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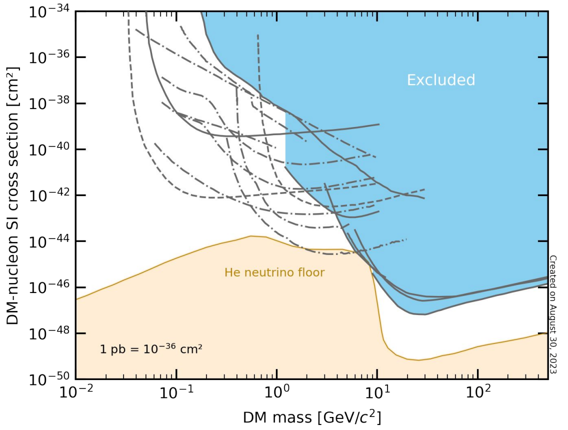
universität freiburg

Light Dark Matter Detection

Invisibles`23 Workshop, Göttingen

Sebastian Lindemann | University of Freiburg | August 30, 2023



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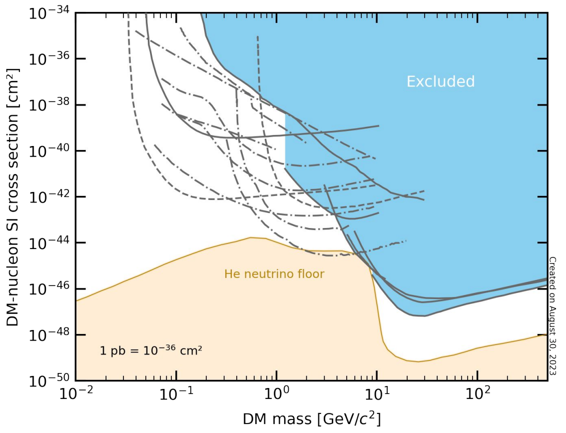
Light Dark Matter *Direct* Detection

Invisibles`23 Workshop, Göttingen



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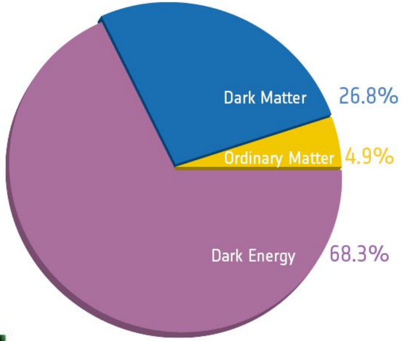
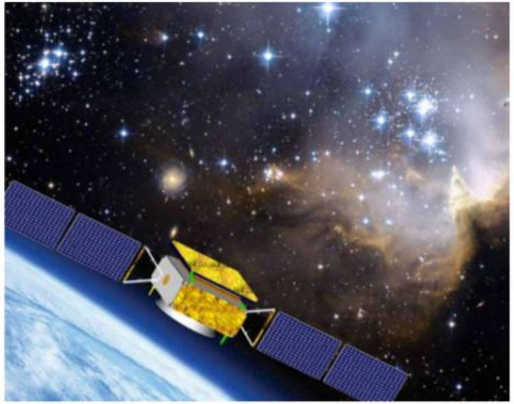
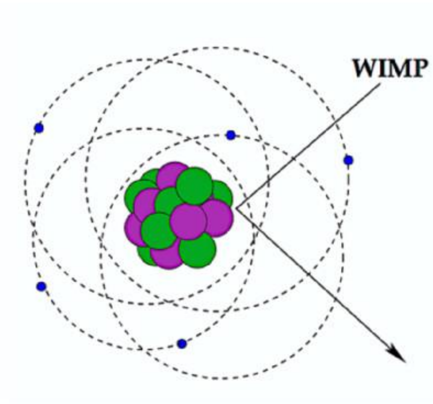
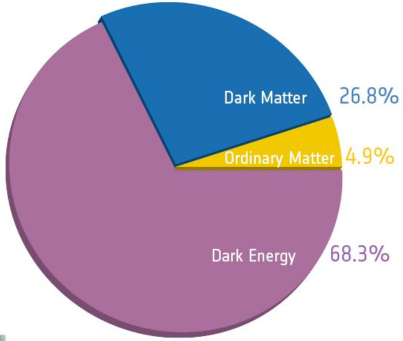
Direct detection of dark matter



Indirect detection	Direct detection	Particle colliders
		
DM annihilation into SM particle	DM scattering off SM particle	Direct or by decay production DM
$\chi\bar{\chi} \to q\bar{q}, \gamma\gamma, \ldots$	$\chi N \to \chi N$	$pp \to \chi\bar{\chi} + X$

Direct detection of dark matter



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	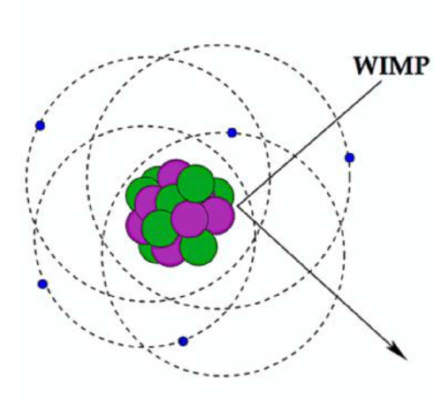	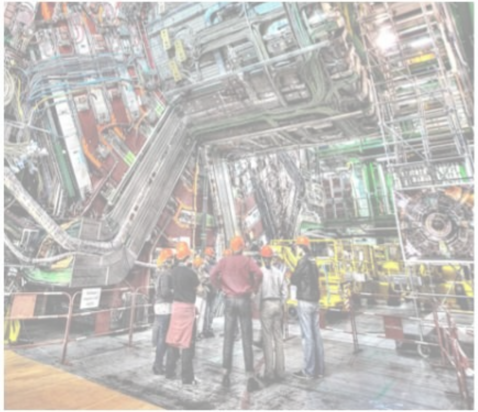
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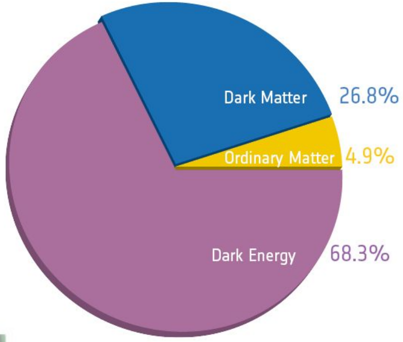

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	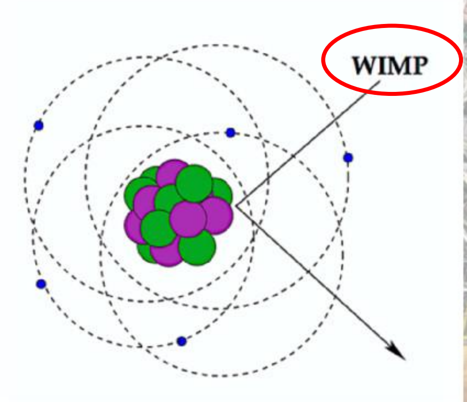	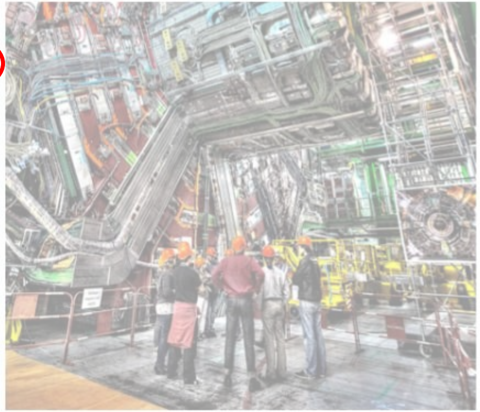
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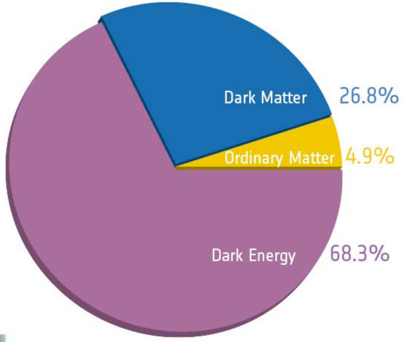
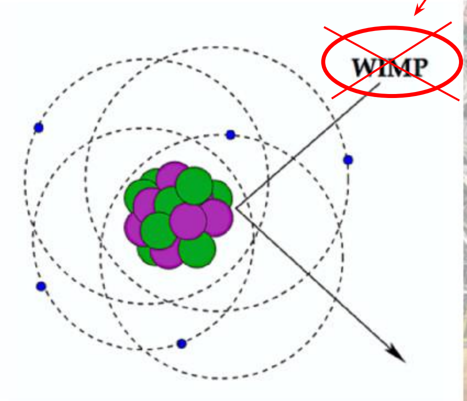
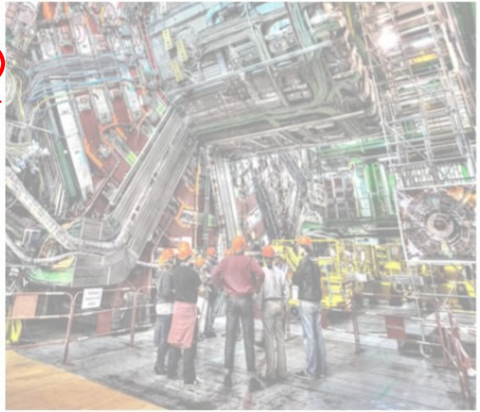
Direct detection of dark matter



Light DM (LDM)

Indirect detection	Direct detection	Particle colliders
		
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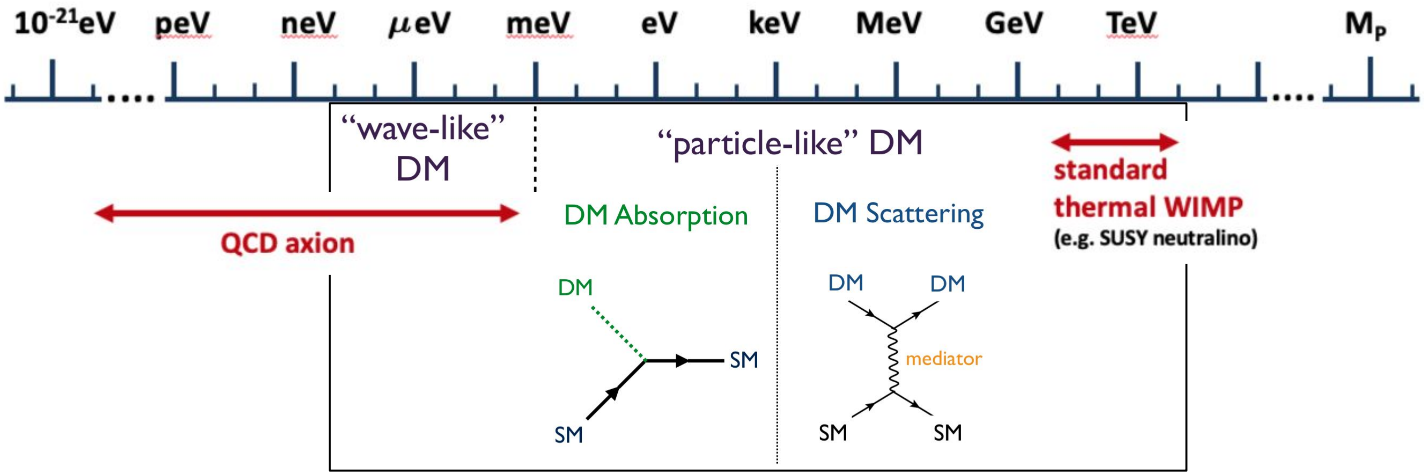
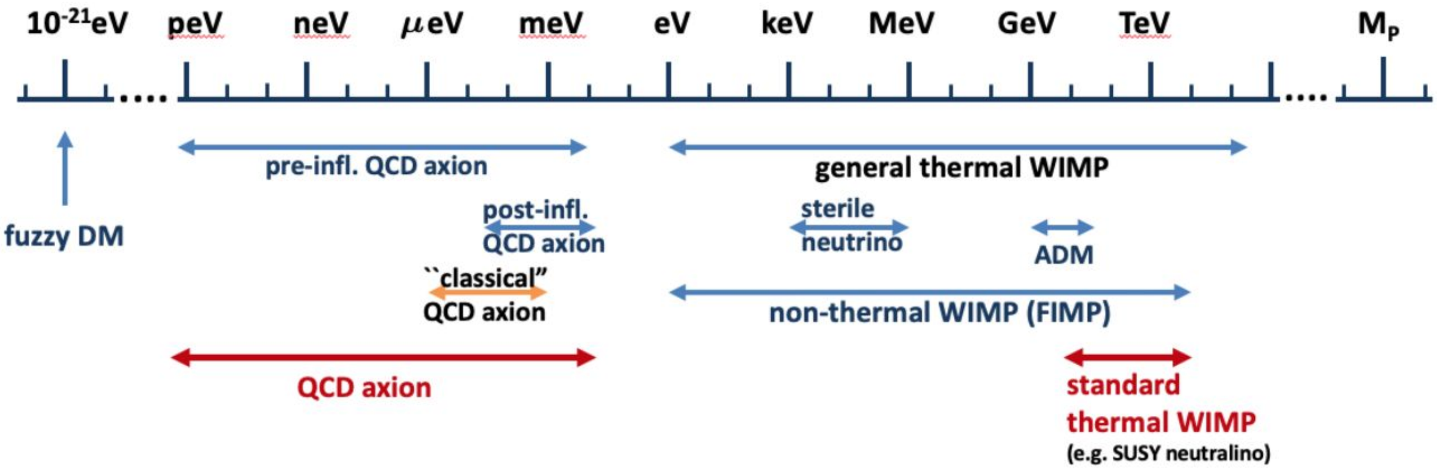
Dark Matter models (beyond the WIMP)



Dark Matter models (beyond the WIMP)

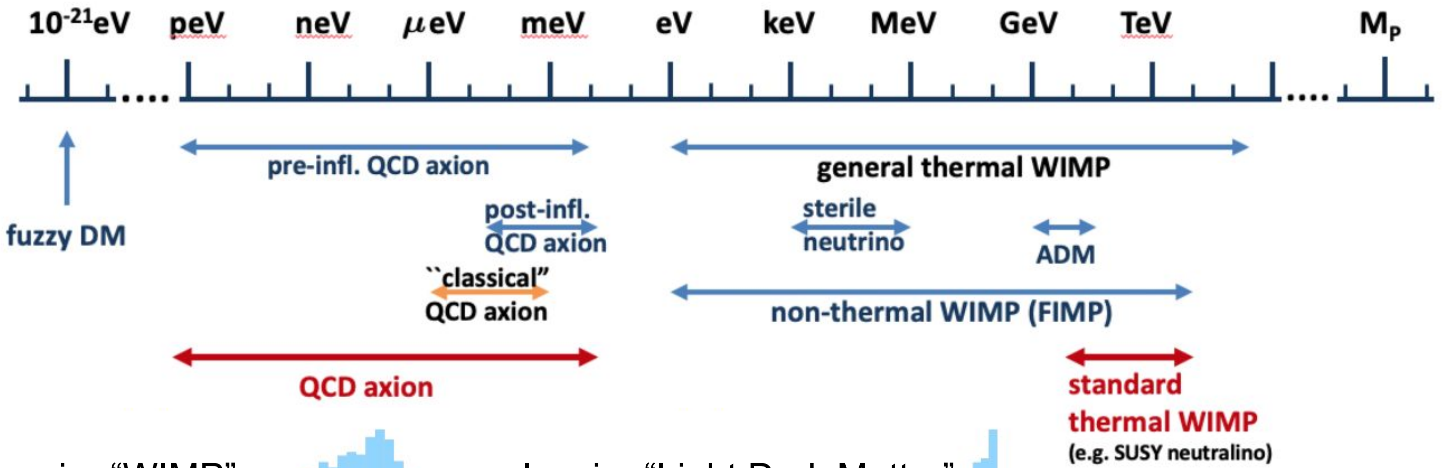


And many more:

- **ELDER,**
- **SIMP,**
- **…**

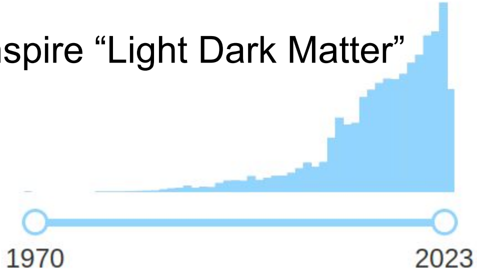
[Rep. Prog. Phys. **85** 056201]

Dark Matter models (beyond the WIMP)



Inspire “WIMP”

Inspire “Light Dark Matter”



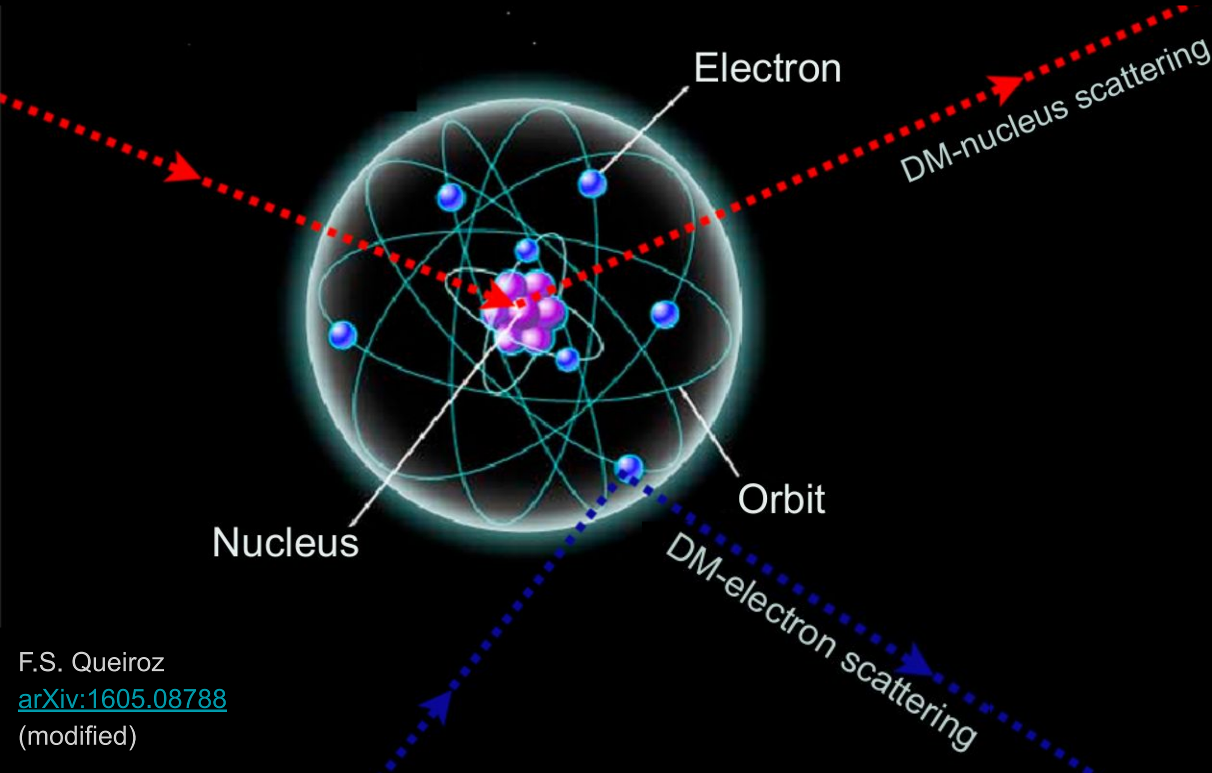
And many more:

- **ELDER,**
- **SIMP,**
- **…**

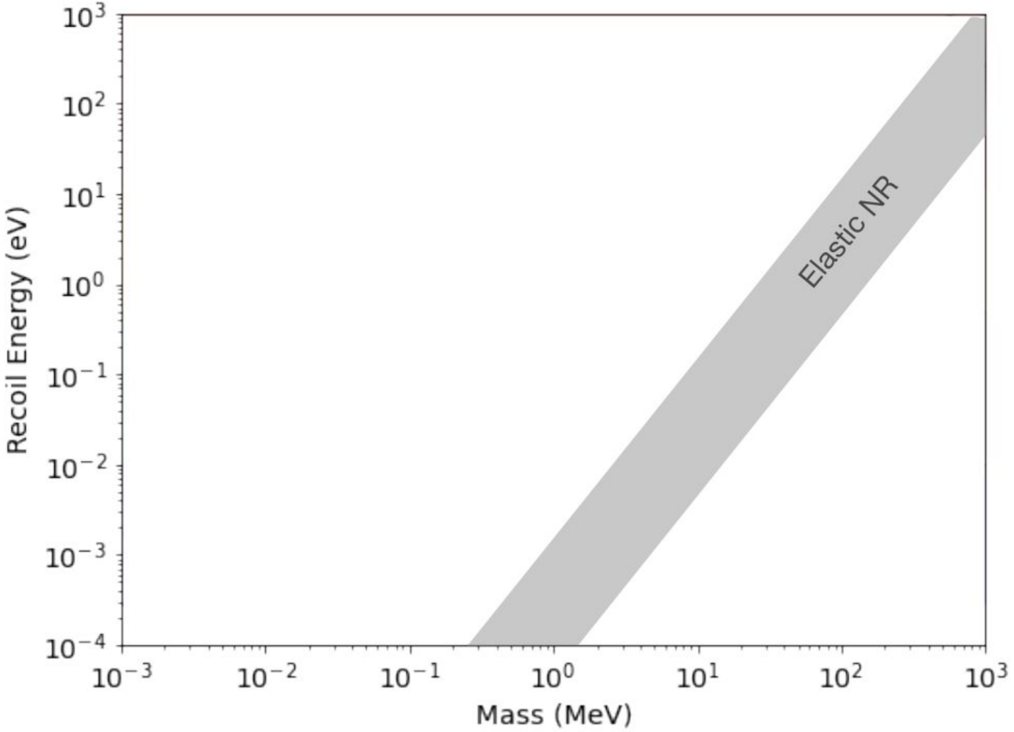
[*Rep. Prog. Phys.* **85** 056201](https://doi.org/)

How to search for LDM?

Basic idea: DM scattering off nucleus or shell electron



F.S. Queiroz
arXiv:1605.08788
(modified)

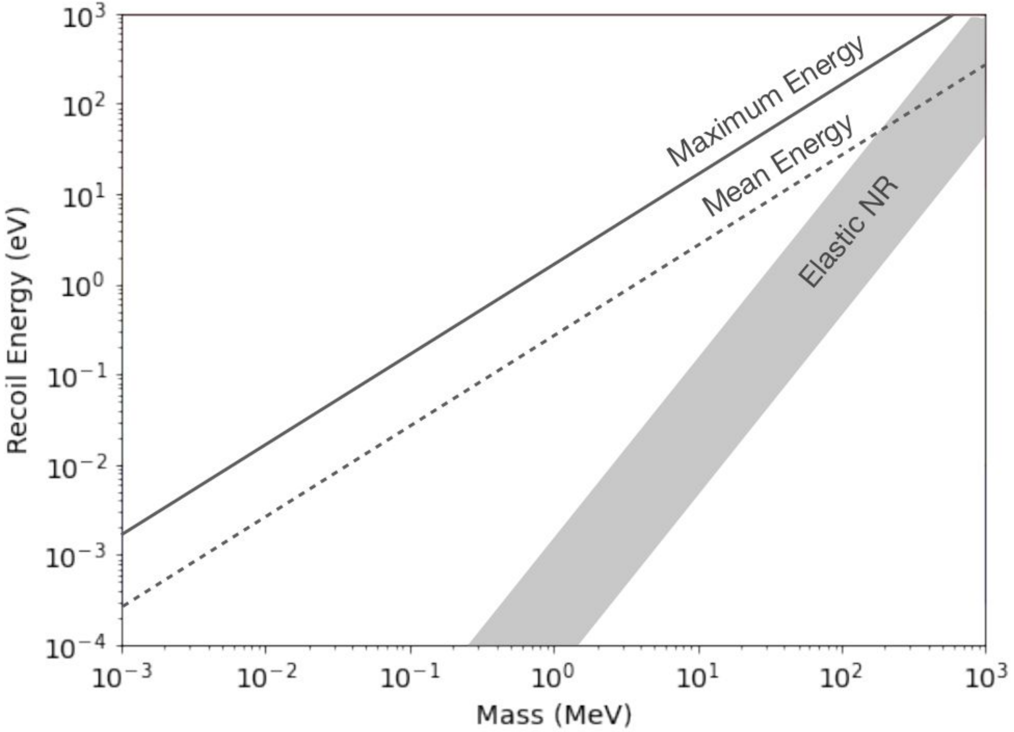


R. Essig, UCLA Dark Matter 2023

elastic DM-nucleus scattering:

$$E_{\rm NR} = \frac{q^2}{2m_N} \sim 1\ {\rm eV}\left(\frac{m_{\rm DM}}{100\ {\rm MeV}}\right)^2\left(\frac{28\ {\rm GeV}}{m_N}\right)$$

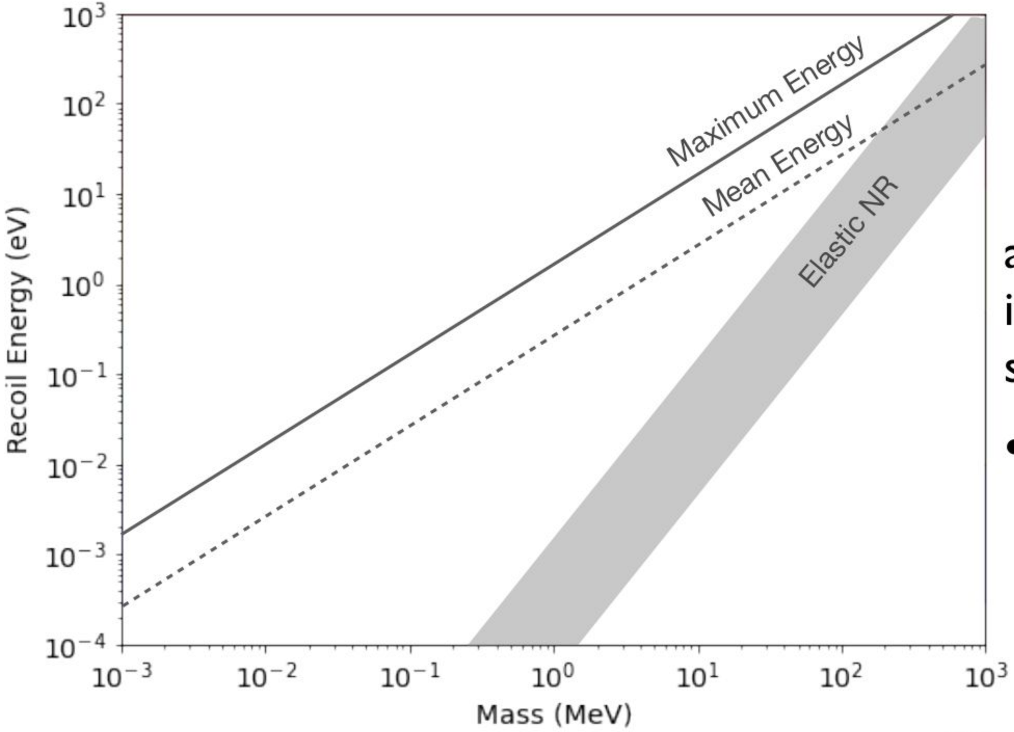
R. Essig, UCLA Dark Matter 2023



DM kinetic energy

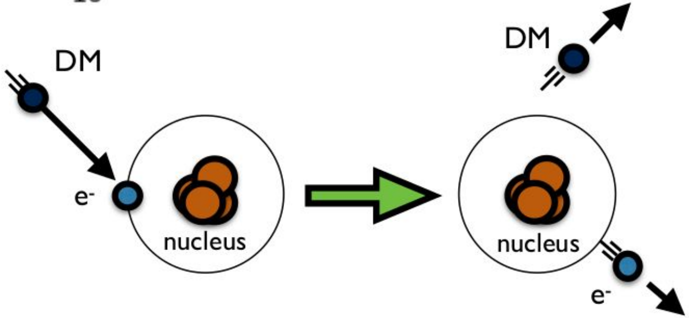
$$E_{\rm kin} = \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 \sim 1 \text{ eV} \left(\frac{m_{\rm DM}}{1 \text{ MeV}} \right)$$

R. Essig, UCLA Dark Matter 2023

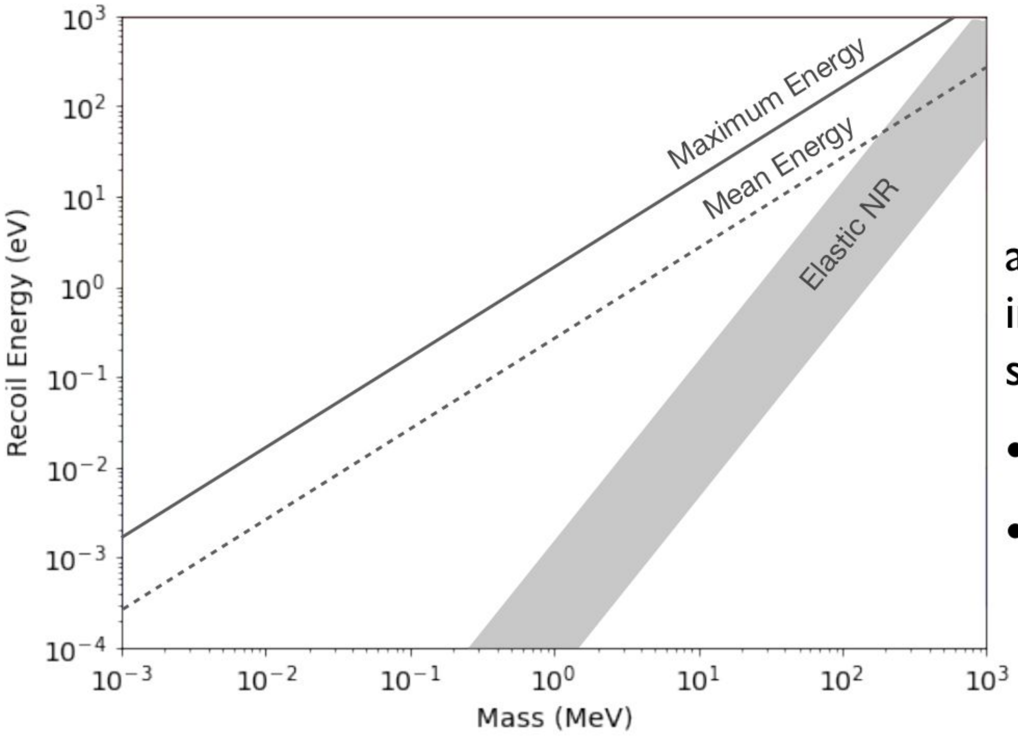


accessible through <u>inelastic</u> interactions (sometimes w/ suppressed rate), e.g.:

- DM-e scattering

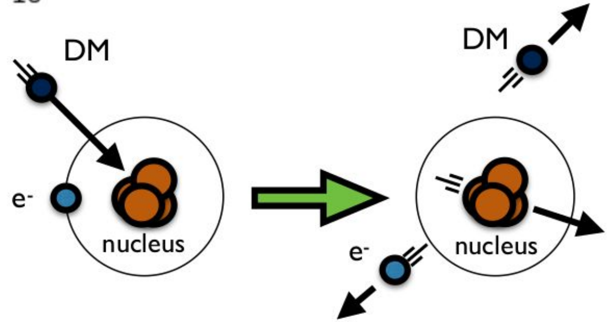


R. Essig, UCLA Dark Matter 2023

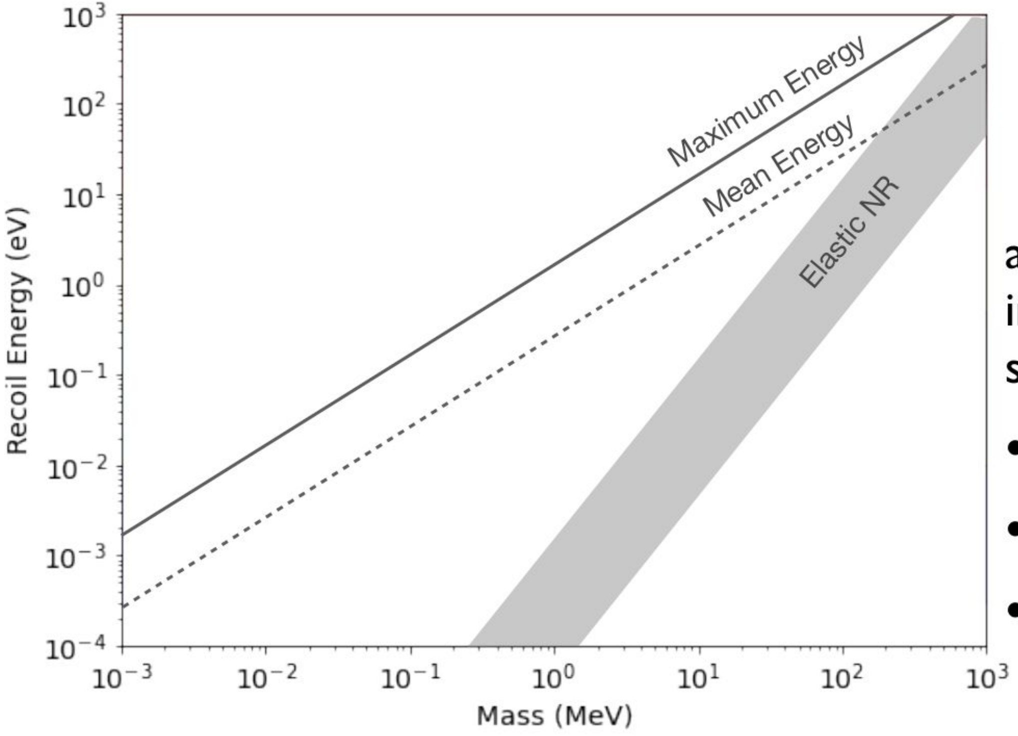


accessible through <u>inelastic</u> interactions (sometimes w/ suppressed rate), e.g.:

- DM-e scattering
- DM-N scattering w/ Migdal

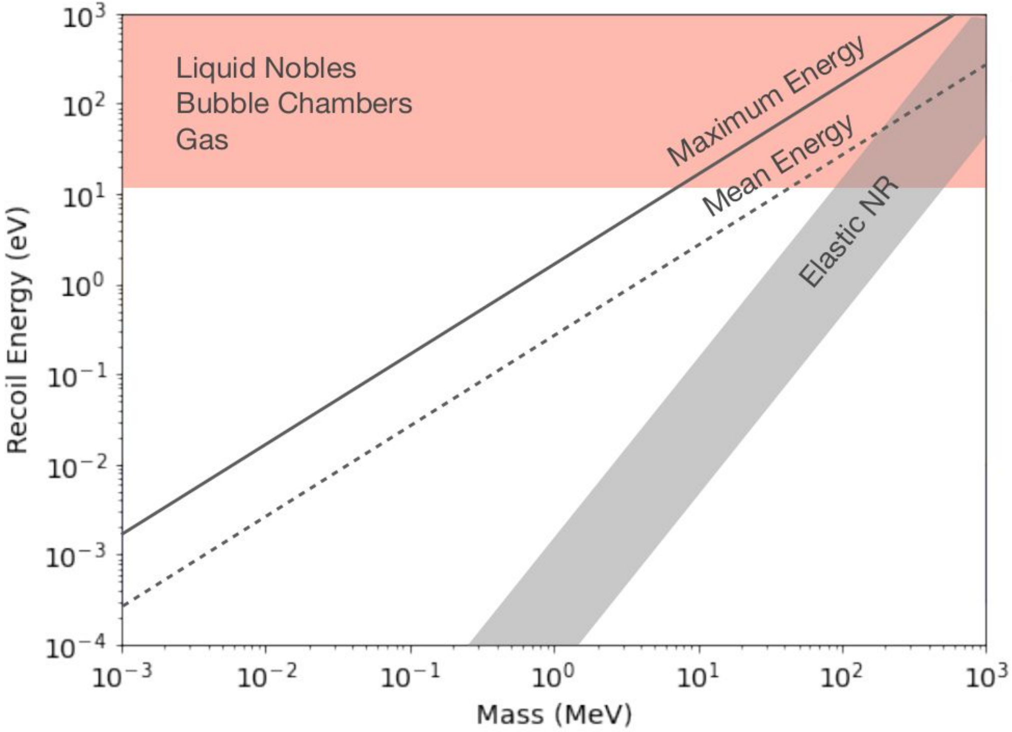


R. Essig, UCLA Dark Matter 2023



accessible through <u>inelastic</u> interactions (sometimes w/ suppressed rate), e.g.:

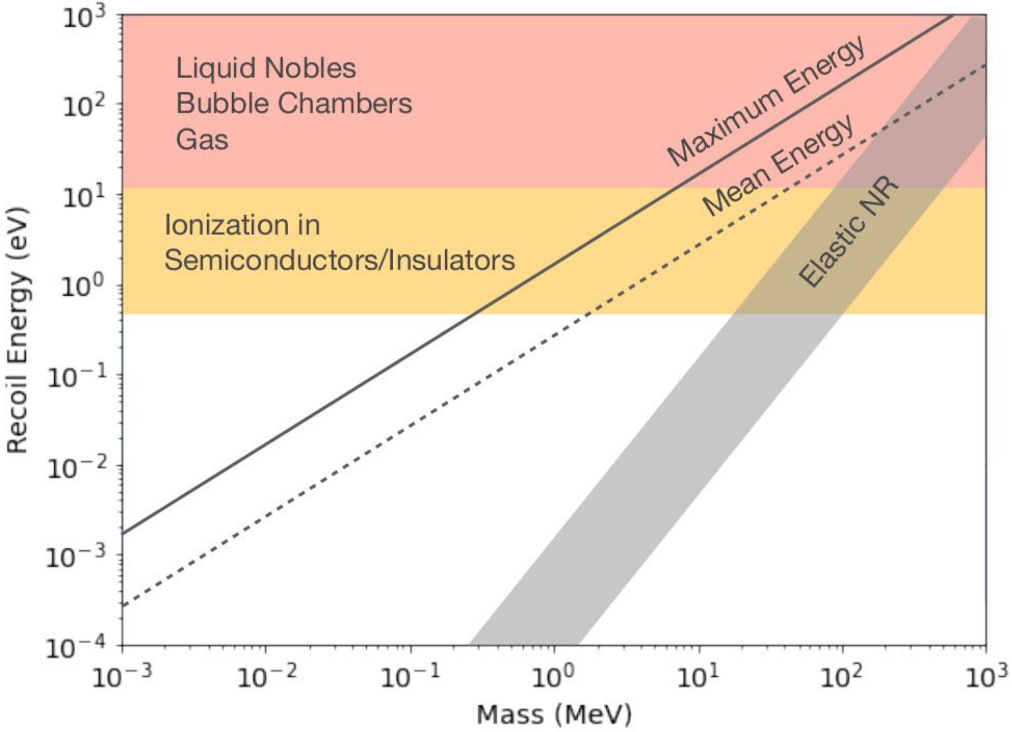
- DM-e scattering
- DM-N scattering w/ Migdal
- DM scattering w/ collective modes (e.g. phonons, magnons)



$\Delta E \sim 10$ eV

e.g. Xe, Ar, He

R. Essig, UCLA Dark Matter 2023



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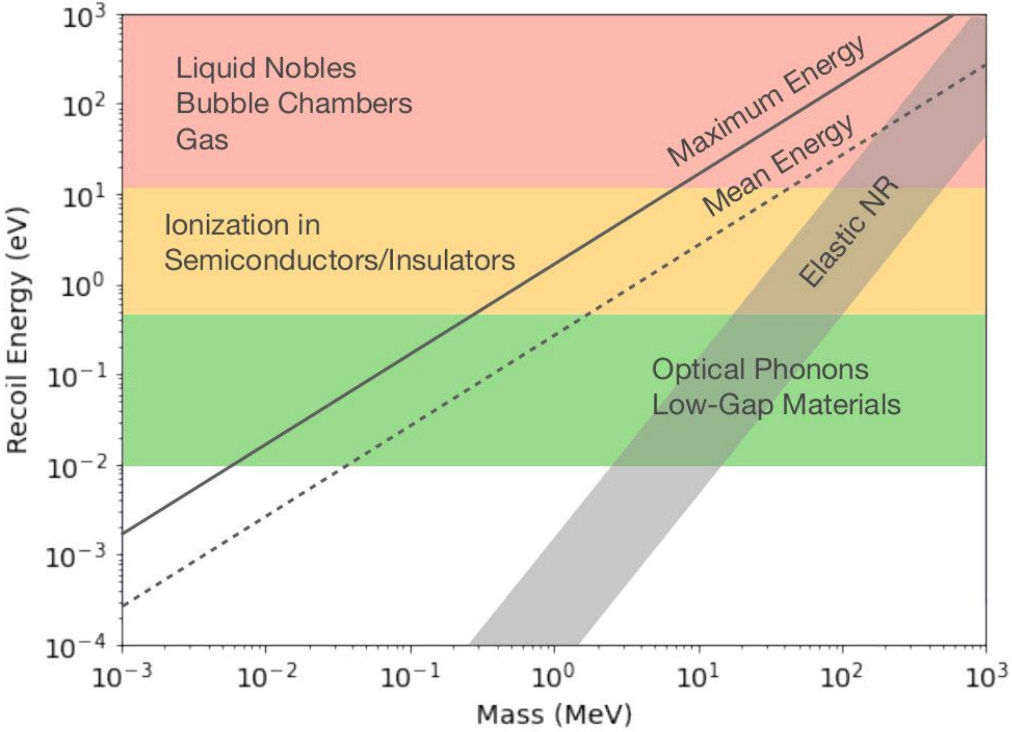
$\Delta E \sim 1$ eV

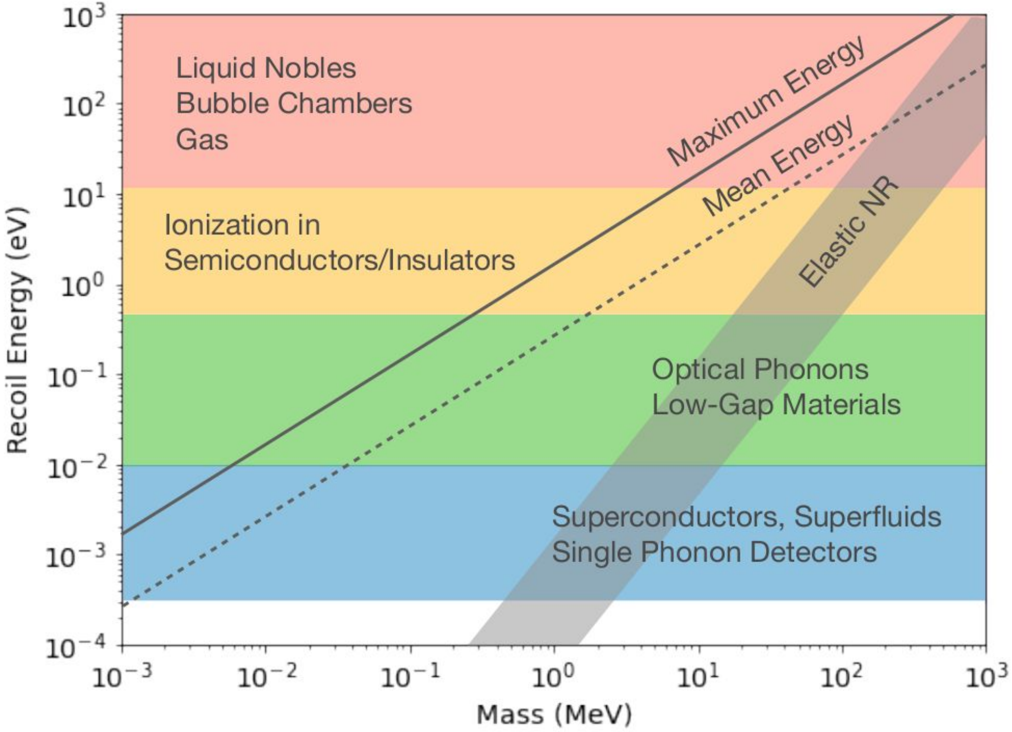
e.g. Si, Ge, GaAs, diamond, Quantum Dots, organic scintillators…

R. Essig, UCLA Dark Matter 2023



$\Delta E \sim 10 - 100$ meV
e.g. GaAs, sapphire, Dirac materials, doped s/c, …

R. Essig, UCLA Dark Matter 2023

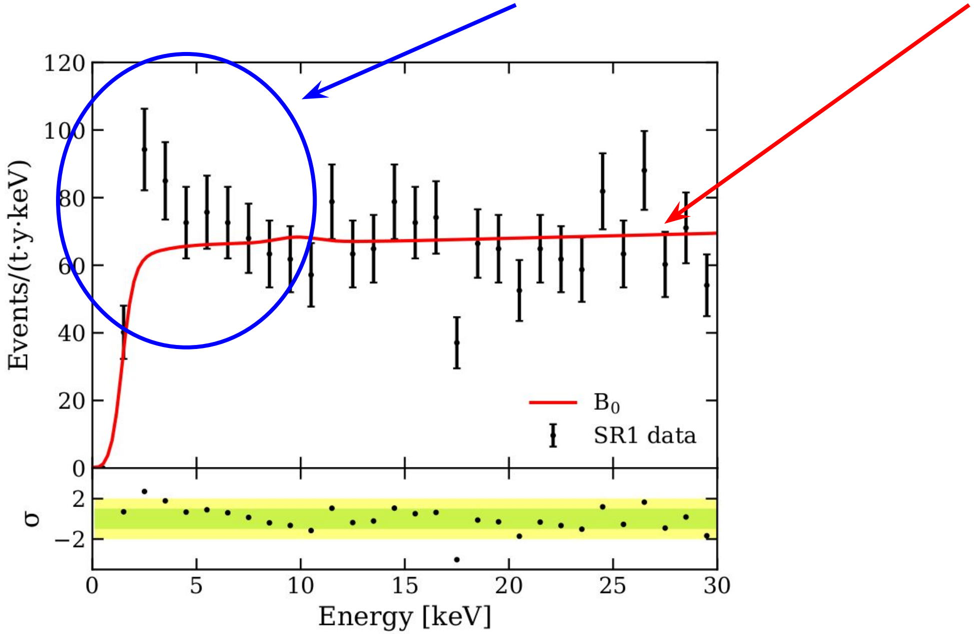


$\Delta E \sim 1$ meV

e.g. superfluids,
superconductors

Principle concepts

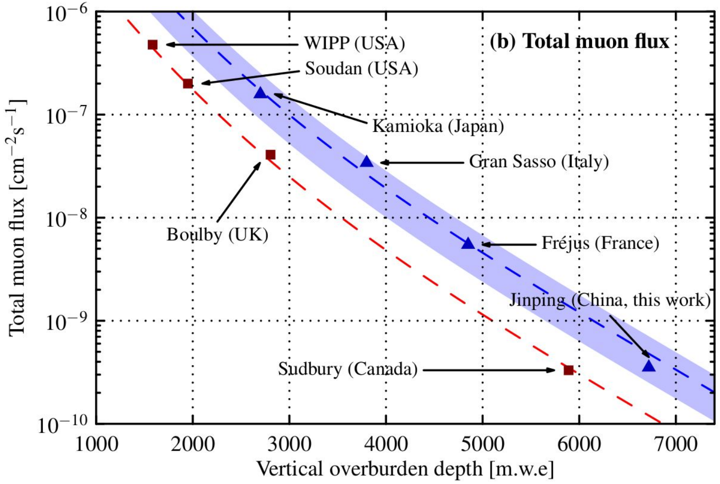
Search for excess events above background prediction…



e.g., XENON1T low-ER excess arXiv:2006.09721
(excluded by XENONnT arXiv:2207.11330)

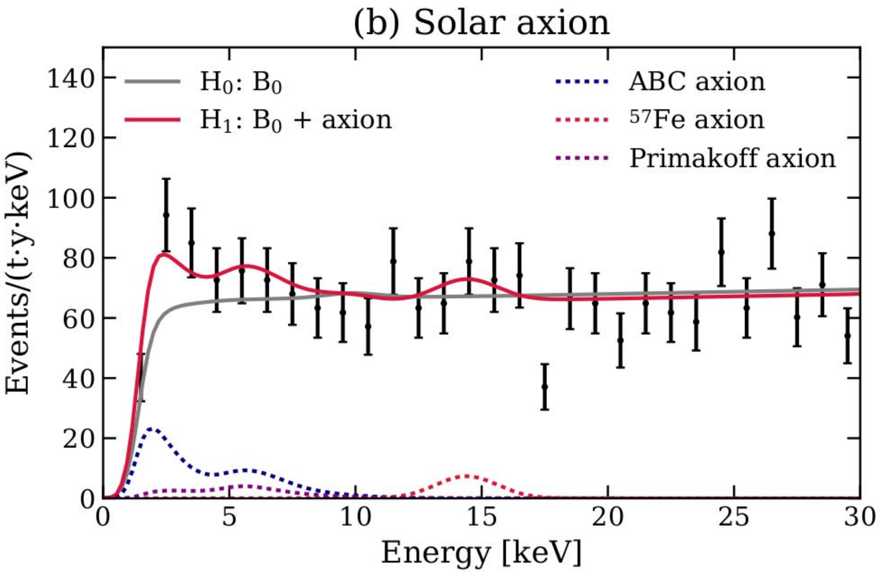
Typical background mitigation strategies:

- radiopurity control,
- deep underground labs

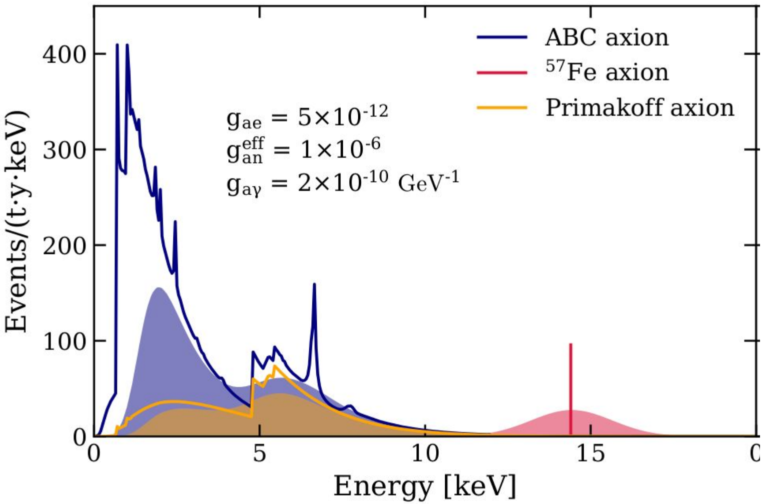


arXiv:2007.15925

… fit your favorite models …

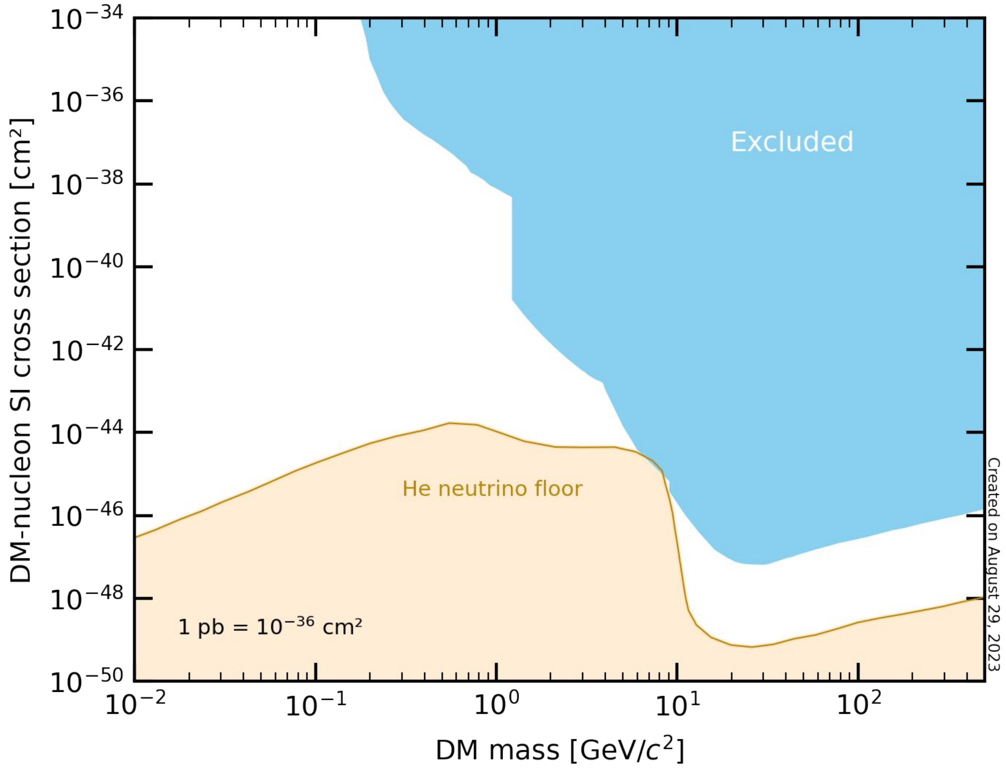


fit



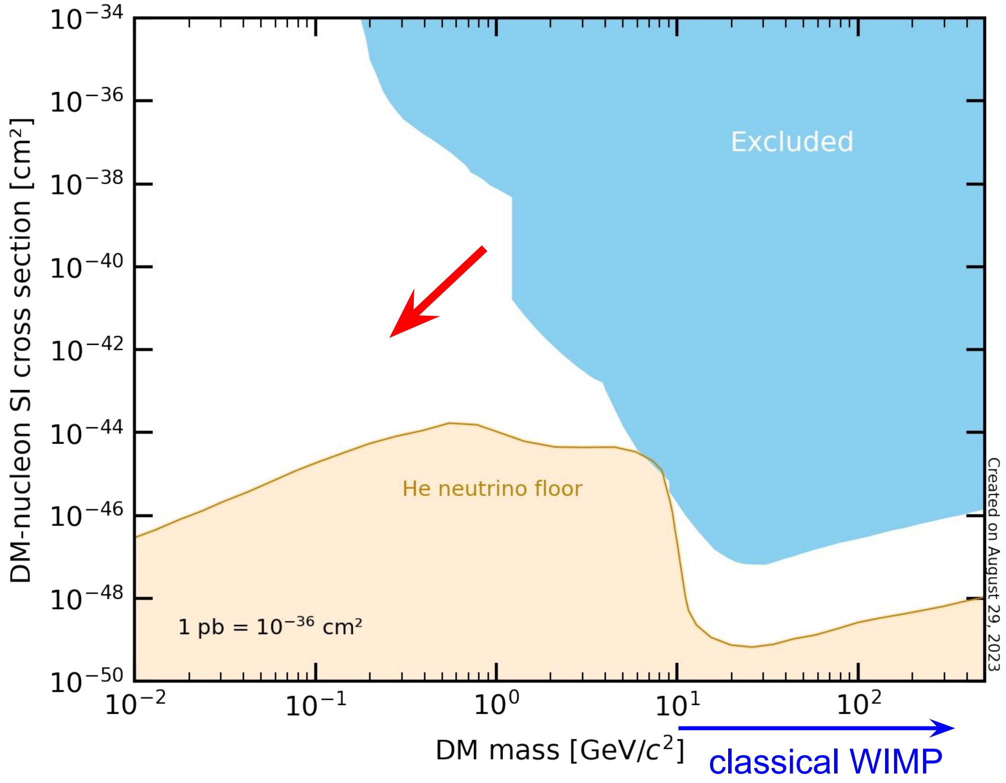
e.g., XENON1T low-ER excess arXiv:2006.09721
(excluded by XENONnT arXiv:2207.11330)

… and draw exclusion curves.



The direct detection landscape today

… and draw exclusion curves.



The direct detection landscape today

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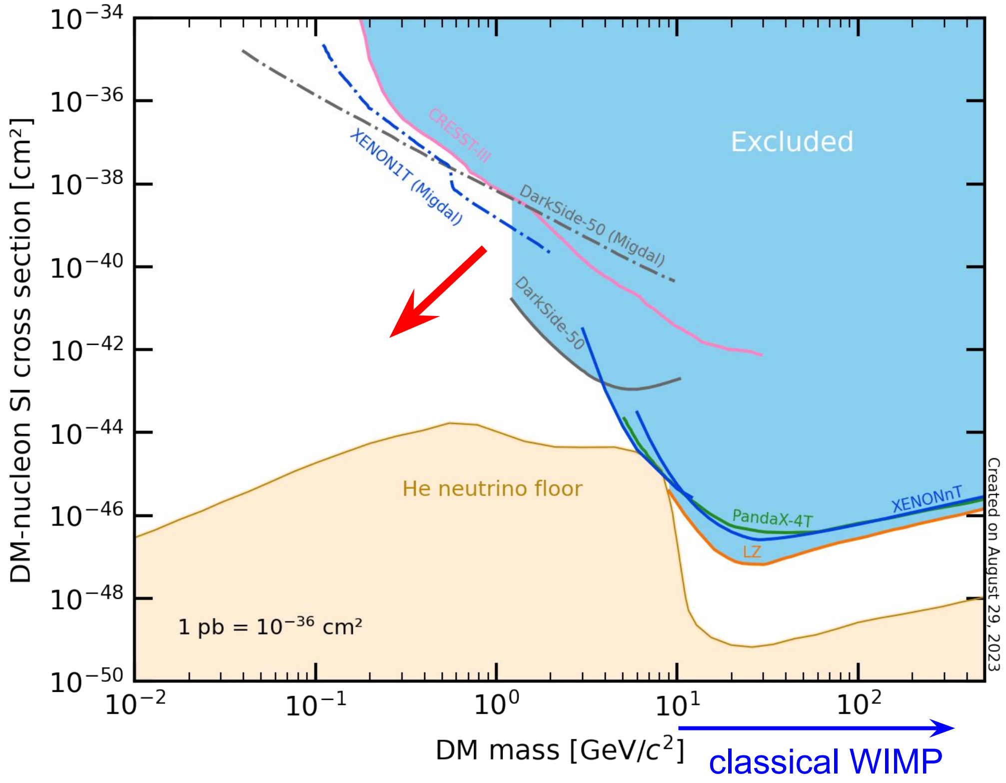
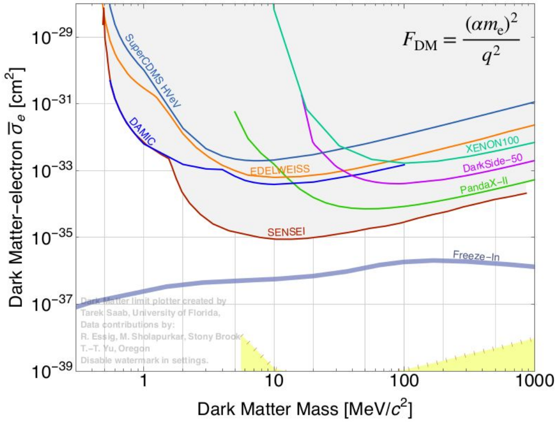


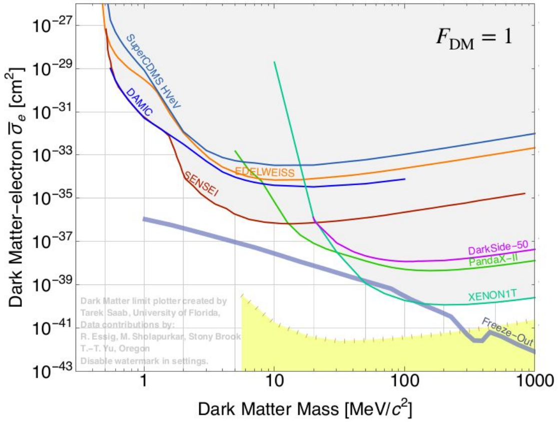
The direct detection landscape today

Disclaimer

To keep it simple, I will focus on **DM-nucleon SI cross-sections** only.

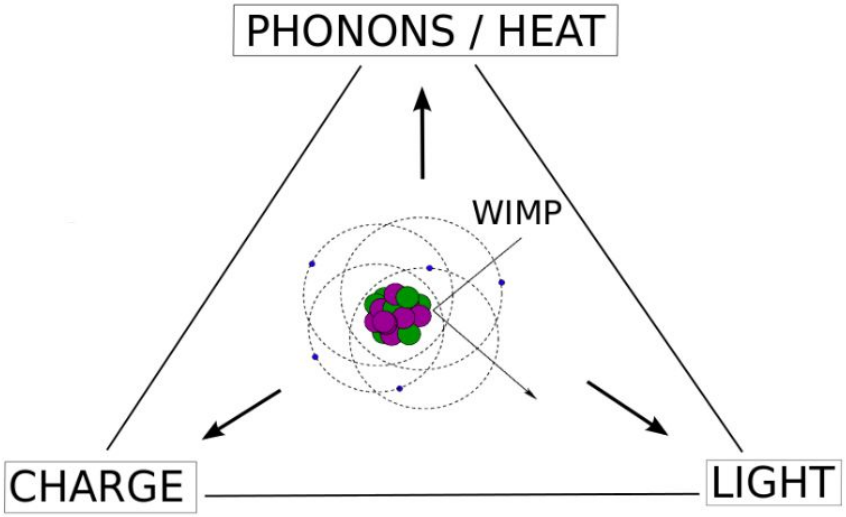
- DM-e scattering is often kinematically favorable,
- absolute numbers are subject to change,
- but overall trend similar,
- and hopefully story clearer.



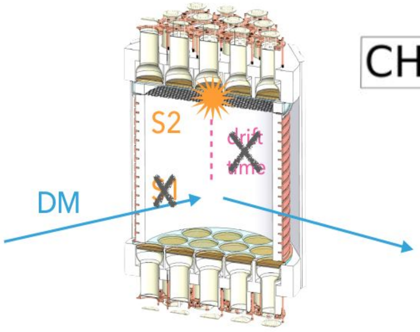


(Liquid) nobles

Liquid-gas TPCs: DarkSide-LowMass



Low Mass Search
Low Energy Events



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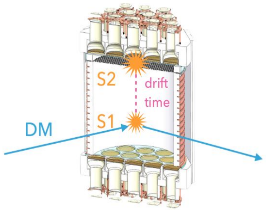
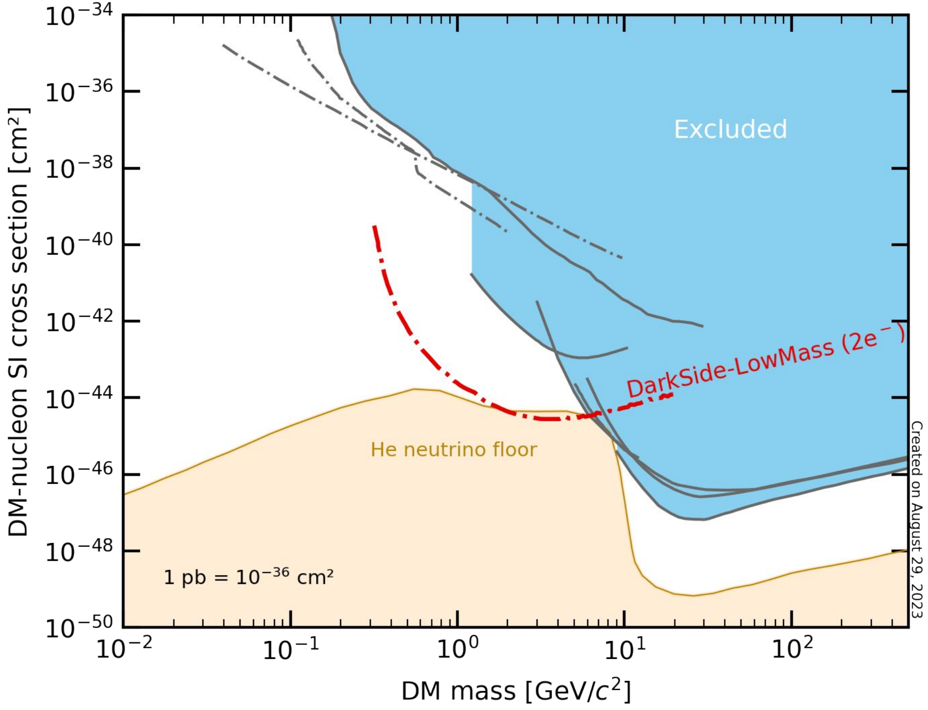
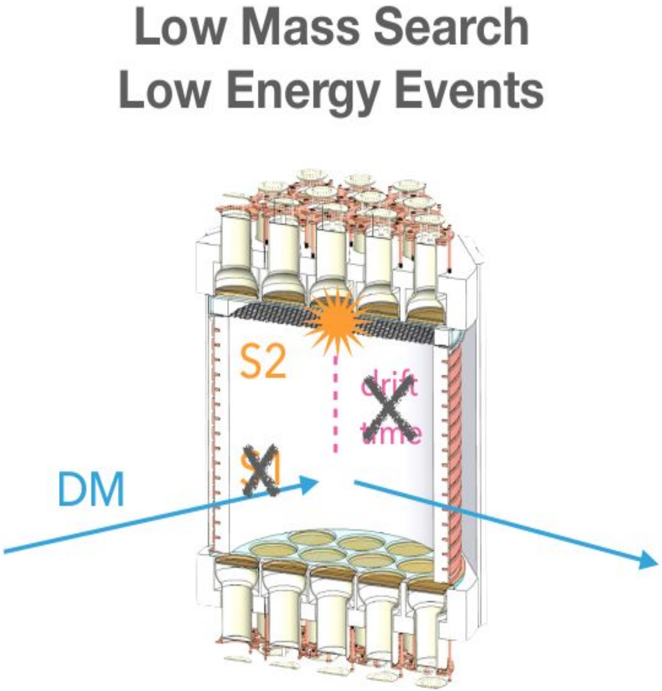


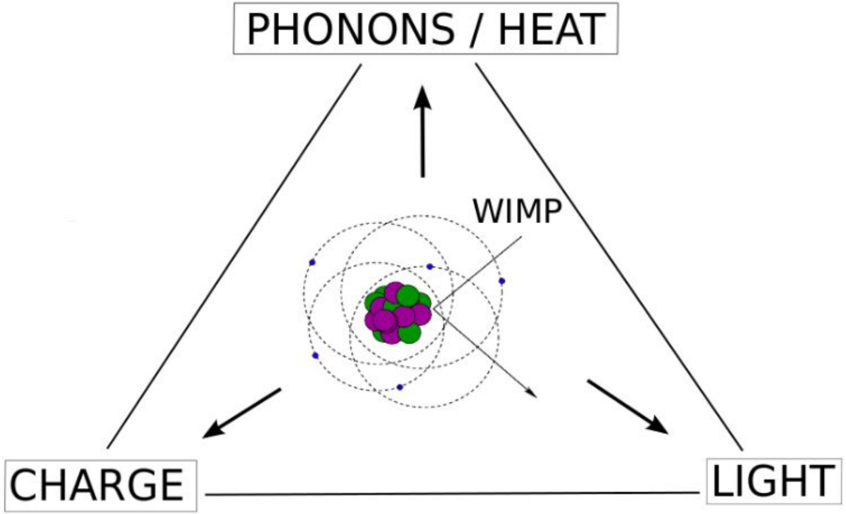
Liquid-gas TPCs: DarkSide-LowMass

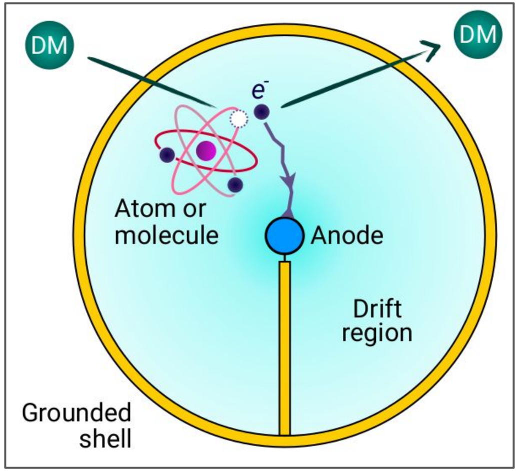
Phys. Rev. D 107, 112006



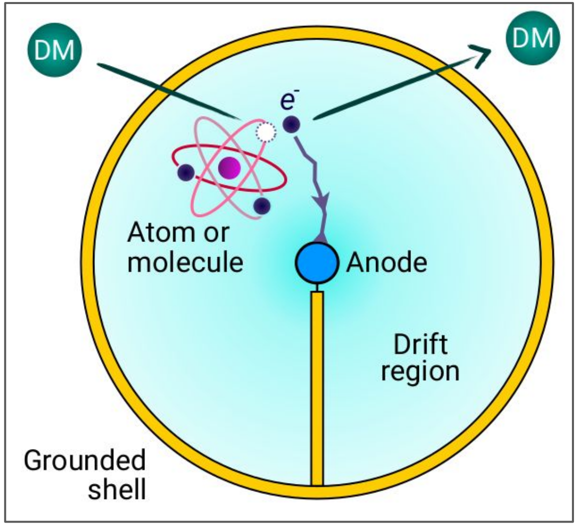


Gas spherical proportional counters: NEWS-G

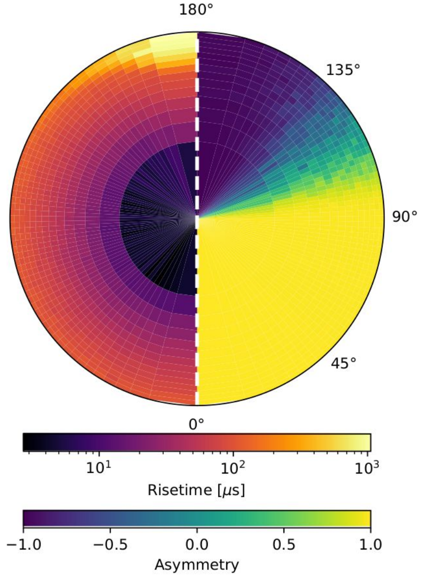




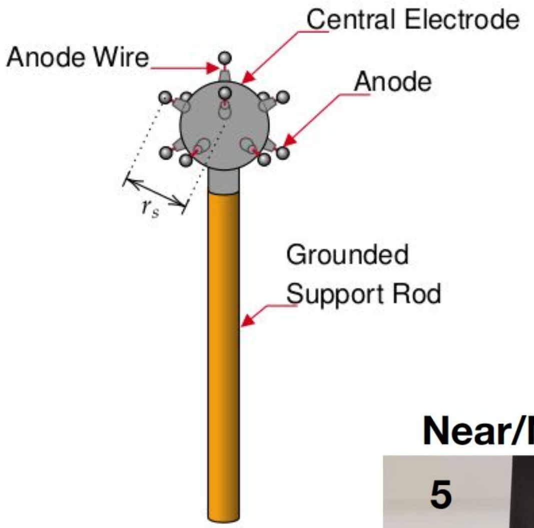
Gas spherical proportional counters: NEWS-G



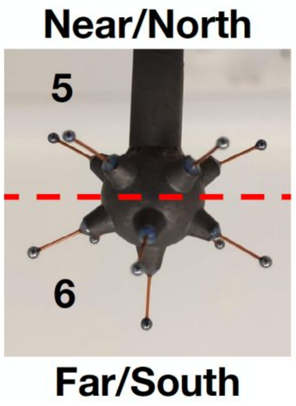
- Lowest surface to volume ratio
- Light and variable target
- Pulse-shape (Risetime and Asymmetry):
  - Event classification
  - Position reconstruction



Gas spherical proportional counters: NEWS-G



ACHINOS
anode design



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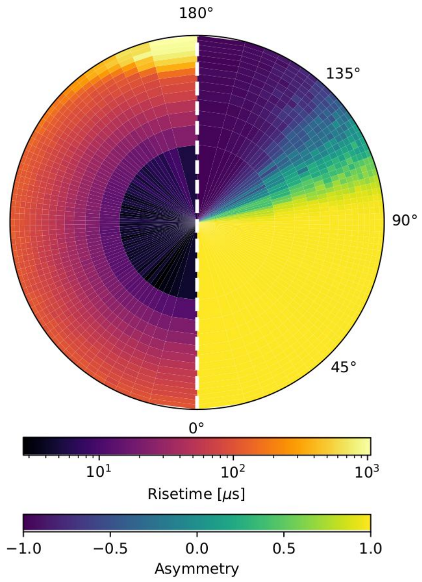
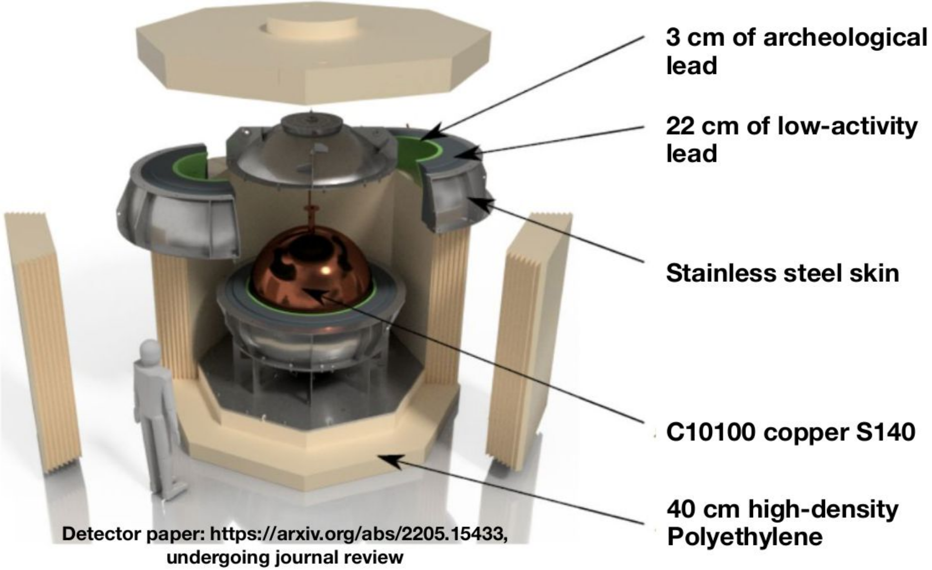


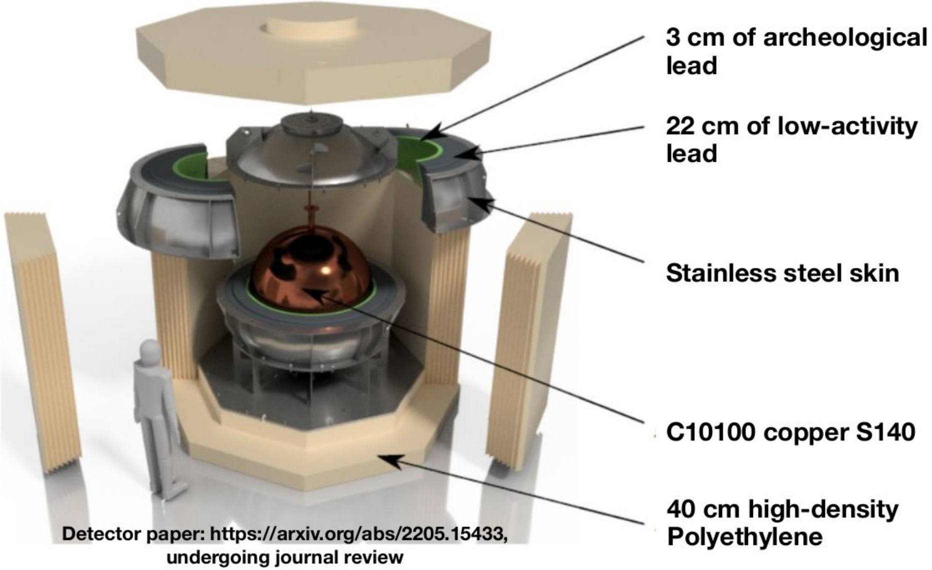
Gas spherical proportional counters: NEWS-G

S140 “SNOWGLOBE” taking data at SNOWLAB since 2022

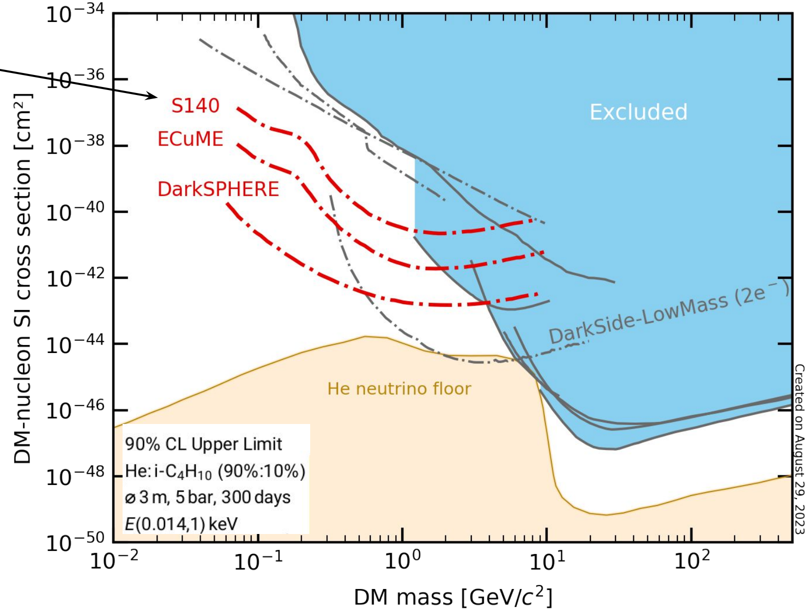


Gas spherical proportional counters: NEWS-G

S140 “SNOWGLOBE” taking data at SNOWLAB since 2022



arXiv:2301.05183

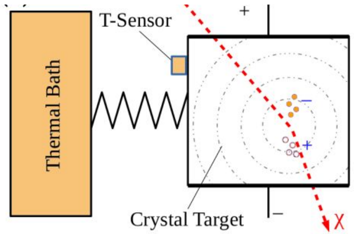


Semiconductors

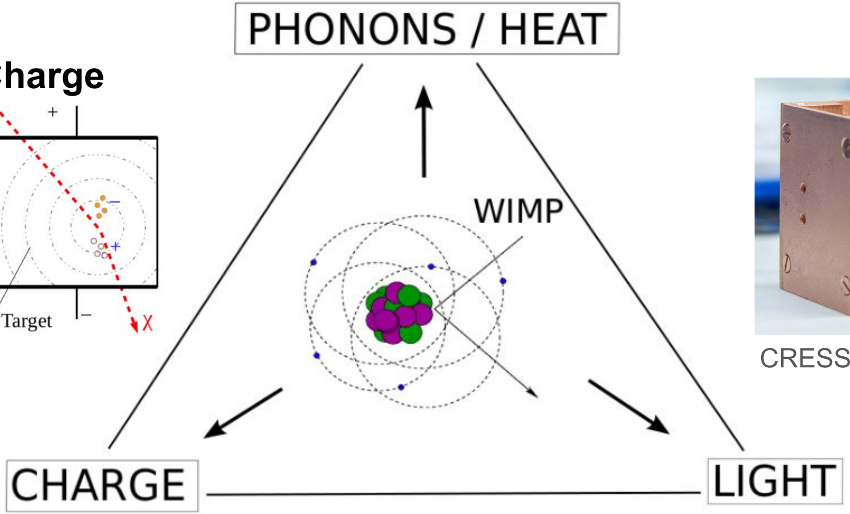
Cryogenic Bolometers

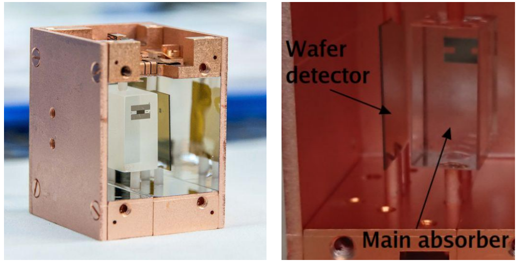
SuperCDMS, EDELWEISS, CRESST

Heat + Charge



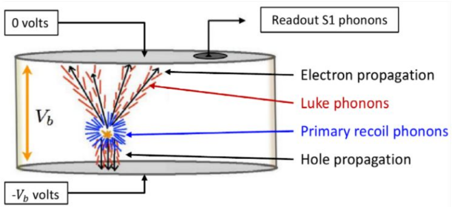
SuperCDMS
EDELWEISS





CRESST (new results @TAUP'23)

~~Heat~~ + Charge



Lite/HV-mode:

Charge mediated phonon amplification
(Neganov-Trofimov-Luke Effect)

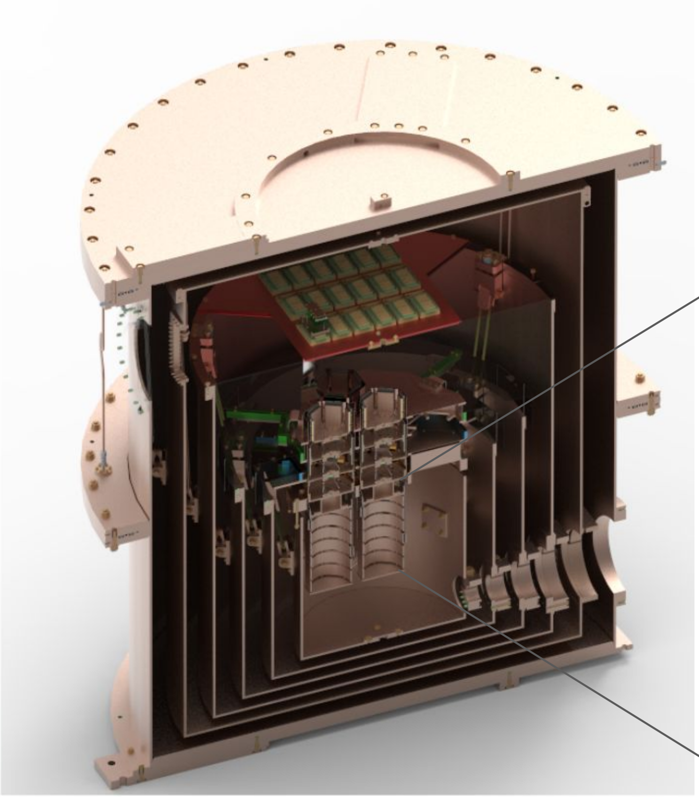
SuperCDMS @ SNOLAB

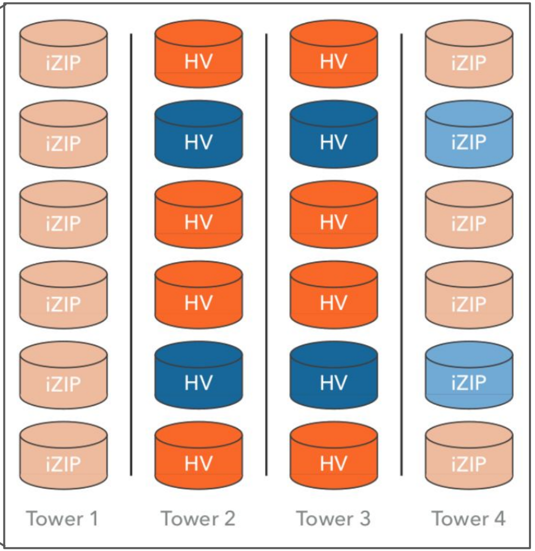
iZIP towers:

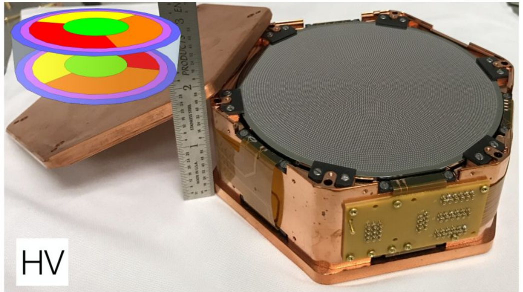
10 Ge + 2 Si crystals
low background

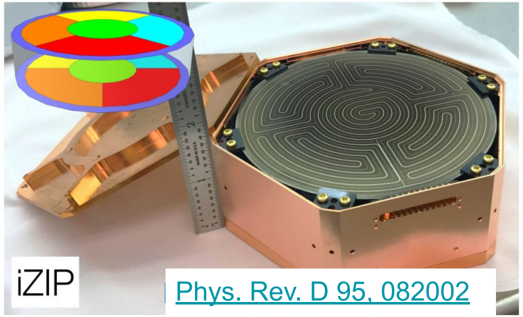
HV towers:

8 Ge + 4 Si crystals
low threshold



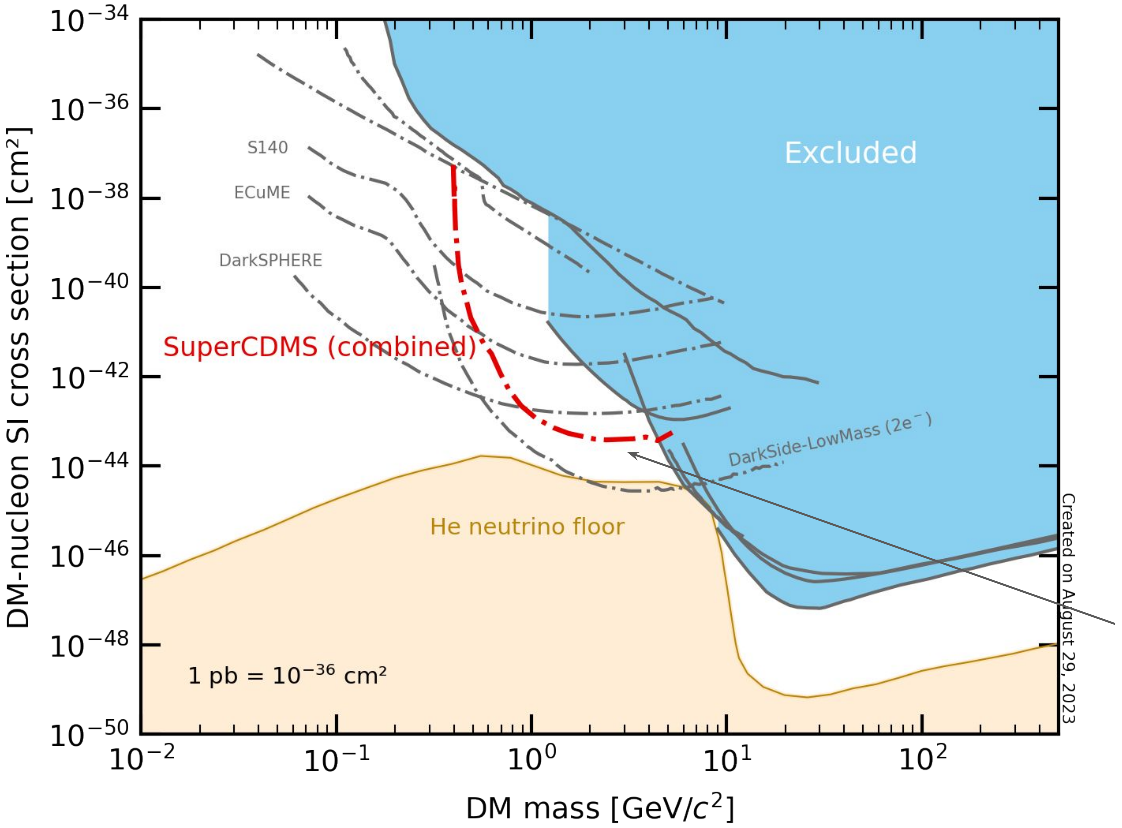


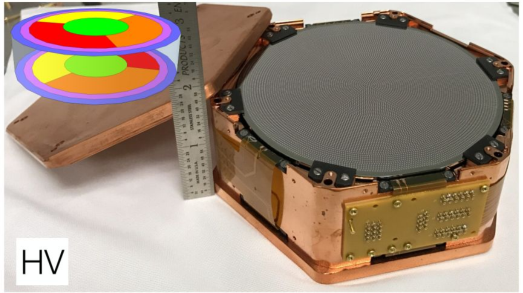


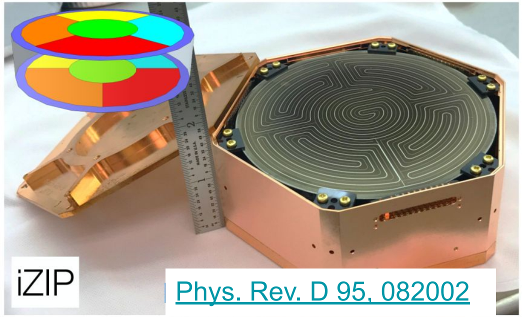


Phys. Rev. D 95, 082002

SuperCDMS @ SNOLAB





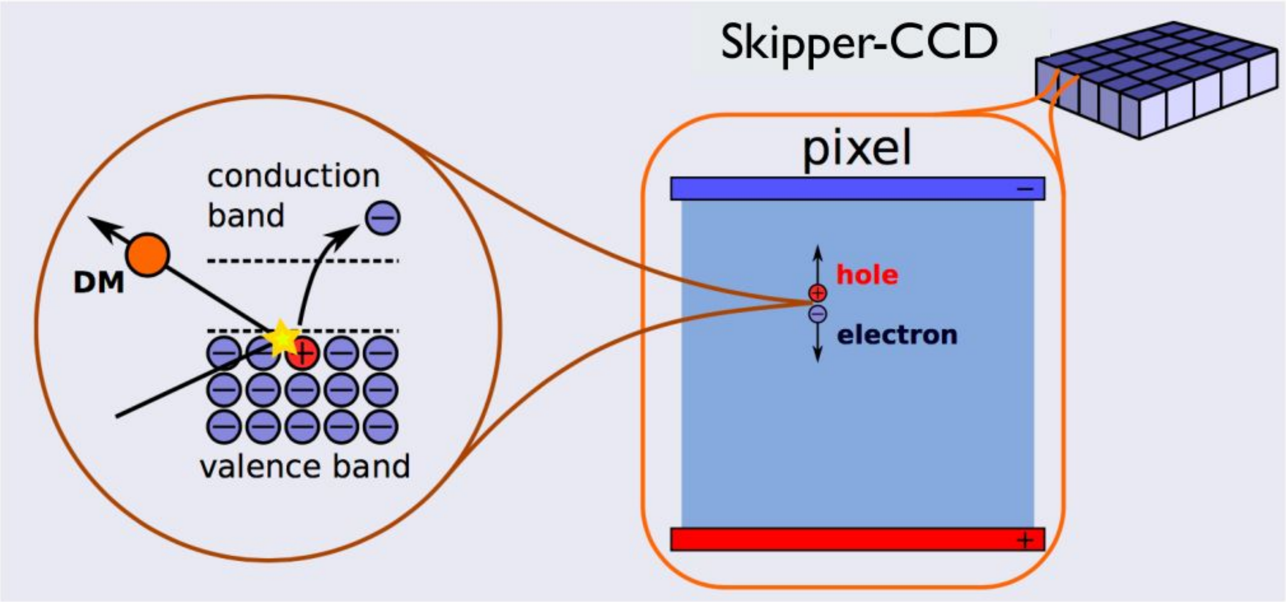


[Phys. Rev. D 95, 082002]

Start data taking 2024

Skipper-CCDs

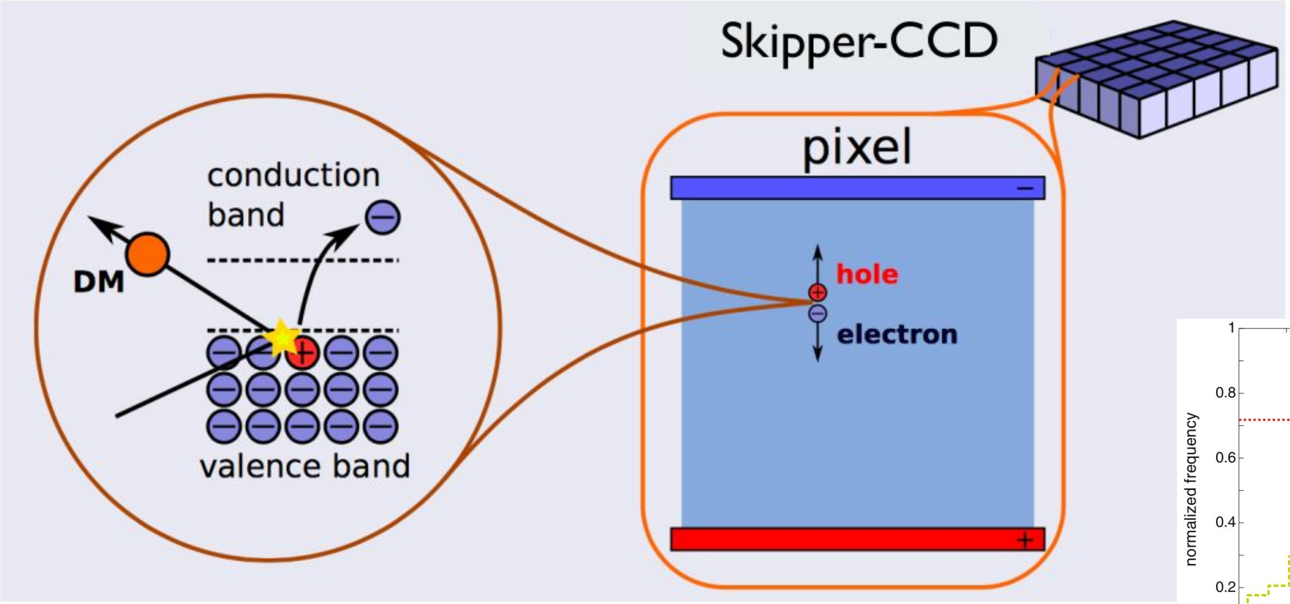
SENSEI, DAMIC, OSCURA



DM would create one or a few electrons in a pixel

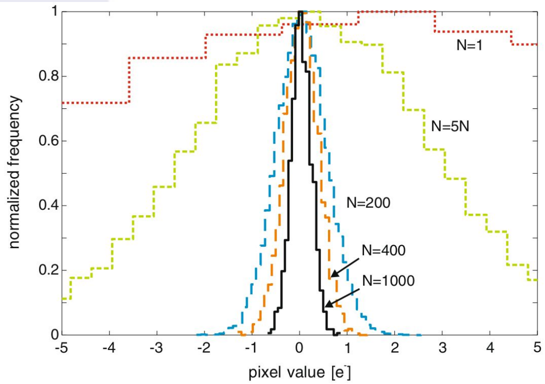
Skipper-CCDs

SENSEI, DAMIC, OSCURA



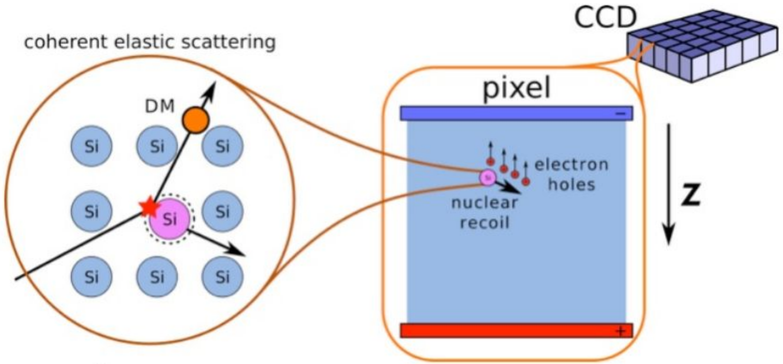
Readout noise < 1e⁻

[Exp Astron 34, 43–64 (2012)]

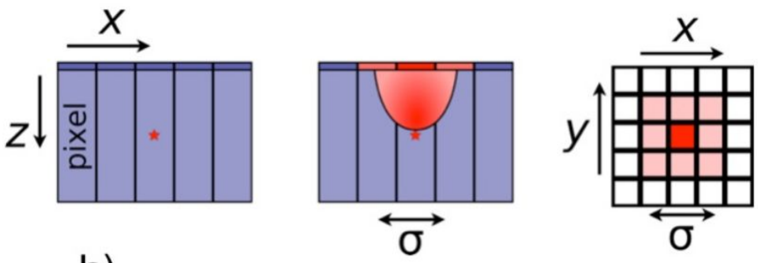


DM would create <u>one</u> or a <u>few</u> electrons in a pixel

Skipper-CCDs
SENSEI, DAMIC, OSCURA



a)



b)

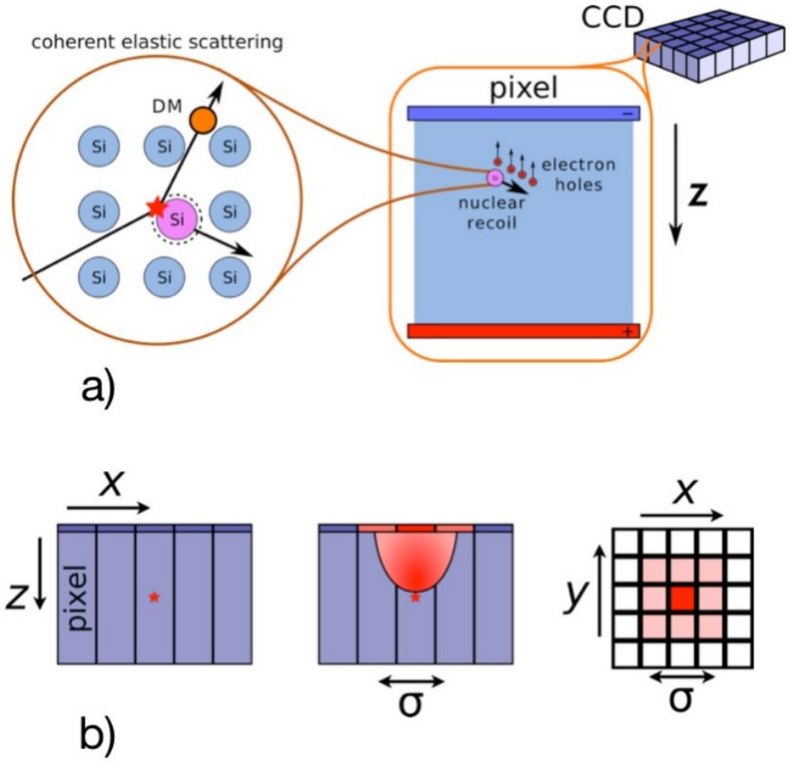
- A DM particle can scatter off a nucleus or a valence electron and create a point-like ionization event
- Charge will be drifted to the pixel array under a voltage bias
- Lateral spread of the charge cloud due to thermal diffusion
- The lateral spread is proportional to the drift time (depth of the interaction)

3D reconstruction of the interaction location	Identification of particle type via cluster pattern

3

Skipper-CCDs

SENSEI, DAMIC, OSCURA



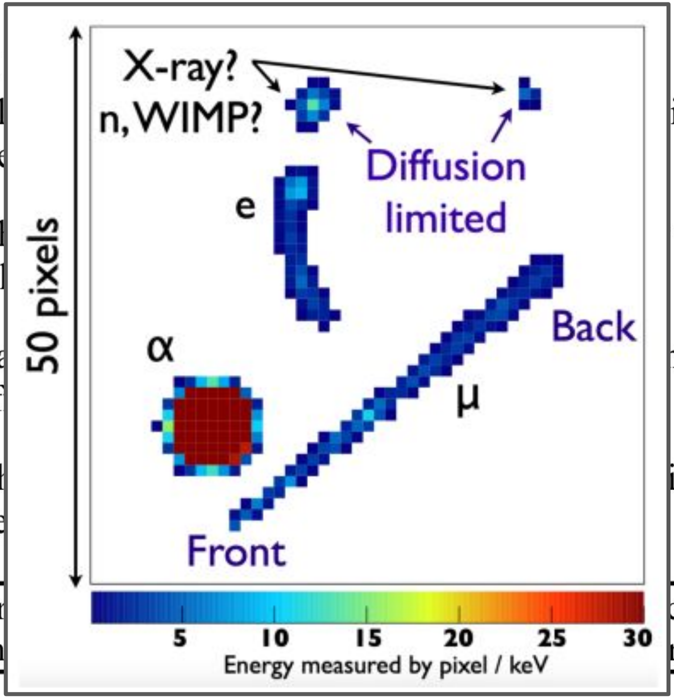
◉A … ion
val
eve

◉Cl … a
vol

◉La … mal
dif

◉Th … ime
(de

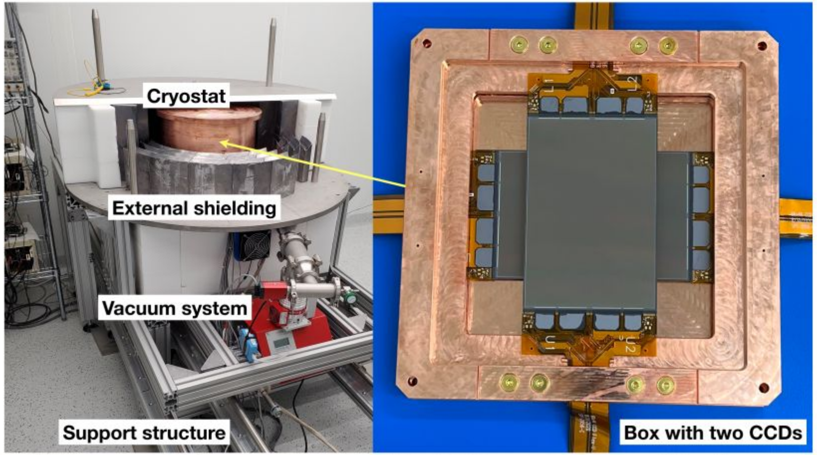
3D r … cle
in … rn

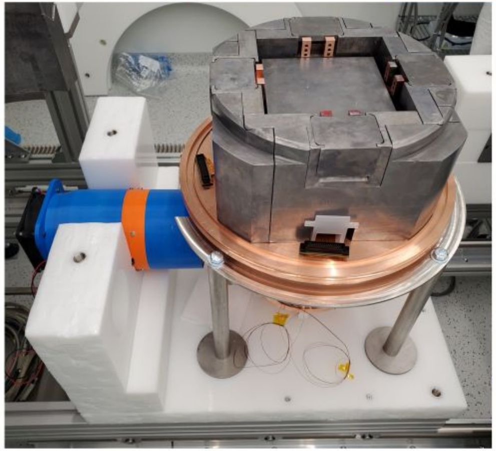


3

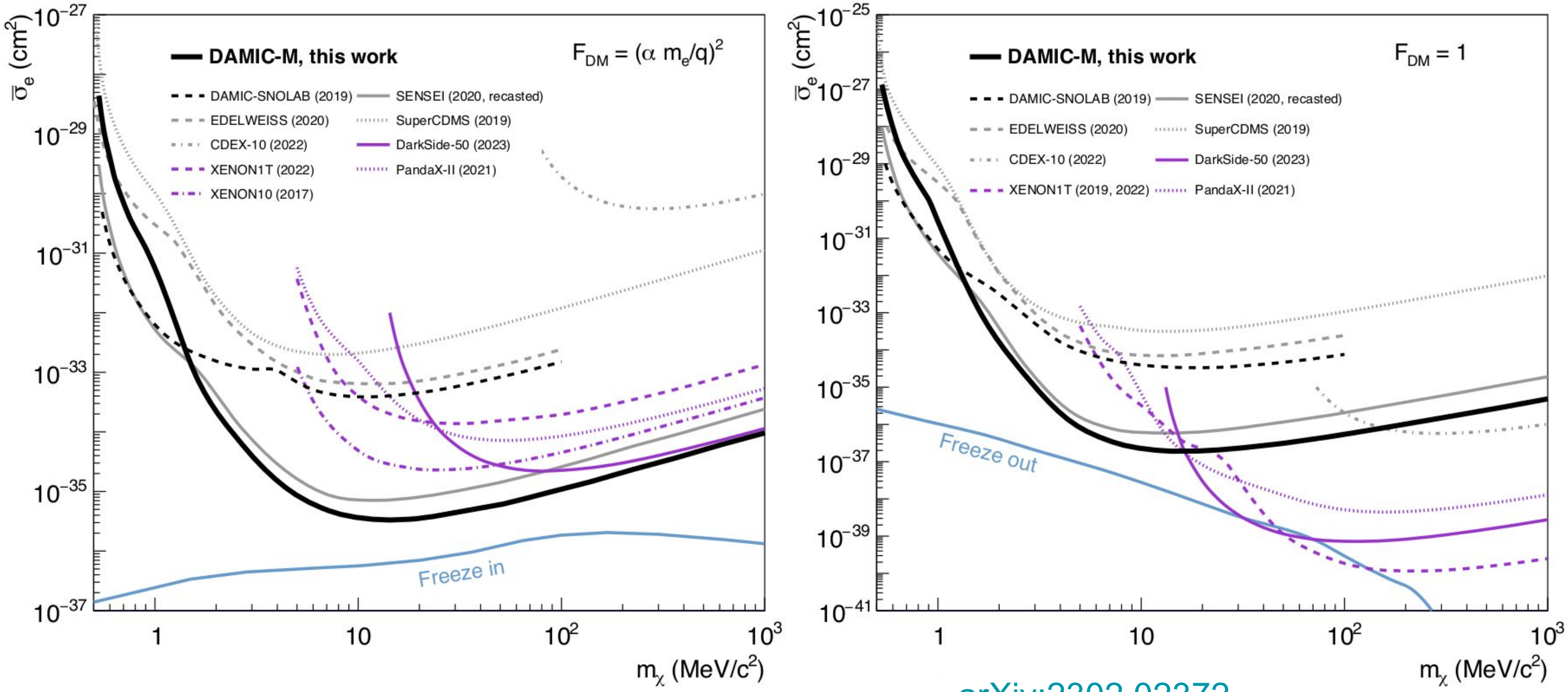
DAMIC-M LBC

- Laboratoire Souterrain de Modane
- Low Background Chamber (LBC)
- 6k × 4k pixel skipper CCDs (× 2)
- Total mass of active target **~18 g**
    - Goal: ~700 g
- Integrated exposure of **85.23 g days**





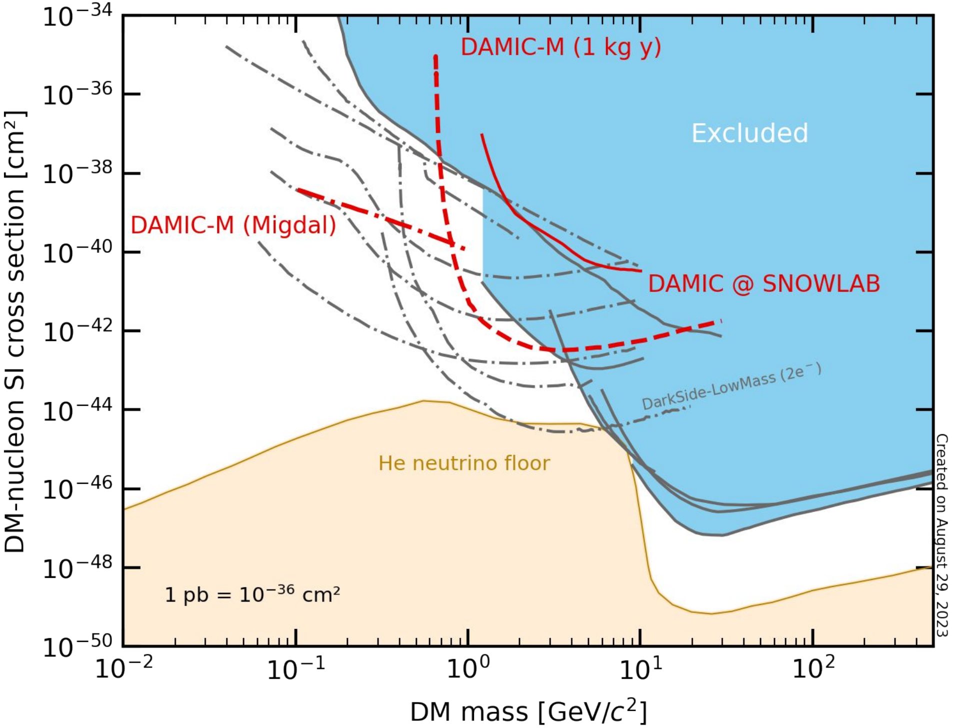
DAMIC-M LBC



arXiv:2302.02372

DAMIC-M

- Laboratoire Souterrain de Modane
- Full mass of **~700 g**
- Expected exposure of **1 kg y**



DAMIC @ SNOLAB

Confirmation of the spectral excess in DAMIC at SNOLAB with skipper CCDs

A. Aguilar-Arevalo,[1] I. Arnquist,[2] N. Avalos,[3] L. Barak,[4] D. Baxter,[5] X. Bertou,[3] I.M. Bloch,[6,7] A.M. Botti,[5] M. Cababie,[8,9,5] G. Cancelo,[5] N. Castelló-Mor,[10] B.A. Cervantes-Vergara,[1] A.E. Chavarria,[11] J. Cortabitarte-Gutiérrez,[10] M. Crisler,[5] J. Cuevas-Zepeda,[12] A. Dastgheibi-Fard,[13] C. De Dominicis,[14] O. Deligny,[15] A. Drlica-Wagner,[5,12,16] J. Duarte-Campderros,[10] J.C. D'Olivo,[1] R. Essig,[17] E. Estrada,[3] J. Estrada,[5] E. Etzion,[4] F. Favela-Perez,[1] N. Gadola,[18] R. Gaïor,[14] S.E. Holland,[7] T. Hossbach,[2] L. Iddir,[14] B. Kilminster,[18] Y. Korn,[4] A. Lantero-Barreda,[10] I. Lawson,[19] S. Lee,[18] A. Letessier-Selvon,[14] P. Loaiza,[15] A. Lopez-Virto,[10] S. Luoma,[19] E. Marrufo-Villalpando,[12] K.J. McGuire,[11] G.F. Moroni,[5] S. Munagavalasa,[12] D. Norcini,[12] A. Orly,[4] G. Papadopoulos,[14] S. Paul,[12] S.E. Perez,[8,9,5] A. Piers,[11] P. Privitera,[12,14] P. Robmann,[18] D. Rodrigues,[8,9,5] N.A. Saffold,[5] S. Scorza,[19] M. Settimo,[20] A. Singal,[17,21] R. Smida,[12] M. Sofo-Haro,[5,22] L. Stefanazzi,[5] K. Stifter,[5] J. Tiffenberg,[5] M. Traina,[11] S. Uemura,[5] I. Vila,[10] R. Vilar,[10] T. Volansky,[4] G. Warot,[13] R. Yajur,[12] T-T. Yu,[23] and J-P. Zopounidis[14]

(DAMIC, DAMIC-M and SENSEI Collaborations)

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[2] *Pacific Northwest National Laboratory (PNNL), Richland, WA, United States*
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[8] *Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, Buenos Aires, Argentina*
[9] *CONICET - Universidad de Buenos Aires, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina*
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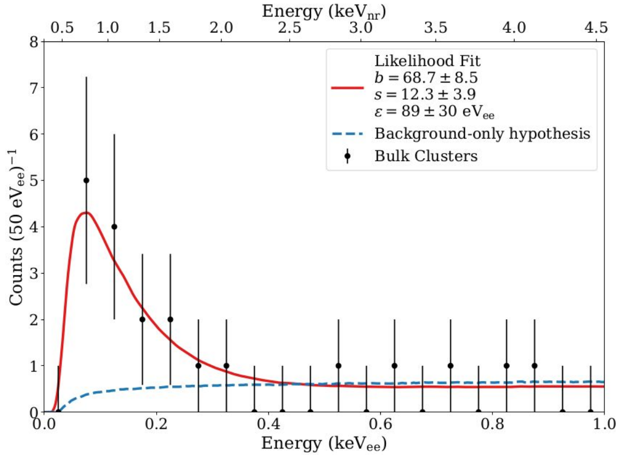
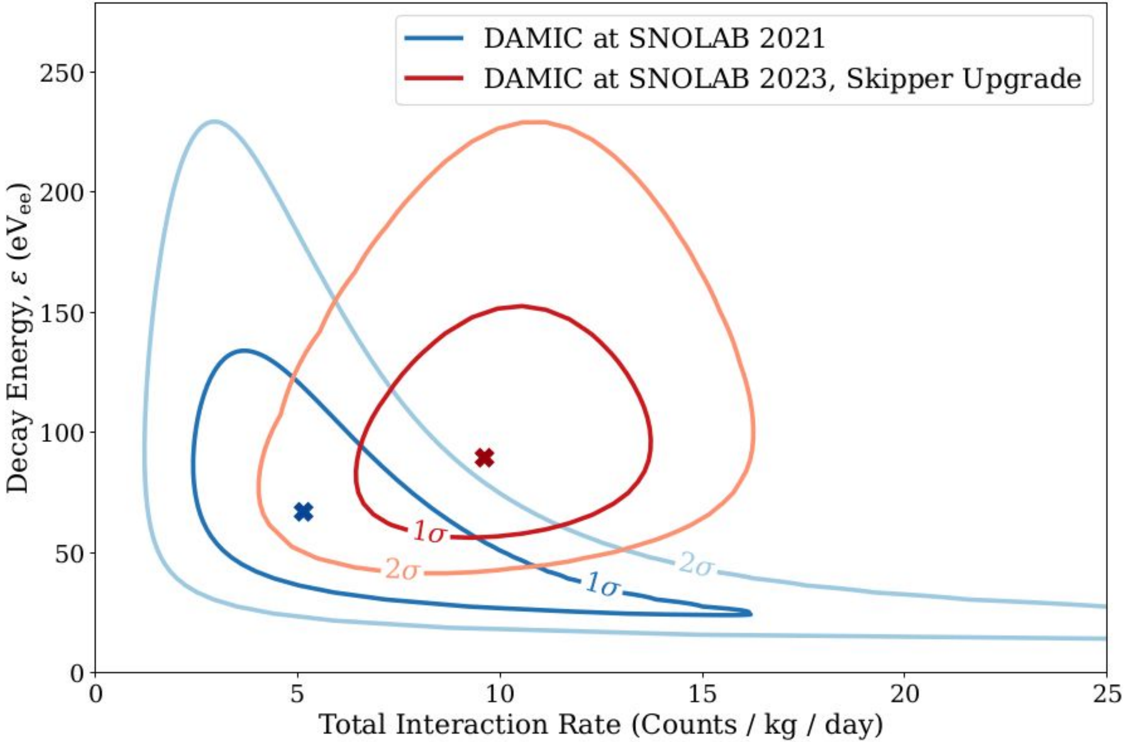
[11] *Center for Experimental Nuclear Physics and Astrophysics, University of Washington, Seattle, WA, United States*
[12] *Kavli Institute for Cosmological Physics and The Enrico Fermi Institute, The University of Chicago, Chicago, IL, United States*



arXiv:2306.01717

DAMIC @ SNOLAB



"The observed excess ionization events likely arise from an unidentified source of ***radiation*** *…"*

"The only known interactions that could give rise to the observed excess spectrum are those from ***neutrons*** *…"*

"No such source of neutrons has been identified."

"… the excess corresponds to a ***WIMP*** *with mass ~2.5 GeV/c2 and a WIMP-nucleon scattering cross section ~3x10^{-40} cm^2. This interpretation is nominally* ***excluded by*** *results from* ***CDMSlite*** *and* ***DarkSide-50****."*

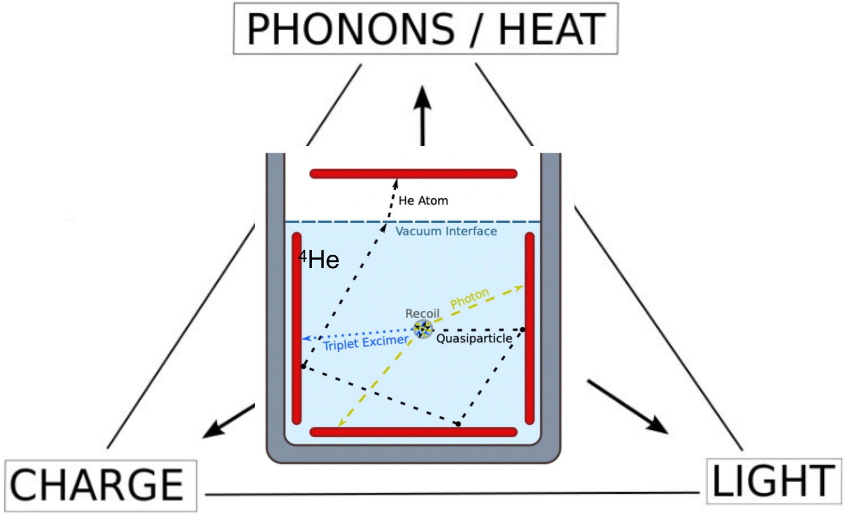
arXiv:2306.01717

Avoid bounds: arXiv:2308.12176

Superfluids

Superfluid He-4

HeRALD, DELight

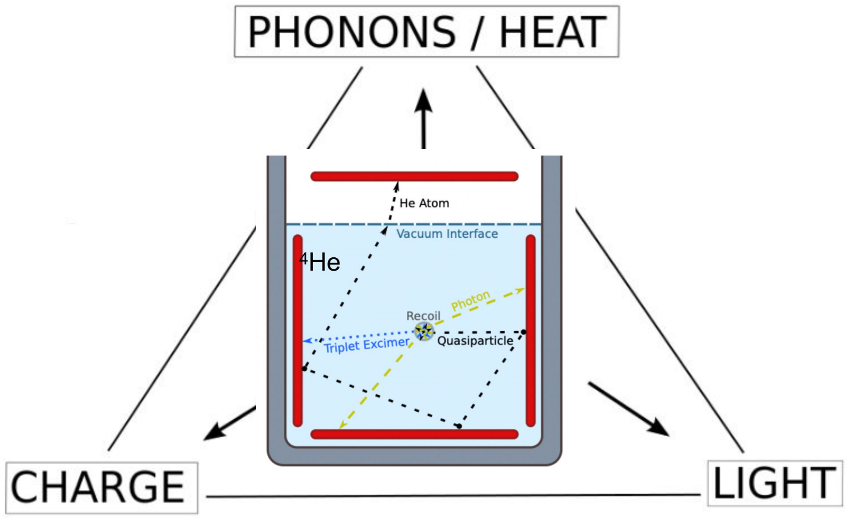


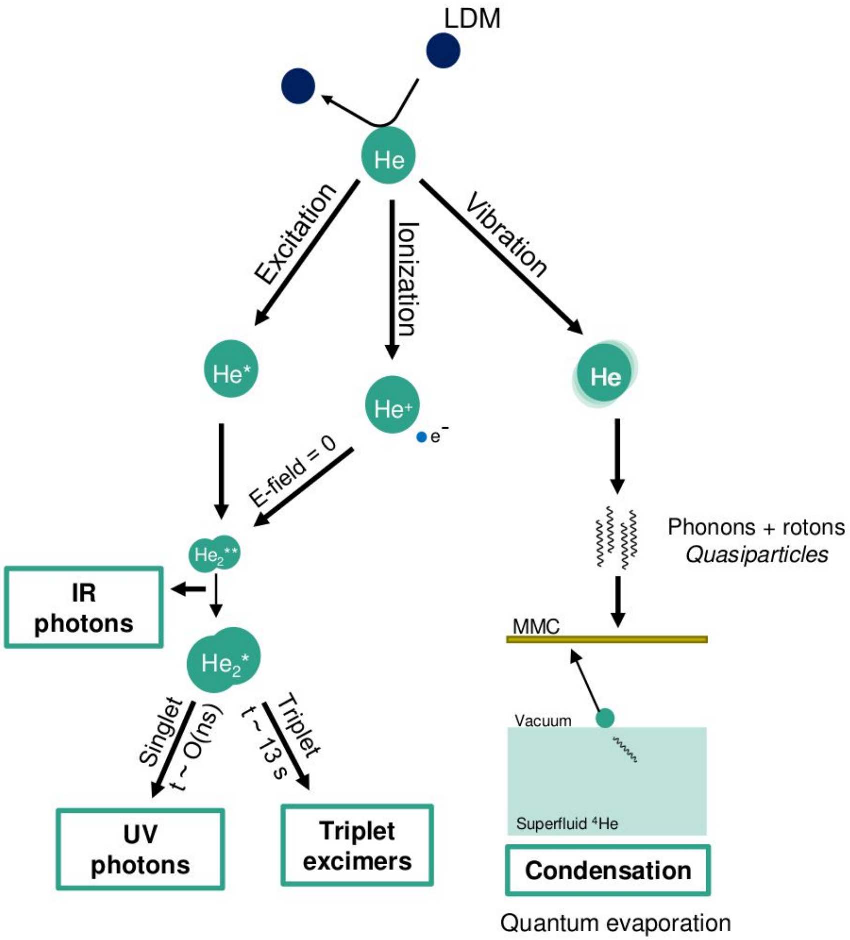
HeRALD paper:

- Phys. Rev. D 100, 092007 (2019)
- arXiv:2307.11877

Superfluid He-4

HeRALD, DELight

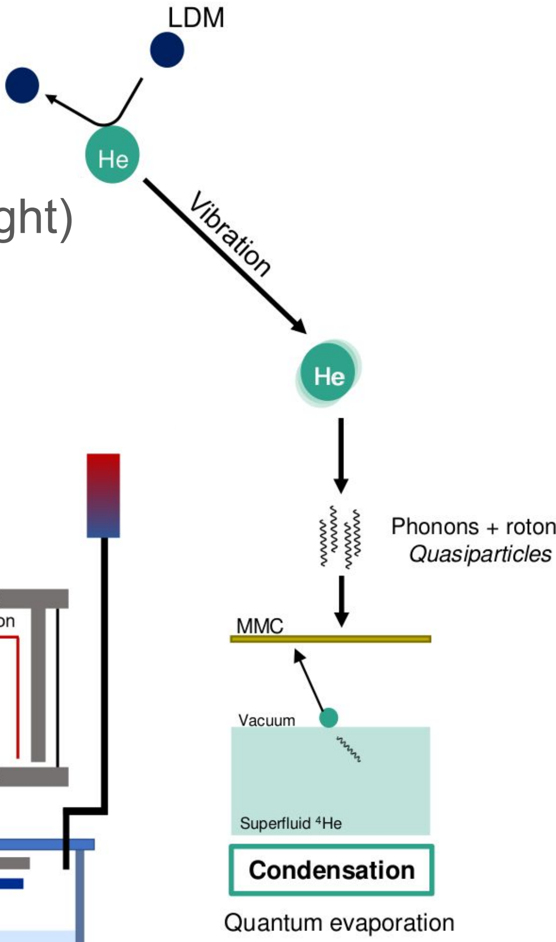


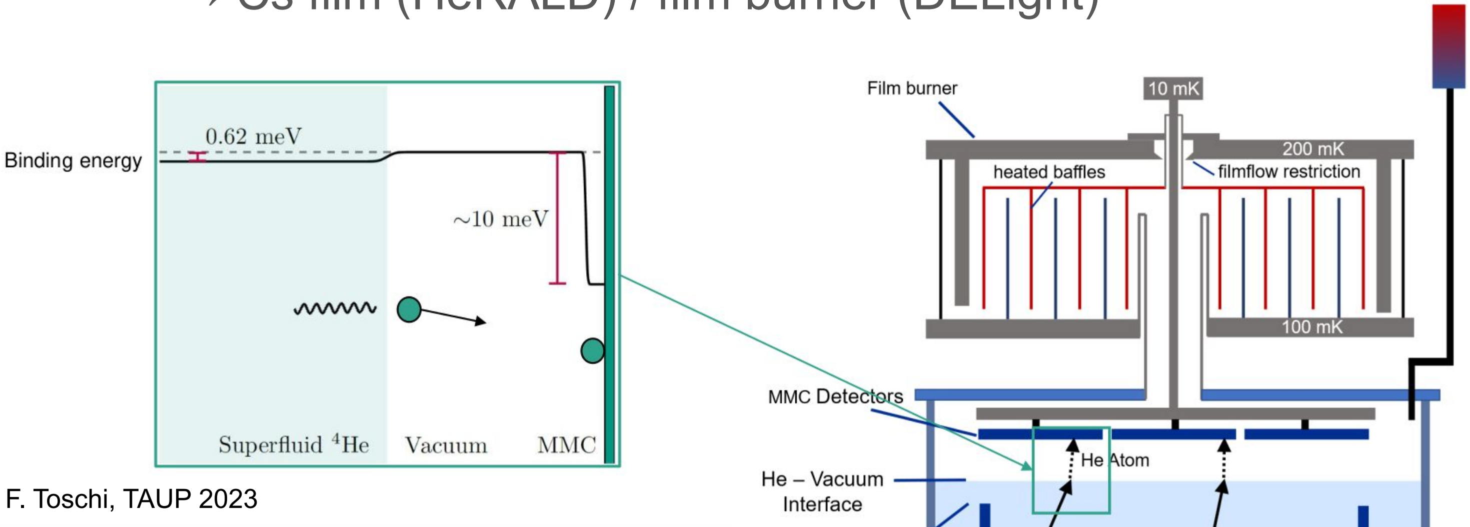


Superfluid He-4

HeRALD, DELight

- Noise-free gain $\gtrsim$10 in the TES (HeRALD) / MMC (DELight) as binding energy He-He is smaller than He-absorber
- MMCs in vacuum need to be He-4 film-free
  → Cs film (HeRALD) / film burner (DELight)

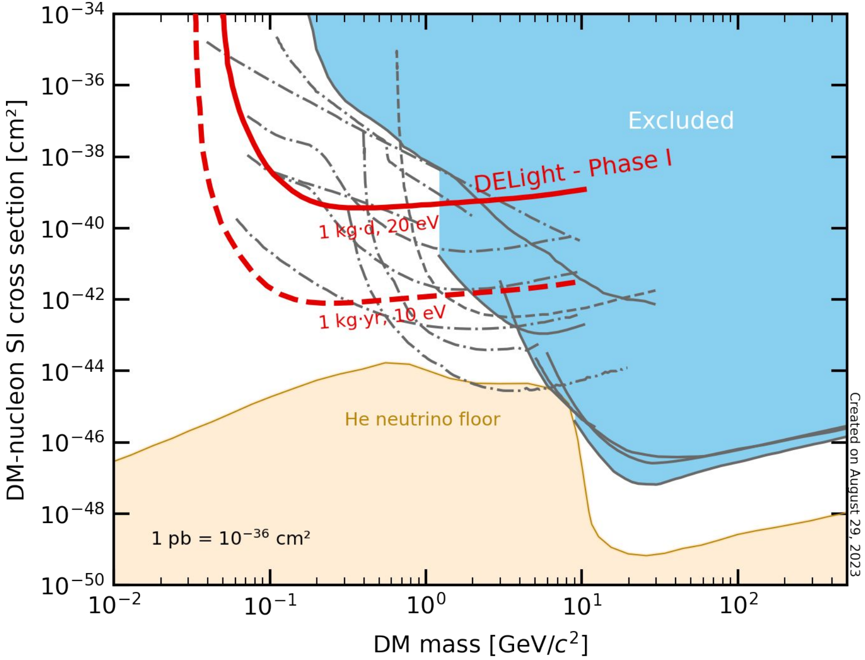




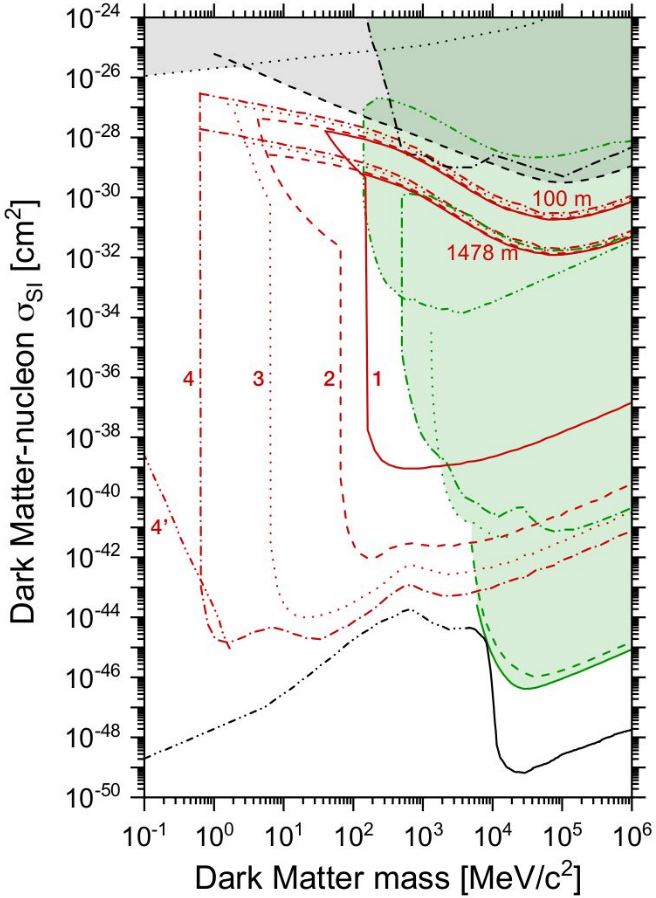
F. Toschi, TAUP 2023

Superfluid He-4

HeRALD, DELight



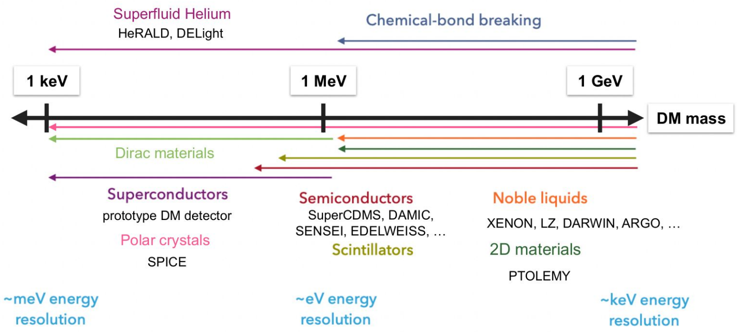
1) 1 kg-d, 40 eV
2) 1 kg-yr, 10 eV
3) 10 kg-yr, 0.1 eV
4) 100 kg-yr, 1 meV



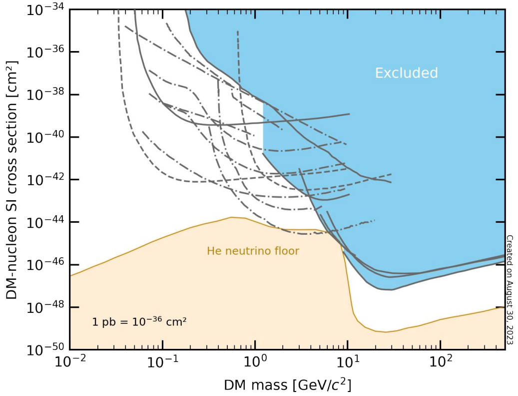
F. Toschi, TAUP 2023

[Phys. Rev. D 100, 092007 (2019)](https://doi.org/10.1103/PhysRevD.100.092007)

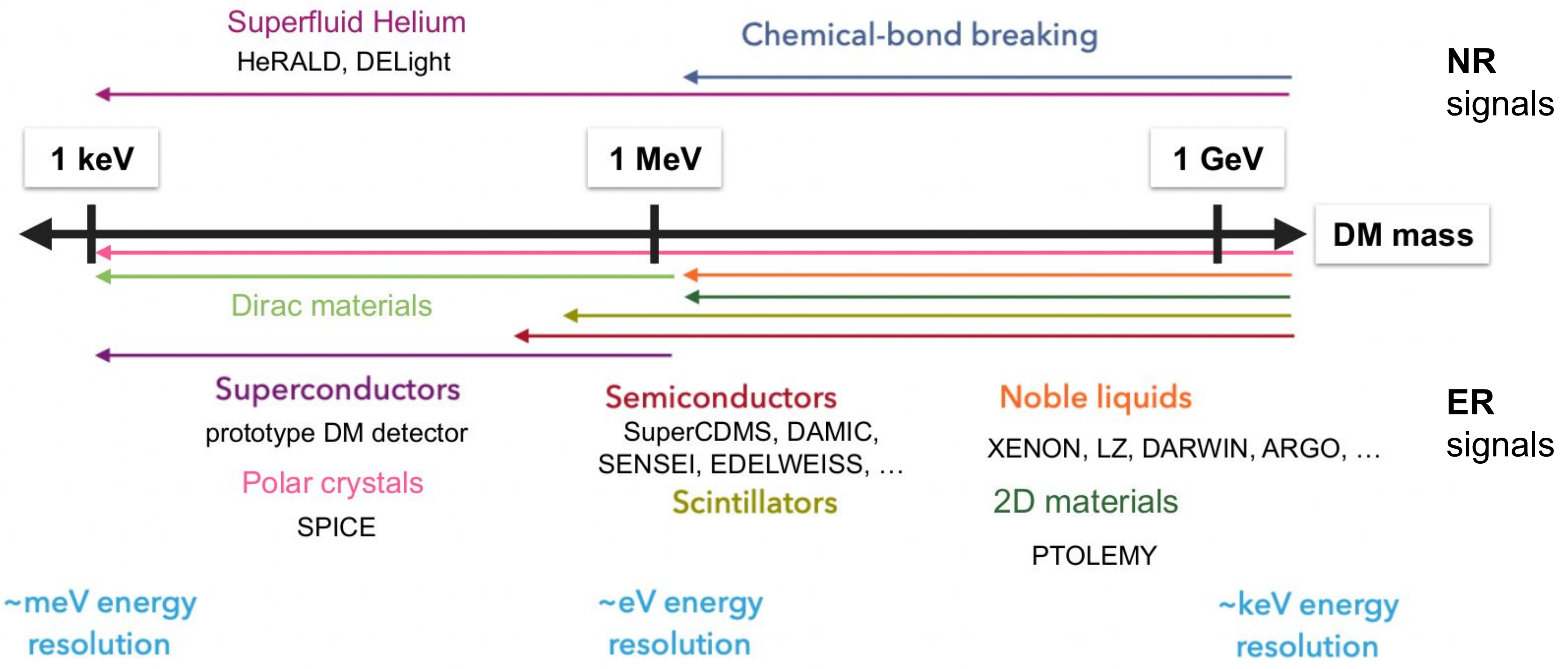
LDM direct detection summary



- Today's direct detection experiments can probe sensationally low WIMP-nucleon scattering cross sections.
- Searching for Light Dark Matter (LDM) is physically motivated.
- Moving beyond nuclear recoils is crucial to access broader areas of DM parameter space.
- Target diversity essential.
- Many more ideas on the way.



LDM direct detection summary



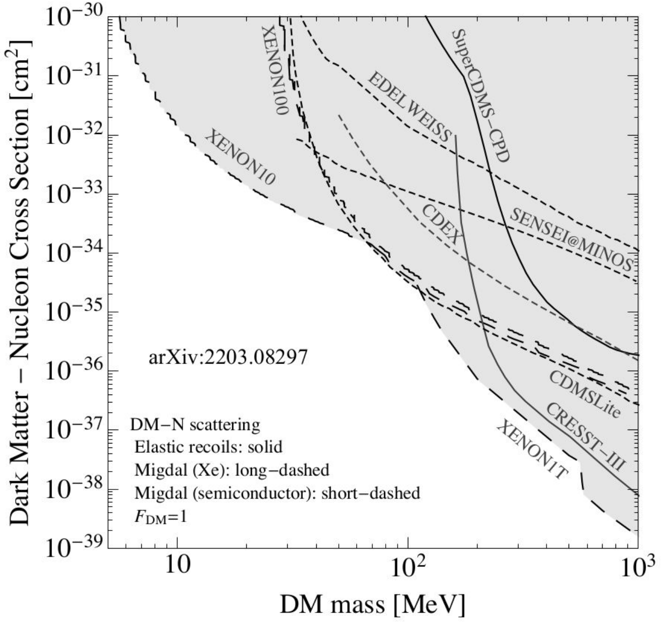
B. von Krosigk, modified after [arXiv:1608.08632](https://arxiv.org/abs/1608.08632)

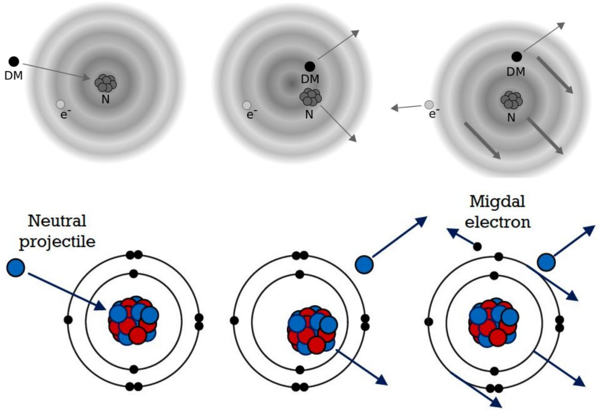
Backup

Migdal effect

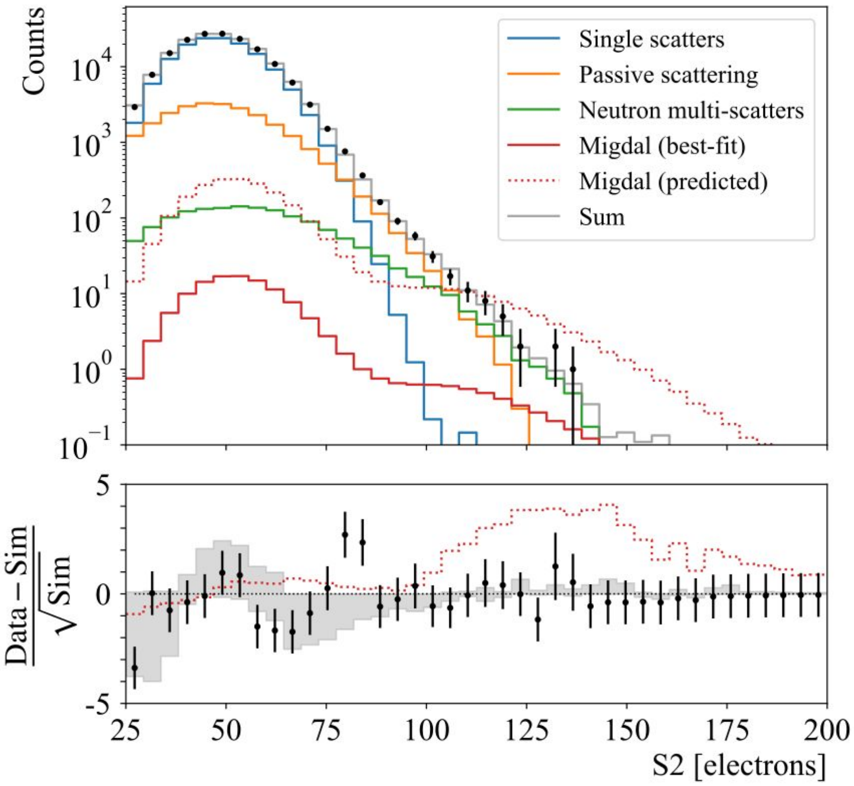
Newfound sensitivity in existing experiments

- Potential enhancement of low-mass dark matter sensitivity has been explored
  - LUX, PRL 122 131301 (2019)
  - XENON1T, PRL 123, 241803 (2019), PRD.106.022001 (2022)
  - DarkSide50, PRL 130, 101001 (2023)
  - EDELWEISS, PRD 106, 062004 (2022)
  - CDEX-1B, PRL 123.161301 (2019)
  - SuperCDMS, PRD 107, 112013 (2023)
  - and more …
- The Migdal effect has not been experimentally verified





Migdal effect

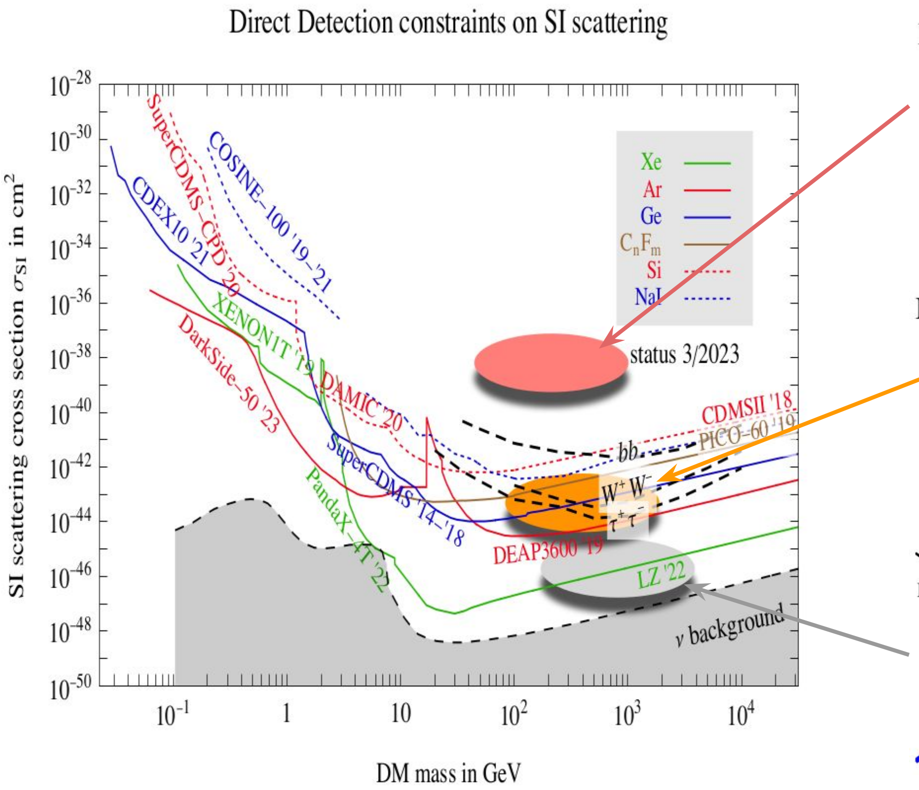


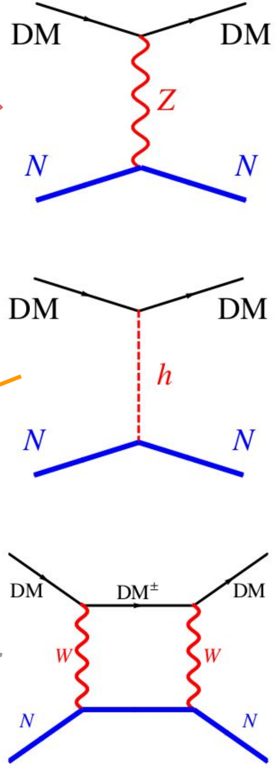
We carried out a direct search for the Migdal effect in liquid xenon and achieved a lower background rate than the expected signal rate

- Analysis of experimental data suggests that we do not observe events at the predicted rate in our expected signal region
- Xenon recombination physics may explain the null result
- If enhance recombination is the correct explanation, low-mass dark matter searches could still benefit from the Migdal effect (negligible NR component)

arXiv:2307.12952

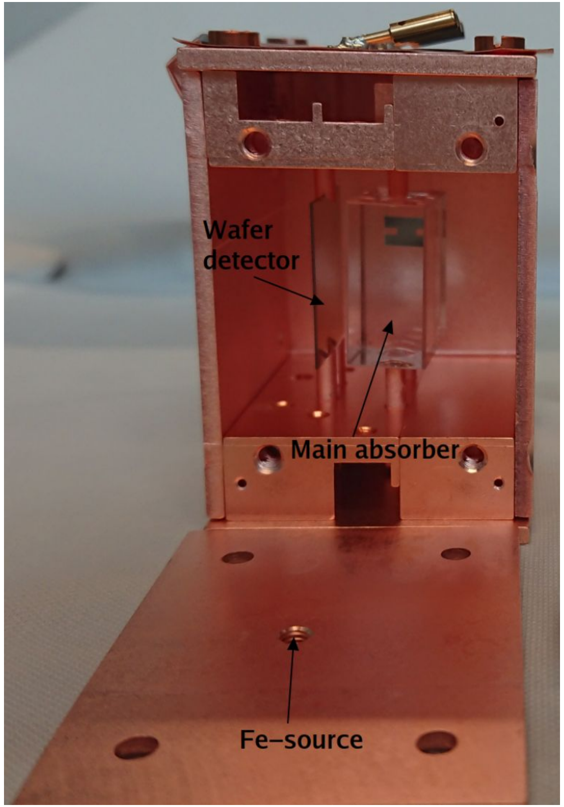
WIMP Dark Matter constraints



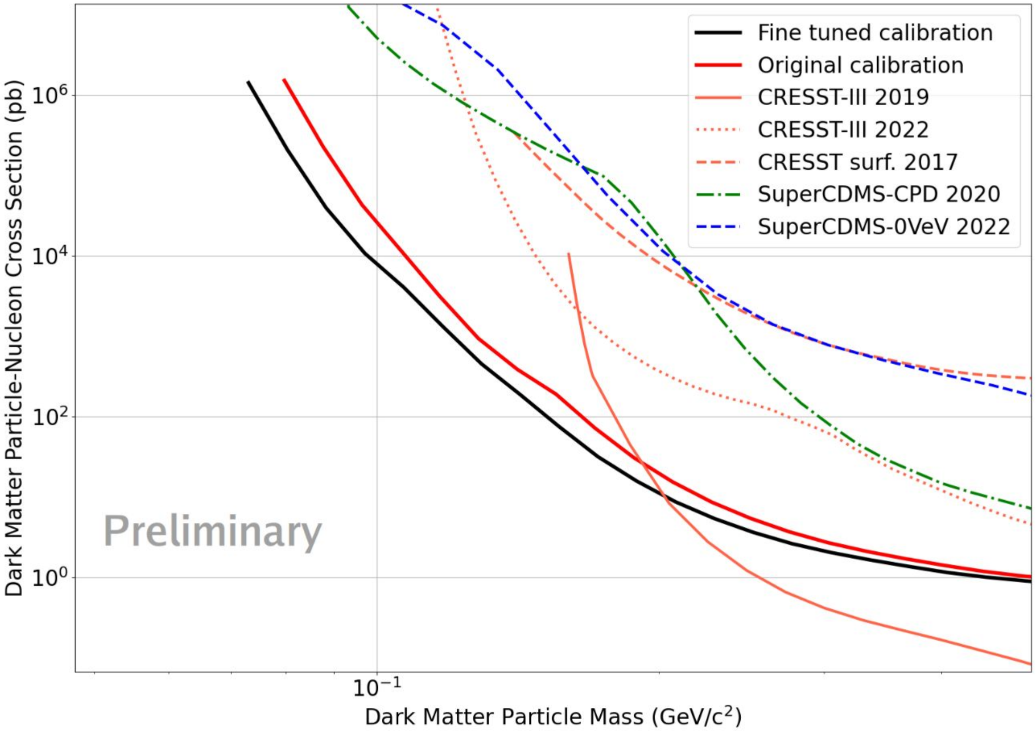


M. Cirelli, TAUP 2023

CRESST



D. Fuchs, TAUP 2023

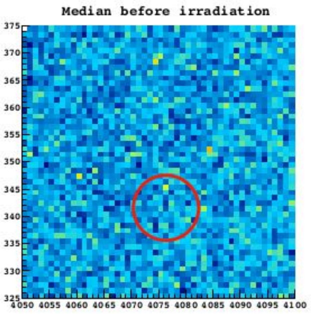


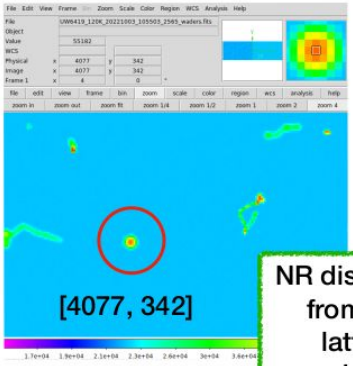
Nuclear recoils in skipper-CCDs

Idea: Distinguishing NR signals from electronic recoil (ER) backgrounds could enhance the sensitivity of future CCD experiments.

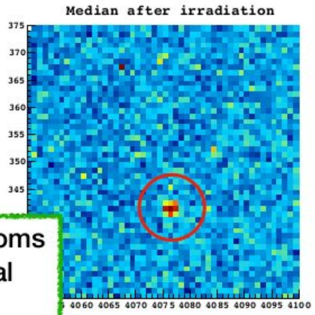
Experiment at U. Washington

Series of warm images (223 K) to identify existing defects → Cold images (147 K) during irradiation with AmBe source (4.2 MeV neutrons) to identify primary ionization events → Series of warm images (223 K) to identify new defects





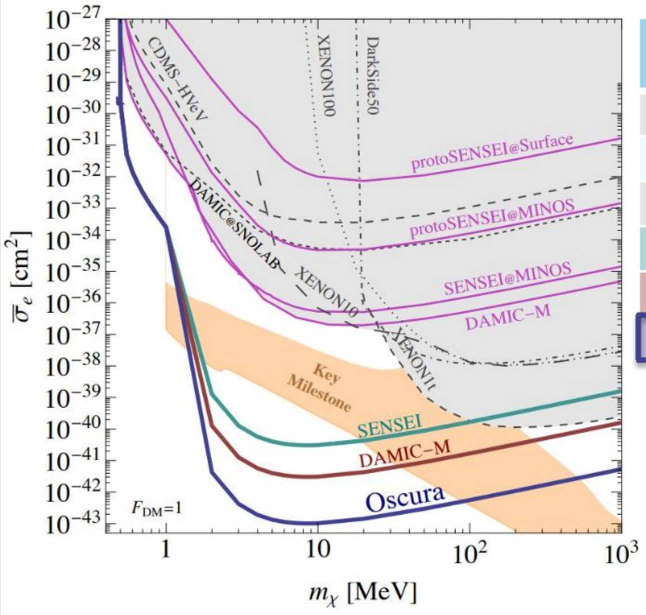
NR dislocates atoms from the crystal lattice, which produces a defect



Stable for at least 12 h

Skipper-CCDs

World best limits for sub-GeV DM candidates with this technology → Ongoing program



Experiment	Mass [kg]	#CCDs	Radiation bkgd [dru]	Instrumental bkgd [e-/pix/day]	Commissioning
SENSEI @ MINOS	~0.002	1	3400	1.6×10^{-4}	late-2019
DAMIC @ SNOLAB	~0.02	2	~10 (exp*)	$\sim 3 \times 10^{-4}$ (exp*)	late-2021
DAMIC-M LBC	~0.02	2	10	3×10^{-3}	late-2021
SENSEI-100	~0.1	50	10 (goal)		mid-2022
DAMIC-M	~1	200	0.1 (goal)		~2023
OSCURA	~10	20,000	0.01 (goal)	1×10^{-6} (goal)	~2028

* expected from DAMIC with standard CCDs [PRL 123, 181802/PRL 125, 241803]

Oscura builds on existing efforts

The challenges are to increase mass (from 10s to 10,000s CCDs) and to reduce the backgrounds (2 orders of magnitude)

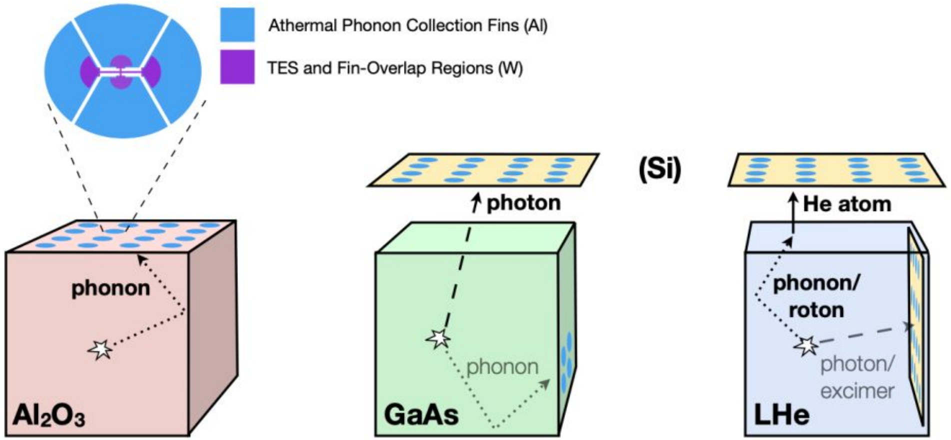
Major R&D ←

From Brenda Cervantes, UCLA Dark Matter 2023

TESSERACT

Transition Edge Sensors with Sub-EV Resolution And Cryogenic Targets

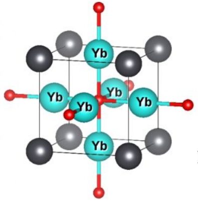
Goal: use multiple target materials + advances in TES sensor technology

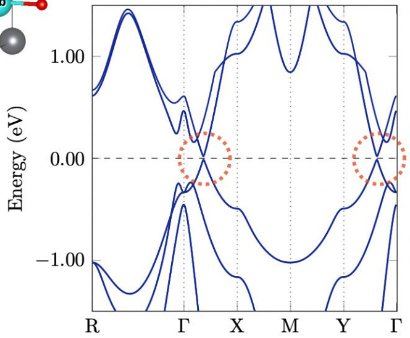


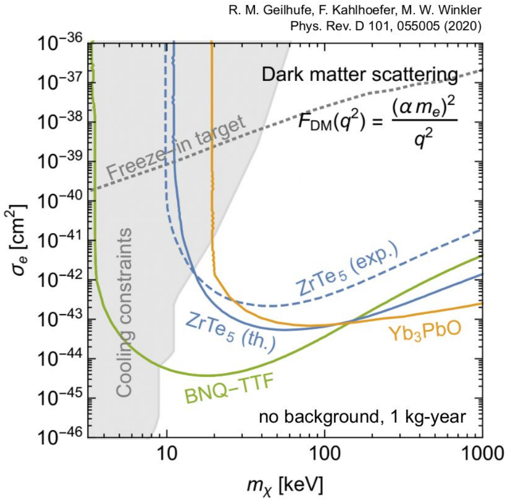
Liquid helium experiment (HeRALD)
GaAs and Sapphire-based experiments (SPICE)

Figure from: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF2-IF1_IF8-120.pdf

Dirac Materials: Example Yb_3PbO







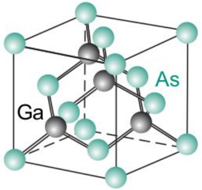
[R. M. Geilhufe, F. Kahlhoefer, M. W. Winkler Phys. Rev. D 101, 055005 (2020)]

- Band gap: ~17 - 19 meV

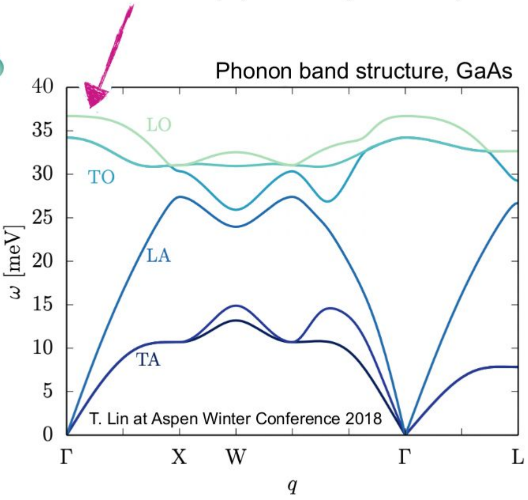
Because of their tiny band gaps Dirac materials promise to improve the sensitivity for dark matter particles in the sub-MeV mass range by many orders of magnitude. We study several candidate materials and calculate the expected rates for dark matter scattering via light and heavy dark photons as well as for dark photon absorption. A particular emphasis is placed on how to distinguish a dark matter signal from background by searching for the characteristic daily modulation of the signal, which arises from the directional sensitivity of anisotropic materials in combination with the rotation of Earth. We revisit and improve previous calculations and propose two new candidate Dirac materials: bis(naphthoquinone)-tetrathiafulvalene (BNQ-TTF) and Yb3 PbO. We perform detailed calculations of the band structures of these materials and of ZrTe5 based on density functional theory and determine the band gap, the Fermi velocities, and the dielectric tensor. We show that in both ZrTe5 and BNQ-TTF the amplitude of the daily modulation can be larger than 10% of the total rate, allowing us to probe the preferred regions of parameter space even in the presence of sizable backgrounds. BNQ-TTF is found to be particularly sensitive to small dark matter masses (below 100 keV for scattering and below 50 meV for absorption), while Yb3 PbO performs best for heavier particles.

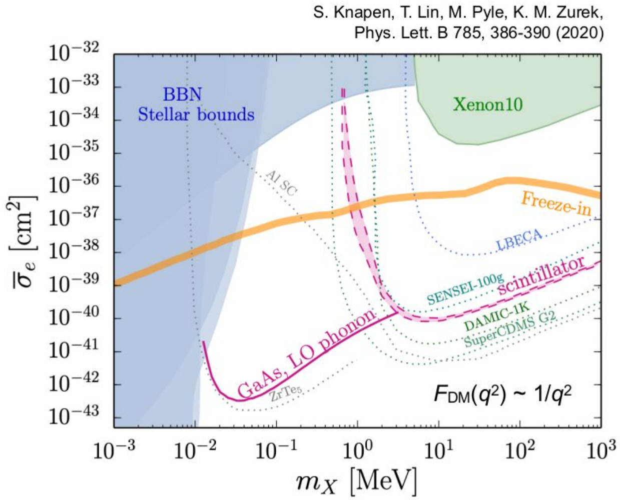
Polar Crystals: Example GaAs

[S. Knapen, T. Lin, M. Pyle, K. M. Zurek, Phys. Lett. B 785, 386-390 (2020)]



- Gapped optical phonons





The scope of dark matter (DM) searches in recent years has dramatically broadened beyond traditional candidates such as the weakly interacting massive particle (WIMP) and axion. Theoretically compelling candidates exist in hidden sectors consisting of DM and new light mediators, with numerous mechanisms for setting the DM relic density. These models have motivated a suite of new direct detection experiments, aimed at sub-GeV DM. SuperCDMS [1–3], DAMIC [4], SENSEI [5], NEWS-G [6] and CRESST [7] are working to detect energy depositions as small as an eV from scattering of MeV mass DM, or absorption of eV mass DM. There are also proposals for eV-scale detection with e.g. atoms [8], graphene [9], liquid helium [10], scintillators [11], molecular bonds [12], and crystal defects [13,14].