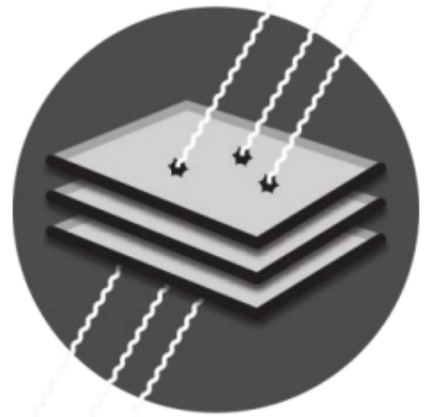
Dark Matter Searches and Prospects with (Skipper-)CCDs

Tien-Tien Yu (University of Oregon)

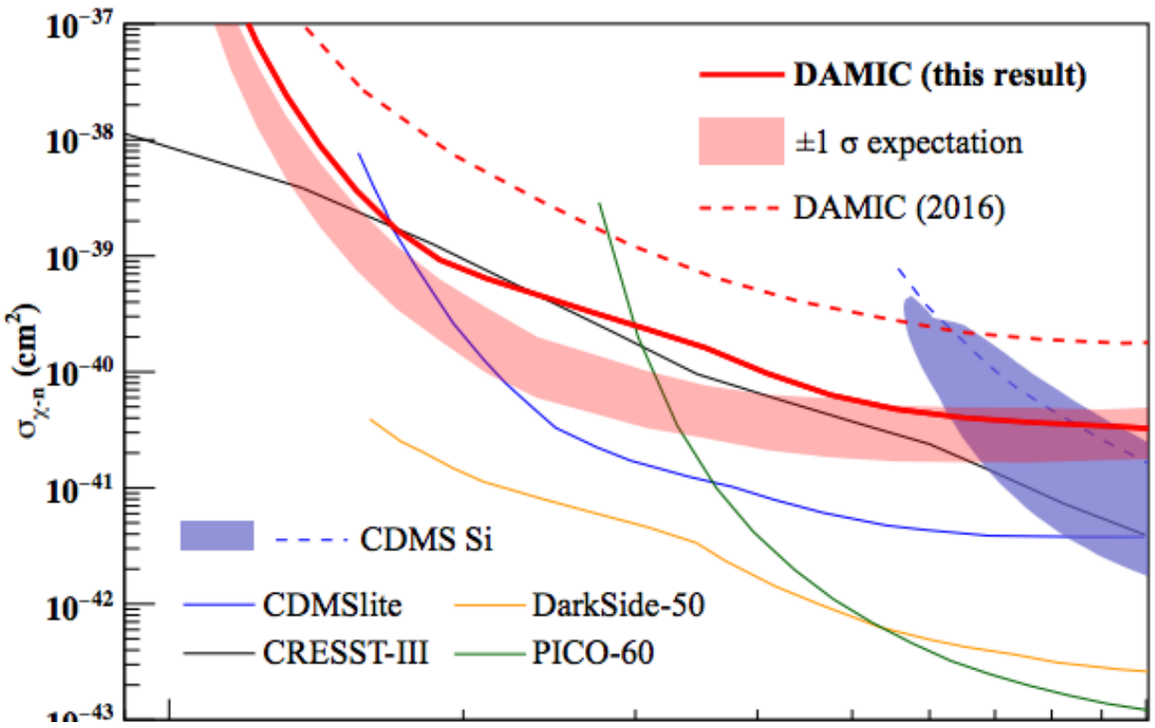
Snowmass CF1: Direct Detection Searches at Low Mass, Part 1 — September 25, 2020

a brief history

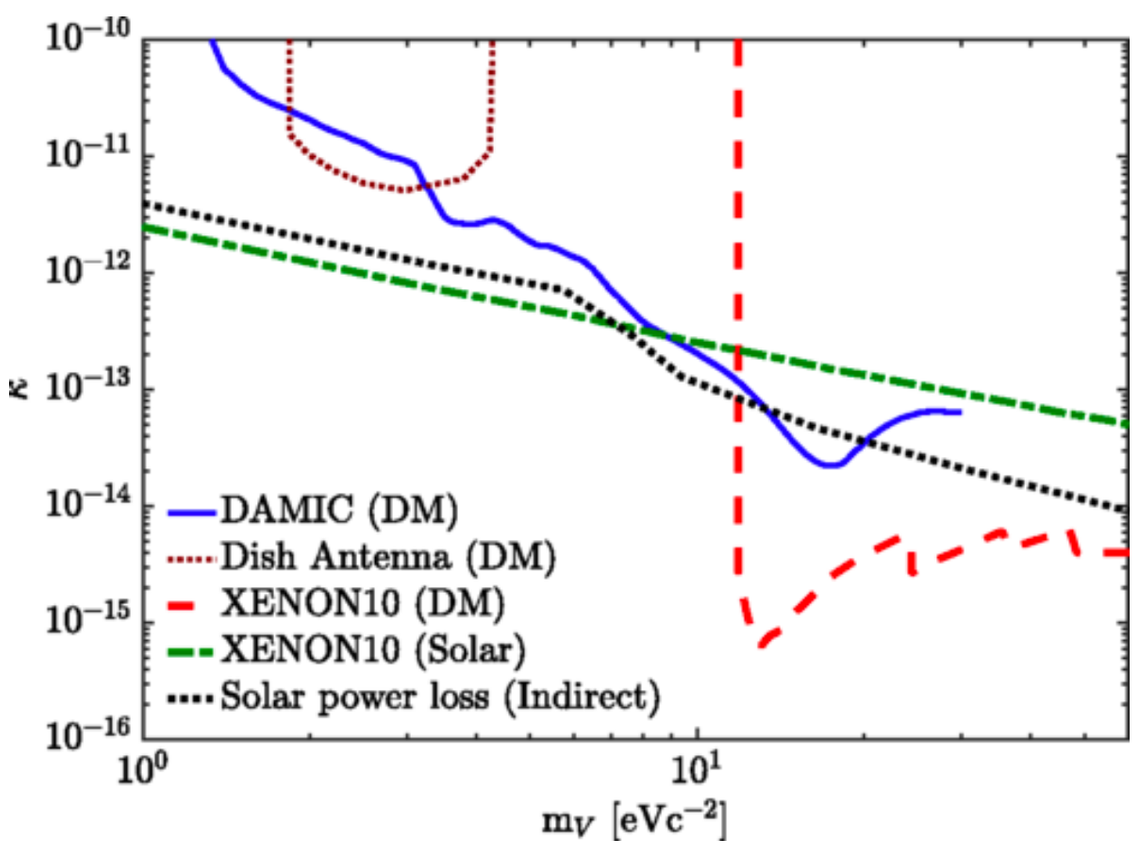


in the beginning, there was DAMIC

first demonstration that CCDs can be used for DM searches
~2e noise resolution



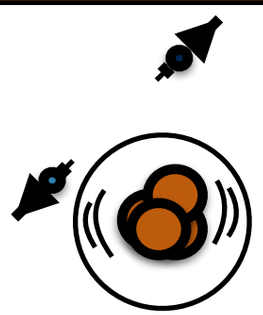
DAMIC-SNOLAB [arXiv:2007.15622]



Phys.Rev.Lett. 118 (2017) 14, 141803 [arXiv:1611.03066]

theory models

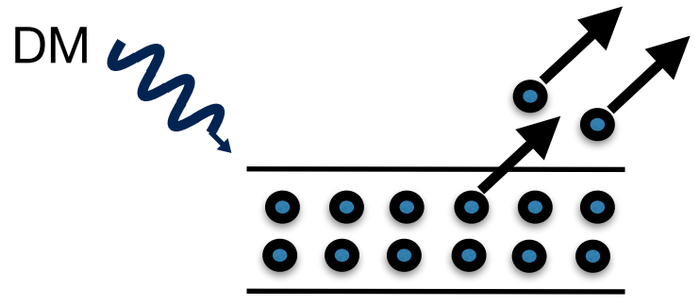
Dark matter-electron scattering



Rate ~ $\overline{\sigma}_e$ x exposure

$$m_\chi \gtrsim 0.3\ \text{MeV} \times \frac{\Delta E_B}{1\ \text{eV}}$$

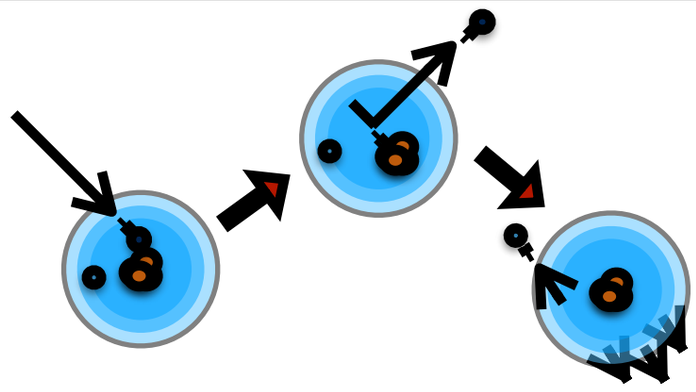
Bosonic dark matter absorption



Rate ~ ε^2 x exposure

$$m_\chi \gtrsim \Delta E_B$$

Dark matter-nuclear scattering



Rate ~ $\overline{\sigma}_n$ x exposure

$$m_\chi \gtrsim 0.3\ \text{MeV} \times \frac{\Delta E_B}{1\ \text{eV}}$$

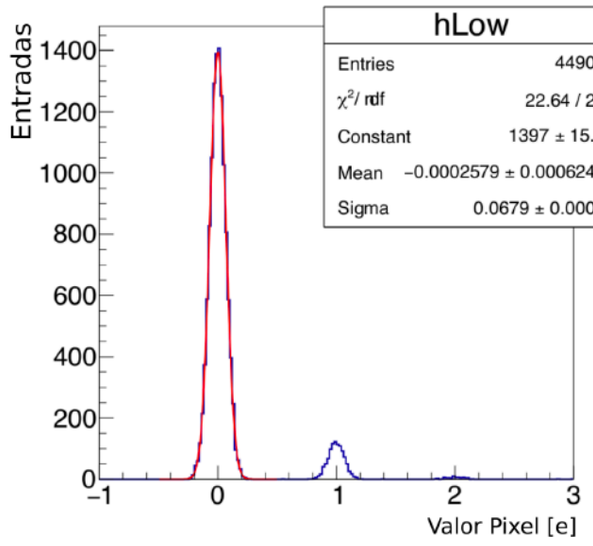
See Dan Baxter and Jonathan Kozaczuk's talk last week

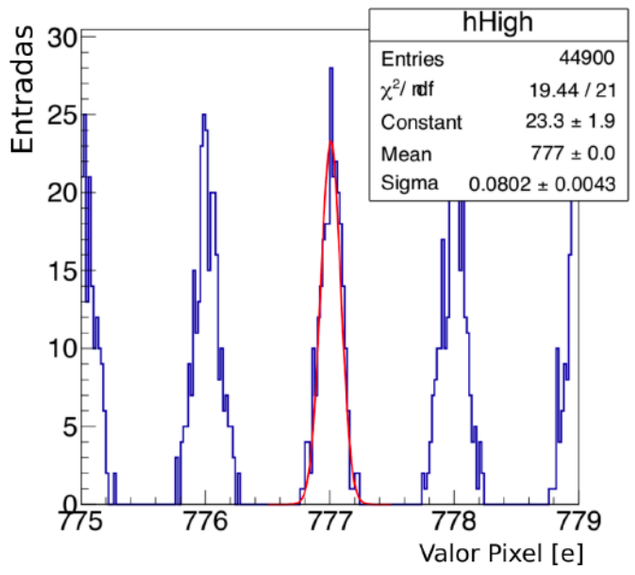
Fermilab

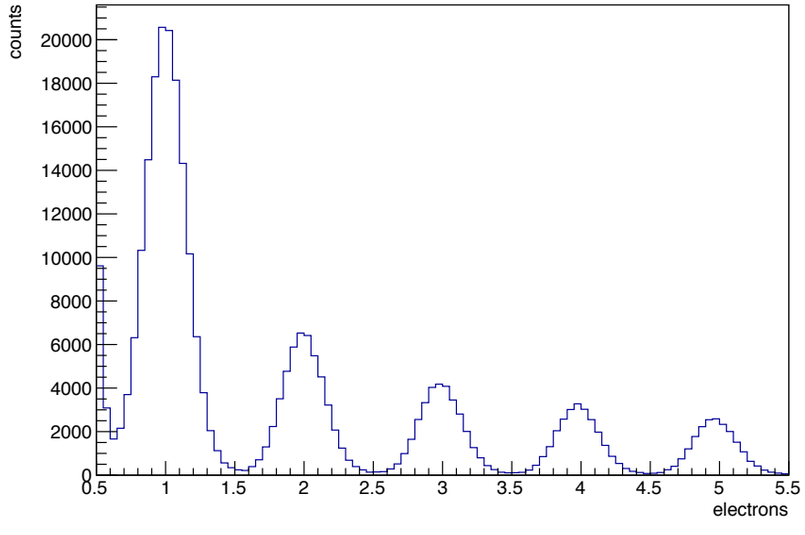
a brief history

Demonstration of 0.068 e^- noise in Skipper CCD

2017 2018 2019 2020 2021 2022 2023 2024







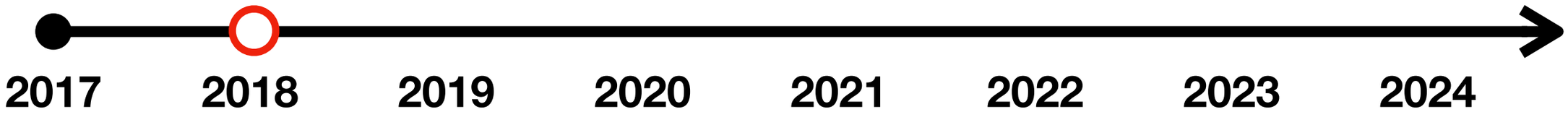
SENSEI collaboration [arXiv:1706.00028], *Phys.Rev.Lett.* 119 (2017) 13, 131802

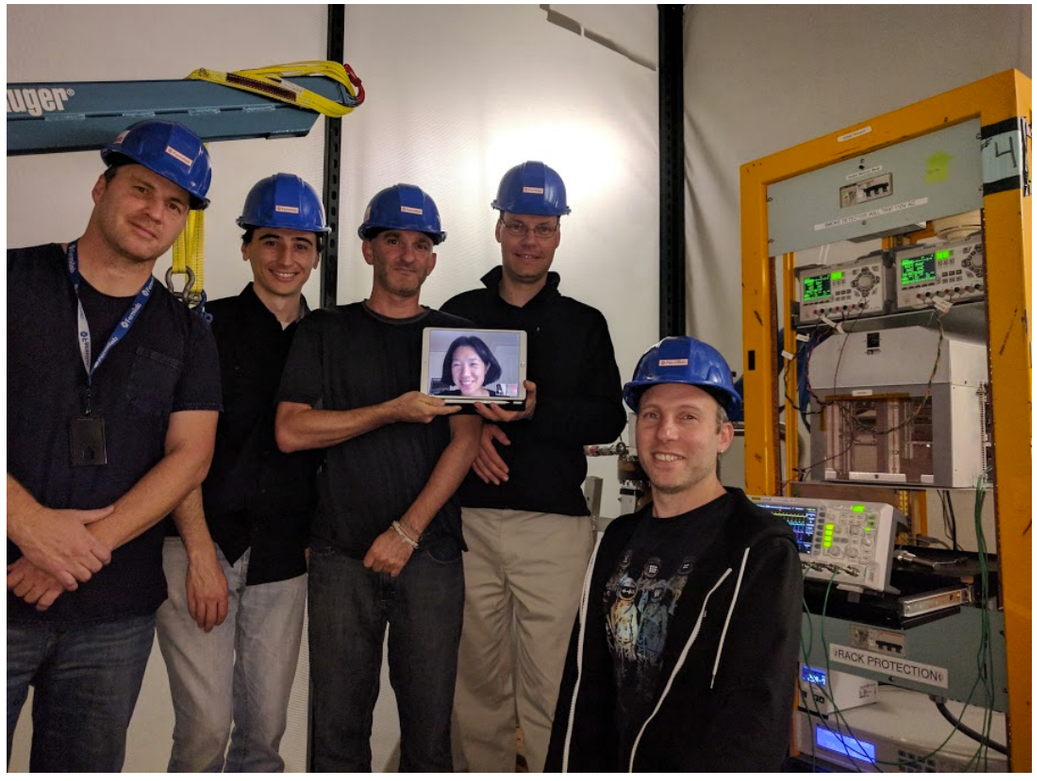
SENSEI

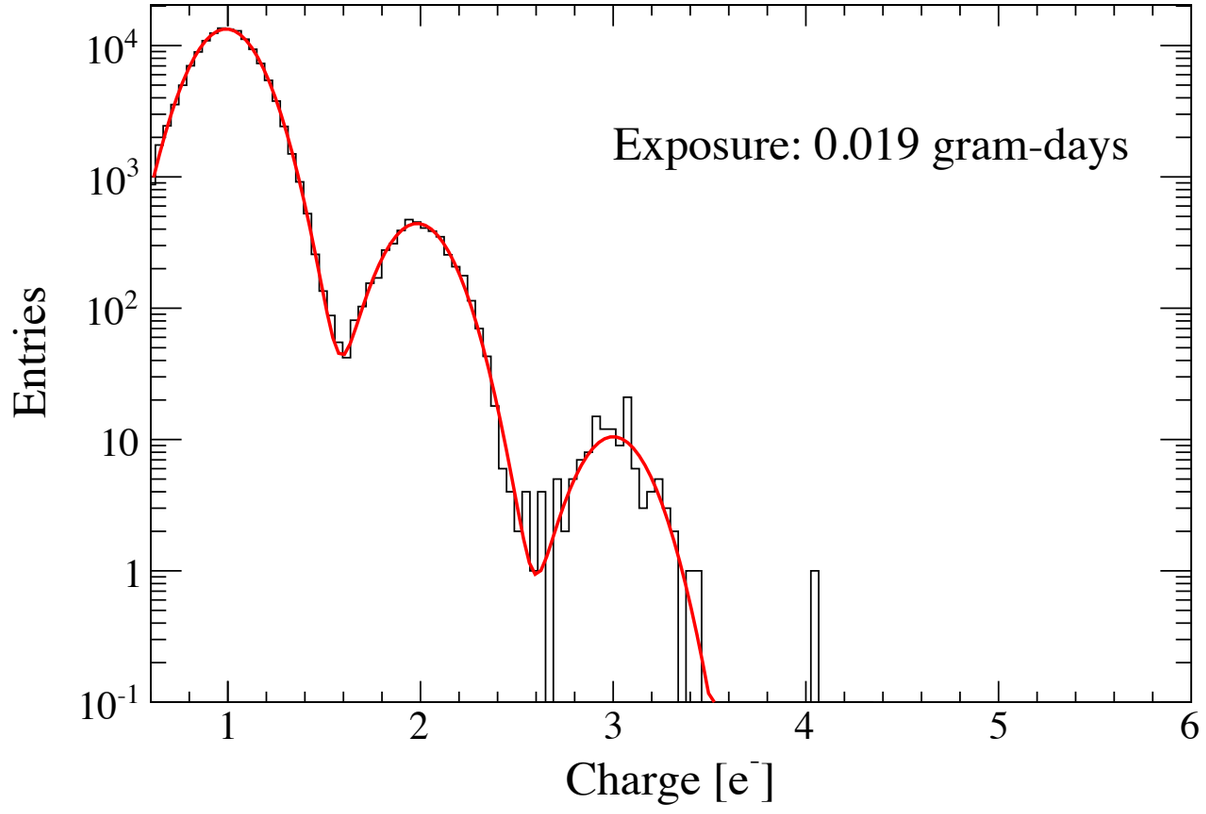
Fermilab

HEISING-SIMONS FOUNDATION

Surface Run of Prototype: exposure ~0.02 g-days



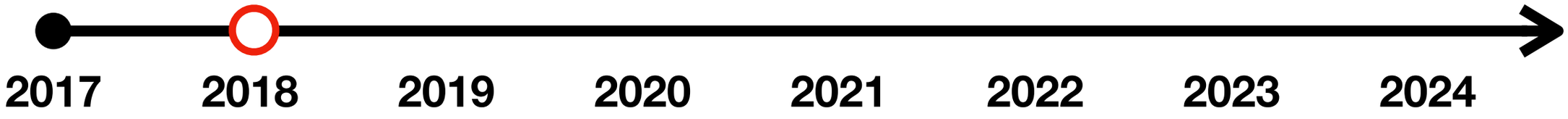


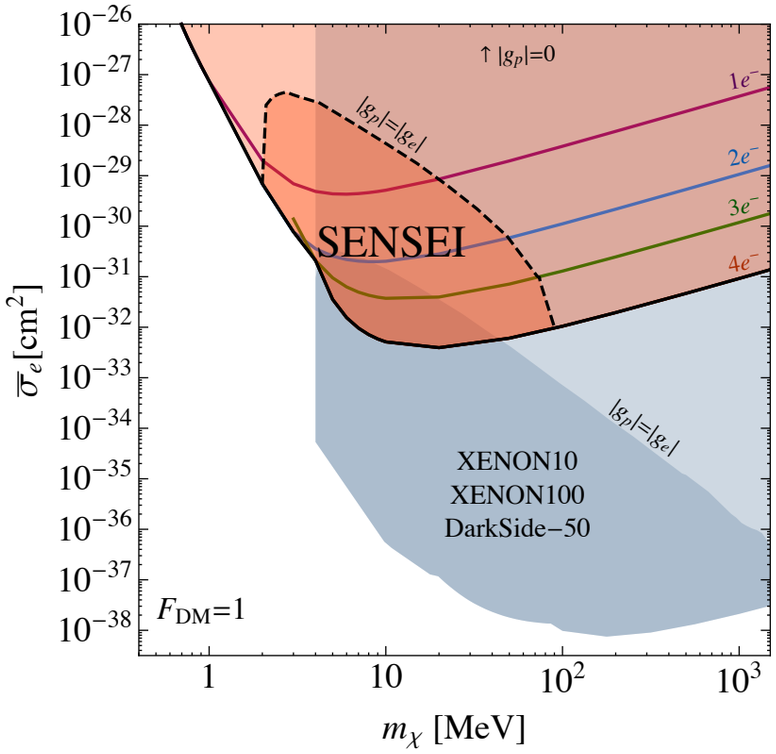


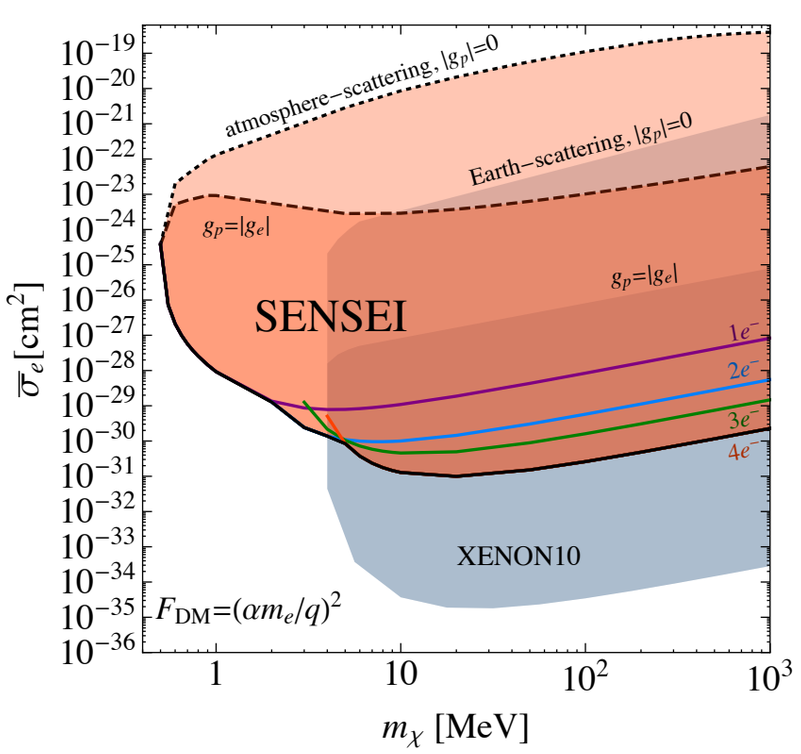
SENSEI collaboration [arXiv:1804.00088], *Phys.Rev.Lett.* 121 (2018) 6, 061803

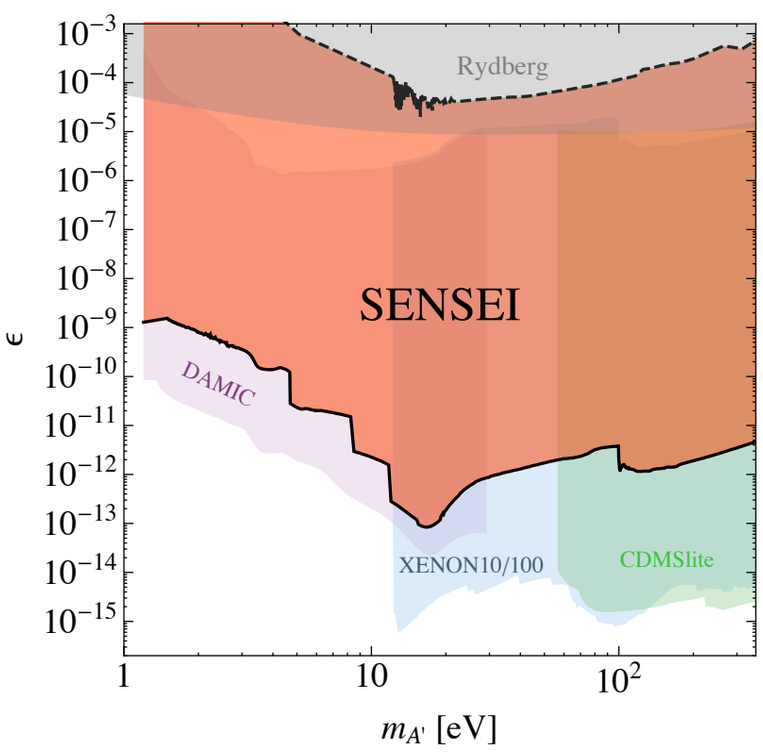
SENSEI

Surface Run of Prototype: exposure ~0.02 g-days







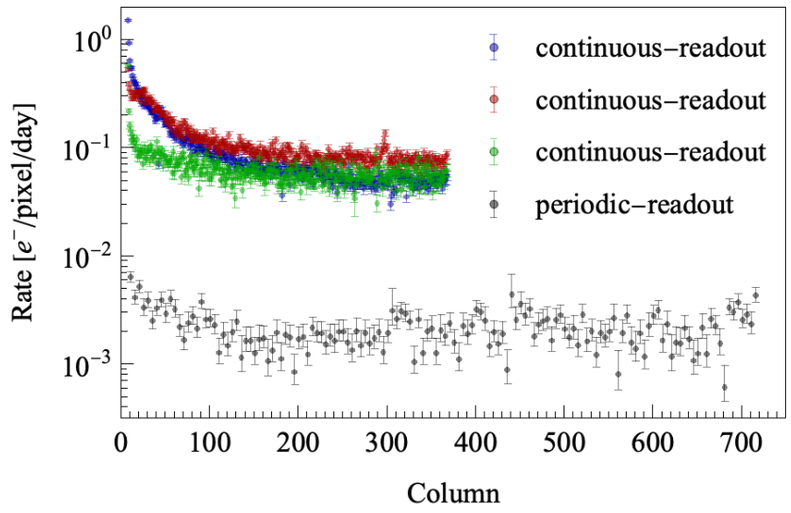


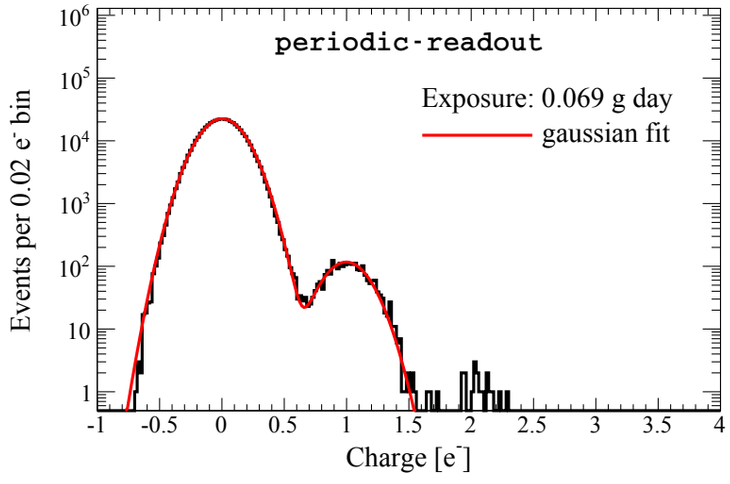
SENSEI collaboration [arXiv:1804.00088], *Phys.Rev.Lett.* 121 (2018) 6, 061803

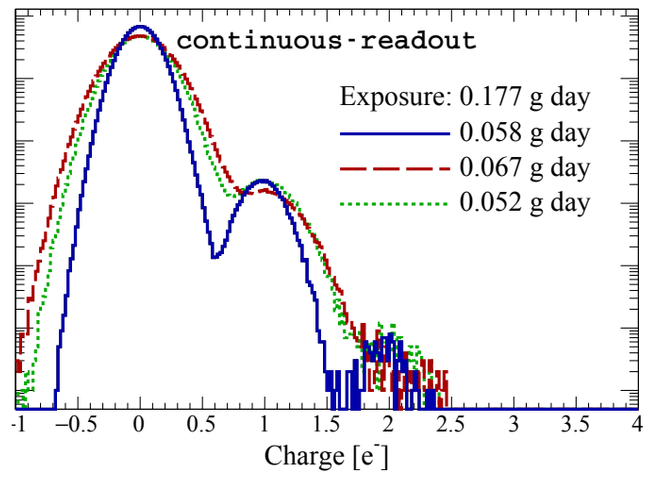
SENSEI

Underground Run of Prototype: exposure ~0.25 g-days

2017 — 2018 — 2019 — 2020 — 2021 — 2022 — 2023 — 2024





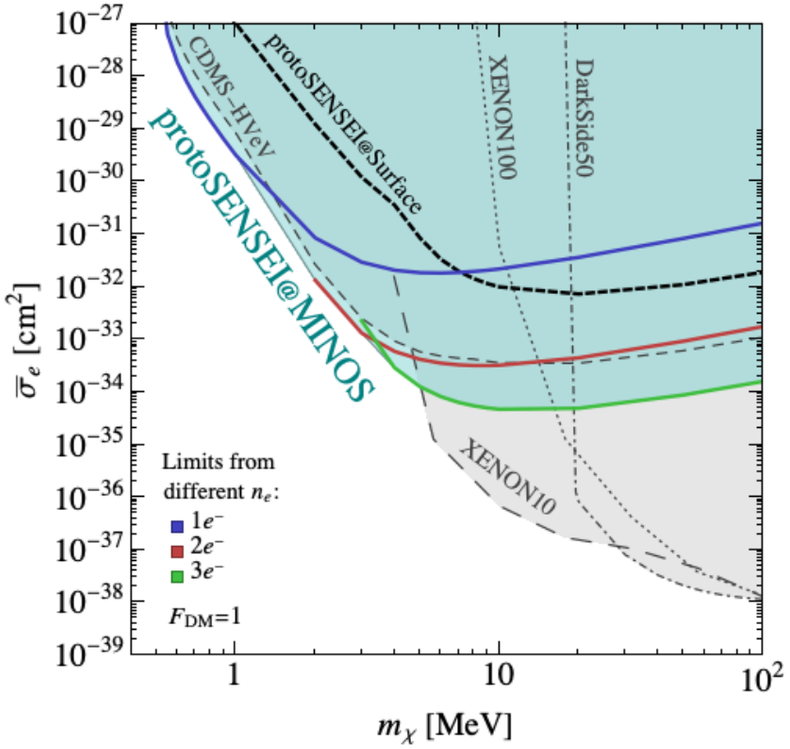


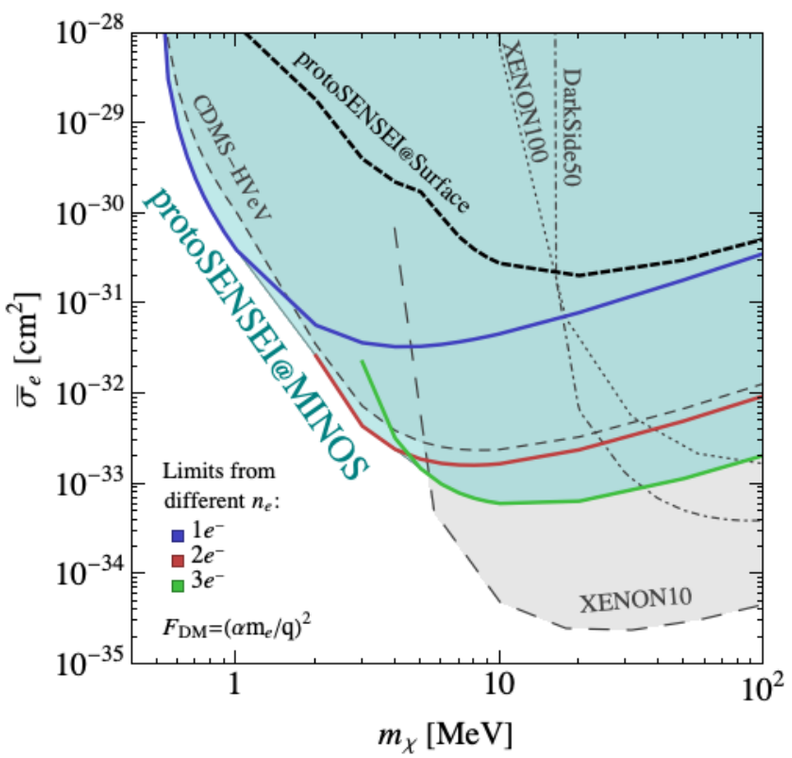
SENSEI collaboration [arXiv:1901.10478], *Phys.Rev.Lett.* 122 (2019) 16, 161801

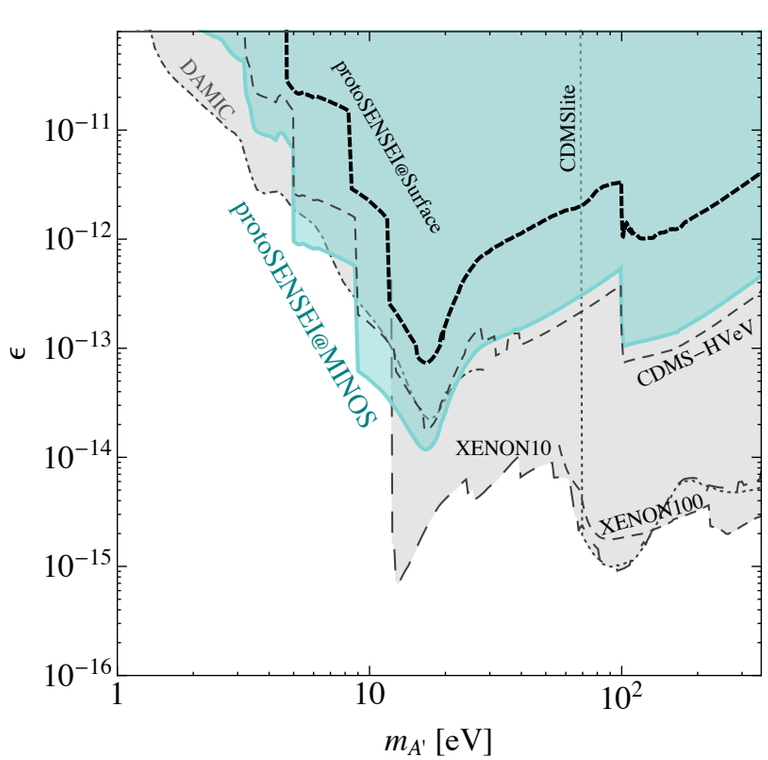
SENSEI

Underground Run of Prototype: exposure ~0.25 g-days

2017 — 2018 — 2019 — 2020 — 2021 — 2022 — 2023 — 2024







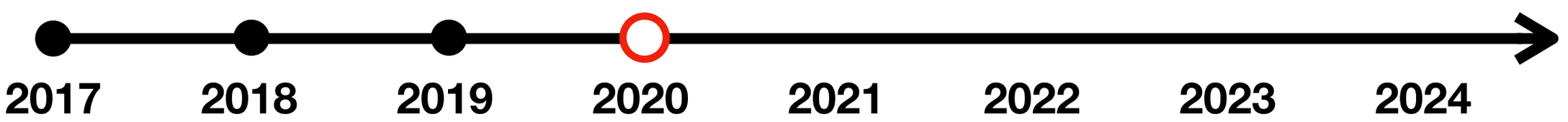
SENSEI collaboration [arXiv:1901.10478], *Phys.Rev.Lett.* 122 (2019) 16, 161801

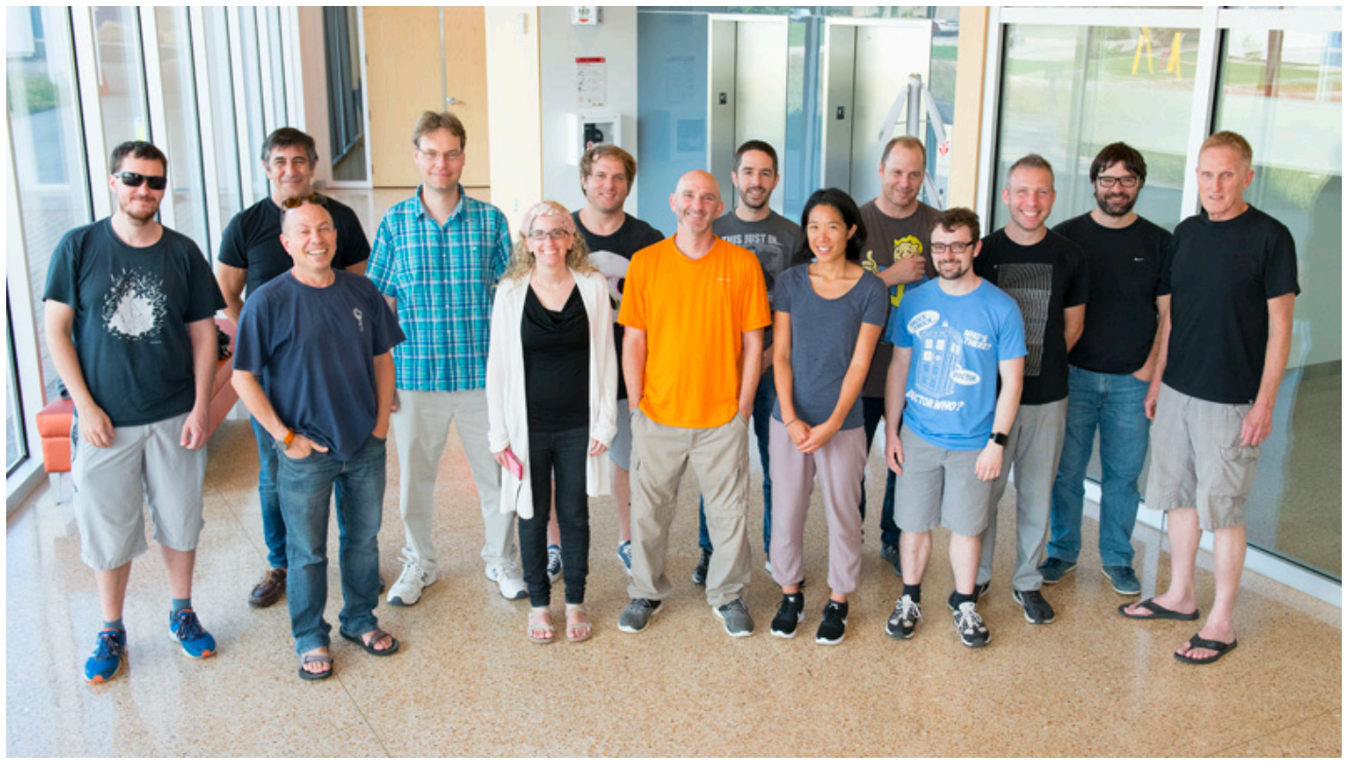
SENSEI

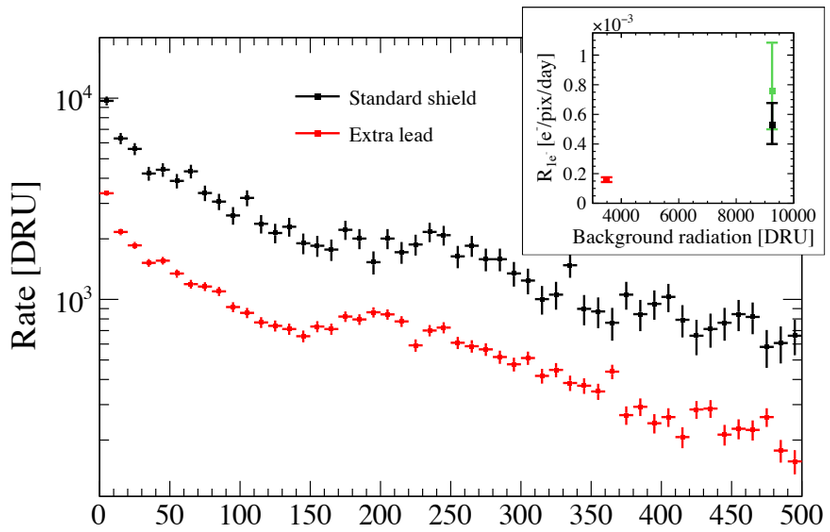
Fermilab

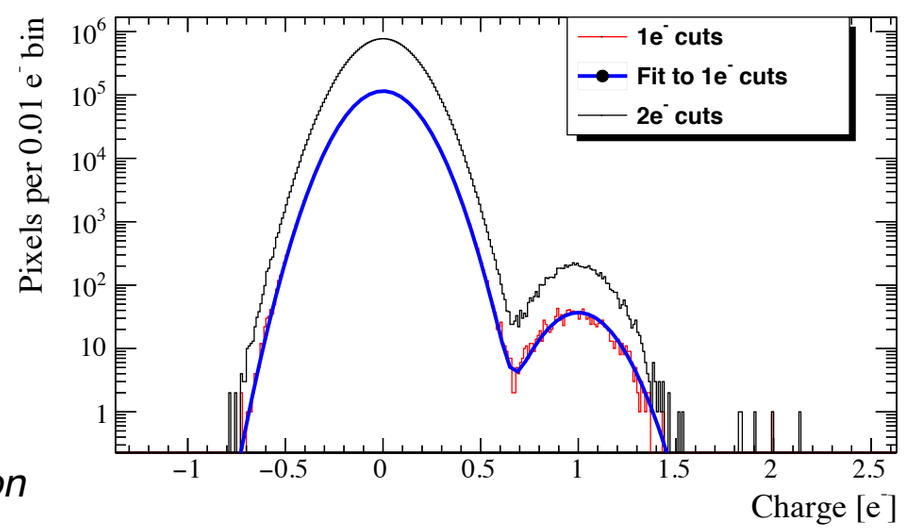
HEISING-SIMONS FOUNDATION

MINOS Run of Science-grade Sensors: exposure ~20 g-days









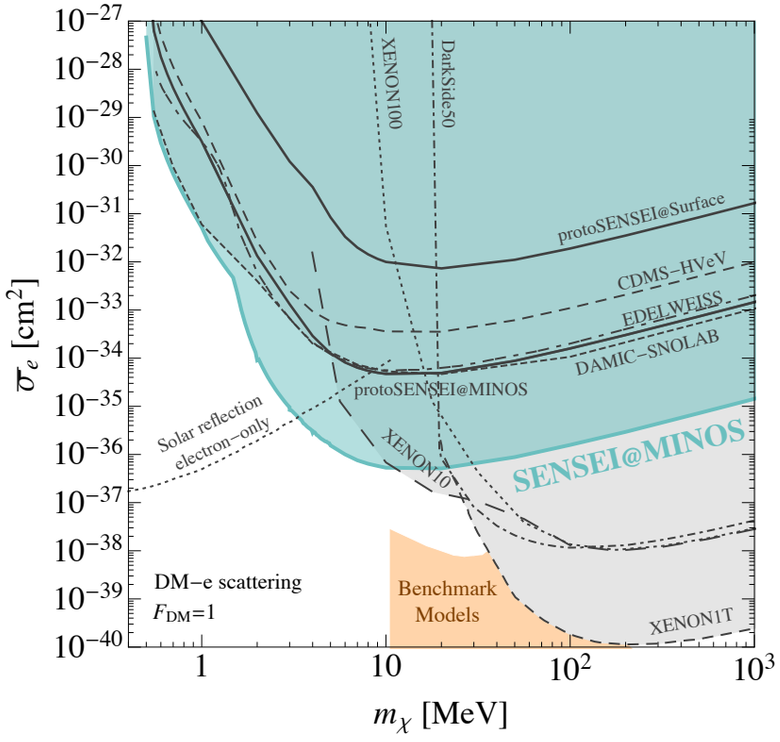
SENSEI collaboration [arXiv:2004.11378], *accepted to PRL - Editors' Suggestion*

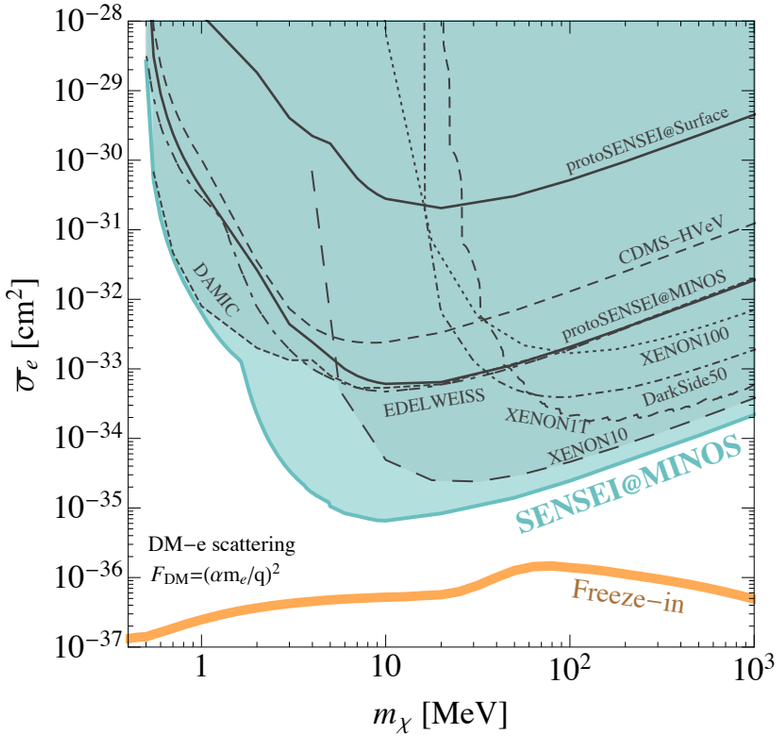
SENSEI

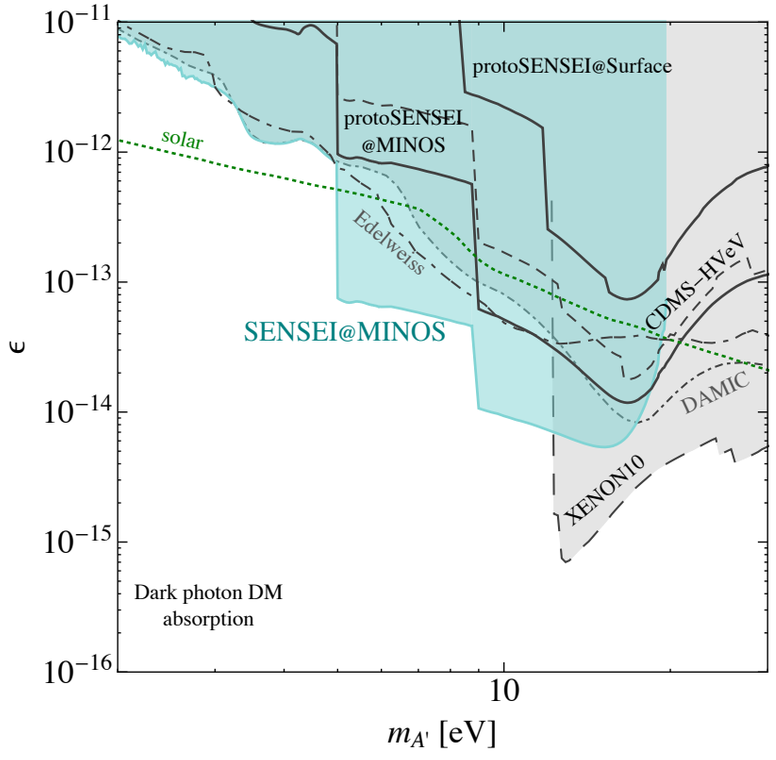
Fermilab

HEISING-SIMONS FOUNDATION

MINOS Run of Science-grade Sensors: exposure ~20 g-days







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current status

	SENSEI@MINOS
1e	525.2 events/g/day
2e	4.449 events/g/day
3e	0.255 events/g/day
4e	0.253 events/g/day

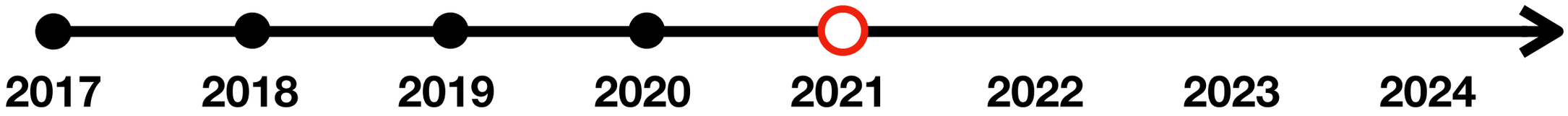
improvements:

1e channel is background-dominated:
better shielding, reduce spurious charge
2e channel has low-background:
same as above
3e, 4e clusters have ZERO background:
increase detector mass

on-going:

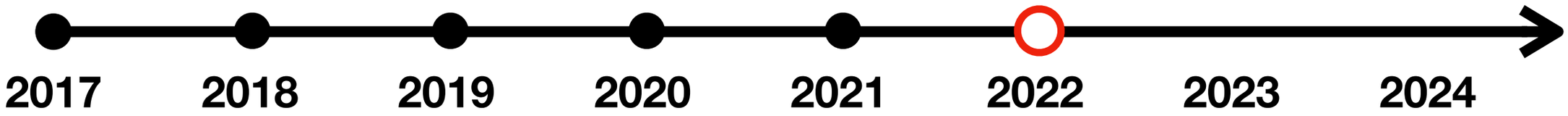
- building full-scale SENSEI at SNOLAB with low-background shielding.
- detailed studies to understand the backgrounds
- Currently operating “Phase 1” system

looking forward



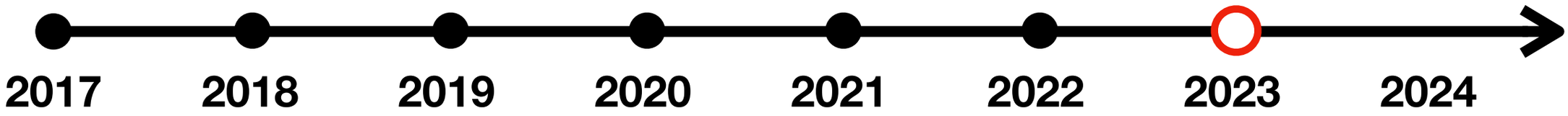
- **construct SENSEI at SNOLAB**

looking forward



- construct SENSEI at SNOLAB
- **continue data-taking for SENSEI at SNOLAB**

looking forward



- construct SENSEI at SNOLAB
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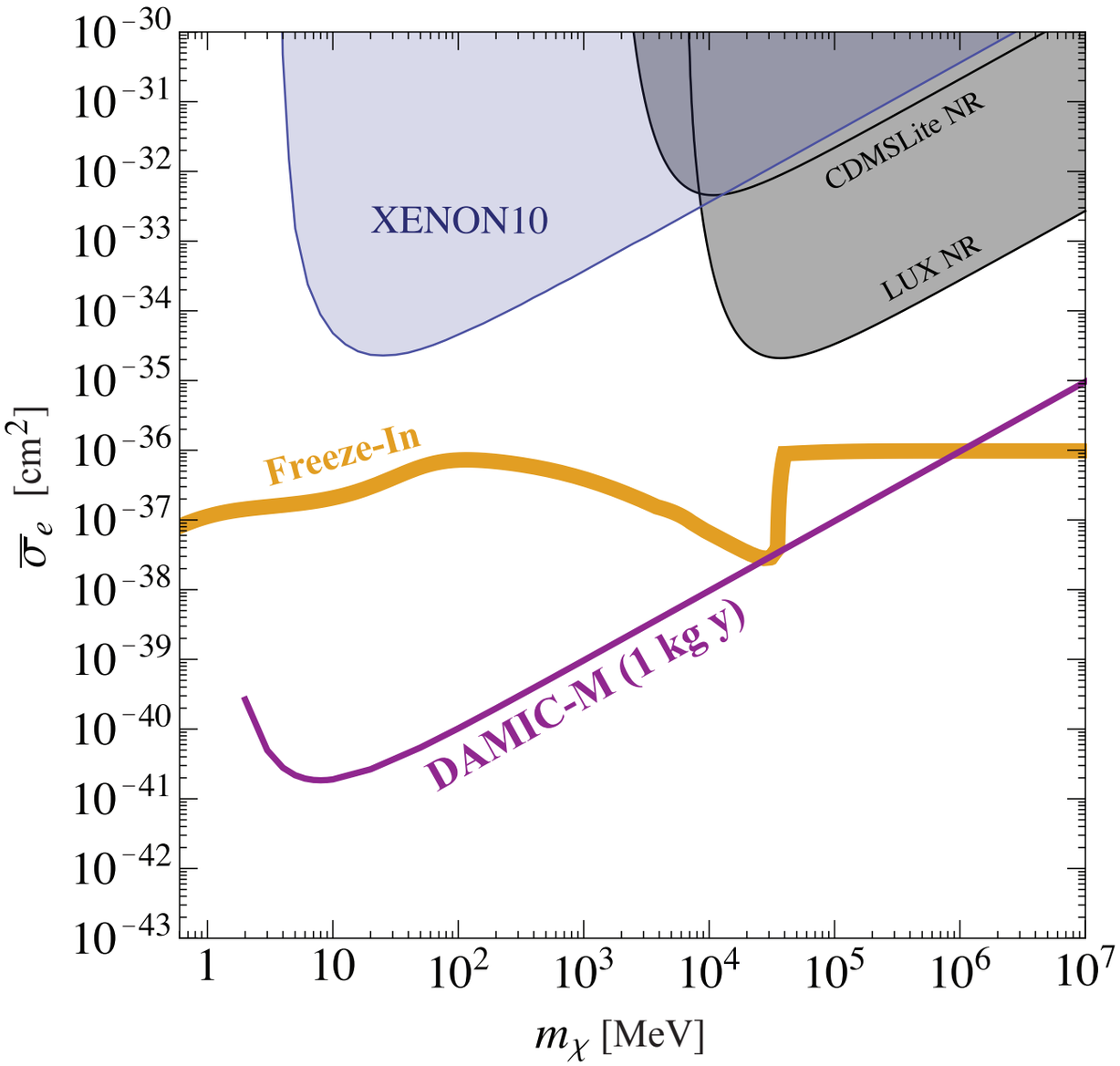
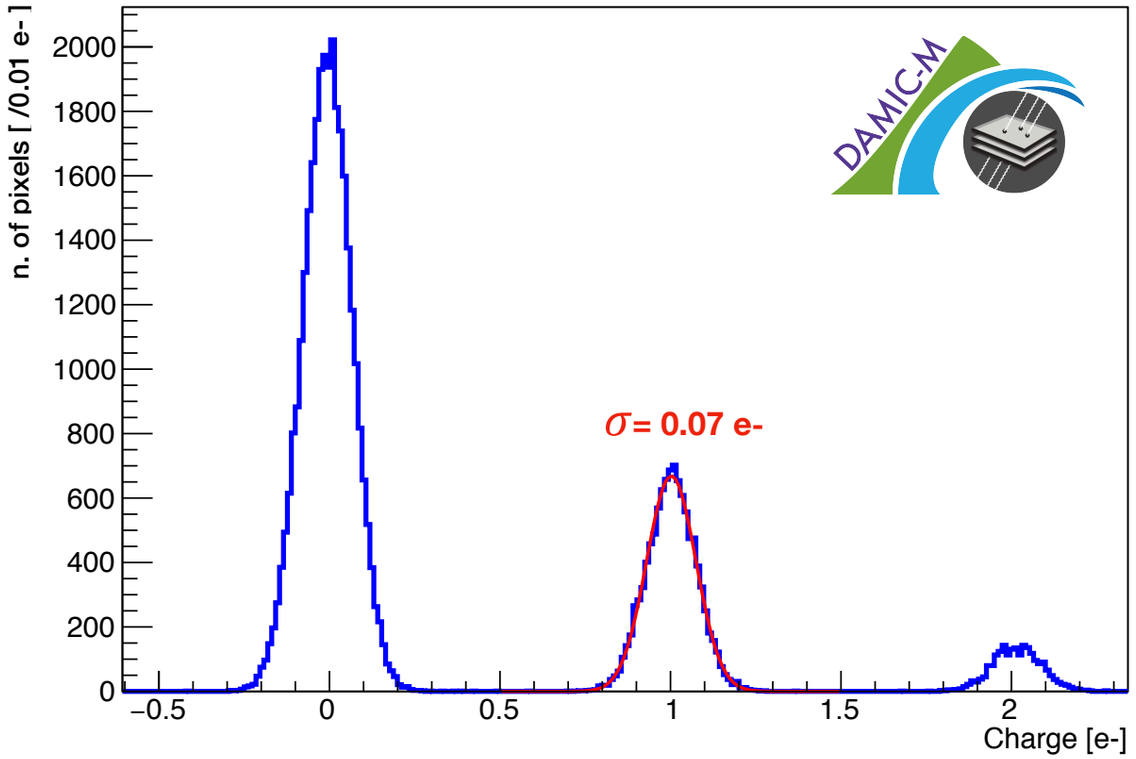
- **final analysis of 100-gram SENSEI data**
- **launch of 1-kg DAMIC-M at Modane**

DAMIC-M

- Search for light dark matter with **<u>kg-year</u>** target exposure of Skipper CCDs
- a fraction of dru background
- Laboratoire Souterrain de Modane, France

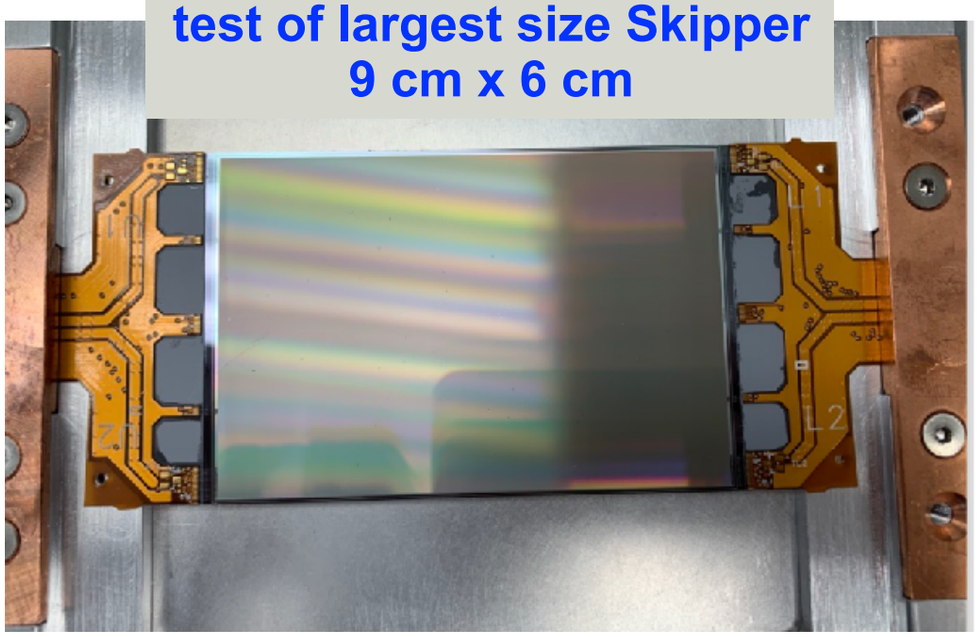


- example of scientific reach



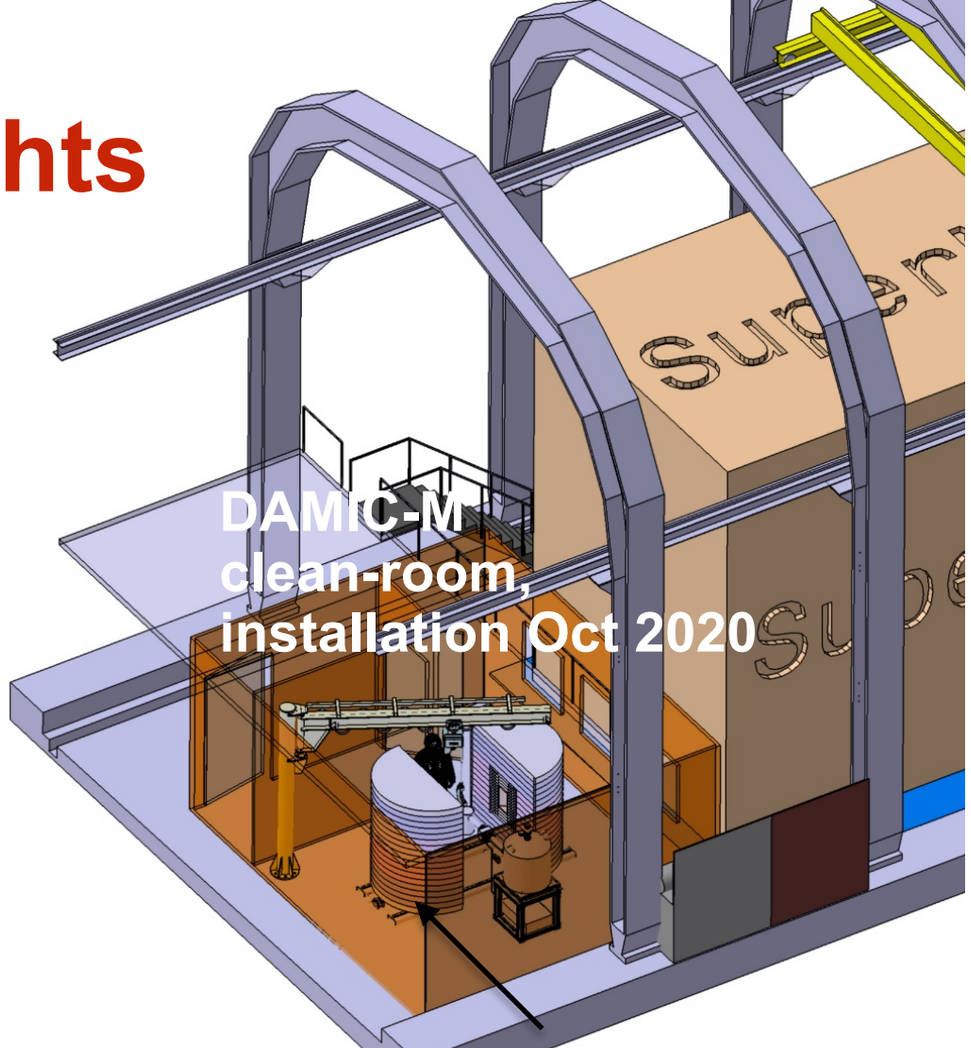
- Single electron resolution with DAMIC-M prototype CCDs

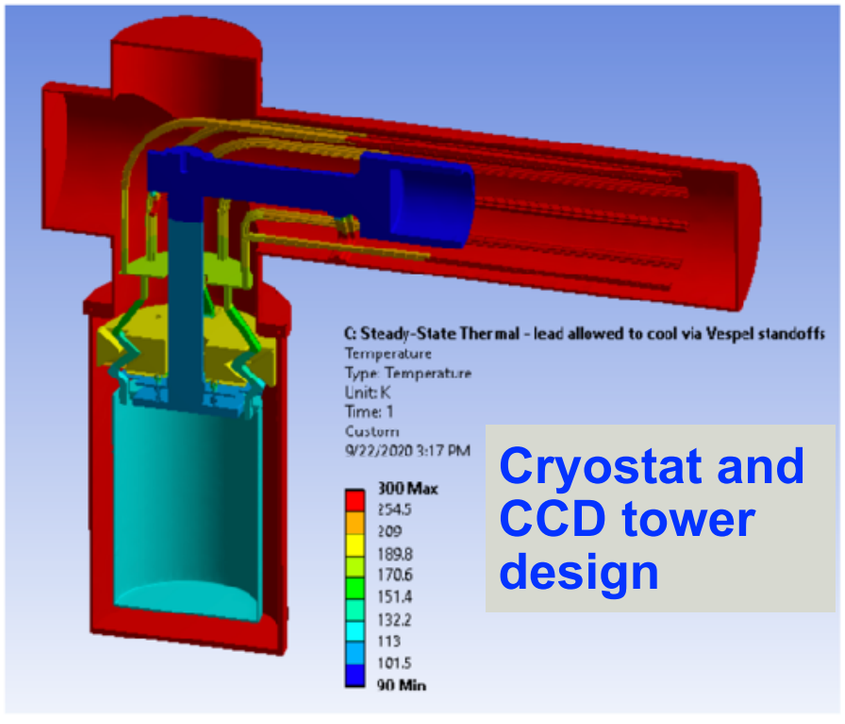
A few DAMIC-M highlights



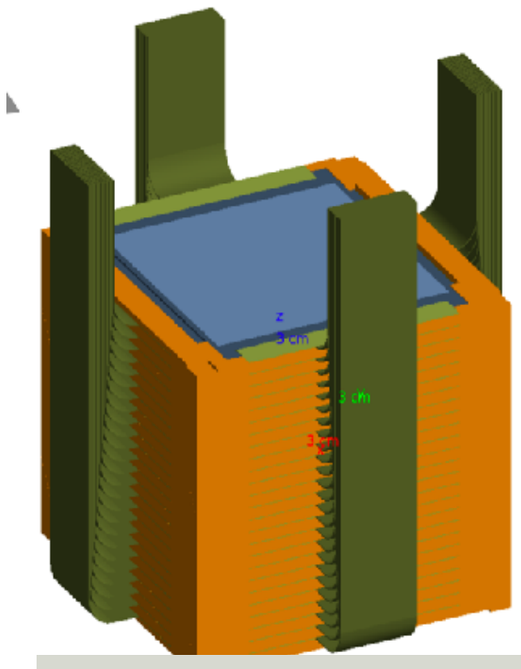
test of largest size Skipper
9 cm x 6 cm

e.f copper

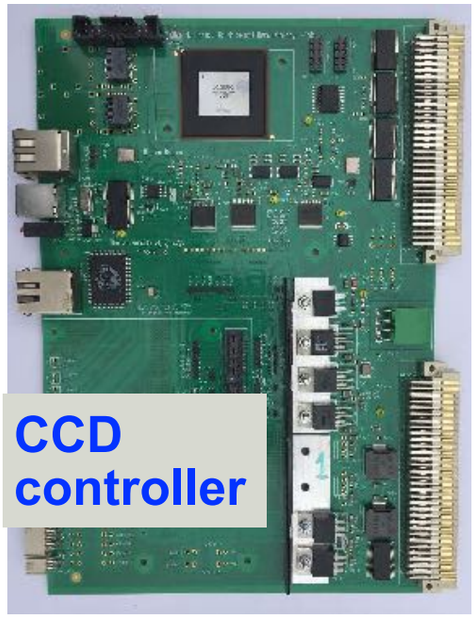




Cryostat and
CCD tower
design



CCD tower Geant4

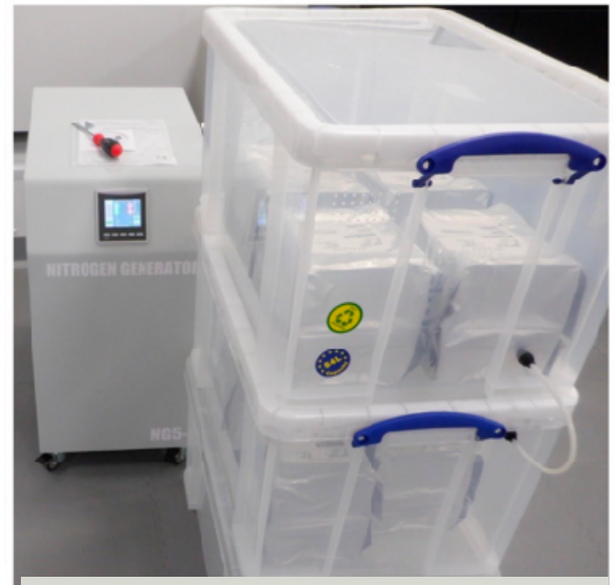


CCD
controller

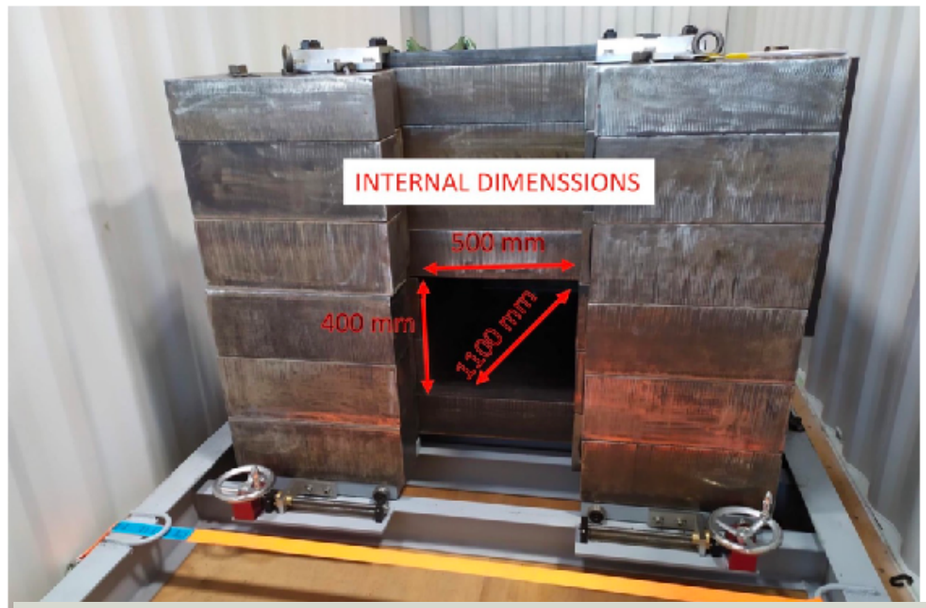
- DAMIC-M is now in advanced design and prototype testing phase

Status and Timeline

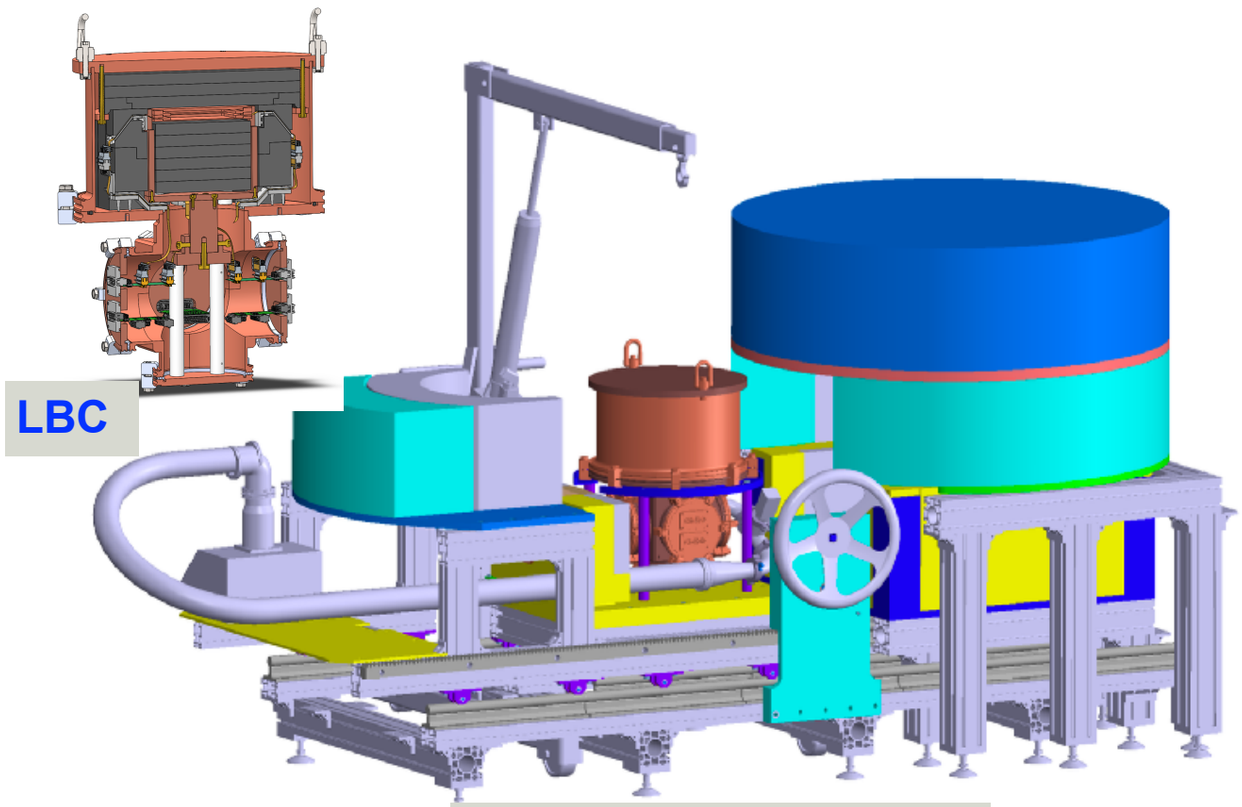
- Fabrication of pre-production CCDs started this month at DALSA, Canada
- Wafers for production CCDs currently at Boulby, UK, will be shipped in shielded container this fall
- The Low Background Chamber (LBC; ≃1dru background, few tens of g target mass) is in construction, installation first quarter of 2021



DAMIC-M wafers underground at Boulby



DAMIC-M shielded container (18 tons)

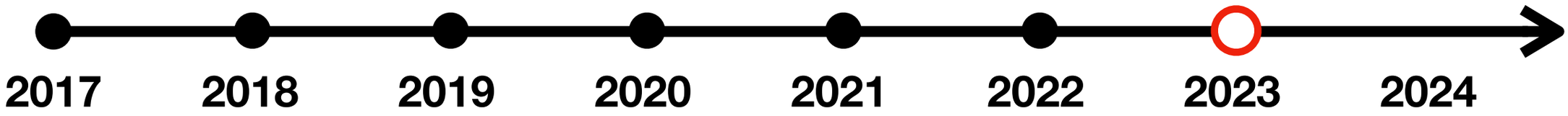


LBC

LBC and its shielding

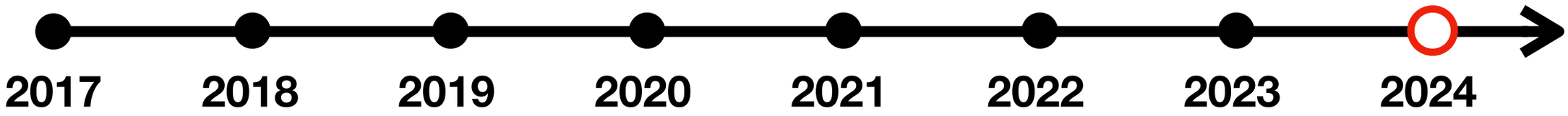
- LBC will provide early science data and validate components
- Installation and commissioning of full DAMIC-M detector in 2023

looking forward



- construct SENSEI at SNOLAB
- continue data-taking for SENSEI at SNOLAB
- **final analysis of 100-gram SENSEI data**
- **launch of 1-kg DAMIC-M at Modane**
- **complete R&D for Oscura**

looking forward



- construct SENSEI at SNOLAB
- continue data-taking for SENSEI at SNOLAB
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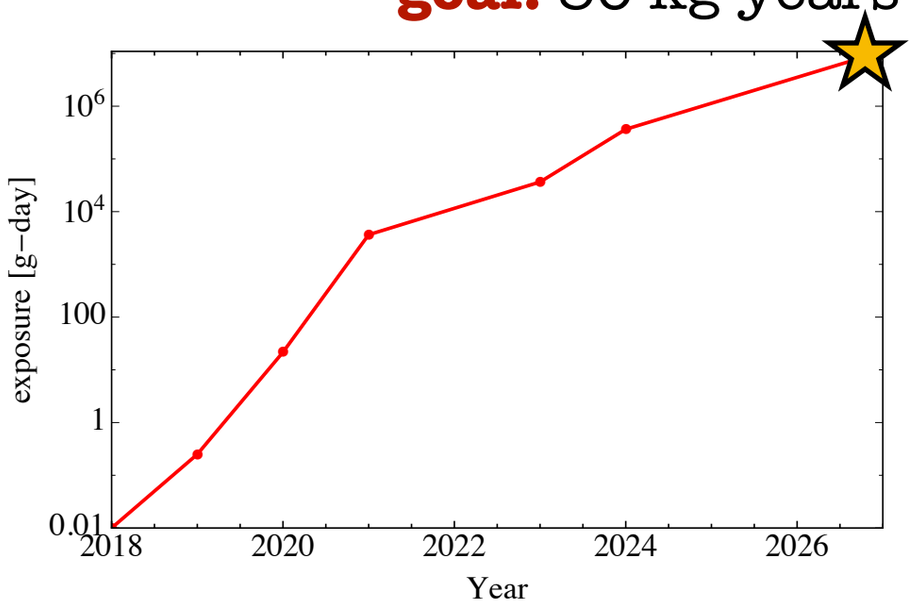
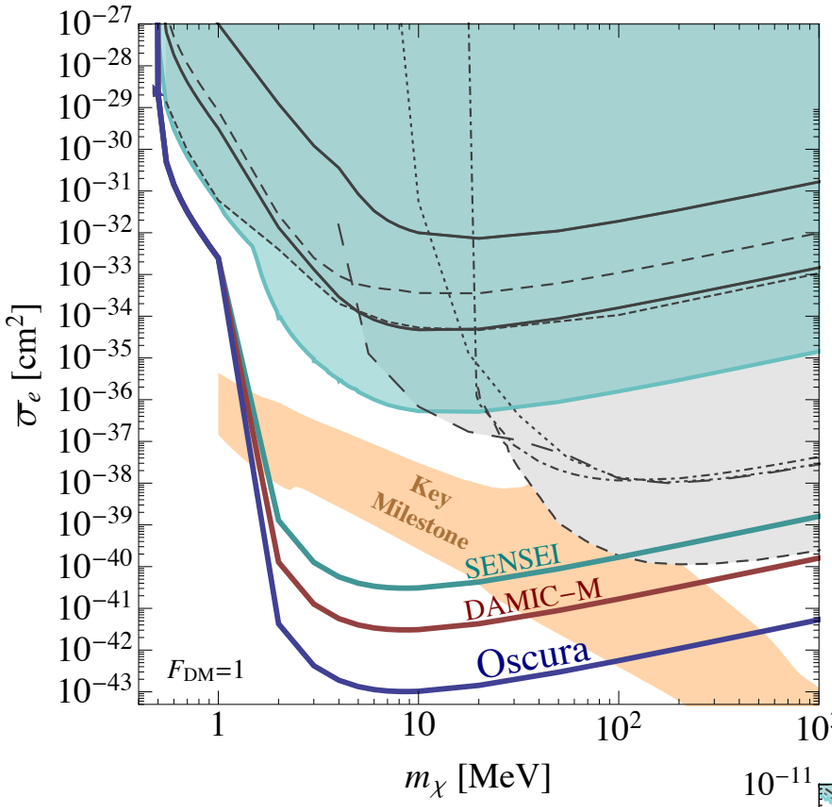
- complete R&D for Oscura
- **launch of 10-kg Oscura**

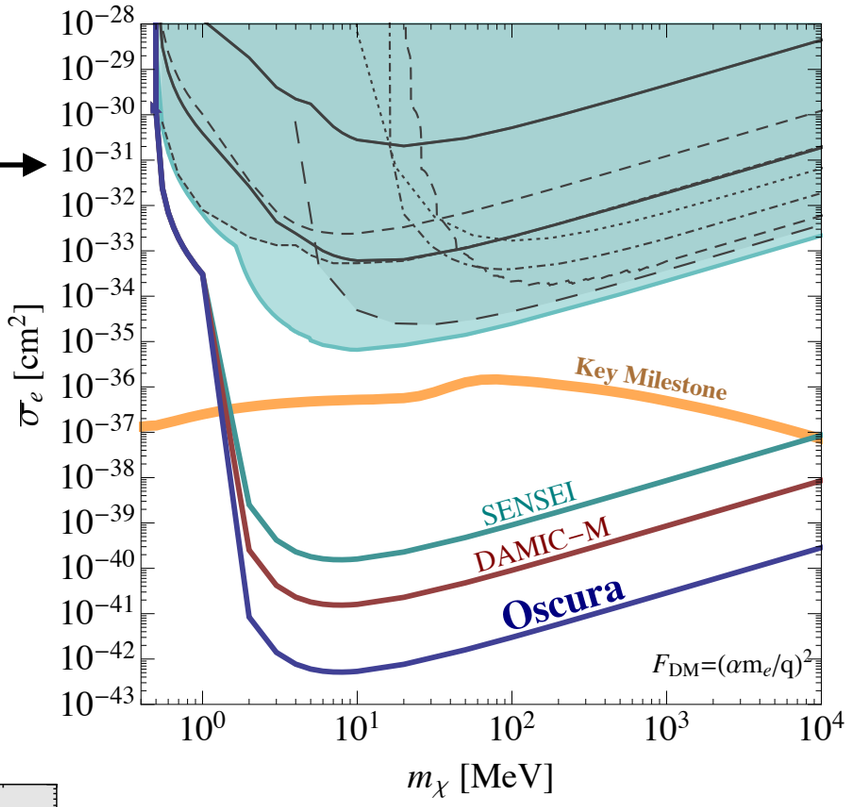
goal: 30 kg-years



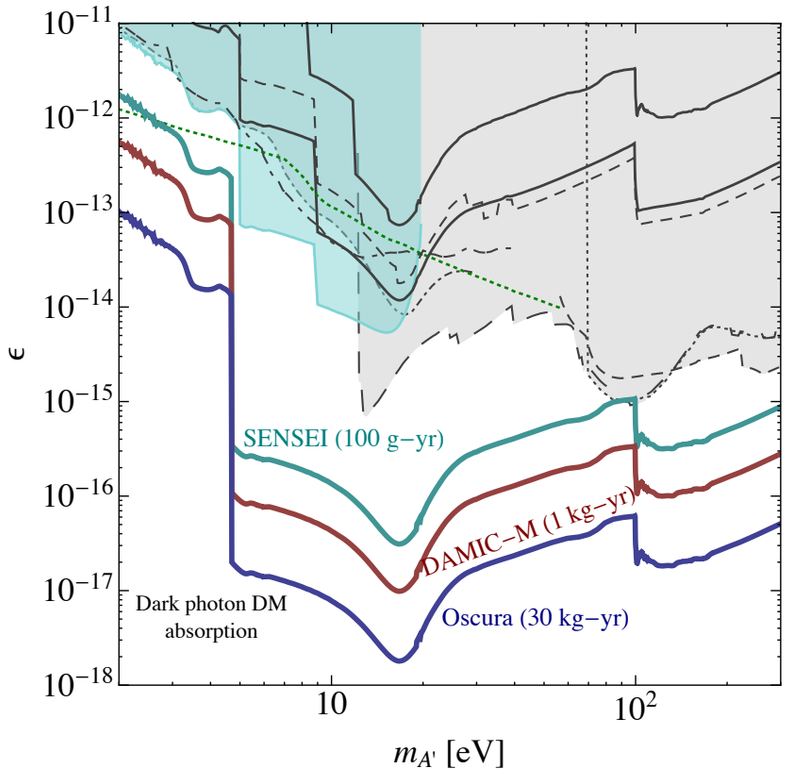
Projections

← Dark Matter-electron scattering →





Dark Photon DM absorption ↓



Oscura

Snowmass2021 - Letter of Interest

Status and plans for Oscura: A Multi-kilogram Skipper-CCD Array for Direct-Detection of Dark Matter.

Thematic Areas:

■ (CF1) Cosmic Frontier: Dark Matter: Particle Like
■ (IF2) Instrumentation Frontier: Photon Detectors

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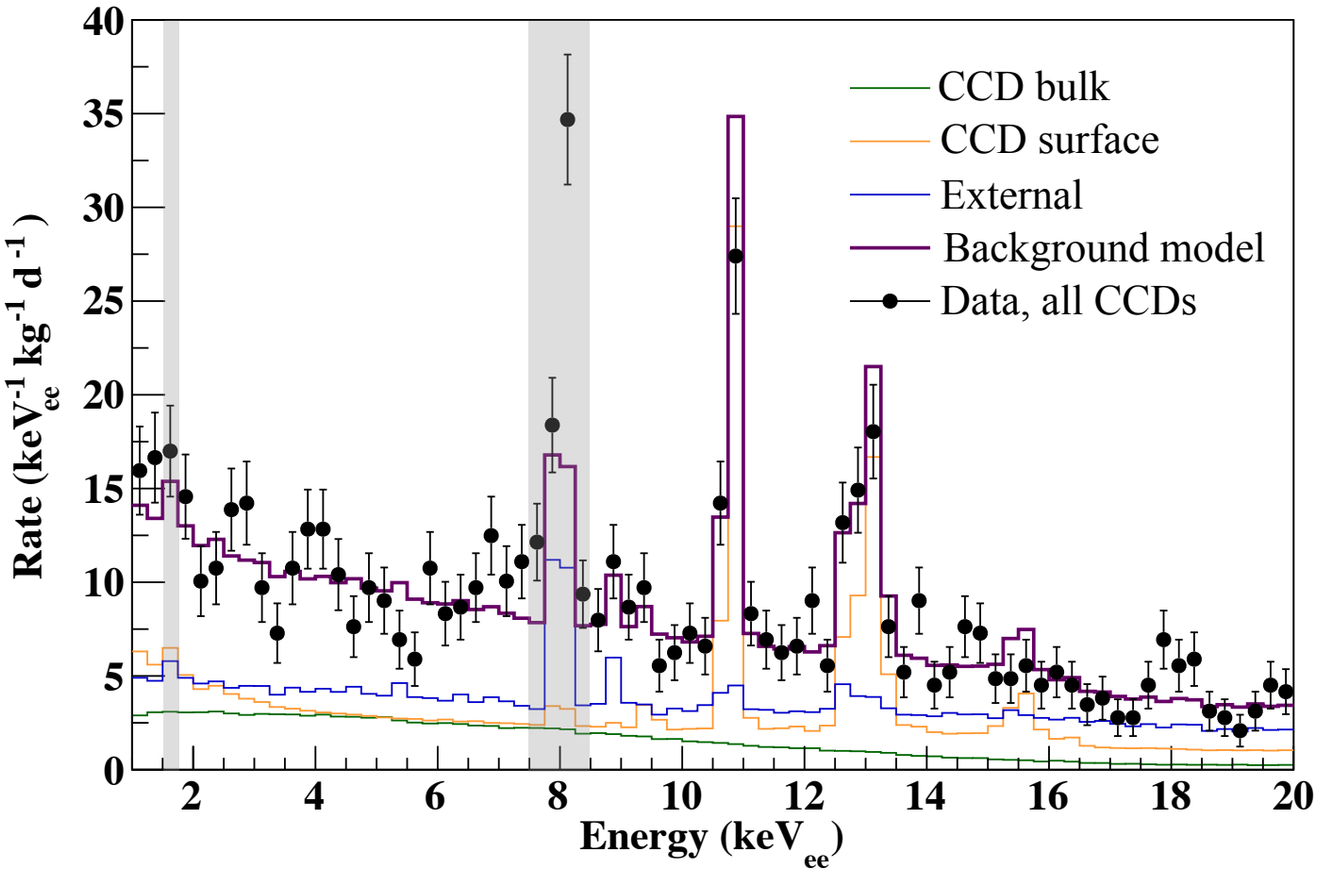
Abstract: Recent advances in silicon skipper-CCDs have demonstrated this technology as a powerful probe for sub-GeV dark matter by enabling ultra-sensitive searches for electron recoils from dark matter-electron interactions. World-leading results have already been produced by the SENSEI collaboration using a single skipper-CCD with an active mass of ∼2 gram. Pathfinder experiments using skipper-CCDs are planned for the coming years, with SENSEI-100 (∼100 g detector) and DAMIC-M (∼1 kg detector) expected to start operations during 2020 and 2023, respectively. We are preparing a white paper describing the status and plans of the Oscura R&D effort to develop a ∼10-kg skipper-CCD experiment for dark matter.

Brings together Si CCD community

Challenges

For DAMIC-M, we will need backgrounds ~ 0.1 counts/kg/keV/day
(two orders of magnitude better than where we are now)
For Oscura, we will need backgrounds < 0.01 counts/kg/keV/day
(three orders of magnitude better than where we are now)



DAMIC-SNOLAB [arXiv:2007.15622]

Mitigation techniques:

- validate and understand DAMIC-SNOLAB spectrum
- removing cosmogenic tritium
- remove radioactive impurities in CCD packaging and instrumentation
- control fabrication cleanliness for CCD-in-CMOS
- reject surface backgrounds
- develop nuclear/electron recoil discrimination

another challenge:
fabricating the CCDs
c.f. Miguel Sofo-Haro, Steve Holland

Snowmass2021 - Letter of Interest

Charge-Coupled Device Technology Development for Future Dark Energy and Dark Matter Studies

Thematic Areas: (check all that apply ☐/■)

■ (IF1) Quantum Sensors
■ (IF2) Photon Detectors
■ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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Javier Tiffenberg (Fermilab)

DAMIC-SNOLAB [arXiv:2007.15622]

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01 counts/kg/keV/day
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litigation techniques:
alidate and understand
AMIC-SNOLAB spectrum
moving cosmogenic tritium

Non-destructive readout in CMOS technology.

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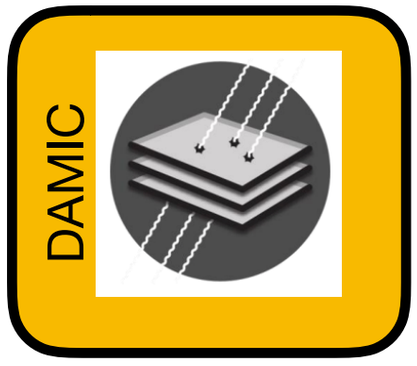
Authors: Fabricio Alcalde Bessia (CNEA), Gustavo Cancelo (FNAL), Angelo Dragone (SLAC), Juan Estrada (FNAL), Farah Fahim (FNAL), Guillermo Fernandez Moroni (FNAL), Christopher Kenney (SLAC), Dario Rodrigues (UBA), José Lipovetzky (CNEA), Julie Segal (SLAC), Miguel Sofo Haro (FNAL/CNEA).

c.f. Miguel Sofo-Haro, Steve Holland

Summary

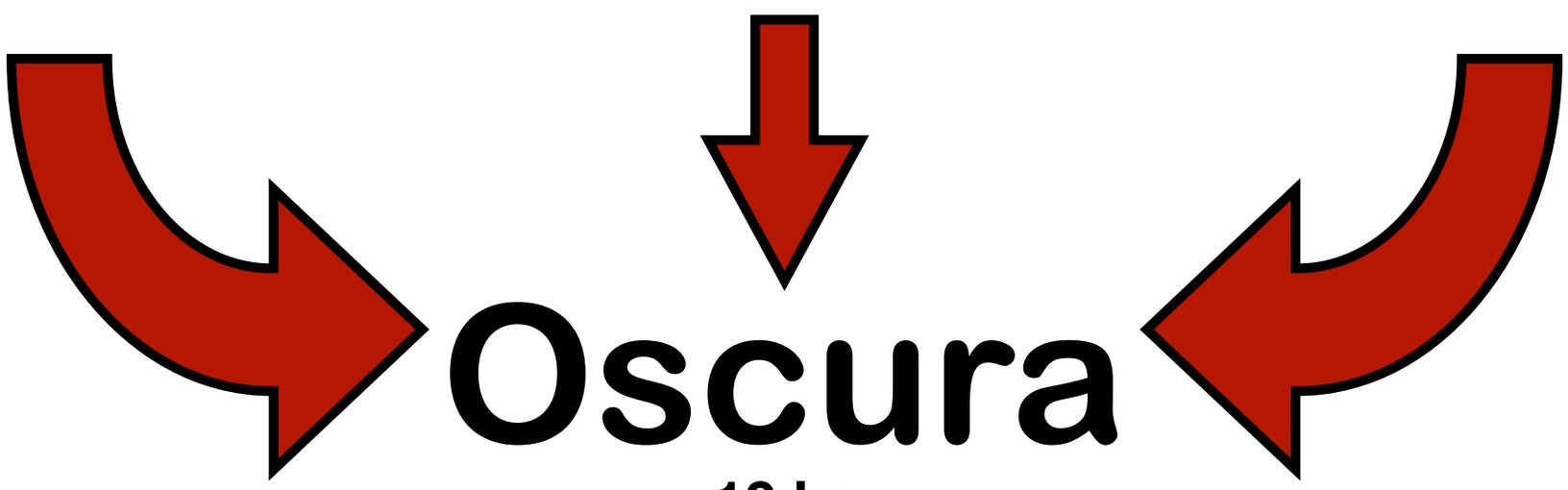


7 CCDs, 40 g

skipper

48 CCDs, 100 g

50 CCDs, 1 kg



Oscura

10 kg

R&D funded by DOE

will seek funding for 10-kg detector in 2023

collective effort of the silicon CCD DM community

will achieve unprecedented sensitivity to (sub-)GeV dark matter

thanks to

Dan Baxter
Alvaro Chavarria
Rouven Essig
Juan Estrada
Paolo Privitera

Sho Uemura

+ DAMIC collaboration
+ SENSEI collaboration
+ DAMIC-M collaboration

backup

Challenges

potential new source of background

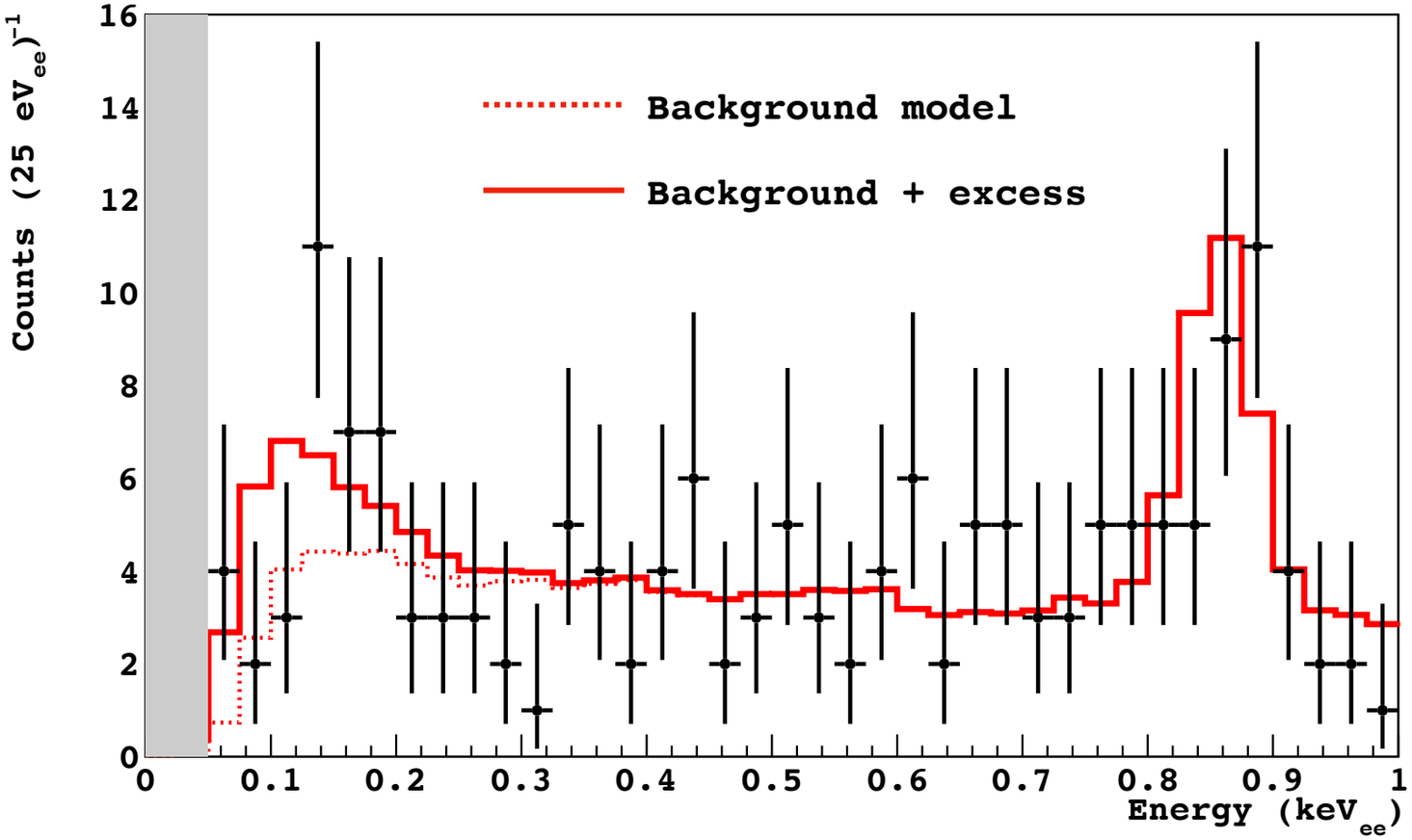


figure from A. Chavarria

priority to understand and characterize this excess!

DAMIC-SNOLAB [arXiv:2007.15622]