Review of DIRECT SEARCHES for LIGHT DARK MATTER (+DAMIC-M results)

XVII CPAN DAYS

Valencia, 21st November 2025

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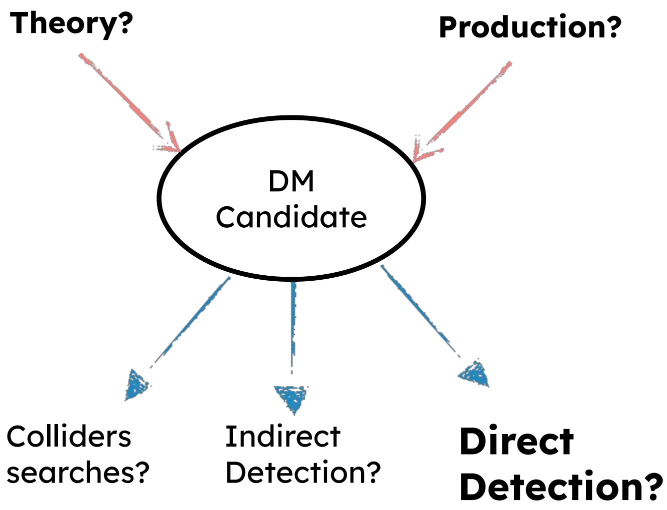
Review of direct searches for **light** dark matter (**+DAMIC-M results**)



O(100) papers in the past 5 years

Different detection technologies

Active and growing community with various R&D programs and small-scale projects

This is not an exhaustive review of all experiments, I focus on sub-GeV dark matter (so no ALPs)!

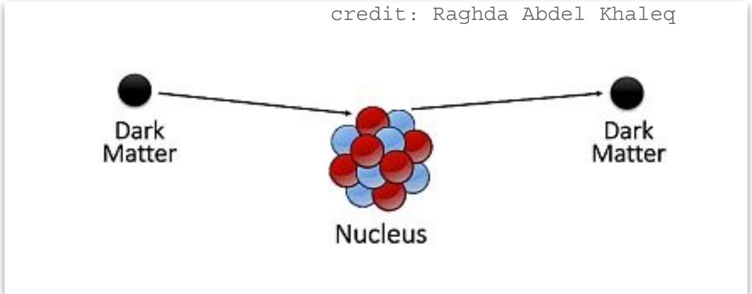
Dark Matter Particle Direct Detection

Dark Matter is **cold**, meaning it **moves slowly** compare with the the speed of light, about a few ~100 km/s, which means is **non-relativistic**, so its **kinetic energy** is **tiny**.

$$E_\chi = \frac{1}{2} M_\chi v^2 = \frac{1}{2} M_\chi c^2 \beta^2 \approx \left(\frac{M_\chi c^2}{\mathrm{MeV}} \right) \mathrm{keV}$$

non relativistic DM: A 1 GeV (proton mass) particle has 1 keV of kinetic energy (very little) ⇒ It's set the the scale of the signals we look for

Local density is ~0.3 GeV/c²/cm³, but we do not know the particle mass (M□)



The most natural interactions is elastic scattering off an atom in the detector

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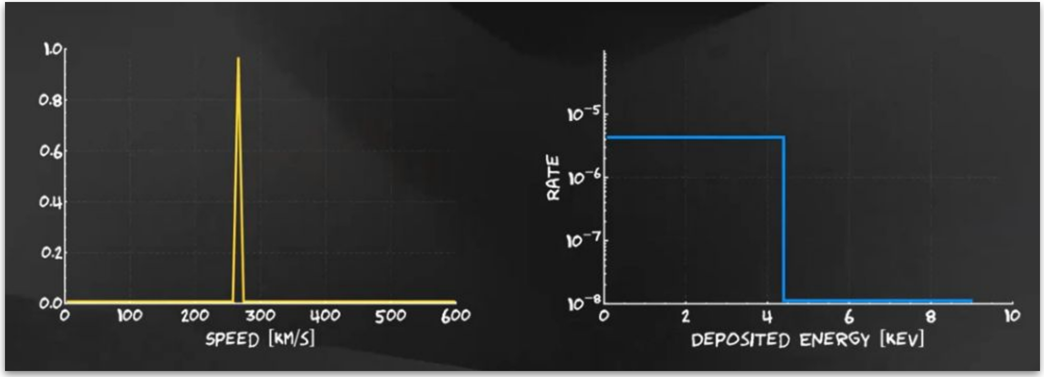
Velocity Distribution Recoil Energy Spectrum



If all particles had the same had the same speed, the recoil energy would range up to a maximum set by the DM mass and velocity.

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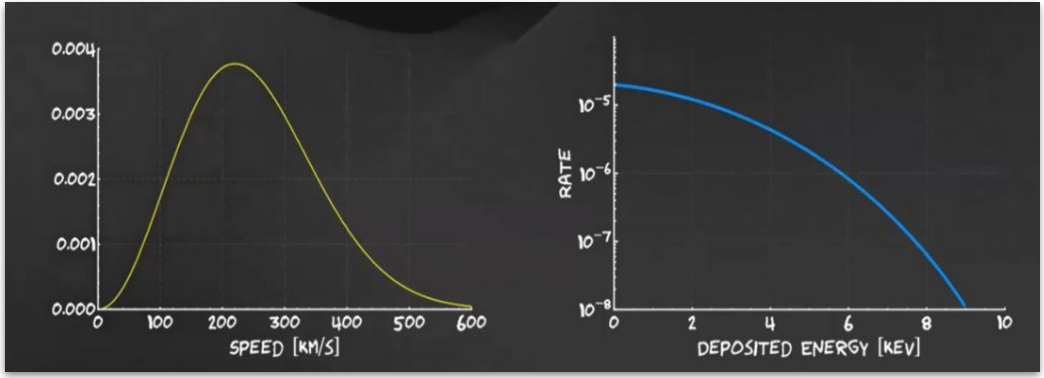
Velocity Distribution   Recoil Energy Spectrum

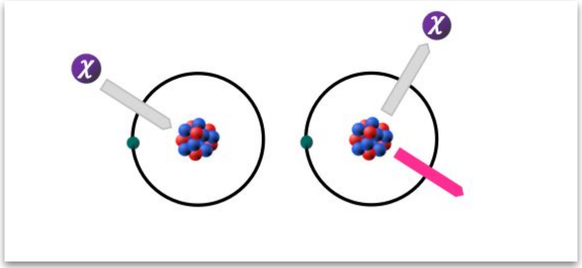


But in reality, DM follows a velocity distribution, typically modelled by a Maxwell-Boltzman distribution, so most recoils are at the very low energies, in the keV range.

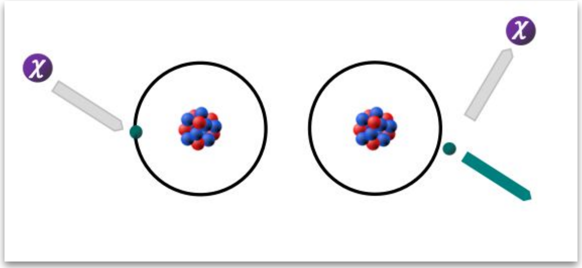
Dark Matter Scattering with SM

Detection Mechanism

Elastic DM–nucleus scattering (mass GeV-TeV)



Inelastic DM–electron scattering (mass sub-GeV)



DM-nucleus scattering with Midgal (promising avenue)

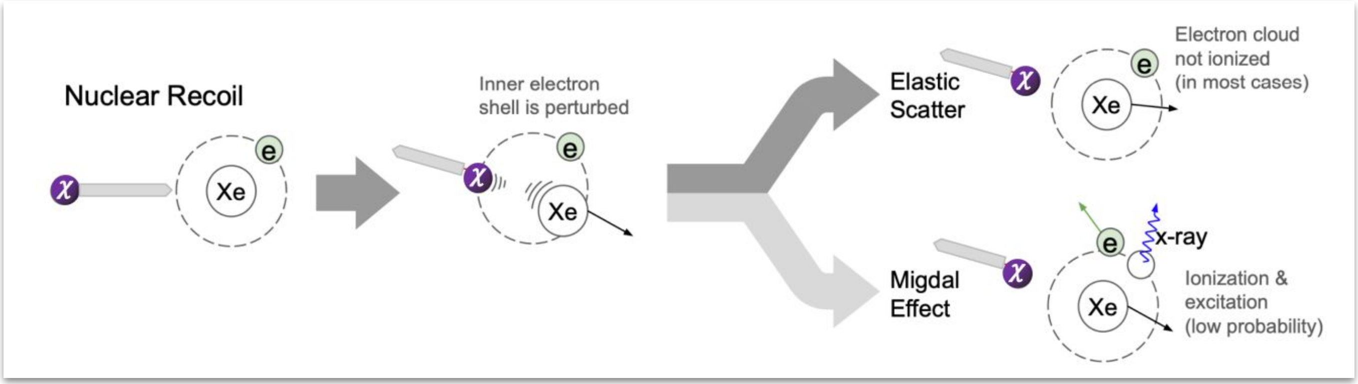


figure credit: Karoline Schäffner

Dark Matter Interactions and Signals

How do we turn “an interaction” into an experimental prediction?

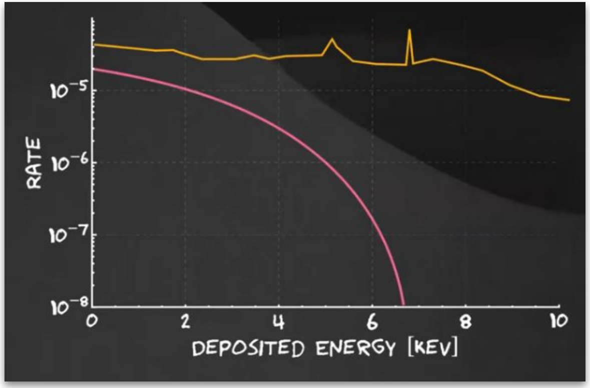
Given a particular theory for DM interactions with quarks/nuclei, some astrohphysical input, and a detectore response, we can calculate

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi\, m_A} \cdot \int v\, f(\mathbf{v},t) \cdot \sigma_0\, F_{\mathrm{DM}}^2(q) \cdot F^2(E)\, d^3\mathbf{v}$$

But here is the reality: the **expected signal** is **tiny compared** to **backgrounds**: Low energy (~ keV scattering), Rare events < 10^{-5} evt/kg/day

Experimental challenges:

- Reduce backgrounds (undergrond, shieldings, ultra-clean materials)
- Achieve low energy thresholds
- Maximize exposure



..wait for an extremely rare interaction to happen

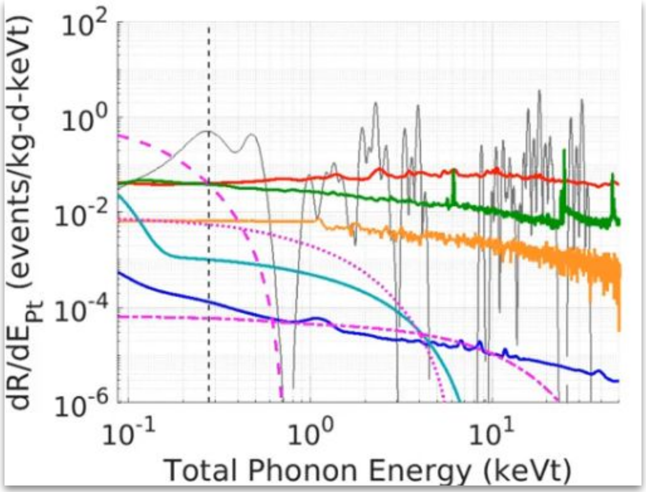
Dark Matter Interactions and SIGNALS

Even underground, backgrounds remain a major challenge

Expected background spectra of single scatter interactions for **SuperCDMs** experiment

DM Candidates
- - - 1.6 GeV
· · · · 5.0 GeV
- · - 16 GeV

Compton scatters from **gamma-rays**
Surface **betas**
Surface 206Pb **recoils**
neutrons (rock, and muon induced)
coherent elastic **neutrino-nucleus scattering**



adapted from arXiv: 2203.08463v2

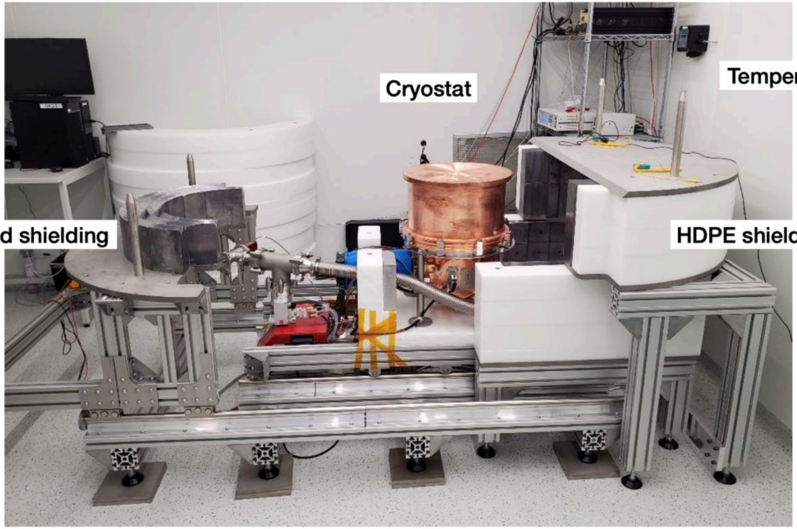
These experiments are so complex, they are not just about building a sensitive detector, but also about creating an environment where the signal can emerge from the noise.

Dark Matter Interactions and SIGNALS

Even underground, backgrounds remain a major challenge

total exprected background **~5 d.r.u.** → **15 d.r.u.** (not fully closed, 5-cm open shielding ⇒ muon-induced neutron background ⇒ 1 event in 1.3 kg-year exposure time) C

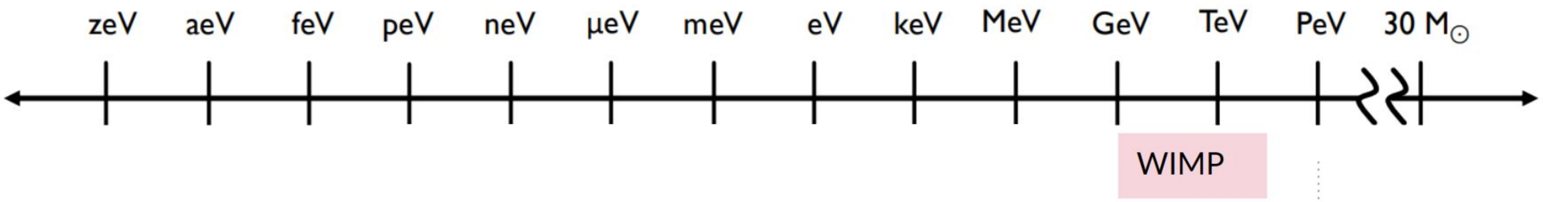
LBC (Low-Background Chamber)
the DAMIC-M prototype



What exactly are we looking for?

A matter of perspective: plausible mass range

by MASS RANGE



by PHYSICAL BEHAVIOR

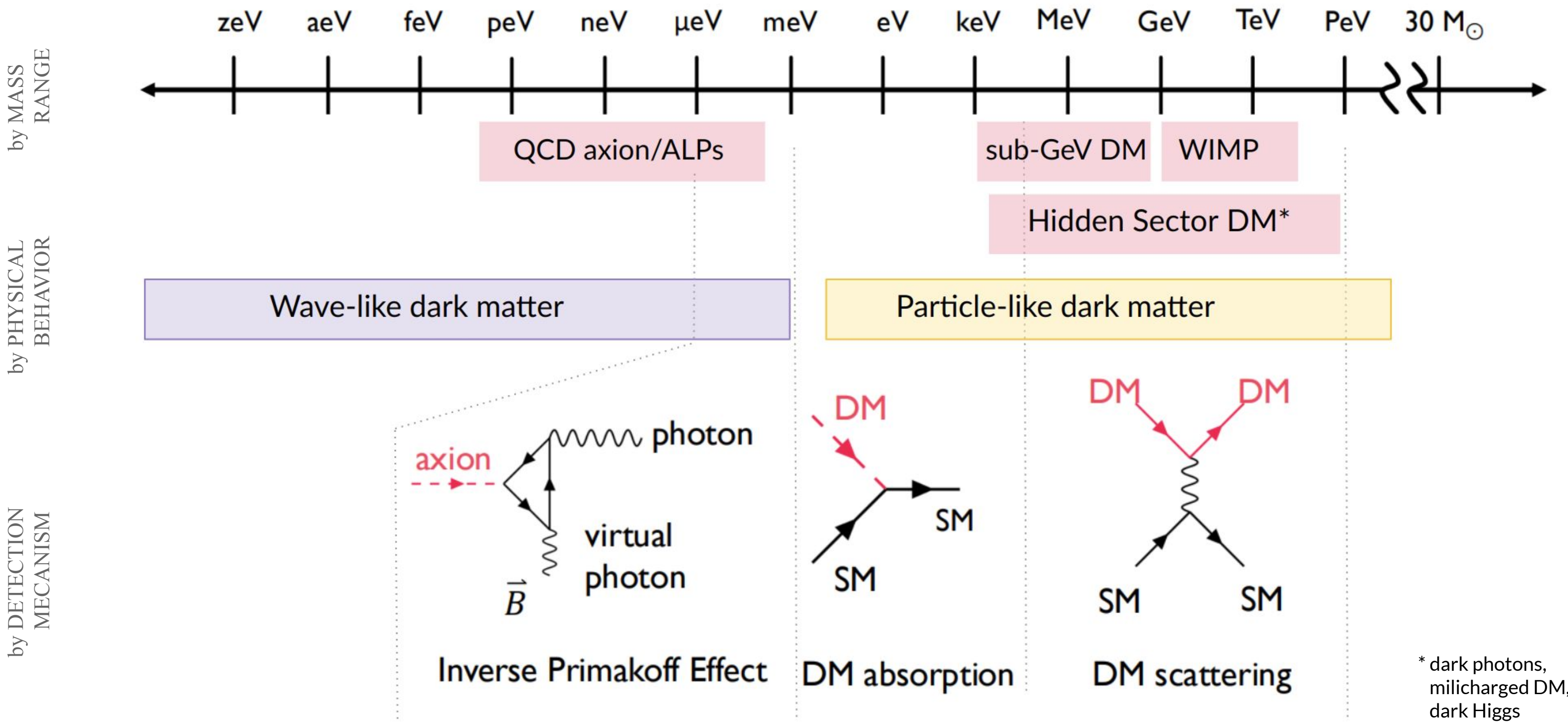
mass ~10-100 GeV and weak interaction, makes them a **perfect thermal relic candidates**

If WIMPs exists, they should scatter elastically off nuclei, producing nuclear recoils in the keV range, that is whay mostly experiments were deign to look for

by DETECTION MECANISM

What exactly are we looking for?

The landscape is broader

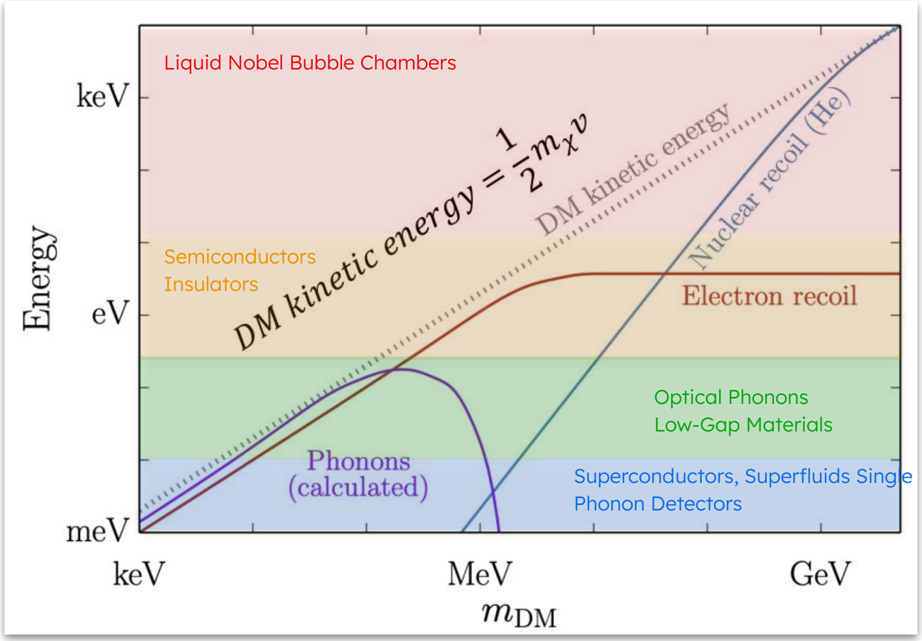


* dark photons, milicharged DM, dark Higgs

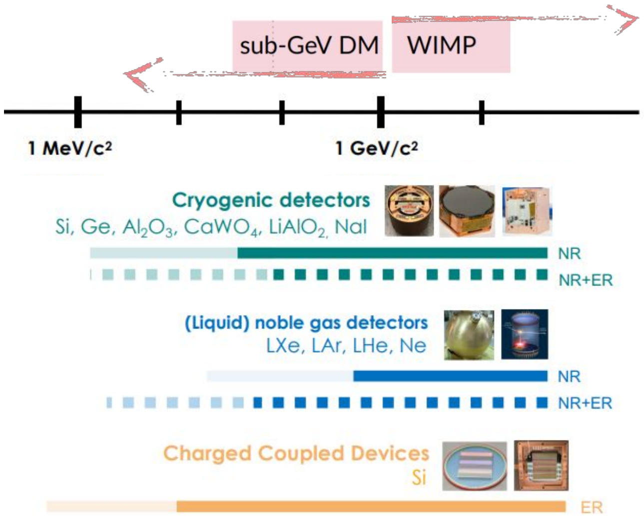
Detection Techniques and Targets

Energy Thresholds

From WIMPs to light DM, the physics forces us to rethink detection from the gourd up



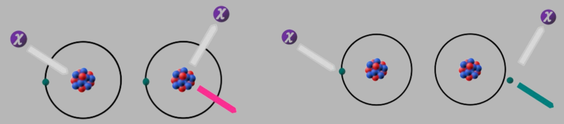
Adapted from: arXiv:1904.07915

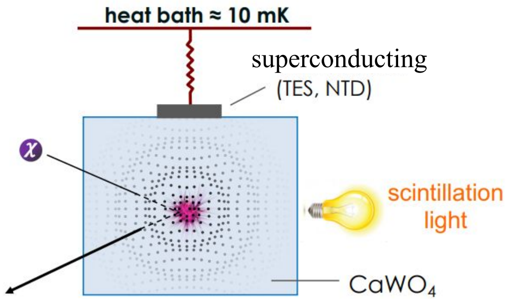


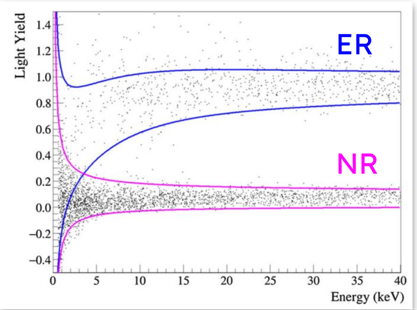
sub-GeV DM WIMP

Cryogenic Detectors

CRESST-III, SuperCDMs @SNOLAB @SURFACE, EDELWEISS







J Low Temp Phys 193:1160–1166

ANATOMY OF AN INTERACTION

Primary signal: DM creates phonons/heat

→ temperature increase measured by thermometer

→ precise measurement of (almost) full deposited energy

Secondary signal: scintillating target

→ separate cryogenic detector for light signal

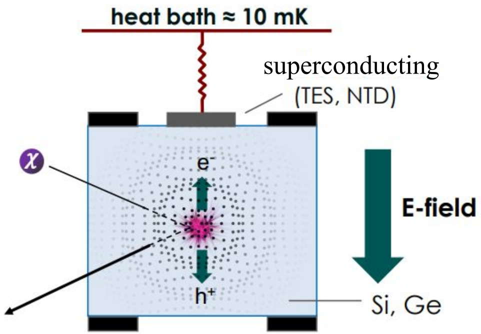
→ particle identification via ratio of light to primary phonon

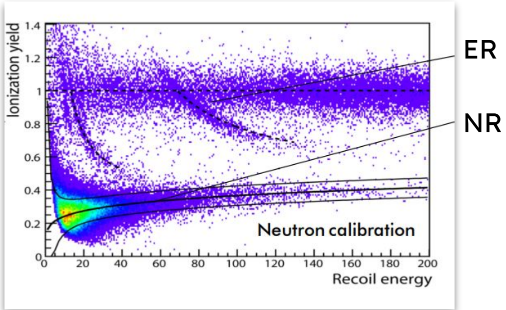
Secondary signal: semiconducting target

→ phonon and charge sensors on target

→ particle identification via ratio of ionization to primary phonon

→ surface event rejection via ID electrodes

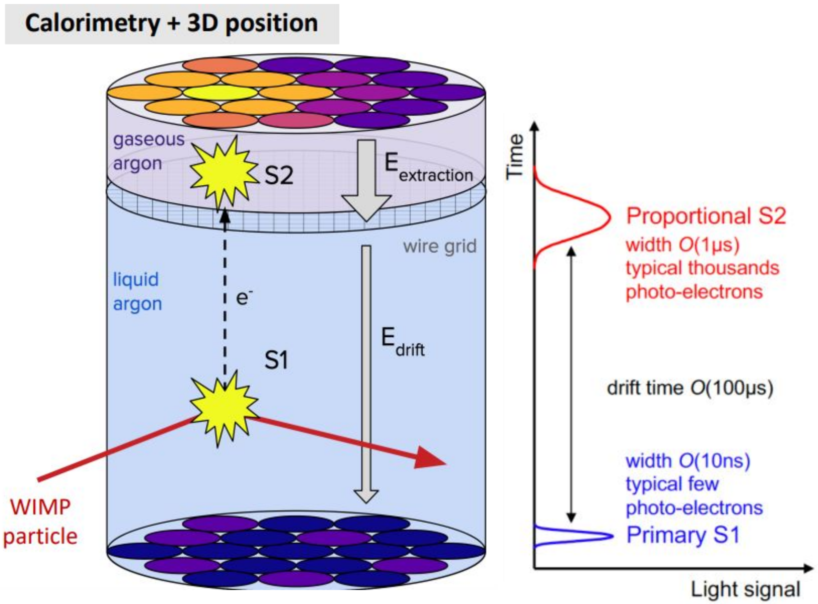




yield: Ionization signal / phonon signal

Liquid Noble Gas TPCs for Xe, Ar

LZ, XENONnT, DarkSide-50



ANATOMY OF AN INTERACTION

Dual-phase time projection chambers

→ primary scintillation signal S1

→ ionisation electrons via secondary scintillation S2 in the gas

→ particle identification via ratio S2/S1

→ position reconstruction

→ multi-scatter rejection

+ in Ar: pulse shape discrimination (PSD)

Light production less efficient than ionization

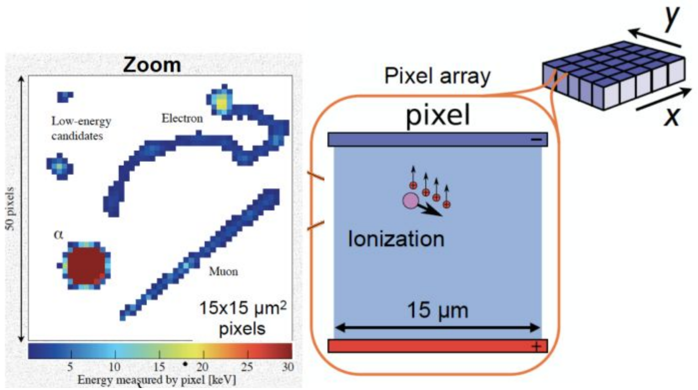
S2 only-mode [light DM]:

→ sensitive to single extracted electrons

→ lower energy thresholds e.g. XENON1T: ~5 keVnr versus ~1.5 keVnr

Charge Coupled Devices

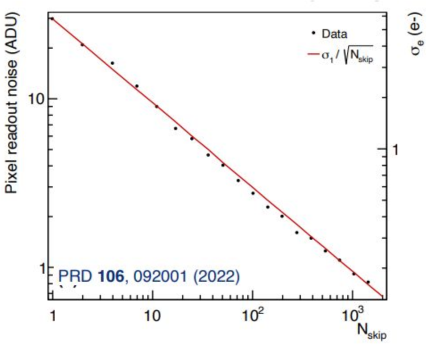
DAMIC, Sensei, DAMIC-M

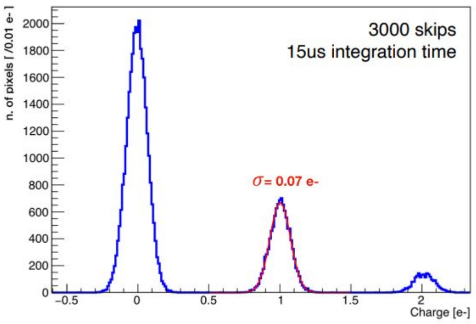


15x15 um^2
depth 69m um

ANATOMY OF AN INTERACTION

→DM-electron scattering in silicon CCDs
→Charge is drifted to pixel gates (readout)
→Position reconstruction form diffusion
→Spatial resolution allows particle ID

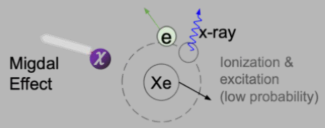


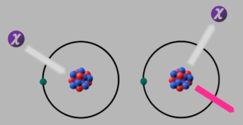


Excellent spatial resolution
Particle identification
Surface background rejection
Extremly low dark current: ~10-4 e-/pixel/day
Single electron resolution w/ skipper (0.16 e-)

Searching for “the” WIMP

Historical perspective (last 50 years)



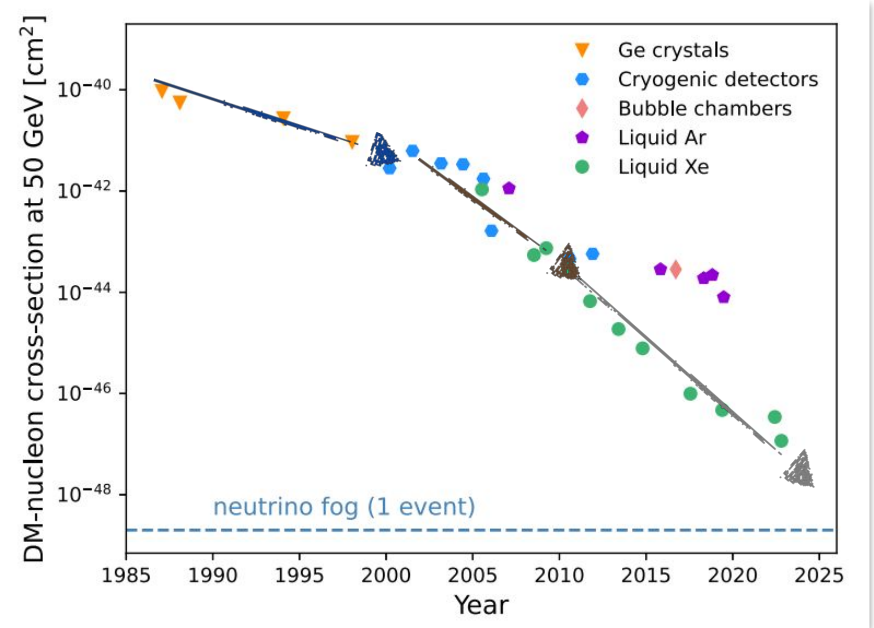


World-wid **effort** with enormous **technological progress** in the last decades

Continuos optimization of design drivers detector categories:

- clean materials
- ER/NR rejection
- Scalability

A factor 10 every ~3.3 years



initial plot from Gaitskell ()

Searching for “the” WIMP

but NO DISCOVERY*!

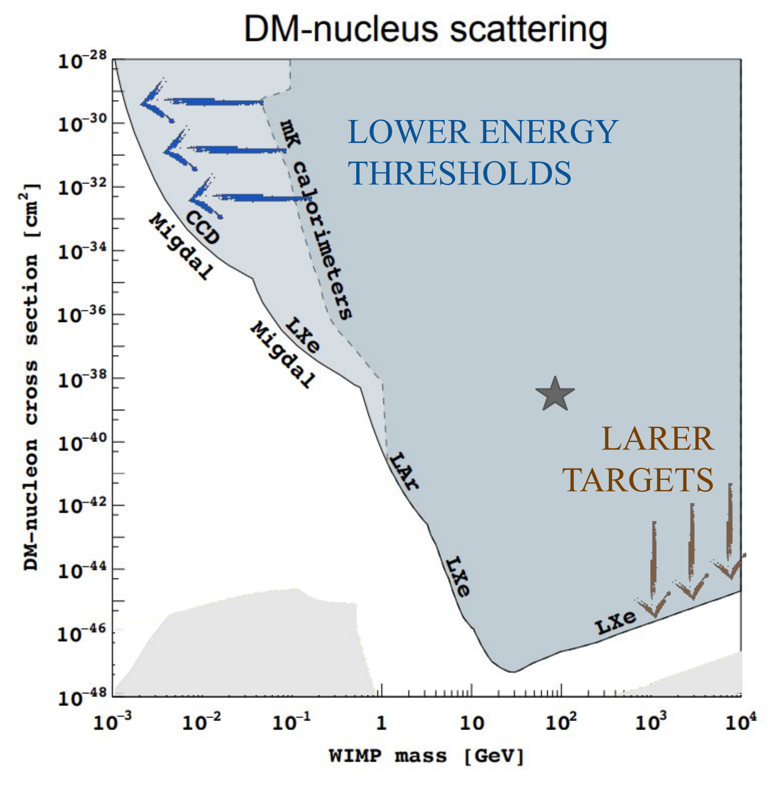
(* everyone who isn’t DAMA or CoGENT)

Tonne-scale experiments with extremely rare interaction rate **current limit:** 0.01 cts/(keV tonne year)

Migdal strongly pushes sensitivity of liquid noble gas detector

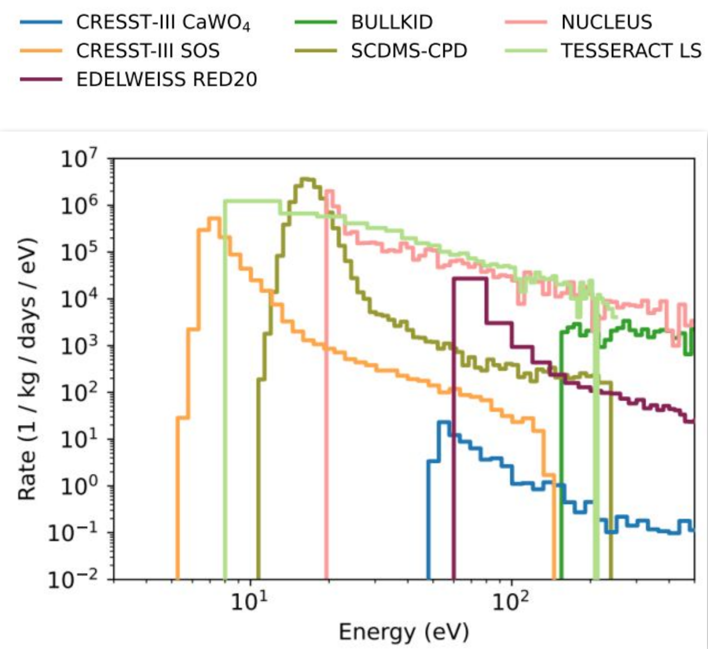
For “particle” DM, the search currently spans from ~1MeV to the Planck mass

In the next decade, experiments will reach the neutrino floor!



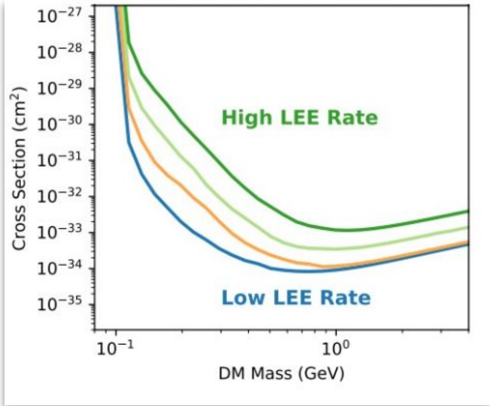
Main challenge: Low-Energy Excedss (LEE)

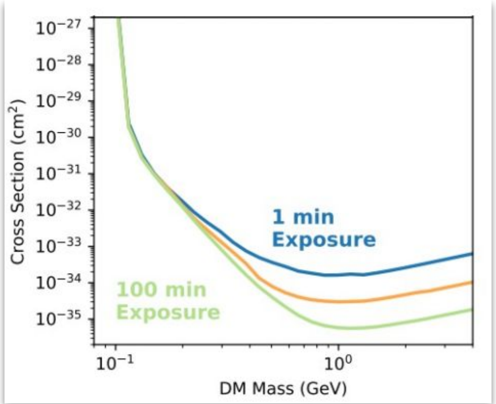
Observed in ALL solid-state cryogenic detectors below ~100eV



Impact on the DM sensitivity: in the LEE presence the DM sensitivity is worsened by orders of magnitude!

And exposure increase does not help in the sub-GeV DM regime

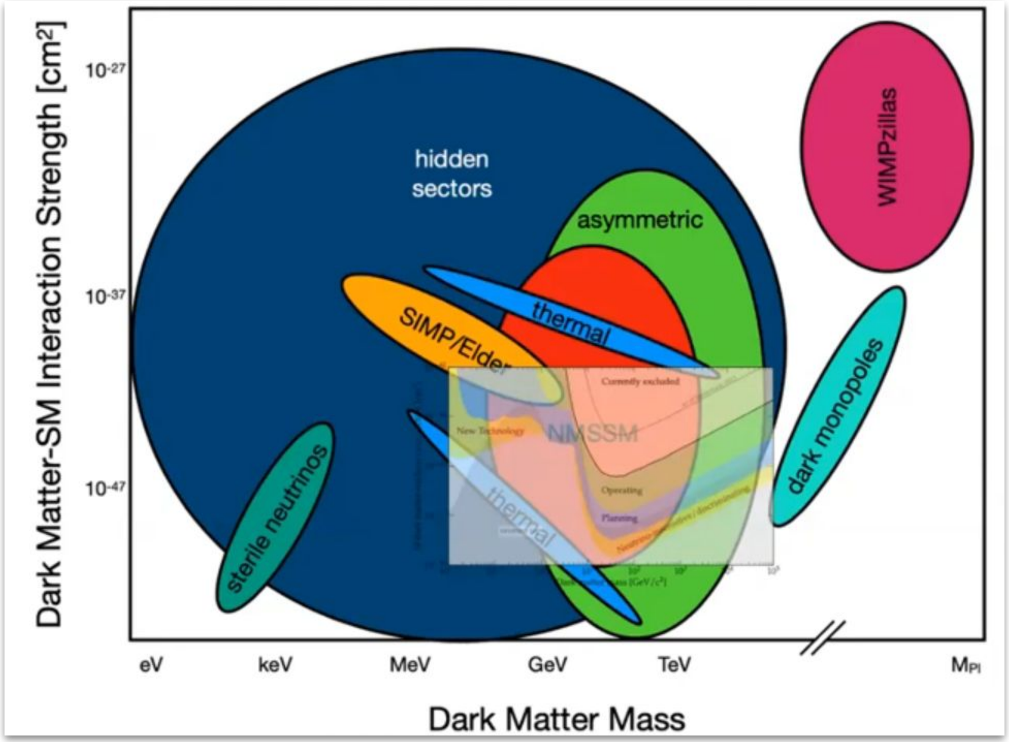




arXiv: 2503.08859

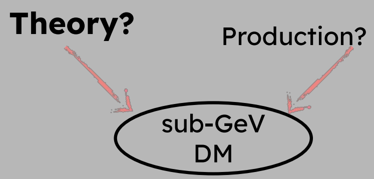
The Big “big picture”: a matter of prespective

Why not explore other regions?



Light Dark Matter

Change of paradigm: what and why

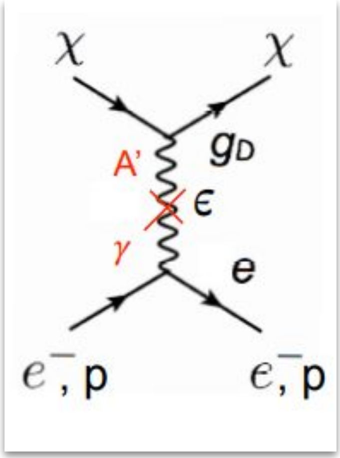


WIMP Miracle: If dark matter interacts with weak-like strength, relic density is naturally correct.

WIMPless Miracle: Hidden sectors allow many different masses and couplings ⇒ same relic density without requiring SM-like weak interactions.

Dark QED Framework: Add a dark photon (A') that mixes with the ordinary photon. This acts as a portal between the hidden sector and the SM.

$$\mathcal{L}_{int} \sim A'_\mu (g_D J^\mu_D + \epsilon e J^\mu_{EM})$$

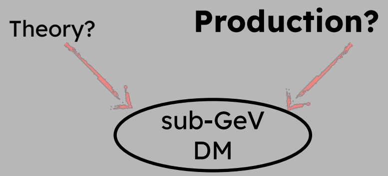


How to? Practically accessible via DM-electron scattering with very low thresholds detectors

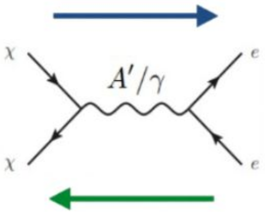
Also absorption, migadal effect, …

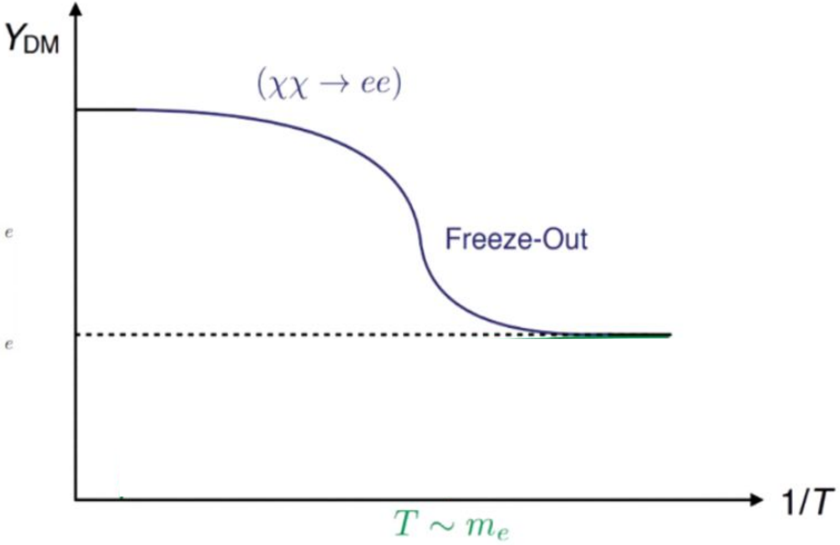
Light Dark Matter

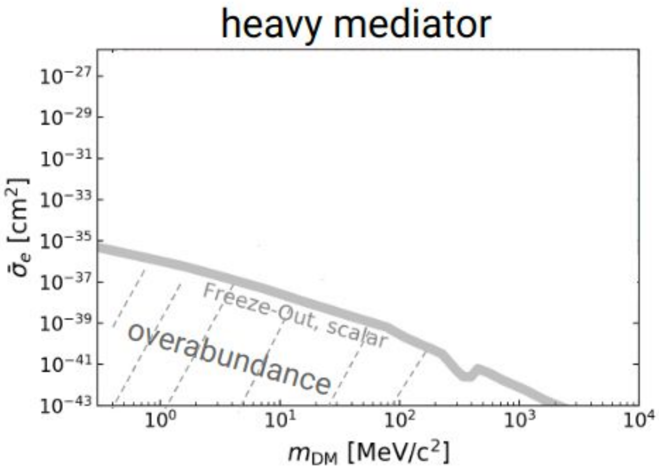
Benchmark Models: heavy mediator



limit where: $m_\phi \gg q$: $\quad F_{\mathrm{DM}} \propto \dfrac{1}{q^2 + {m_\phi}^2} \approx \dfrac{1}{{m_\phi}^2}$







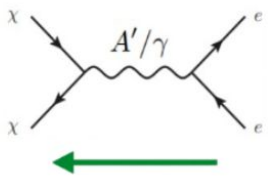
Light Dark Matter

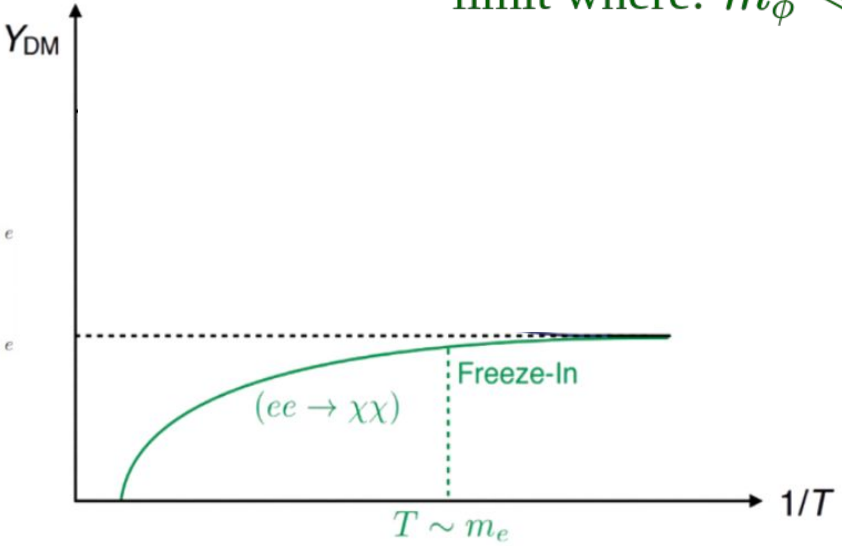
Benchmark Models: ultra-light mediator

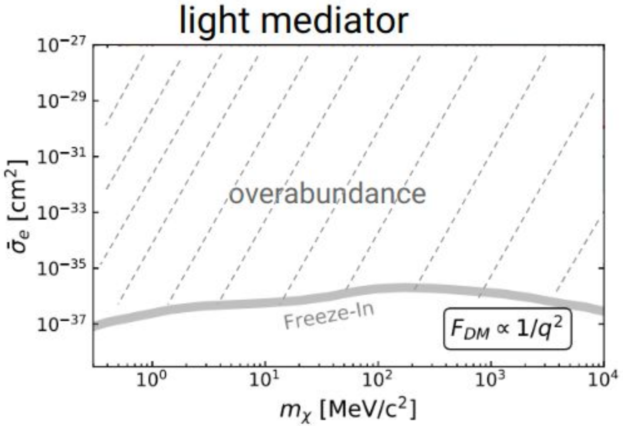
Theory?   **Production?**

sub-GeV DM

limit where: $m_\phi \ll q$: $F_{\mathrm{DM}} \propto \frac{1}{q^2+{m_\phi}^2} \approx \frac{1}{q^2}$

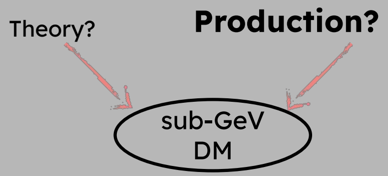


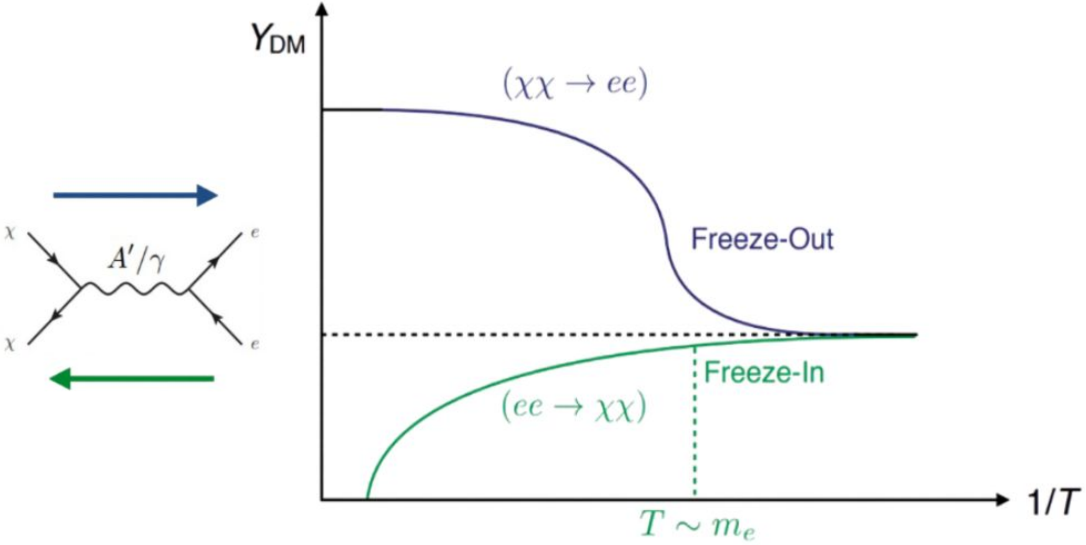


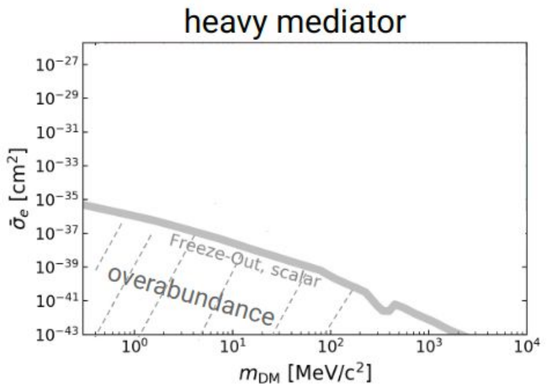


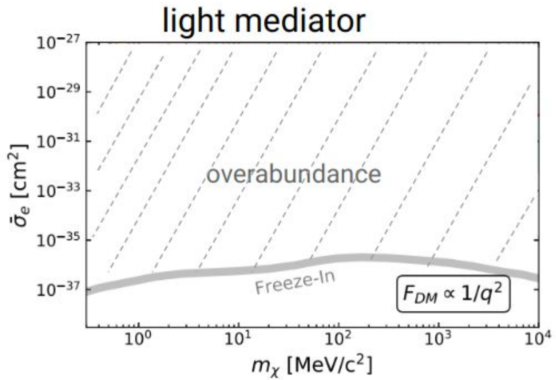
Light Dark Matter

Benchmark Models





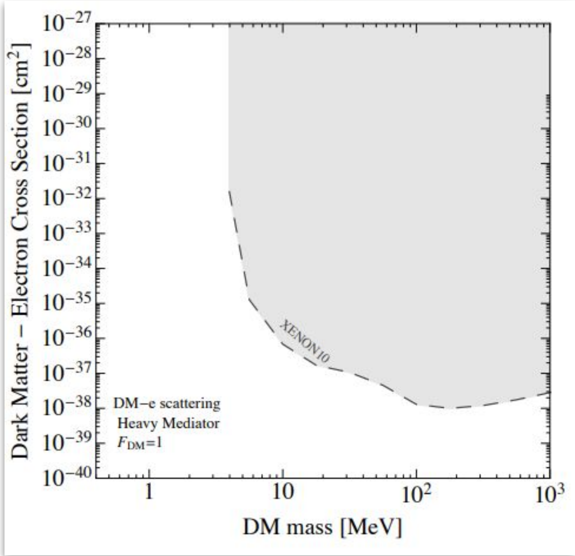




Exciting experimental progress in past years

DM-electron scattering, heavy mediator case

2012

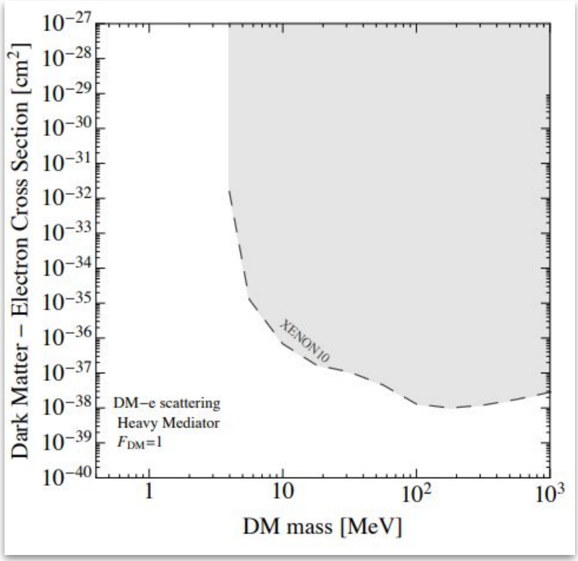


RE, Manalaysay, Mardon, Sorensen, Volansky

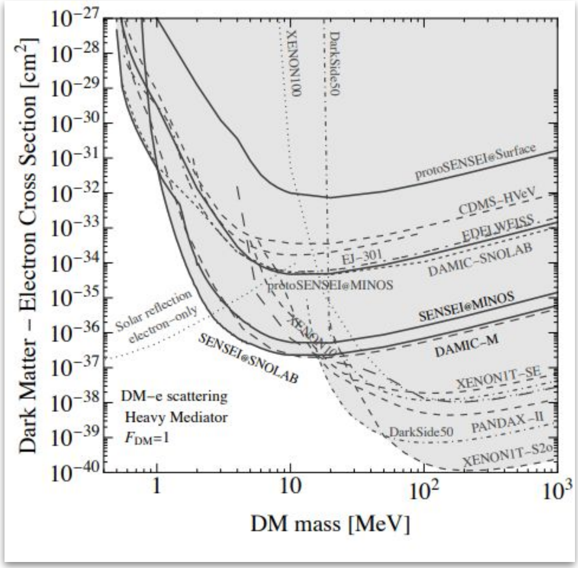
Exciting experimental progress in past years

DM-electron scattering, heavy mediator case

2012



2024



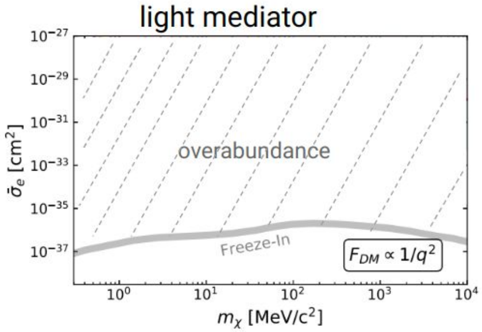
Several ultrasensitive detectors can measure the procedure charge (2-phase TPCs, Skipper-CCDs, TES, …)

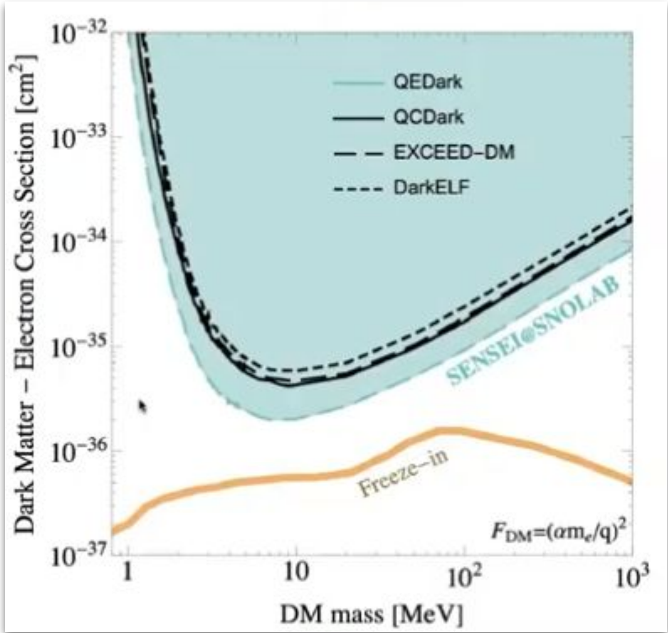
Exciting experimental progress in past years

DM-electron scattering, light mediator case

2024

freeze-in DM is a future* target





*as of 17/03/2025

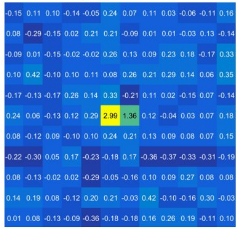
Current status: DM-electron scattering

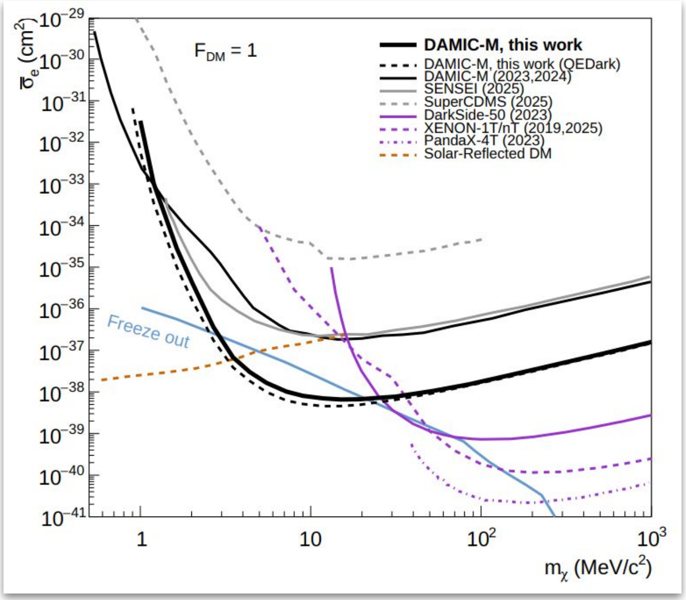
DAMIC-M: world-leading exclusion limits for sub-GeV hidden-sector DM!

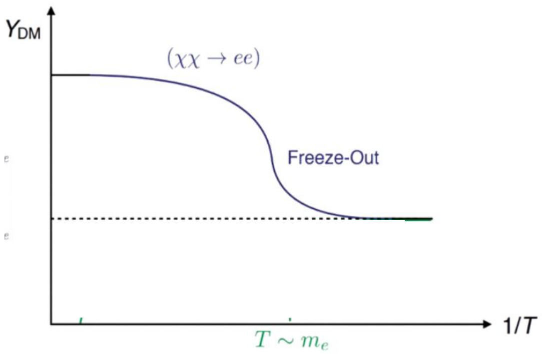
DAMIC-M probes benchmark hidden-sector dark matter models: freeze-out rolued out, reaching freeze-in for the first time

Phys. Rev. Lett. 135, 071002 (2025)

	Pattern p		
	{11}	{21}	{111}
D_p	144	0	0
$B_p^{\rm rc}$	141.4	0.111	0.042
$B_p^{\rm rad}$	0.039	0.039	0.016
	{31}	{22}	{211}
D_p	1	0	0
$B_p^{\rm rc}$	0.019	$2.5 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$
$B_p^{\rm rad}$	0.052	0.011	0.035







Current status: DM-electron scattering

DAMIC-M: world-leading exclusion limits for sub-GeV hidden-sector DM!

DAMIC-M **probes benchmark hidden-sector dark matter models**: freeze-out rolued out, **reaching freeze-in for the first time**

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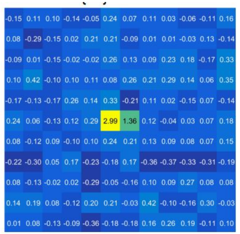
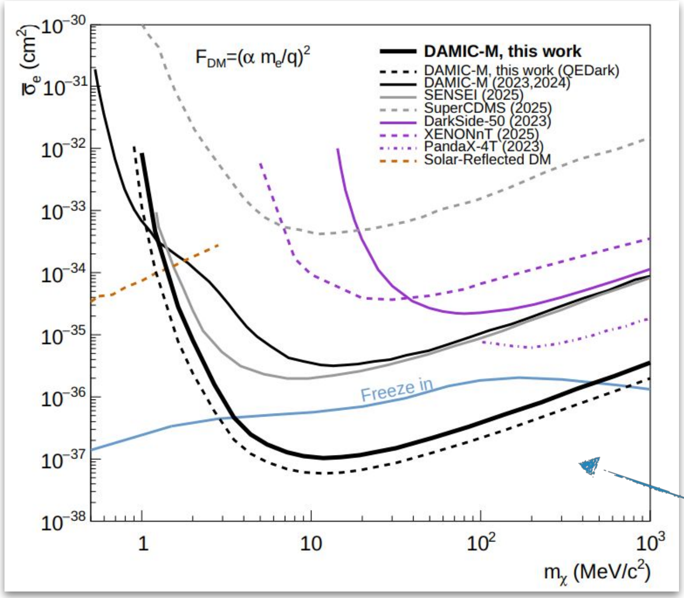
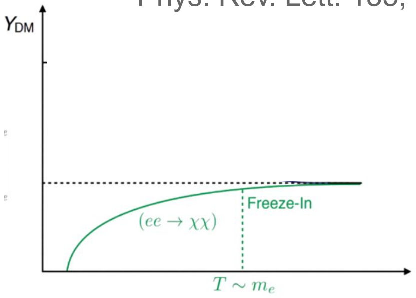
	Pattern p		
	{11}	{21}	{111}
D_p	144	0	0
$B_p^{\rm rc}$	141.4	0.111	0.042
$B_p^{\rm rad}$	0.039	0.039	0.016
	{31}	{22}	{211}
D_p	1	0	0
$B_p^{\rm rc}$	0.019	$2.5 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$
$B_p^{\rm rad}$	0.052	0.011	0.035





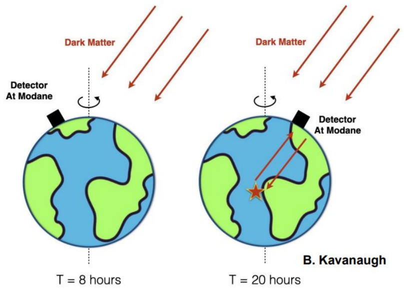


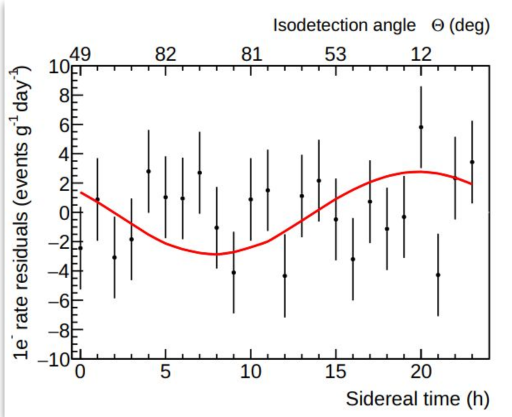
When you are going here you are de facto decoupling why we are looking for DM there from the one thing we know about it is abundance

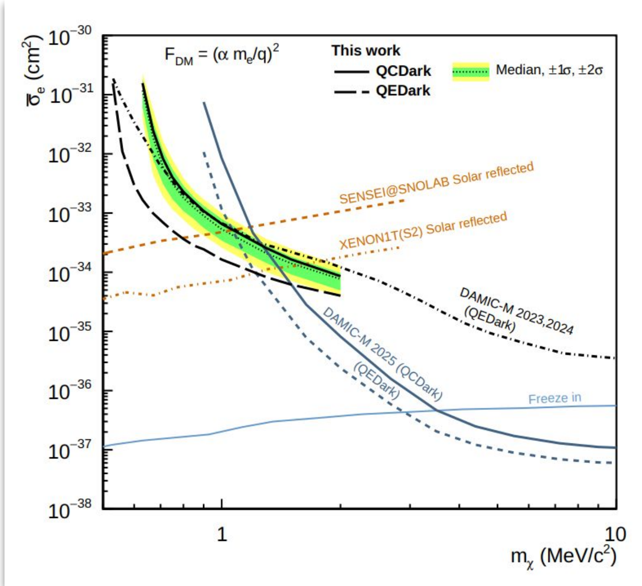
Current status: DM-electron scattering

DAMIC-M: world-leading exclusion limits for sub-GeV hidden-sector DM!

DAMIC-M probes benchmark hidden-sector dark matter models: freeze-out rolued out, reaching freeze-in for the first time … AND **PUSHING TO LOWER ENERGIES WITH DAILY MODULATION**







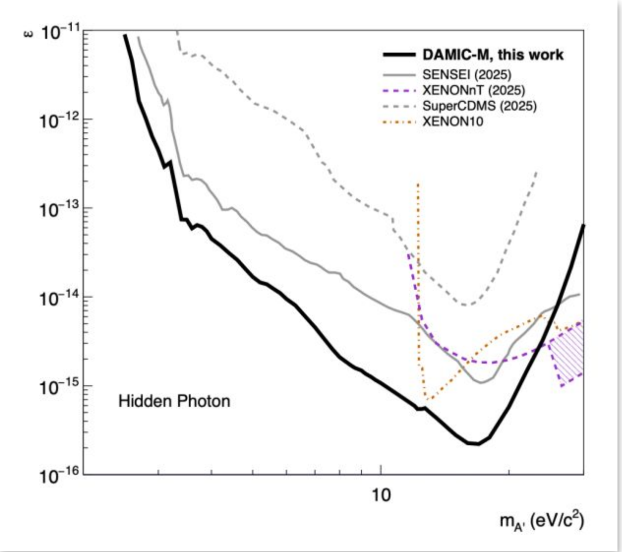
arXiv: 2511.13962 (published this week)

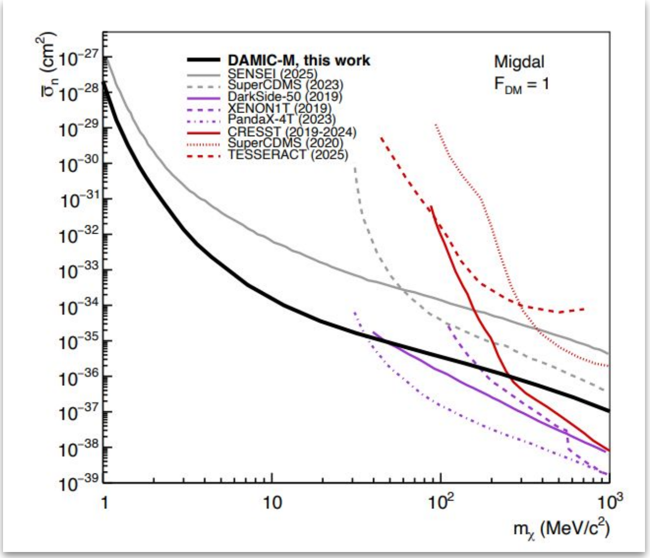
Current status: Absorption and Migdal

DAMIC-M: other exclusion limits

DAMIC-M also sets stringent constraints **on absorption of relic hidden photon by atomic electron on silicon** and **DM-nuclear scattering via Migdal effect** (see End Matterial arXiv:2503.14617). All limits available as text on linked github.

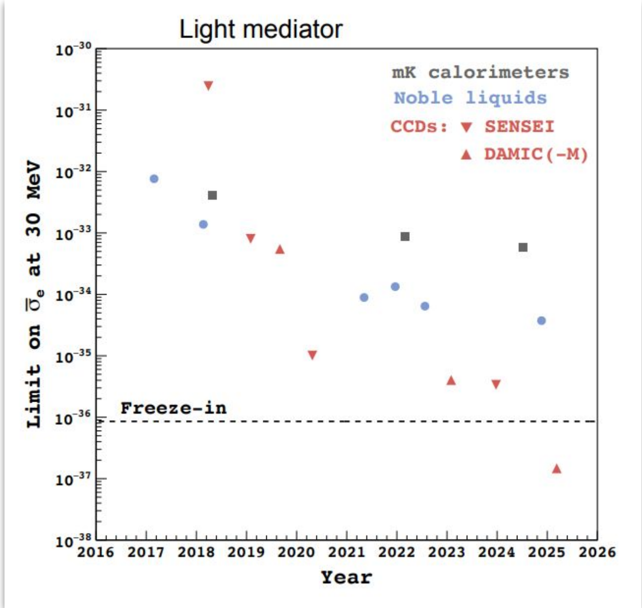
Phys. Rev. Lett. 135, 071002 (2025)

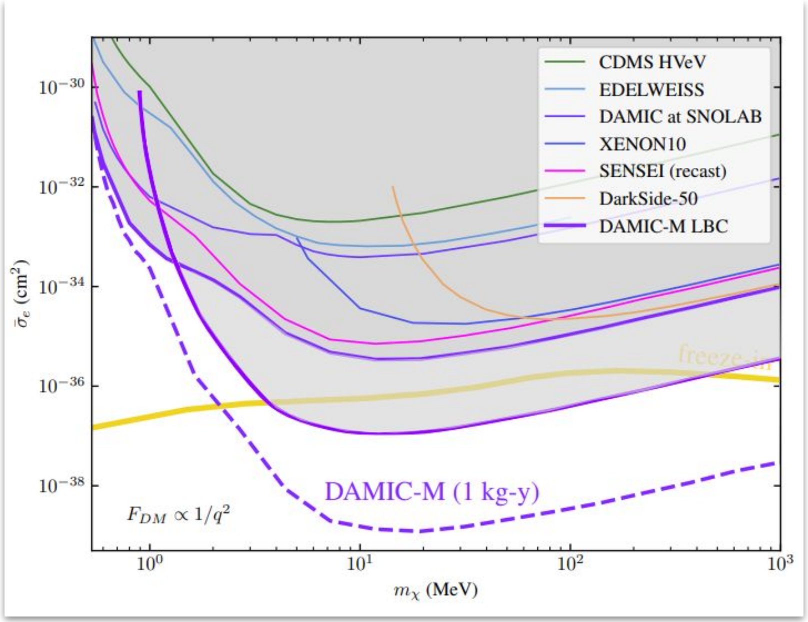




Light Dark Matter: DM-e scattering

CCD time line and Forecast





SUMMARY

Given the null results after decades of efforts, starting to focus on light dark matter.

New technical challenges due to lower interaction energies.

- for NR, conventional detector ~ O(100 MeV) , then microcalorimeter seems to be the most popular choice.
- for ER, TPC (10MeV), CCD/semiconductor (1MeV), superconductor (sub-MeV)

New cryogenic detector evolving fast: in the next few years, they will be scaled up and moving underground for real science runs.

Broad detector development programs for pusing to lower mass: new detector designs, new sensors, new materials, new interactions, but also Investigation of the detector response in the eV-range

Challenge on the theory side

WHAT WE SHOULD DO…

Short Term

Construct DM **models** which still predict signals

Find new use cases for these incredible experiments

Agree on **benchmarks as** a **community**

Reach the **rest** of the WIMPs

Discover **new** DM and experimental **paradigms**

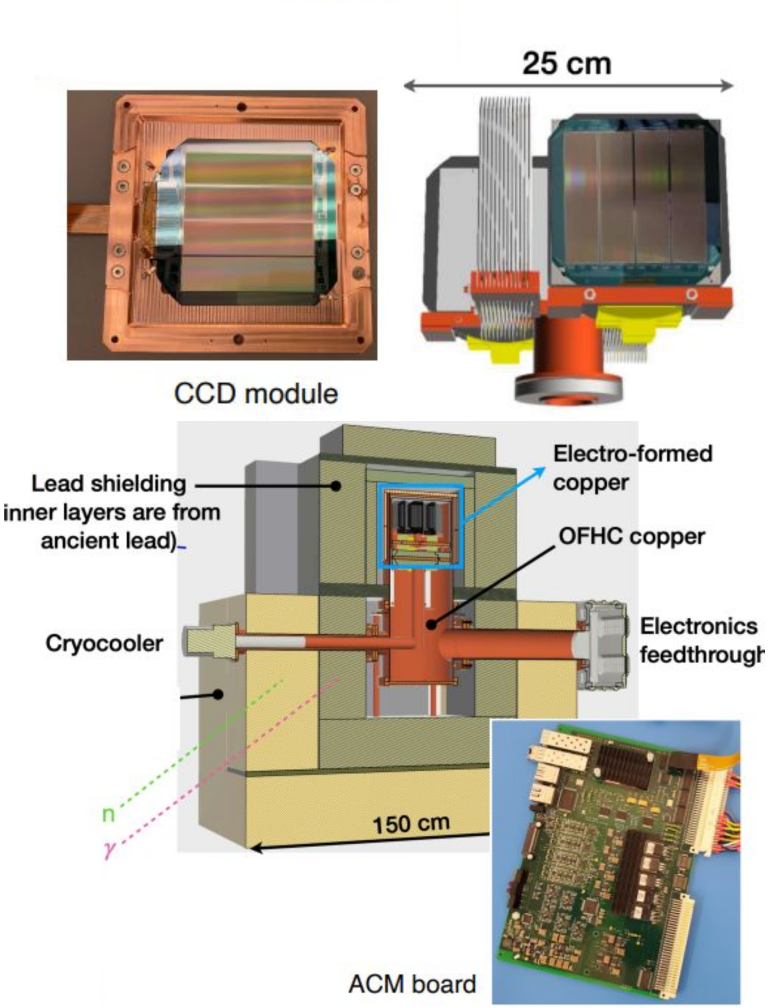
Long term

Thanks for your attention

Status of DAMIC-M online by 2026!

- **208 skipper CCDs,** kg-scale **design finalized**
- low background assays, cosmogenic mitigation procedures for transport/production
- **CCD modues** send to **LSM**, and **being tested**
- **low-noise electronics** designed, tested, and **being produced** for **full-scale experiment**

- **Detector response calibrations:**
  - Si atomic shells Compton spectrum: PRD 106, 092001 (2022)
  - silicon nuclear ionization efficiency in prep
  - NR/ER discrimination: PRD 110, 043008 (2024)
- **Installation and operation of prototype Low Background Chamber (LBC):** JINST 19 T11010 (2024)
- **Several science results within DM-e space with LBC**
  - PRL 130, 171003 (2023)
  - PRL 132, 101006 (2024)
  - PRL 135, 101103 (2025)



Search For Hidden-Sector DM with LBC

1. Two CCD Modules (DAMIC-M will have 50!) each with 4 skipper CCDs, total 26.4 g
2. *Notable improvements* thanks to *low-noise electronics and better box light tightness*:
    - 0.16 e- charge resolution (~0.2e-)
    - ~1.3x10^{-4} e-/pix/day (400 e-/g/day) dark current (x50 lower than SR1)
3. Collected data October 2024-January 2025: total exposure after selection 1.3 kg day (0.086 kg day SR1)
4. Blind analysis: *pixel selection and DM search criteria defined with 7 days of unblinded data (~10% of total)*
5. Continuous readout with 100 vertical binning, which compresses the 1.5kx6k CCD into images of 16 rows x 6300 columns. 28 min to read one image, allowing for daily modulation analysis.