The DAMIC-M experiment: light dark matter in a kg-scale Skipper CCD detector

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DArk Matter In CCDs @ Modane

DArk Matter In CCDs @ Modane

- The goal: direct detection of MeV-scale Dark Matter with a very low background, kg-scale detector

Focus of this talk

- The detection technology: Skipper CCDs

✓ Talk by J. Tiffenberg

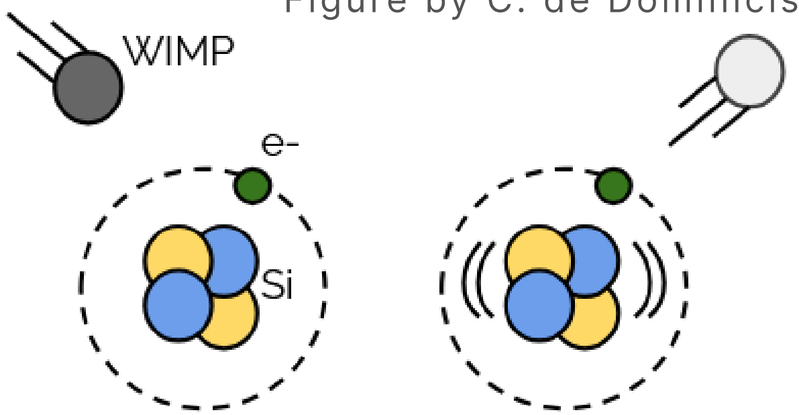
- The location: under the Alps at Laboratoire Souterrain de Modane (LSM), France

✓ Talk by S. Scorza

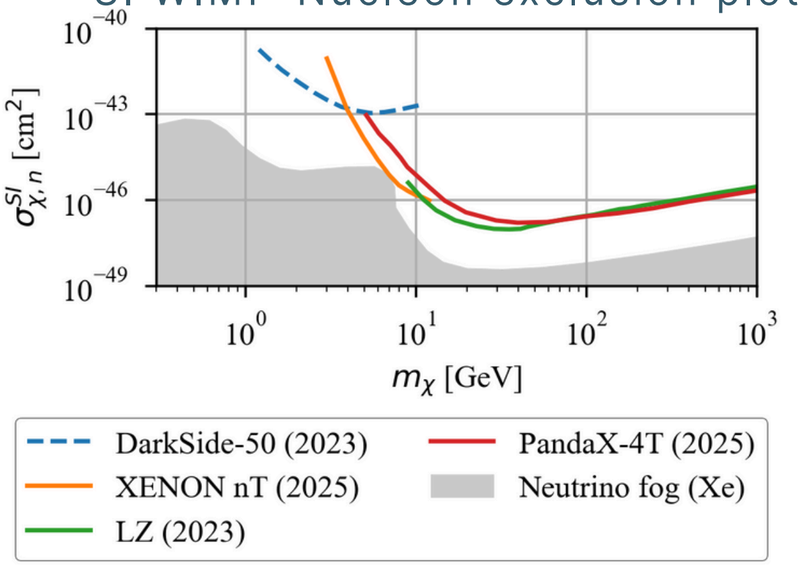
Physics goal

- WIMPs are very well-motivated and compelling candidates for explaining Dark Matter
- They may interact with silicon nucleus, thus WIMP-Nucleon interactions may be probed with CCDs
- A "Low Energy Excess" of events (below 200 eVee) prevents the WIMP search to progress
- The Dark Matter interpretation of this excess is ruled out by other experiments

Figure by C. de Dominicis

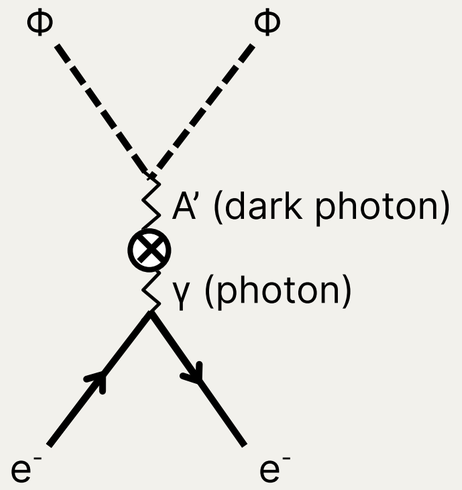


SI WIMP-Nucleon exclusion plot



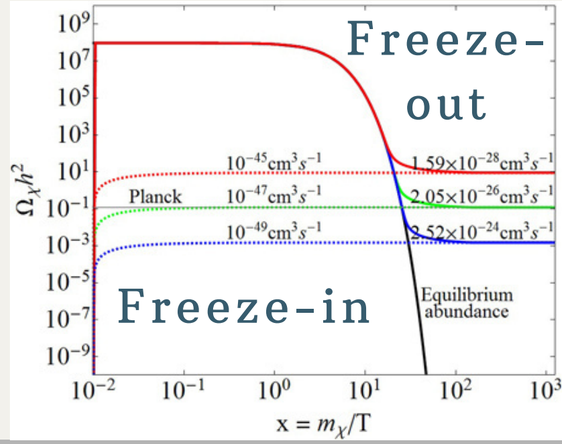
Physics goal

- Other well-motivated candidates for DM are MeV-scale “hidden sector” particles that interact with electrons via massive “kinematically-mixed vector mediators”

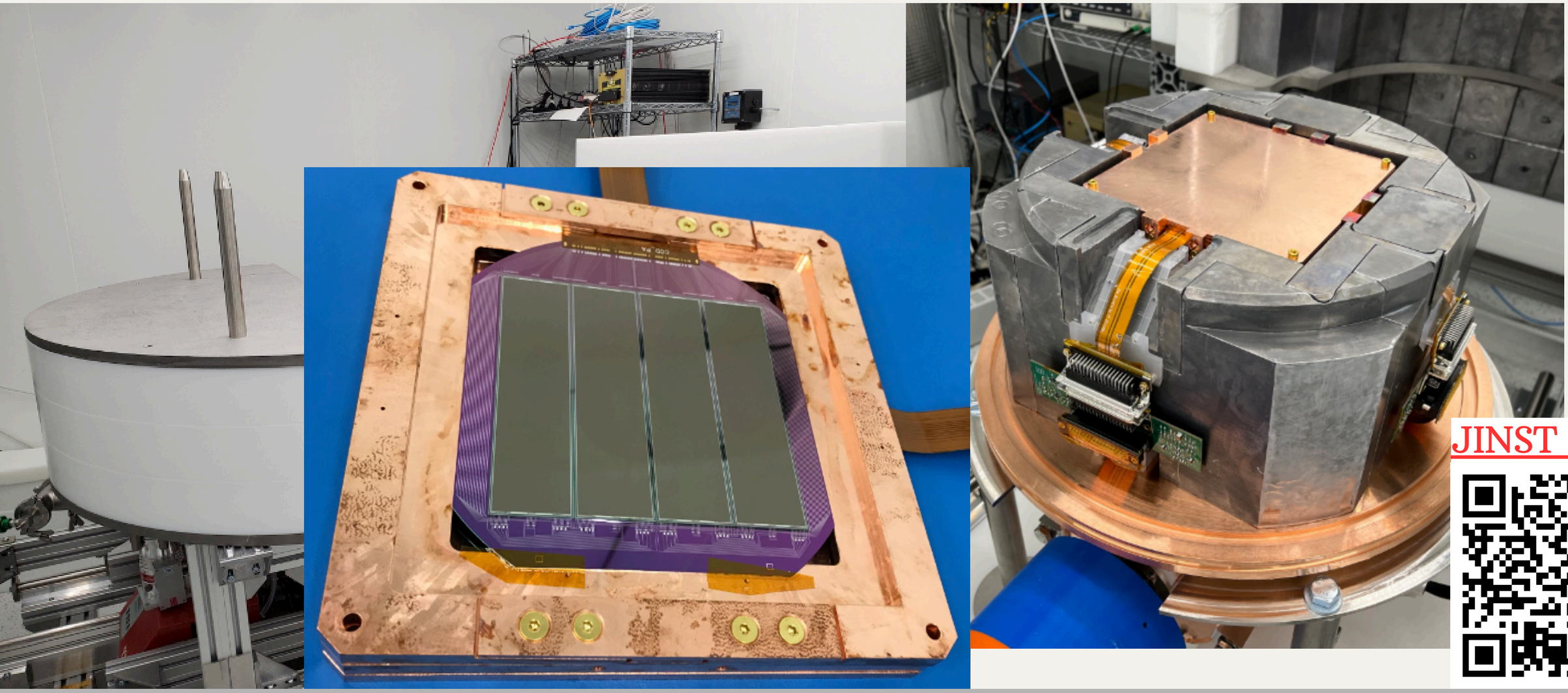


- These would produce electron recoils in silicon
- Ultra-low sensitivity of Skipper CCDs mean they are the ideal detectors to probe these candidates
- Depending on the mediator mass, the current DM abundance may be explained via freeze-out or freeze-in

Dev, Mazumdar, Qutub 2013



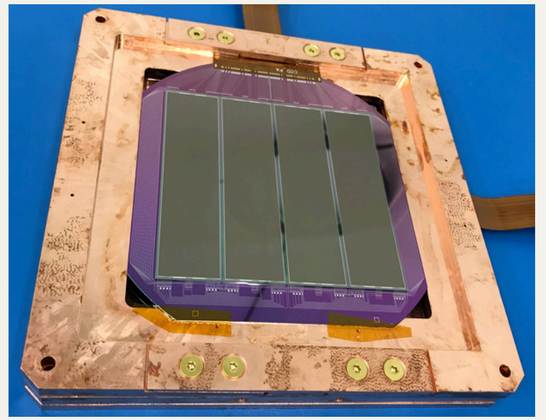
DAMIC-M prototype: the Low Background Chamber (LBC)



JINST Paper:

LBC – Science run 2 (finished)

PRL Paper:

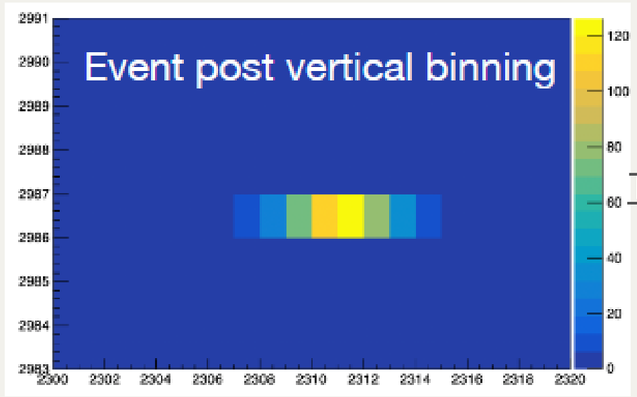


2 CCD modules

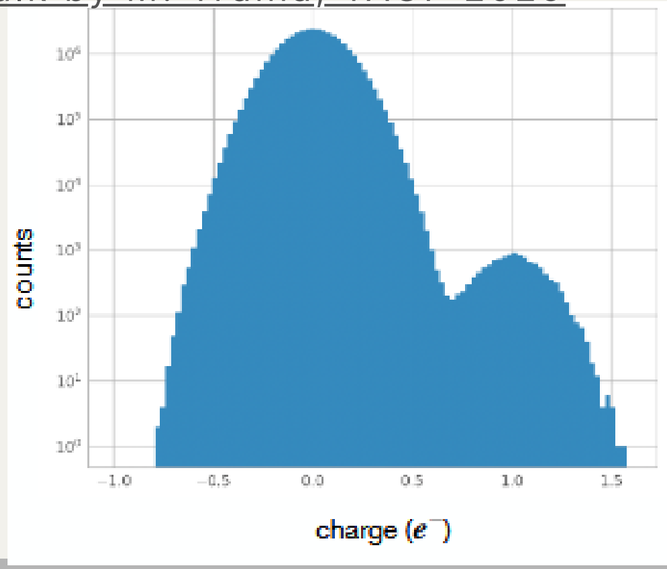
- Each with 4 9-Mpixel Skipper CCDs
- Total sensitive mass: 26 g
- Custom-designed low-noise electronics

Readout:

- 1 amplifier per CCD
- Continuous readout
- 1 x 100 Hardware Binning



Talk by M. Traina, TAUP 2025



Performance:

- Pixel readout noise: 0.16 e- (500 “skips”)
- DC: 10^{-4} e-/pix/day (~400 e-/g/day after cuts)

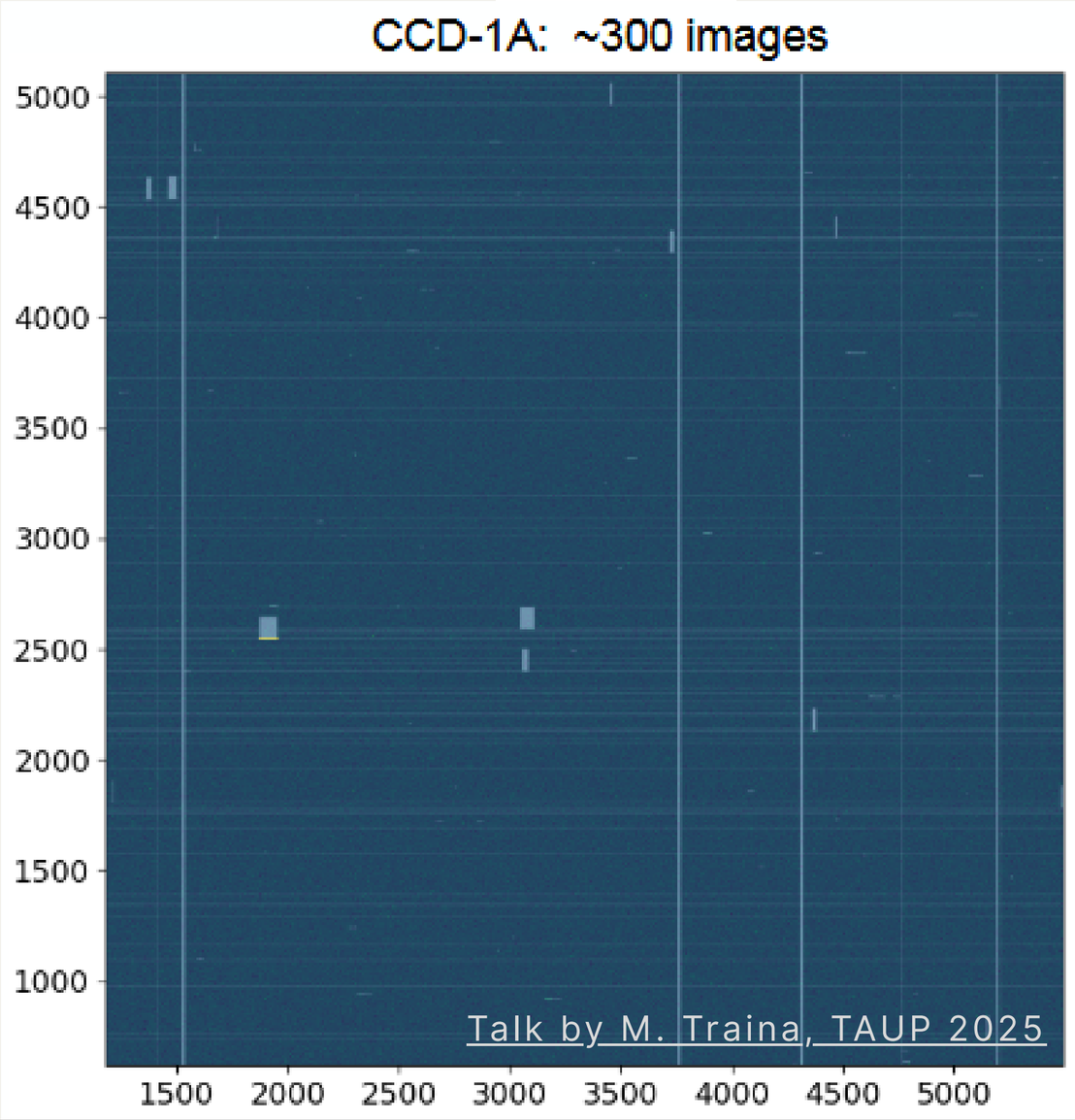
LBC – Science run 2 (finished)

PRL Paper:

Data selection: masks

- Hot columns
- >5e- clusters
- “bleeding” (CTI):
  - Mask 100 rows above high-energy pixels (q>100e-)
- Cross-talk
  - pixels in same-module CCDs from high-energy cluster in one CCD
- Correlated noise
  - Mask pixels with charge in multiple CCDs of the same module

95% of data survive the selection cuts!

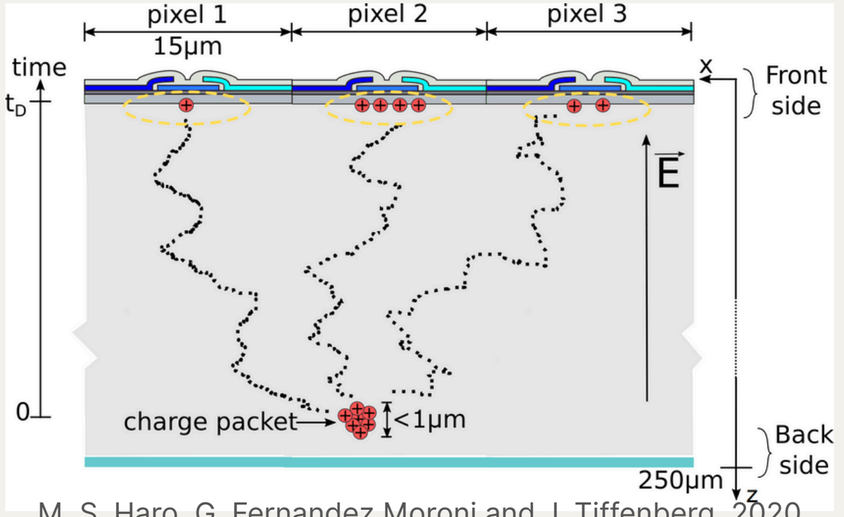


LBC – Science run 2 (finished)

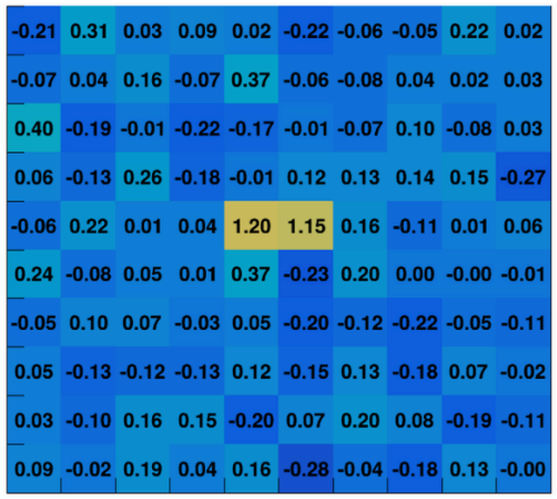
Data analysis

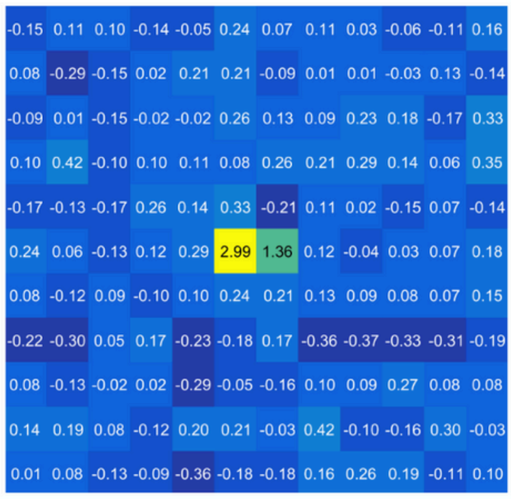
PRL Paper:

- Blinded analysis
  - 139 g-day to establish selection cuts; 1.26 kg-day blind
- Pattern analysis
  - Excess in 2, 3 and 4 e- rate with respect to observed 1 e- rate: dark matter?
  - If so, we would see also consecutive pixels forming patterns, because of difussion in the CCD bulk
- Background modeling
  - Patterns due to random coincidences
  - Patterns due to radioactive decays



M. S. Haro, G. Fernandez Moroni and J. Tiffenberg, 2020





LBC – Science run 2 (finished)

PRL Paper:

Results

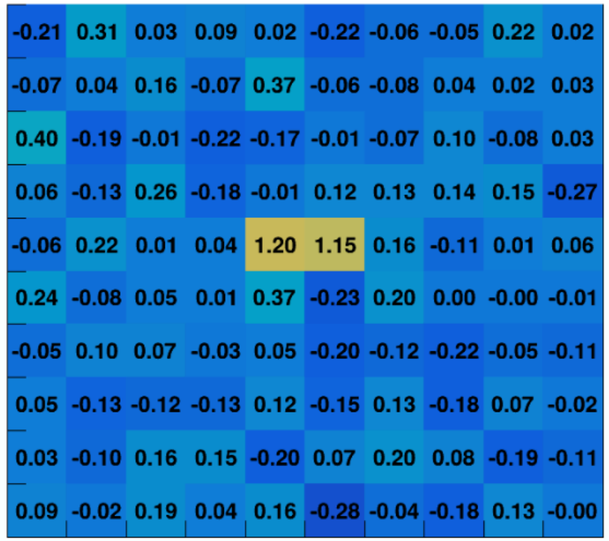
TABLE I. The number of candidates D_p in the D2 dataset, and the number expected from backgrounds due to random coincidences, B_p^{rc}, and to radioactive decays, B_p^{rad}.

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

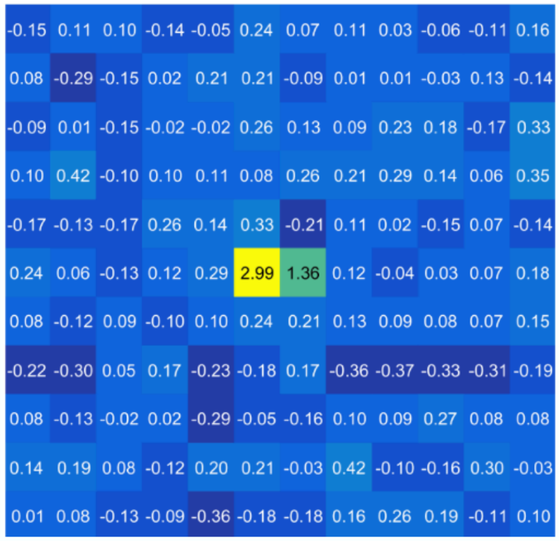
Pattern events are compatible with background-only hypothesis (even the {3 1} event)

→ No Dark Matter in the 2-5 e- range

{ 1 1 } candidate



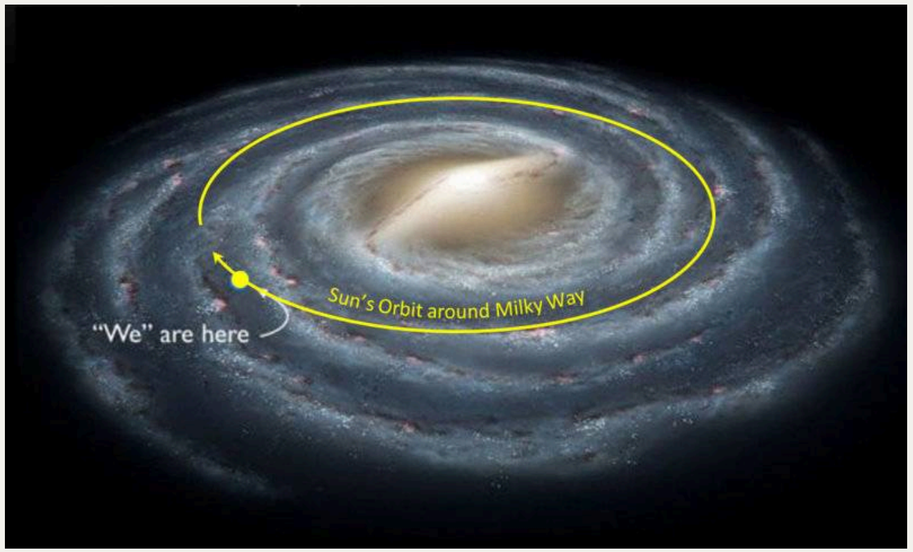
{ 3 1 } candidate

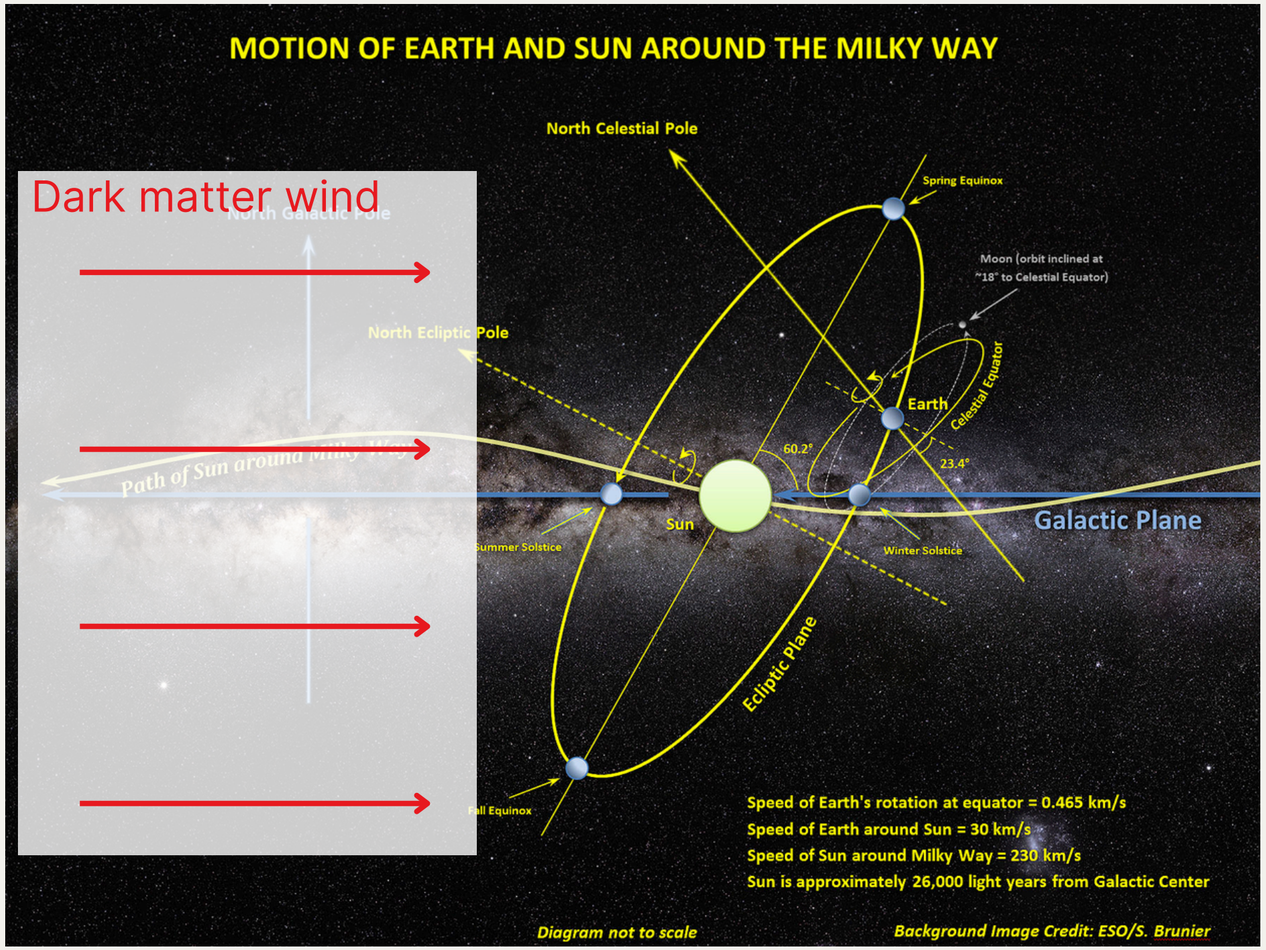


Diurnal modulation analysis

What about the single-electron events? Could they be Dark Matter?

If so, they would appear in a time-dependent fashion, due to a "diurnal modulation of events"

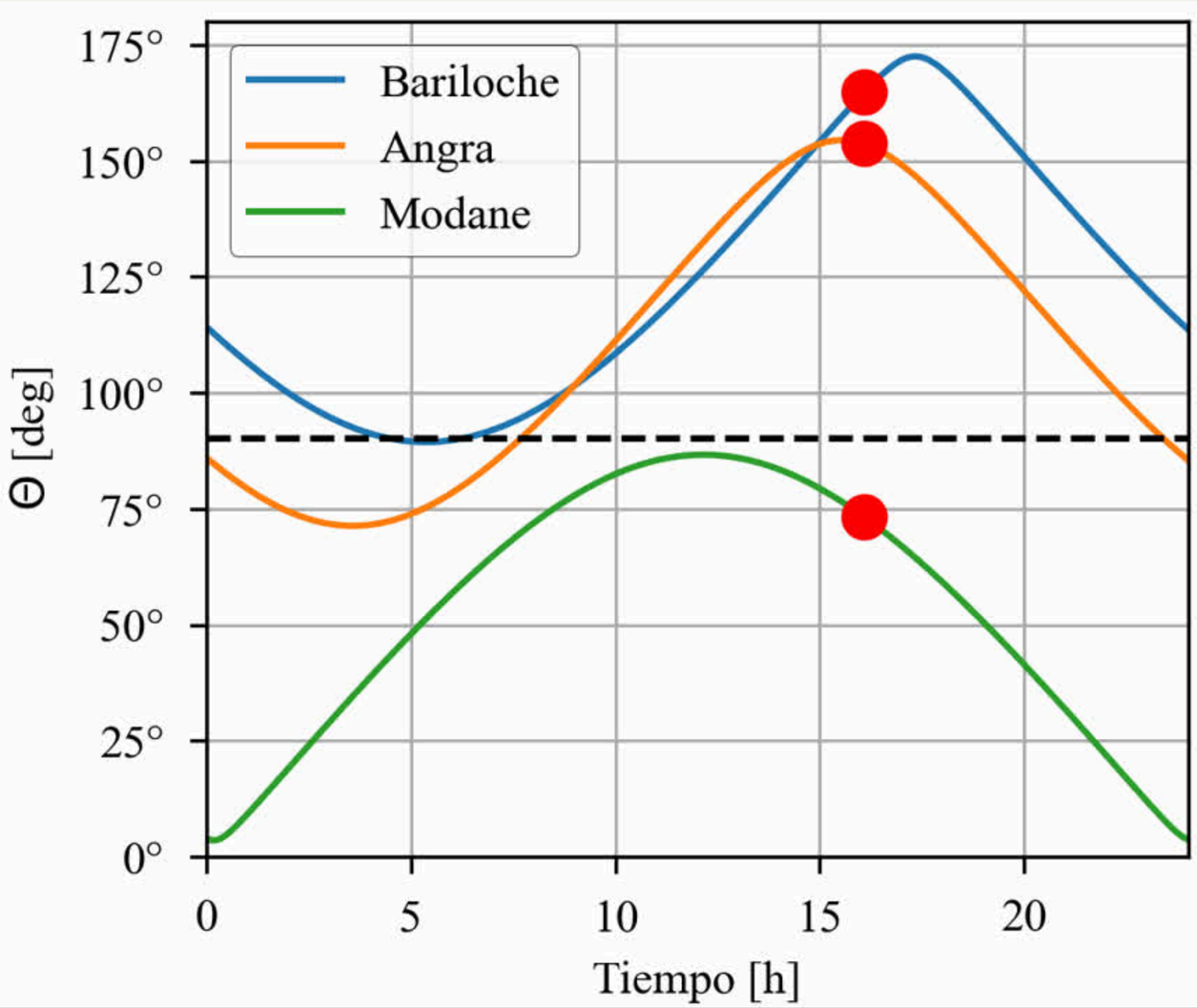


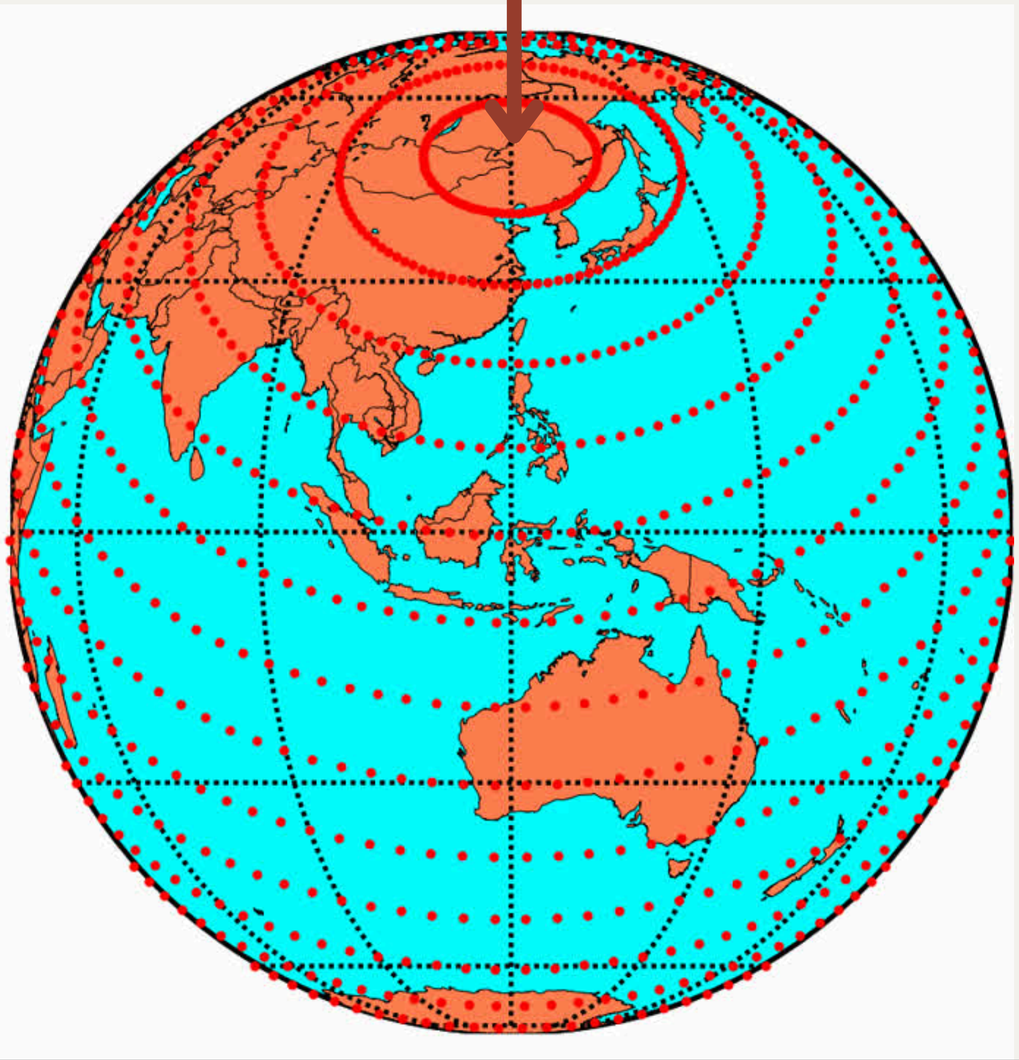


Jim slater307, CC BY-SA 4.0, via Wikimedia Commons

Diurnal modulation analysis

"Isodetection angle" varies with time during a sidereal day, and it also depends on the location of the experiment.

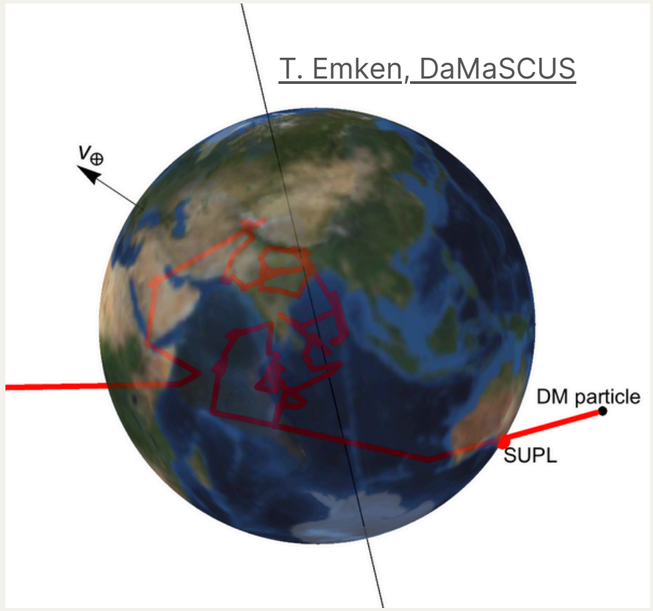


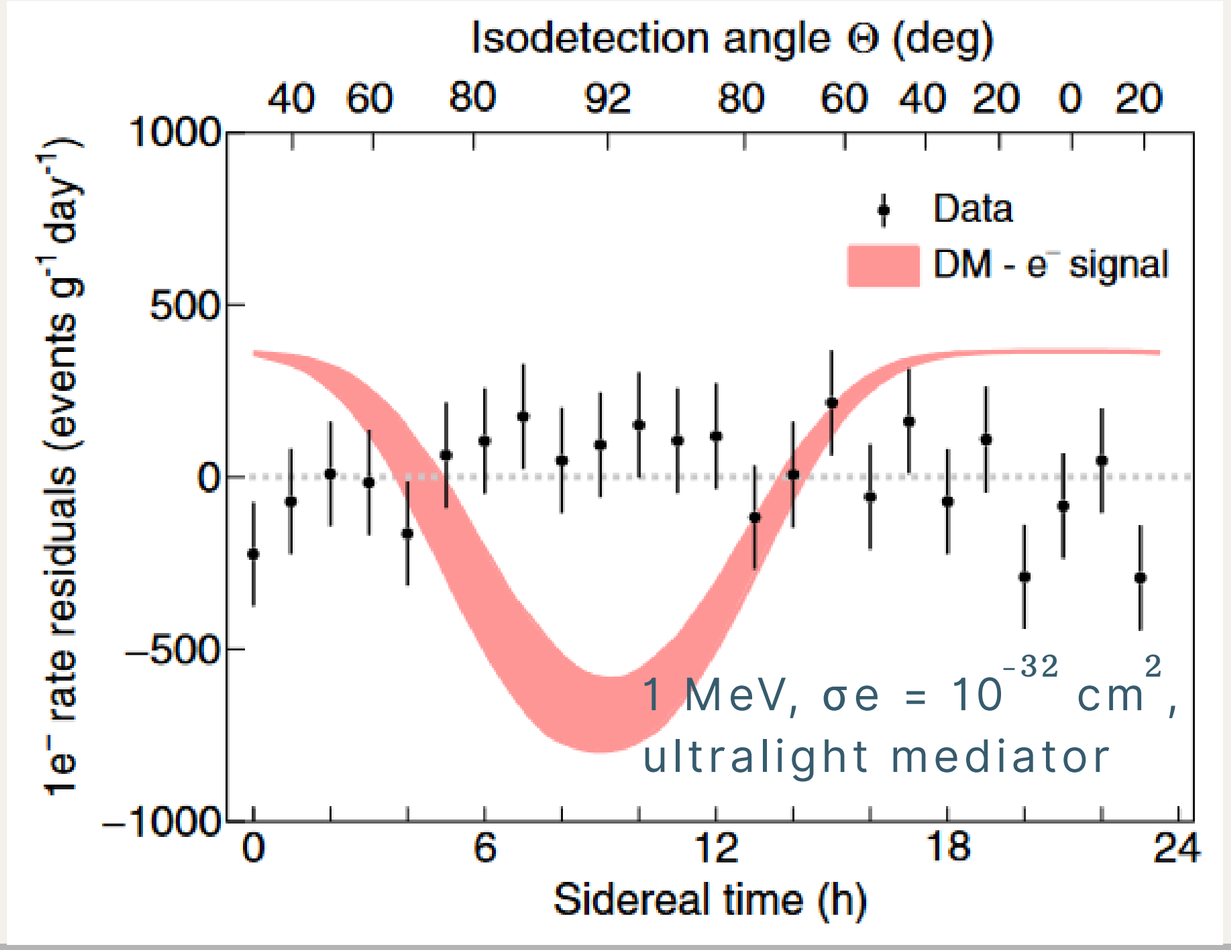


Diurnal modulation analysis

DM particles would interact with protons inside the Earth's crust, deflecting their path along their way and creating different velocity and flux distributions at the experiment location

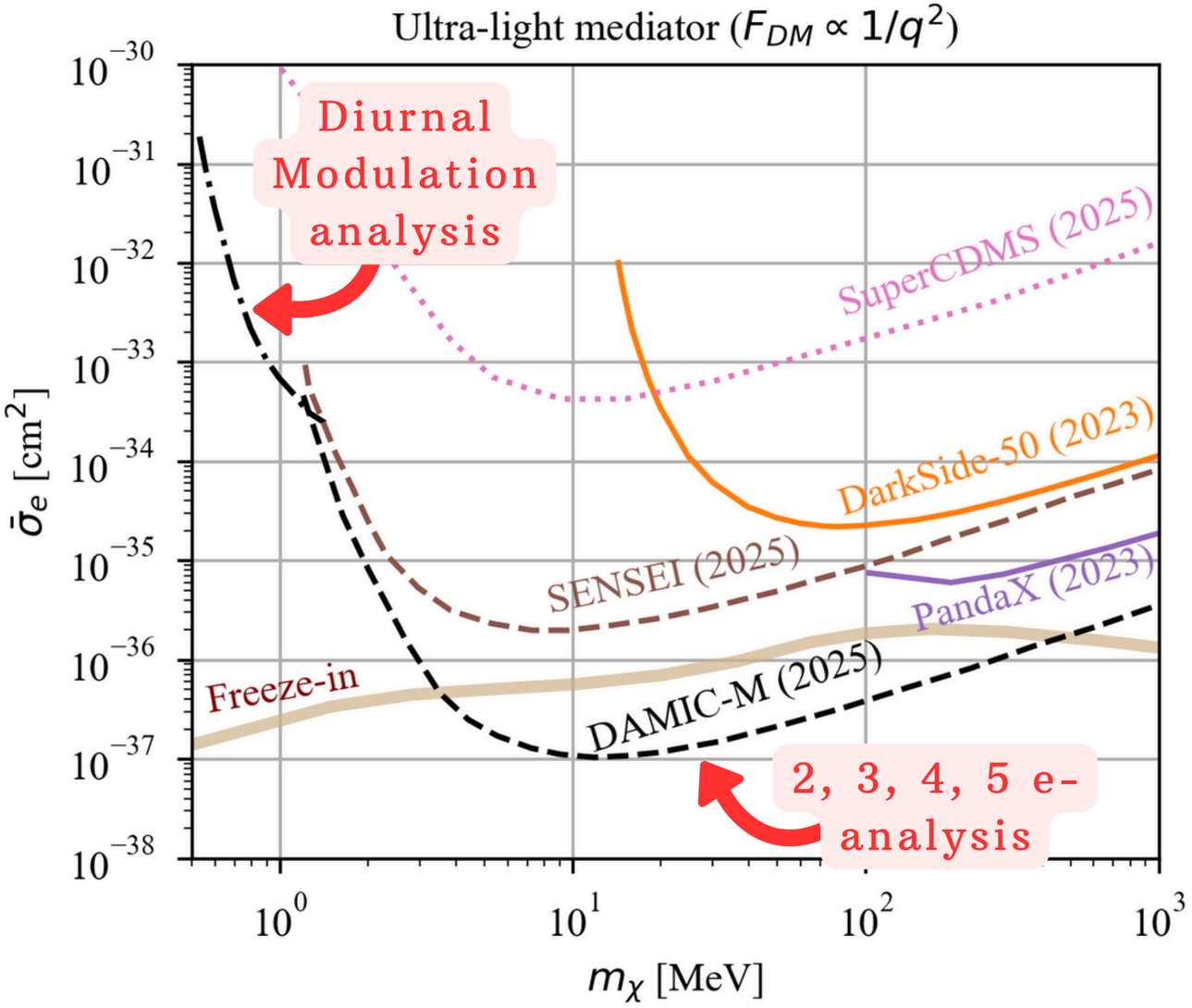
PRL Paper:

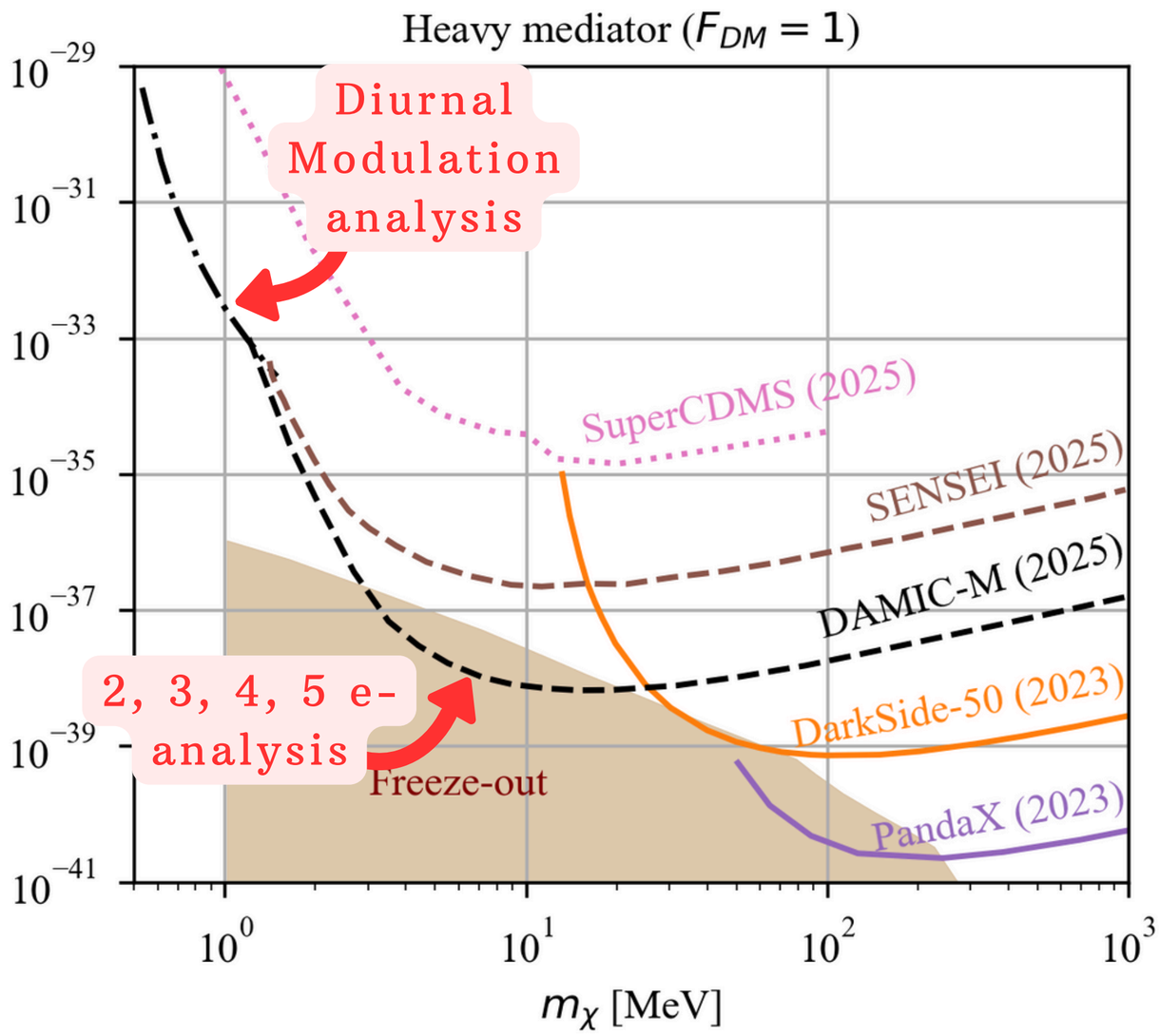




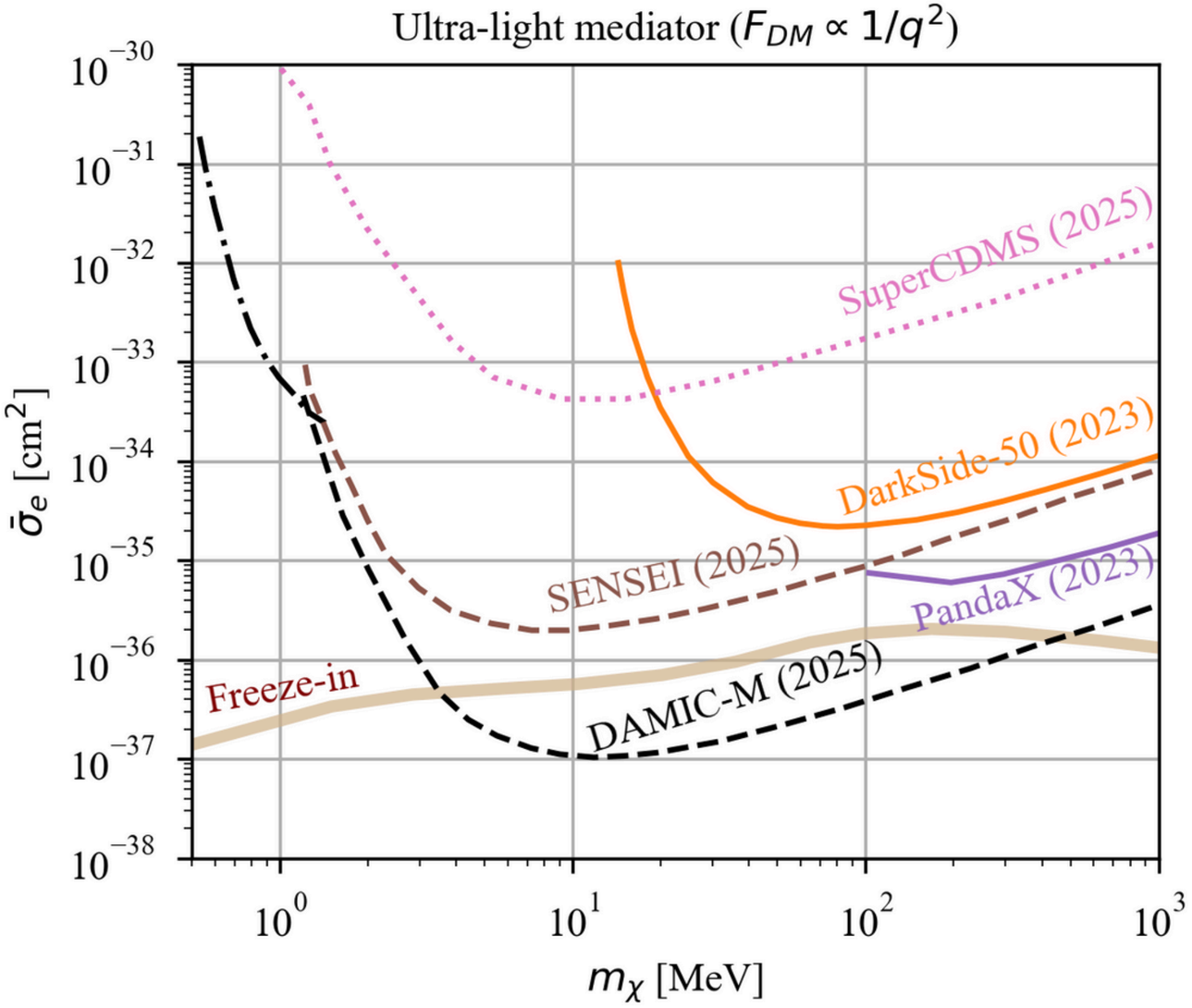
DAMIC-M LBC results

No positive signature for DM yet. We can calculate exclusion limits:





DAMIC-M LBC results



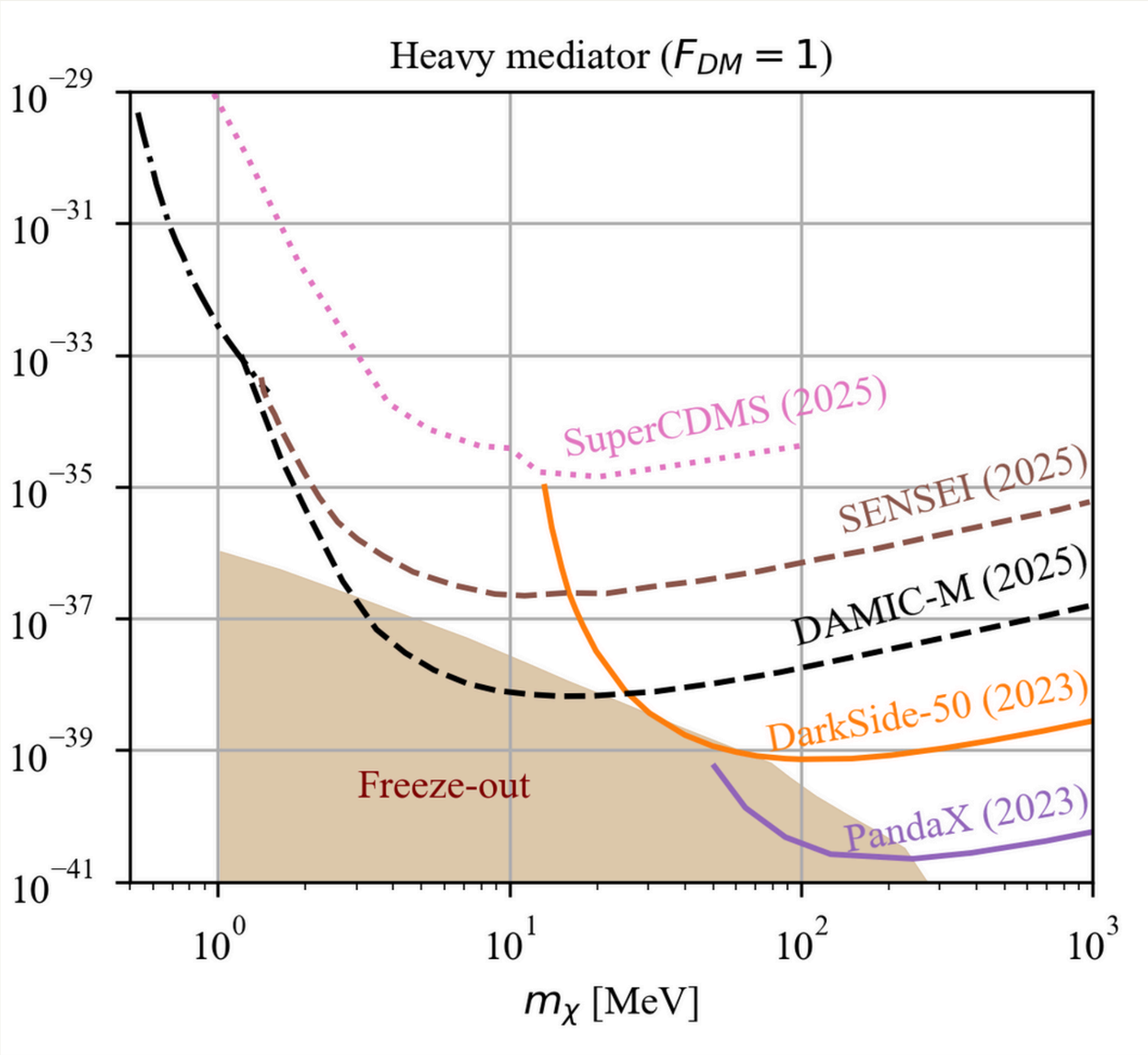
Ultra-light mediator (mA' << mX)

- Skipper-CCDs are the most sensitive detectors in the whole MeV mass range
- Particles with masses between 3.5-490 MeV are excluded from making up the dominant component of Dark Matter: cross-section would be too small, leading to an under-abundance.

DAMIC-M LBC results

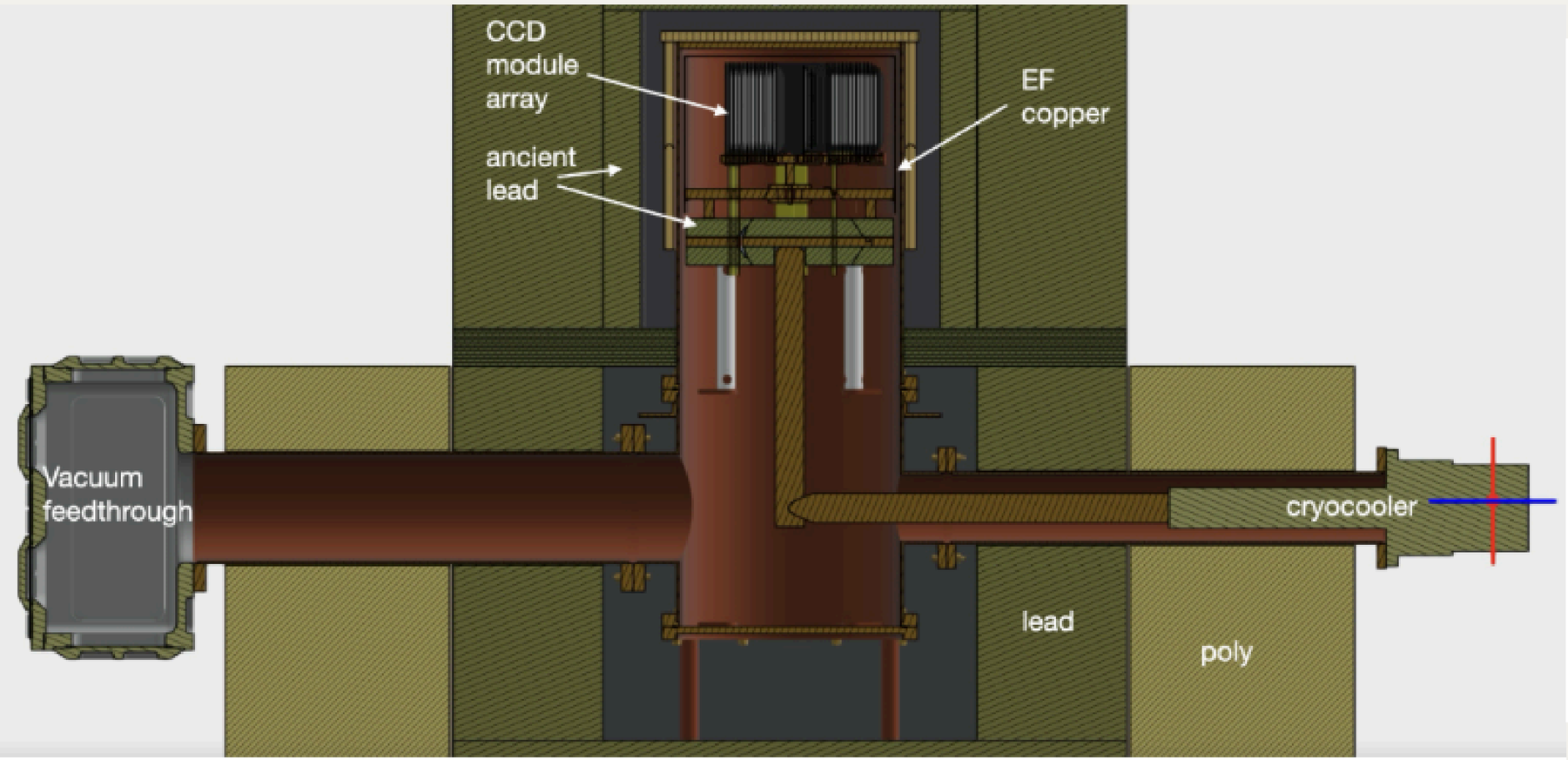
Heavy mediator (mA' >> mX)

- Skipper-CCDs are the most sensitive detectors in the 1-20 MeV mass range
- Complex scalar particles with masses between 3-20 MeV are totally excluded from making up any fraction of Dark Matter: cross-section would be too small, leading to an over-abundance.
- Other candidates (e.g. fermion particles) still viable

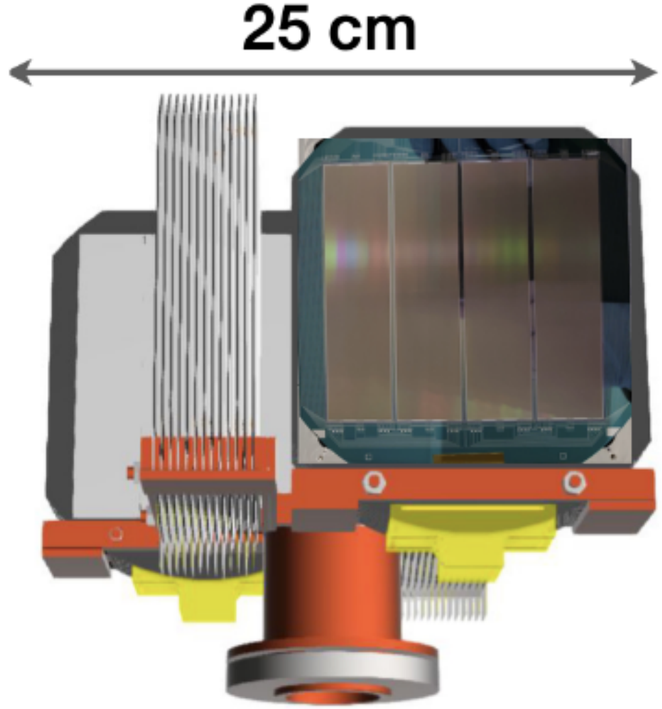


Towards DAMIC-M full installation

Next step: Installing ~350 g of Skipper CCDs at LSM



Rendering of DAMIC-M final design

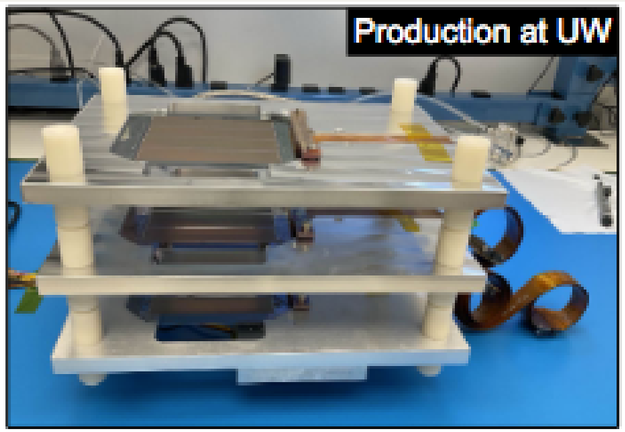


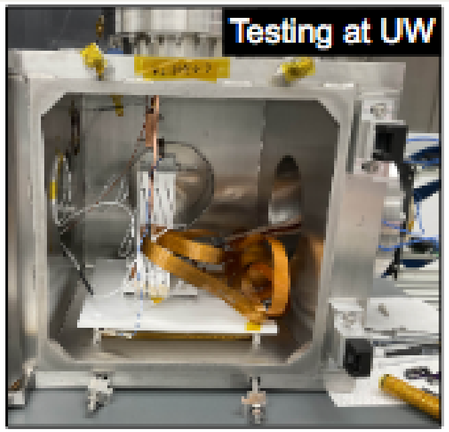
Rendering of DAMIC-M CCD array

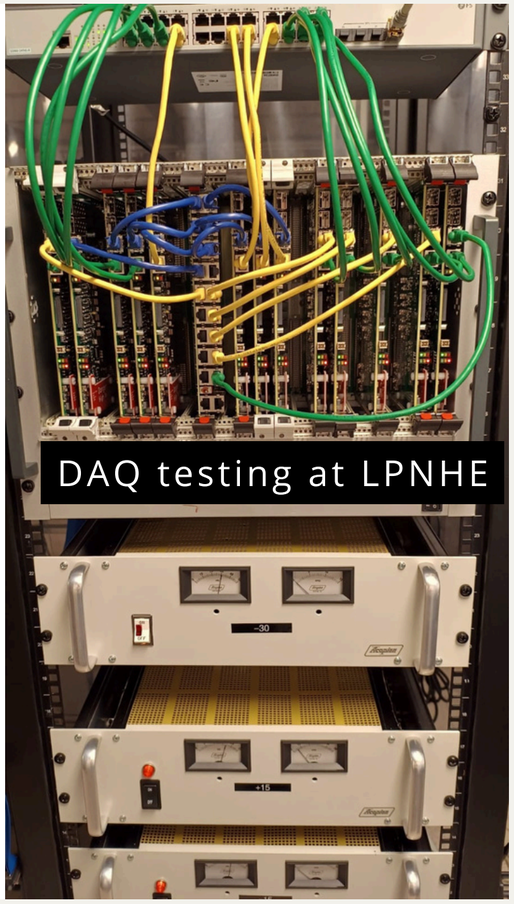
Towards DAMIC-M: scaling the detector mass

Module production preprint:

- 28 Skipper CCD modules, with 4 CCDs each, have been manufactured
- Underground testing is almost done at a specifically-designed test chamber in LSM
- All readout boards have been manufactured, DAQ stress testing ongoing at LPNHE



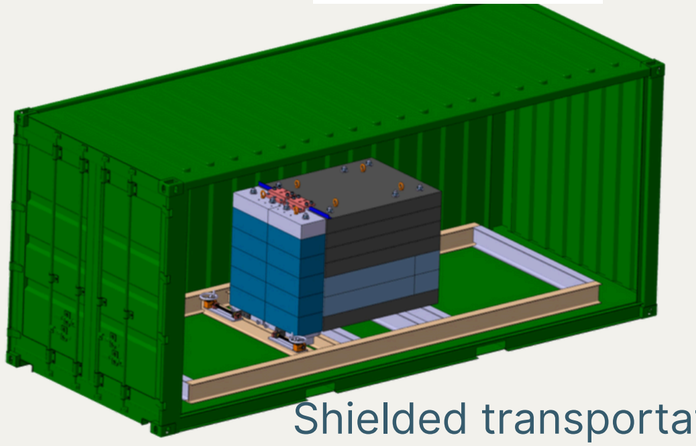




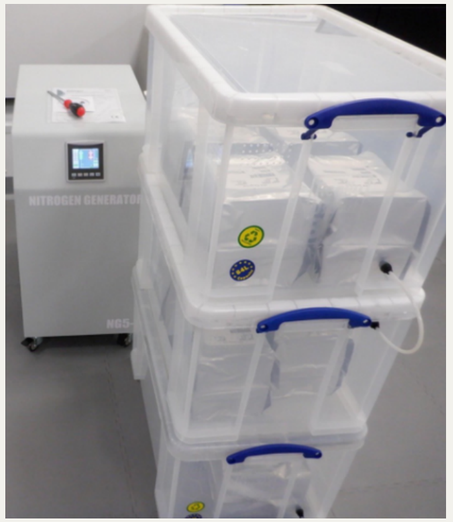
Towards DAMIC-M: controlling our backgrounds

Module production preprint:

- Limit exposure time to cosmic rays
- Limit the detector surfaces' exposure to radon
- New materials: Electro-Formed copper, low-background cables
- Remove Si wafer surface (to reduce surface Pb210)
- Chemical treatments of Cu, Pb components to remove surface Pb210



Shielded transportation



Radon-free storage

Shield during CCD production

Summary

- DAMIC-M prototype sensor has set stringent limits to MeV-scale particles interacting with electrons
- It has ruled out that particles with masses between 3.5 and 490 MeV and ultra-light mediator are a dominant component of DM
- It has ruled out that particles with masses between 2.9 and 21.5 MeV and heavy mediator can explain any fraction of DM
- 28 Skipper CCDs will be installed at LSM during 2026 and their operation will explore deeper into the DM phase space

Stay tuned, and do not hesitate in asking further questions!

Thank you.