The search for light dark matter with DAMIC-M

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40 years of dark matter hunting

LIMITS ON COLD DARK MATTER CANDIDATES FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

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Phys. Rev. B 195, 4 (1987)

The first experiment to place constraints on the scattering cross section of dark matter with nuclei was carried out in 1986 at the Homestake Mine in South Dakota by a collaboration of scientists at the Pacific Northwest National Laboratory, the University of South Carolina, Boston University, and Harvard [18]. Using a low-background germanium ionization detector (originally designed to search for neutrinoless double beta decay), they accumulated an exposure of 33 kg-days, yielding a limit that significantly constrained dark matter candidates with unsuppressed spin-independent scattering cross sections with nuclei (such as heavy neutrinos or sneutrinos) [18].

G. Bertone, D. Hooper (2016)

The direct detection strategy

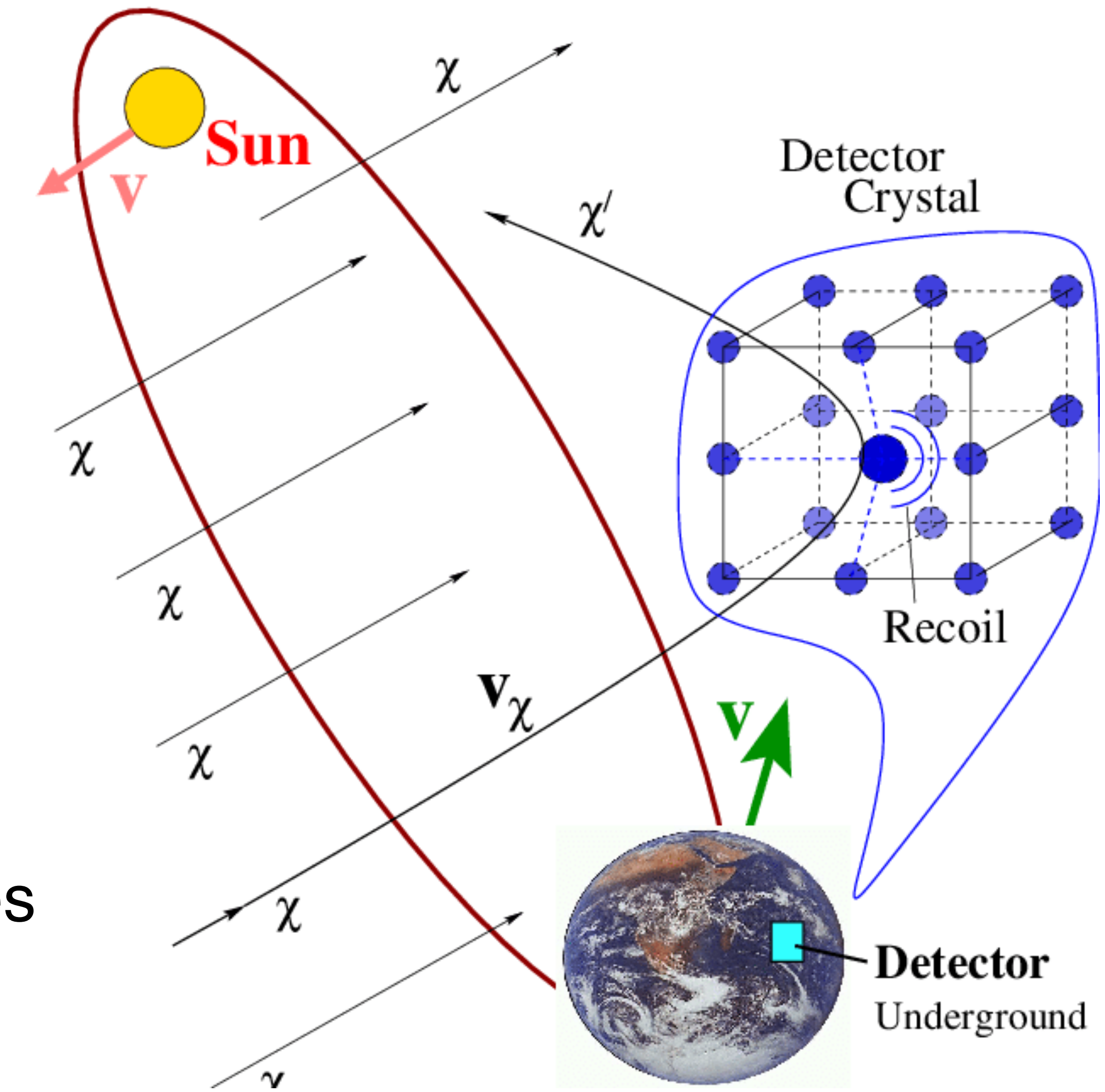
It's all scattering physics!

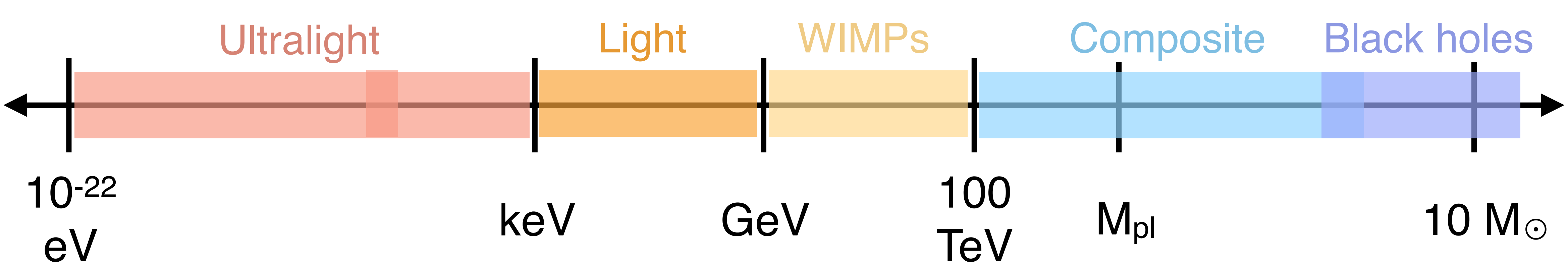
1. Detectors optimized for kinematics, e.g. dark matter mass, cross section
→ energy thresholds, target mass

For example:
m_χ = 100GeV/c^2, $v_\chi = 10^{-3}$c, $E_{n,recoil}$ ~10keV

2. Detectors also have to be radio-pure and operated underground to shield from particles that have stronger interactions.

BUT, theory doesn't tell us where to look…





The WIMP

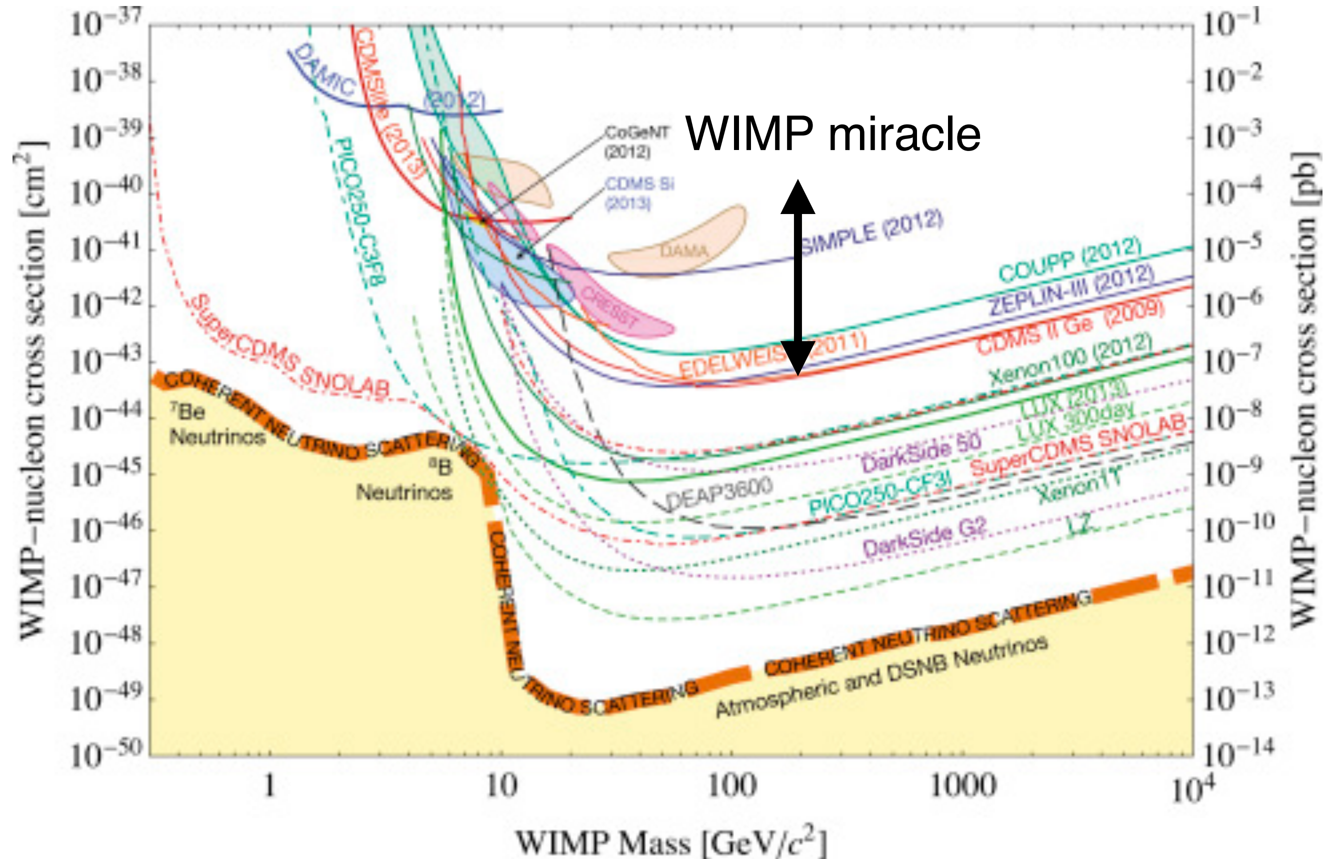
The field has been dominated by searches for the Weakly Interacting Massive Particle (WIMP). Historically, there is good or "natural" reasons for that.

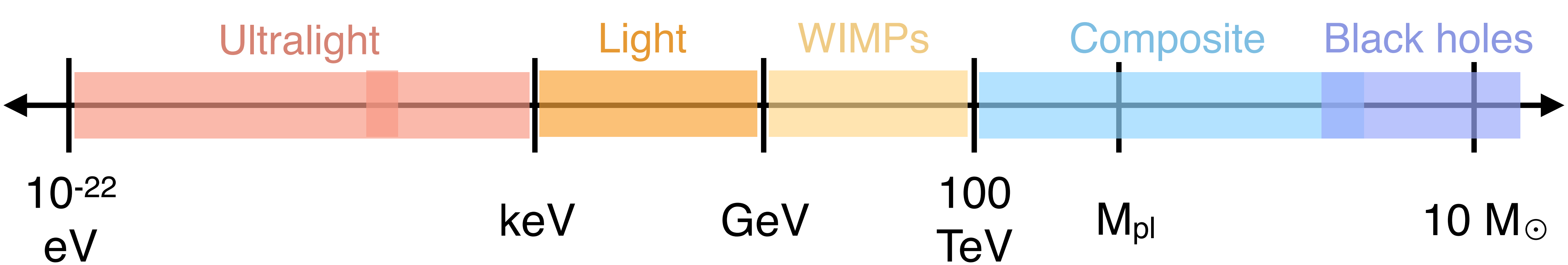
"WIMP miracle" (abundance, SUSY): annihilation cross section (σv)~10^{-26} cm^3/s, i.e. weak-scale physics.

GeV-scale (~proton mass), use heavy nuclei as targets

Has been pursued by many experiments, now multi-ton, including at SURF!

Limits shown are old (Phys. Rev. D, 89 (2014)), but show the complex landscape!

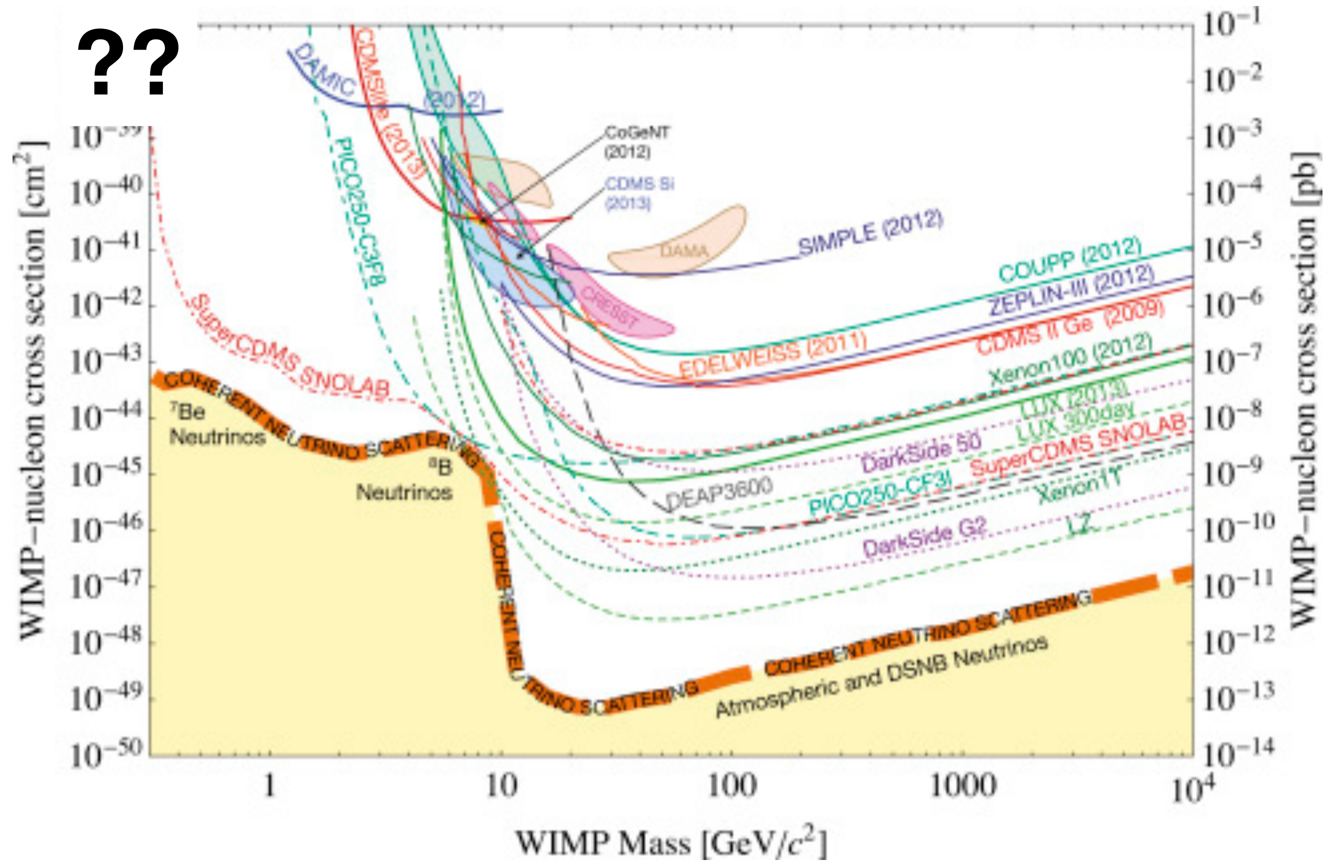




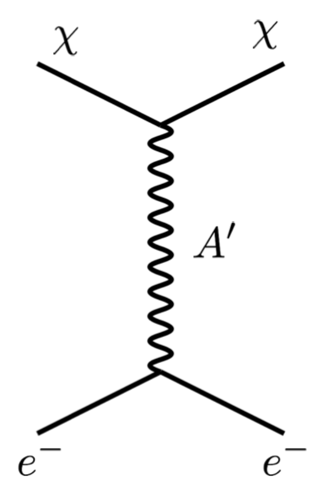
Wimpier than the WIMP

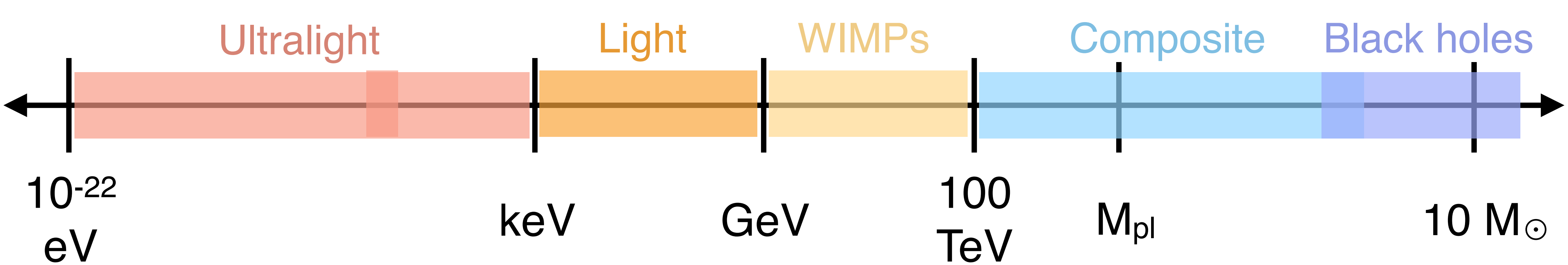
However, the WIMP has yet to appear: strong upper limits but no new particle.
Beyond "naturalness", theory becomes much richer, constraints more open.

For **sub-GeV candidates**, new forces, mediators below weak-scale are required.



This **"hidden" or "dark" sector** is linked to the Standard Model through kinematic mixing. The most minimal scenario (need benchmarks!) is "dark" photon mediator:



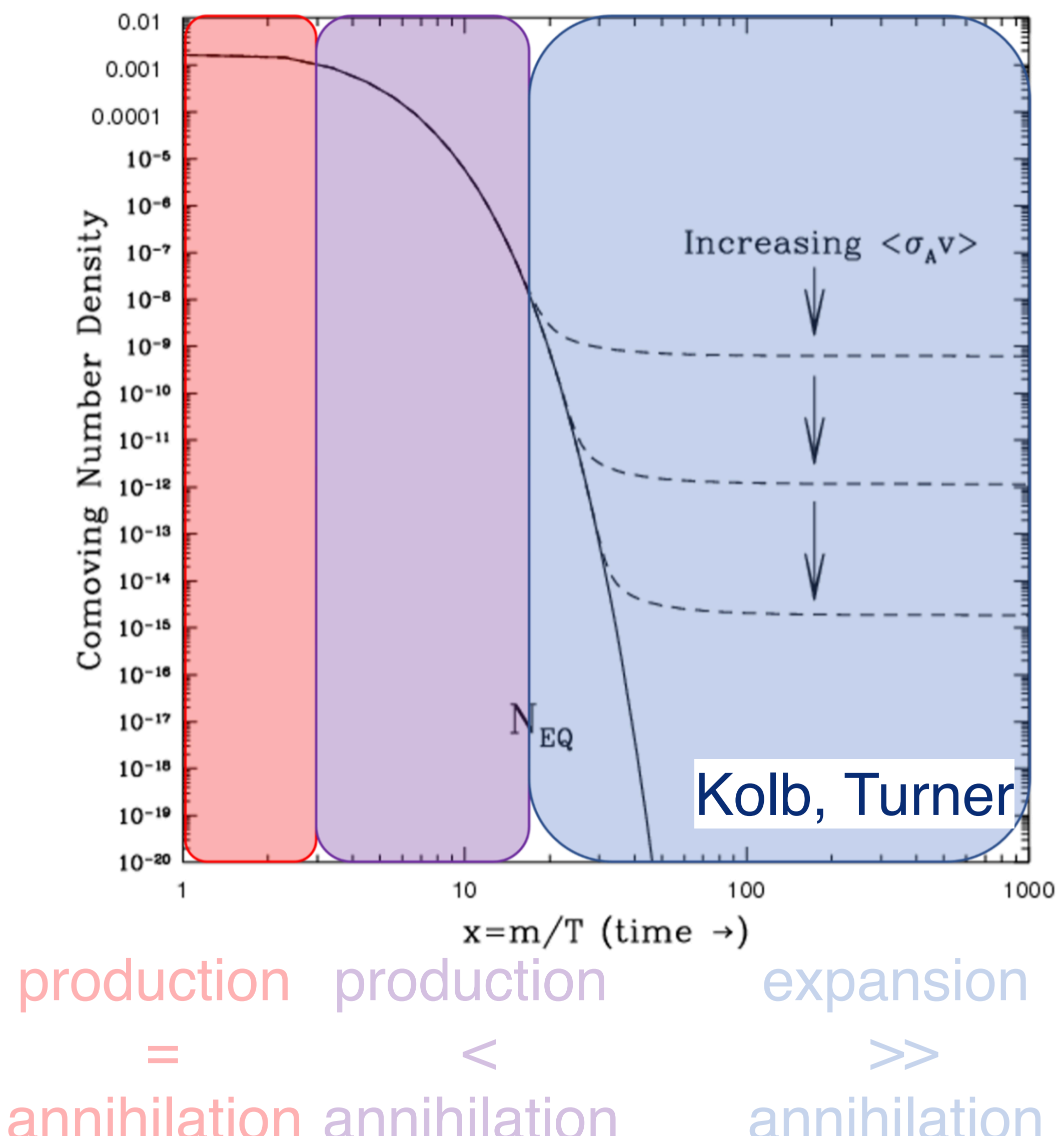


Light dark matter cosmology

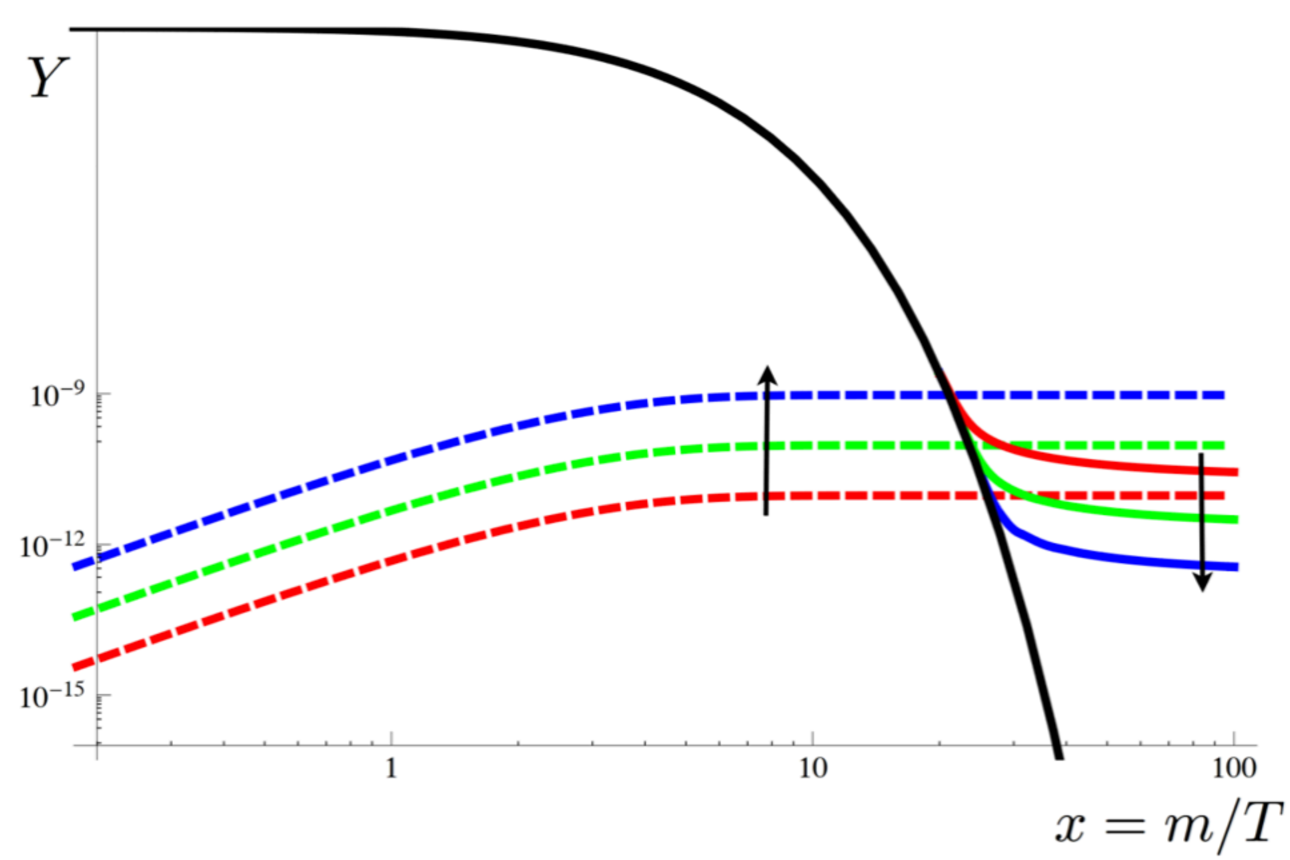
Different candidates depending on how the abundance "froze" in early universe.
Many models, minimal gauge bosons targets:

- **"Heavy" mediator** ($m_\chi < m_{A'}$): thermal freeze-out $\quad \chi\bar{\chi} \to A' \to \mathrm{SM}\,\overline{\mathrm{SM}}$
- **"Ultra-light" mediator** ($m_\chi >> m_{A'}$): freeze-in $\quad \mathrm{SM}\,\overline{\mathrm{SM}} \to \chi\bar{\chi}$

Freeze-out

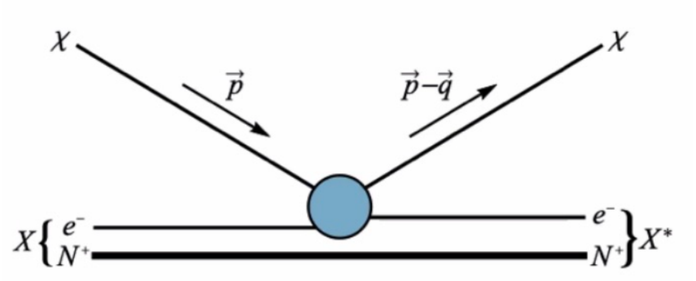


Freeze-in



Light, low mass, sub-GeV, … dark matter

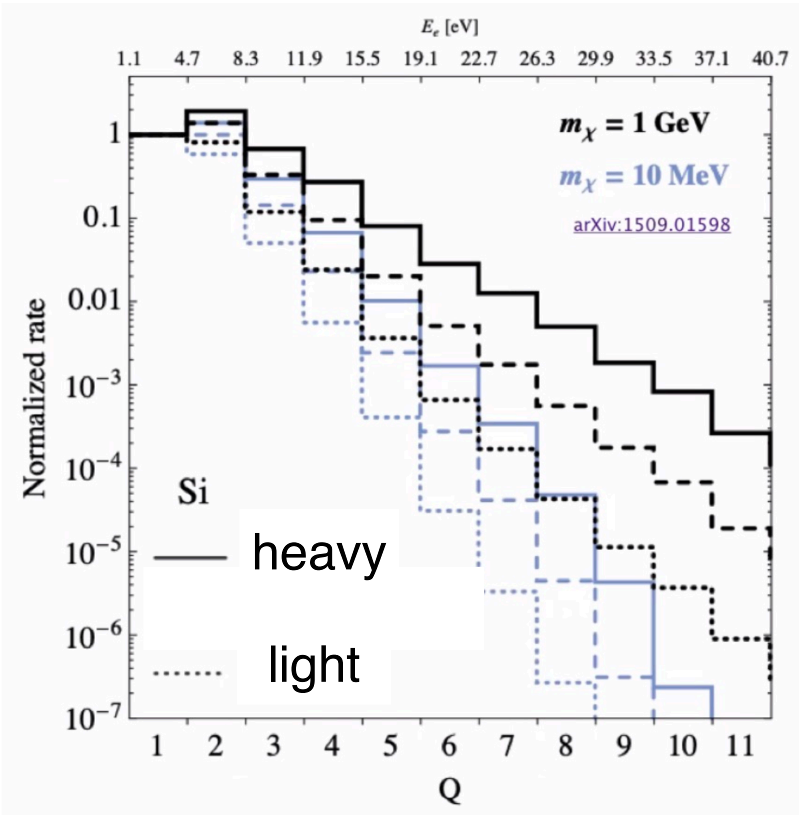
Back to scattering kinematics…
Parameter space is open, targets from freeze-out/in.
Less than proton mass, **use bound electrons as targets!**

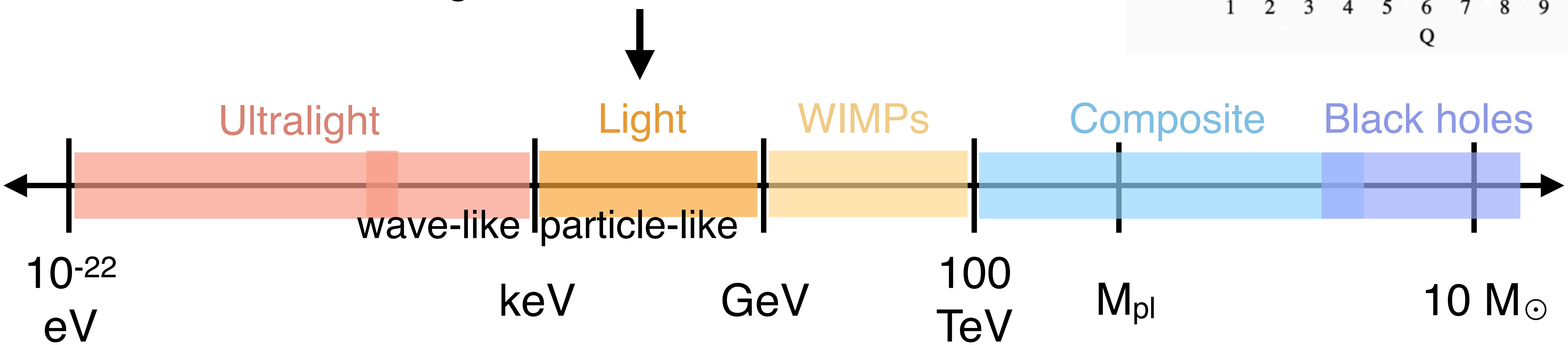


This is difficult:
1. DM-electron scattering is SMALL! but no quenching..
m_χ = 10MeV/c^2, v_χ = 10^{-3}c, **$E_{e,recoil}$ ~eV**

2. More complicated to predict rate, as small momentum transfers can't neglect inter-atom interactions.

Previously did not have the technology or calculations to do this. Semiconductor detectors optimized for low thresholds and low backgrounds/dark counts.



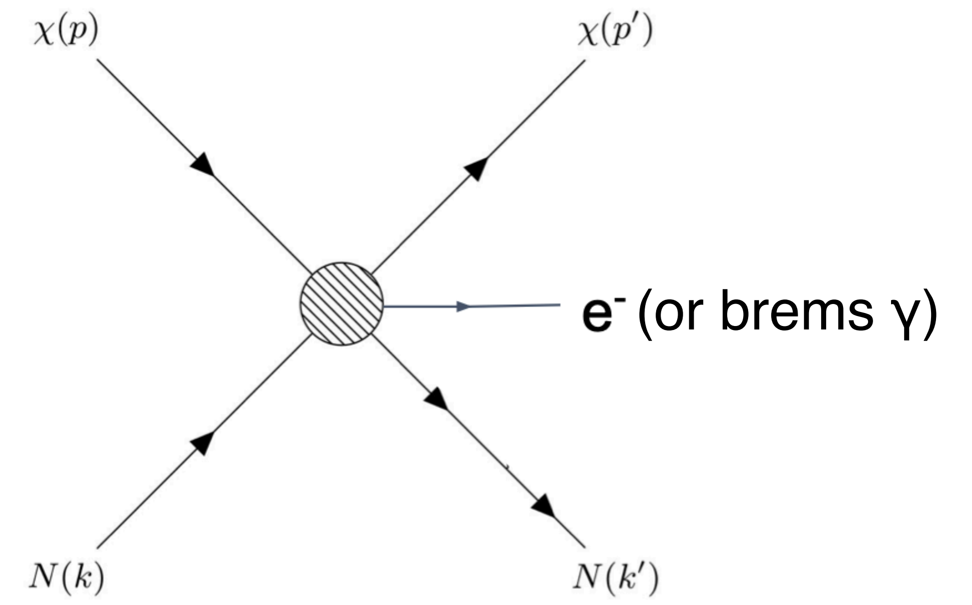


Quick aside…

There are other dark matter scattering modes in a given target that also produce electronic recoils, e.g.

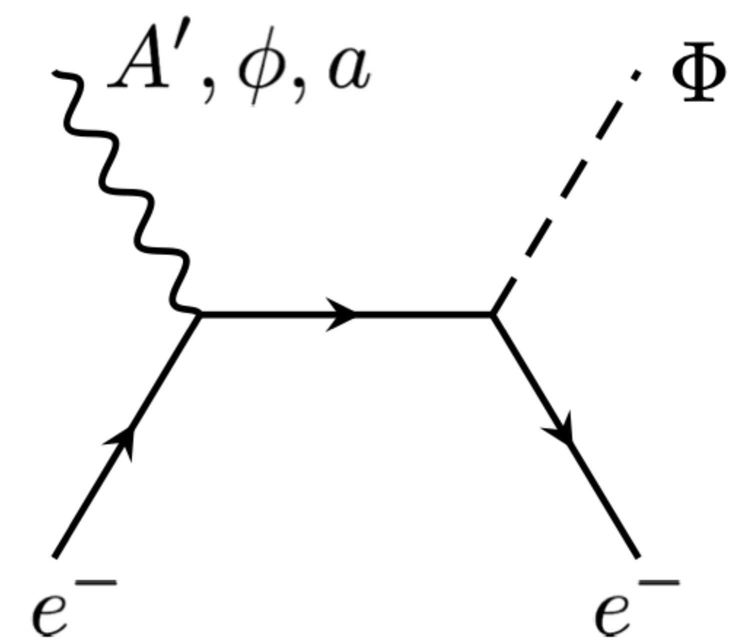
Migdal effect

- small probability ($<10^{-6}$) nuclear recoil is accompanied by an inelastic electron
- never been observed for keV recoils, uncalibrated
- result would be interpreted as DM-nuclean scattering



Bosonic DM absorption

- bosonic dark matter (i.e. dark photon) absorbed by electron
- mass energy transferred in equal amounts to electronic recoil and emission of phonons (momentum conservation)



We will use DM-e scattering parameter space as comparison benchmark

The landscape

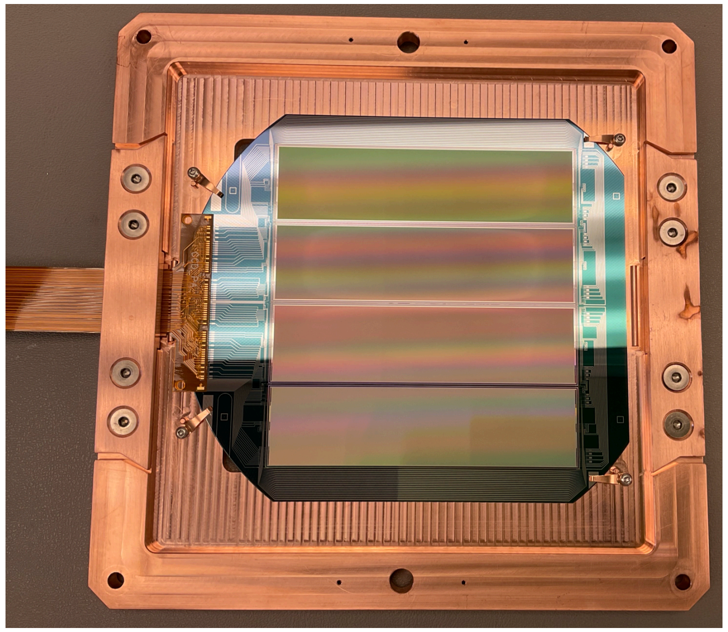
*achieved, ** NR only

Experiment	Location	Technology	Signal	Mass	Threshold	Stage
SENSEI	SNOLAB	Si Skipper CCD	ionization	0.013 kg*	few eV*	running
DAMIC-M	Modane	Si Skipper CCD	ionization	1 kg*	few eV*	construction
OSCURA	SNOLAB	Si Skipper CCD	ionization	10 kg	few eV*	design
SuperCDMS	SNOLAB	Si,Ge calorimeter	ionization, phonon	28 kg*	100s eV*	construction
EDELWEISS/ CRYOSEL	Modane	Ge calorimeter	phonon	1 kg	σ_{phonon} ~ 17.8 eV	R&D
CRESST-III	LNGS	$CaWO_4$, ++ calorimeter	scintillation, phonon	0.024 kg*	30 eV*,**	running
TESSERACT	Modane?	^4He,GaAs,Al_2O_3 calorimeter	scintillation, phonon, quasiparticle	0.1-1 kg	sub eV**	R&D

Mostly semiconductors, some only NR; **Skipper CCDs have the best limits**

DAMIC-M

Under construction now!



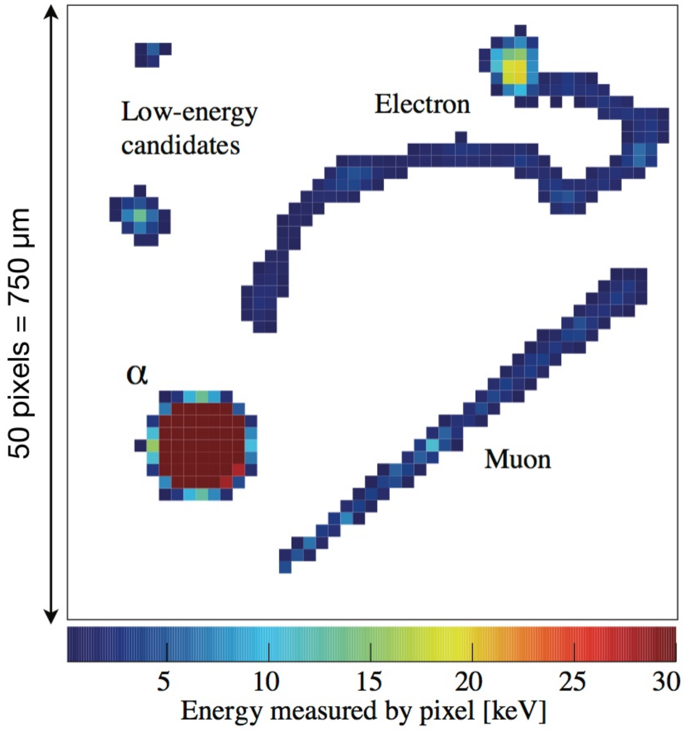
Detector specs

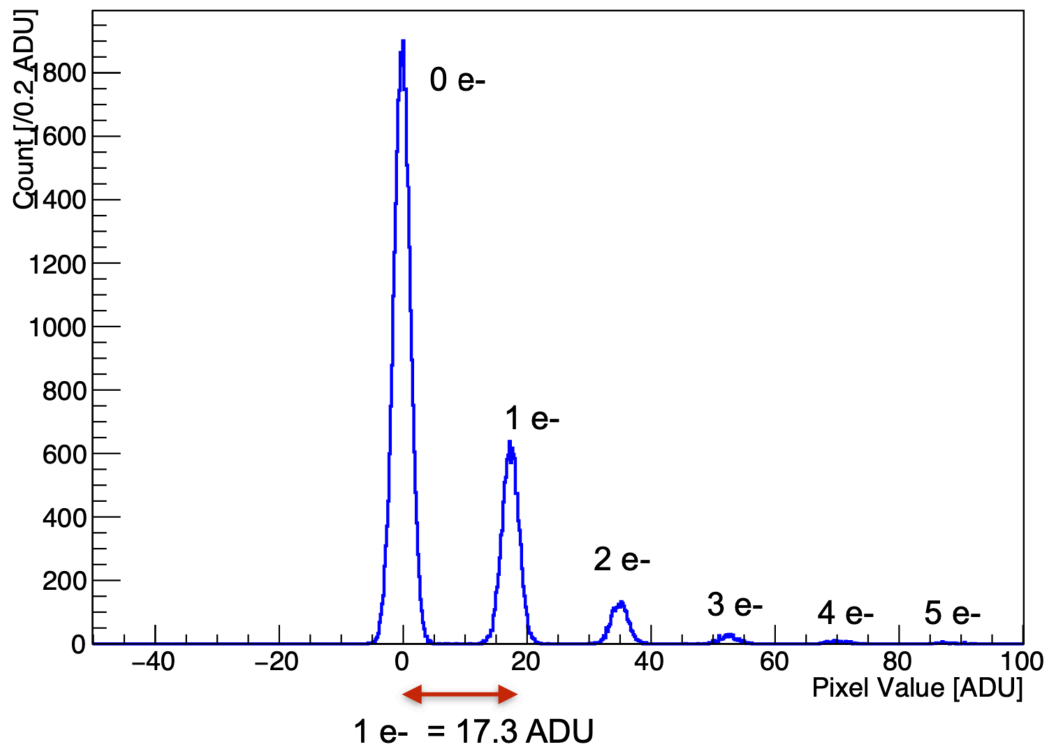
- thick (675um), massive (~3.5g), 9Mpixel CCDs

→ generate e-h, ionize+drift, read pixel by pixel

- array of 208 CCDs for kg-scale mass
- “skipper” amplifier readout for single electron energy resolution (sub-eV) and self-calibration
- ~0.1 dru background rate (1 differential rate unit = 1 event/keV/kg/day)
- 3D reconstruction (with diffusion)

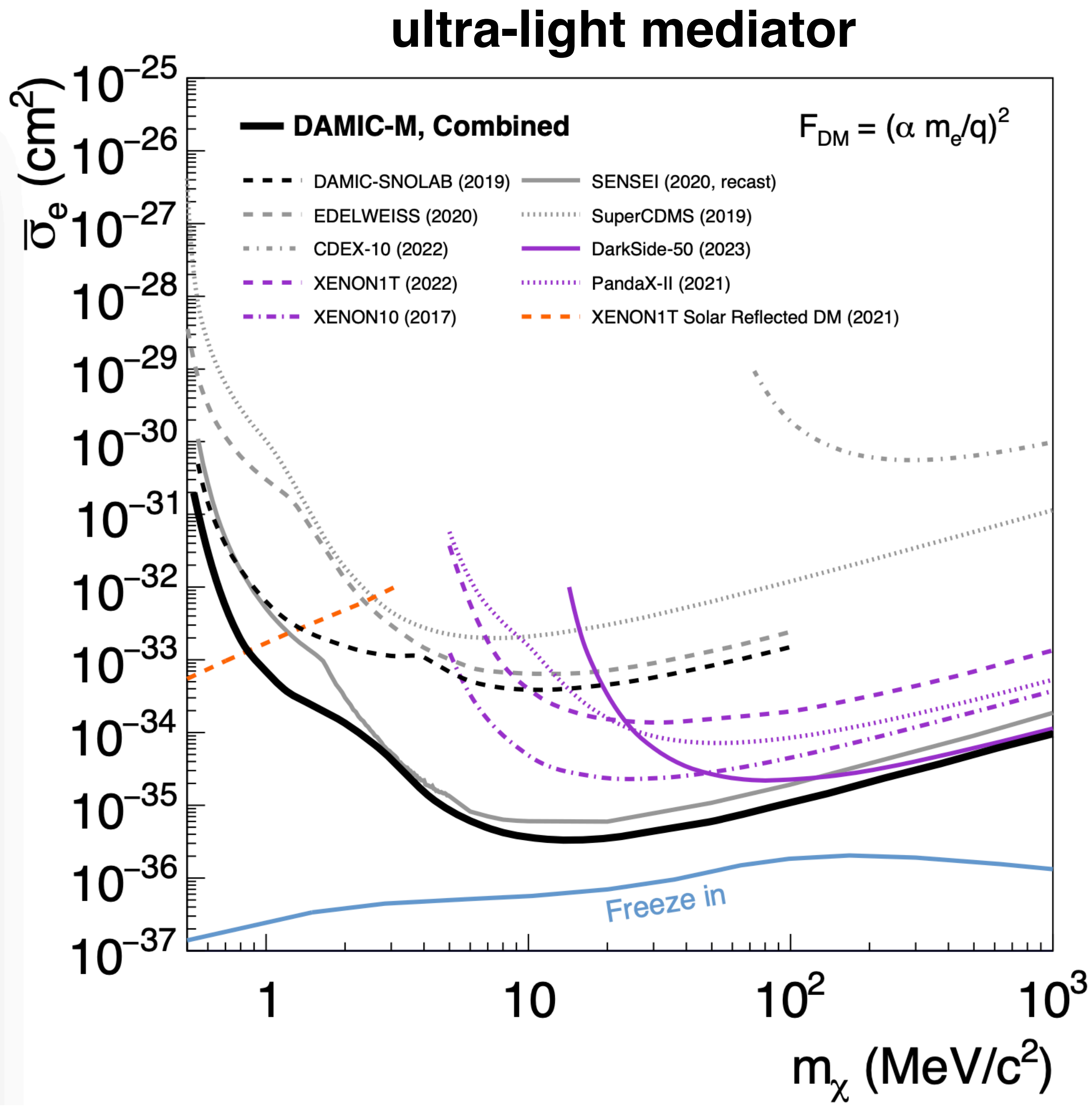
Silicon band-gap: 1.2 eV
Mean energy 1 e-h pair: 3.8 eV

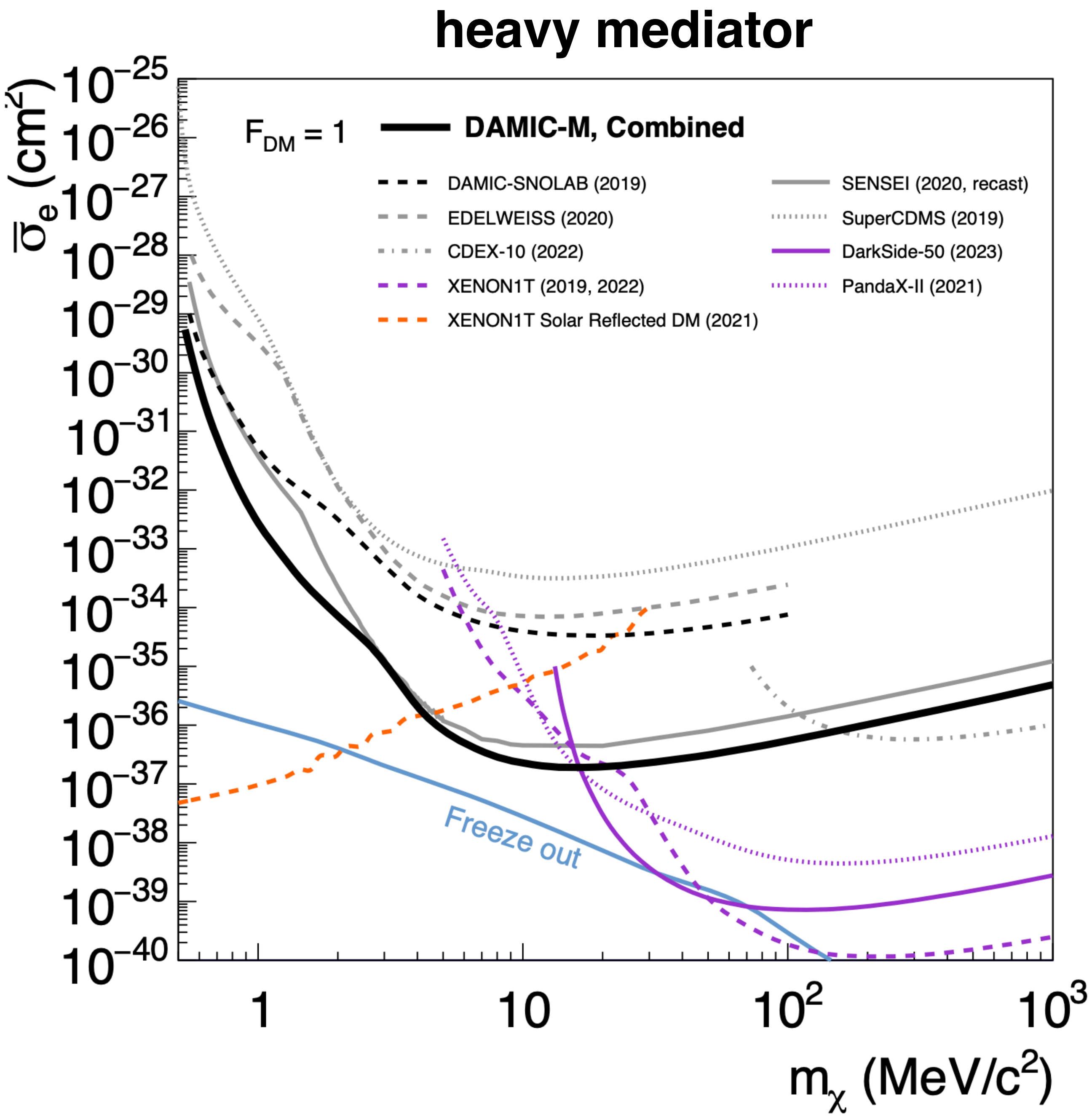




DAMIC-M LBC prototype

PRL 132, 101006 (2024)





2 CCDs, a few months of data

world-leading for all masses results with new modulation analysis!

OSCURA

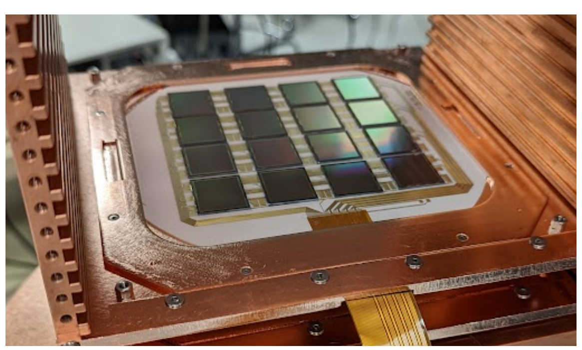
Preparing for a 10-kg skipper CCD detector, R&D/design funded by US DOE (US groups; now forming international collaboration)

Ambitious experiment at SNOLAB (scaling like WIMP detectors):

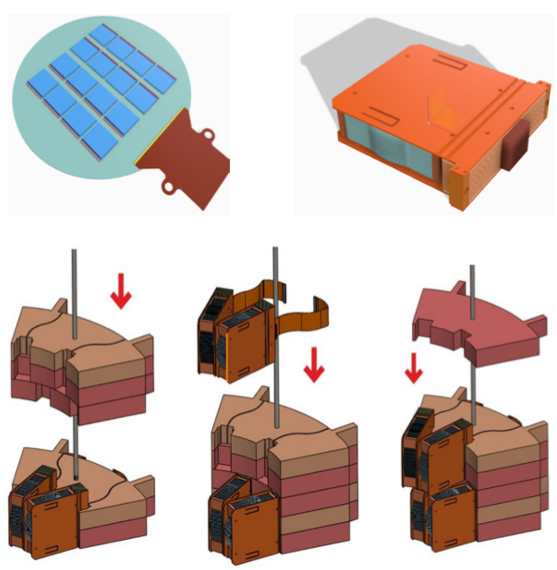
- 20,000 CCDs (smaller format), 10kg
- 20 Gpixels low noise electronics, multiplexing
- 10x lower background than DAMIC-M goal (0.01 dru)

construction in 2028

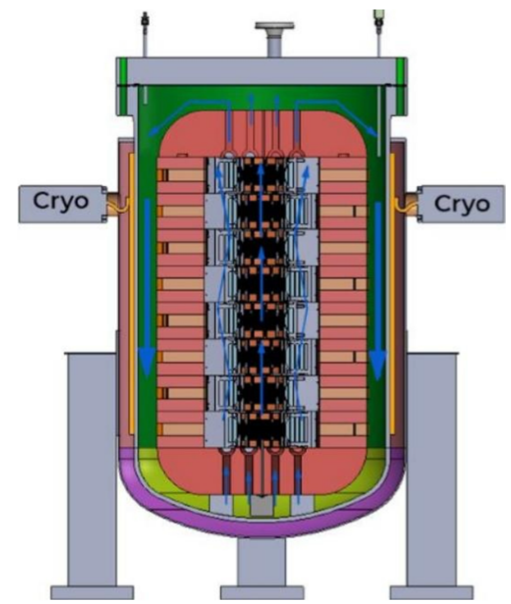
DAMIC-M success essential for the Oscura program:
operating kg size detector, understanding of backgrounds, and dark current



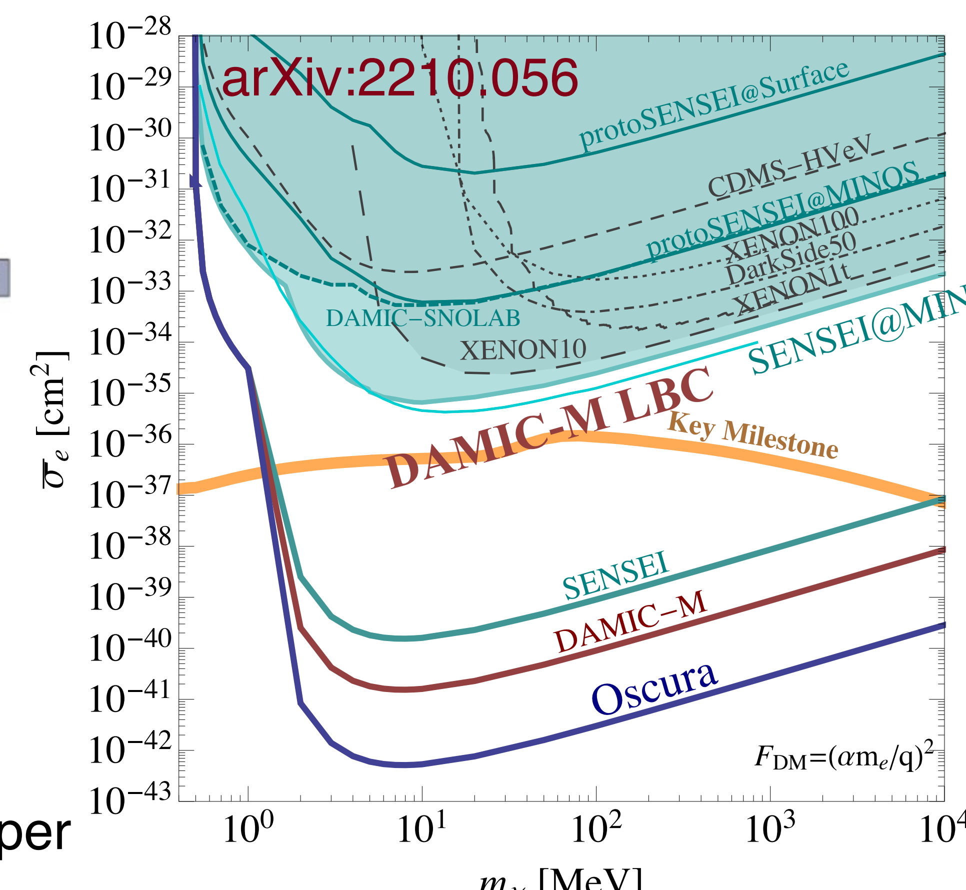
16 skipper CCD modules



16 modules per supermodule



LN2 pressure vessel surrounded by lead/copper

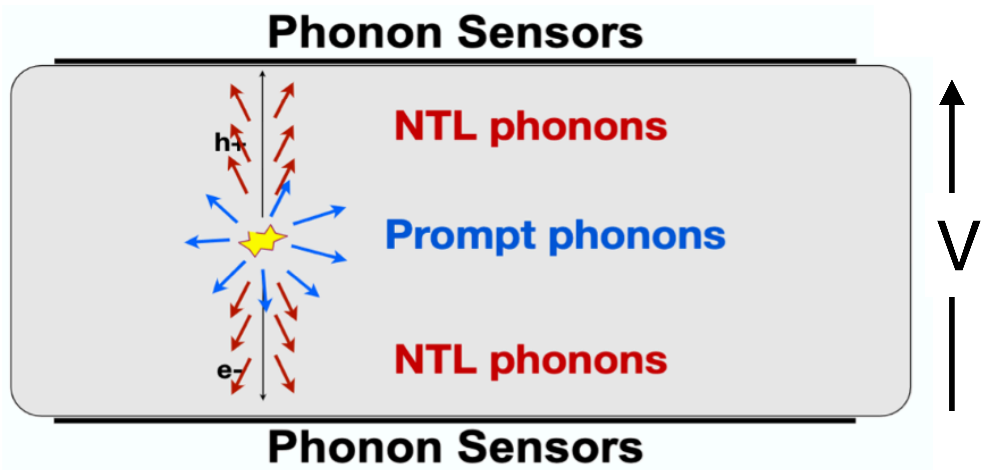


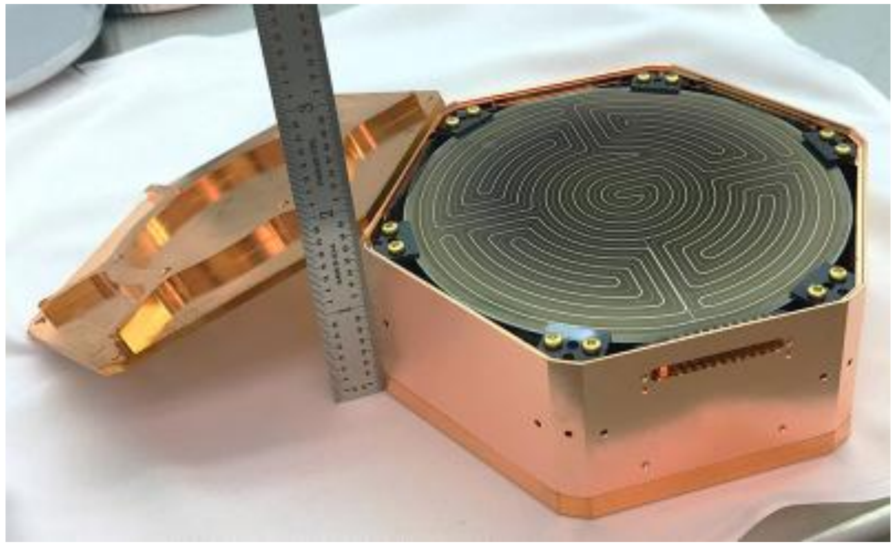
SuperCDMS

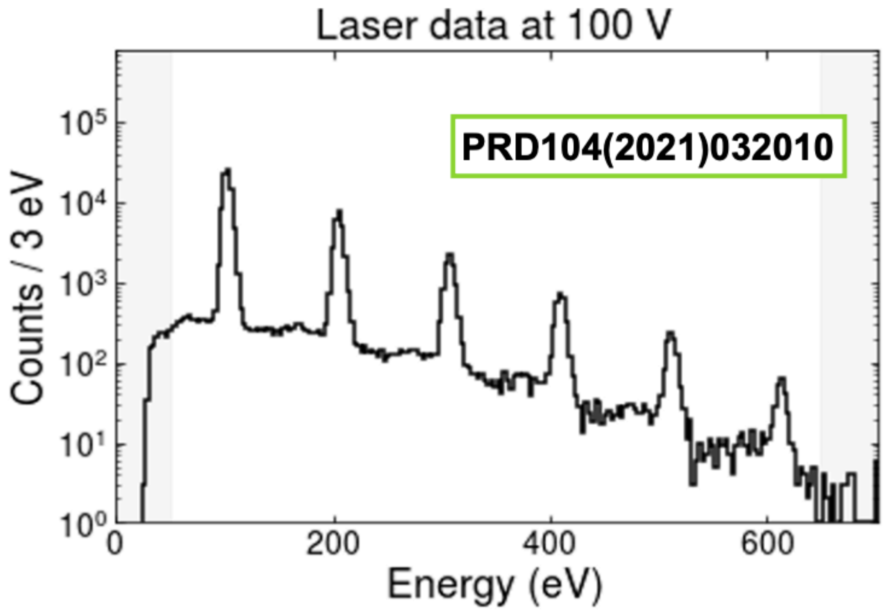
Under construction now!

Detector specs

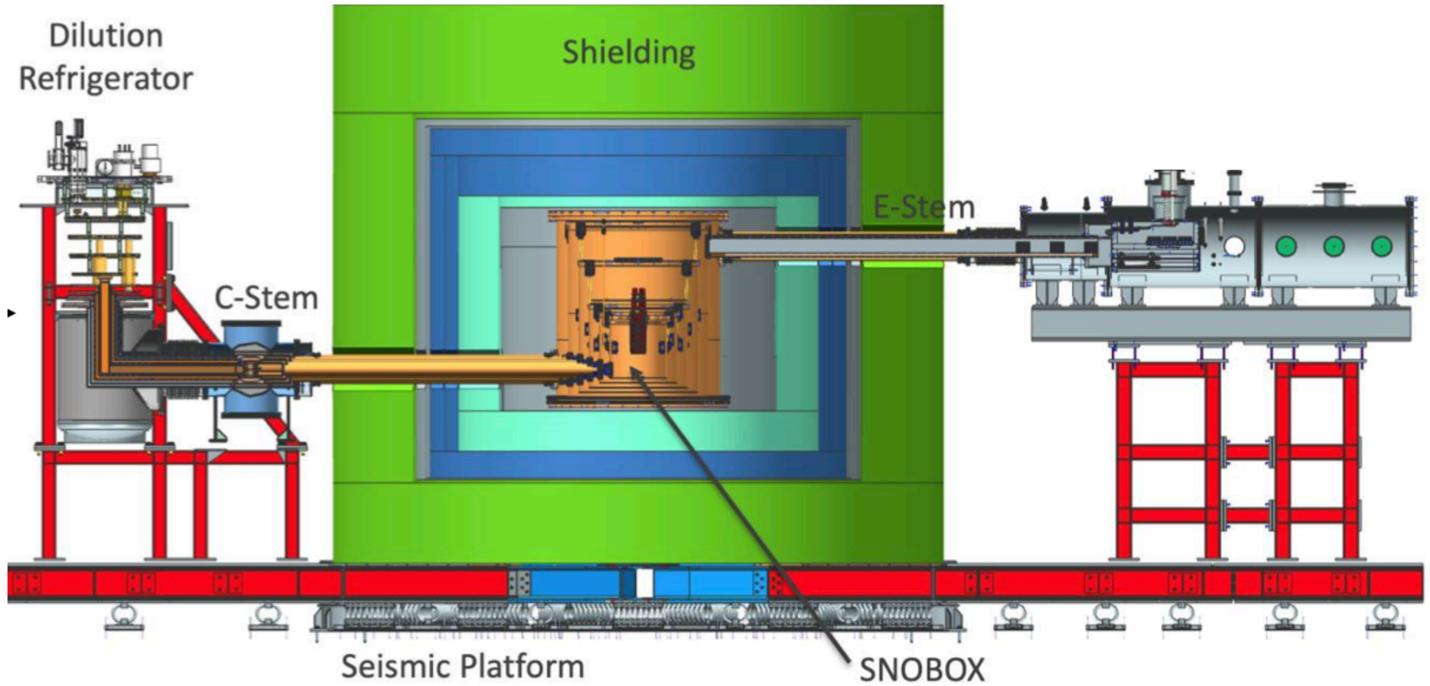
- 24 Si, Ge cryogenic calorimeters
→ generate e-h, ionize+drift, amplify heat in E field
- amplification ~ ionization signal + applied bias
- readout: phonon TES, ionization high-electron-mobility transistors
- iZiP: ionization+phonon, higher threshold
- HVeV: phonon only, no NR-ER discrimination
- initial 4 tower payload: 2 HV, 2 iZiP







(= Recoil energy + Neganov Luke effect gain)



CRESST-III

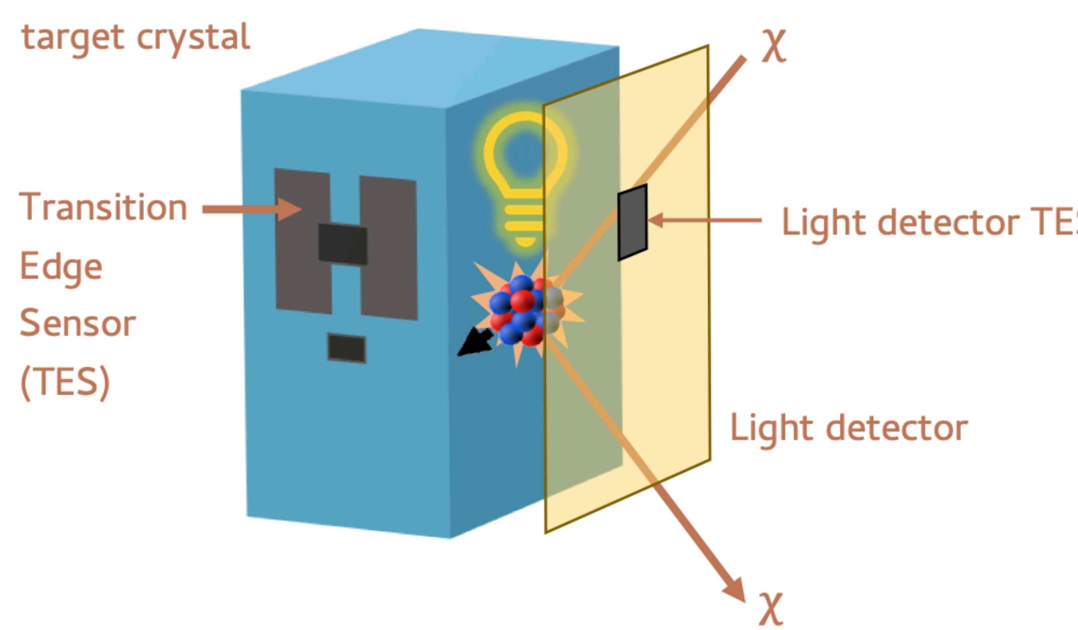
Phase I run started in 2016

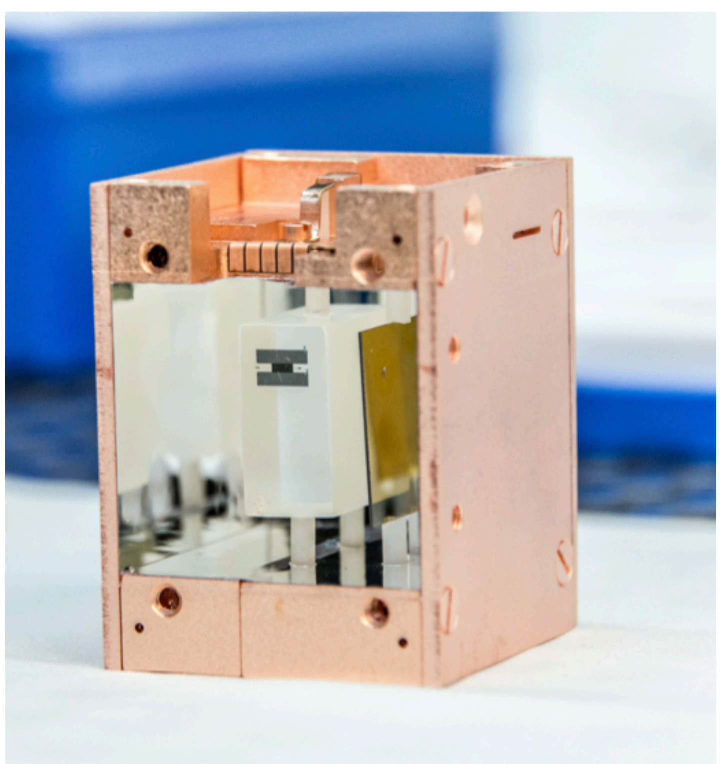
Detector specs

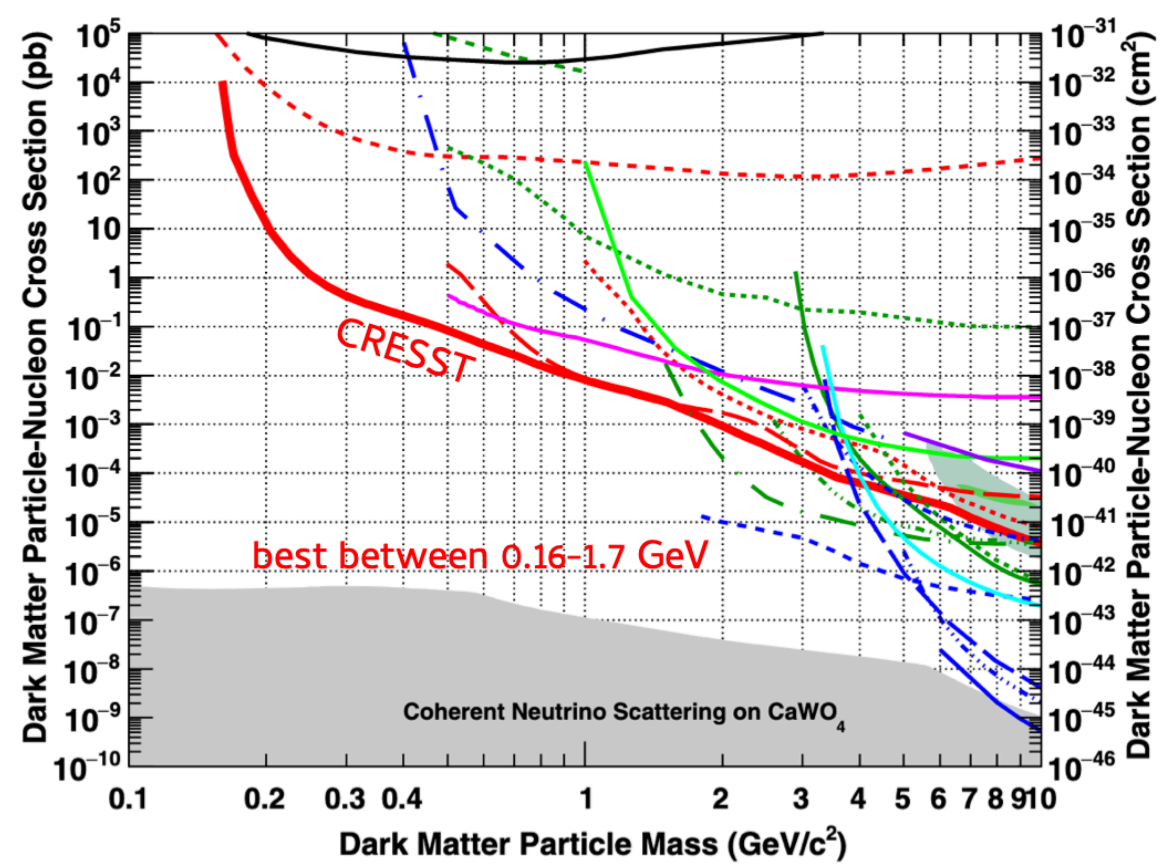
- $CaWO_4$ cryogenic calorimeters

→ NR produces heat, a small fraction of energy also goes into scintillation

- Al_2O_3, $LiAlO_2$, Si, diamond lower thresholds
- readout: phonon + light TES
- light signal allows for NR-ER discrimination
- expecting major upgrade this year (?)







TESSERACT

Searching for MeV-scale Dark Matter at TESSERACT
William Matava

R&D phase, 2x 10g ^{4}He prototypes

Detector specs

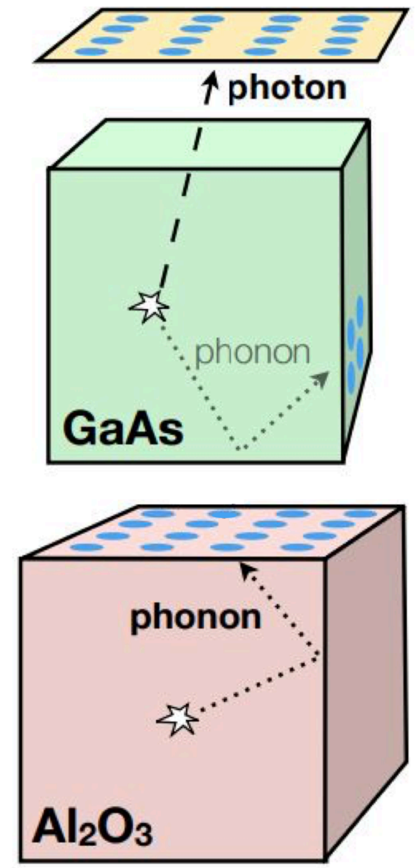
- SPICE: GaAs and sapphire

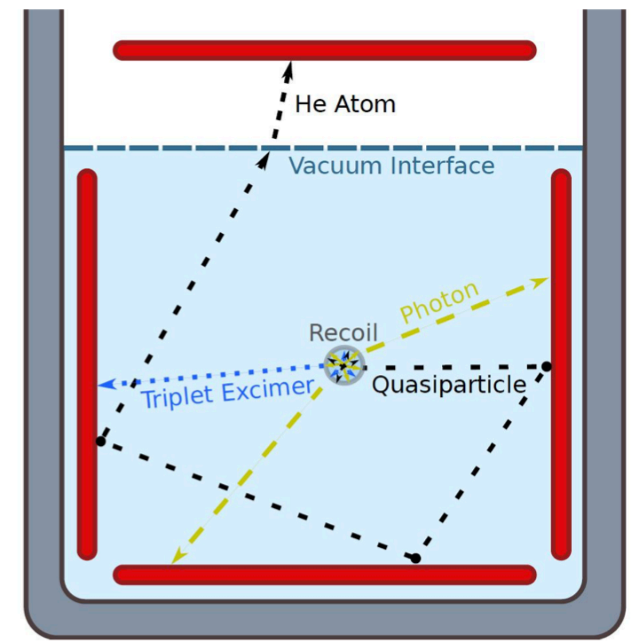
→ NR produces heat, (GaAs) small fraction of energy also goes into scintillation

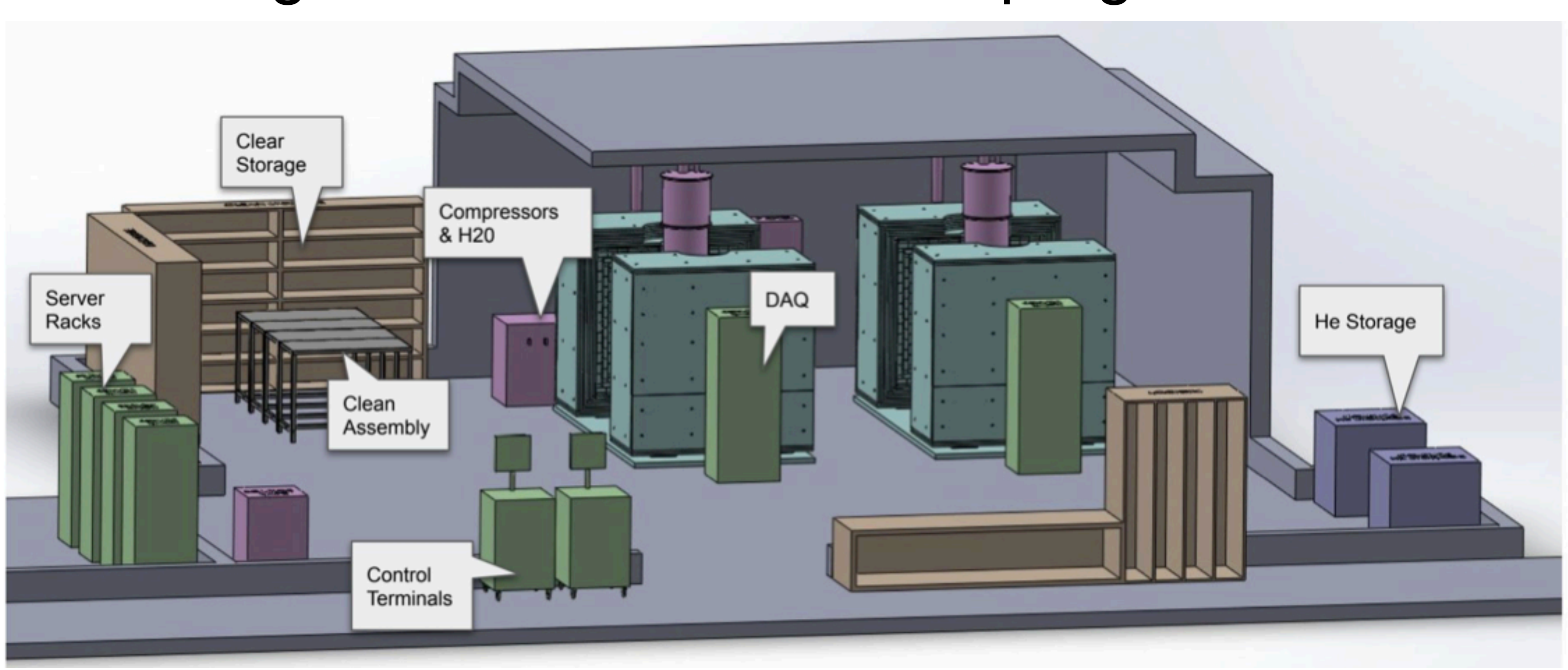
- HeRALD: superfluid ^{4}He

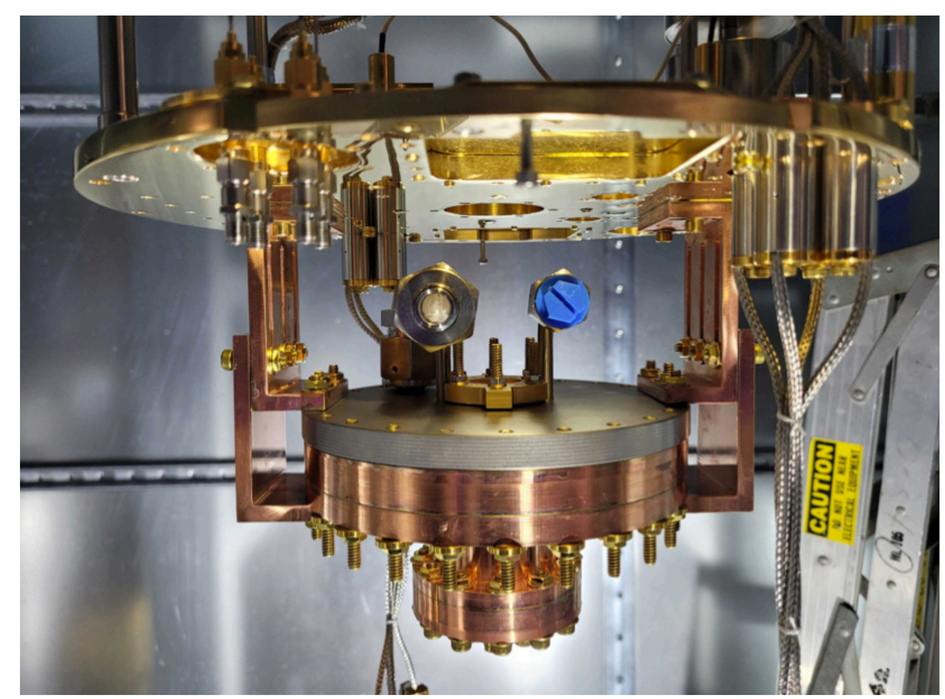
→ lower NR quasiparticle + quantum evap, fast scintillation, slower scintillation

- readout: phonon + light TES
- multiple signals NR-ER discrimination
- working towards low mass DM program

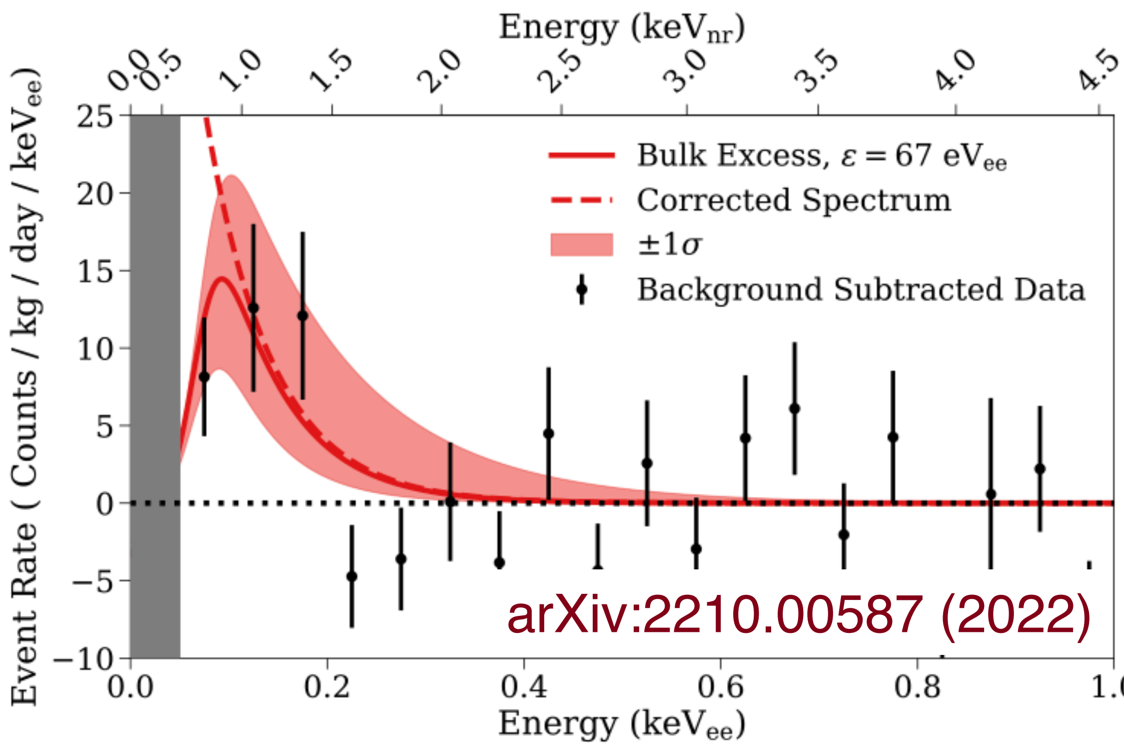


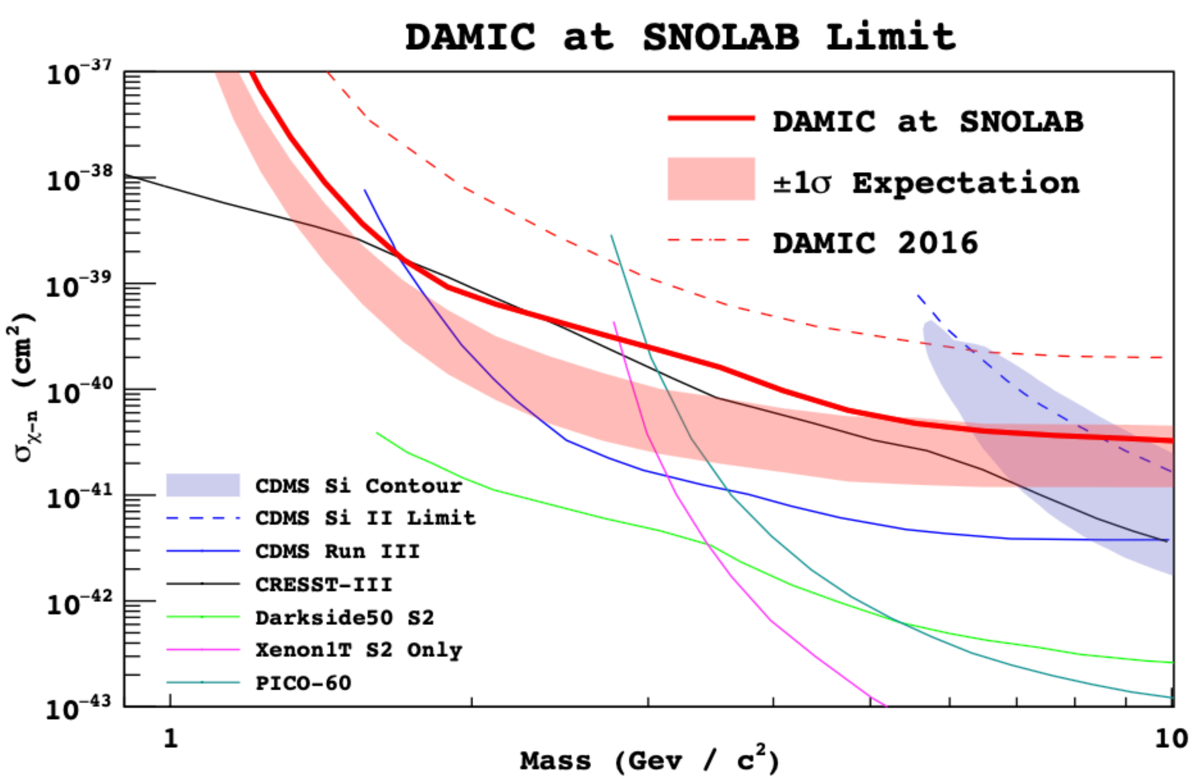






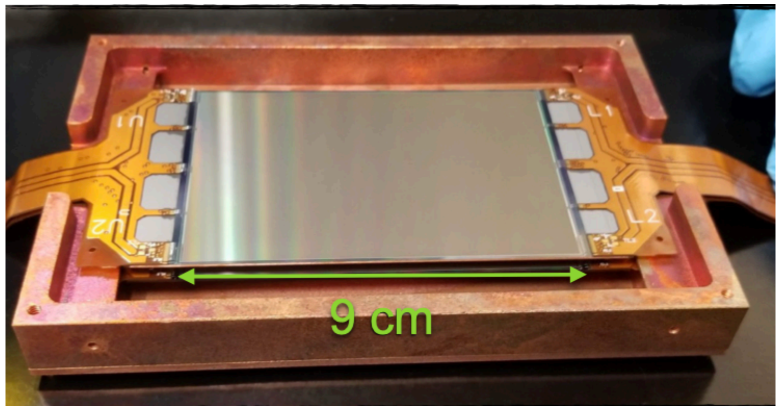
Low energy excess: DAMIC@SNOLAB 2020



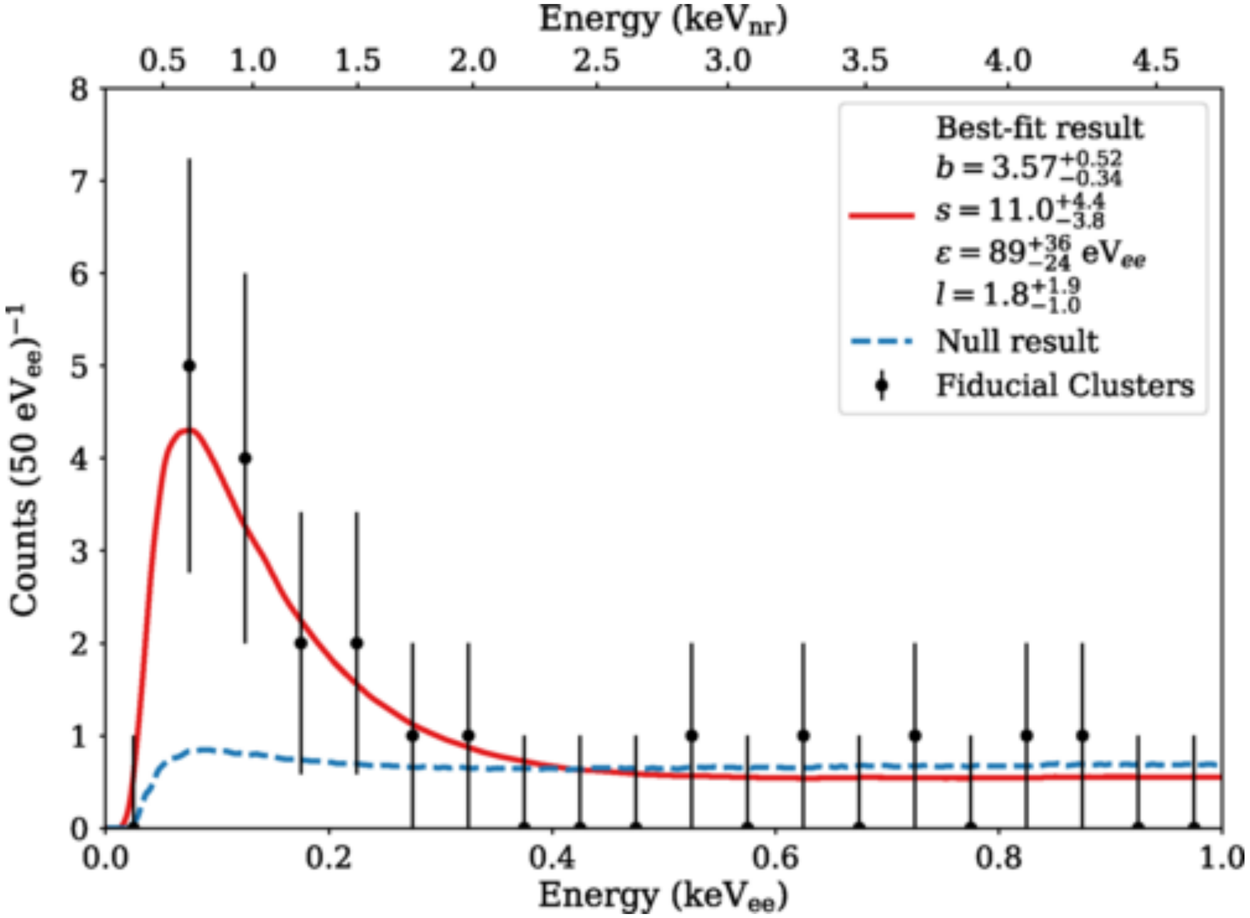


- DAMIC@SNOLAB used conventional CCDs to look for WIMPs
- saw excess of events around 50e- (~0.1 keV) with decay exponential distribution
- all known backgrounds and backside partial charge collection incorporated in model, many systematic checks
- events appear to be in silicon bulk
- what is the source? could be explained by some low energy neutron source, but none found inside shielding
- standard WIMPs excluded, more exotic?

Low energy excess: DAMIC-M@SNOLAB 2023



Phys. Rev. D 109, 062007 (2024)



- in-depth investigation has shown that these events are inconsistent with detector effects
- installed DAMIC-M CCDs @SNOLAB, same mass as LBC ~17g, with skipper amplifiers to confirm/deny excess in bulk
- detector environment same, but different readout mode, lower threshold, better depth reconstruction (surface vs. backside)
- **energy spectrum of bulk events show clear exponential component** (5.4σ)
- result disfavors (all?) instrumental origin of excess, discovered new source of radiation not in background model…
- DAMIC-M will collect more data with higher resolution, lower backgrounds, and longer exposure

Outlook

- We have been looking for DM for 40-ish years, we have come a very long way, but WIMPs have yet to be detected
- Once we expand mass range, diverse set of DM candidates available
- Kinematic challenge! Electronic recoil searches allow searches at MeV-scales!
- Skipper CCD detectors are well-established, leading limits right now
- Significant progress in single-charge resolution in cryogenic calorimeters
- Next ~5 years will see orders-of-magnitude improvement in sensitivity!