Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Sub-GeV dark matter searches with SENSEI

Nate Saffold, for the SENSEI collaboration

International Workshop on Double Beta Decay and Underground Science 23 (DBD23)

12/3/2023

sensei

The SENSEI collaboration

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Tel Aviv: L. Barak, M. Daal, E. Etzion, Y. Korn, A. Orly, T. Volansky

U. Oregon: A. Desai, T.-T. Yu

Buenos Aires: S. Perez, D. Rodrigues

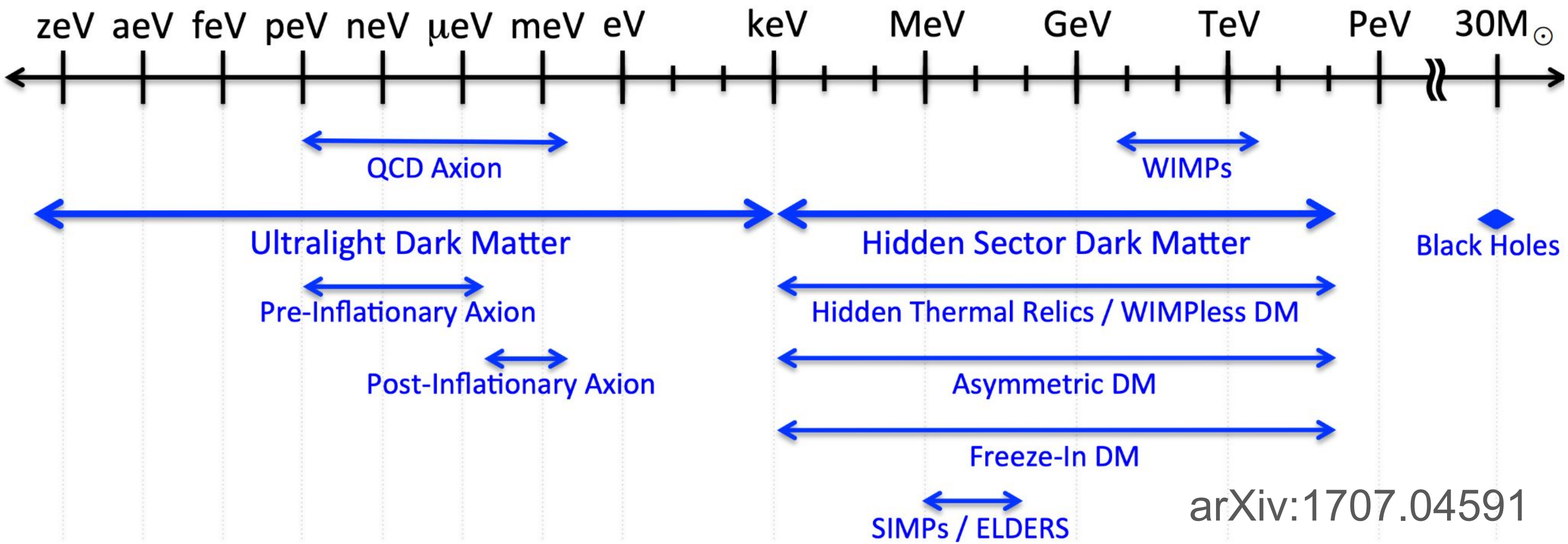
U.C. Berkeley: I. M. Bloch

SNOLAB: I. Lawson, S. Luoma, S. Scorza

LBNL: S. Holland

Fully funded by Heising-Simons Foundation + R&D support from Fermilab

The Dark Matter Landscape



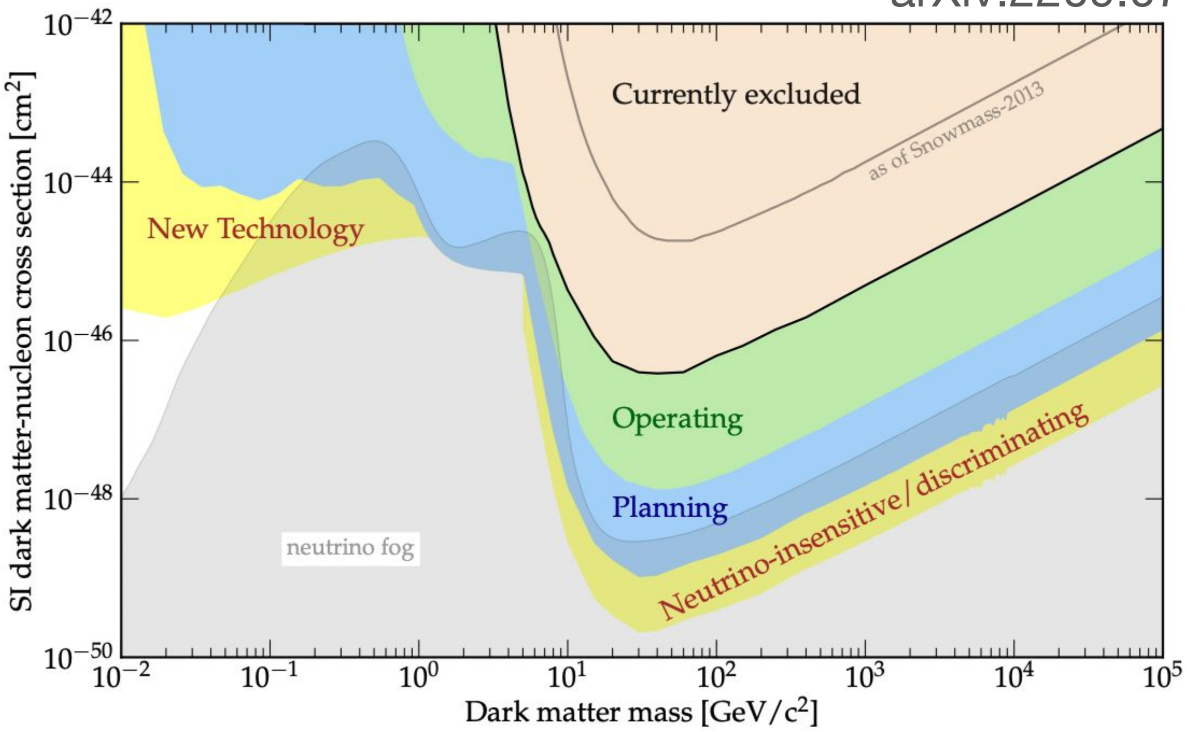
arXiv:1707.04591

Potential DM masses span many orders of magnitude

Have to choose where to look!

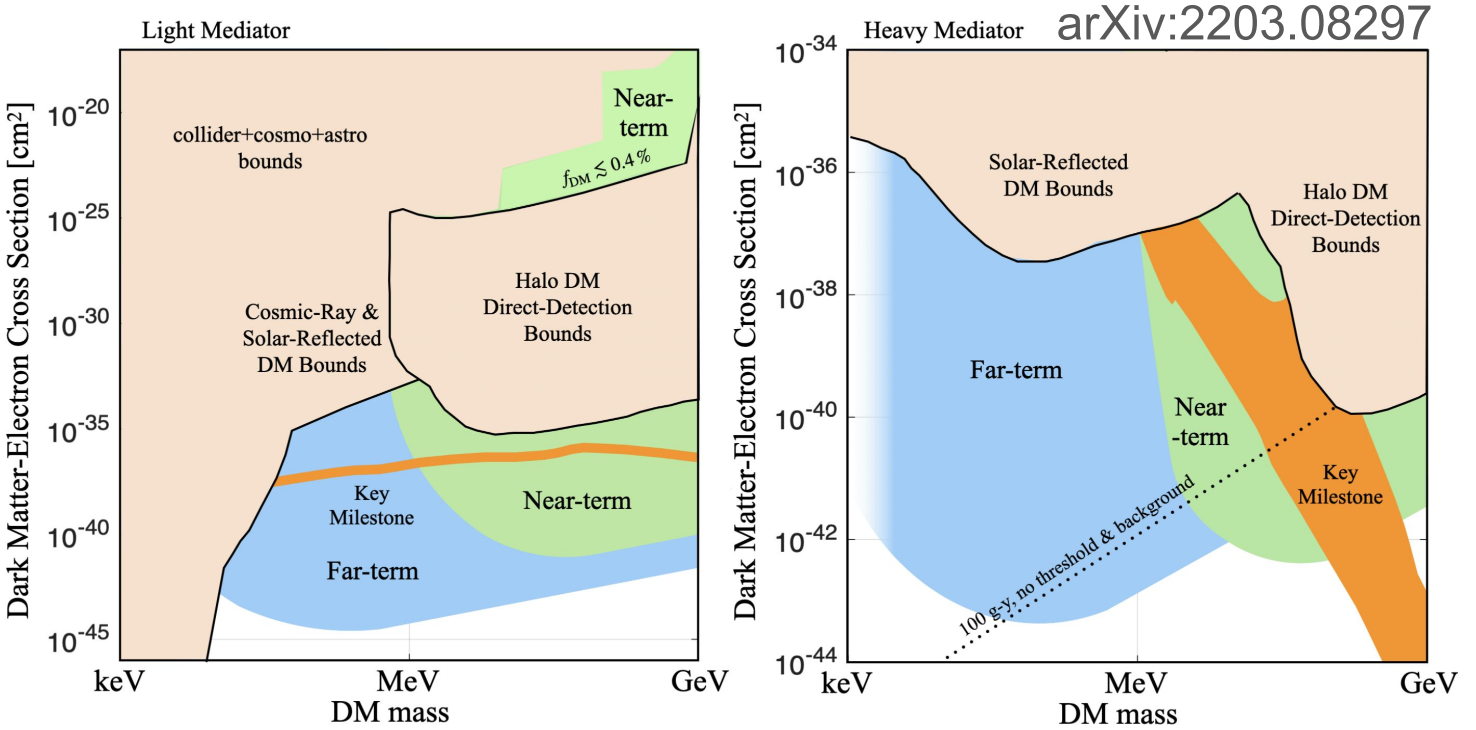
Dark Matter-Nucleon Parameter Space

arXiv:2209.07426



DM-nucleus scattering heavily constrained in the traditional WIMP mass range

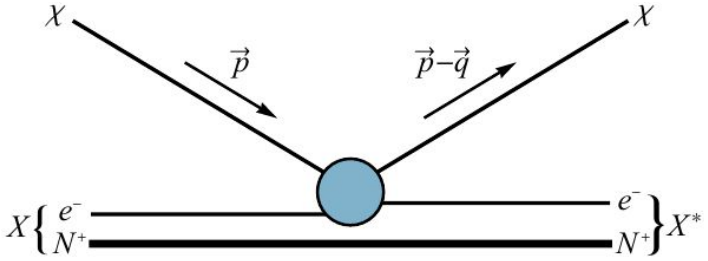
Dark Matter-Electron Parameter Space



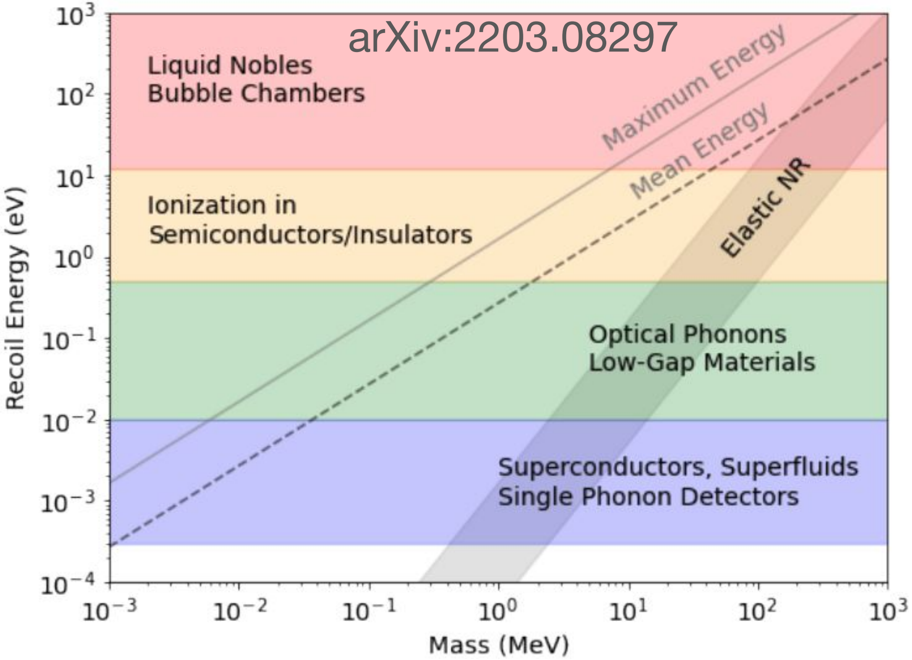
DM-electron interactions allow us to cast a wider net in the search for dark matter!

Probing Sub-GeV Dark Matter

- Energy deposited in target material (recoil energy) scales with DM mass
- For a given DM mass, **electron recoils** deposit more energy than nuclear recoils
- Need **detectors** with a **low energy threshold** to search for sub-GeV DM



Schematic of DM-electron scattering
arXiv:1509.01598



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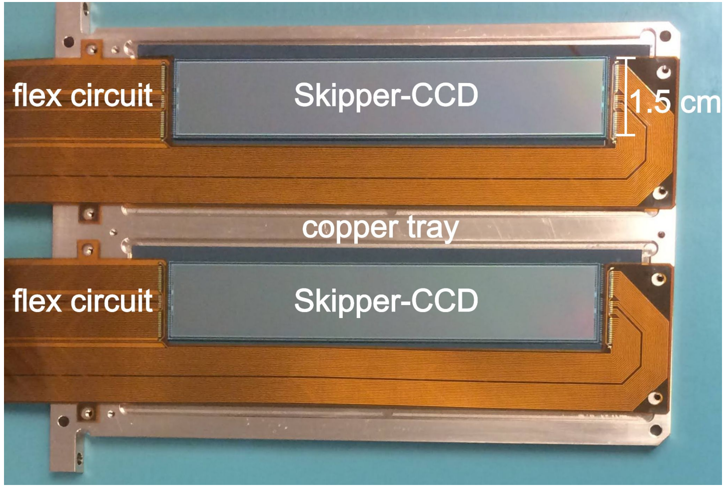
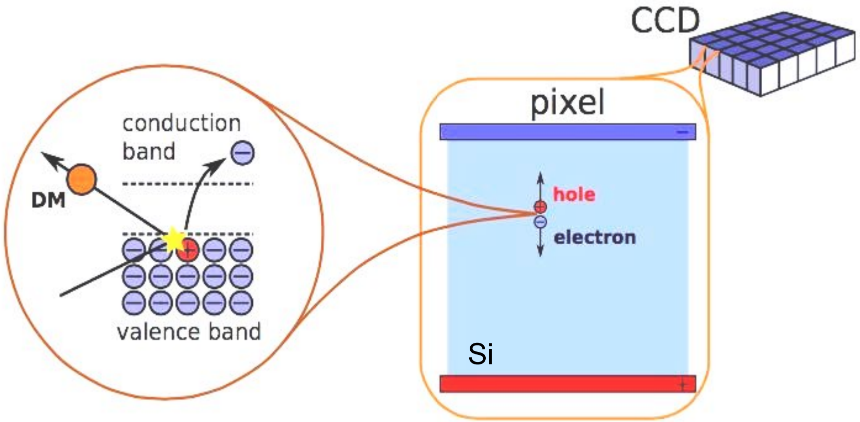
The SENSEI* experiment

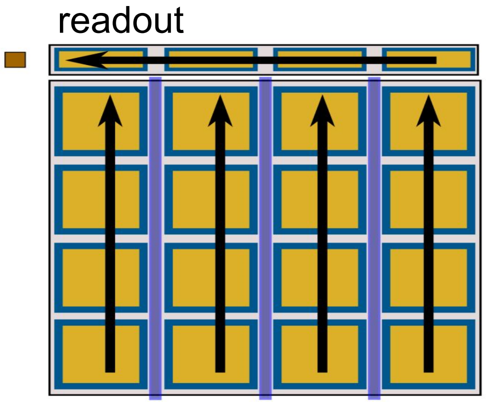
*Sub-Electron-Noise Skipper-CCD Experimental Instrument

Silicon charge-coupled devices (CCDs) w/ Skipper amplification (designed by LBNL):

- Energy threshold of Si bandgap (~1.1 eV)
- Low dark current (~10^{-4} e^-/pix/day)
- Sub-electron (~0.1e^-) readout noise







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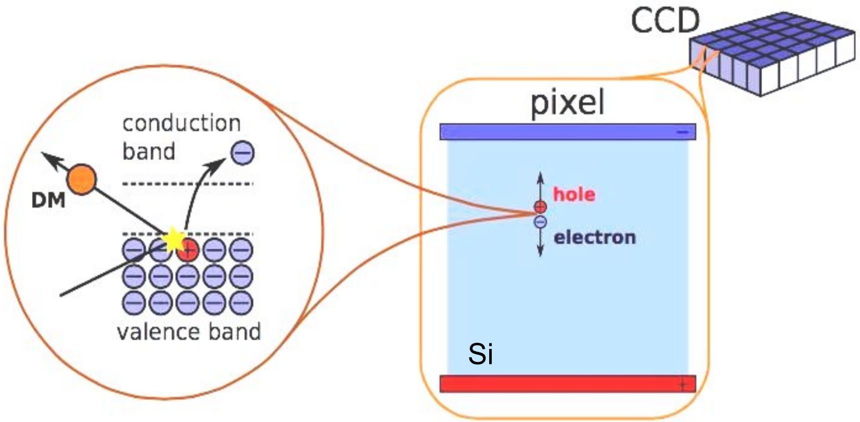

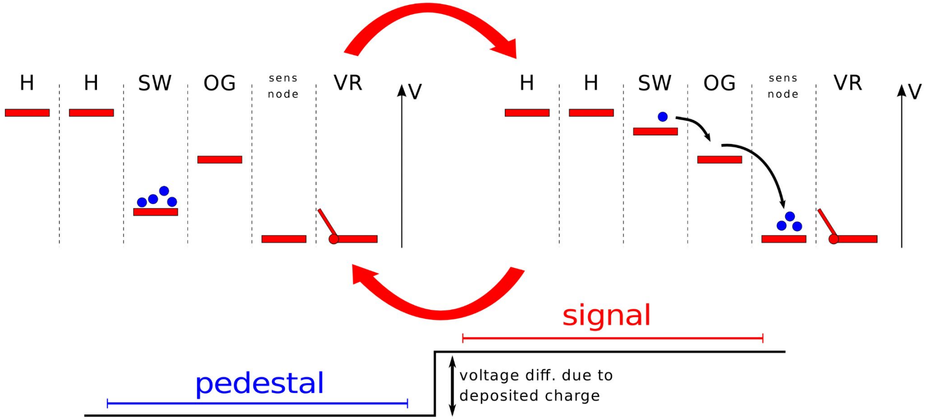

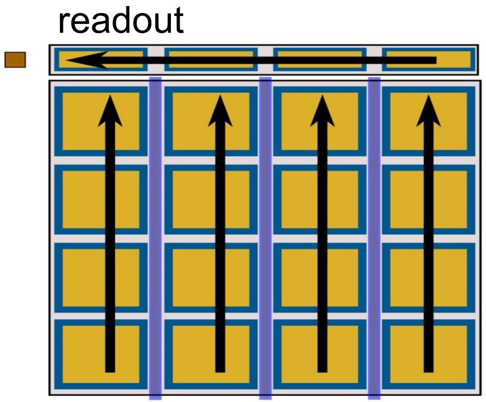

Skipper amplifier makes repetitive, non-destructive measurement of the pixel charge, reducing noise to sub-electron levels

The SENSEI* experiment

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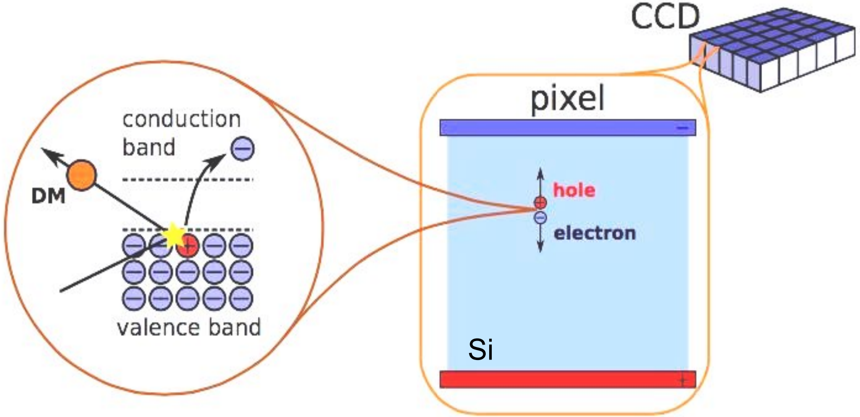
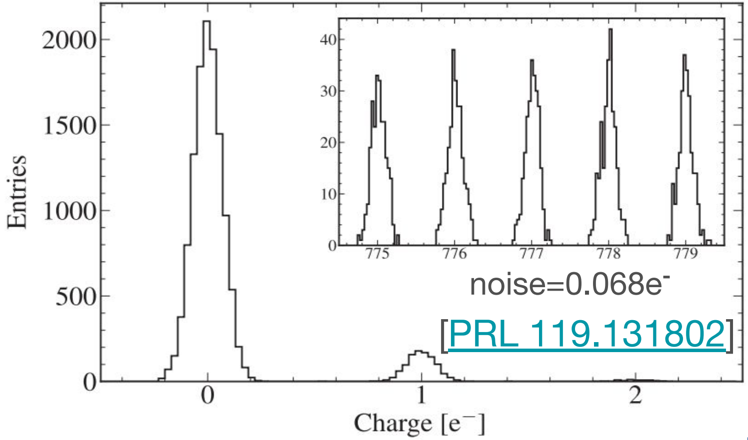
Low threshold enables low-mass searches:

- Electron scattering of 1-1000 MeV DM
- Nuclear scattering of 1-1000 MeV DM via Migdal effect
- Absorption of 1-1000 eV DM
- Scattering of milli-charged particles
- Etc…

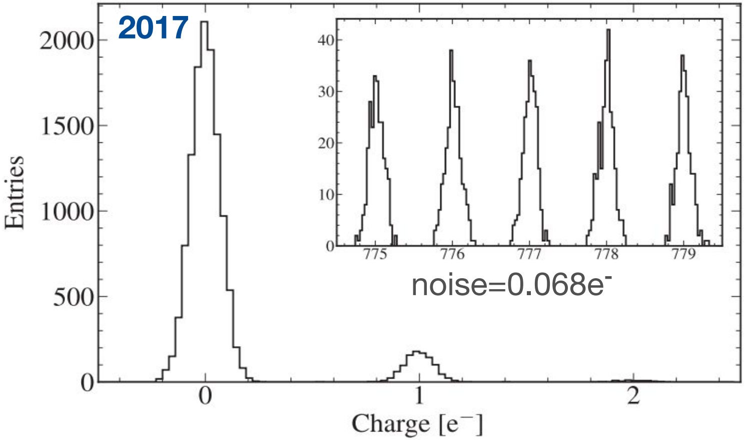


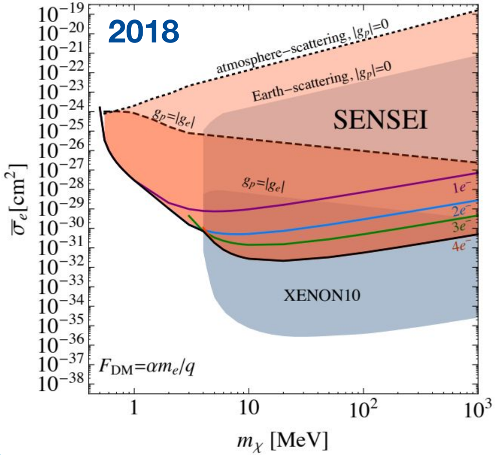


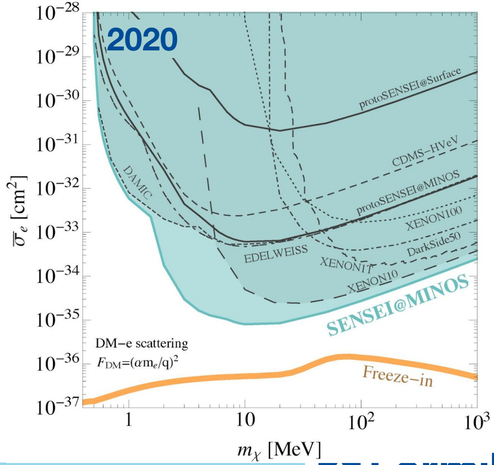
[PRL 119.131802]

History of SENSEI results

2017	Demonstration of 0.068e^- noise in SENSEI prototype [PRL 119.131802]
2018	DM search with surface run of SENSEI prototype CCD [PRL 121.061803]
2019	DM search with underground run of SENSEI prototype CCD [PRL 122.161801]
2020	DM search with underground run of SENSEI science-grade CCD [PRL 125.171802]







SENSEI in JAHEP High Energy News

- Thanks to Sho Uemura, SENSEI overview and 2020 dark matter result is presented in JAHEP High Energy News (Vol. 41, No. 1 2022/04.05.06)

高エネルギーニュース
HIGH ENERGY NEWS

ライトダークマターを探る SENSEI

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上 村 翔
suemura@fnal.gov

2022 年 (令和 4 年) 2 月 23 日

1 はじめに

10 年前の話では，ダークマターの正体を粒子と思えば第一候補は WIMP ダークマターだったであろう。現在では，WIMP 以外のダークマター理論が徐々に有力視されている。WIMP 検出実験が大規模化するうち，アクシオンやライトダークマターの探索に興味が増す時代である。

ライトダークマターとは 1 GeV より質量の小さいダークマター粒子を指す。ライトダークマター理論は一般的にダークセクターにもとづく。つまり，ライトダークマターは標準模型以外のゲージ相互作用（ダークフォトンなど）を感じる。あるいは，ダークフォトンなどのゲージボソンがダークマター粒子かも知れない。ライトダークマター粒子は質量が小さいので，数密度が高いであろう。従って，比較的小規模の検出器でも良い感度が可能である。

WIMP 探索は原子核反跳を用いるが，ライトダークマター探索は主にライトダークマターの電子反跳を探す。その理由はキネマティクスである。ライトダークマ

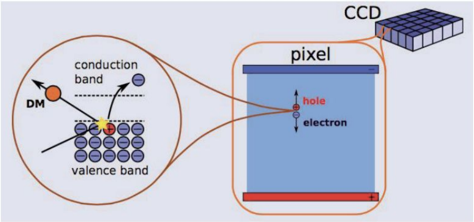


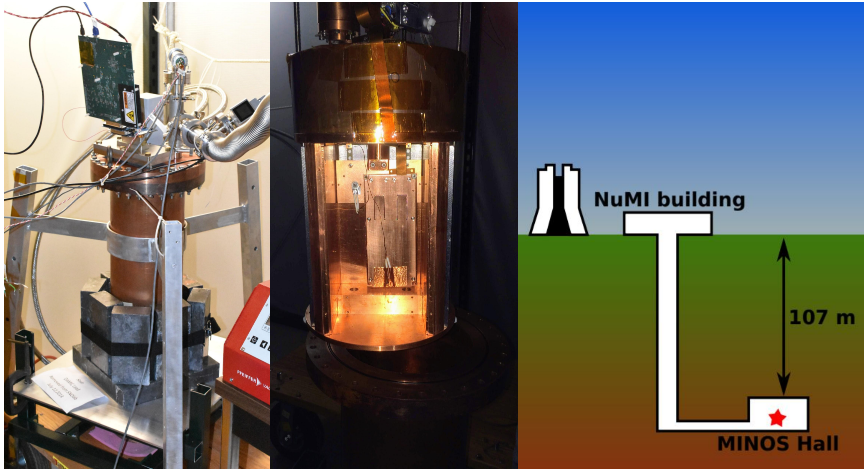
図 1: CCD 検出器の原理。CCD のシリコンはダークマター粒子の電子反跳エネルギーを電子-ホールペアに変換する。そのホールはバイアス電圧によって CCD の表面のピクセルに引き込まれて，のち読み出される。

2 Skipper-CCD

CCD はイメージセンサーとして長らく利用されているが，SLAC の SLD バーテックス検出器 (VXD) など，素粒子物理学でも活躍の歴史がある。基本的に，CCD はフォトダイオードの表面の酸化膜上に電極を設け，多数の MOS キャパシタに分割したものである。これらの

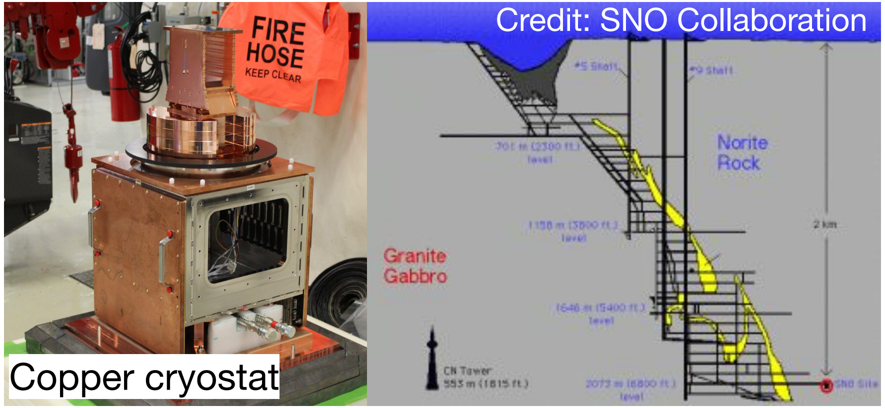
Current status: two science-capable SENSEI setups

SENSEI@MINOS



One CCD module installed in copper cryostat

SENSEI@SNOLAB



Up to 48 CCDs installed in copper cryostat

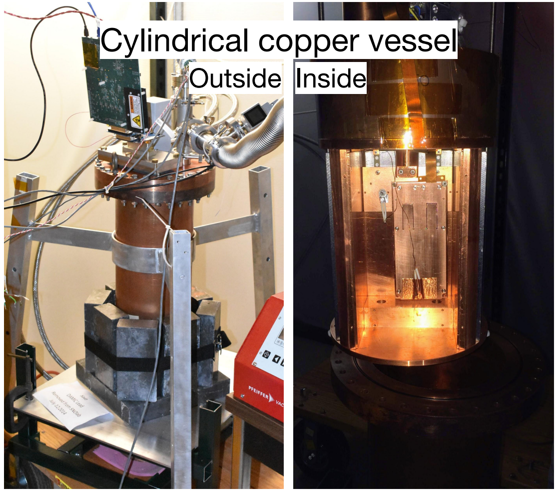
Will show results from *both* detectors today

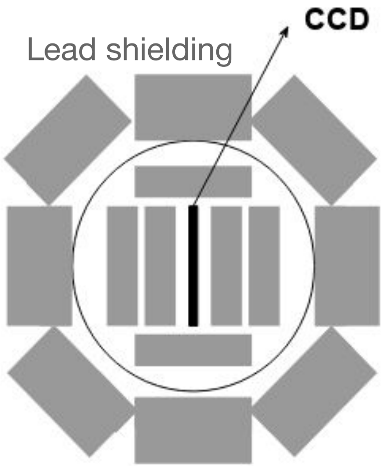
SENSEI@MINOS

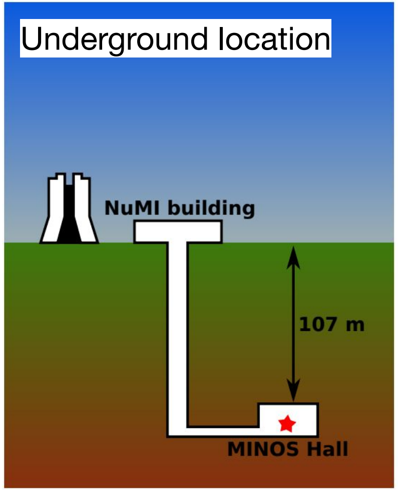
One CCD module installed in copper cryostat: ~1.925 g, operated at 135 K

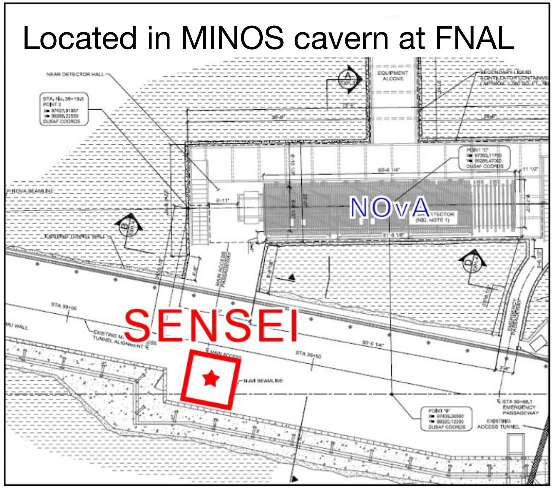
Shielding: inner and outer layers of lead shielding, underground site at FNAL in MINOS cavern (~107 m)

Intersects with NuMI beamline





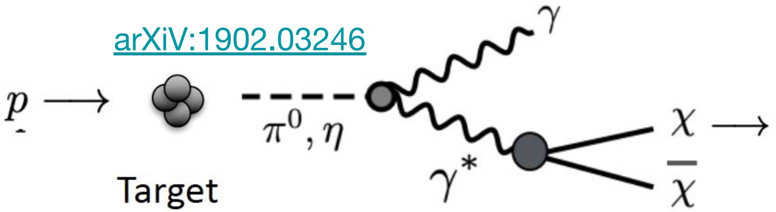


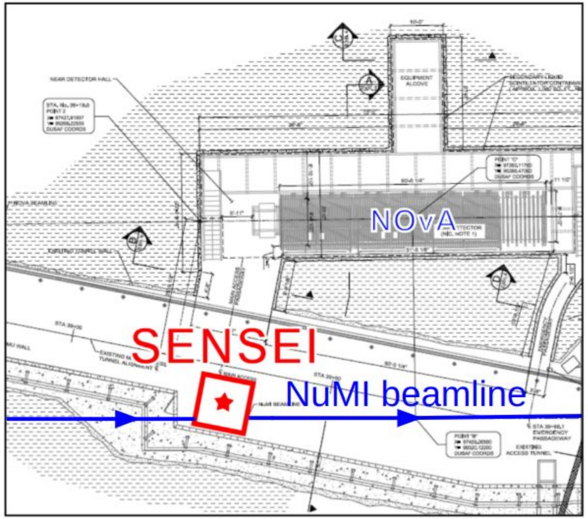


Milli-charged particle (mCP) search in SENSEI@MINOS

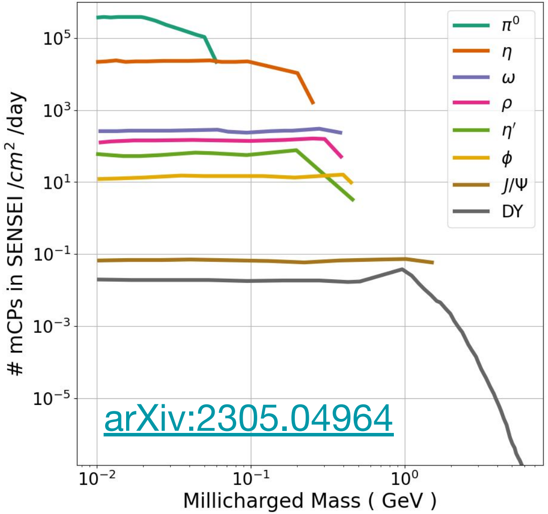
Proton collisions w/ fixed target can produce mCPs collinear w/ NuMI beamline:

arXiV:1902.03246





Using production rates accepted by SENSEI@MINOS…



… and data from SENSEI@MINOS:

	$1e^-$	$2e^-$	$3e^-$	$4e^-$	$5e^-$	$6e^-$
Efficiency	0.069	0.105	0.325	0.327	0.331	0.338
Exp. [g-day]	1.38	2.09	9.03	9.10	9.23	9.39
Obs. Events	1311.7	5	0	0	0	0

Using same analysis as PRL 125.171802, but extending up to $6e^-$

Milli-charged particle (mCP) search in SENSEI@MINOS

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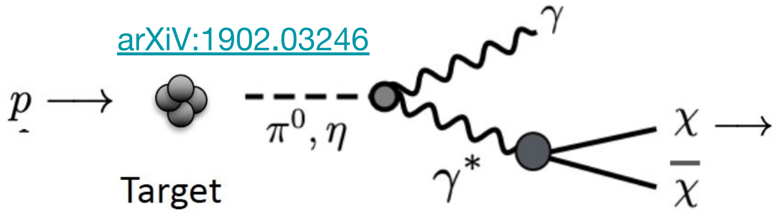
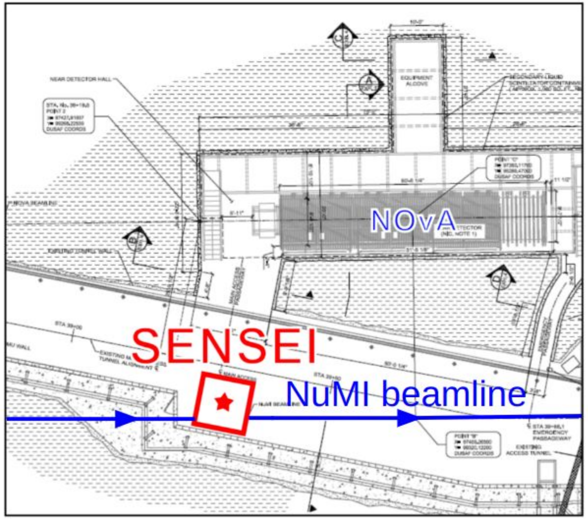
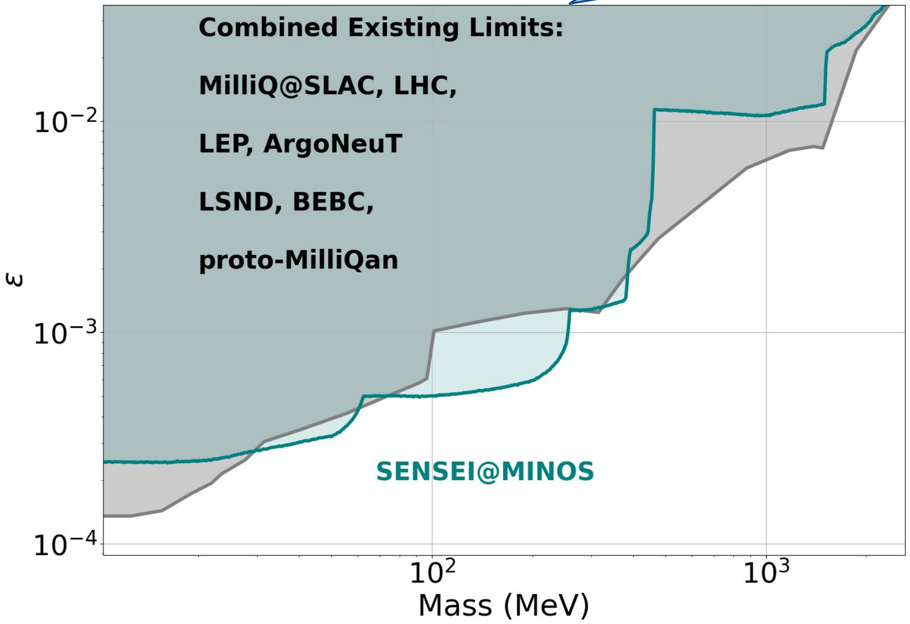




World-leading limits around 100 MeV!

arXiv:2305.04964



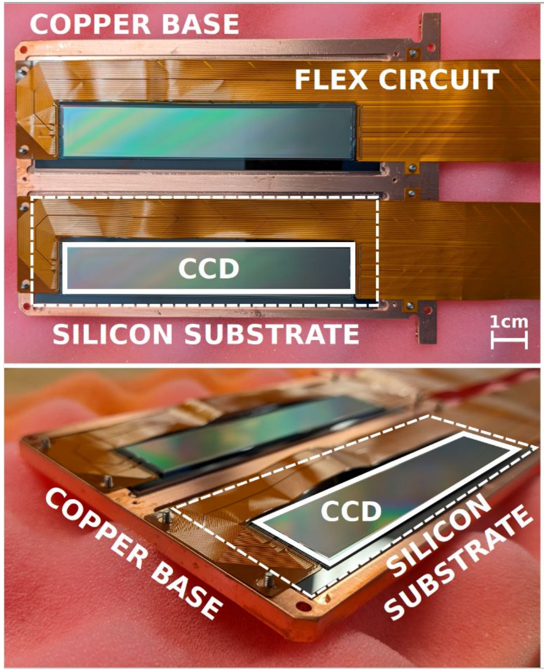
Significant potential for future mCP searches with CCDs

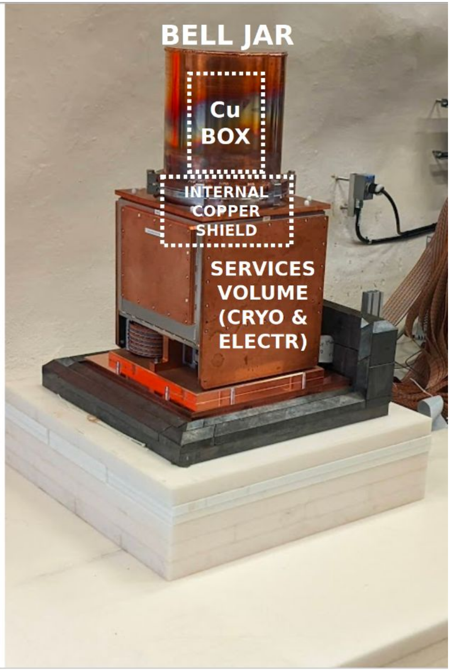
SENSEI@SNOLAB setup

Copper trays fit two to four ~2 g CCDs

Copper box fits 12 copper trays

Vacuum pump (< 2×10^{-4} mbar)
Cryocooler + heater (~140 K)

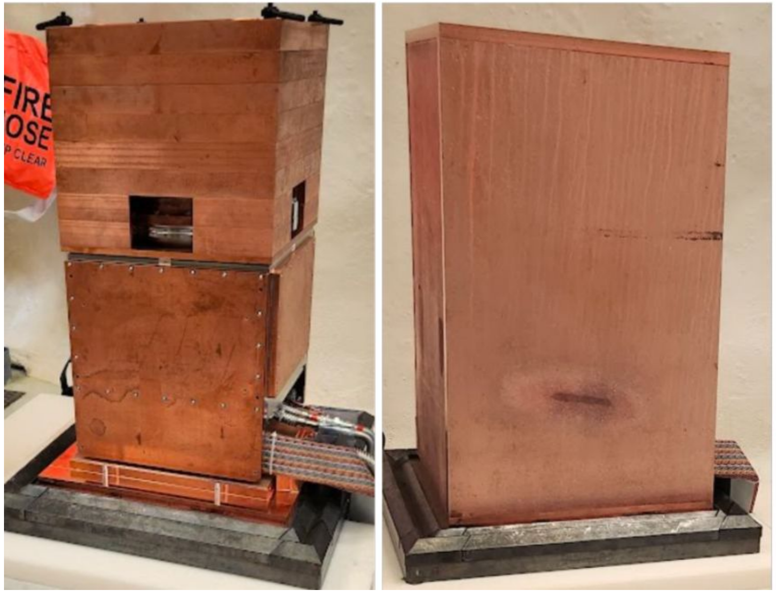




Each CCD is 6144 x 1024 pixels (15 µm pitch) and 675 µm thick

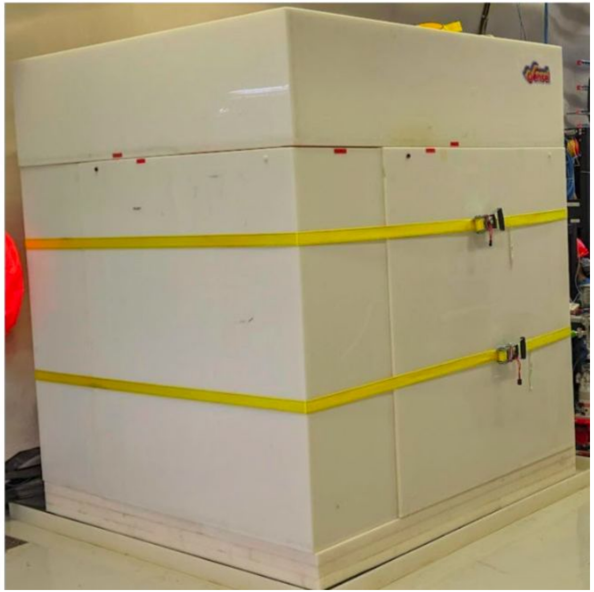
SENSEI@SNOLAB setup

Two layers of copper shielding



Three inches of lead shielding

42 inches of polyethylene and water shielding



SENSEI@SNOLAB first science run

- Six CCDs (~13 g) used for first science run
- Installation: 4-7/2021
- Commissioning: 10/2021-8/2022
- Science: 9/2022-4/2023

Fully assembled and shielded SENSEI@SNOLAB

Many thanks to the SNOLAB staff for their support!!

CCDs are operating well!

20 hour exposures: 129 images, no binning, ~50% hidden for bias mitigation

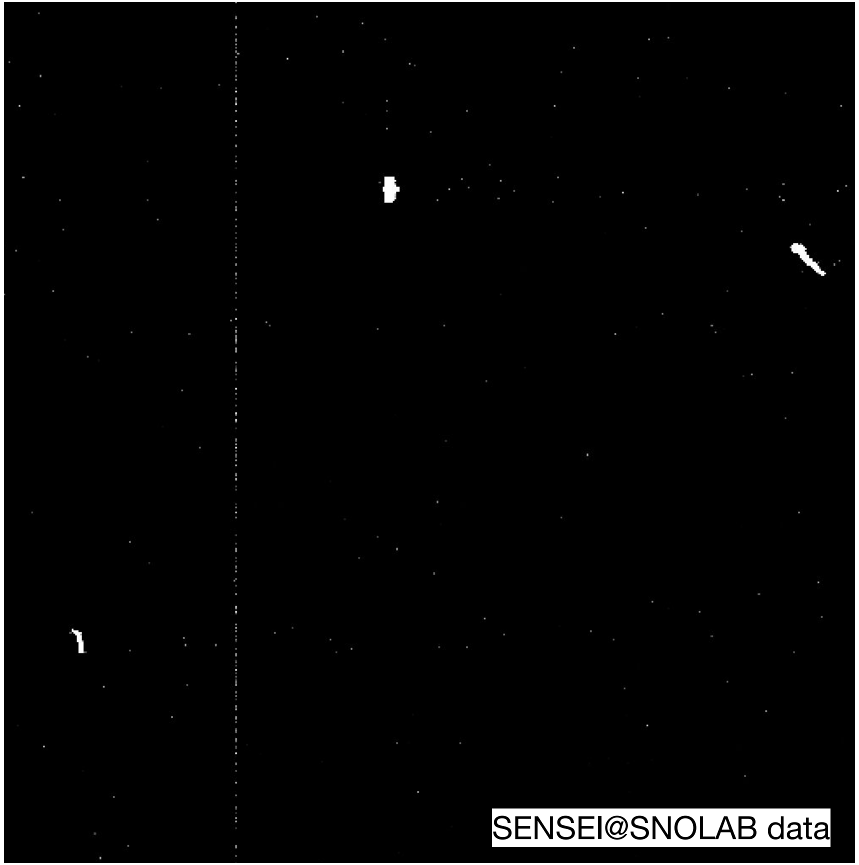
300 Skipper samples → 7.3 hours readout, noise of **~0.14 *e*$^{-}$**

3 hour "clear" following each image to sweep charge from active area

Temperature variations of **135 K-155 K** due to failing cryocooler

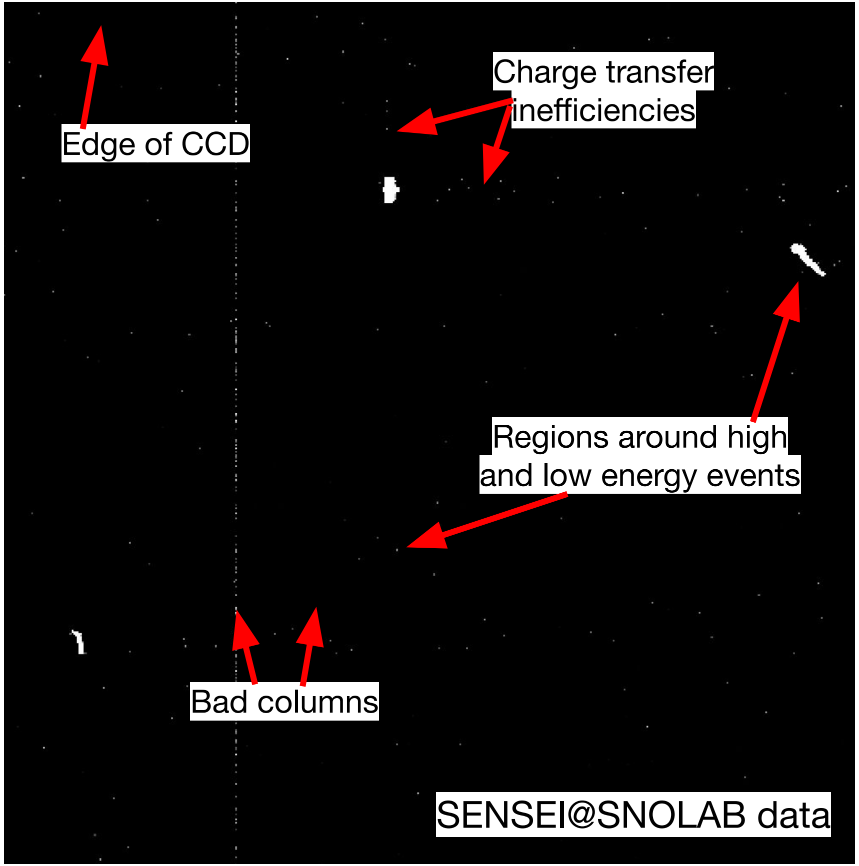
1 *e*$^{-}$ density (after cuts): **~2 x 10^{-4} *e*$^{-}$/pixel**

- No dark rate measurement performed



Cluster reconstruction + selection

1. **Data quality cuts to remove anomalous images**
2. **Cluster any contiguous pixels ≥1 e^-**
3. **Apply masks to images to remove:**
   - Electronic noise
   - Cross-talk
   - Edges of CCDs
   - Bad pixels and columns
   - Serial register events
   - Charge transfer inefficiencies (CTI, size varies by charge)
   - Region surrounding any ≥1e^- pixels (size varies by charge)
4. **Remove clusters with any pixels overlapping a mask**
5. **Remove individual high-background cluster shapes**



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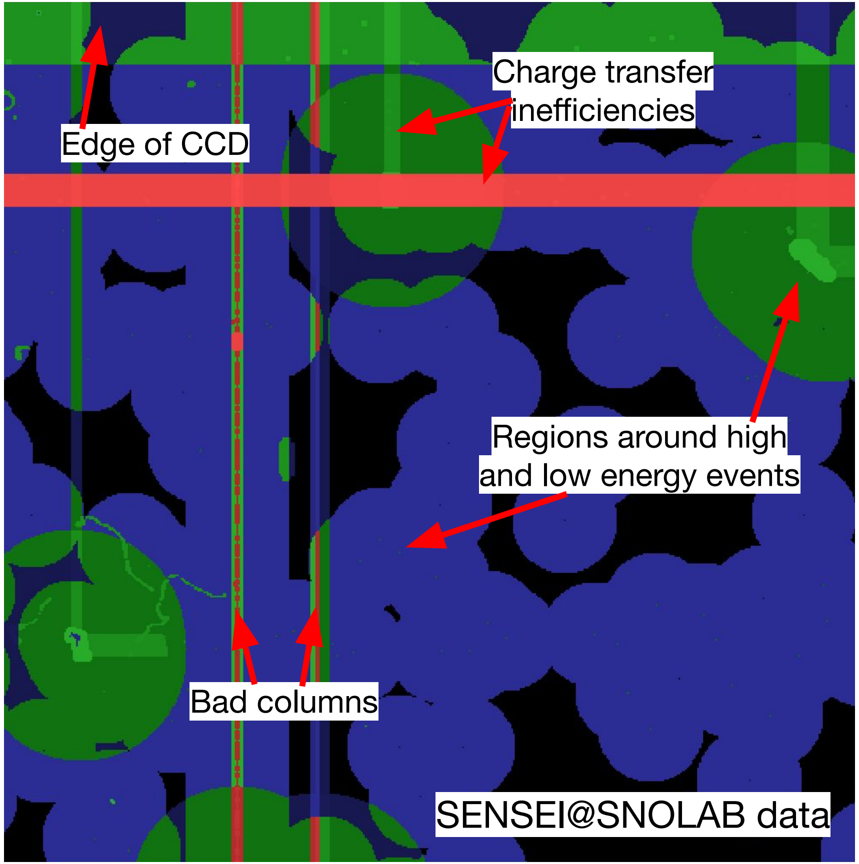


Dark matter-electron scattering limit setting

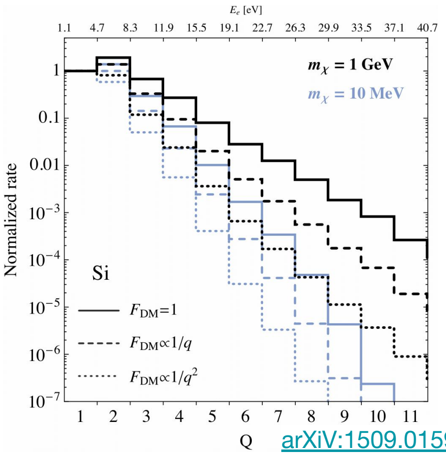
Signal model: generate expected DM events per electron channel using QEdark (upper right) and other calculations given astrophysical parameters from PhystatDM and ionization model (lower right)

Bin by shape: split each electron channel into bins based on number of pixels and/or shape of cluster

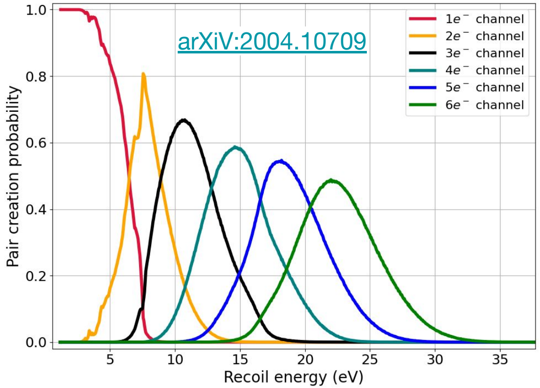
Exposure: determine effective exposure for each bin using Monte Carlo simulation given actual masks and charge diffusion parameters measured in SENSEI@MINOS

Backgrounds: calculate expected coincidence background in each bin given measured 1e^- density

Limit: Determine a combined likelihood over all bins to set 90% C.L. upper limits in cross section-DM mass parameter space



arXiV:1509.01598



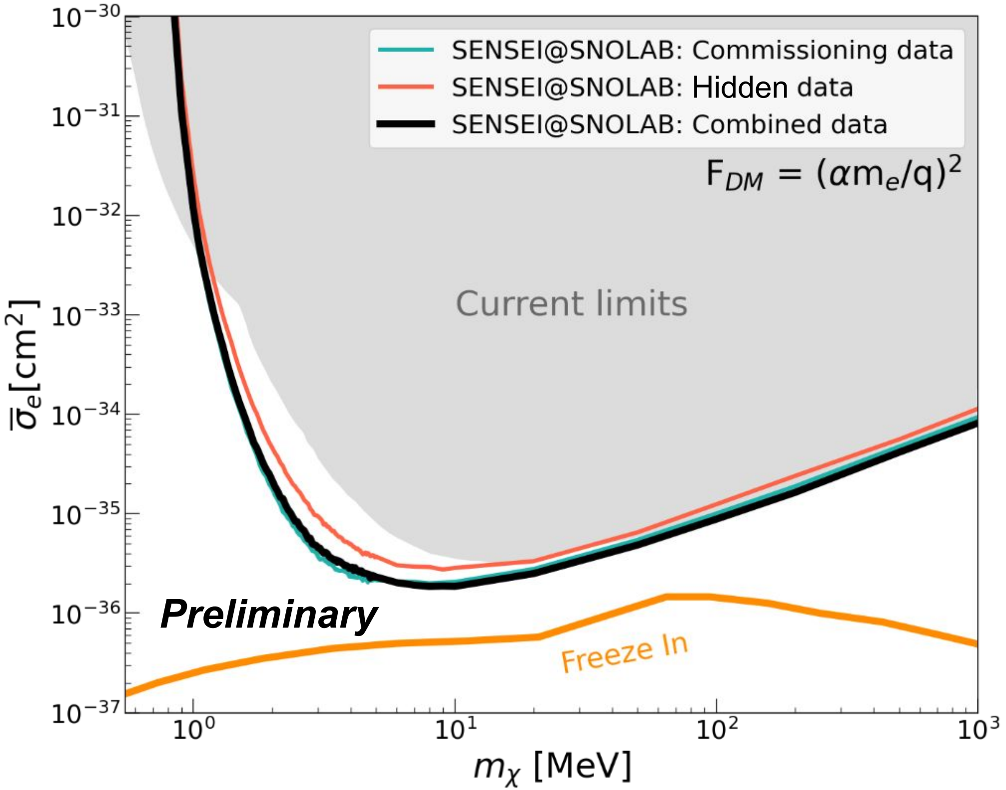
First SENSEI@SNOLAB results: DM-electron scattering

Data: 45 commissioning images, 37 hidden images, 2-10 e^- channels

Exposure: combined datasets amount to ~70 g-days per electron channel with current masks

Three limits: hidden dataset, commissioning dataset, and combined commissioning + hidden exposure

Paper in preparation to present full results



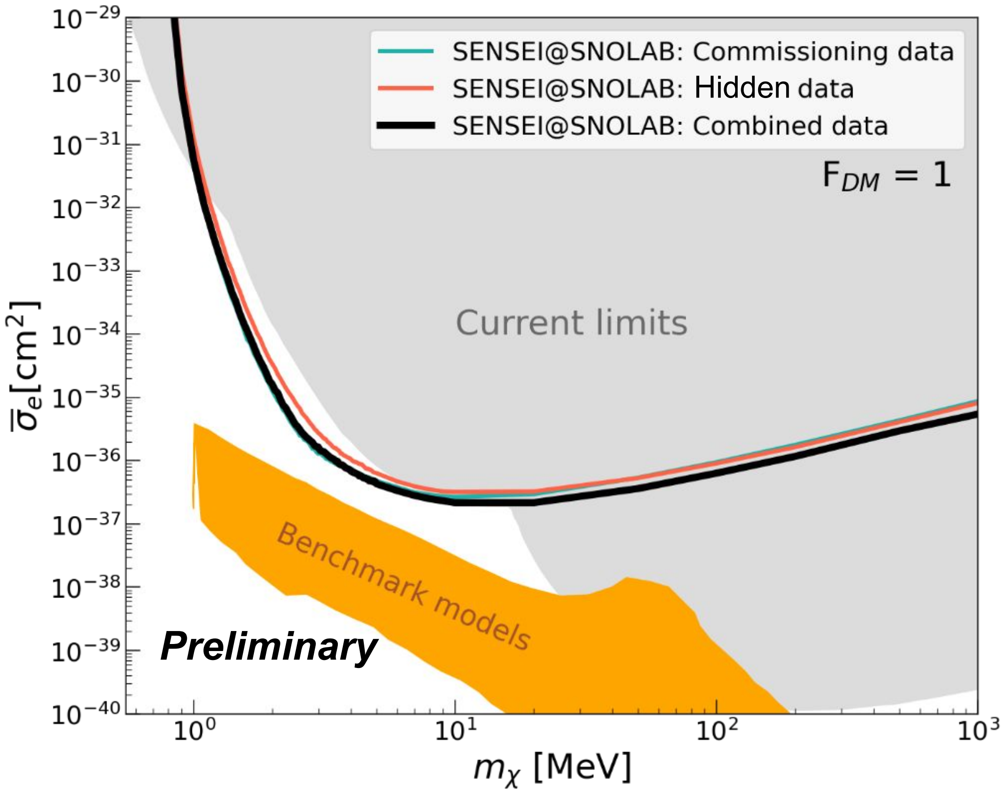
First SENSEI@SNOLAB results: DM-electron scattering

Data: 45 *unblinded* commissioning images, 37 blinded images, 2-10 e^- channels

Exposure: combined datasets amount to ~70 g-days per electron channel with current masks

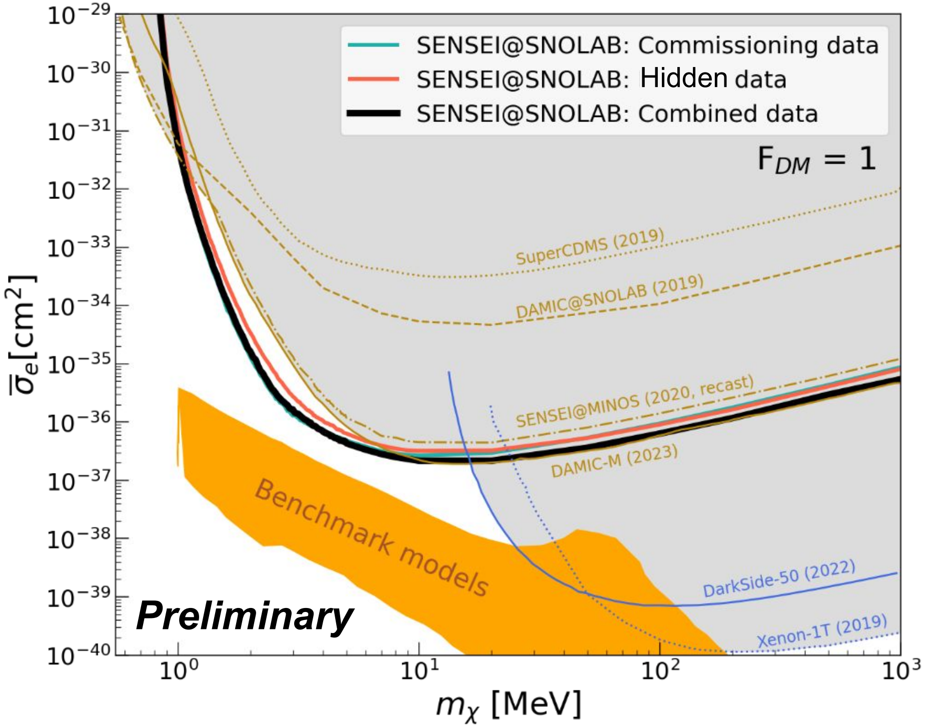
Three limits: hidden dataset, commissioning dataset, and combined commissioning + hidden exposure

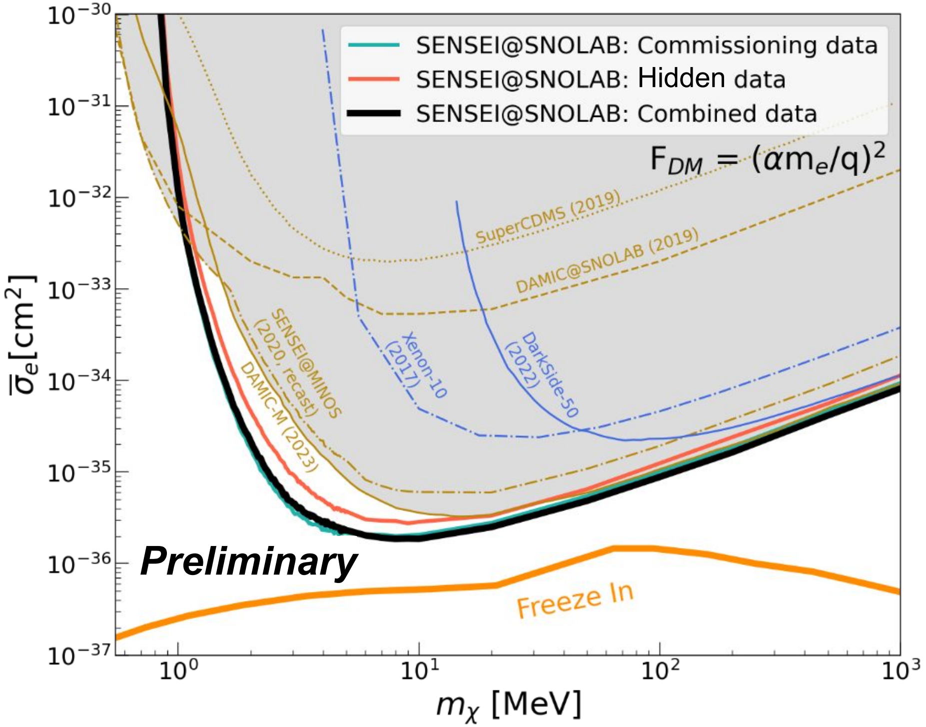
Paper in preparation to present full results



Fermilab

First SENSEI@SNOLAB results





SENSEI@SNOLAB exclusion limits on dark matter interacting with electrons

SENSEI@SNOLAB: Current Status

Ended Science Run 1 in April 2023

Performed hardware intervention at SNOLAB to:

- Repair cryocooler
- Install additional CCDs
- Improve noise environment

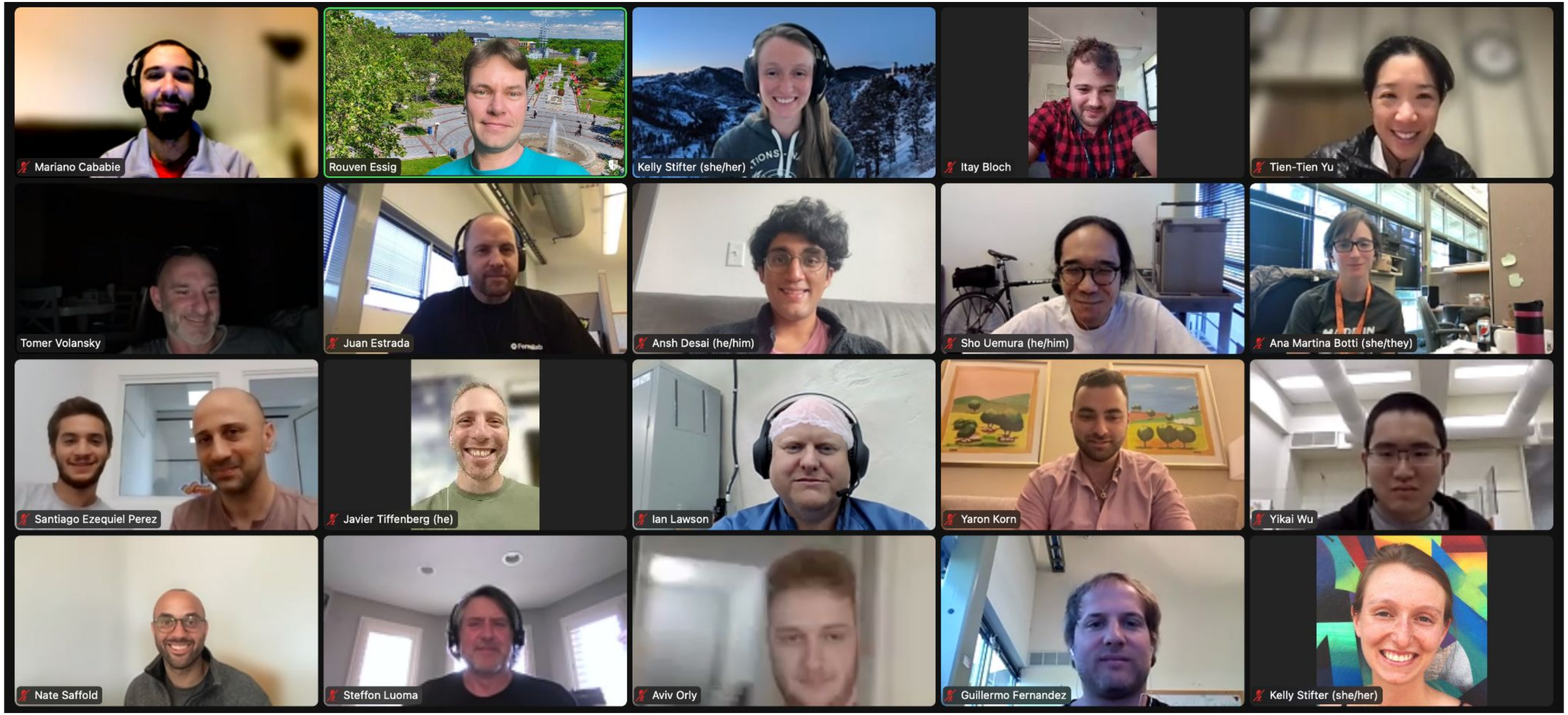
Hardware intervention was successful, Science Run 2 is underway!

Results of Science Run 1 to appear soon

Pursuing additional measurements and analyses with SNOLAB and MINOS data:

- 1 e^- studies
- Alternate interactions, including Migdal, absorption, solar reflection, etc.
- Alternate signatures, including daily modulation

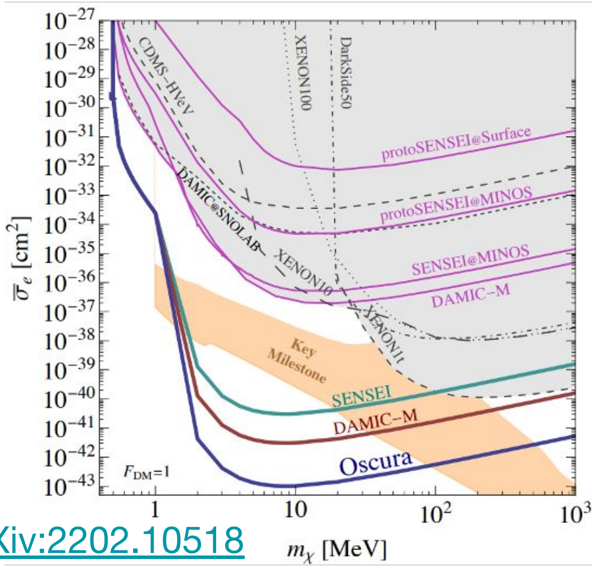
Many hands make light work…



Thanks to my collaborators for all their hard work to help us reach this milestone!

More to come from skipper-CCDs…

SENSEI (100 g)	DAMIC-M (1 kg)	Oscura (10 kg)
2021	2024	2027



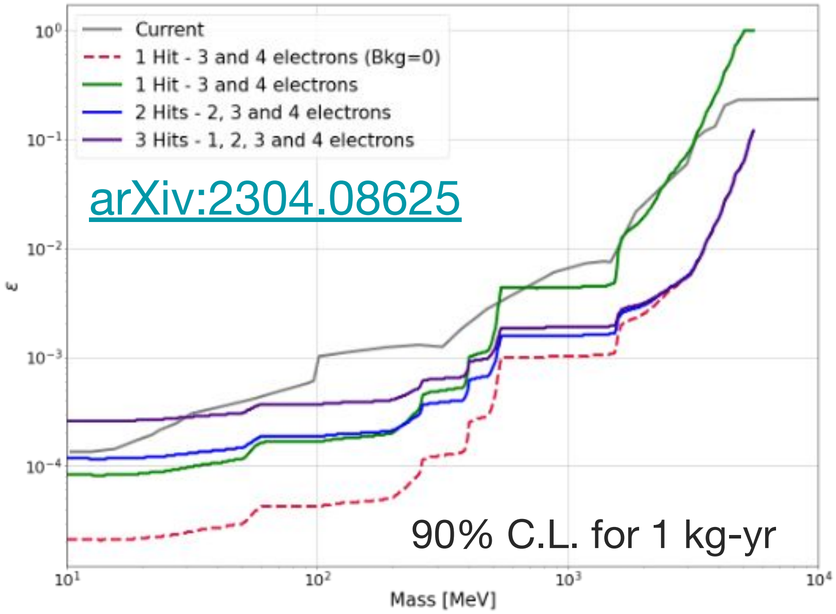
arXiv:2202.10518

Experiment	Mass [kg]	#CCDs	Radiation bkgd [dru]	Instrumental bkgd [e-/pix/day]	Commissioning
SENSEI @ MINOS	~0.002	1	3400	1.6 x 10^{-4}	late-2019
DAMIC @ SNOLAB	~0.02	2	5	~3 x 10^{-3}	late-2021
DAMIC-M LBC	~0.02	2	~10	3 x 10^{-3}	late-2021
SENSEI-100	~0.1	50	10 (goal)		mid-2022
DAMIC-M	~1	200	0.1 (goal)		~2023
OSCURA	~10	20,000	0.01 (goal)	1 x 10^{-6} (goal)	~2028

Next-generation skipper-CCD experiments are in development!

More to come from skipper-CCDs…

SENSEI (100 g)	DAMIC-M (1 kg)	Oscura (10 kg)
2021	2024	2027

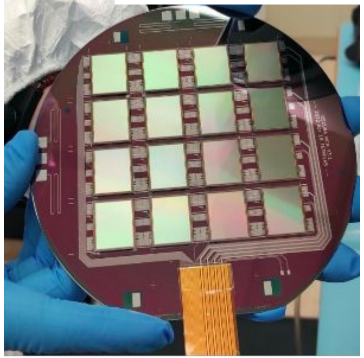


Oscura Integration Test (1 kg):

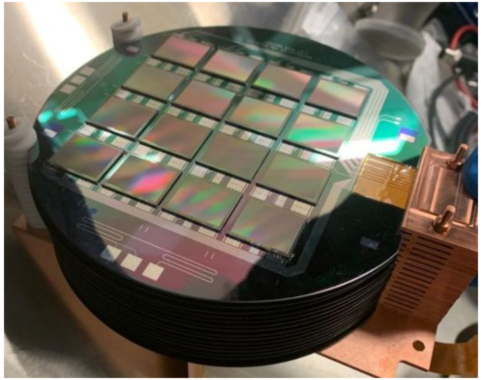
- Engineering test with 10% of Oscura detector payload
- Will conduct a search for millicharged particles from the NuMI beam at Fermilab
- Projected exclusion limits are promising!

From SENSEI to Oscura: scaling up mass

arXiv:2304.04401

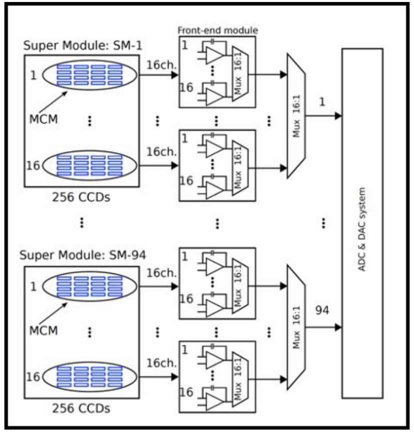


Multi Chip Module (MCM):
16 skipper-CCDs



Super Module:
16 MCMs (125 g)

arXiv:2210.16418



Multiplexing schematic

arXiv:2004.07599

Low Threshold Acquisition (LTA) electronics

SENSEI:

- 50 CCDs, 200 channels
- One LTA board per CCD

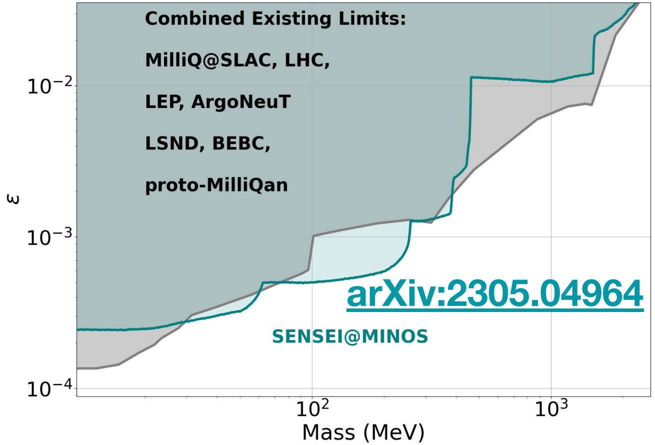
Oscura:

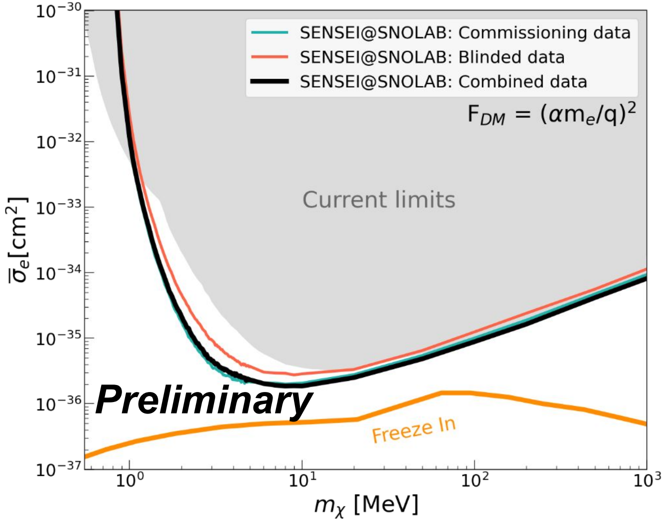
- 24,000 CCDs, 24,000 channels
- One LTA board per 4000 CCDs

A lot of progress has been made to develop sensors and readout electronics!
See Brenda Cervantes's UCLA DM 2023 talk for more details

Conclusions

- **The SENSEI collaboration has two detectors utilizing Si Skipper-CCDs to perform world-leading science:**
  - SENSEI@MINOS has set new, world-leading limits on milli-charged particles around 100 MeV
  - SENSEI@SNOLAB has ended its first science run, and set world-leading limits on sub-GeV dark matter interacting with electrons
- **Many more exciting results to come, paving the way for the next generation of CCD experiments**





Fermilab

Thank you!