eV-threshold Direct Dark Matter Searches

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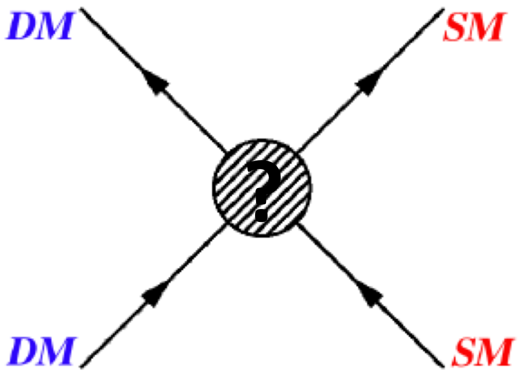
…on behalf of the DAMIC Collaboration

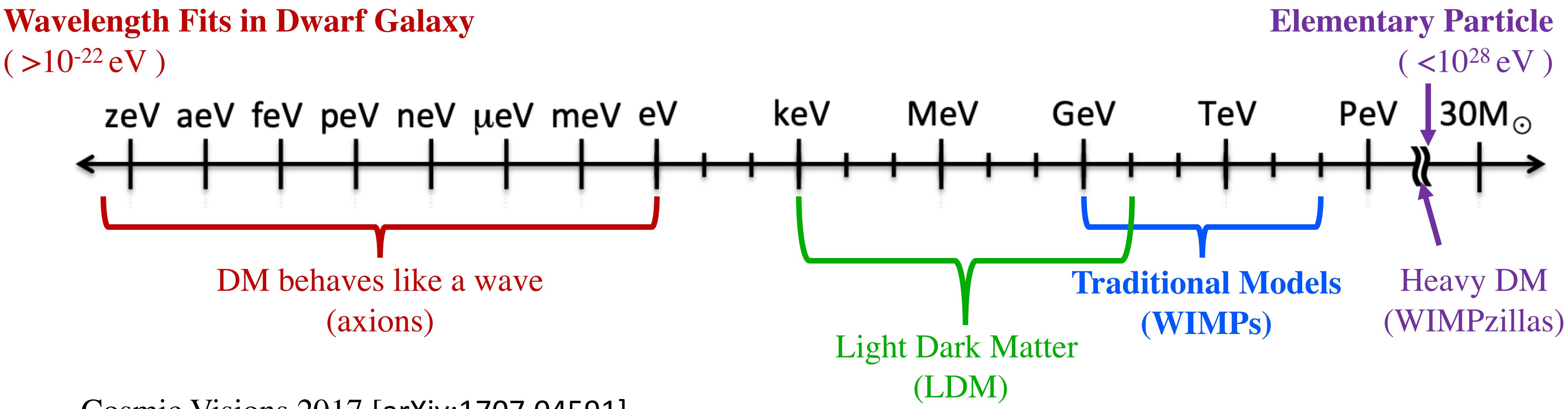
EPS-HEP Conference

July 26, 2021

Dark Matter

- Gravity – YES (*matter*)
- EM – No* (*dark*)
- Weak? – Not the W±/Z

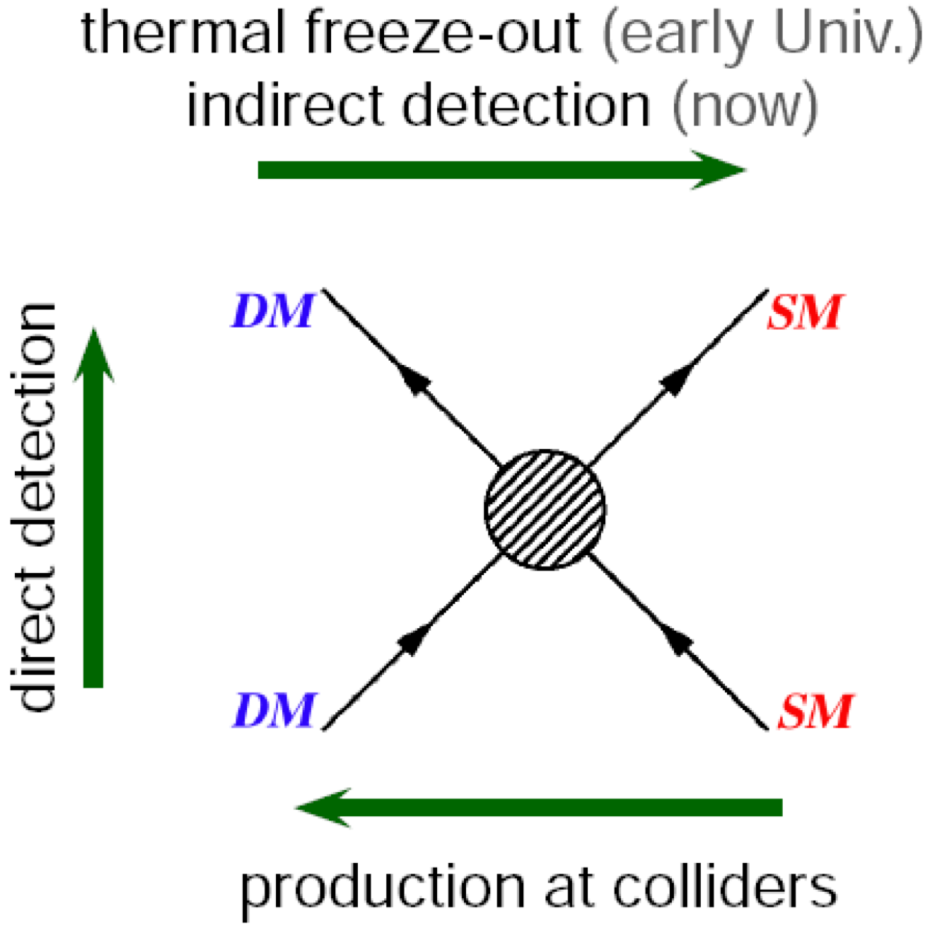




Cosmic Visions 2017 [arXiv:1707.04591]

Direct Detection

- Build a detector to identify the small energy deposition of dark matter scattering off SM particles
- Scattering off nuclei (elastic):
  - The standard WIMP paradigm
  - 1-1000 GeV DM masses
  - 0.3-300 keV recoil energy
- Scattering off electrons (inelastic):
  - As in the case of a dark photon
  - 1-1000 MeV DM masses
  - 1-100 eV recoil energy



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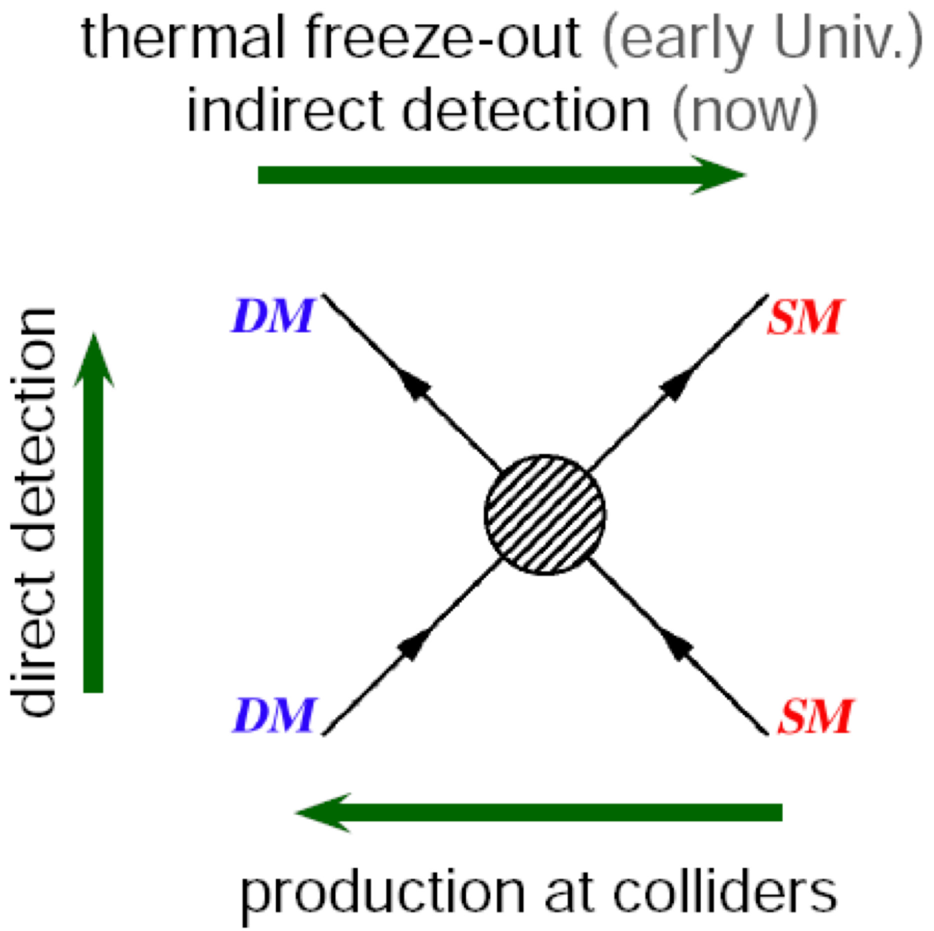
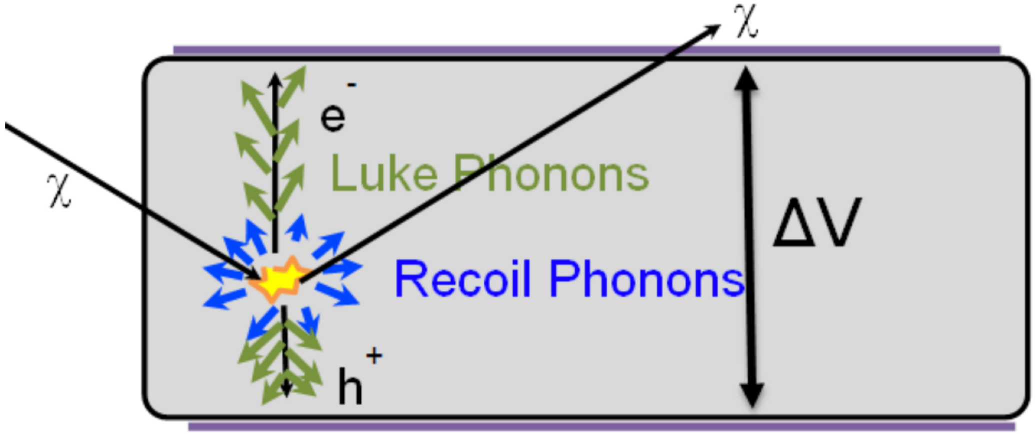


SuperCDMS HVeV (Silicon)

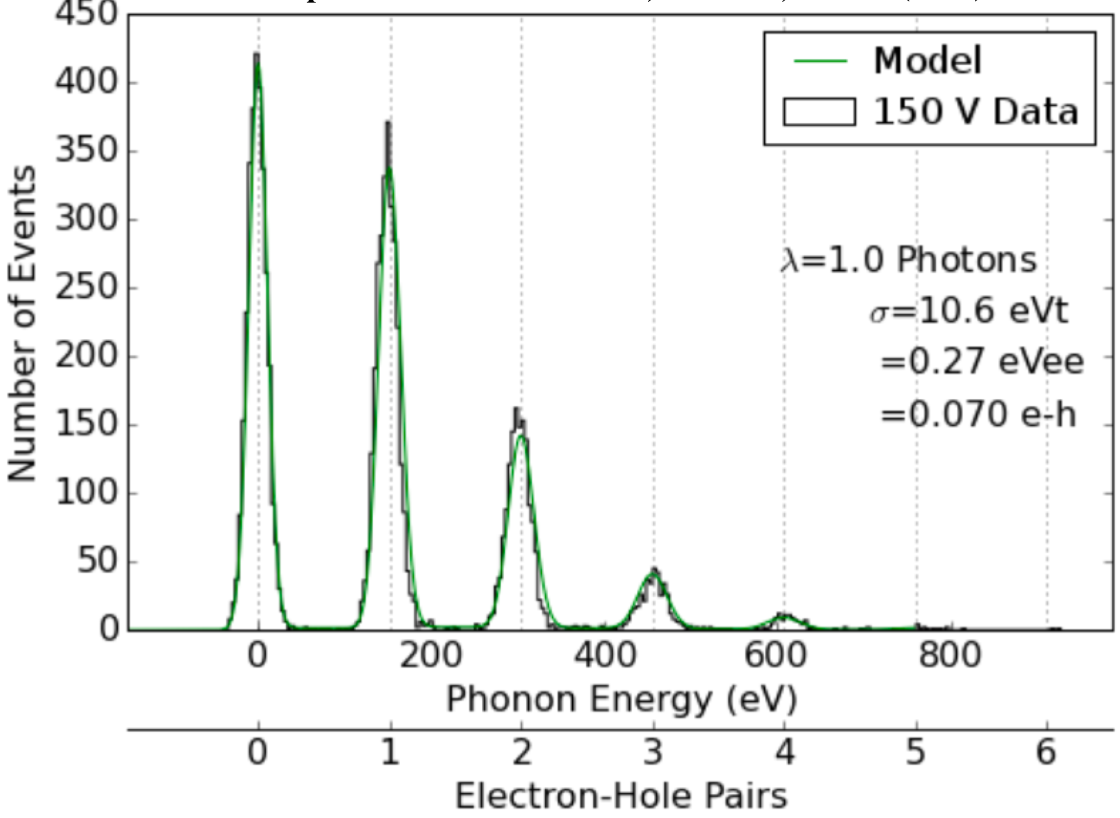
See also Yan Liu's talk (next)

- Detectors take advantage of the Neganov-Trofimov-Luke effect to amplify single-charge production into above-threshold phonon signal



N. Kurinsky, Ph.D. thesis (2018)

SuperCDMS Collaboration, PRL 121, 051301 (2018)



EDELWEISS (Germanium)

Pros and Cons of NTL detectors

- **sub-Kelvin temperatures suppress thermal dark rates well below current detector sensitivity**
- **Operation in 0V mode (turning off NTL effect) allows same-detector measurement of calorimetric rates to compare with ionization rates**
- Backgrounds from both phonon and charge production must be decoupled
- **Excellent timing resolution**
- Poor position resolution makes separation of surface and bulk effects/backgrounds challenging

Charge Coupled Devices

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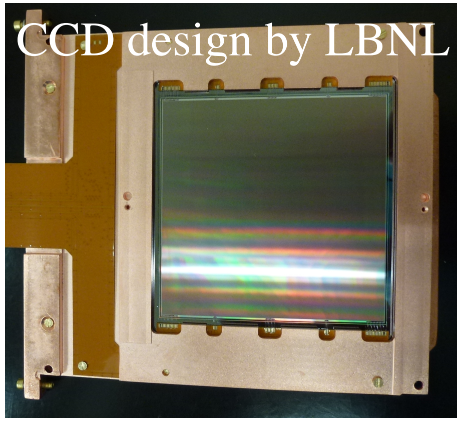
✓ **Operation of 100-140K is sufficient to produce low dark rate measurements (*see later slides*)**

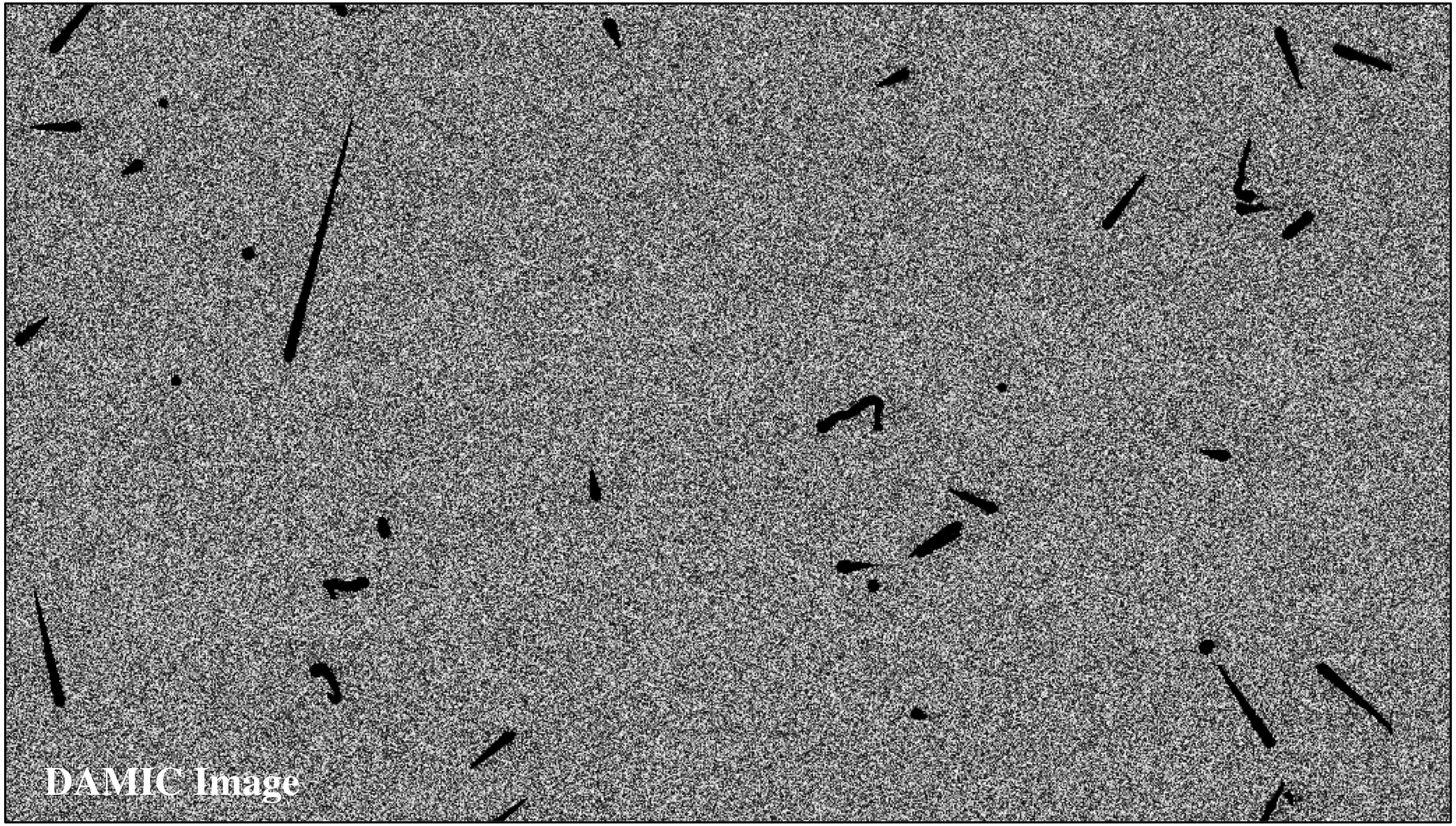
✓ **Pure charge/ionization measurement**

✓ **Sacrifice timing information for 15 micron position resolution**

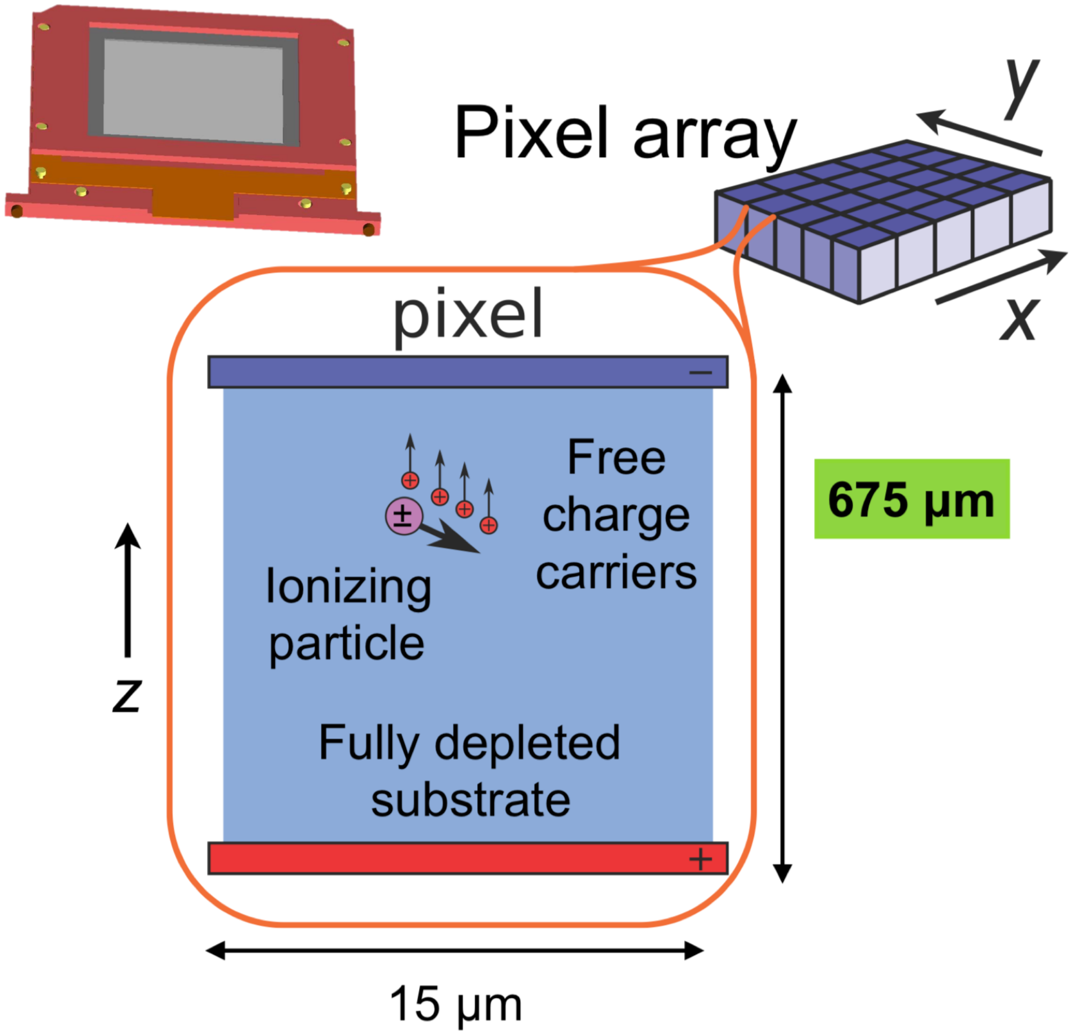
DAMIC Collaboration



Charge Coupled Devices



Charge Coupled Devices

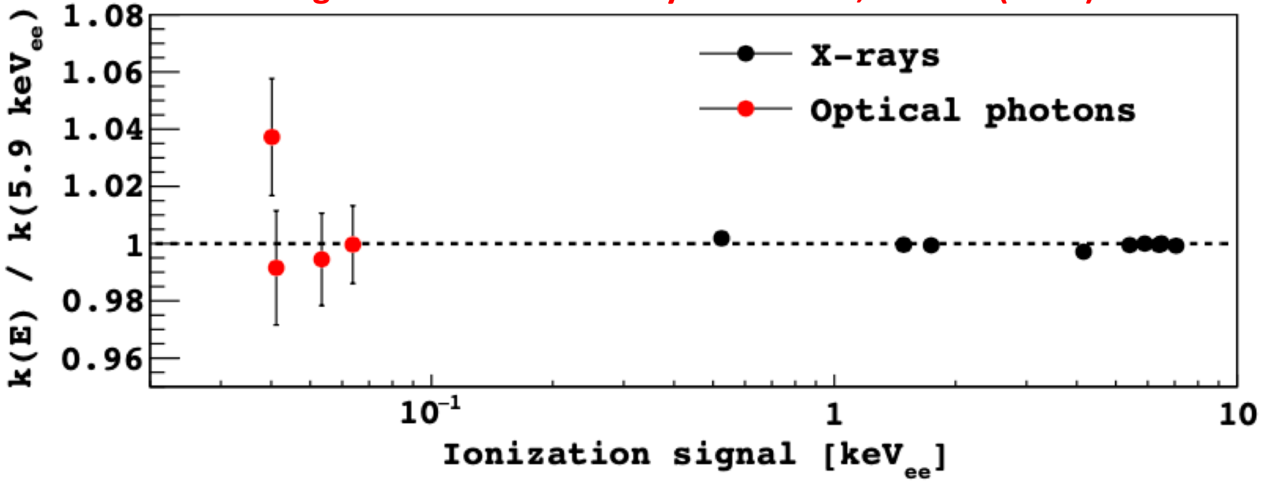


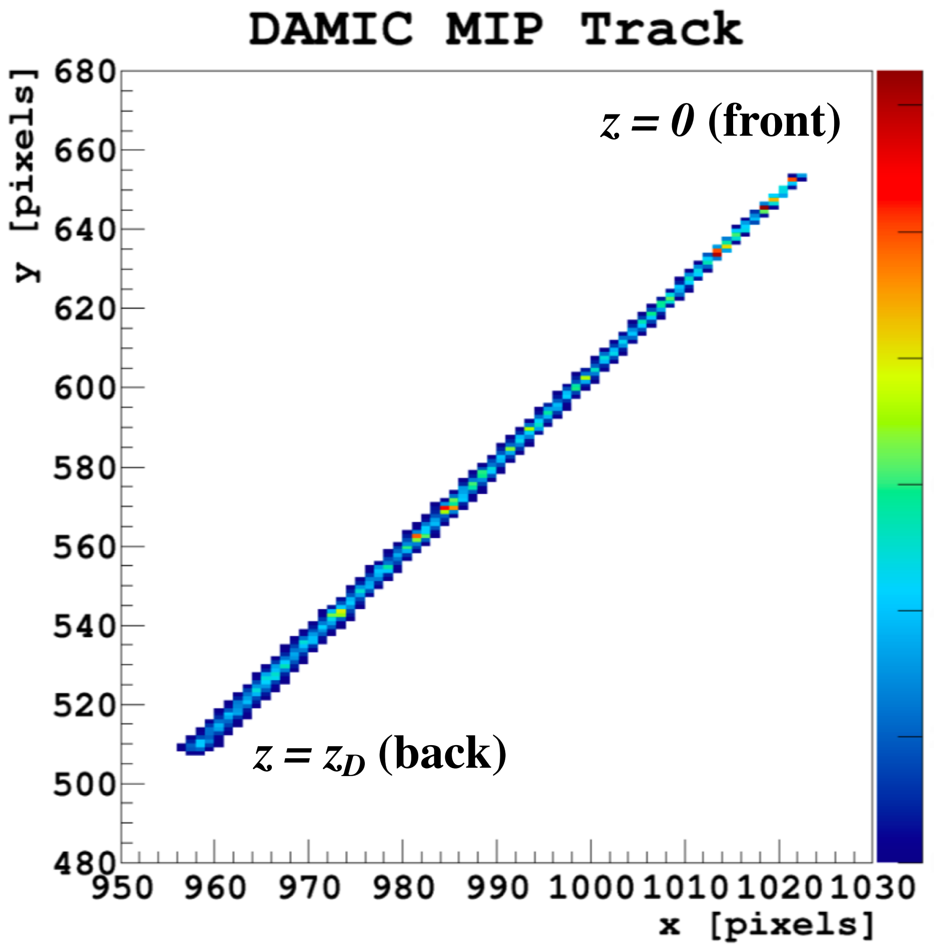
- Interaction with silicon produces free charge carriers…
  - …which are drifted across fully-depleted region… → *No loss of charge*
  - …and collected in 15 micron square pixels… → *exceptional position resolution*
  - …to be stored until a user-defined readout time after many hours. → *large exposures*

Calibrating Detector Response

- Extremely linear energy response down to eV energies
- Spread of charges on pixel array is a measurement of event depth

A. Aguilar-Arevalo et al. Phys. Rev. D 94, 082006 (2016)

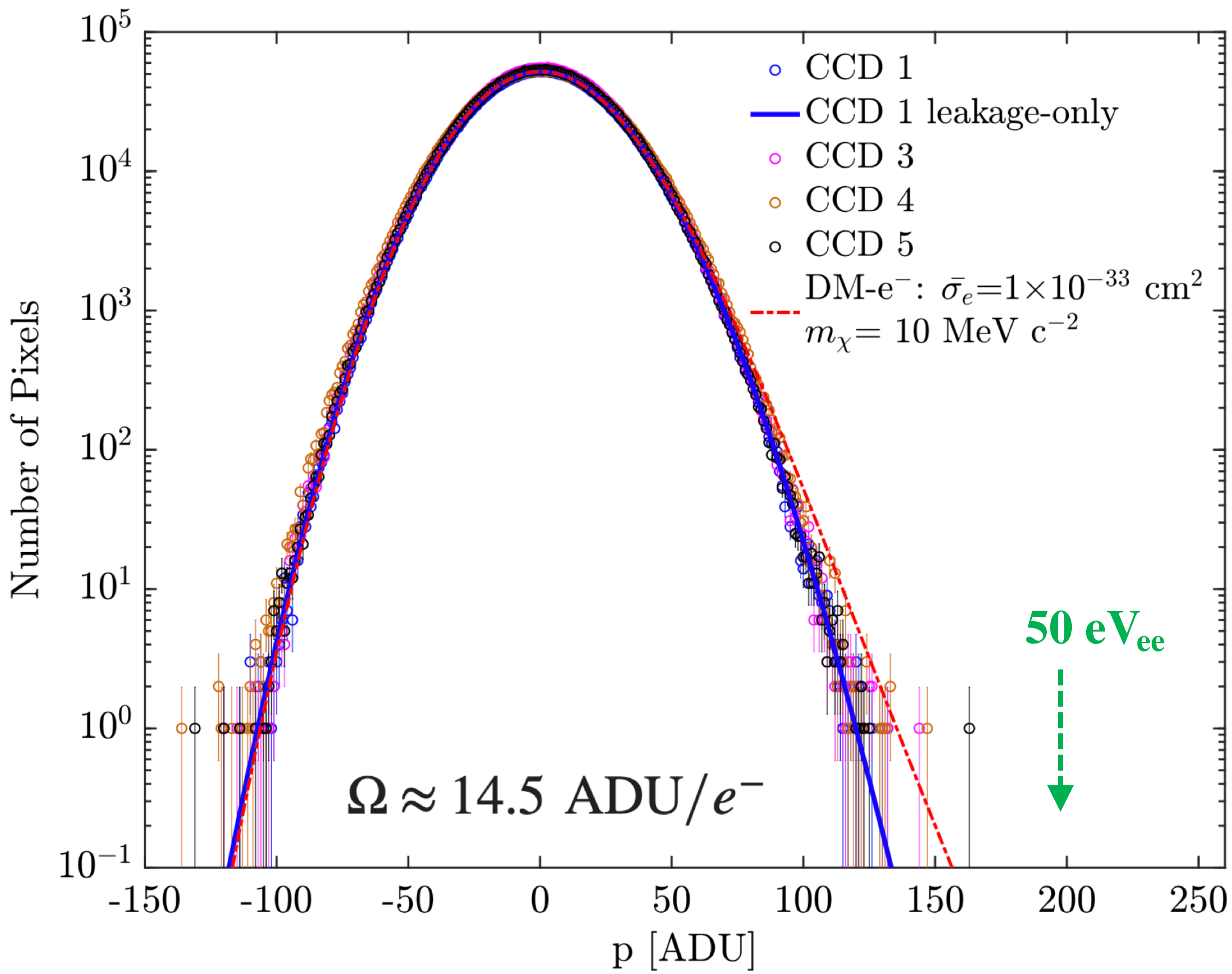




Dark Current

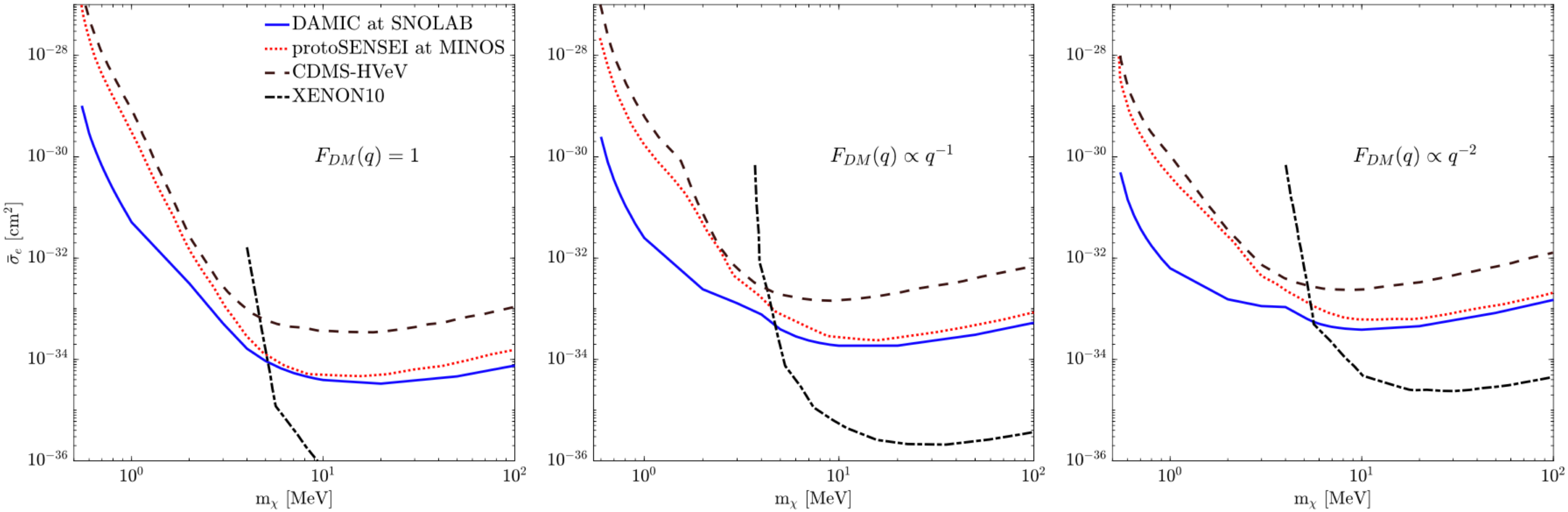
- DAMIC at SNOLAB reported the lowest published dark current of any silicon experiment (at the time): **2 x 10^{-22} A cm^{-2}**
- SENSEI more recently achieved 1.3 x 10^{-22} A cm^{-2} using Skipper CCDs [arXiv:2004.11378]

CCD No.	σ_{pix} $[e^-]$	λ_d $[e^-\ \text{mm}^{-2}\ \text{img}^{-1}]$	μ_0 $[e^-]$	$\lambda = \lambda_{\text{tot}} - \lambda_d$ $[e^-\ \text{mm}^{-2}\ \text{d}^{-1}]$
1	1.628(1)	8.2(2)	–0.185(3)	2.8(2)
3	1.572(1)	7.8(2)	–0.160(4)	1.7(2)
4	1.594(1)	10.0(2)	–0.219(4)	1.0(2)
5	1.621(1)	8.5(2)	–0.183(4)	2.0(2)



A. Aguilar-Arevalo et al. PRL 123, 181802 (2019) [arXiv:1907.12628]

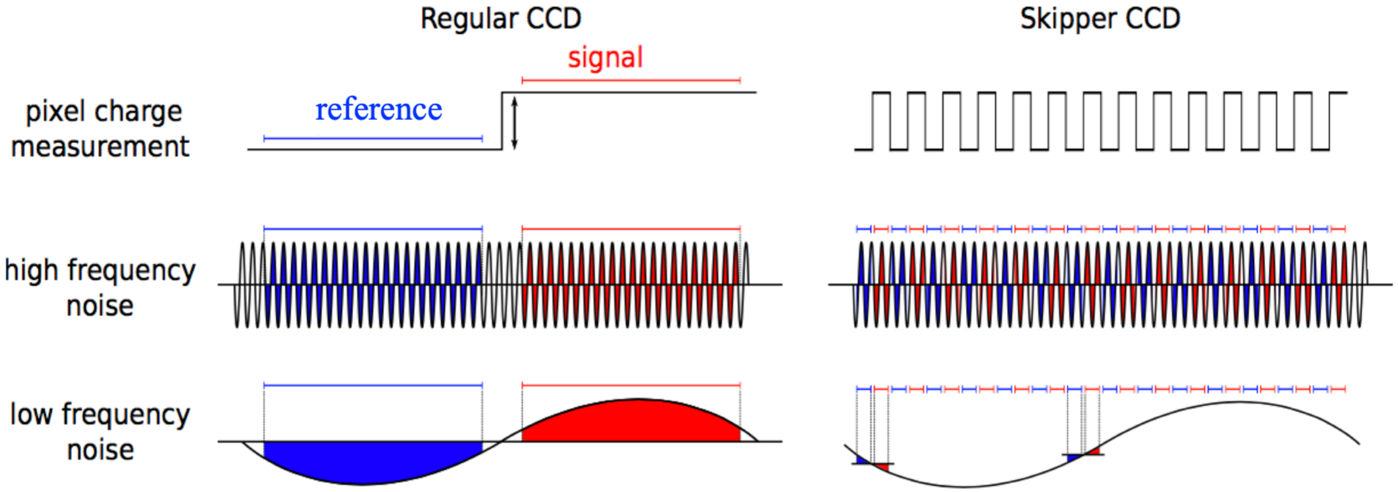
Limits from DAMIC at SNOLAB

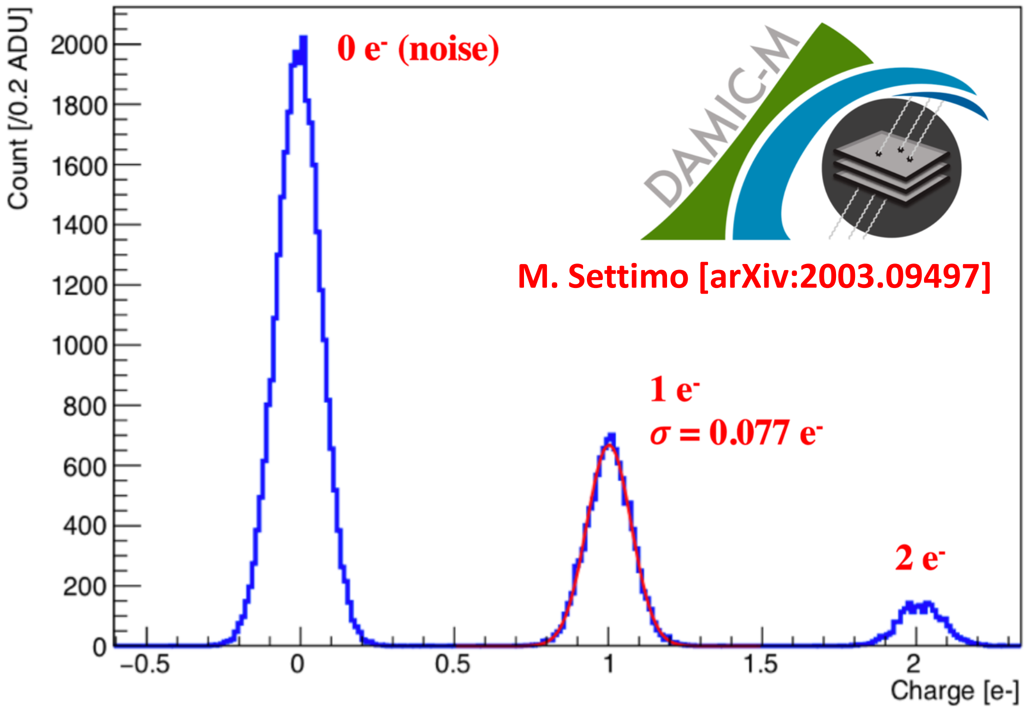


A. Aguilar-Arevalo et al. PRL 123, 181802 (2019) [arXiv:1907.12628]

Skipper CCDs

- DAMIC at SNOLAB CCDs have 2e⁻ resolution
  - Limited by low-frequency noise
- "Skipper" CCDs average over multiple non-destructive measurements

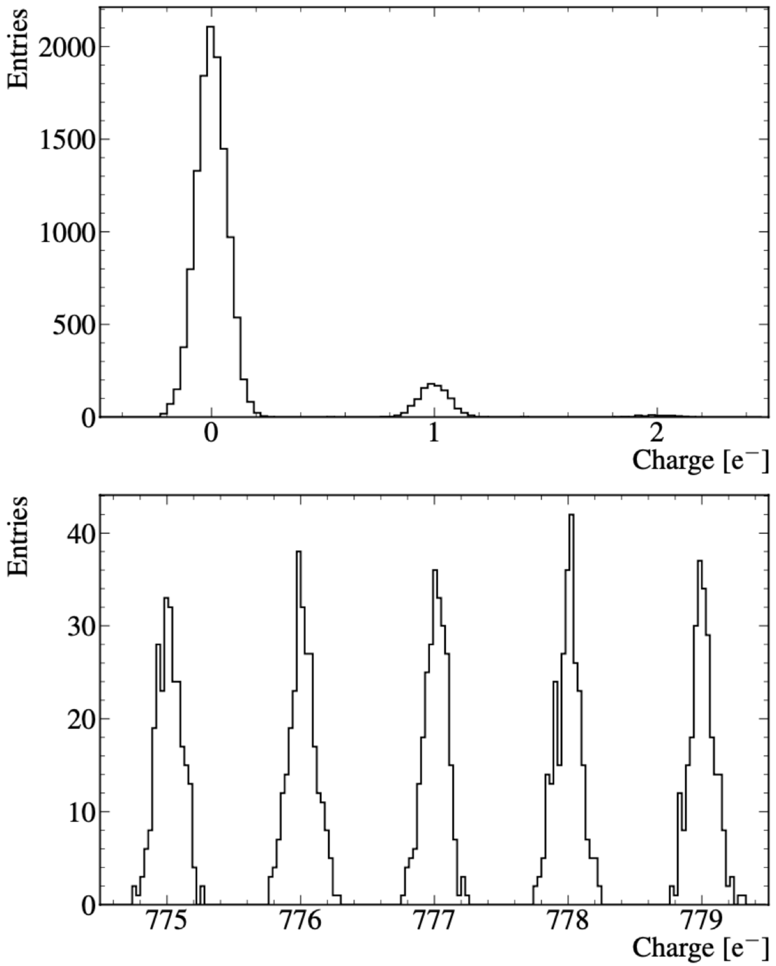




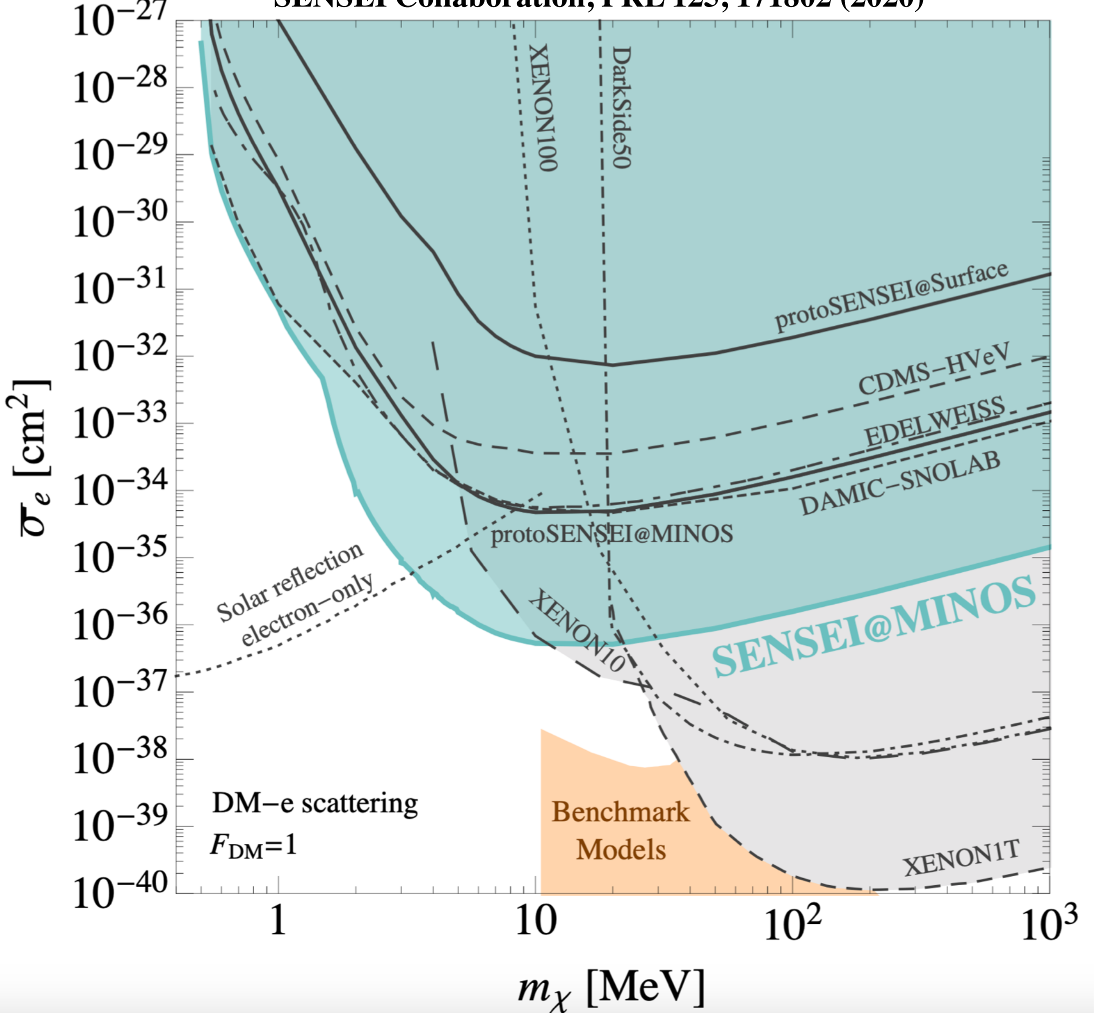
- **0.07e⁻ resolution achieved in test chamber at Chicago!**

SENSEI

Tiffenberg et al, PRL 119, 131802 (2017)

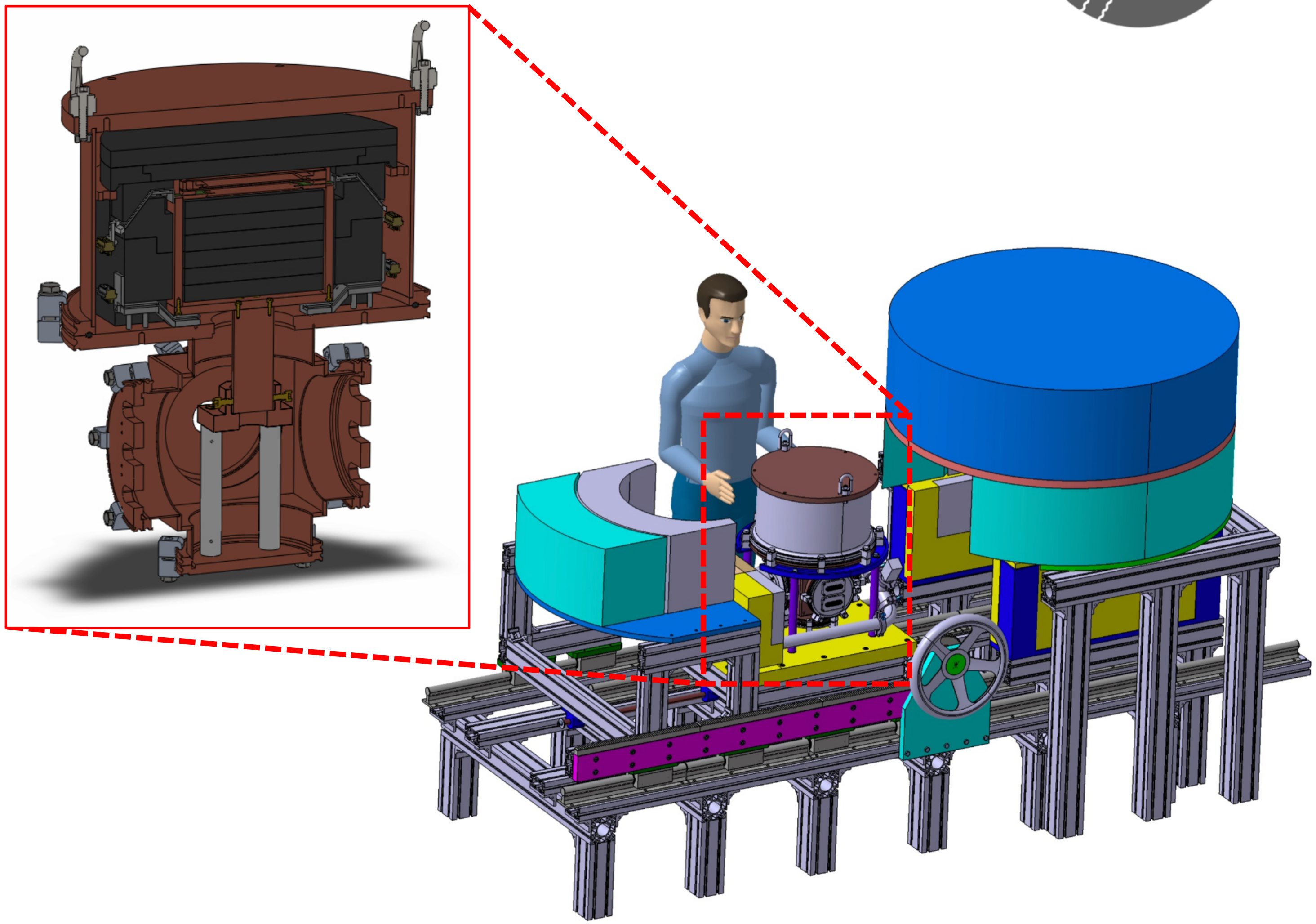


SENSEI Collaboration, PRL 125, 171802 (2020)



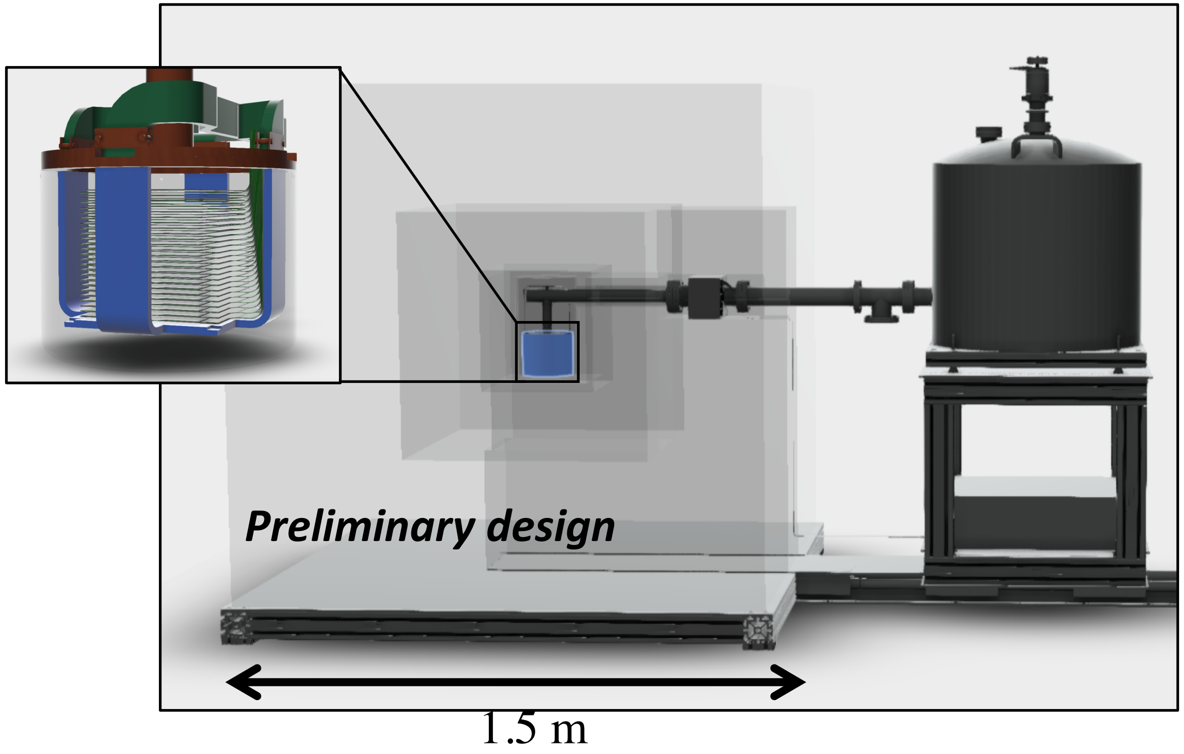
Looking to the Future – DAMIC-M

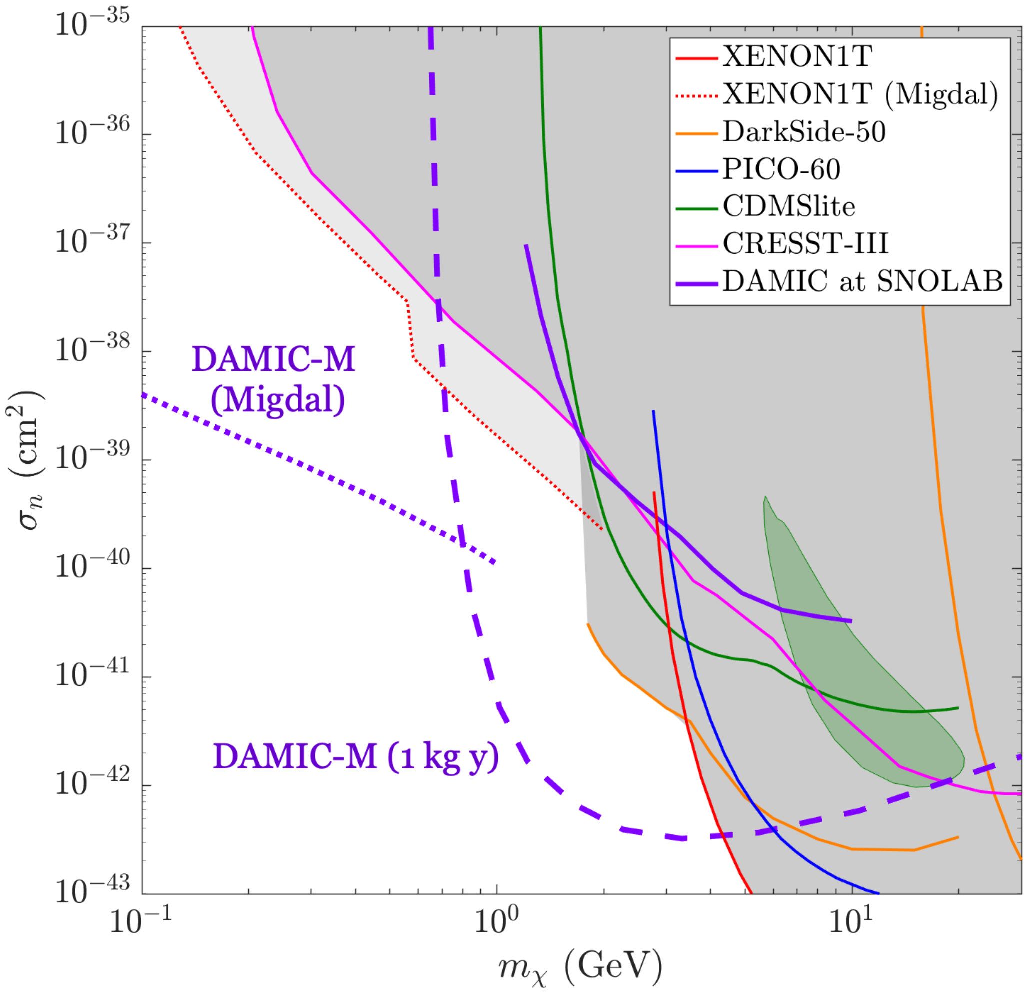
- Prototype DAMIC-M “low background chamber” is ready to deploy…
- 25g of low background Skipper CCDs
- 2 (+4) cm of ancient (low background) lead on all sides of CCD
- Goal: 1 dru and 2 e^- threshold
- **Data this year**



Looking to the Future – DAMIC-M

- Full DAMIC-M detector to be deployed at Modane in 2023, with data and analysis extending at least through 2025

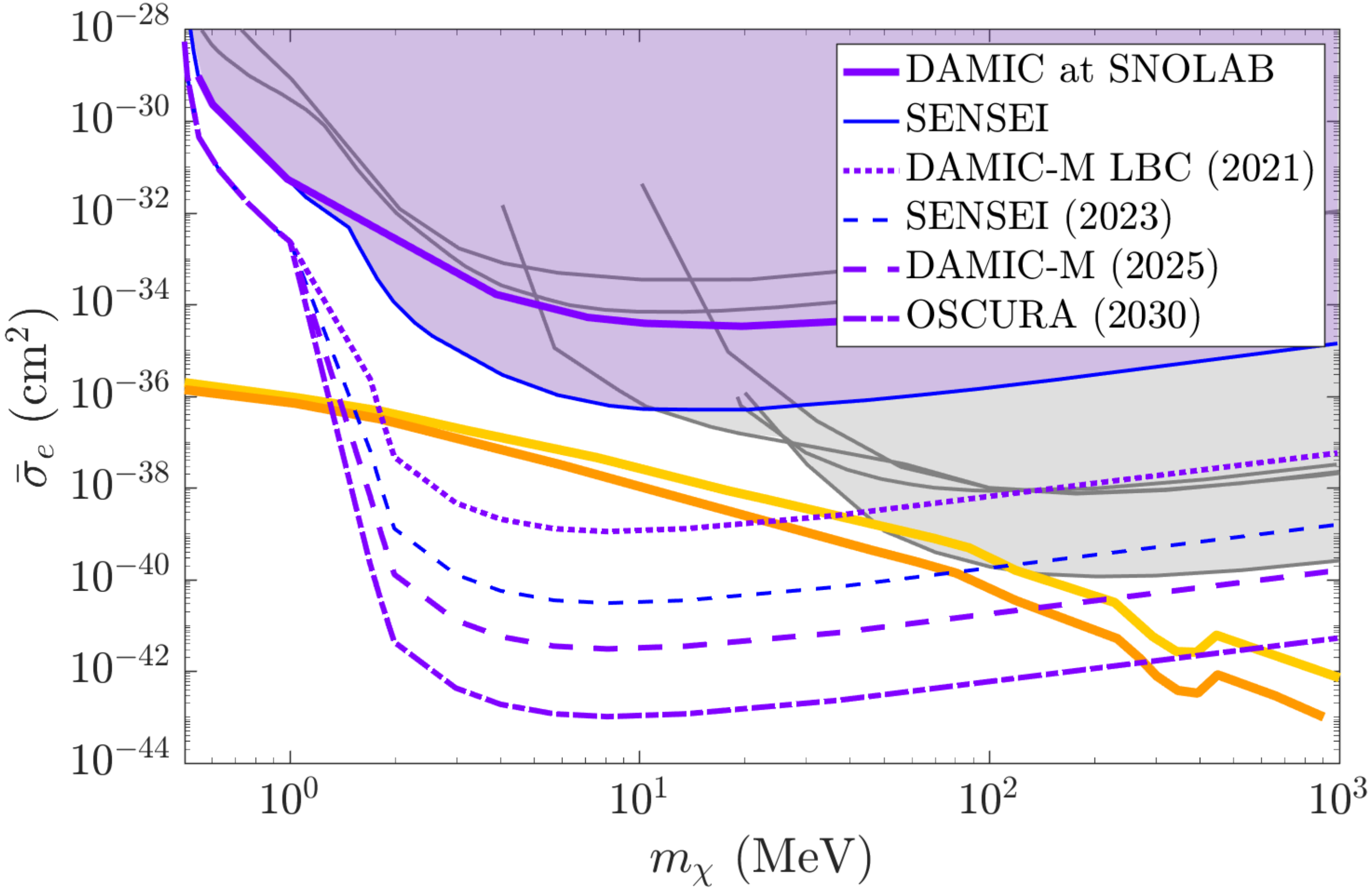




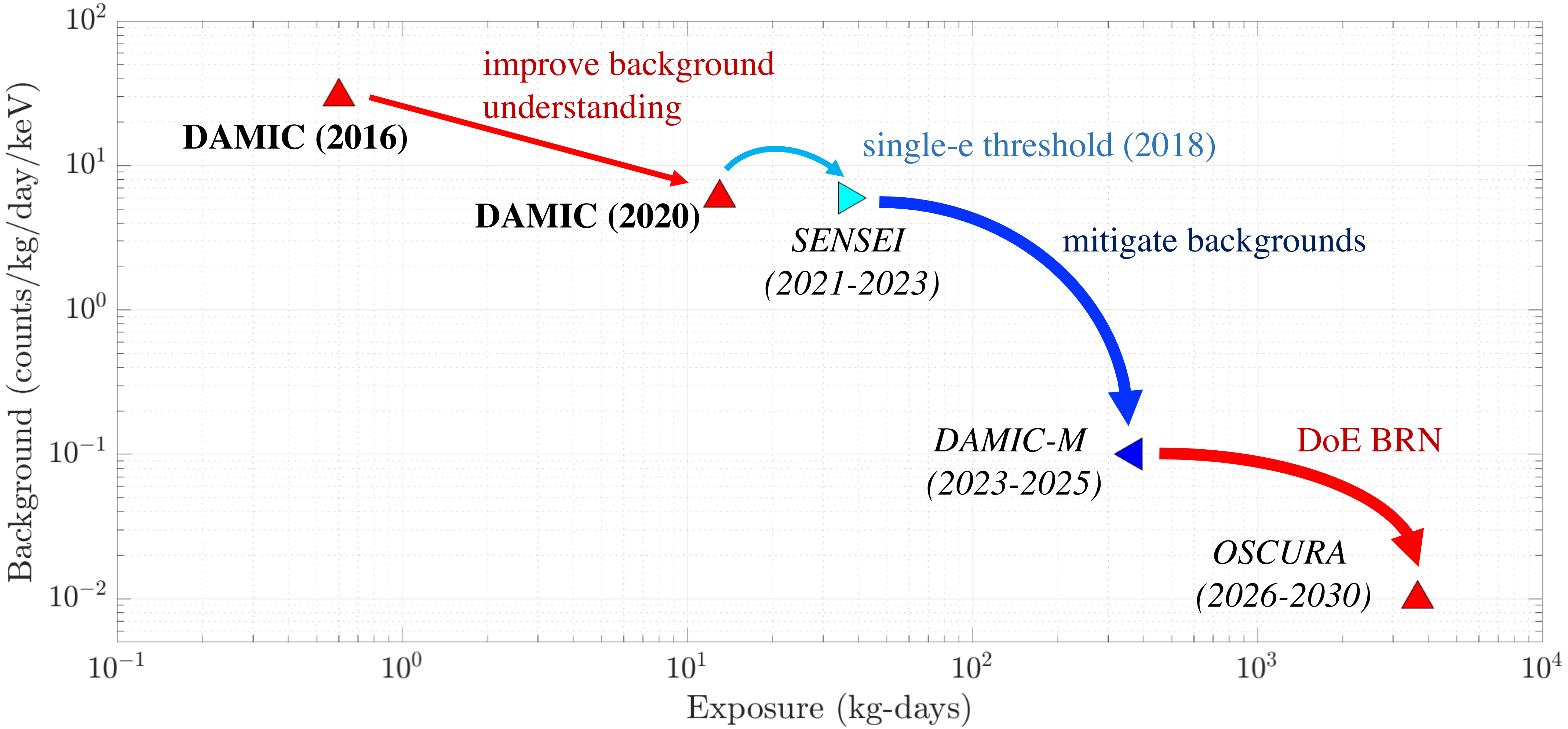
Looking to the Future – OSCURA

OSCURA

- DoE-funded R&D project merging the efforts of DAMIC at SNOLAB, DAMIC-M, and SENSEI
- Full OSCURA funding expected pending delivery of technical design proposal
- Target 3 years of cumulative exposure with 10 kg silicon detector by 2030

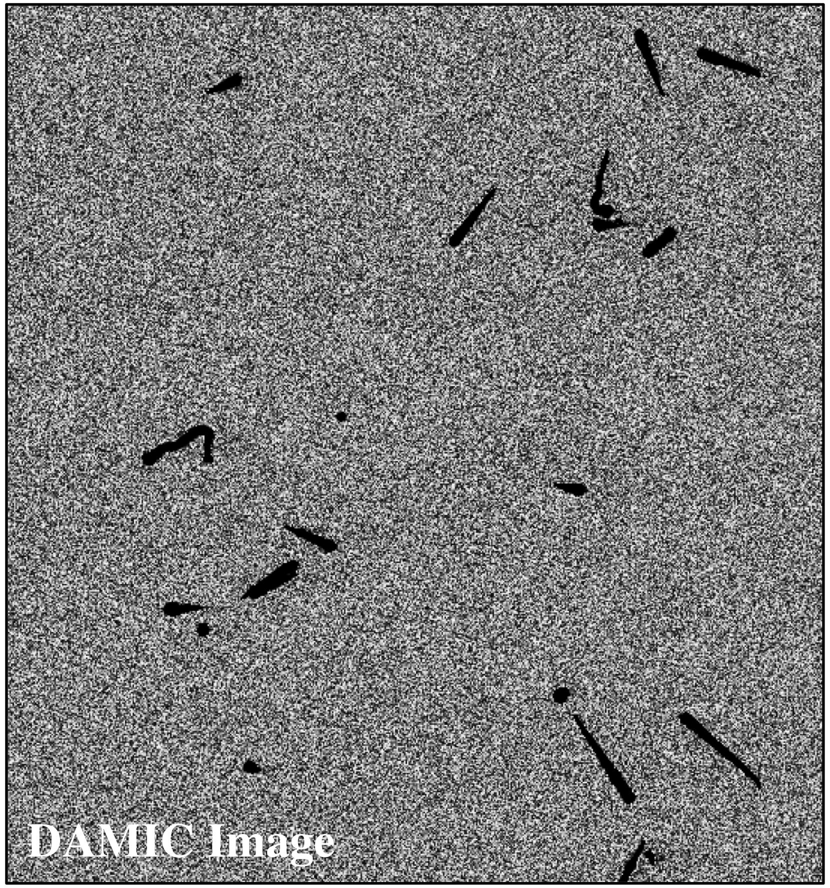


Timeline of CCD Program



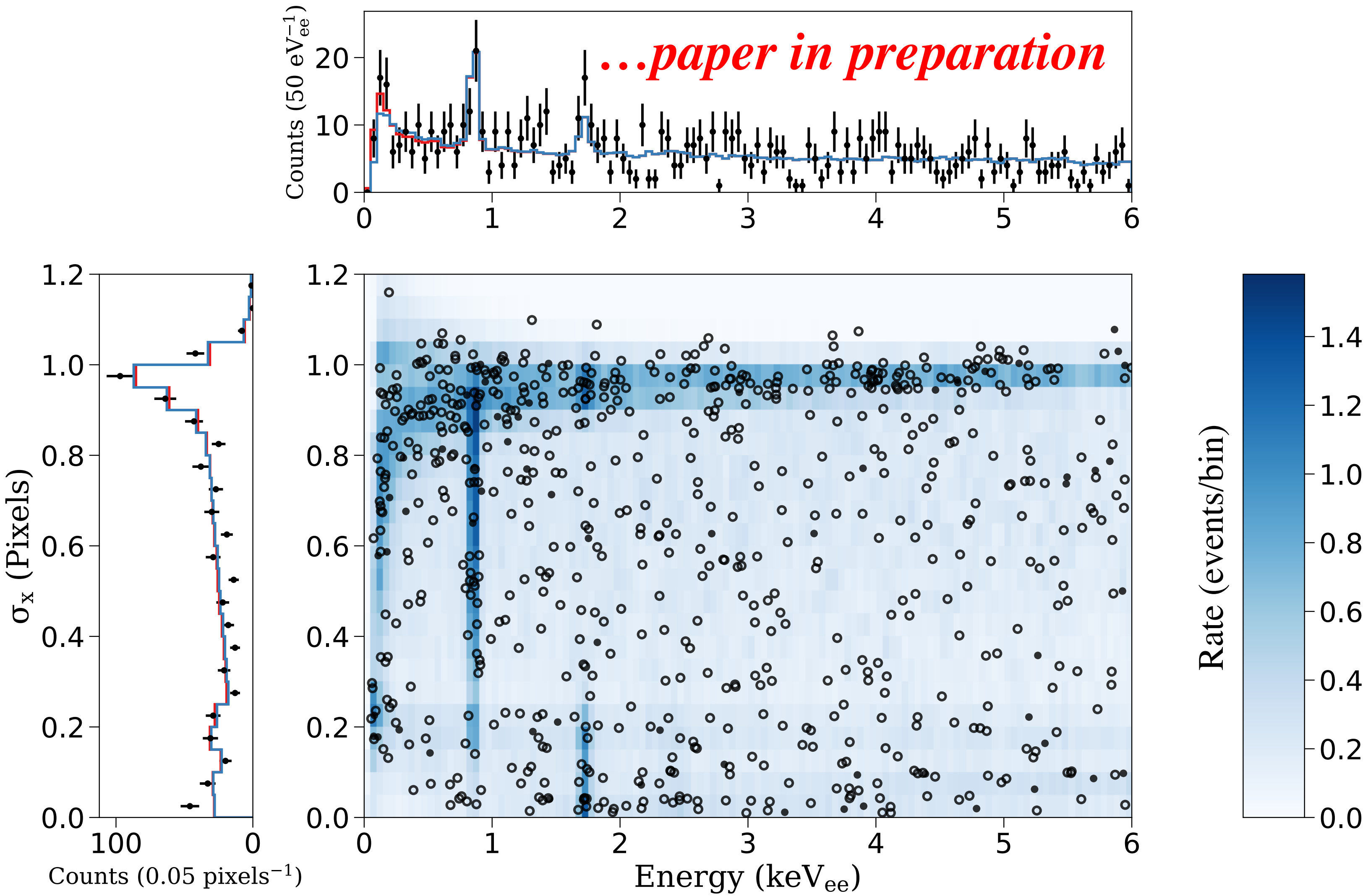
Conclusions

- DAMIC at SNOLAB continues to produce new, interesting results:
  - **ER Limits:** *PRL 123, 181802 (2019) [arXiv:1907.12628]*
  - **NR Limits:** *PRL 125, 241803 (2020) [arXiv:2007.15622]*
  - **Backgrounds:** *JINST 16, P06019 (2021) [arXiv:2011.12922]*
- SENSEI has advanced the CCD technology with single-electron resolution Skipper amplifiers
  - And will continue to improve limits with larger exposures with lower background rates
- DAMIC-M will improve on this with lower backgrounds, single electron resolution, and much larger exposure
  - Low background chamber (2021-2022)
  - Full detector (installation 2023)
- OSCURA will push the limits of the CCD technology to 10 kg of silicon, single-electron threshold, 0.01 dru detector
  - DoE BRN funded R&D experiment merging the efforts of DAMIC at SNOLAB, DAMIC-M, and SENSEI



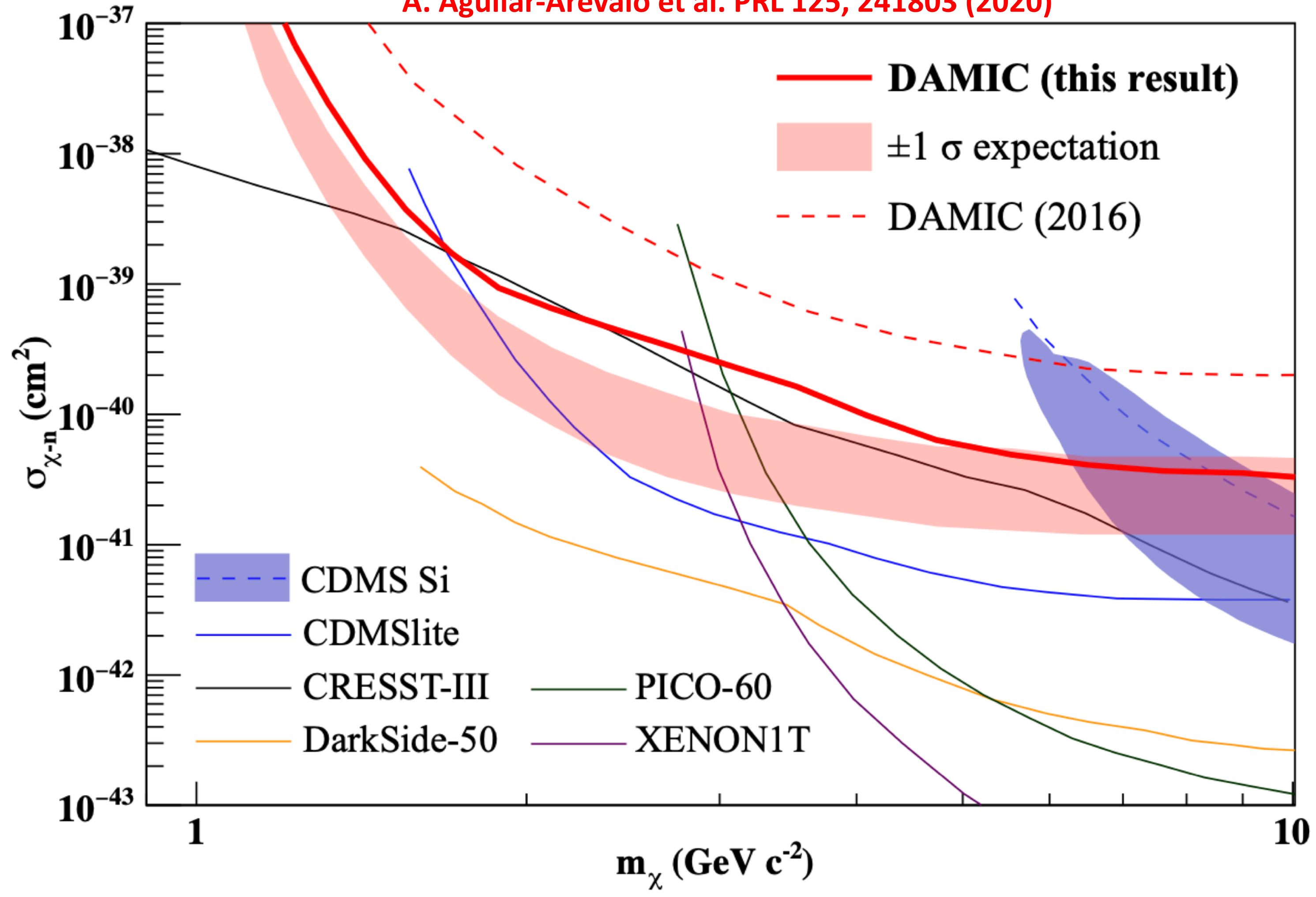
Extra Slides

DAMIC Background Model (2020)



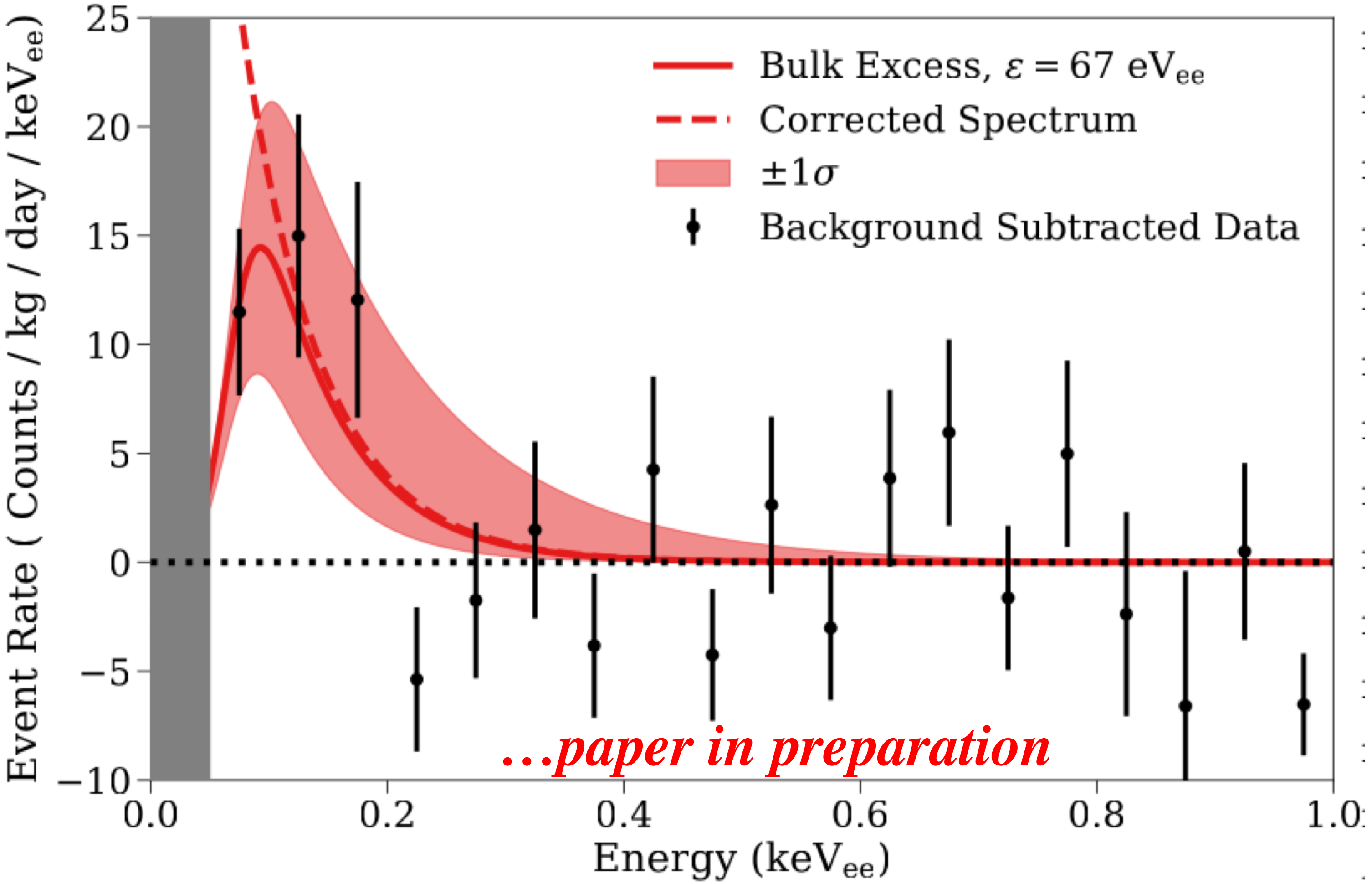
DAMIC WIMP Results (2020)

A. Aguilar-Arevalo et al. PRL 125, 241803 (2020)



DAMIC at SNOLAB w/ Skipper

- Upgrade of SNOLAB detector with Skipper CCDs is underway
- Lower threshold enables us to study background model down to few eV



Background Contributions

- ~30% of background comes from the CCD bulk
  - ^{3}H production from silicon activation or intrinsic ^{32}Si
- ~15% of background comes from wafer surface ^{210}Pb
- ~10% of background comes from CCD surface ^{210}Pb
- ~30% of background comes from OFHC copper
- …remaining ~15% comes from a mixed bag of detector materials
  - Kapton cables and lead

Spatial coincidences allow rejection of decay chain isotopes intrinsic to bulk Si

A. Aguilar-Arevalo et al., JINST 16, P06019 (2021) [arXiv:2011.12922]