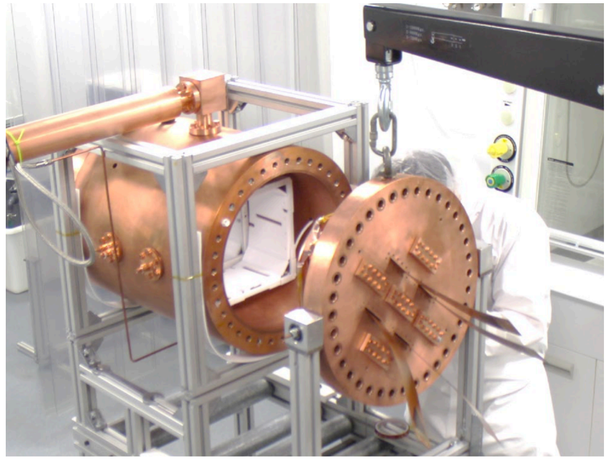
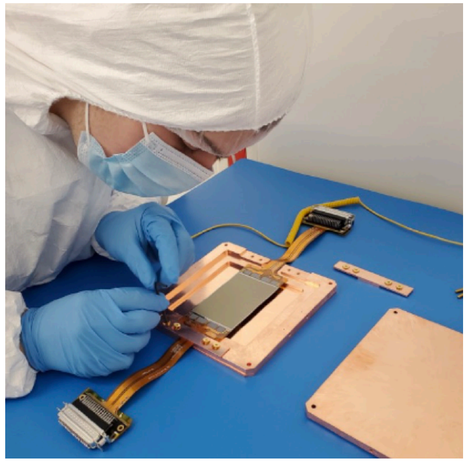
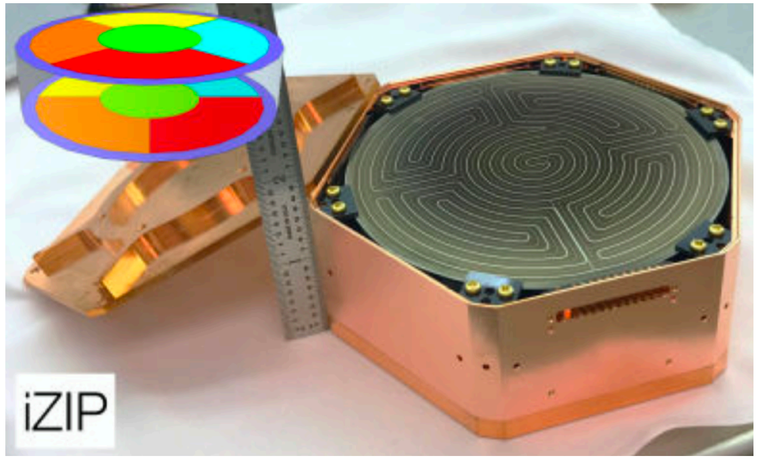
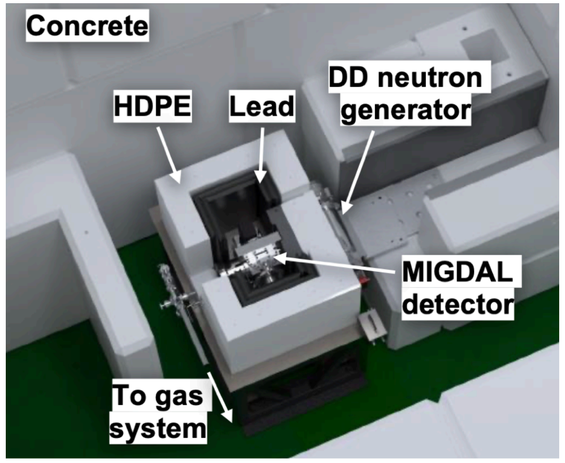








Light WIMPs & Light DM

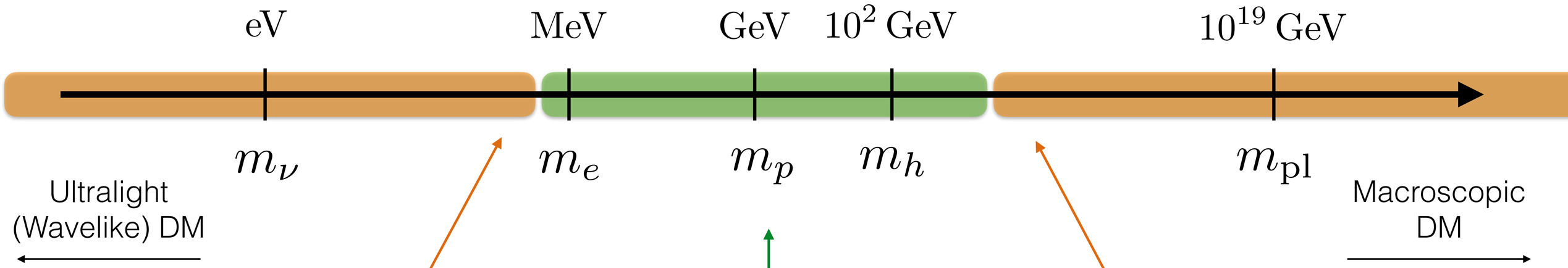
Bradley J Kavanagh
Instituto de Física de Cantabria
(CSIC-Universidad de Cantabria)

8th October 2024 - RENATA/MultiDark Meeting

kavanagh@ifca.unican.es
@BradleyKavanagh

Why Light DM?

Here by “light”, we mean “sub-GeV”…



DM with $m \lesssim \mathbf{MeV}$ will be relativistic during Big Bang Nucleosynthesis (BBN), spoiling the yields of light elements

[E.g. Sabti et al., 1910.01649]

Allowed to reach equilibrium at some point in the early Universe, with the possibility of producing the correct relic abundance (“Thermal” DM)

DM with $m \gtrsim 100\,\mathbf{TeV}$ would be overproduced in the early Universe (“Unitarity Bound”)

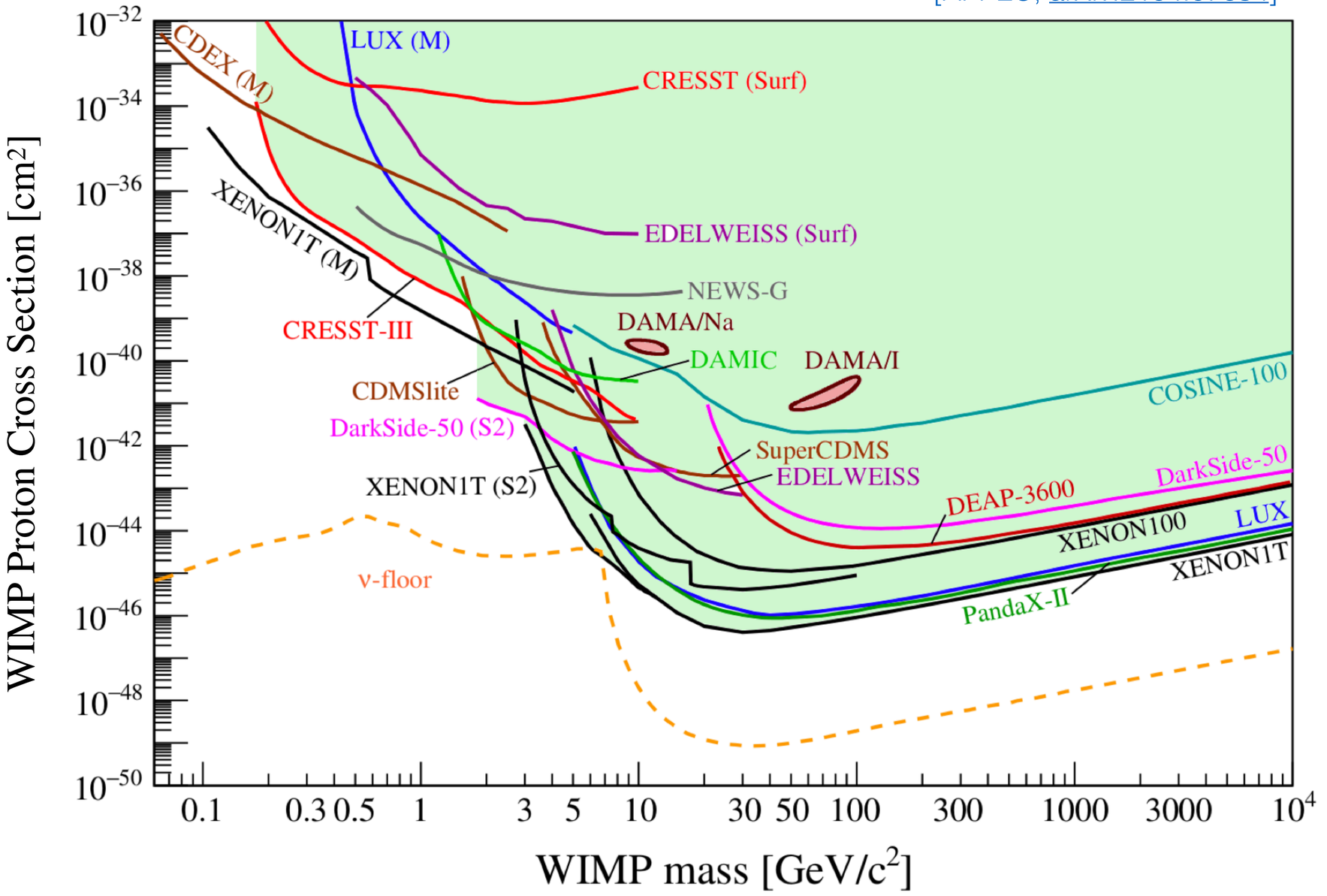
[Griest & Kamionkowski, PRL, 1990]

[Inspired by slides from Gordon Krnjaic]

*There are caveats, especially for more complicated Dark Sectors

WIMP Landscape

[APPEC, arXiv:2104.07634]

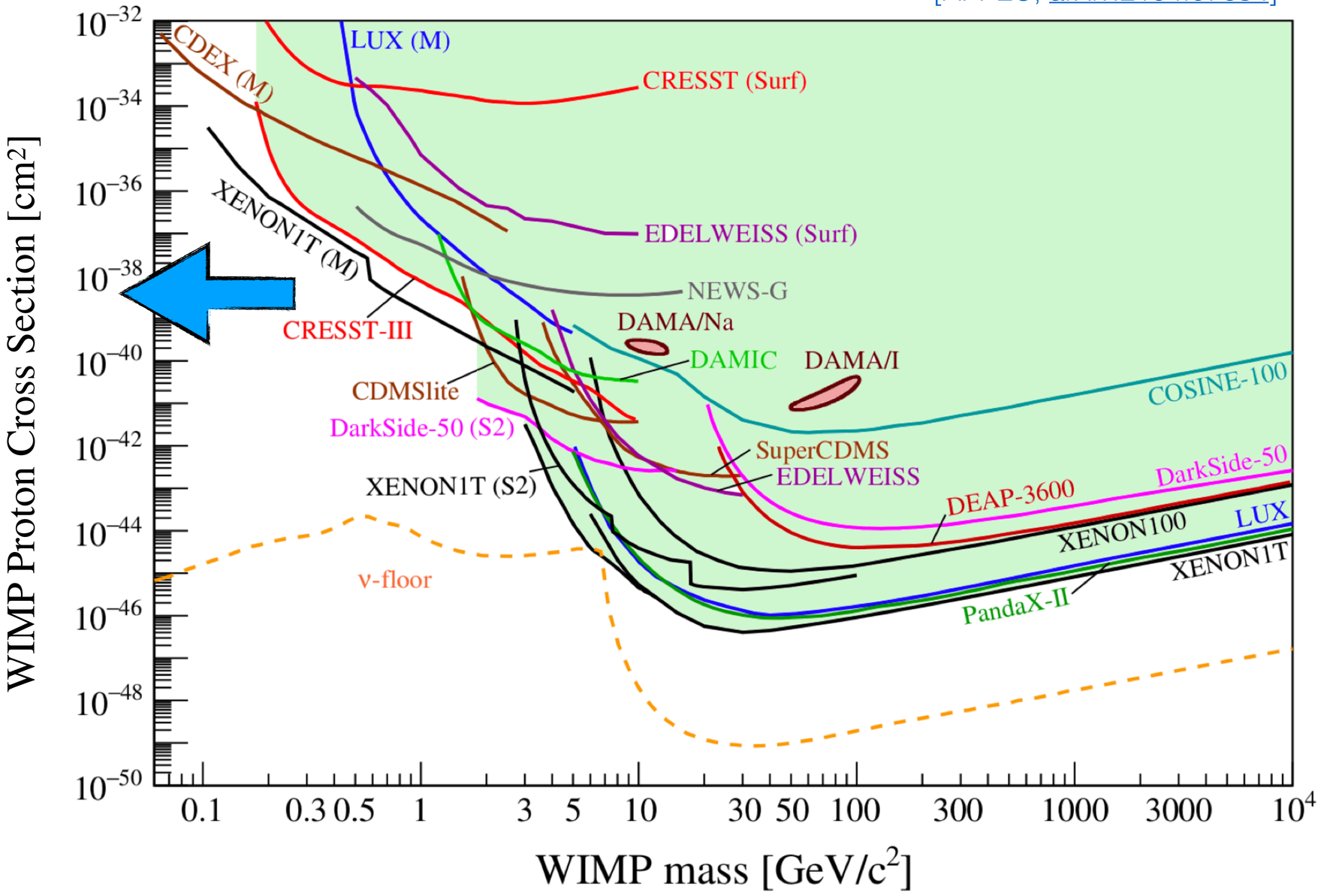


WIMP Landscape

[APPEC, arXiv:2104.07634]

Avenues:

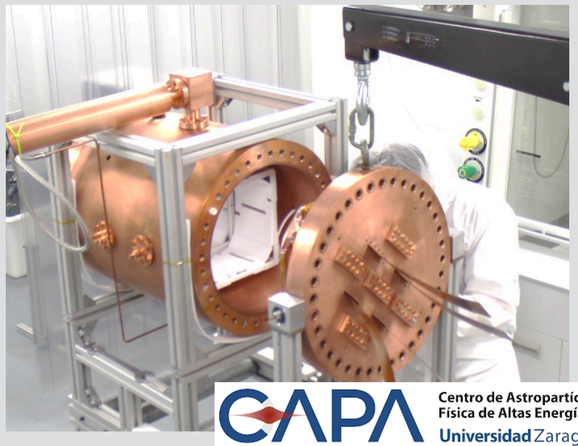
- Lower Energy Thresholds
- New models/interactions/ signatures (beyond DM-proton)



Overview

Links to recent papers/presentations provided.
See also relevant MultiDark Talks!

TREX-DM

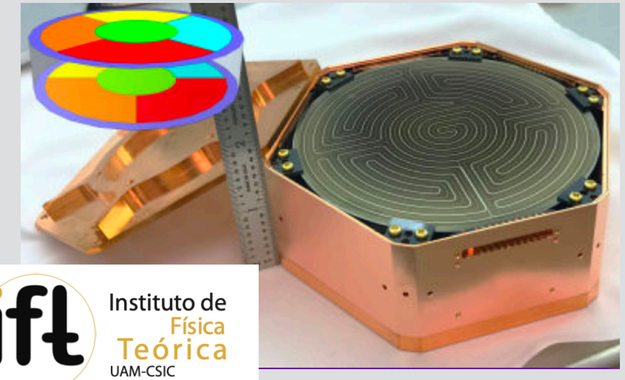


CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

DAMIC-M/OSCURA

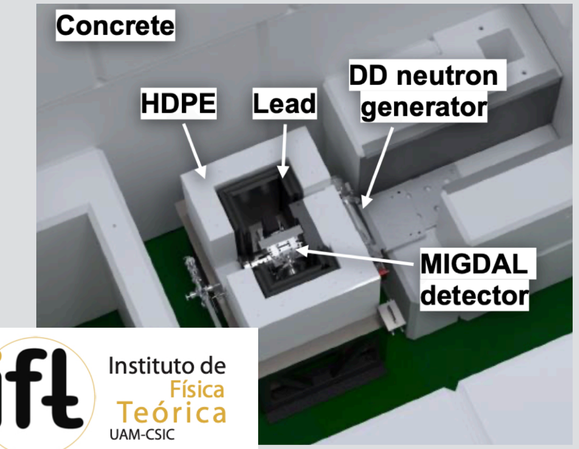
IFCA Instituto de Física de Cantabria

SuperCDMS



ift Instituto de Física Teórica UAM-CSIC

MIGDAL



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QS4DM - Phonon Detector R&D

TREX-DM

TPC for **R**are **E**vent e**X**periments - **D**ark **M**atter

Recent talk: Theopisti Dafni (Sep 2024)
Recent paper: arXiv:2312.12622
Comparable experiment: NEWS-G

High pressure gas TPC (20 L up to 10 bar) installed at Canfranc Underground Laboratory (LSC)

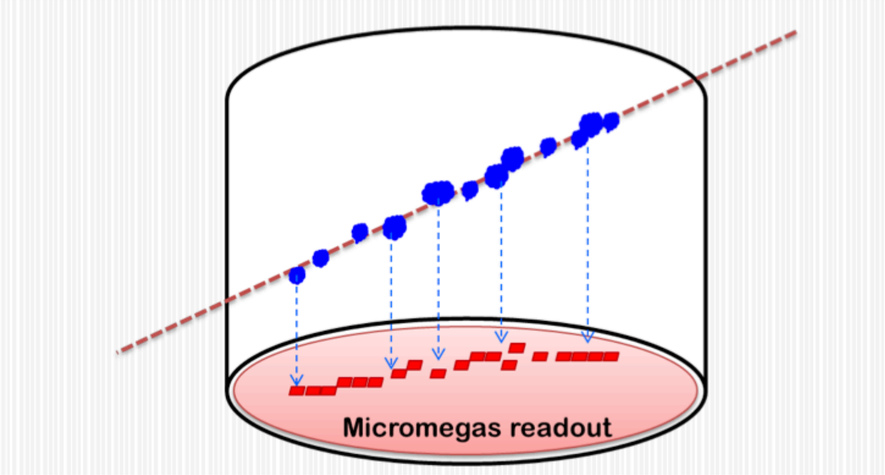
[TREX-DM, 1910.13957]

Detector with very low energy threshold (<1 keV_{ee}), and light elements as targets to probe sub-GeV DM-nucleon scattering

Possibility to change target gases:

- Atmospheric Ar + 1% iC_4H_{10} (2018 data-taking)
- Ne + 2% iC_4H_{10} (2019-2022 data-taking)

Read-out ionisation due to nuclear recoils using microbulk Micromegas (not focused on directionality).



Allows low energy threshold with good energy resolution (minimum threshold of 900 eV_{ee} achieved in 2022, depending on stability and gain of Micromegas readout)

TREX-DM

TPC for **R**are **E**vent e**X**periments - **D**ark **M**atter

2019 - 2022: Data-taking at LSC with Ar & Ne (4 bar)

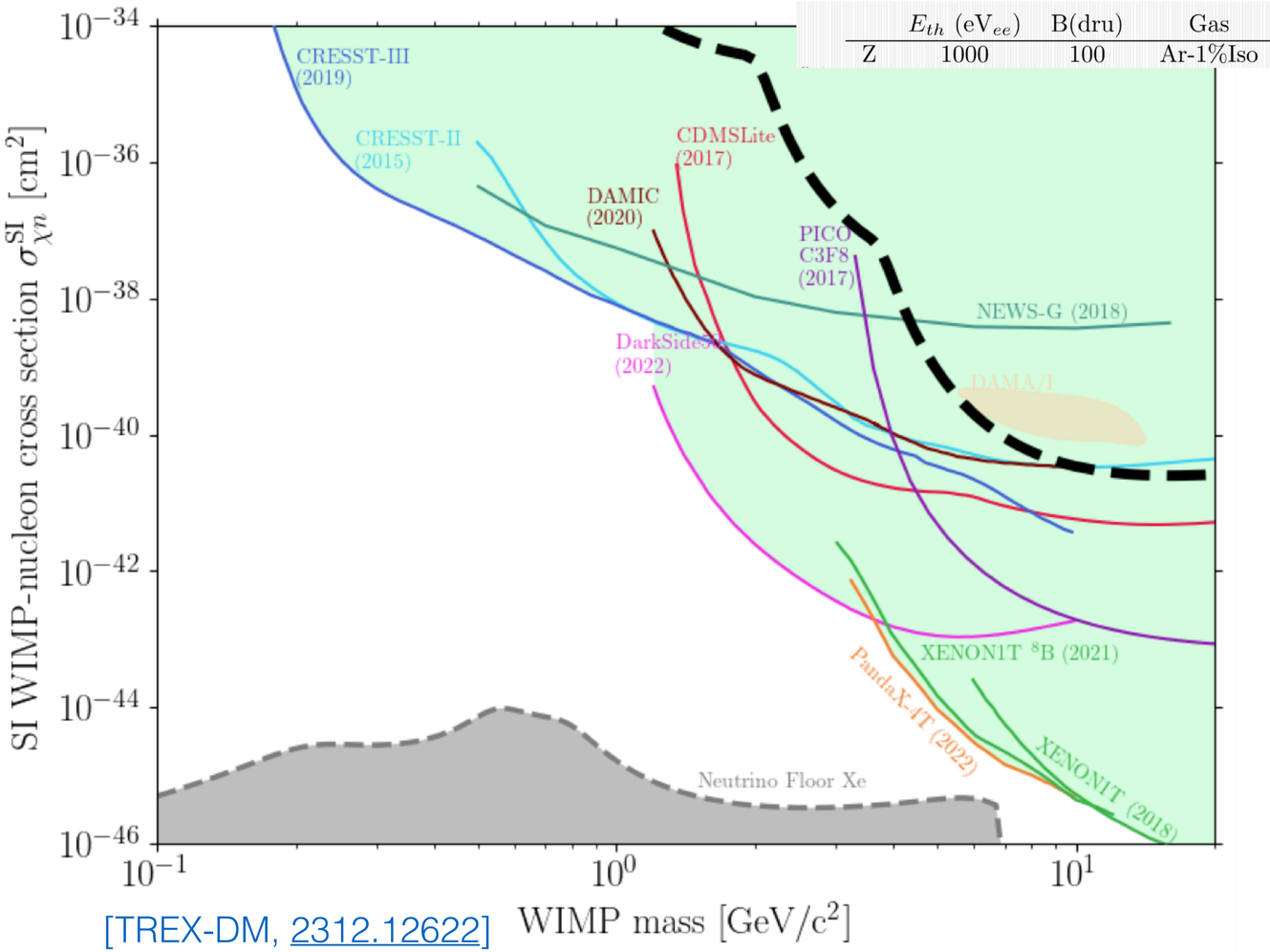
Background levels initially dominated by ^{222}Rn contamination. Reduced down to $\mathcal{O}(100)$ dru*

Sep 2022 - July 2023: Relocation and commissioning in LAB2500 at LSC

Aug 2023 - present: Data-taking for comparison with 2019-2022 campaign.

Plans to reduce threshold down to ~50 eVee, with a pre-amplification stage (GEM) on top of the Micromegas

*1 dru = 1 event/kg/keV/day



[TREX-DM, 2312.12622]

Spanish Contribution

Project of CAPA/University of Zaragoza. Proof of concept operated at University of Zaragoze before being installed at LSC in 2018.

CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

Laboratorio Subterráneo Canfranc

TREX-DM

TPC for Rare Event eXperiments - Dark Matter

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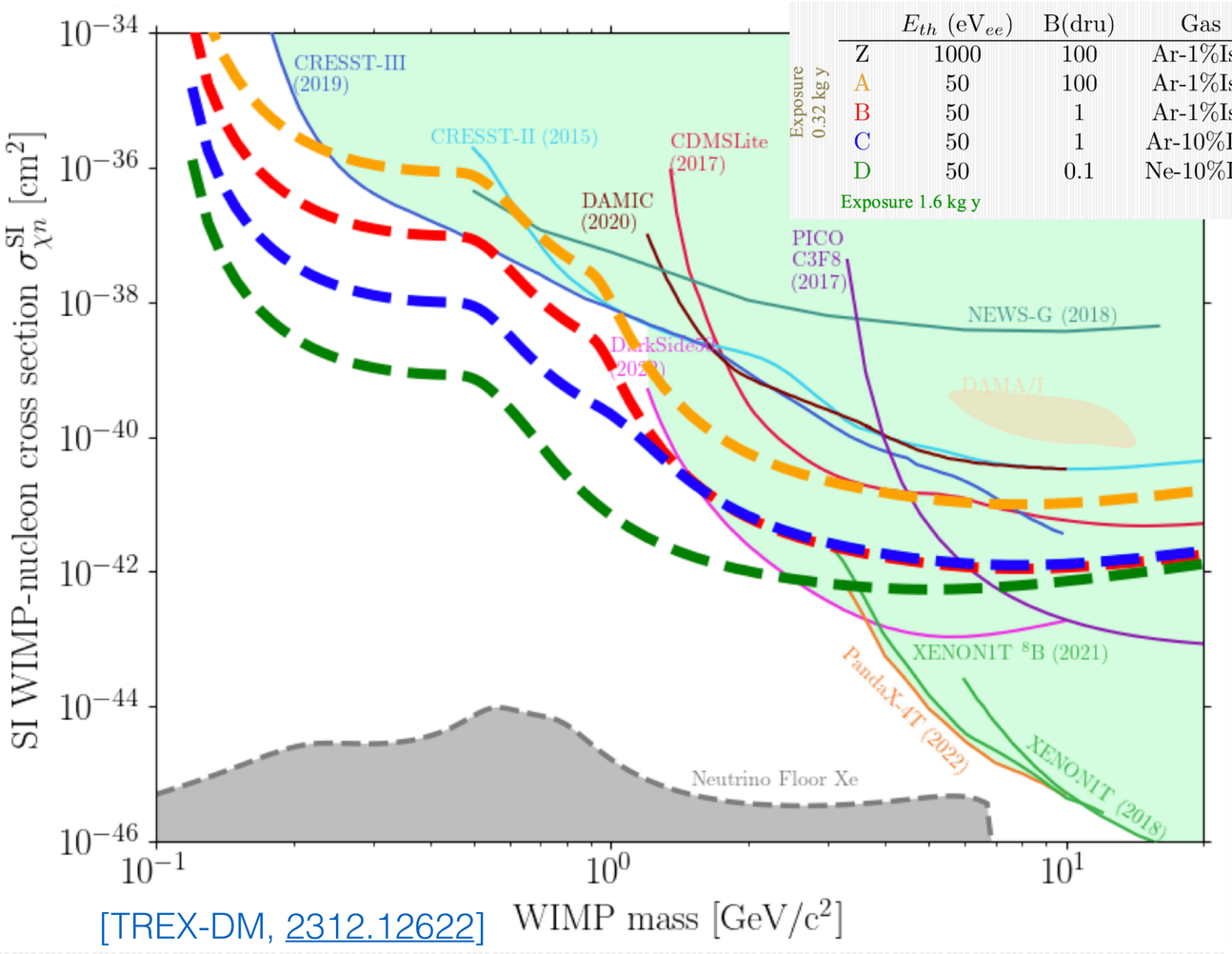

	E_{th} (eV$_{ee}$)	B(dru)	Gas
Z	1000	100	Ar-1%Iso
A	50	100	Ar-1%Iso
B	50	1	Ar-1%Iso
C	50	1	Ar-10%Iso
D	50	0.1	Ne-10%Iso

[TREX-DM, 2312.12622]

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Laboratorio Subterráneo Canfranc

DAMIC-M

DArk **M**atter **I**n **C**CDs at **M**odane

Recent talk: Danielle Norcini (Jul 2024)
See also Nuria Castello's talk on Thursday.
Comparable experiments: SENSEI

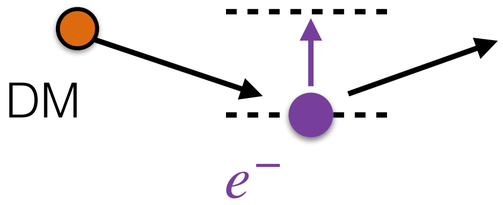
Array of **Charge Coupled Devices (CCDs)** planned to be installed at Laboratoire Souterrain de Modane (LSM), building on success of the DAMIC program at SNOLAB

Array of 208 thick (675um), massive (~3.5g), 9 Mpixel Silicon CCDs for kg-scale mass

[DAMIC-M, 2001.01476]

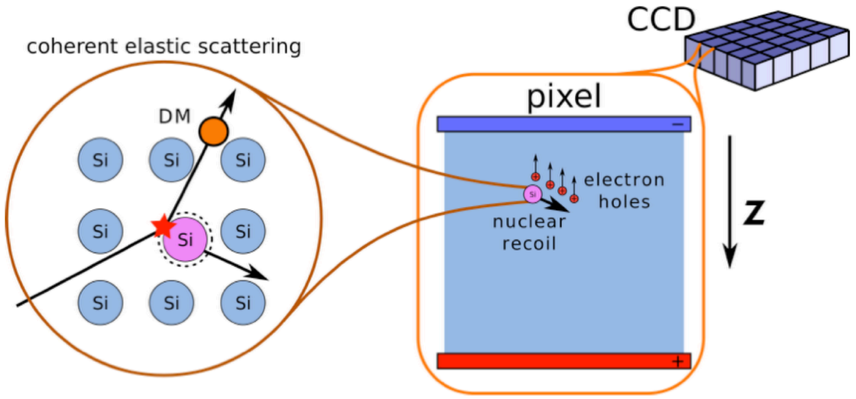
CCDs act as ionisation detectors with **"skipper" amplifier** readout for single electron energy resolution (sub-eV) and self-calibration

Will provide sensitivity to sub-GeV DM-nucleus scattering as well as MeV-scale DM-electron scattering!

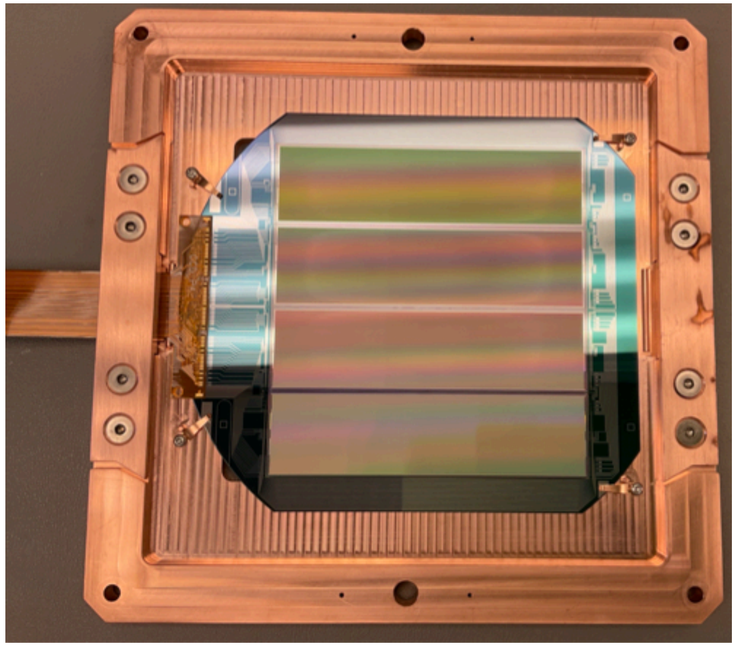


$$\Delta E_e \leq \frac{1}{2}\mu_{\chi N} v^2 \simeq \frac{1}{2}\,\mathrm{eV} \times \left(\frac{m_\chi}{\mathrm{MeV}}\right)$$

[Essig et al., 1108.5383, 1509.01598]



3.7 eV to create e-h pair



DAMIC-M

DArk **M**atter **I**n **C**CDs at **M**odane

Since Feb 2022: Operation of the Low-background chamber (LBC) at Modane (Prototype of 2 skipper CCDs, ~17g target mass)

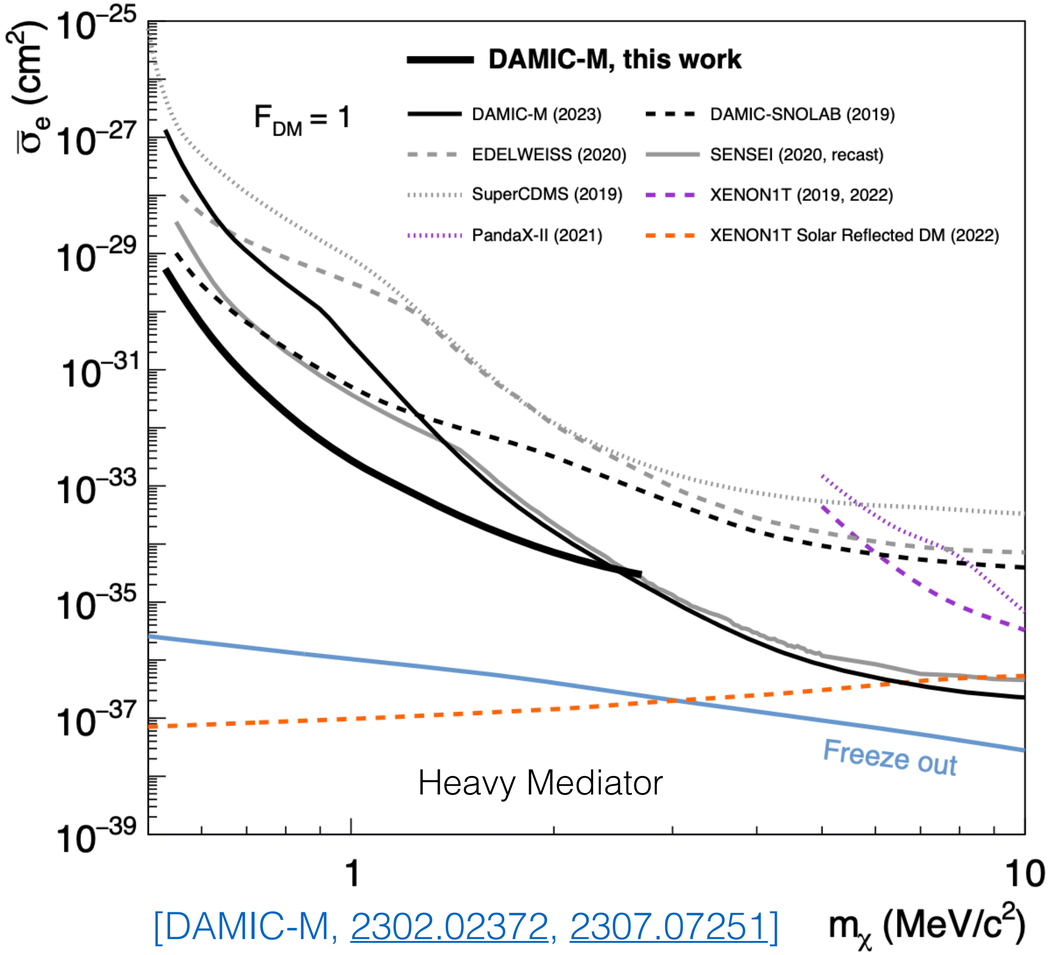
[DAMIC-M, 2407.17872]

May - Nov 2022: Science runs for DM-electron analysis (85 g-days) and daily modulation search (40 g-days)

Present: Testing and packaging of production CCDs, aiming for the DAMIC-M detector to be online in 2025

Future: Planned scale up to OSCURA, with a total exposure of 30 kg-yr (conceptual design phase to end in 2024)

[OSCURA, 2202.10518]



[DAMIC-M, 2302.02372, 2307.07251]

Spanish Contribution

BJK, Nuria Castello, Rocio Vilar and group at IFCA involved in background studies; data analysis & signal modelling; DQM; commissioning and construction.

IFCA Instituto de Física de Cantabria

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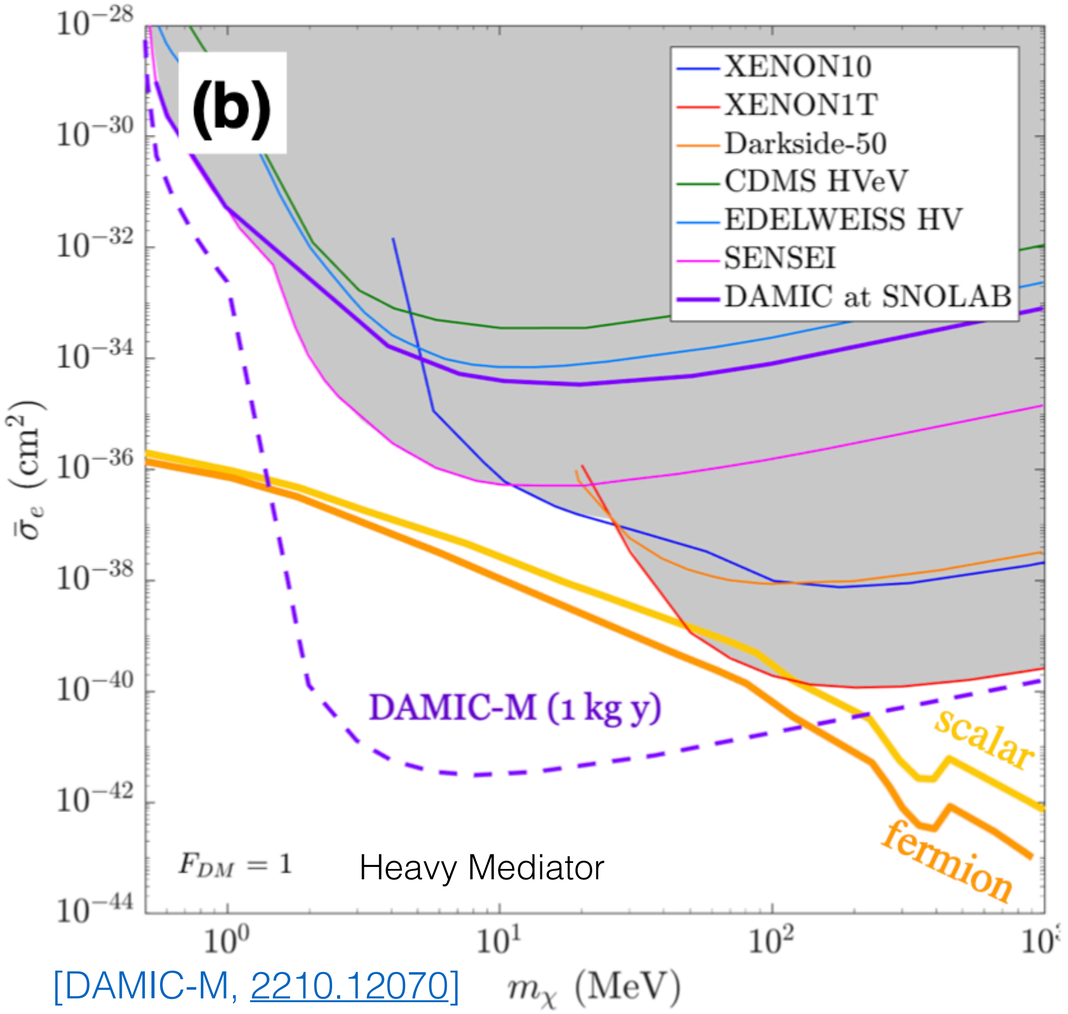

[DAMIC-M, 2210.12070]

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SuperCDMS

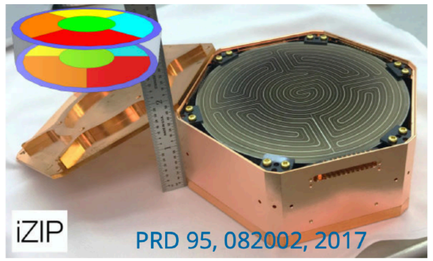
Super **C**ryogenic **D**ark **M**atter **S**earch

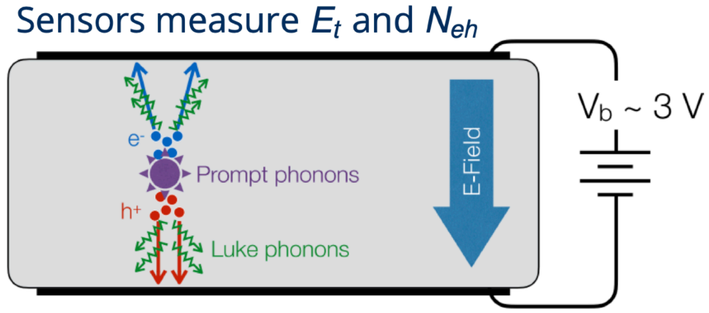
Recent talk: Stefan Zatschler (Aug 2024)
See also Rafael López's talk on Thursday

Cryogenic calorimeters (~10-15 mK) operated at SNOLAB, Canada. Successor to the CDMS program.

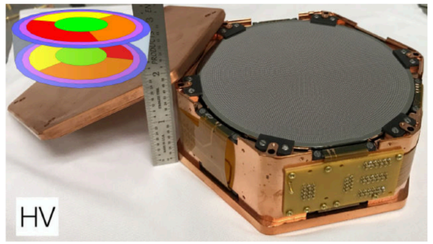
Plan to operate 24 detectors (18 Ge and 6 Si) across 4 towers: [SuperCDMS, 2203.08463]

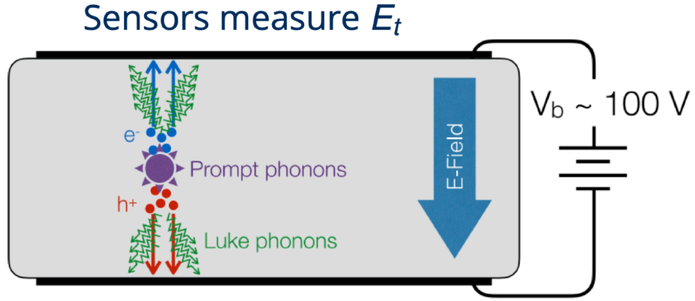
2 towers of **iZIP detectors**:
Low-background ionization + phonon sensors (allows ER/NR discrimination) for nuclear-recoil searches





2 towers of **HV detectors**:
Phonon sensor combined with high voltage provides low energy threshold for electron-recoil searches





HV detectors can achieve a threshold as low as 0.1 keV (4 eV_{ee}), due to production of Luke-Neganov phonons in high voltage. Multiple targets and detectors: aim for a broadband search over eV - GeV DM masses.

SuperCDMS

Super Cryogenic **D**ark **M**atter **S**earch

2017 - 2019: Surface runs of prototype HVeV detectors (gram-scale, with eV resolution)

[SuperCDMS, 1804.10697, 2005.14067]

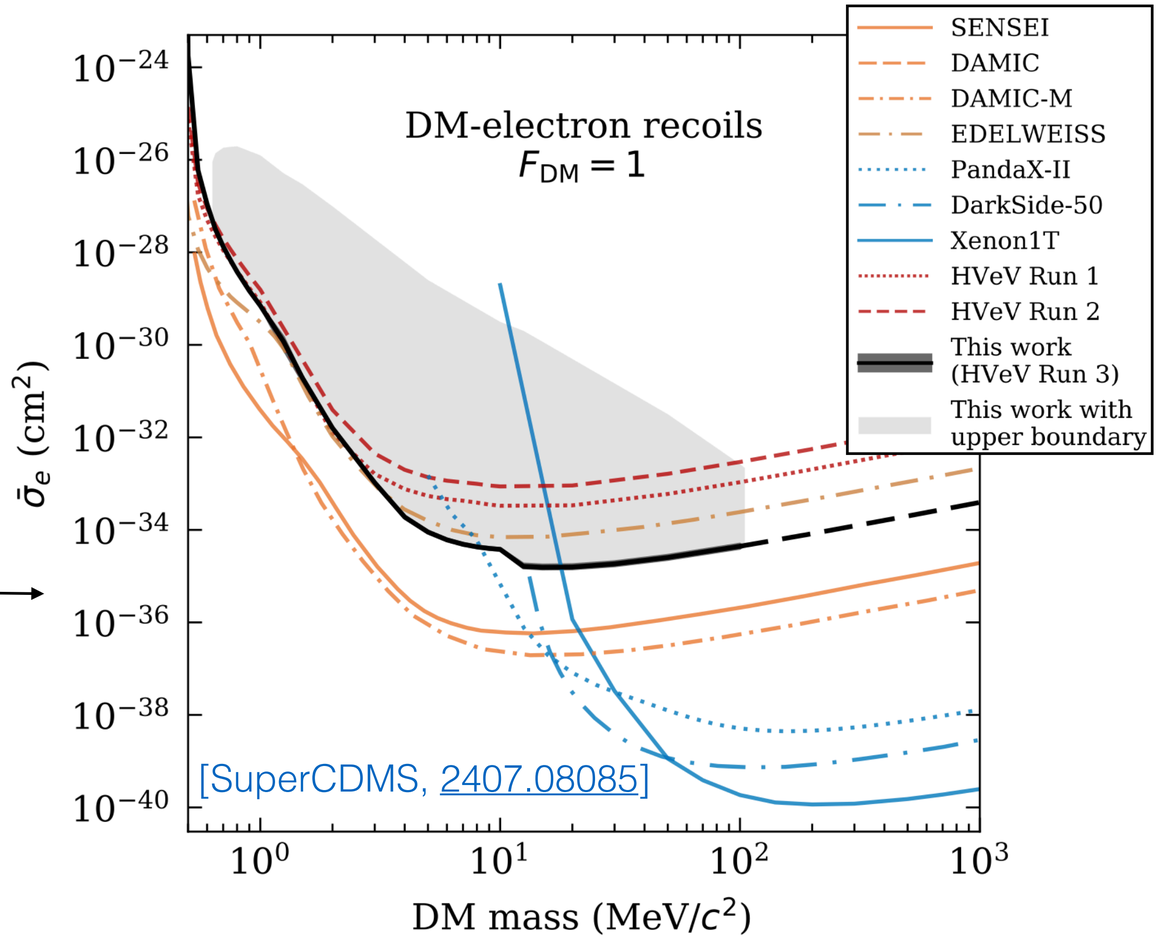
Feb - Jan 2021: Underground run of 4 SuperCDMS HVeV detector (7.63 g-days) [SuperCDMS, 2407.08085]

Current: Detector installation is underway at SNOLAB

2025+: Commissioning and operation

Expect to improve current DM-e limits at 10 MeV by ~ 4 orders of magnitude, and to reach down to DM masses of 0.5 GeV in nuclear recoils

[SuperCDMS, 2203.08463]



Spanish Contribution

David Cerdeño, Elias Lopez, David Alonso, Rafa Lopez at IFT/UAM, with contributions to software; event reconstruction; and remote operation/ construction shifts.

Instituto de Física Teórica UAM-CSIC

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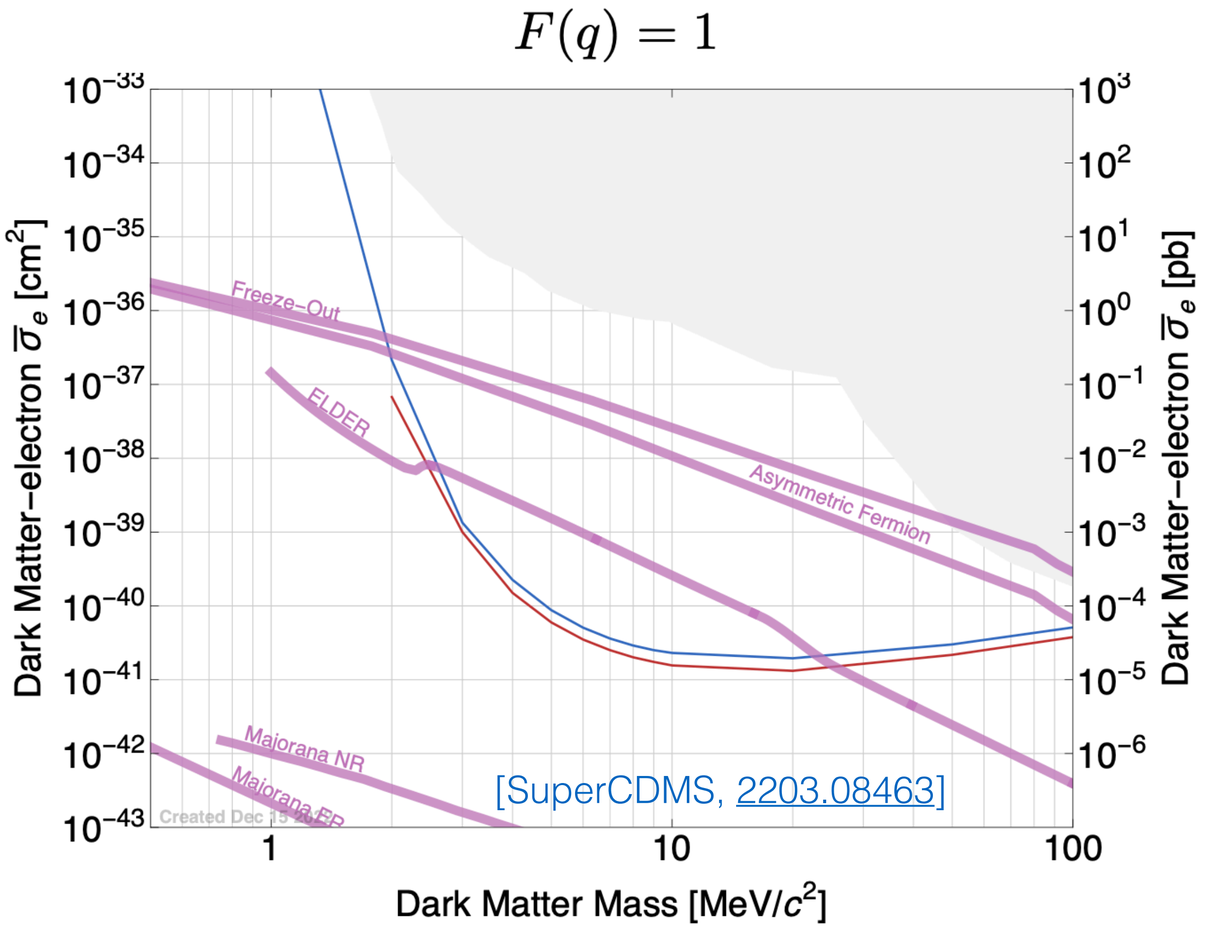

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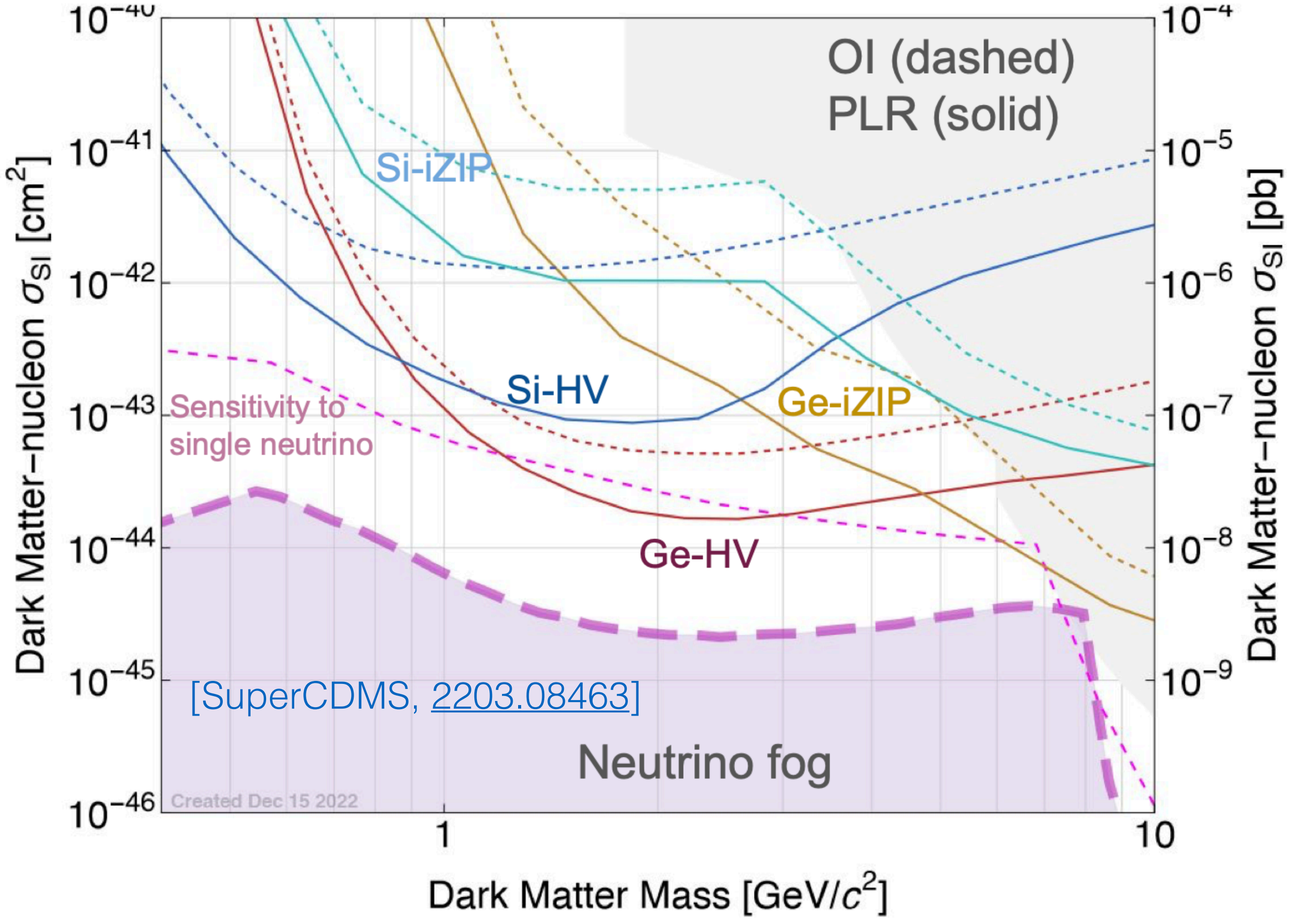

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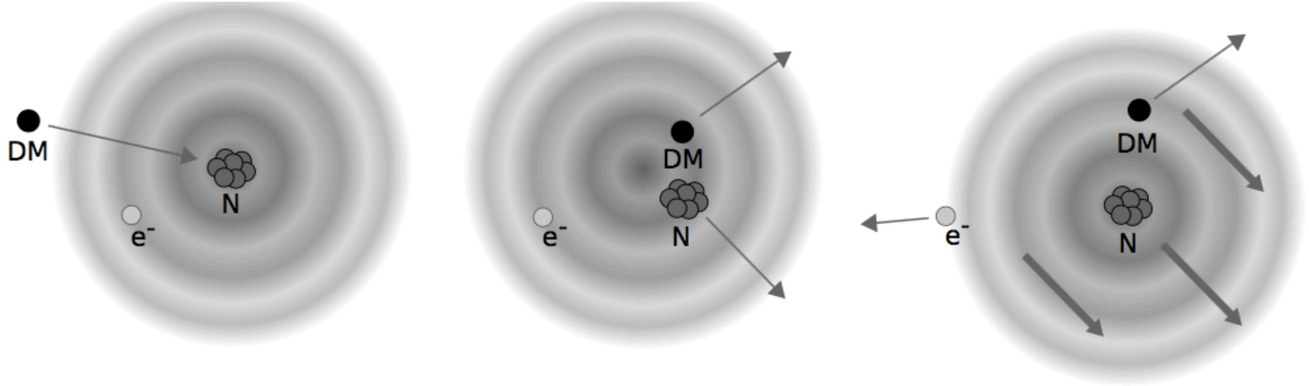
David Cerdeño, Elias Lopez, David Alonso, Rafa Lopez at IFT/UAM, with contributions to software; event reconstruction; and remote operation/ construction shifts.

Instituto de Física Teórica UAM-CSIC

Migdal Effect

Look for the possible ionisation of an electron after a DM-nucleus interaction - "**Migdal Effect**"



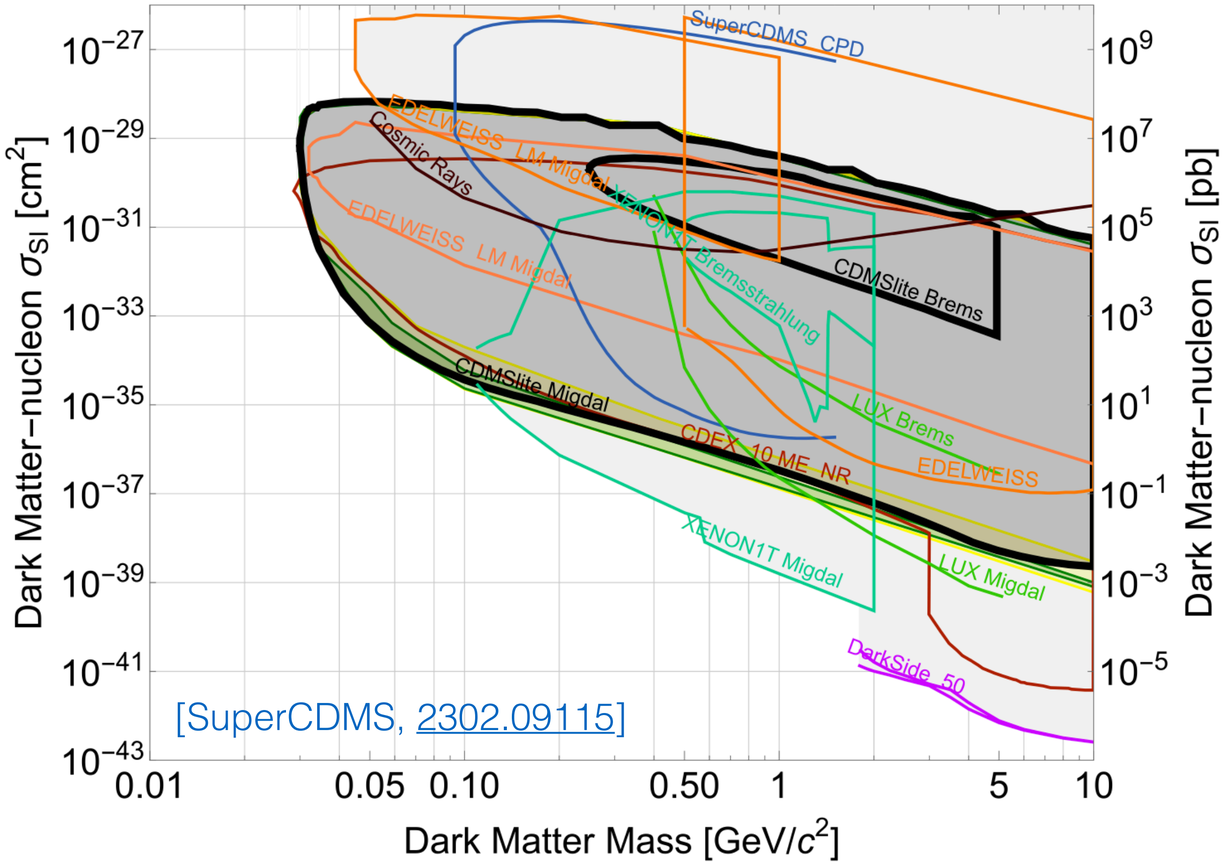
[Migdal (1939, 1941); Ibe et al., 1707.07258; Dolan et al., 1711.09906; Cox et al., 2208.12222]

Energy deposited in nuclear recoil and electromagnetic energy from ionisation:

$$E_{\mathrm{R,max}} = \frac{2\mu_N^2 v_{\mathrm{max}}^2}{m_N}, \quad E_{\mathrm{EM,max}} = \frac{\mu_N v_{\mathrm{max}}^2}{2}$$

Inelastic interaction allows for larger energy deposit, and so **sensitivity to lower masses**!

Not yet recorded in nuclear scattering!



MIGDAL

Migdal **I**n **G**alactic **D**ark m**A**tter exp**L**oration

Recent talk: Tim Marley (Jul 2024)
See also Elias Lopez's talk on Thursday

MIGDAL
Migdal In Galactic Dark mAtter expLoration

[Araújo et al., arXiv:2207.08284]

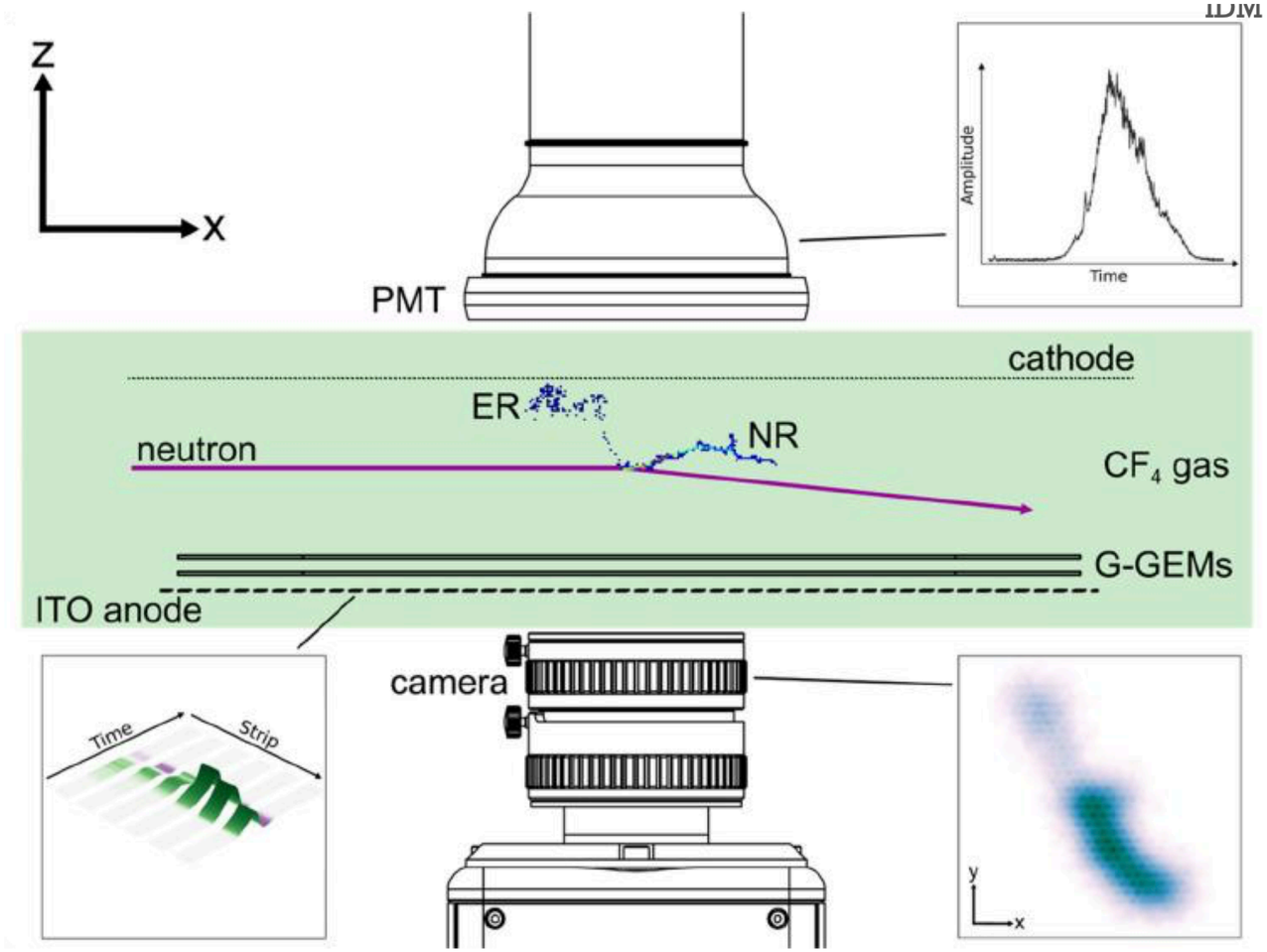
Low-pressure gas TPC, installed at the Rutherford Appleton Laboratory, UK

High-yield neutron source (2.46 MeV, $10^9 n/\mathrm{s}$)

TPC filled with 50 Torr of CF_4 (but can add a fraction of Ar/Xe relevant for DM searches)

3D track readout in optical (camera + PMT) and with charge (ITO anode)

Look for **characteristic Migdal topology**: NR+ER tracks with a common vertex



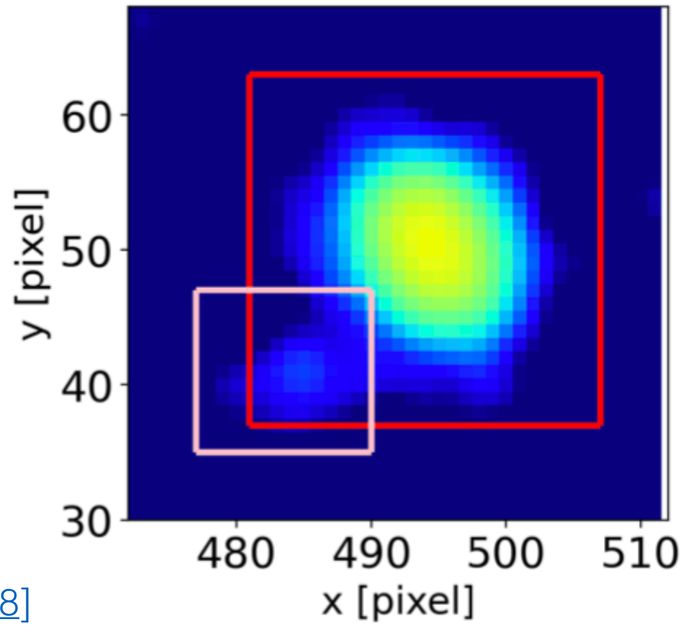
MIGDAL

Migdal **I**n **G**alactic **D**ark m**A**tter exp**L**oration

Data analysis of the two science runs is ongoing:

- SR1: 17/07/23 – 03/08/23
- SR2: 15/01/24 – 06/02/24

~20 million frames! Use CNN to identify NR + ER signals in camera exposures



[2406.07538]

Main background is compton scatters of γ-rays from neutron inelastic scattering, creating events with NR + ER

Camera exposure time (8.33 ms) -> small amount of pileup (can be rejected with ITO, with 2ns timing resolution)

MIGDAL upgrade in progress!
Higher resolution digitizer, higher resolution ITO anode, additional amplification stage, reflection reduction

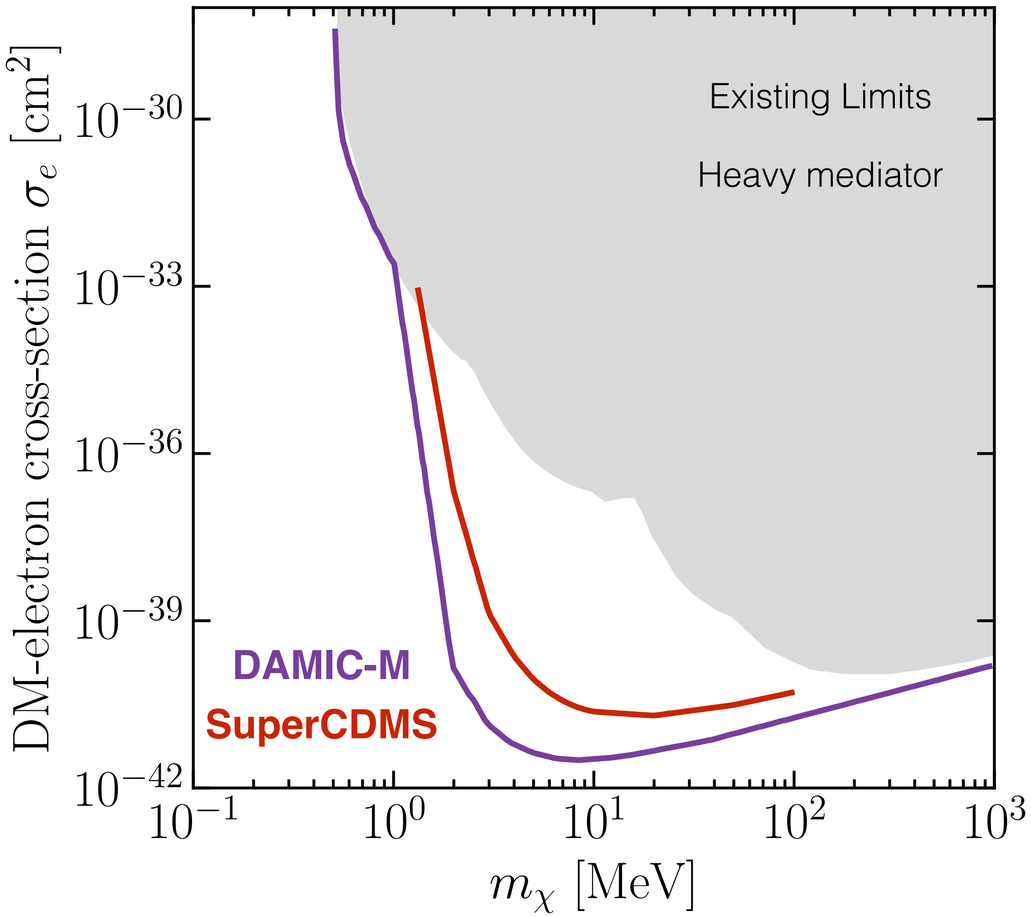
Spanish Contribution

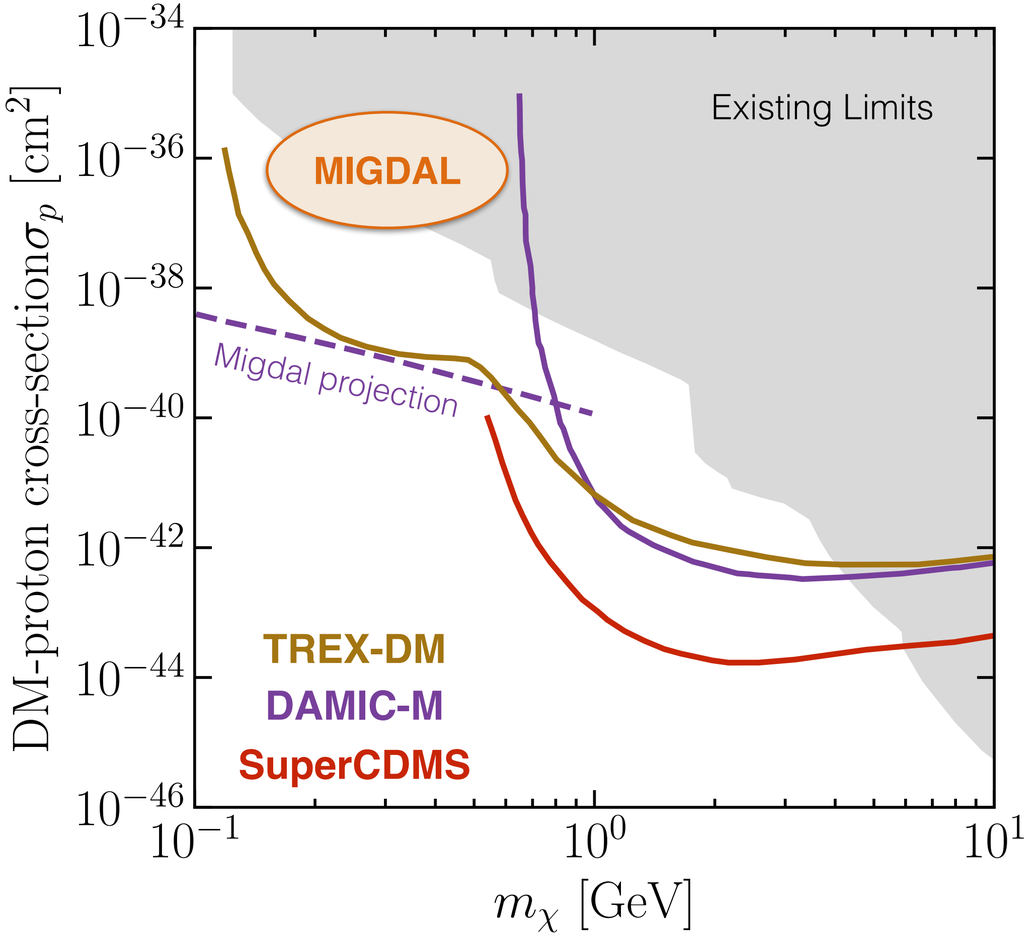
Elias Lopez and lab at IFT/UAM, especially contributions to design and development of the MIGDAL upgrade.

Instituto de Física Teórica UAM-CSIC

Low Mass Landscape

Future projections for light DM…

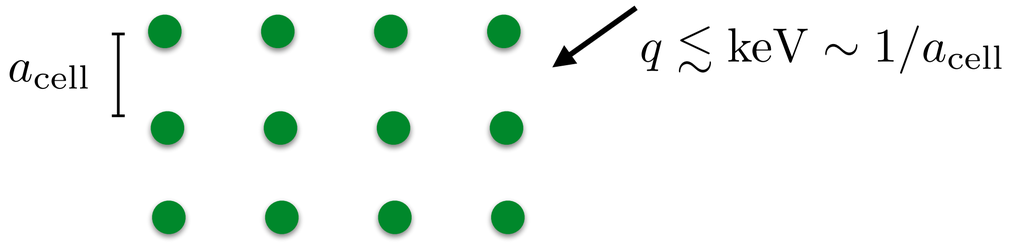




← Sub-MeV may be explored with future **phonon detectors** (new Quantum Sensor R&D)

QS4DM

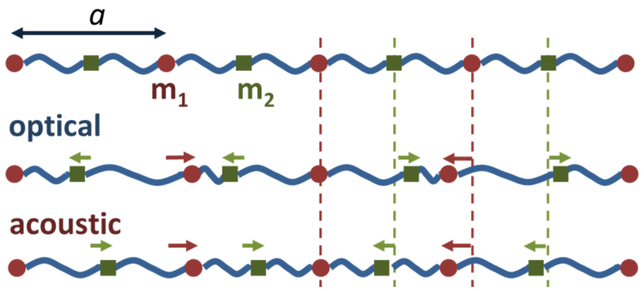
Quantum **S**ensors for **D**ark **M**atter Searches



For sufficiently light DM, $m_\chi < 1\,\mathrm{MeV} \Rightarrow q < \mathrm{keV}$

DM interaction may not be ‘point-like’. Can scatter off excitations in the lattice i.e. **phonons**

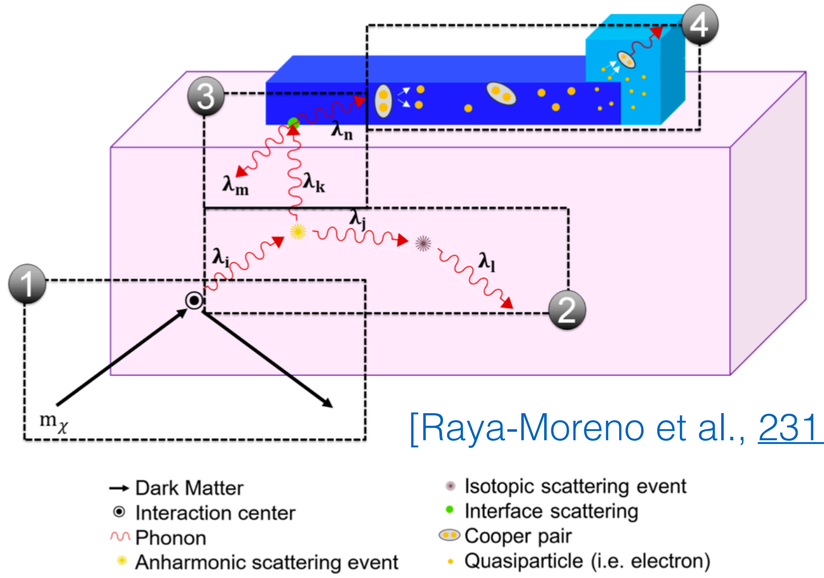
[Trickle et al., 1910.08092]



[Credit]

The phonon band gap can be very small (e.g. ~10s of meV), meaning you could probe very light DM (< MeV).

A number of institutes involved in the modeling, development and testing of Quasiparticle-trap assisted TESs as athermal phonon sensors with thresholds ~100 meV to search for sub-MeV DM (part of QTEP - CSIC quantum technologies platform)

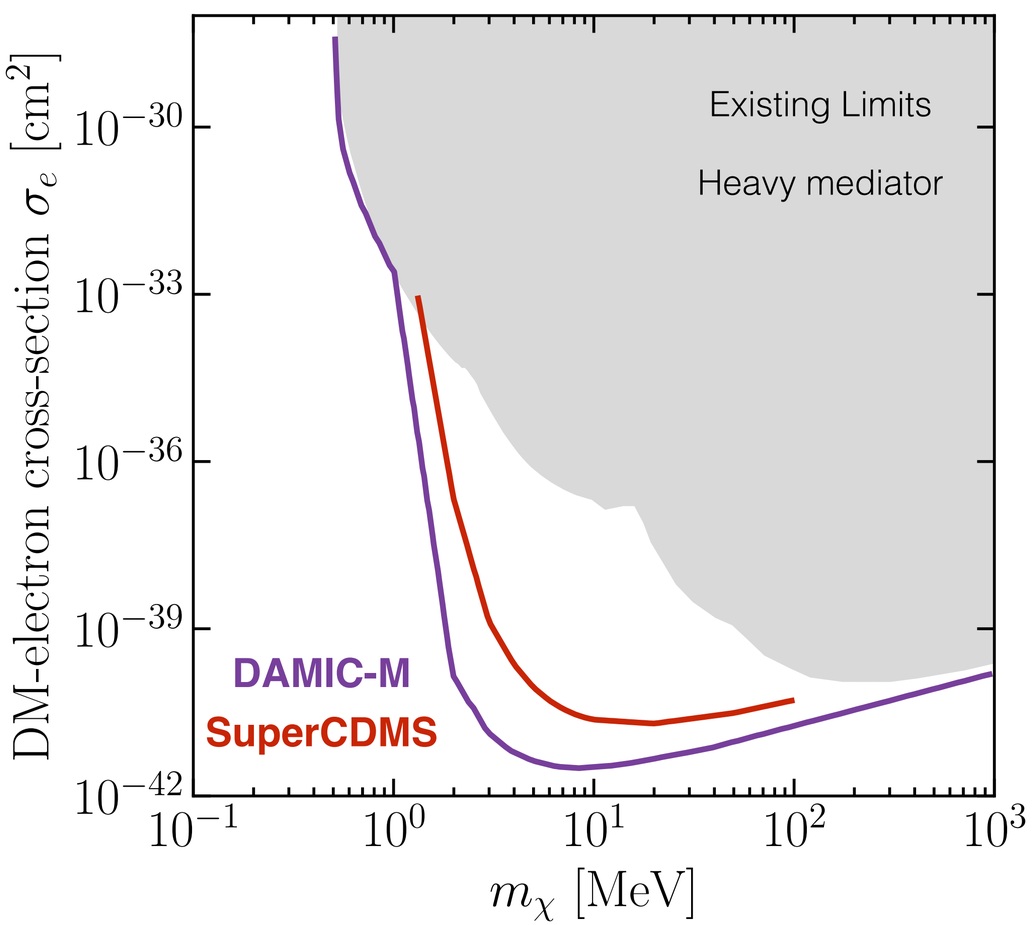


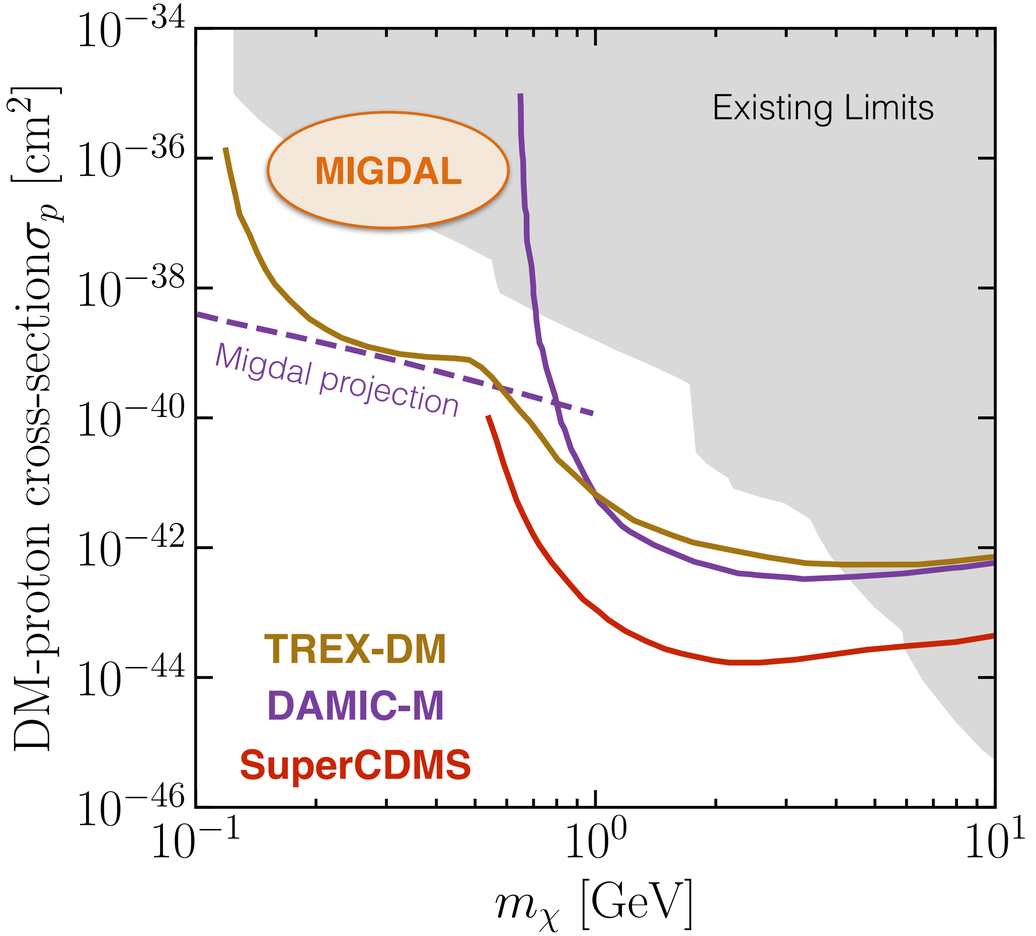
[Raya-Moreno et al., 2311.11930]

[See e.g. slides here for further details]

Low Mass Landscape

Future projections for light DM…





← Sub-MeV may be explored with future **phonon detectors** (new Quantum Sensor R&D)

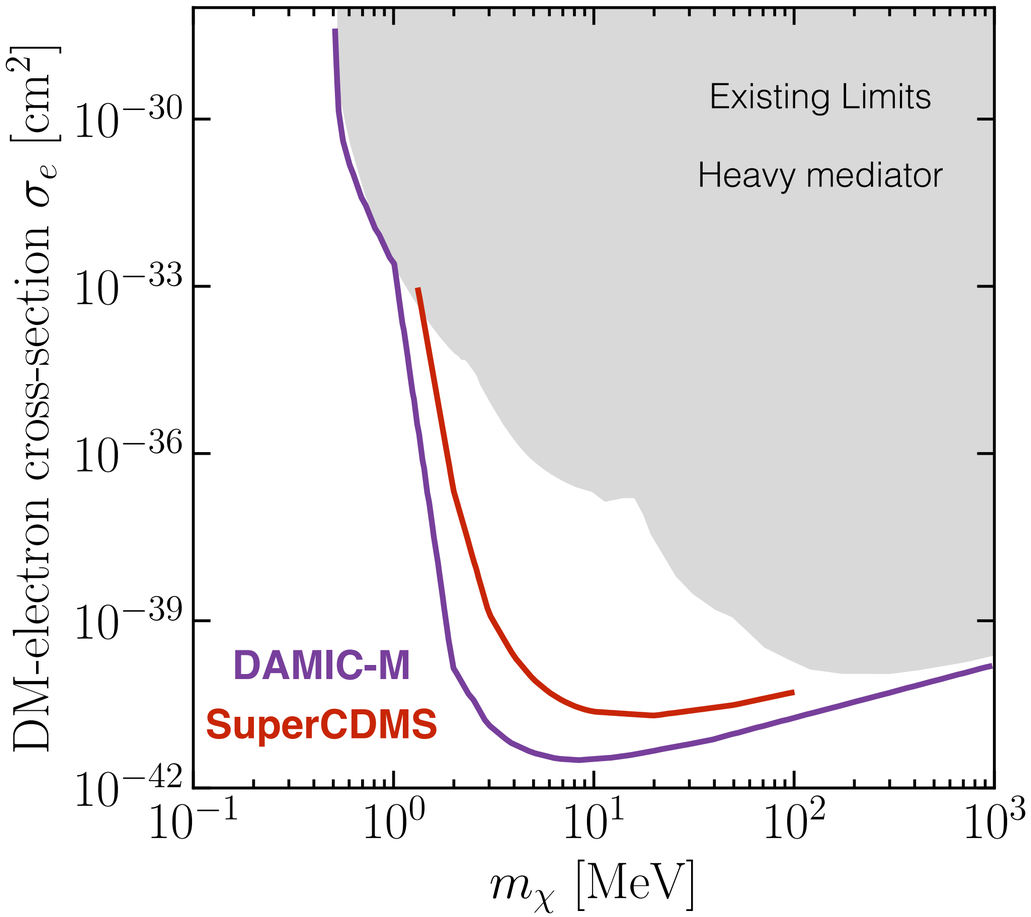
…complementarity across different technologies.

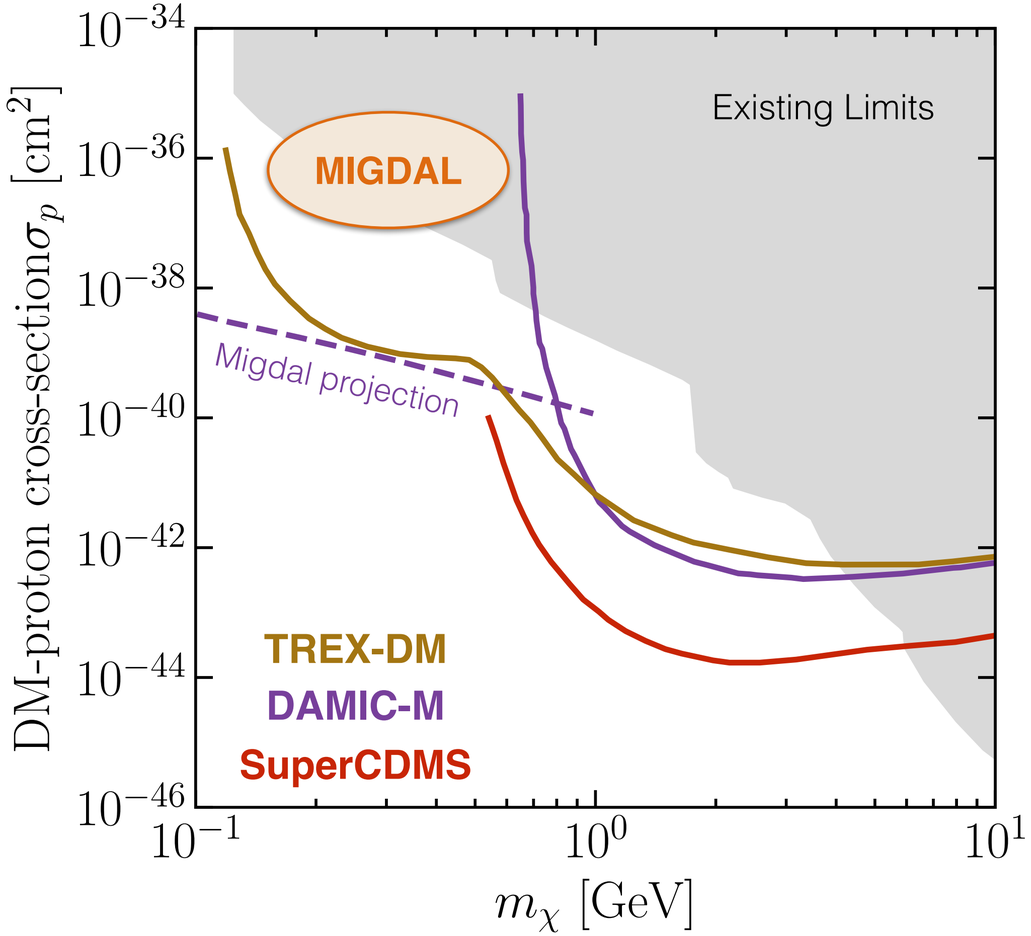
Thanks to Hector Mirallas, Igor Irastorza and Elias Lopez for providing input/links for the talk.

Low Mass Landscape

Thank you!

Future projections for light DM…





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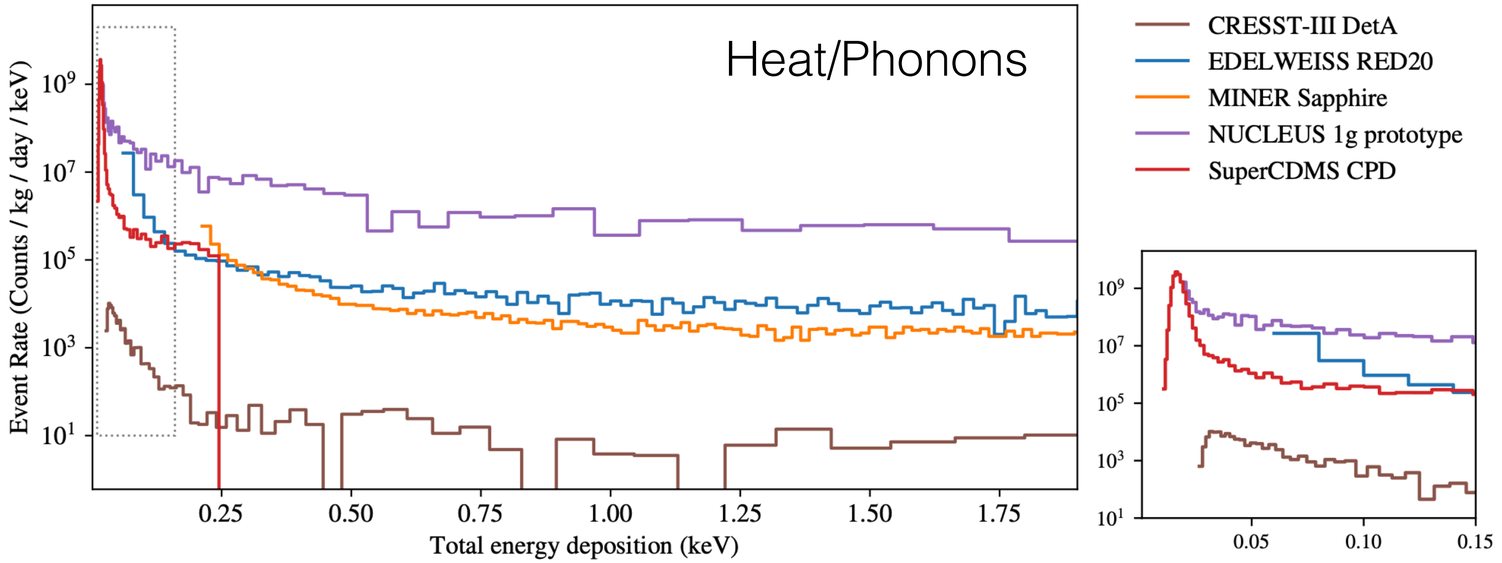
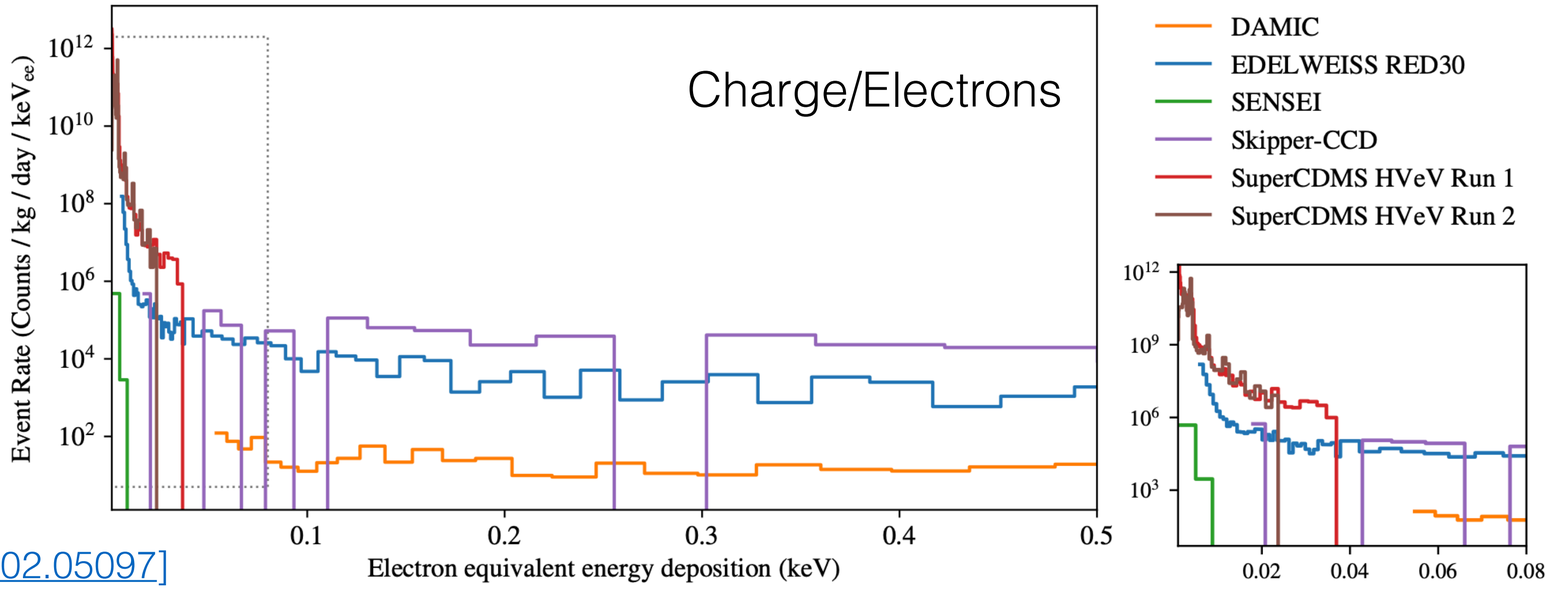
Backup Slides

EXCESS

Understanding low-energy excesses

[EXCESS Workshop Series, https://agenda.infn.it/event/39007/]





[2202.05097]

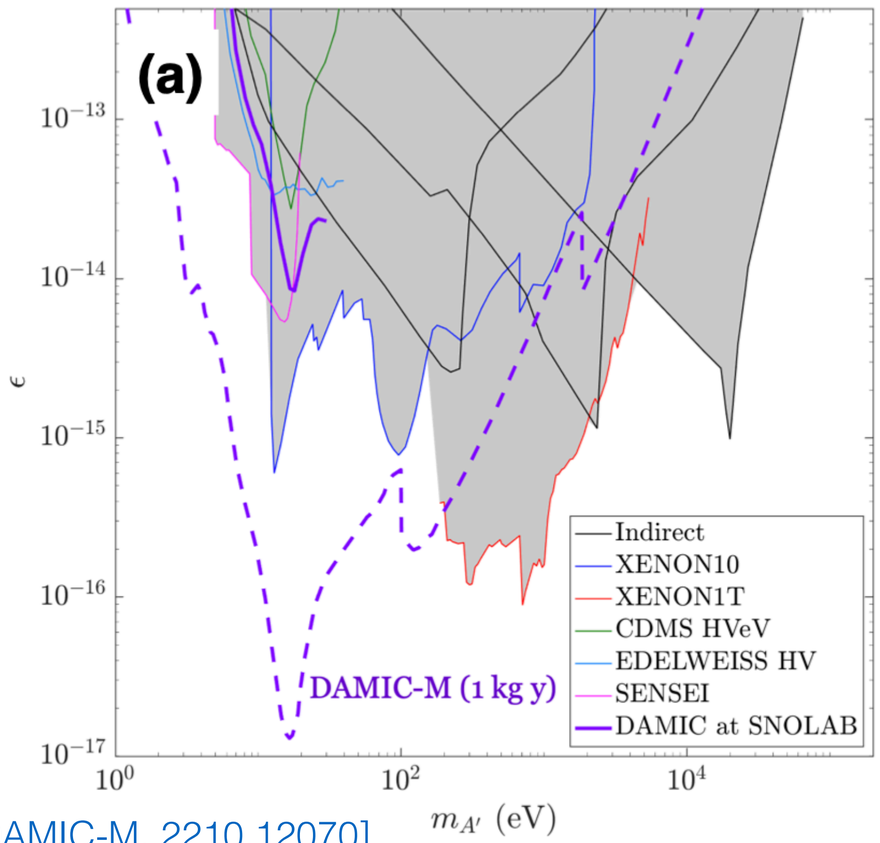
Excess event rate seen in many low-threshold experiments below 1 keV.

Time-dependence and cross-checks in multiple channels suggests that this is not due to DM, but could have a **profound impact on low mass DM sensitivity**!

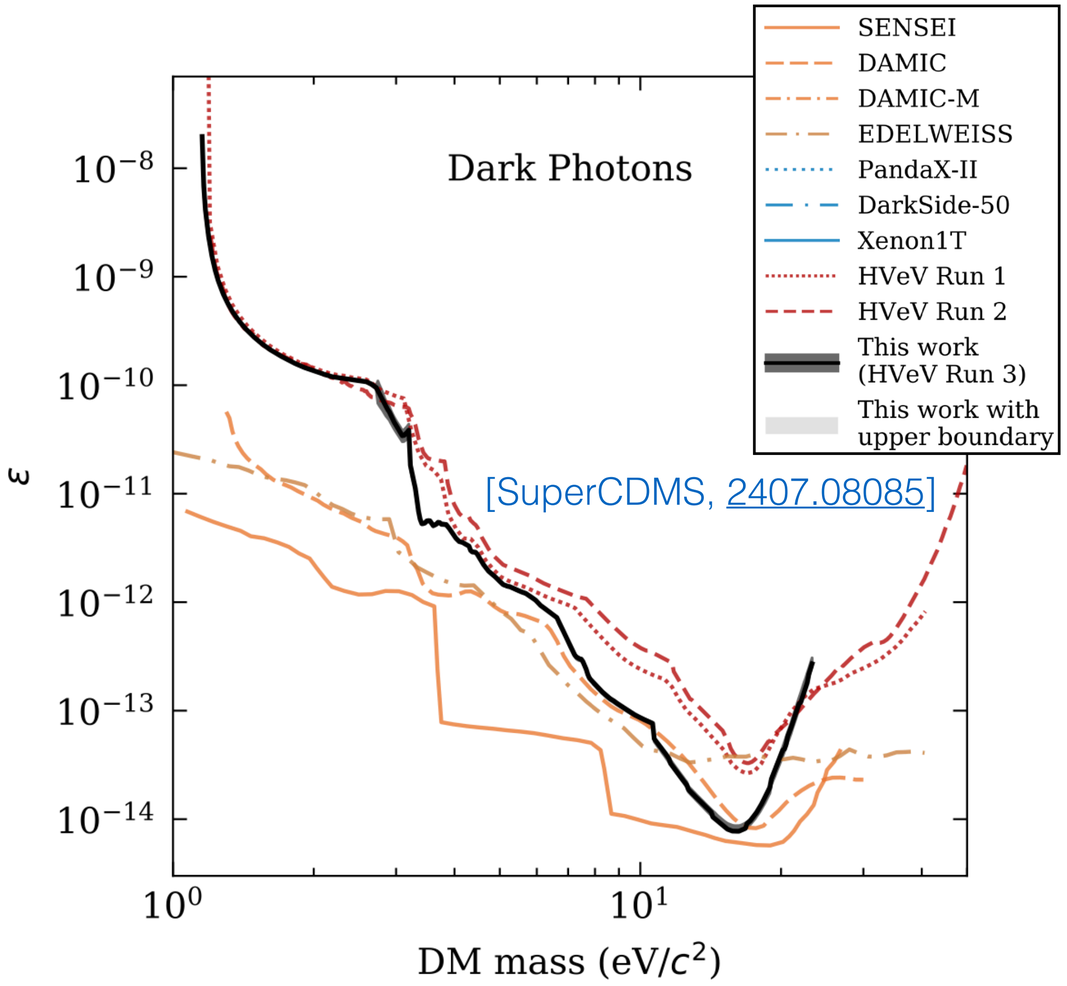
Ongoing work to understand this excess, but could be due to:

- Relaxation of the sensor
- Relaxation of the target material
- Relaxation of supports
- Energy stored in interfaces

Dark Matter Absorption



[DAMIC-M, 2210.12070]



[SuperCDMS, 2407.08085]

Very light vector particles A' may be absorbed directly by electrons, in analogy with the photo-electric effect

Look for a peak of events with a given energy

$$R(\omega) = \frac{\rho_{\mathrm{DM}}}{m_{A'}} \epsilon_{\mathrm{eff}}^2 \sigma_\gamma \left(\omega = m_{A'}\right)$$

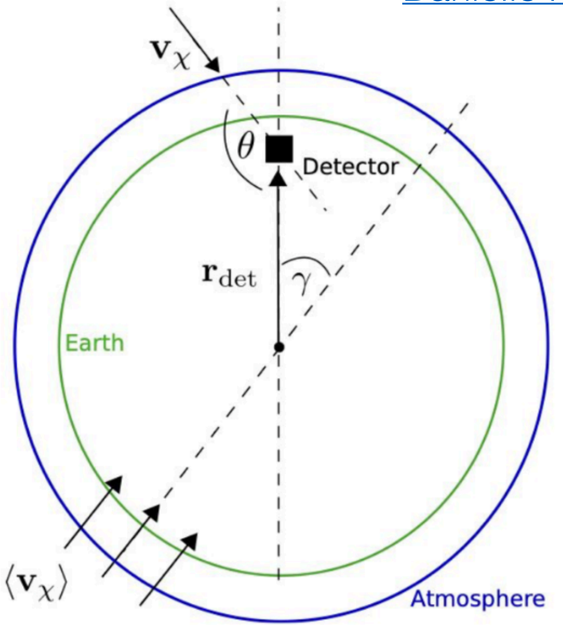
Effective photon-dark photon mixing

Photo-electric cross-section

[Hochberg et al., 1604.06800]

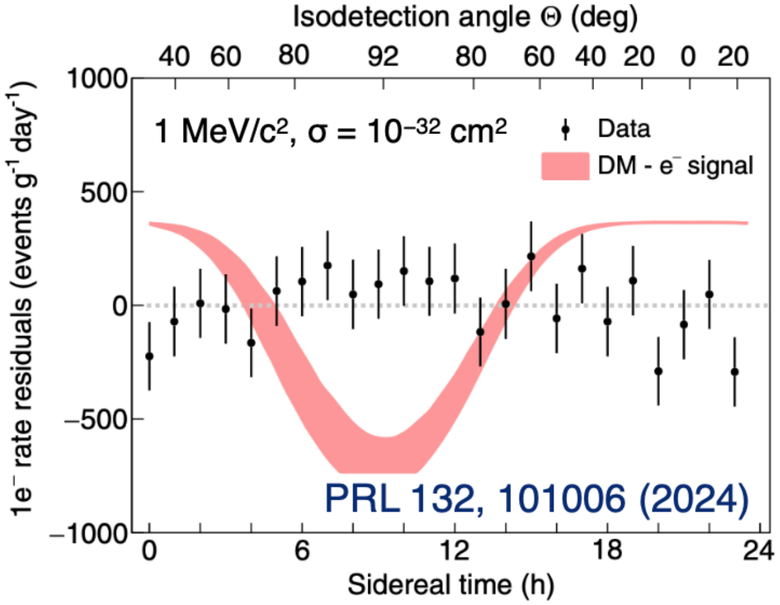
Daily modulation search

Danielle Norcini (Jul 2024)



Motivation:

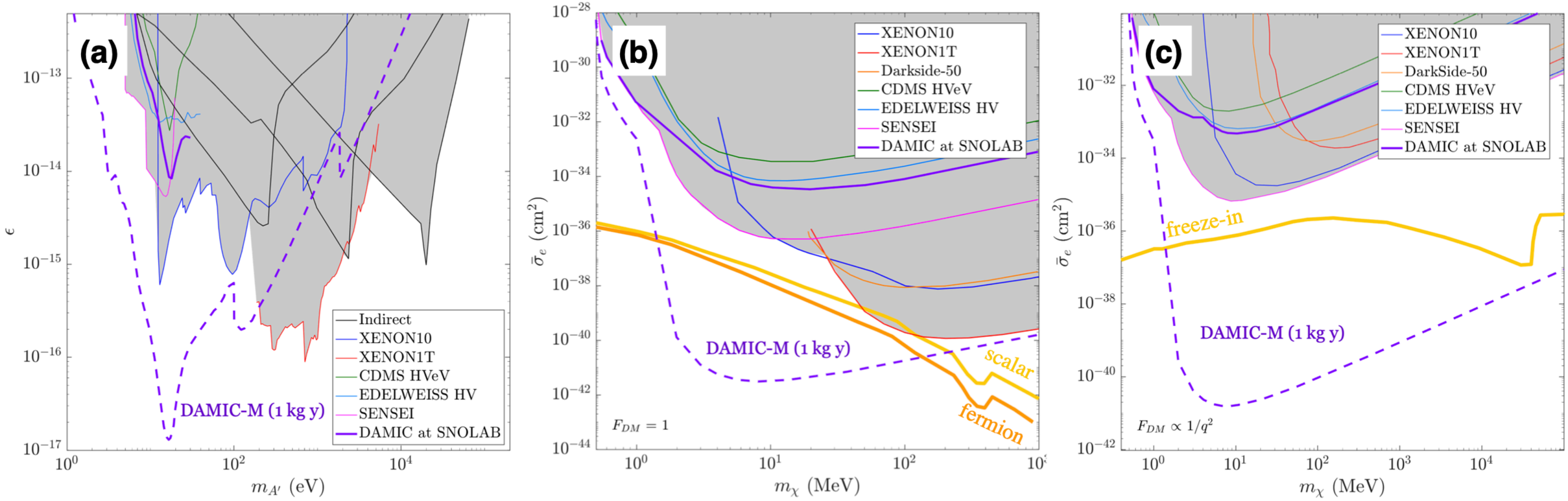
- MeV-scale DM candidates with large cross sections have not been ruled out
- scattering in Earth's bulk becomes relevant for flux/ velocity distribution, DM signal can modulate over day
- in LBC, time-dependent signal vs. independent background strong discriminating power
- new approach for constraining DM-e scattering



LBC result:

- search in 1e- bin, as >1e- already constrained
- same data set as DM-e scattering, except using images taken consecutively every 10min
- no modulation signal found for periods of 1-48 hr
- improves first LBC DM-e by 2 orders of magnitude

DAMIC-M Projections



[DAMIC-M, 2210.12070]

MIGDAL upgrade

- Higher resolution digitiser (CAEN V1730).
  - 14-bit instead of 8-bit.
- Doubling the number of ITO strips to 240, increasing spatial resolution in the ITO subsystem.
  - 0.417 mm instead of 0.833 mm.
- Additional amplification stage.
  - Testing addition of a third GEM (kapton, glass, or ceramic).
  - Testing different structures (M-ThGEMs).
- Reduction of reflections.
  - Opaque GEMs.
  - Considering dark-coating TPC.

Recent talk: Tim Marley (Jul 2024)

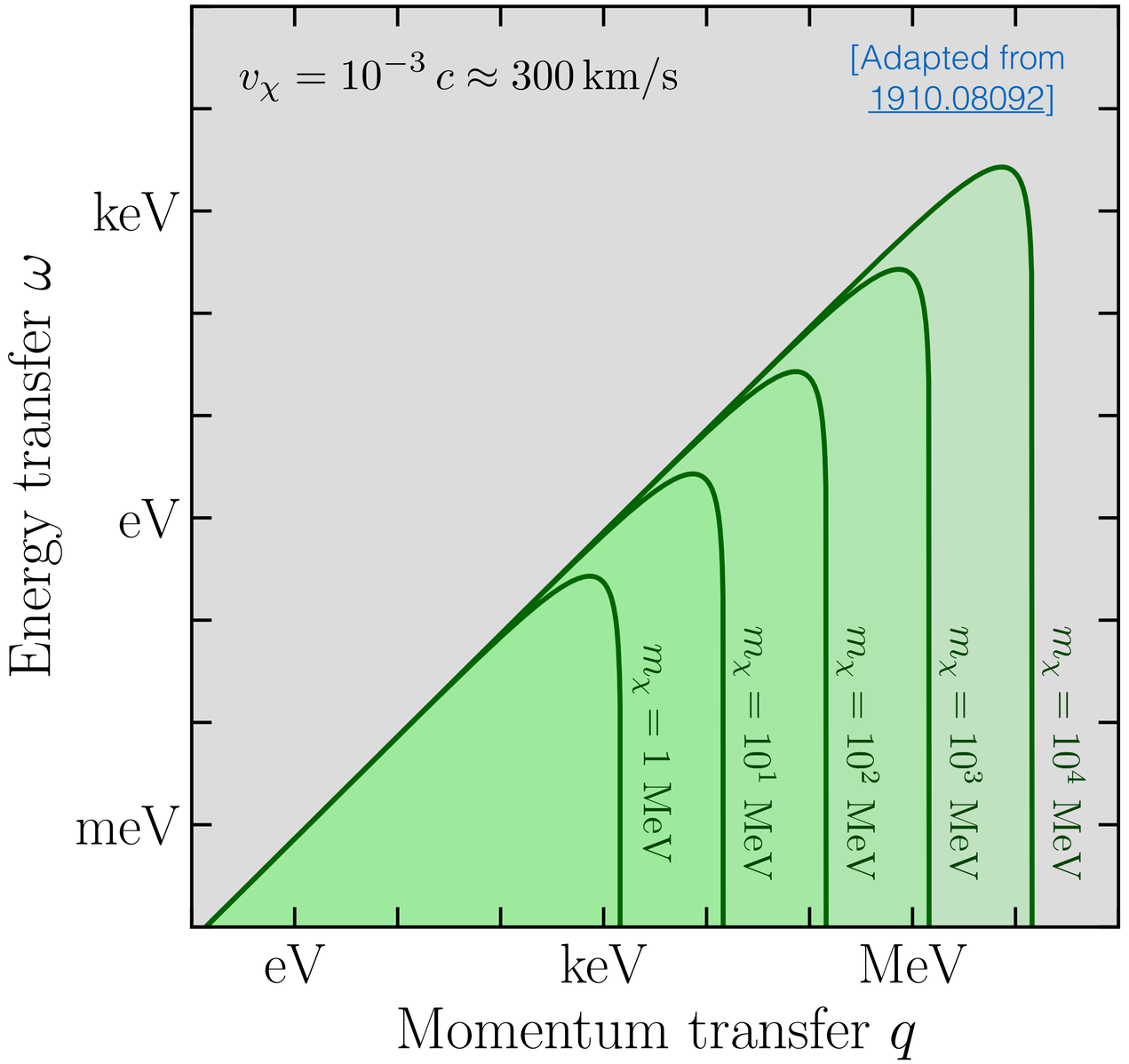
Scattering Kinematics

Allowed range of (ω, q) set by kinematics (green regions):

$$\omega \leq q v_\chi - q^2/2m_\chi$$

Consider:

- **Nuclear recoils** - can probe energies down to eV, but realistically can only measure recoil energies down to ~keV $\rightarrow m_\chi \gtrsim \mathrm{GeV}$
- **Electron ionisation** - possible for $\omega > \Delta \sim \mathrm{eV} \rightarrow m_\chi \gtrsim \mathrm{MeV}$
- **Phonon interactions** - possible for sufficiently small q, with $\omega_{\mathrm{ph}} \sim \mathcal{O}(10\mathrm{s})\,\mathrm{meV} \rightarrow m_\chi \sim \mathrm{keV} - 50\,\mathrm{MeV}$



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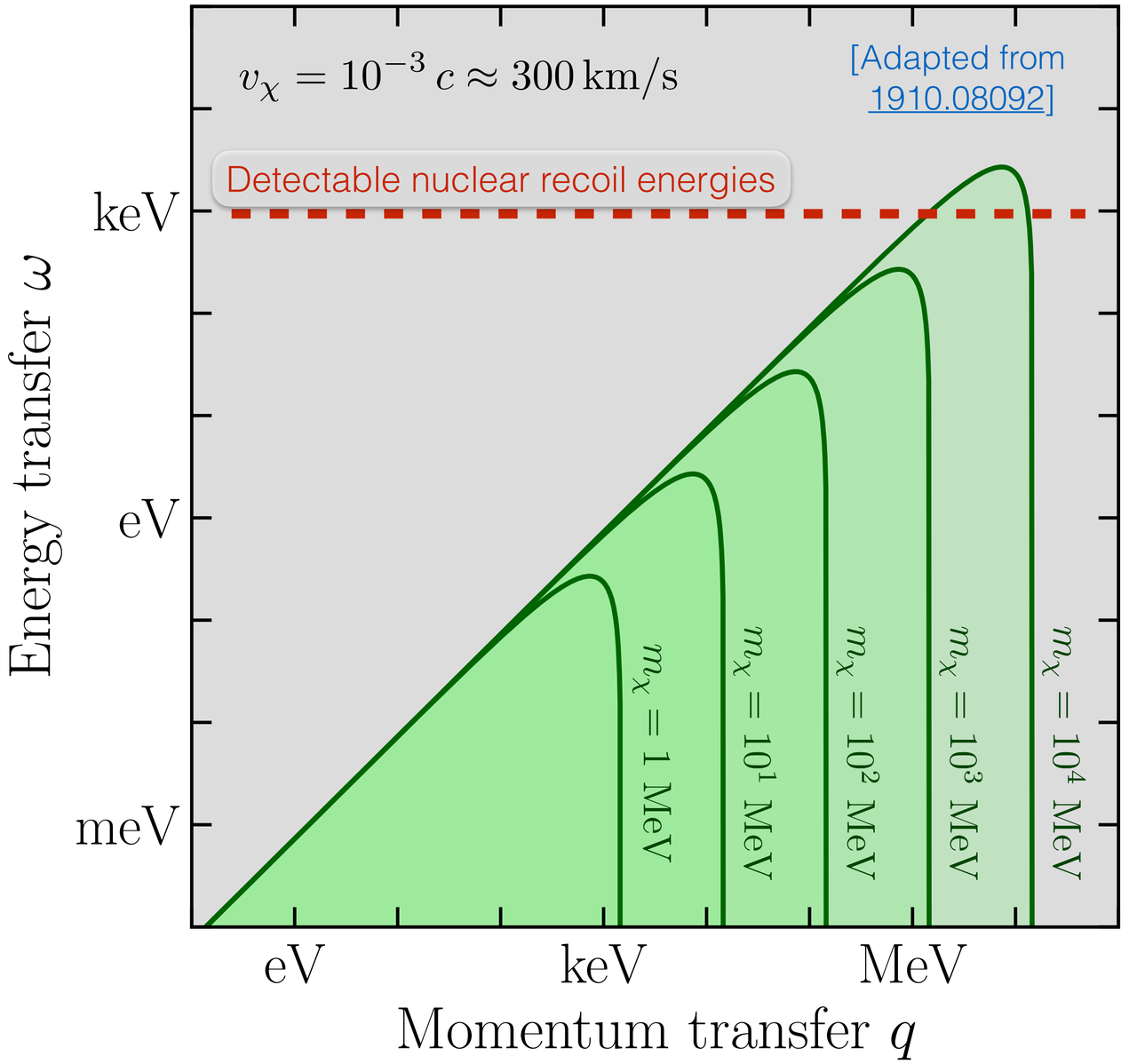

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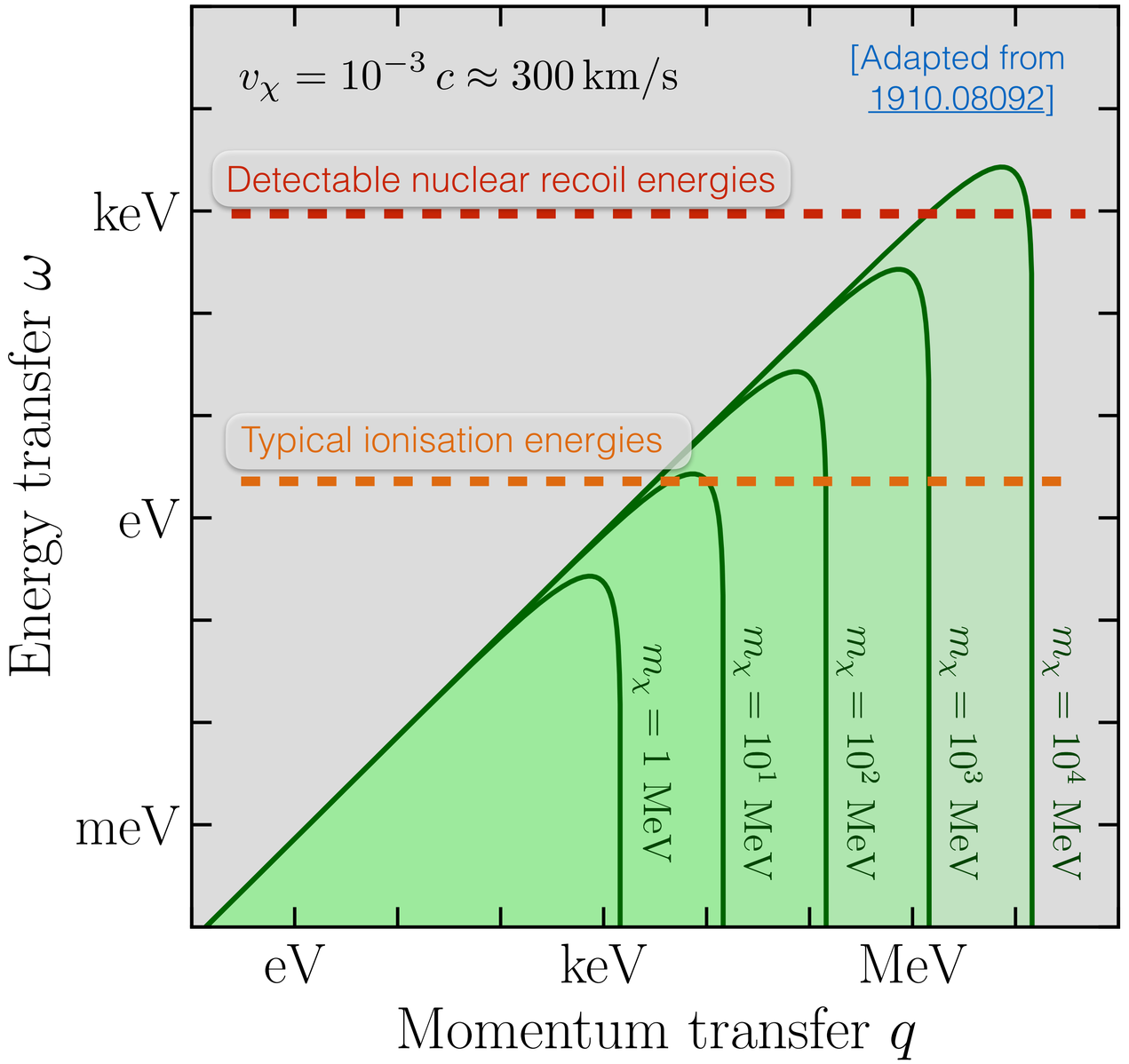

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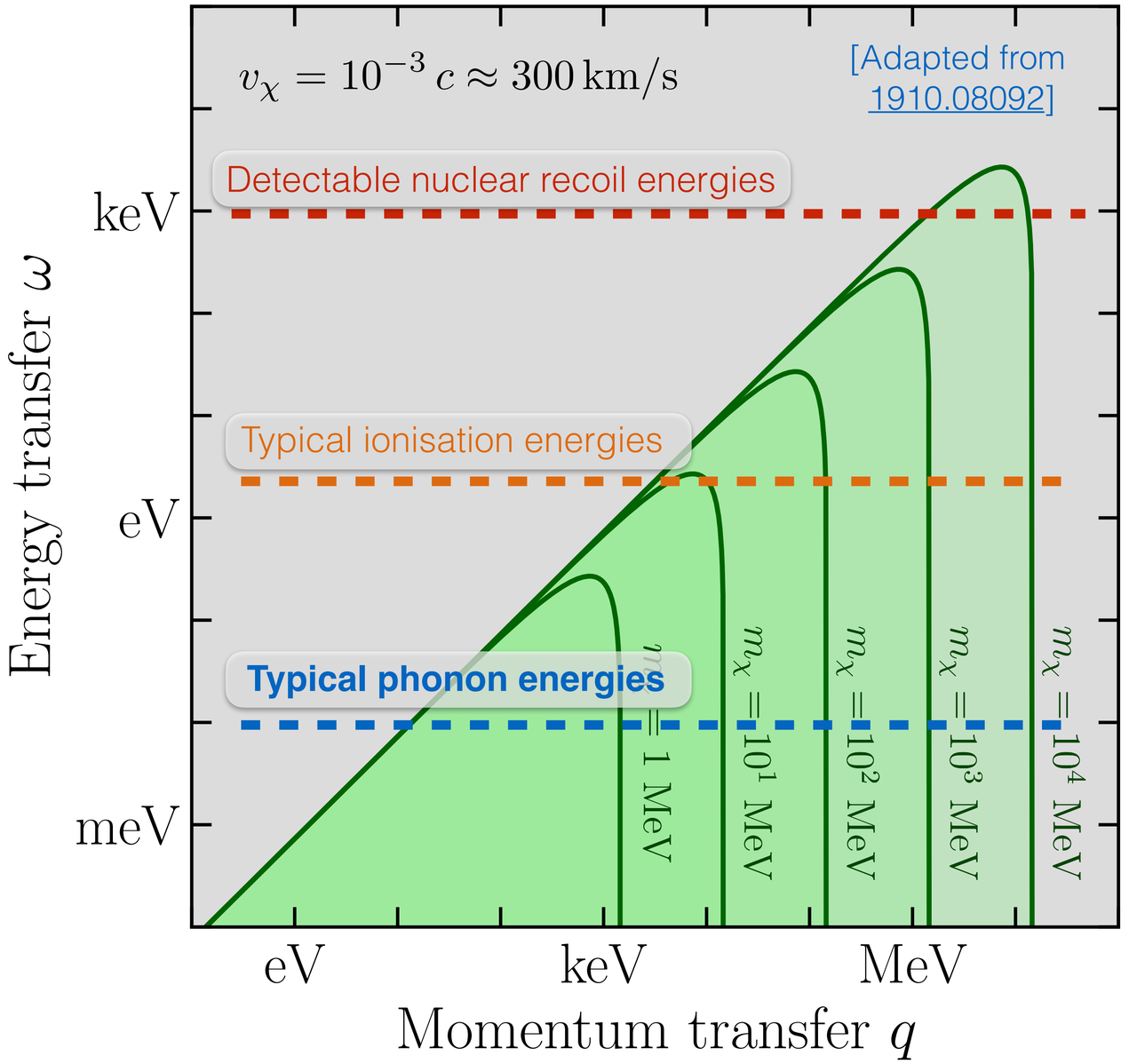

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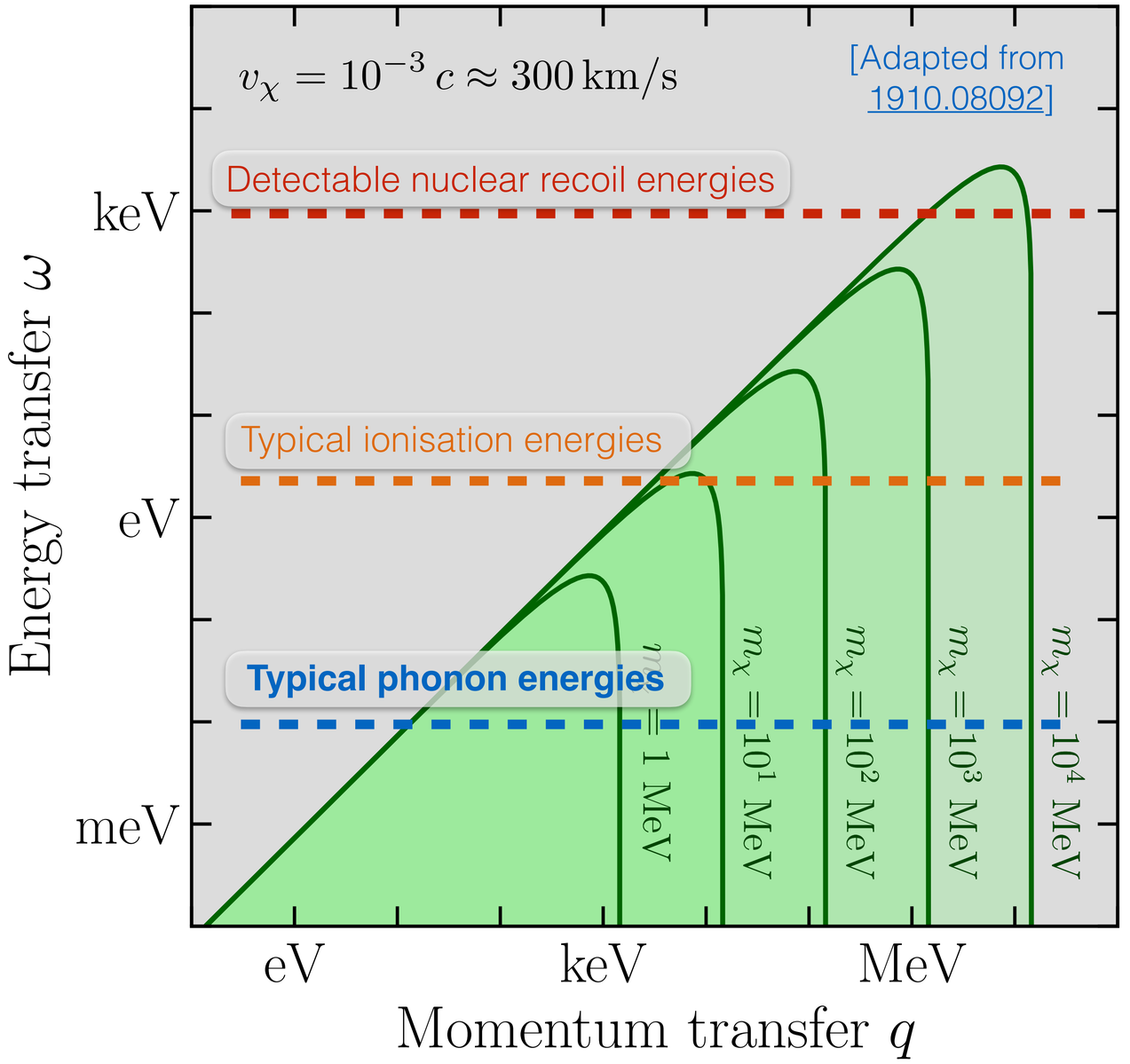

DM mass ranges: