Probing the Dark Sector with Electron Recoil

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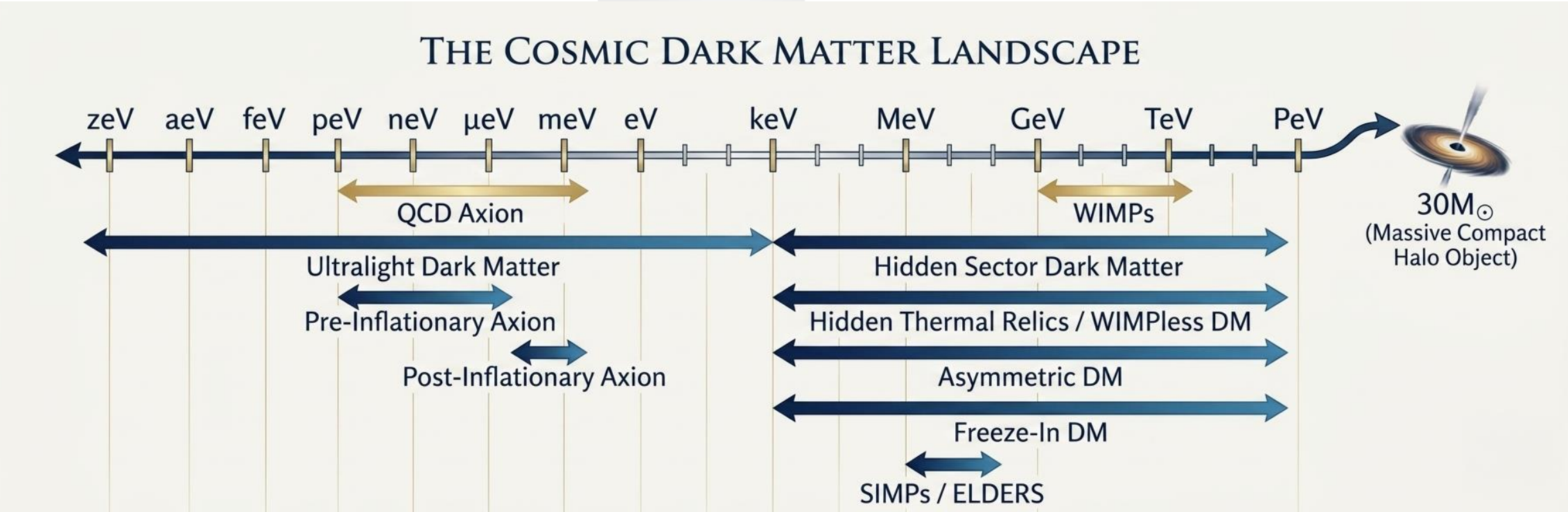
Outline

1. Dark Matter and low mass searches
2. Can I use my Bonafide Xenon/Argon detector to search for Electron Recoil?
3. New technology? The Skipper CCD

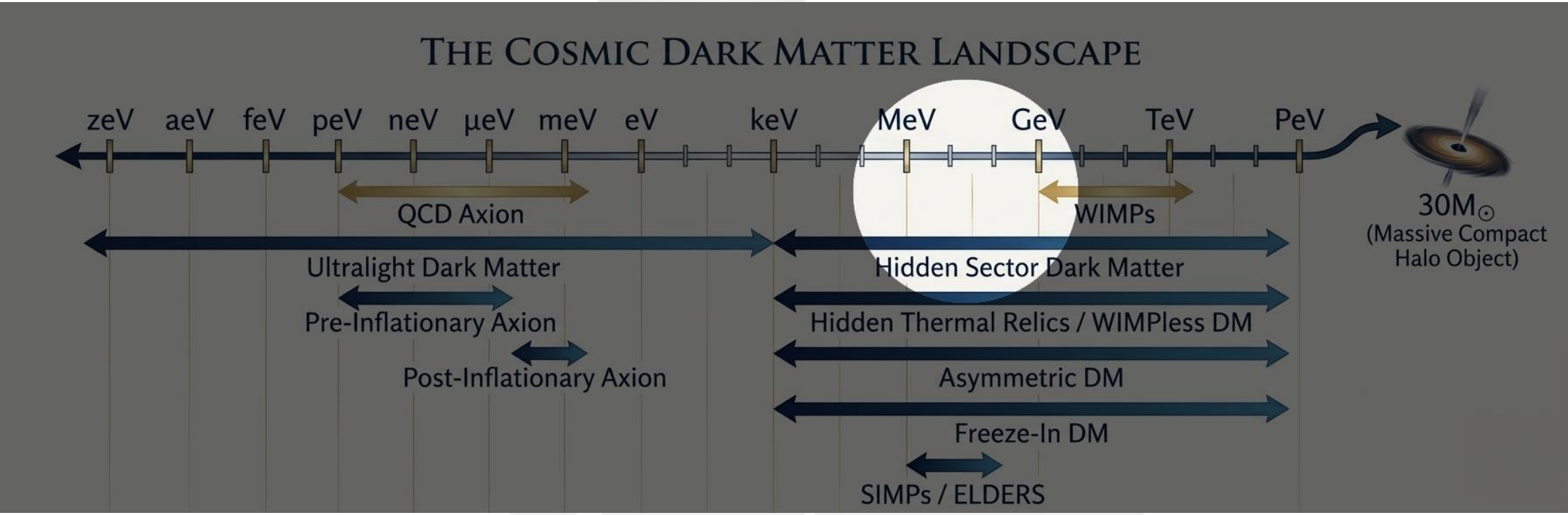
4. The Last 2 years
5. The Next 2 years (?)

(1)
Dark Matter and low mass searches

Mass range


THE COSMIC DARK MATTER LANDSCAPE
zeV
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
QCD Axion
WIMPs
30M⊙
(Massive Compact Halo Object)
Ultralight Dark Matter
Hidden Sector Dark Matter
Pre-Inflationary Axion
Hidden Thermal Relics / WIMPless DM
Post-Inflationary Axion
Asymmetric DM
Freeze-In DM
SIMPs / ELDERS

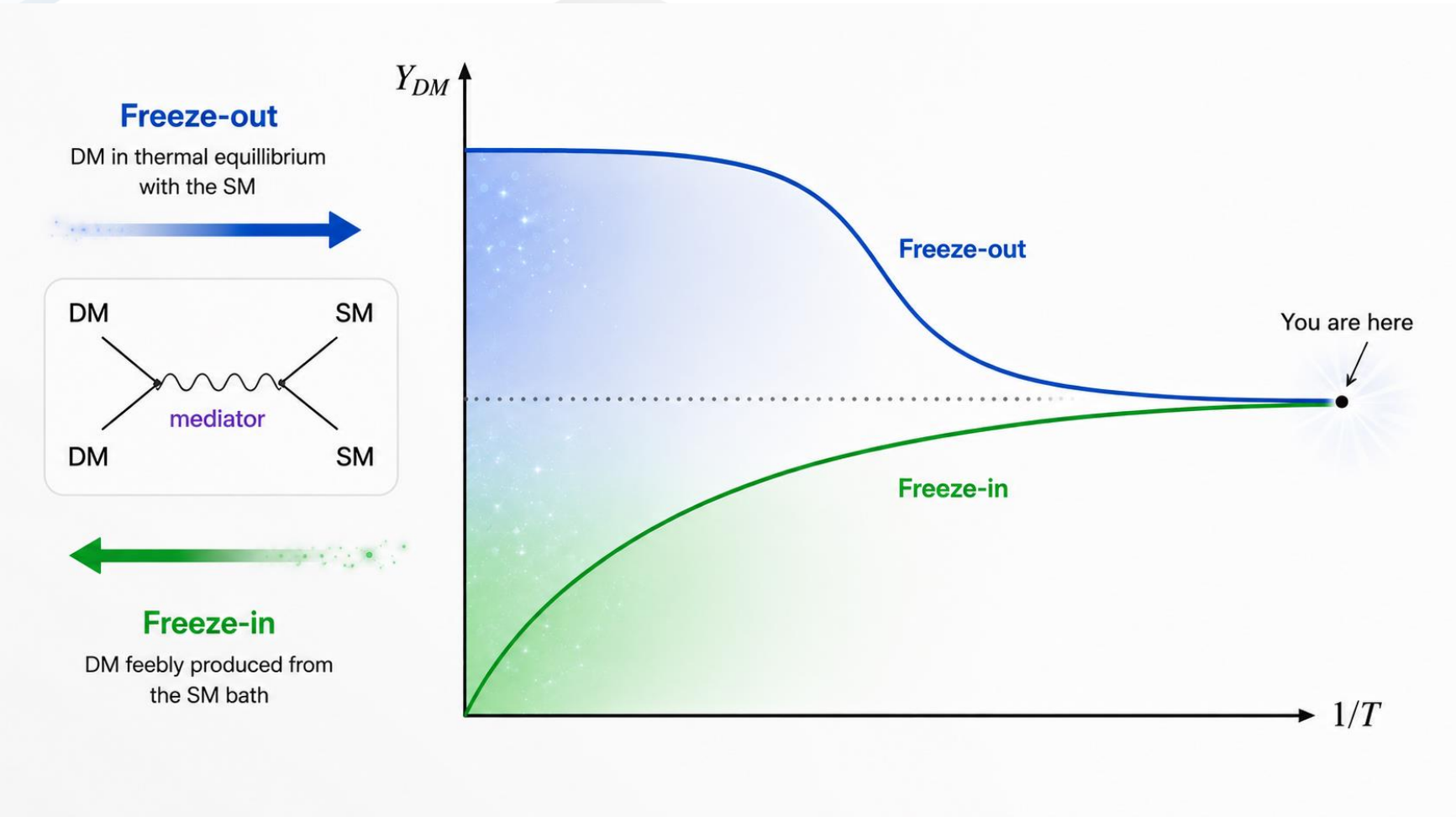
Dark Sector – Electron recoil zone of interest



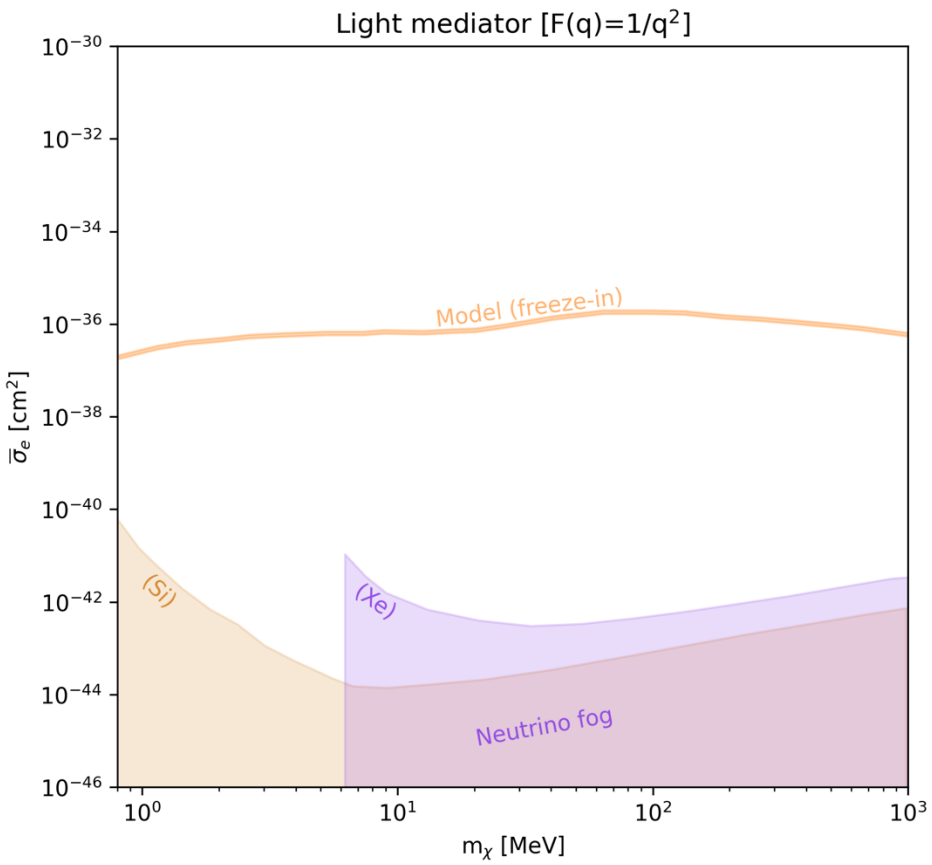
Dark Sector: the simplest expansion of SM

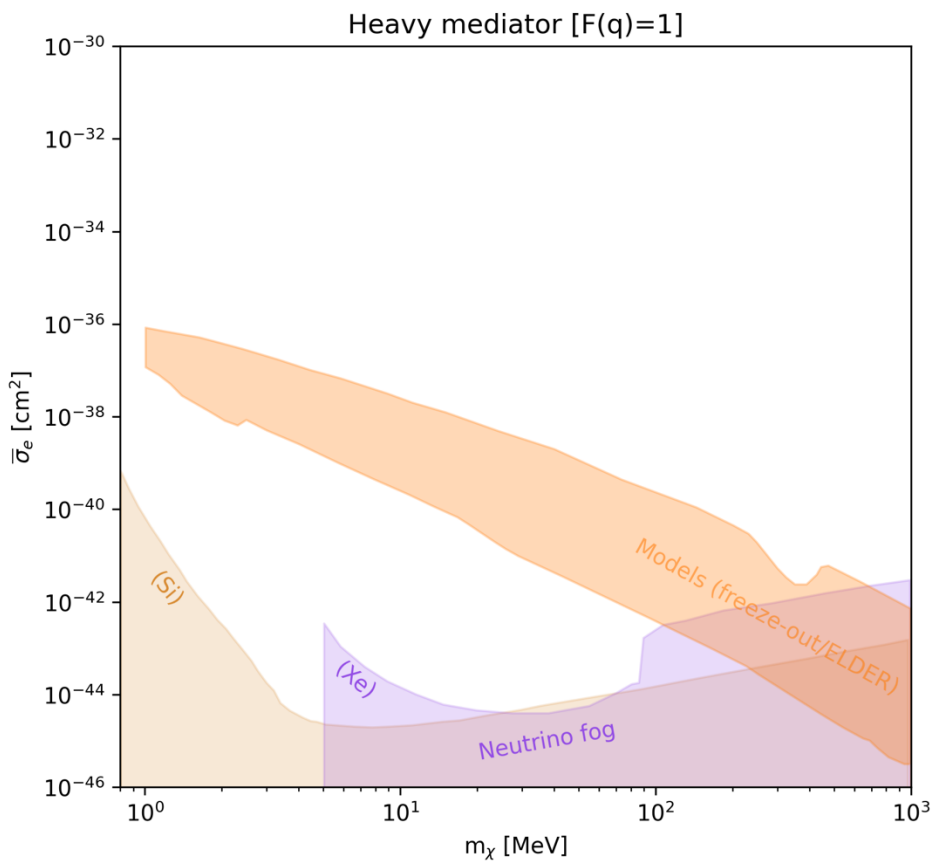
- Add a U(1) symmetry
  - Minimal renormalizable portal to the Standard Model
  - Gauge invariance: kinetic mixing with SM U(1)
  - After EWSB, dark photon couples to electric charge
    - Light DM opens the <GeV scale
    - Nuclear recoils suppressed
    - Ideal to observe as electron recoil
      - Need to observe much smaller energy deposits

How to create Dark Matter – Freeze-in/out



Models



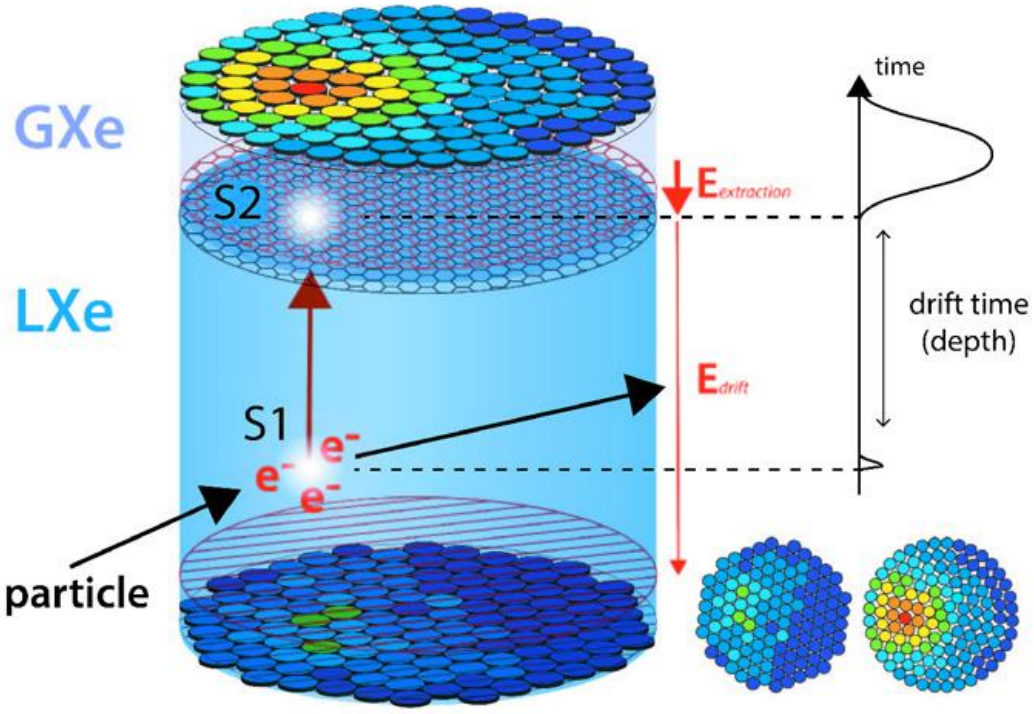


Carew et al.,
Phys. Rev. D 109,
083016 (2024)

(2)

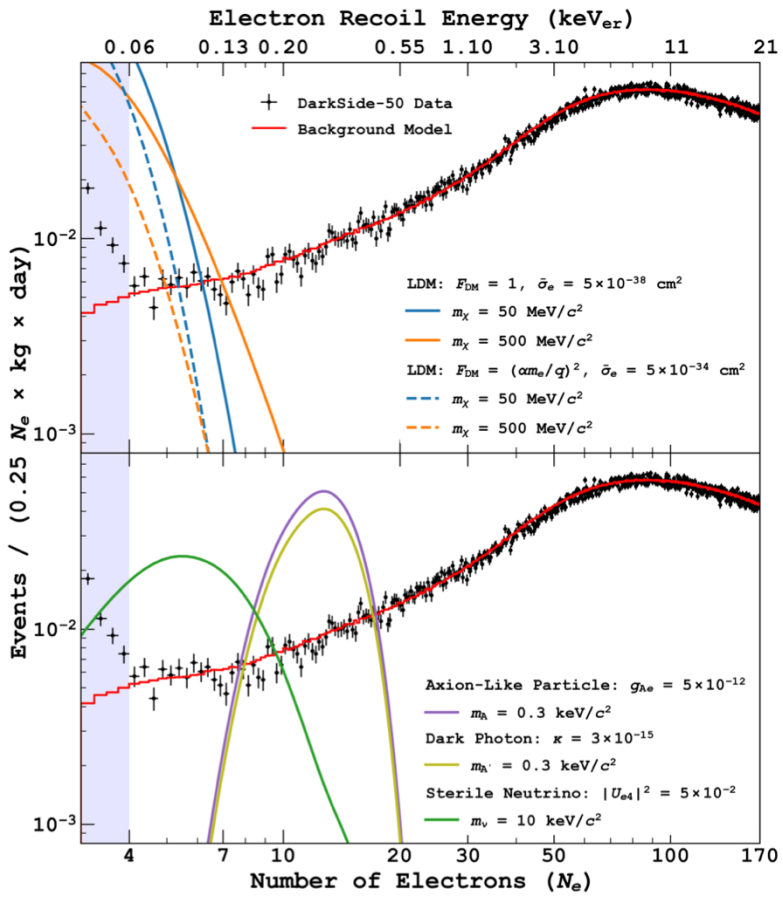
Can I use my Bonafide Xenon/Argon detector to search for Electron Recoil?

Build a detector to observe nuclear recoils



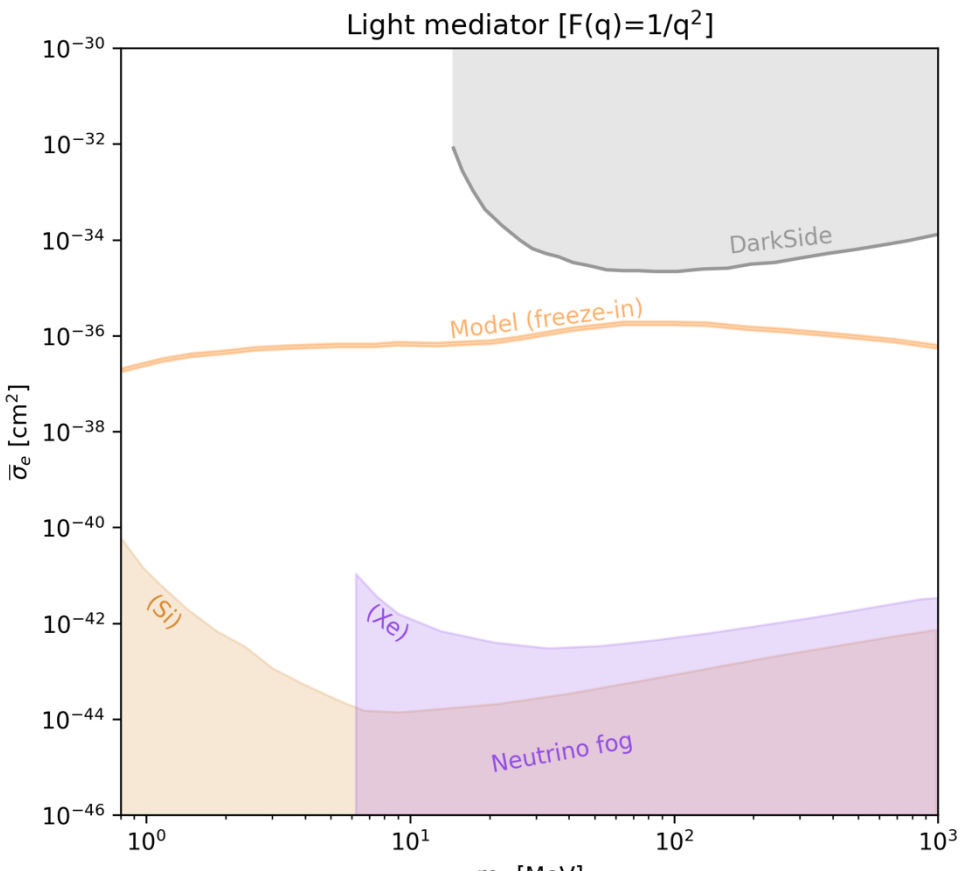
Using only S2

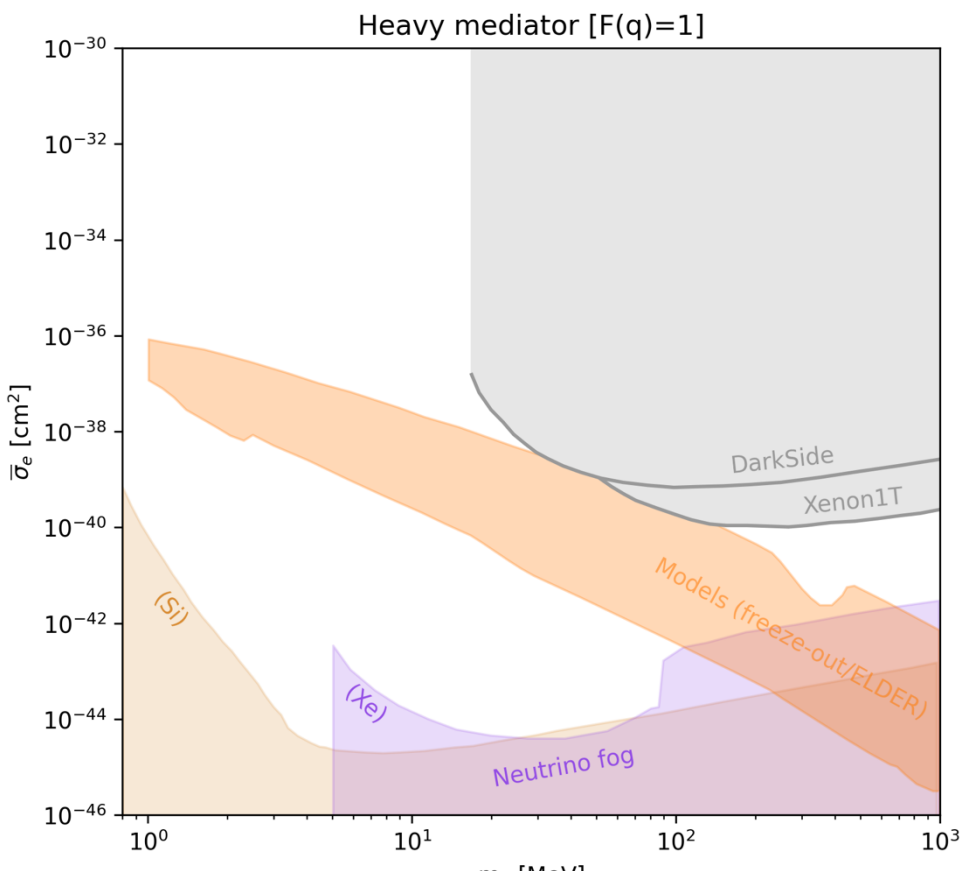
- Electron recoil accessible as an S2 only search
- Losing background rejection capability
  - Ok with a background model
- Usually unreducible background at a few electrons



The DarkSide-50 Collaboration Phys.Rev.Lett. 130 (2023) 10, 101002

Argon/Xenon limits (Noirmoutier 2024)

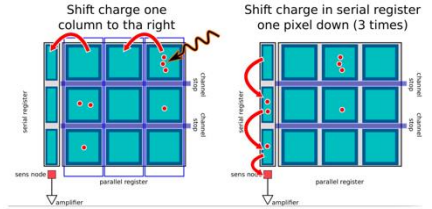


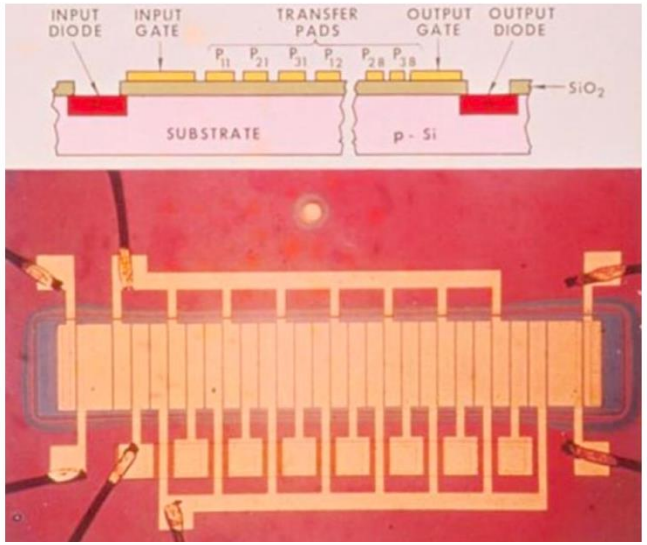


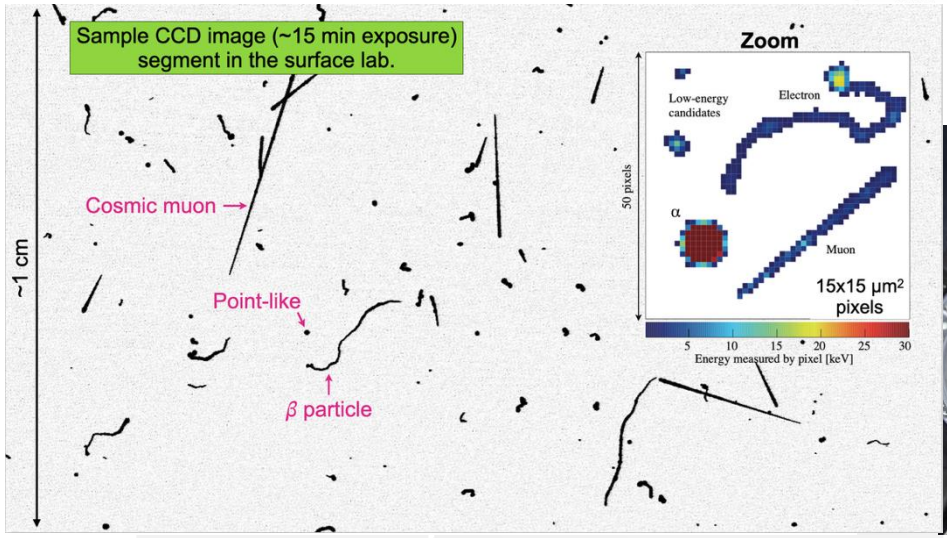
(3)
New technology?
The Skipper CCD

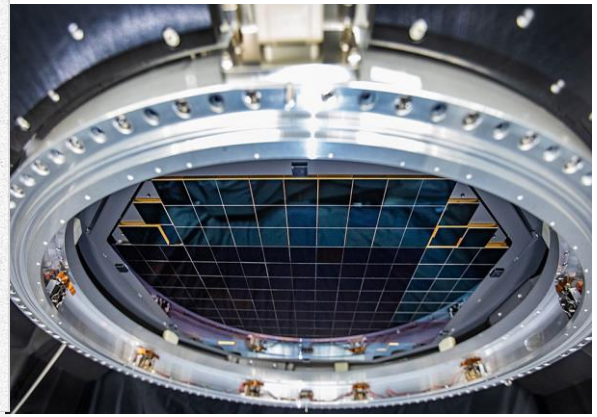
CCD as a particle detector

- CCD were invented in 1969 by Boyle and Smith (Bell Labs) as a memory device. It works better as an image sensor and was quickly used in consumer devices.
- Charge is moved line by line, then pixel by pixel, read at a single sense node.

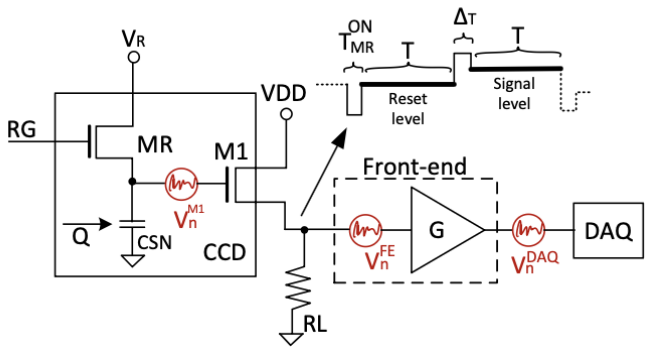


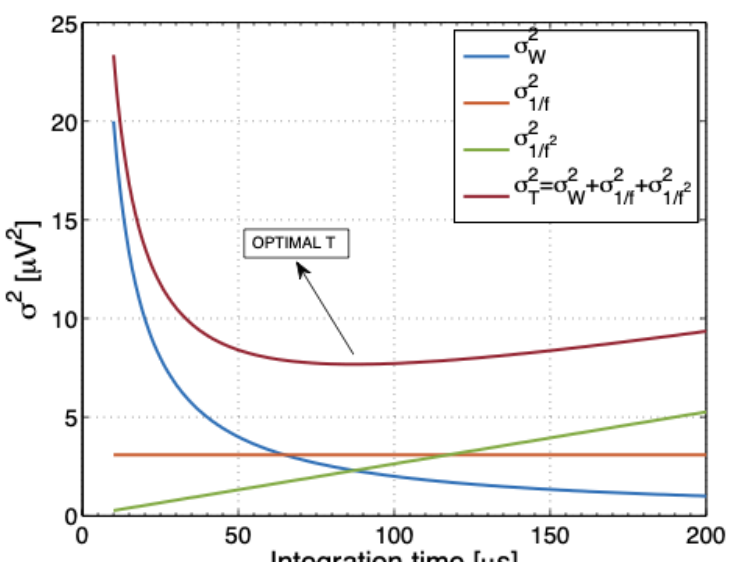


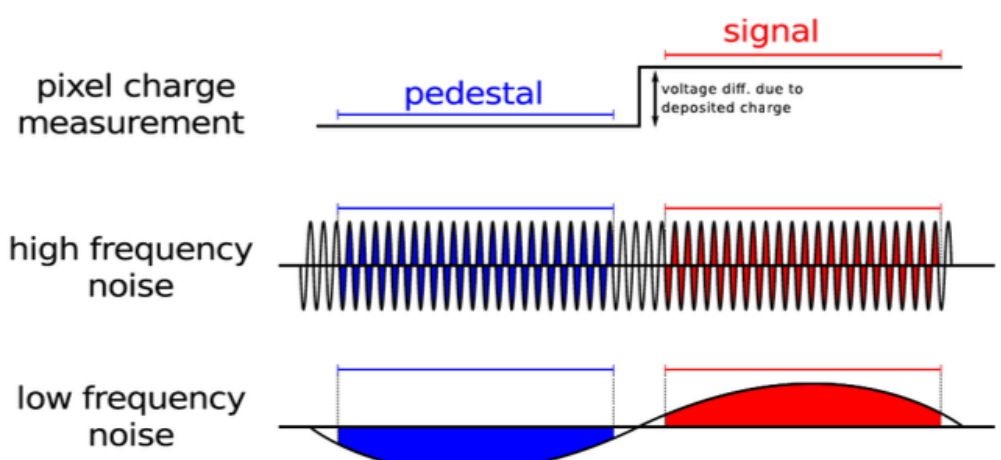




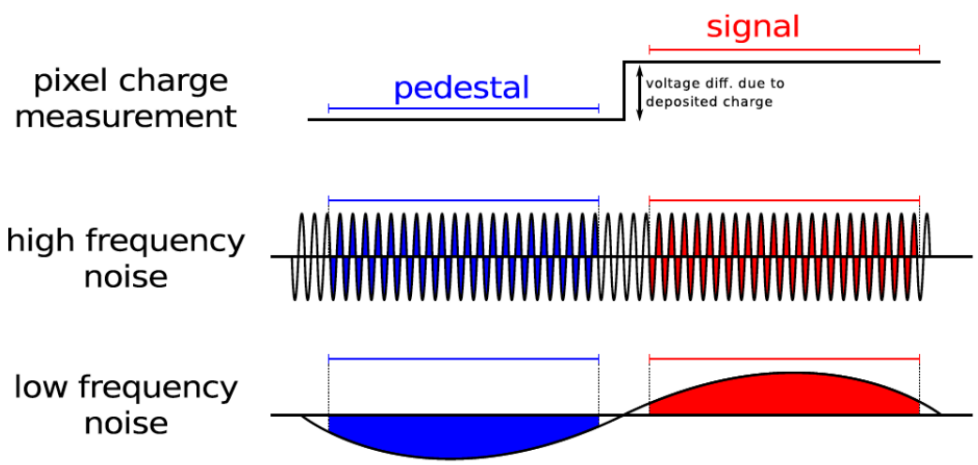
CCD problem: low frequency noise

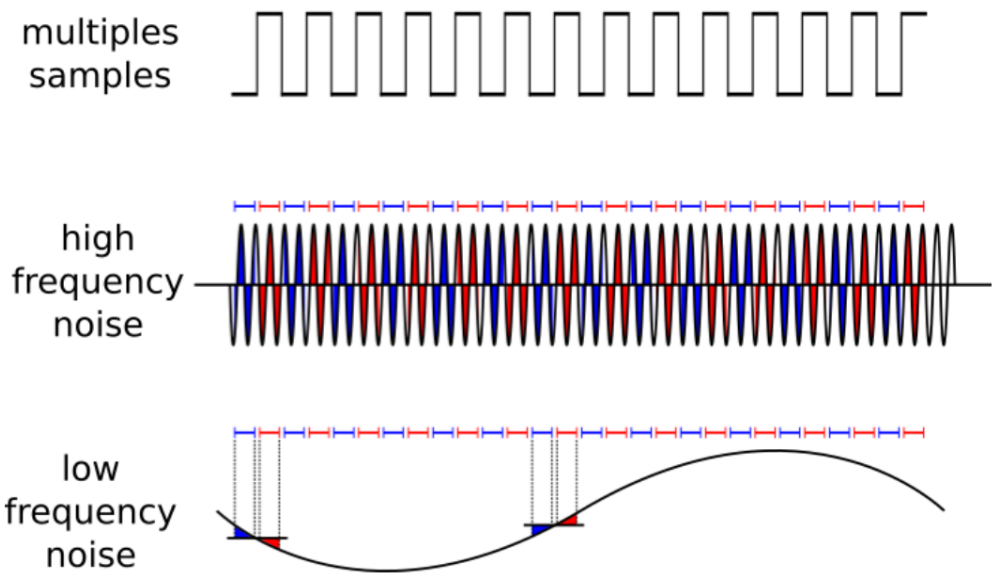






Introducing the Skipper CCD





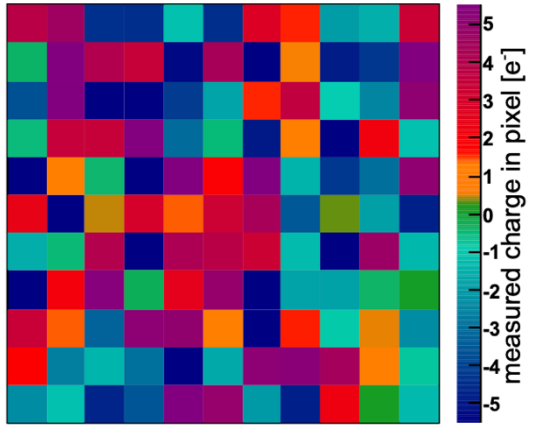
Noise goes in $1/\sqrt{N}$

Introducing the Skipper CCD

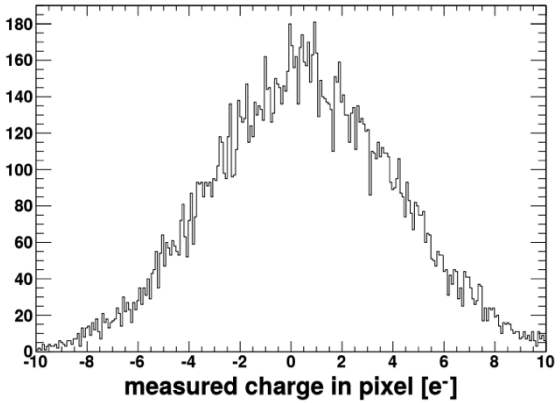
Single electron:
threshold is silicon band gap (1.1 eV)

PRL 119, 131802 (2017)

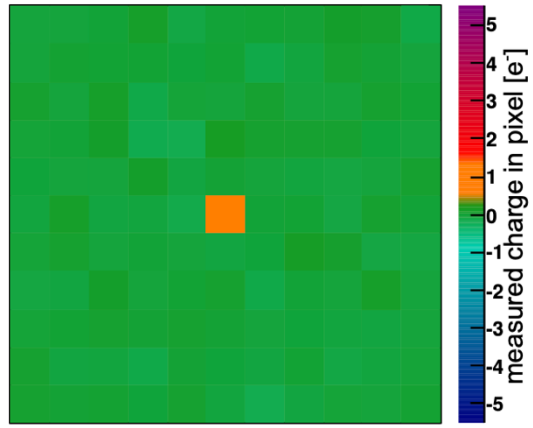
Standard CCD mode: charge in each pixel is measured once



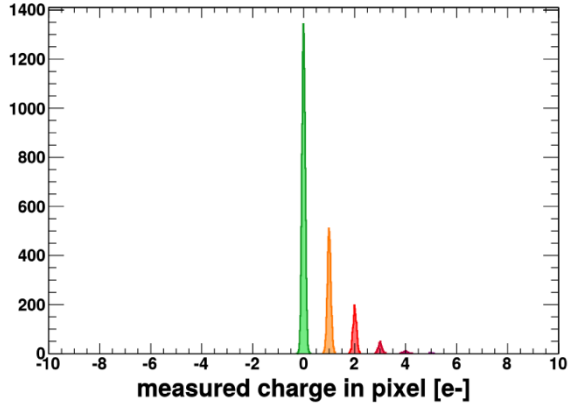
Readout-noise: 3.5 e RMS



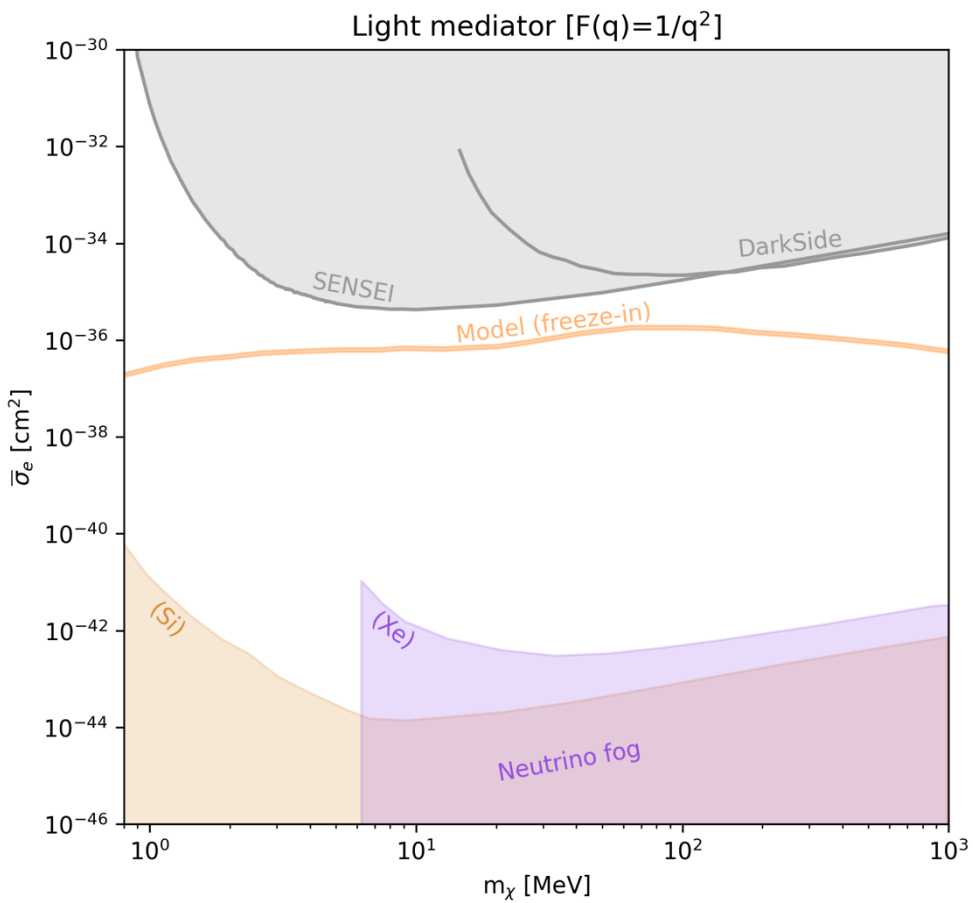
New Skipper CCD: charge in each pixel is measured multiple times

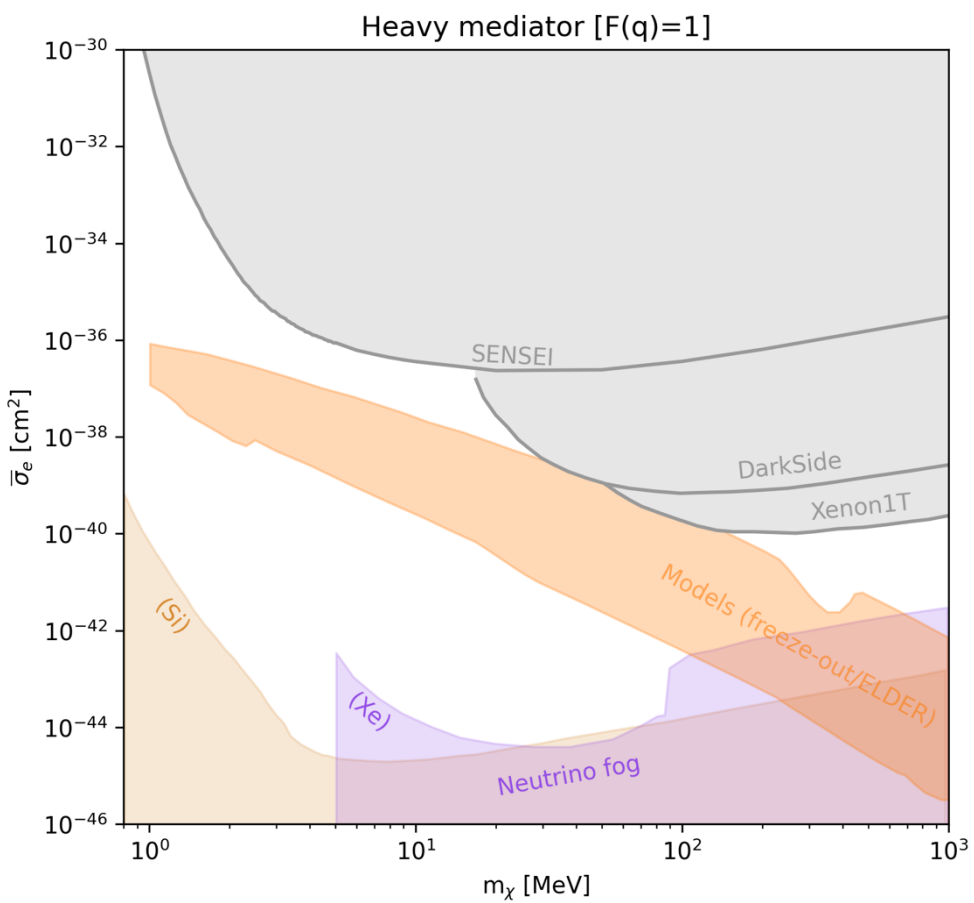


Readout-noise: 0.06 e RMS

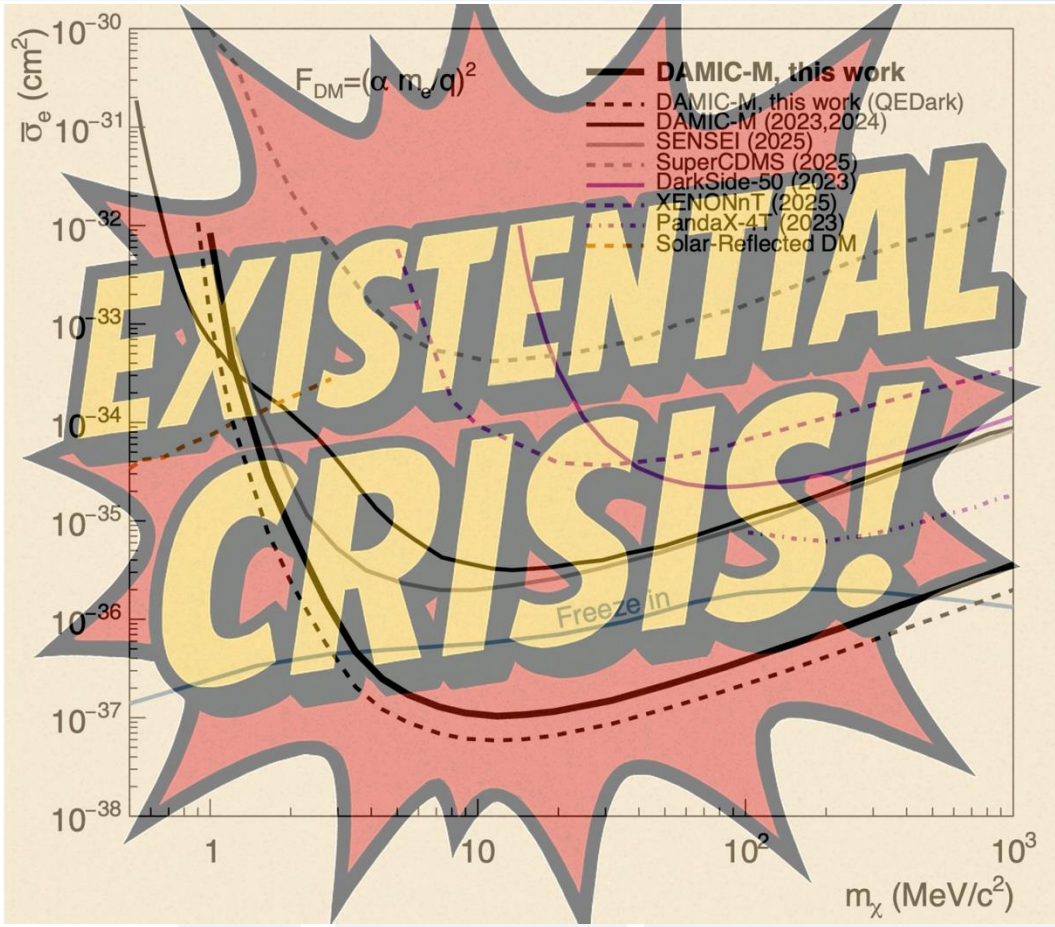


Skipper CCD + Argon/Xenon limits (Noirmoutier 2024)





(4)
The Last 2 years

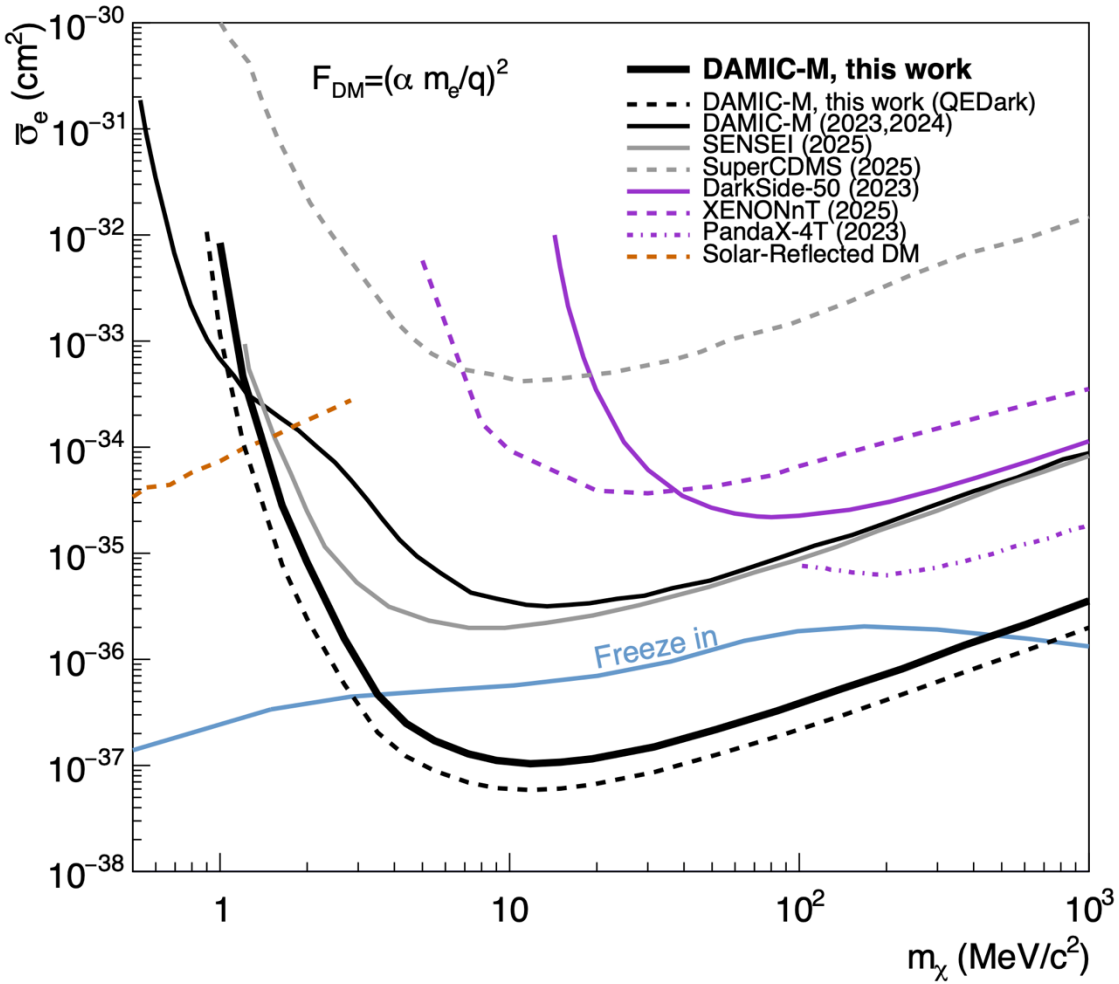


DAMIC-M Collaboration [2503.14617]

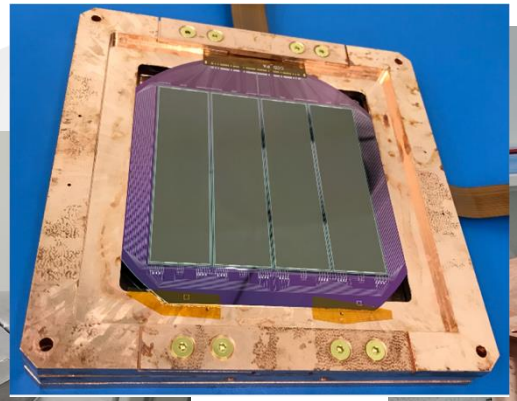
"A Moving Target: Direct Detection in the Light DM Landscape"
The 10th LCTP Spring Symposium : Hunting for Particle Dark Matter - https://indico.global/event/1382/contributions/125550/

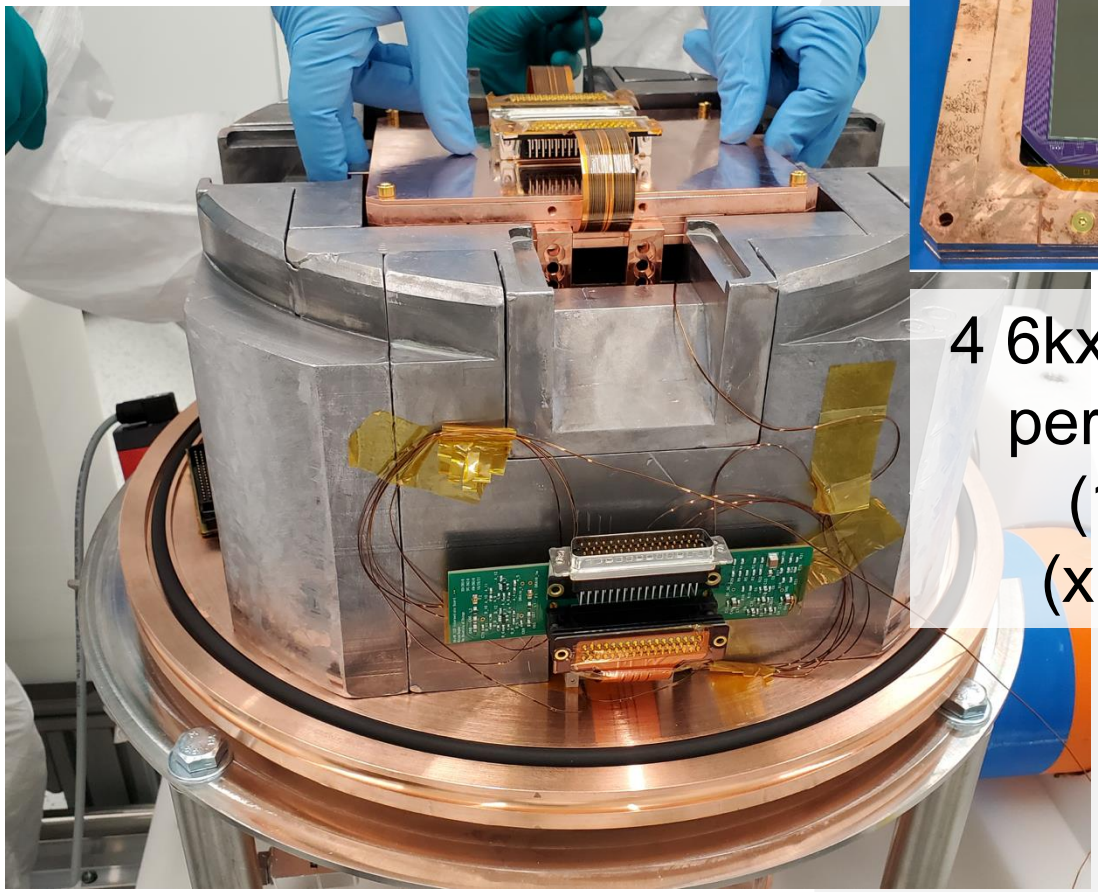
Low Background Chamber: DAMIC-M prototype

DAMIC-M collaboration
Phys. Rev. Lett. 135, 071002 –
Published 13 August, 2025



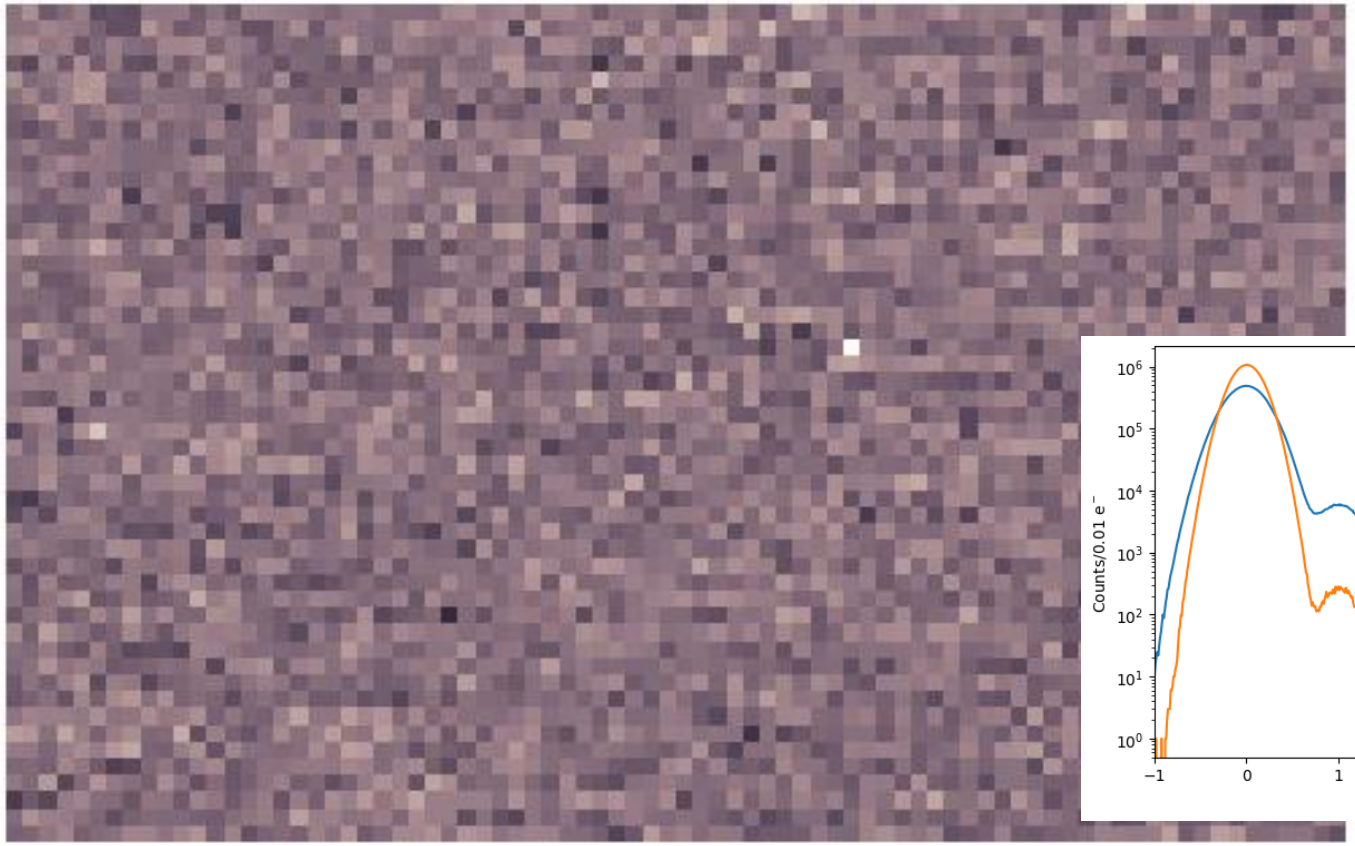
LBC: 27g skipper CCD in improved setup



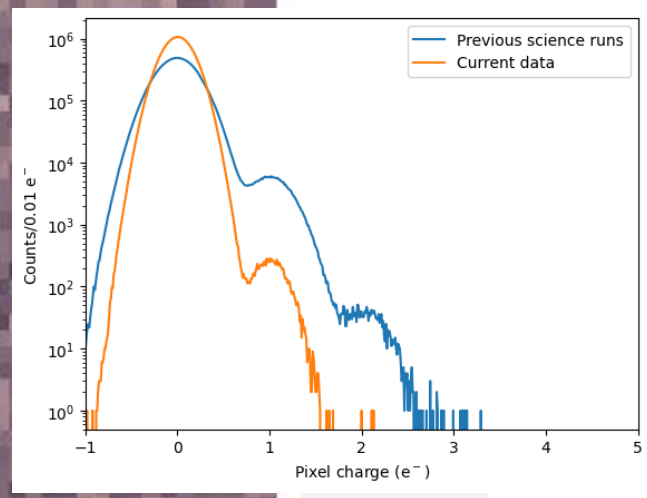


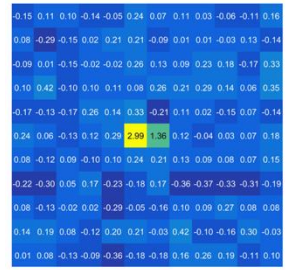
4 6kx1.5k CCD per module (13.4g) (x2=27g)

Physics analysis: looking for pixel patterns

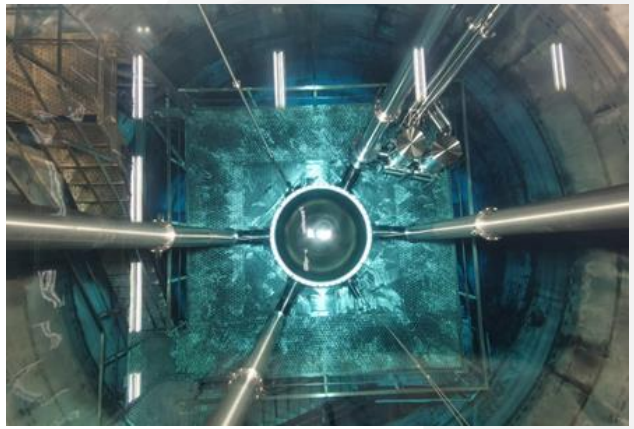


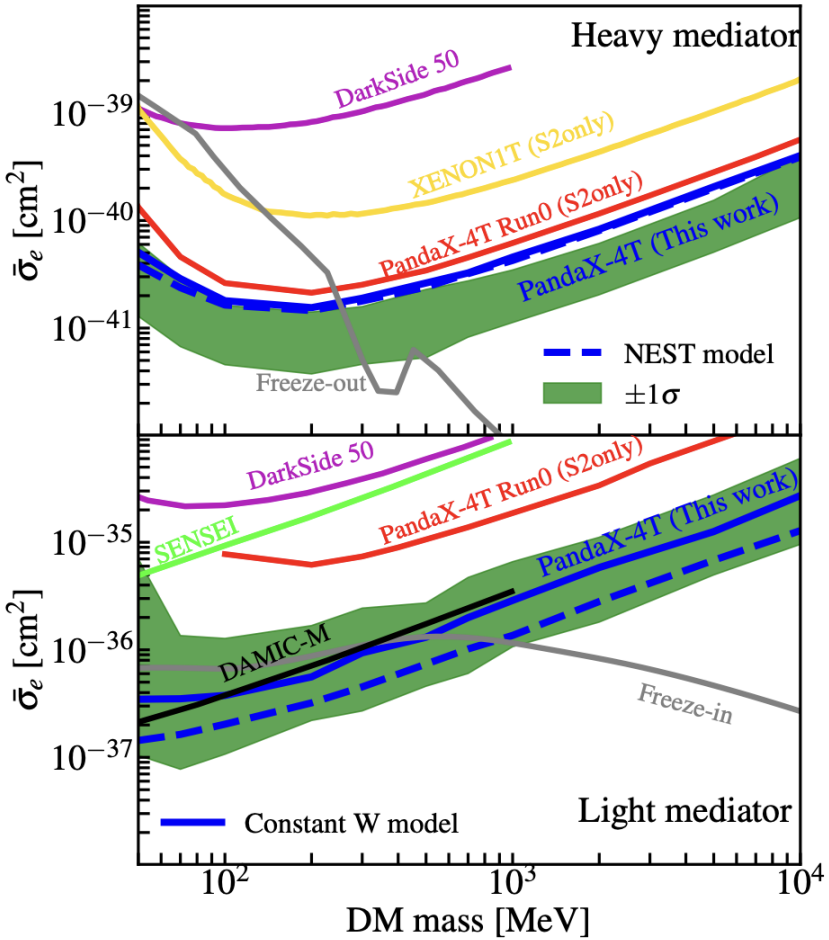
	Pattern p		
	$\{11\}$	$\{21\}$	$\{111\}$
D_p	144	0	0
B_p^{rc}	141.4	0.111	0.042
B_p^{rad}	0.039	0.039	0.016
	$\{31\}$	$\{22\}$	$\{211\}$
D_p	1	0	0
B_p^{rc}	0.019	$2.5 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$
B_p^{rad}	0.052	0.011	0.035



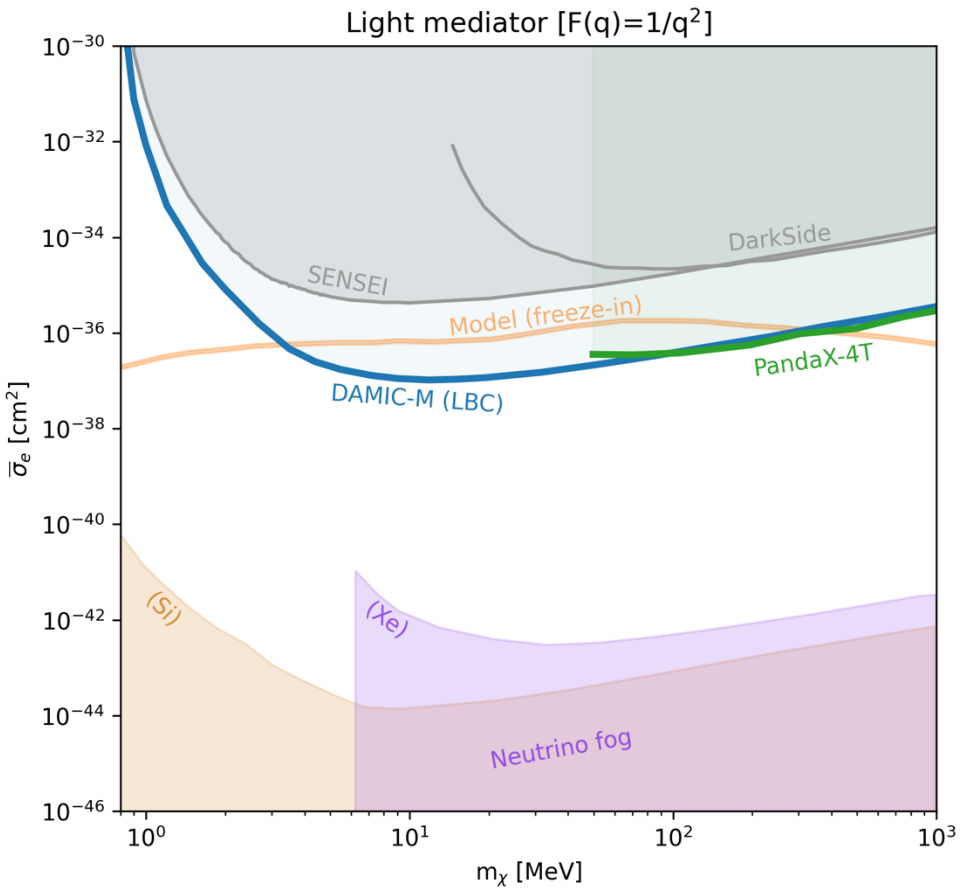


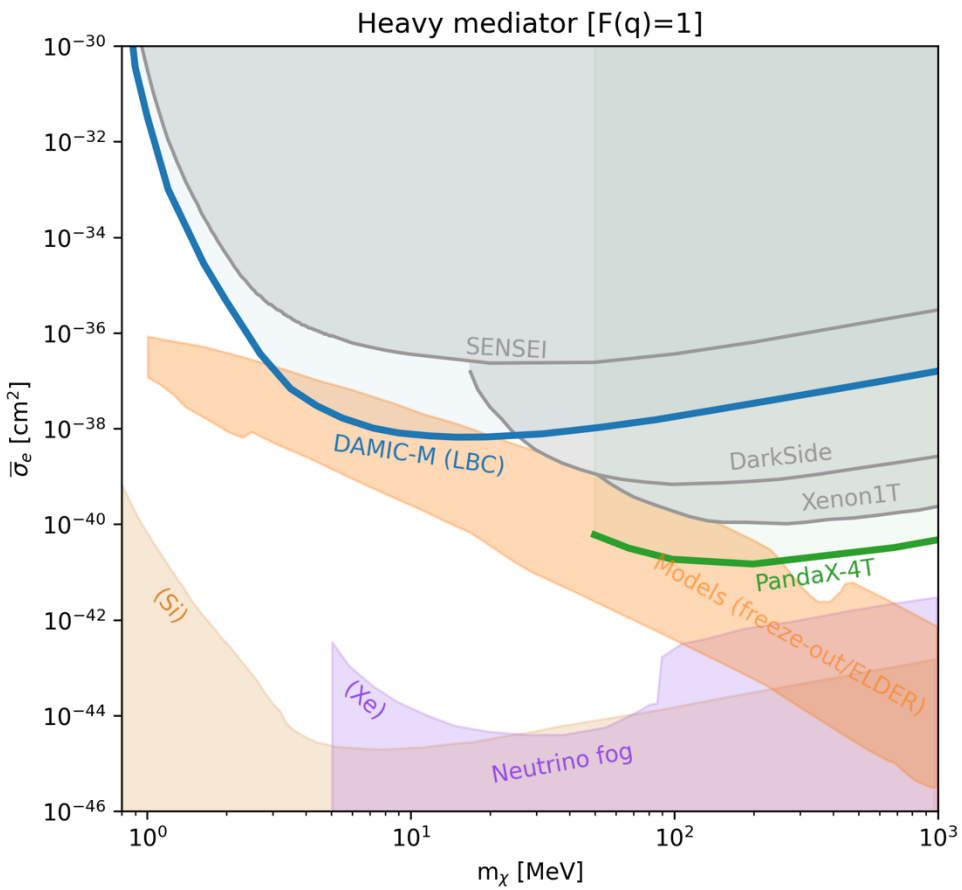
PandaX collaboration
Phys. Rev. Lett. 135, 211001 –
Published 18 November, 2025





Situation as of today





(5)
The Next 2 years (?)

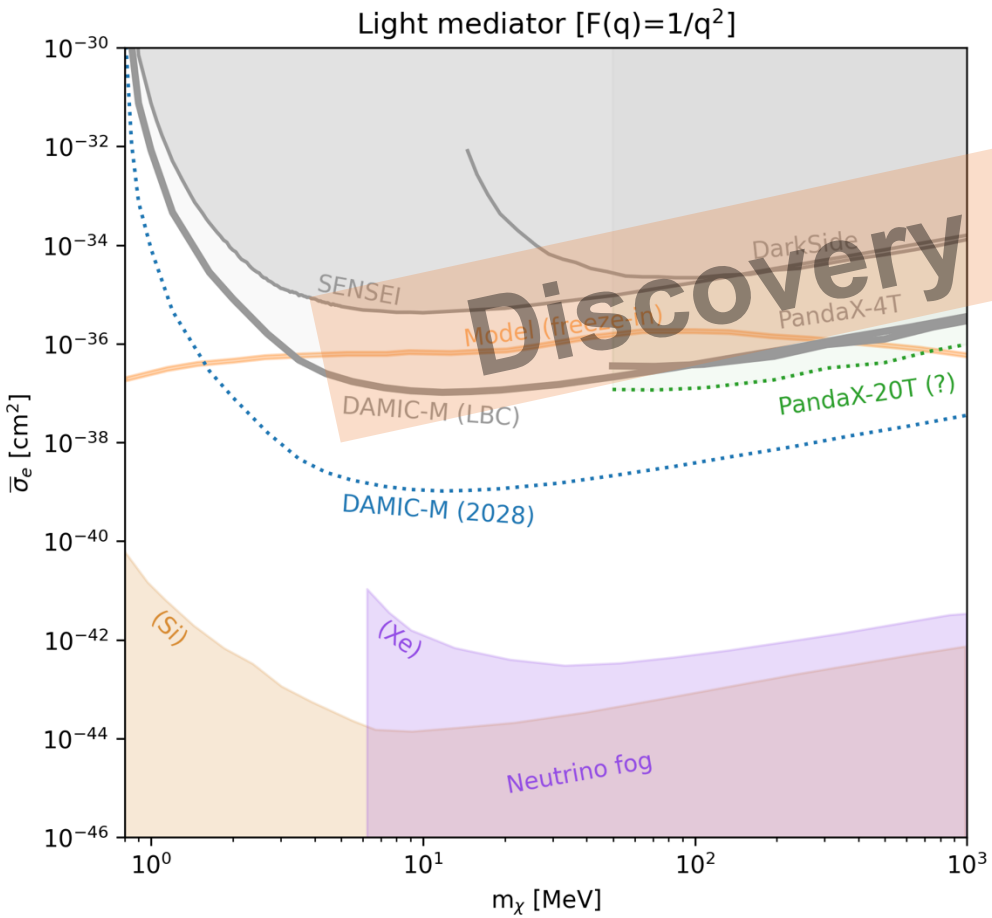
Future Noble liquid detectors

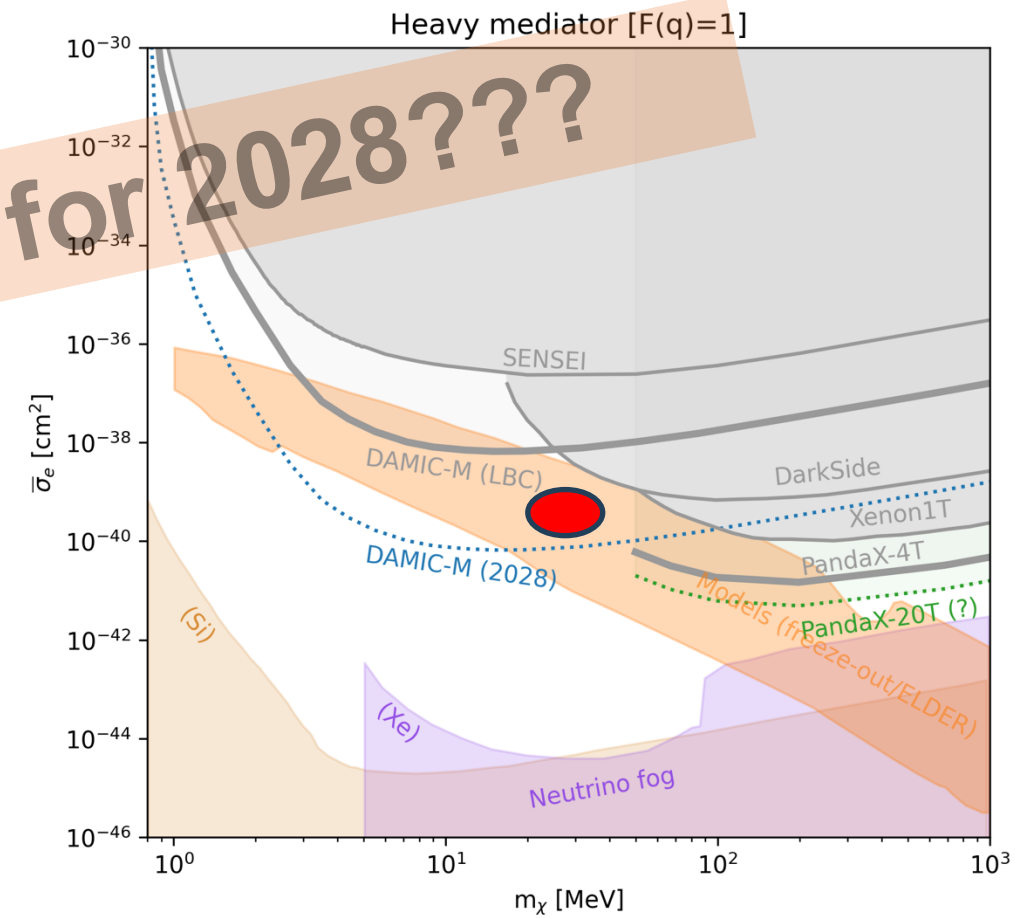
- PandaX-xT:
  - Mass increase towards 43T target (?)
  - First step at 20T (?)
  - Data taking starting in 2027 (?)
  - Sensitivity improving naively 3 to 5 (?)
- DarkSide 20k:
  - Huge size improvement over DarkSide-50
  - Data taking starting in 2027 (?)
  - Likely to be competitive against DAMIC-M/PandaX-20T, but maybe not by next Noirmoutier
- Xenon/LZ/XLZD:
  - Likely not competitive for next Noirmoutier…

Solid state detectors

- DAMIC-M:
  - Installation under way
  - Exposure increase: 27 g → 350 g
  - Exposure increase: 2 months → 2 years
  - Radioactive backgrounds ↓ ~10× (goal)
  - Dark current ↓ ~2× (or better?)
- SuperCDMS:
  - Delayed by >5 years relative to original schedule
  - Currently in commissioning
  - Original projections exceeded competing semiconductor technologies by 2–3 orders of magnitude
  - Current projected advantage over DAMIC-M is typically <1 order of magnitude
  - Ultimate sensitivity depends critically on understanding low-energy / single-charge backgrounds (LEE)

For next Rencontres de Noirmoutier





Discovery for 2028???

Conclusions

- Electron recoil experiments progressing extremely fast in the last years
  - A very significant part of the strongly motivated parameter space in the MeV-GeV region has been explored in the last year or will be explored in the next 3(?) years
- Si neutrino fog is not yet within experiment reach, Xe one isn't far
  - Directional electron recoil still unexplored
- Beside Electron Recoil, absorption processes also contribute to the search
- Dark sector can of course be more complex than a simple U(1)
  - Entering a new age for models in the MeV-GeV range
- Electron Recoil at GeV or more can also be interesting
  - Don't underestimate the electron recoil channel when designing your next Xenon experiment

Thank you