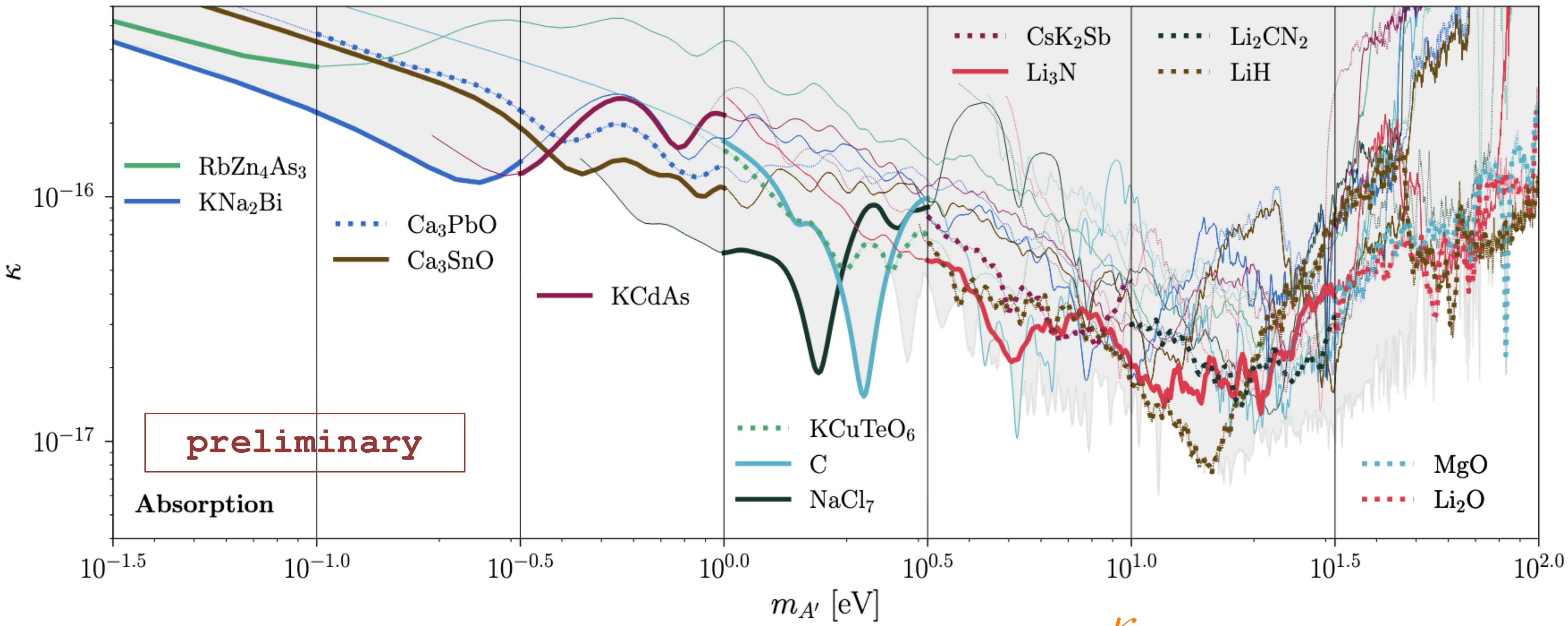
Two (mass ranges) for the price of one :-)



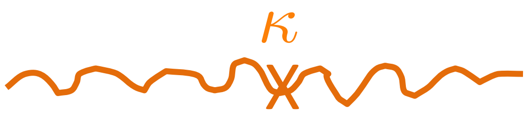
Absorption: Materials Project

The Materials Project

BERKELEY LAB



Kinetically mixed dark photon

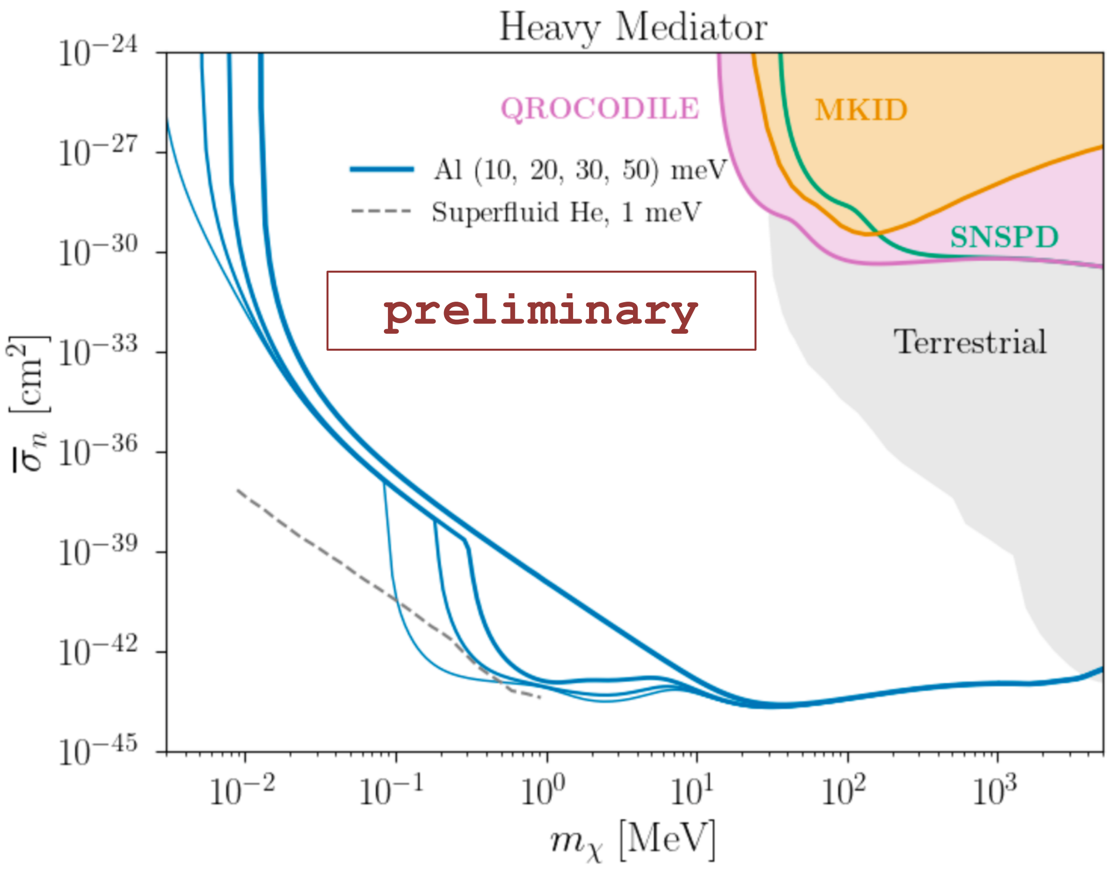


Griffin, **YH**, Lehmann, Ovadia, Suter, Yang 2410.sooon

Two (xsec) for the price of one

Electron-phonon coupling:
energy deposit into one type of dof can be transferred to the other

DM-electron detectors for DM-nuclear interactions



Griffin, Hadas, **YH**, Inzani, Lehmann + w/ QROCODILE, 2410.sooon x 2

H I T O S H I

Interdisciplinary

Outlook

- Lots of activity for light dark matter detection
- 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

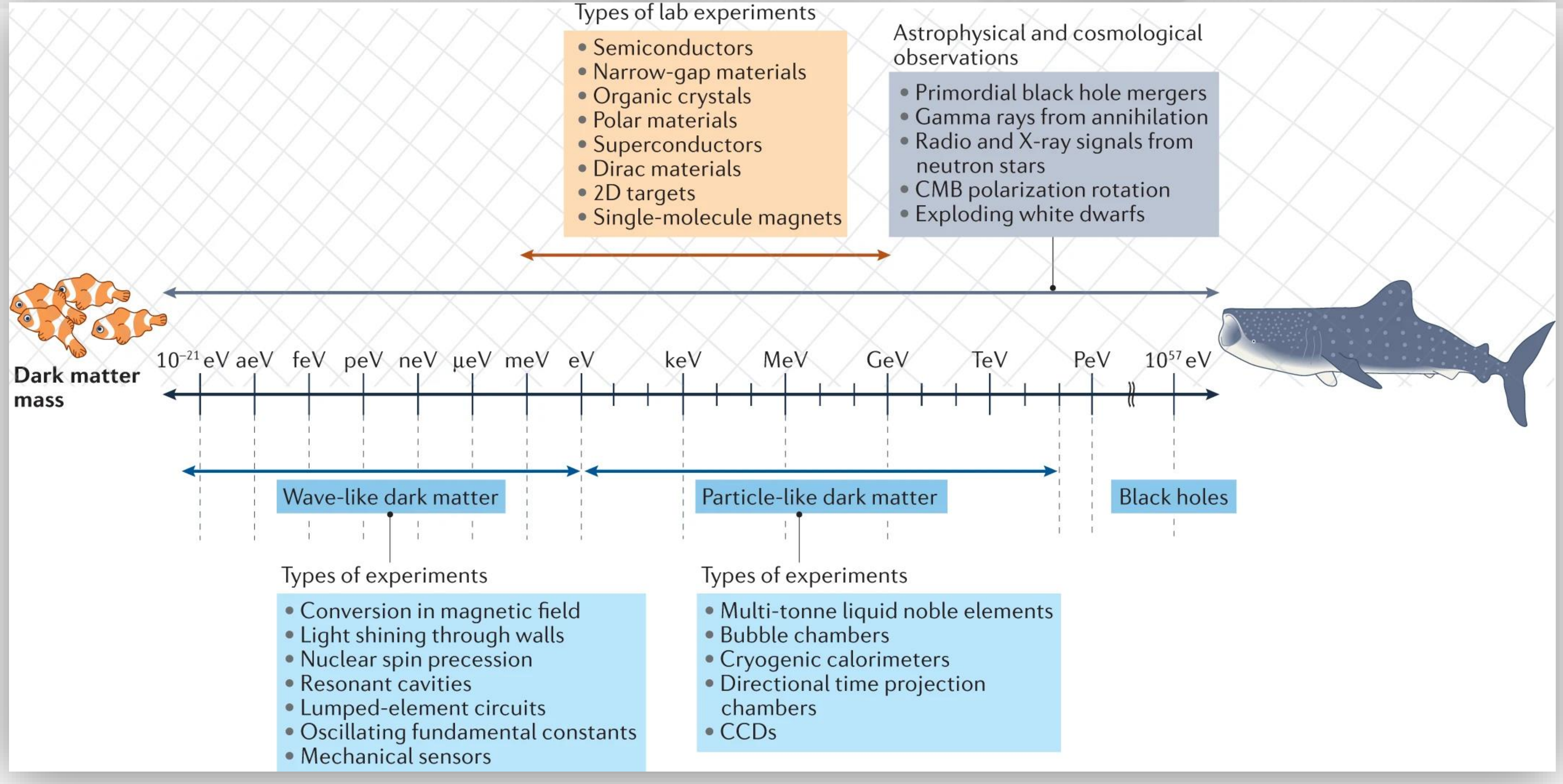


Image: **YH** et al, Nature Rev. Phys. 2022

Prospects

Particle physics / condensed matter / material science / AMO / quantum sensing

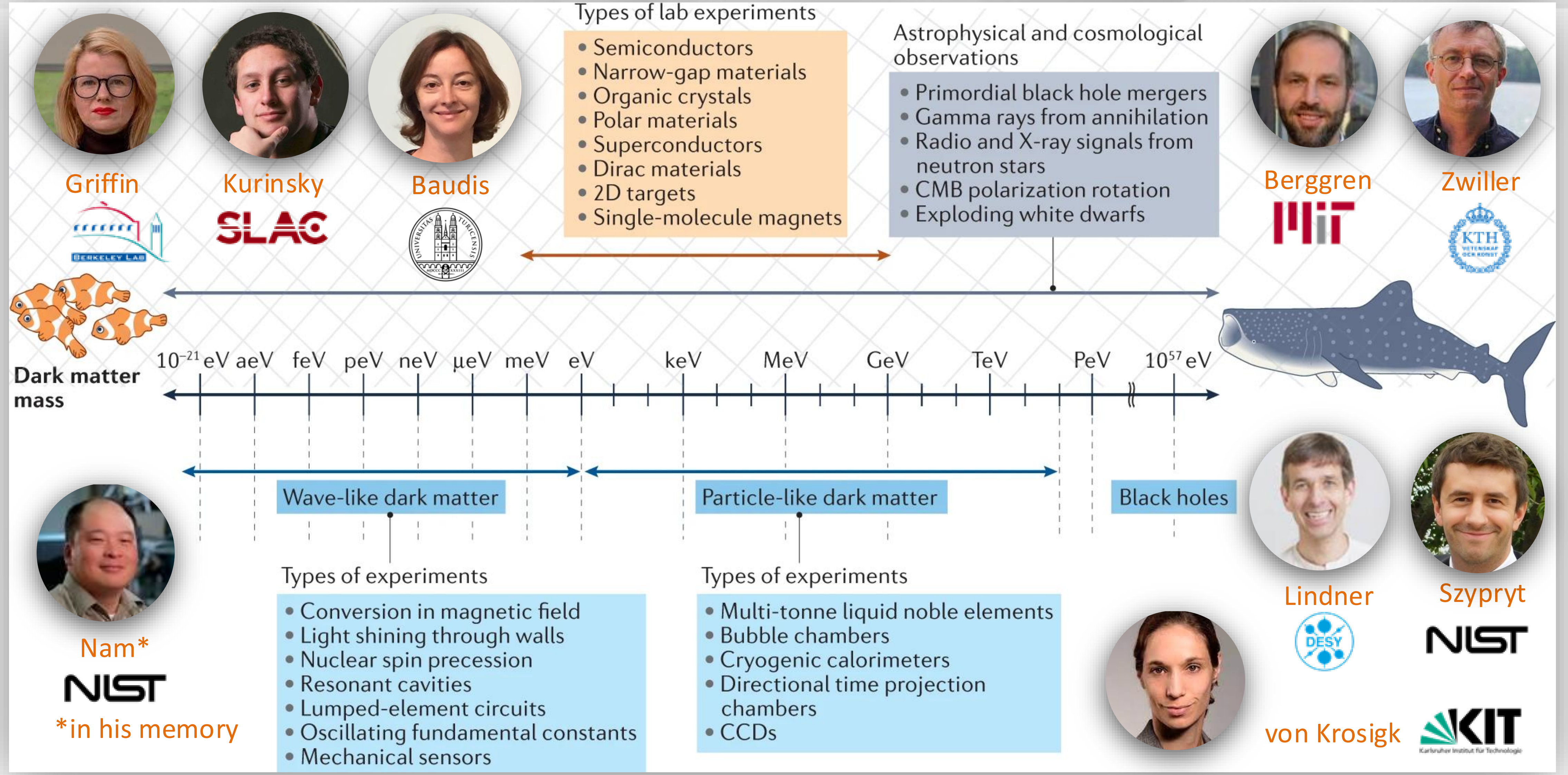


Image: **YH** et al, Nature Rev. Phys. 2022

If you have any (crazy) new ideas,

please be in touch :-)

Happy happy birthdays