Dark matter detection beyond the WIMP: pushing sensitivities with skipper-CCDs

A. M. Botti* for the SENSEI† and OSCURA collaborations

Helmholtz International School for Astroparticle Physics and Enabling Technologies Workshop

Nov 2023

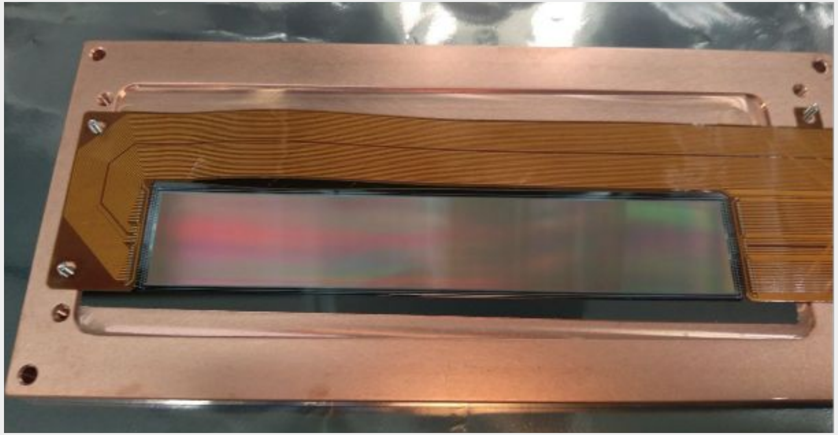


Image: SENSEI sensor

* Fermi National Accelerator Laboratory and the University of Chicago · abotti@fnal.gov
† Sub-Electron-Noise Skipper-CCD Experimental Instrument · https://sensei-skipper.github.iowww

Outline

1. Dark matter and its (direct) detection
2. Building a new detector
3. Examples
4. Skipper-CCDs for Dark Matter detection
5. The Sensei experiment at MINOS
6. The Sensei experiment at SNOLAB
7. Prospects

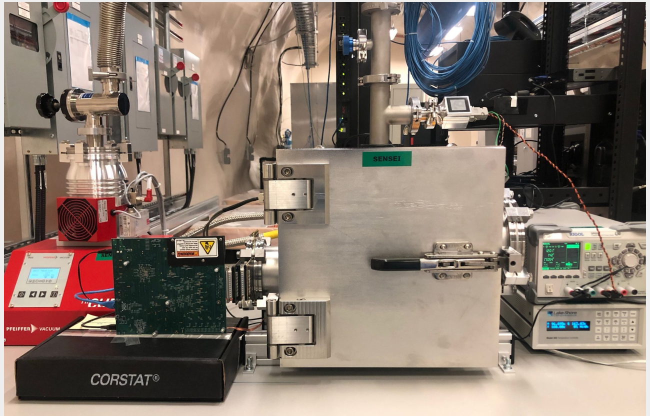


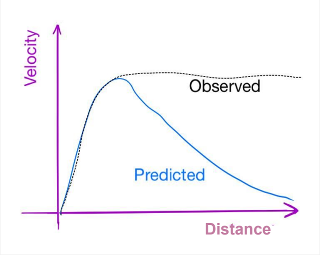
Image: Skipper-CCD testing setup

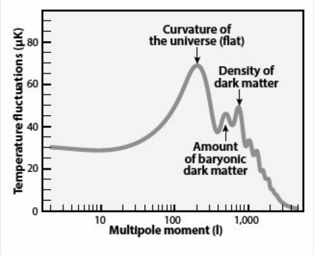
Dark-matter evidence

- → Galaxy gas rotation
- → CMB
- → Cluster collision
- → Gravitational lenses
- → Structure formation
- → etc

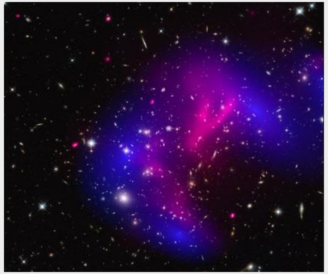
DM exists and its massive… or we **REALLY** don't get gravity

If it is a new particle… we have a lot to search:

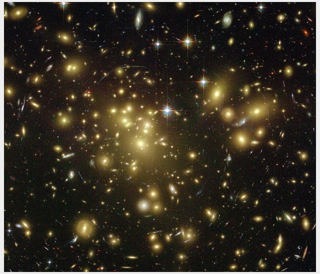




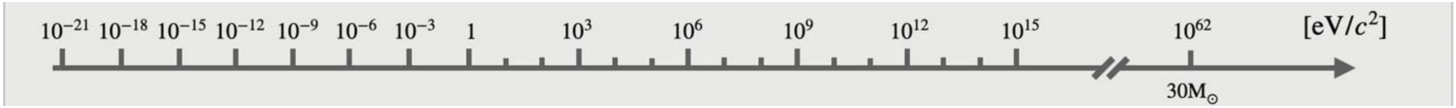
Astronomy: Roen Kelly, after Wayne Hu



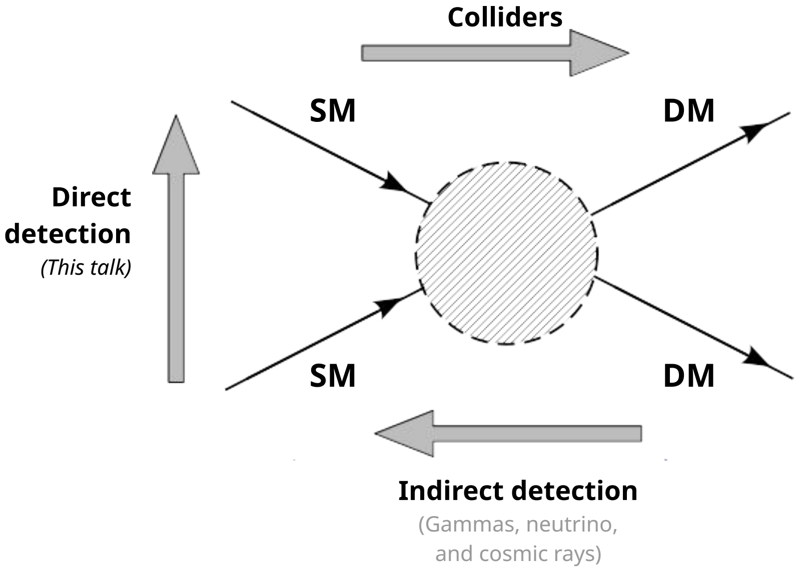
NASA, ESA, STScI, CXC.

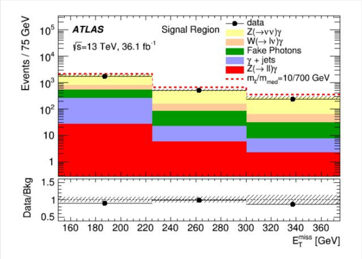


Hubble space telescope

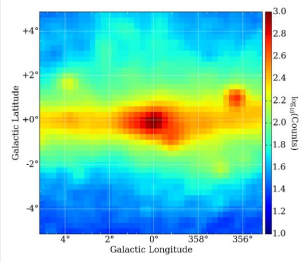


Dark-matter detection

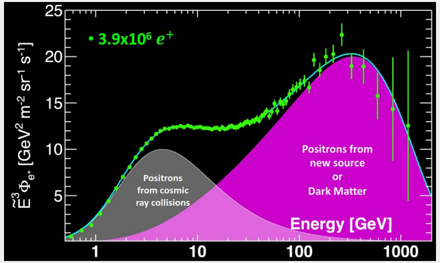




The ATLAS Collaboration. Eur. Phys. J. C 77, 393 (2017)

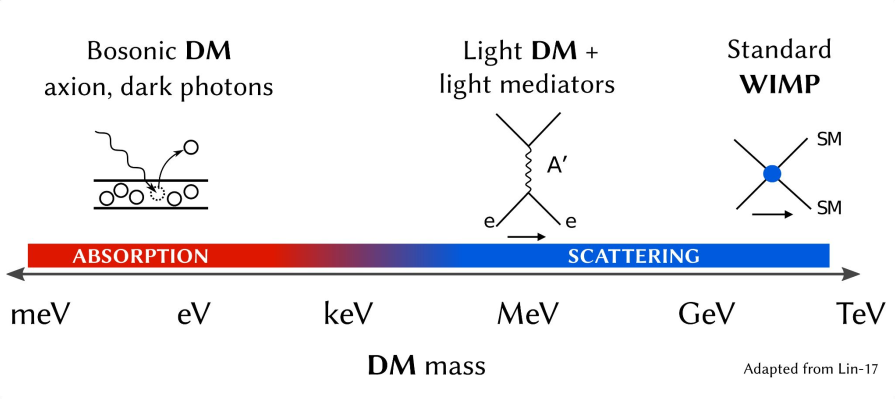


J. M. Gaskins, Contemp.Phys. 57 (2016) 4, 496-525



ICRC 2023. AMS-02 Highlights. Weiwei Xu

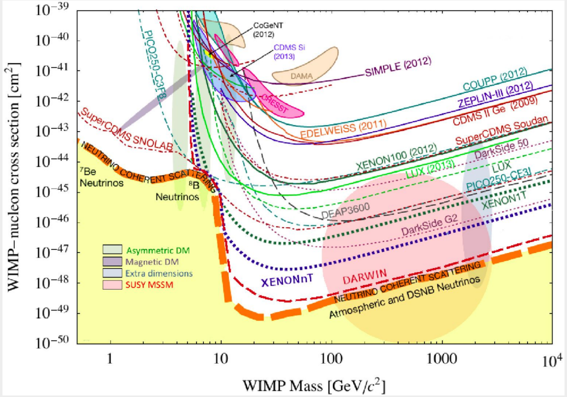
Dark-matter candidates



Field like

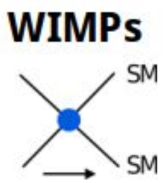
Particle like

WIMPs favoured by ΛCDM

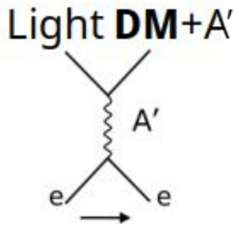


L. Baudis, Phys. Dark Universe 4 (2014) p.50-59

Targets



- → Coherent nucleus interaction σ_{n-DM}
- → Nucleus / electron interactions
- → Light nuclei for m_{DM} << 10 GeV
- → Targets: noble gases / liquids, cryogenic crystals , semiconductors, scintillators



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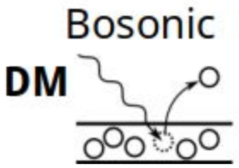
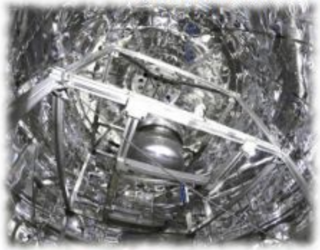
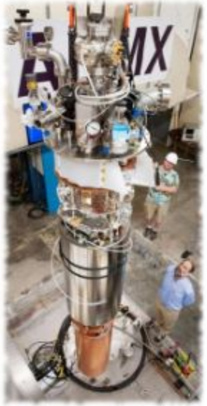


- → Photon mixing, photoelectric absorption
- → Targets: resonant cavities, semiconductors.

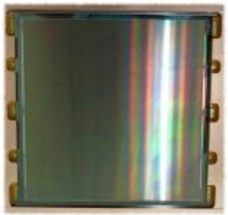
XENON Collaboration





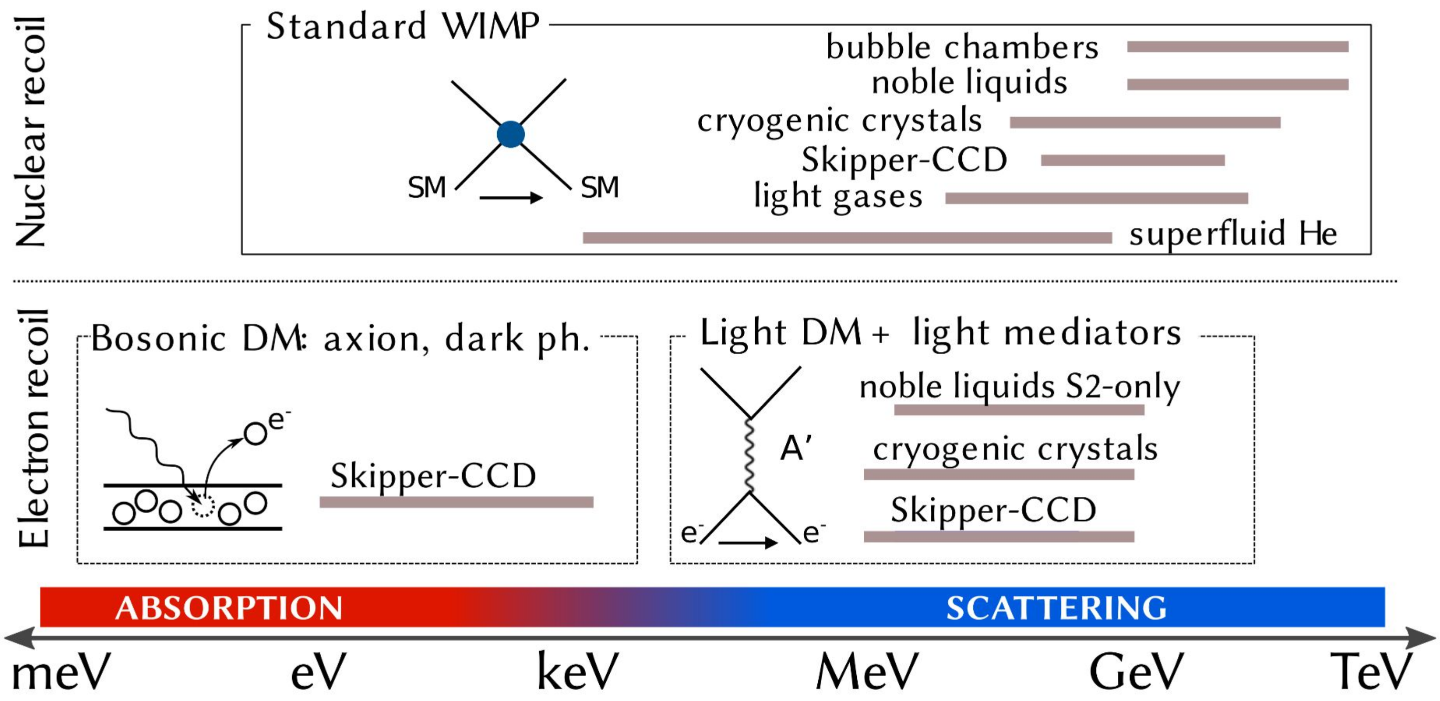
ADMX Collaboration

SuperCDMS Collaboration

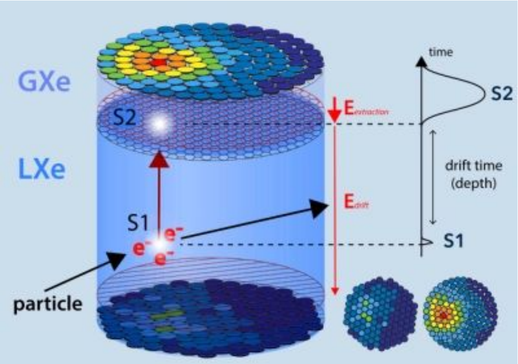


DAMIC Collaboration

Enabling technologies

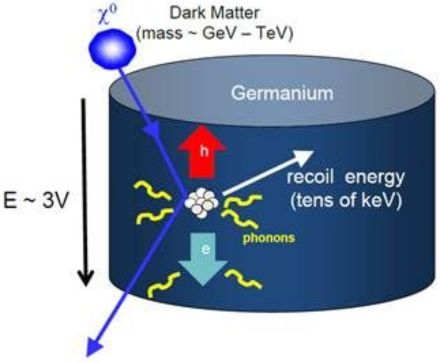


Experimental examples



Xenon 1T (noble Gas/Liquid)

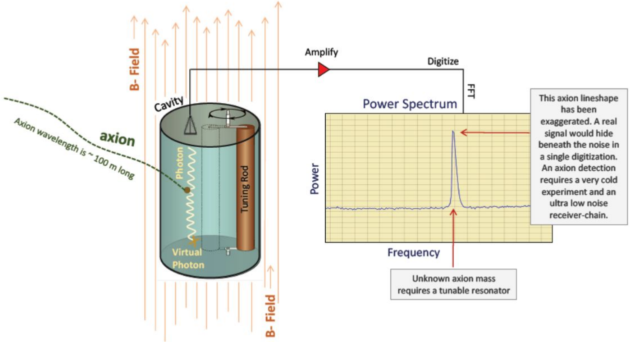
- dual-phase TPC with Xe at T ~ 170 K
- 2016-2018 at LNGS (3600 mwe)
- Nucleus recoil: no evidence of WIMPs
- Electron recoil: reported 3.5 σ excess at about 1~7 keV which turn out to be a background

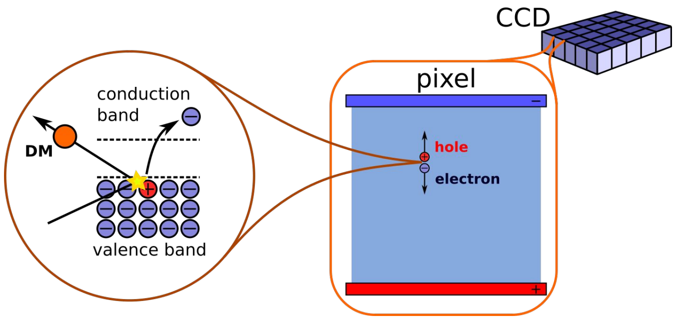


SuperCDMS SNOLAB (cryogenic)

- SuperCDMS SOUDAN (2012 – 2015) sucesor.
- 40 kg Ge/Si solid-state detectors at T ~ mK.
- Beginning 2024 at SNOLAB (6000 mwe).
- Leading limits on low-mass WIMPs

Experimental examples





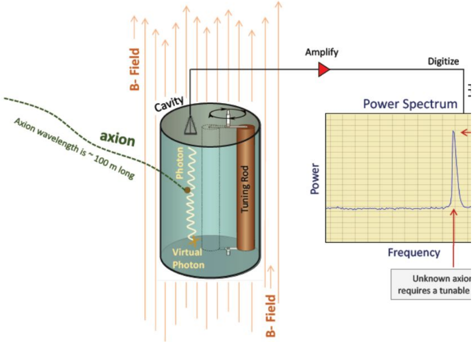
ADMX (resonant microwave cavity)

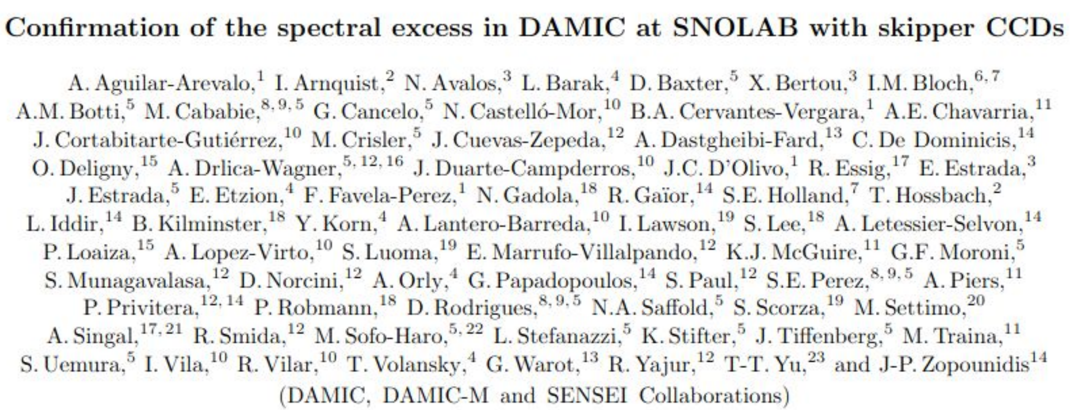
- → 8 Tesla magnet
- → Operated T ~ 100 mK to a few K.
- → Since 2010 at Washington (no overburden).
- → Upgrade undergoing.
- → Best constraints in the 2.66 – 3.31 μeV region.

DAMIC (CCD)

- → 1st DM experiment with CCD.
- → 40 g Si at T ~ 140 K.
- → Beginning ~ 2017 at SNOLAB (6000 mwe).
- → Excess reported (2020) and confirmed with skipper-CCD upgrade (2023)

Experimental examples





Confirmation of the spectral excess in DAMIC at SNOLAB with skipper CCDs

A. Aguilar-Arevalo,[1] I. Arnquist,[2] N. Avalos,[3] L. Barak,[4] D. Baxter,[5] X. Bertou,[3] I.M. Bloch,[6,7] A.M. Botti,[5] M. Cababie,[8,9,5] G. Cancelo,[5] N. Castelló-Mor,[10] B.A. Cervantes-Vergara,[1] A.E. Chavarria,[11] J. Cortabitarte-Gutiérrez,[10] M. Crisler,[5] J. Cuevas-Zepeda,[12] A. Dastgheibi-Fard,[13] C. De Dominicis,[14] O. Deligny,[15] A. Drlica-Wagner,[5,12,16] J. Duarte-Campderros,[10] J.C. D'Olivo,[1] R. Essig,[17] E. Estrada,[3] J. Estrada,[5] E. Etzion,[4] F. Favela-Perez,[1] N. Gadola,[18] R. Gaïor,[14] S.E. Holland,[7] T. Hossbach,[2] L. Iddir,[14] B. Kilminster,[18] Y. Korn,[4] A. Lantero-Barreda,[10] I. Lawson,[19] S. Lee,[18] A. Letessier-Selvon,[14] P. Loaiza,[15] A. Lopez-Virto,[10] S. Luoma,[19] E. Marrufo-Villalpando,[12] K.J. McGuire,[11] G.F. Moroni,[5] S. Munagavalasa,[12] D. Norcini,[12] A. Orly,[4] G. Papadopoulos,[14] S. Paul,[12] S.E. Perez,[8,9,5] A. Piers,[11] P. Privitera,[12,14] P. Robmann,[18] D. Rodrigues,[8,9,5] N.A. Saffold,[5] S. Scorza,[19] M. Settimo,[20] A. Singal,[17,21] R. Smida,[12] M. Sofo-Haro,[5,22] L. Stefanazzi,[5] K. Stifter,[5] J. Tiffenberg,[5] M. Traina,[11] S. Uemura,[5] I. Vila,[10] R. Vilar,[10] T. Volansky,[4] G. Warot,[13] R. Yajur,[12] T-T. Yu,[23] and J-P. Zopounidis[14]

(DAMIC, DAMIC-M and SENSEI Collaborations)

ADMX (resonant microwav

- ➔ 8 Tesla magnet
- ➔ Operated T ~ 100 mK to a few K.
- ➔ Since 2010 at Washington (no overburden).
- ➔ Upgrade undergoing.
- ➔ Best constraints in the 2.66 – 3.31 μeV region.

- ➔ 100 g Si at T ~ 140 K.
- ➔ Beginning ~ 2021 at SNOLAB (6000 mwe).

The SENSEI Collaboration

- L. Barak, E. Etzion, Y. Korn, A. Orly, T. Volansky
- A. M. Botti, G. Cancelo, F. Chierchie, M. Crisler, A. Drlica-Wagner, J. Estrada, G. Fernandez Moroni, N. Saffold, M. Sofo Haro, L. Stefanazzi, K. Stifter, J. Tiffenberg, S. Uemura
- P. Adari, R. Essig, A. Singal, Y. Wu
- L. Chaplinsky, R. Essig, D. Gift, S. Munagavalasa, A. Singal
- A. Desai, T.-T. Yu
- I. Lawson, L. Steffon, S. Scorza
- I. M. Bloch
- S. Holland

[1] Also Fermilab
[2] Also U. Chicago
[3] Also CAB, CNEA-CONICET-IB

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

The Sensei Experiment

Sub-**E**lectron-**N**oise **S**kipper-CCD **E**xperimental **I**nstrument

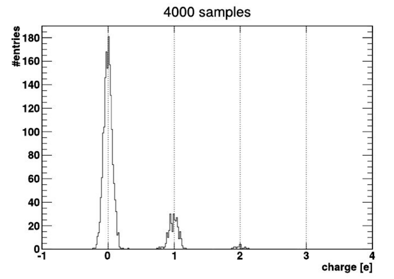
New generation Charge Couple Devices **(CCD)**
LBNL MicroSystems Lab Energy threshold **~ 1.1 eV**
(Si bandgap) and readout noise **~ 0.1 e$^-$**

Main goals

- First DM detector with Skipper-CCDs
- Validate technology for DM and ν detection
- Probe DM masses at the MeV scale (e - recoil)
- Probe axion and hidden-photon DM masses > 1 eV (absorption)

The SENSEI Experiment

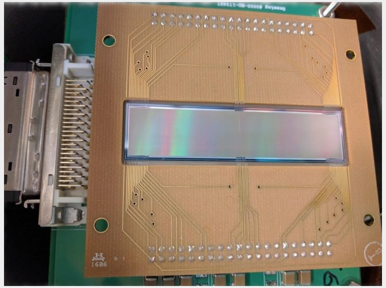
2017	2018	2019	2020	Ongoing
Demonstrate sub-electron resolution	DM search with **proto-SENSEI** (0.1 g) at **surface**	DM search with **proto-SENSEI** at **MINOS** (230 m.w.e.)	DM search with **science grade** (~2 g) at **MINOS**	**Production** (100g) + commissioning at **SNOLAB** (6000 m.w.e.)



Tiffenberg, Javier, et al. Physical Review Letters 119.13 (2017): 131802.

First Skipper-CCD prototypes

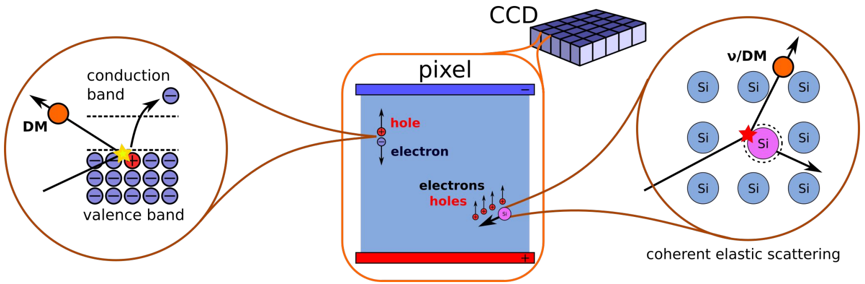
- Prototype designed at LBNL MSL
- 200 & 250 µm thick, 15 µm pixel size
- Two sizes 4k × 1k (0.5gr) & 1.2k × 0.7k pixels
- Parasitic run, optic coating and Si resistivity ~10kΩ
- 4 amplifiers per CCD, three different RO stage designs



Instrument:

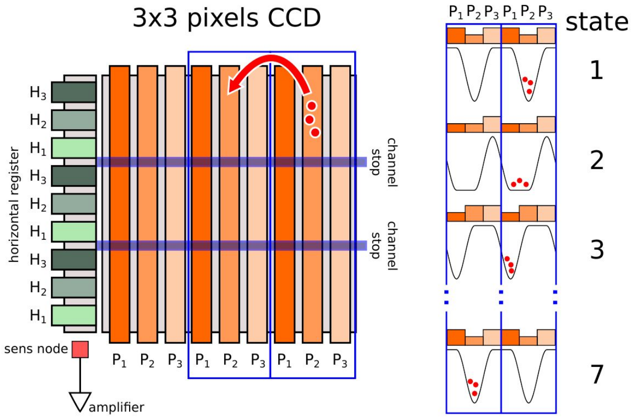
· System integration done at Fermilab
· Custom cold electronics
· Firmware and image processing software
· Optimization of operation parameters

Charge-coupled devices (CCD)



DM-electron scattering

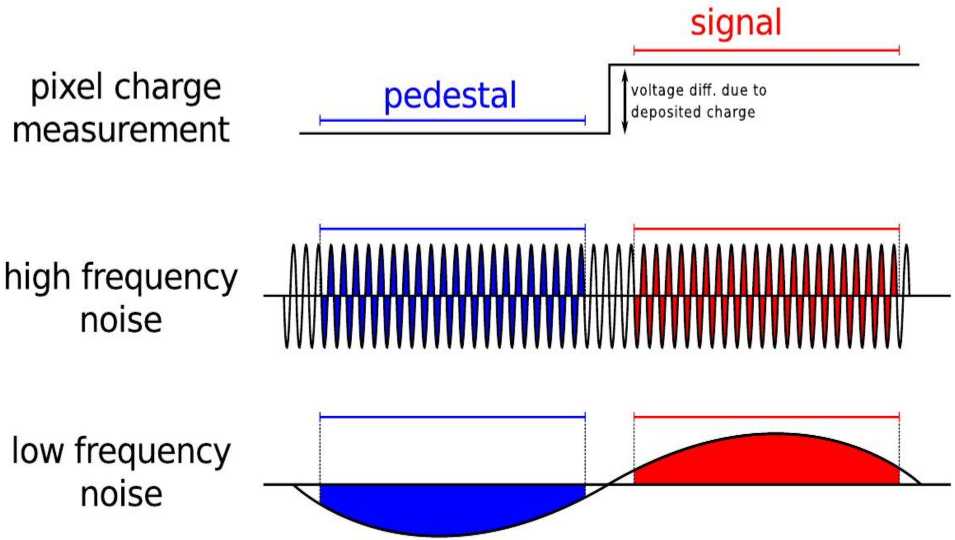
DM-Nucleus scattering



CCD read-out

1. **pedestal** integration.
2. **signal** integration.
3. **charge** = **signal** – **pedestal**.

Good for low-frequency noise is reduced but…

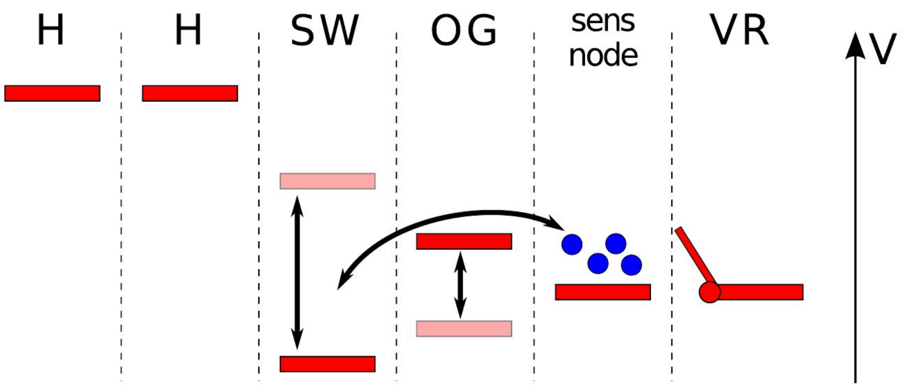


Skipper CCD read-out

Multiple sampling of same pixel without corrupting the **charge** packet.

Pixel value = **average** of all samples

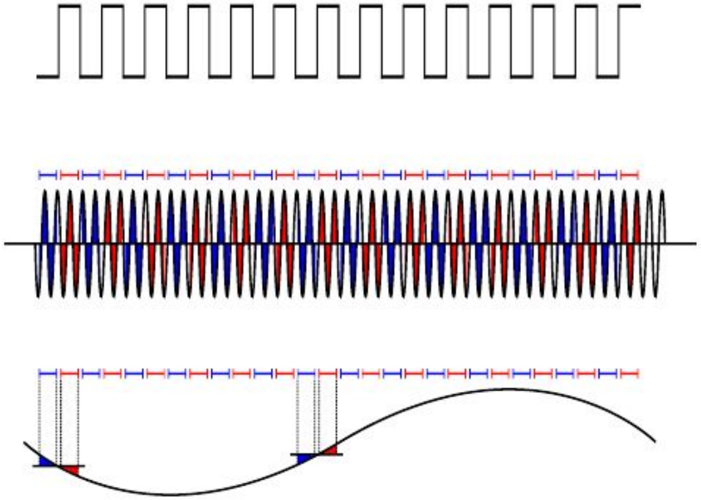
Suggested in **1990** by Janesick et al. (doi:10.1117/12.19452)



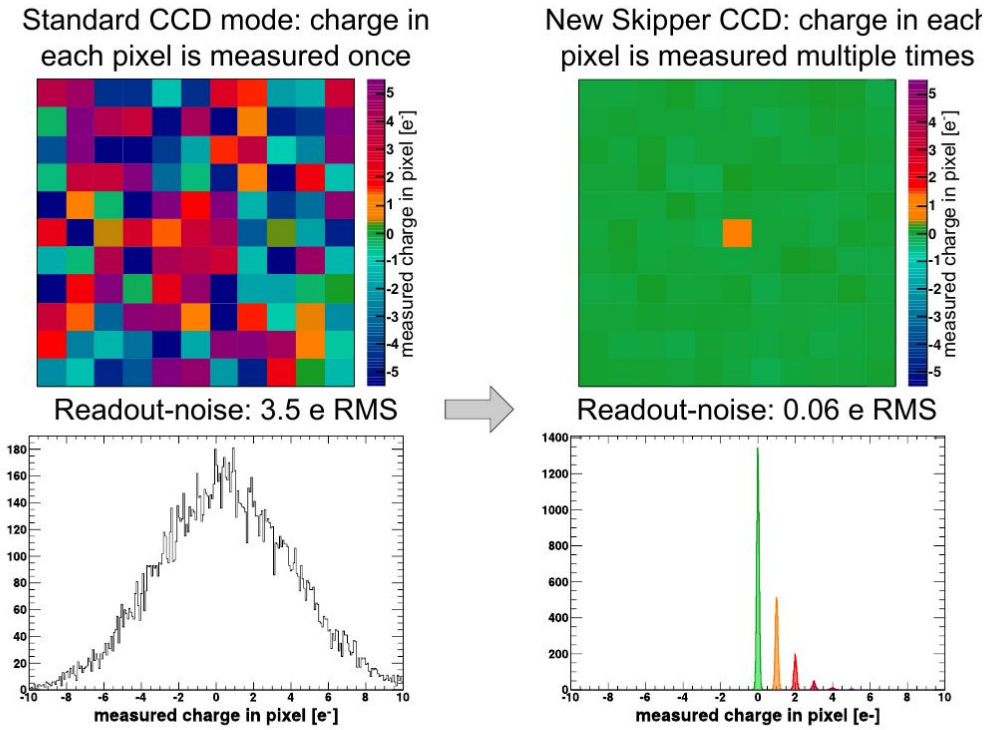
Skipper CCD read-out

1. **pedestal** integration.
2. **signal** integration.
3. **charge** = **signal** – **pedestal**.
4. **Repeat** N times.
5. **Average** all samples.

Then, both high- and low-frequency noise is reduced



Skipper-CCD read-out noise



THE UNIVERSITY OF CHICAGO Fermilab Sensei

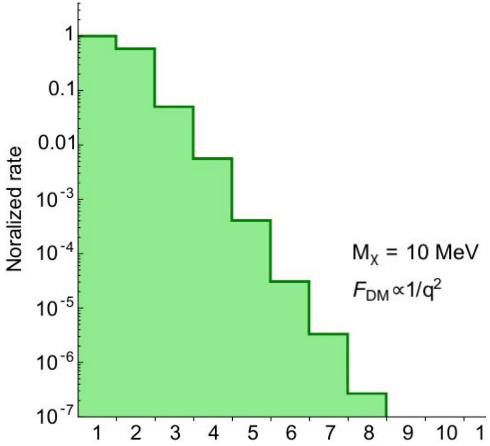
Skipper-CCDs for dark matter

Light-**DM** mass range:
- 1-1000 MeV for **e⁻** recoil
- 1~1000 eV for **absorption**
- 0.5~1000 MeV **Nucleus** recoil (Migdal effect)

Sensitivity to **1,2,3 e⁻** signals needed: **Skippers** can do this!

But only if we understand and control **backgrounds…**

Expected spectrum from benchmark models (e⁻ recoil)



R. Essig et al, JHEP 05 (2016), 046

Background sources: detector

Exposure independent

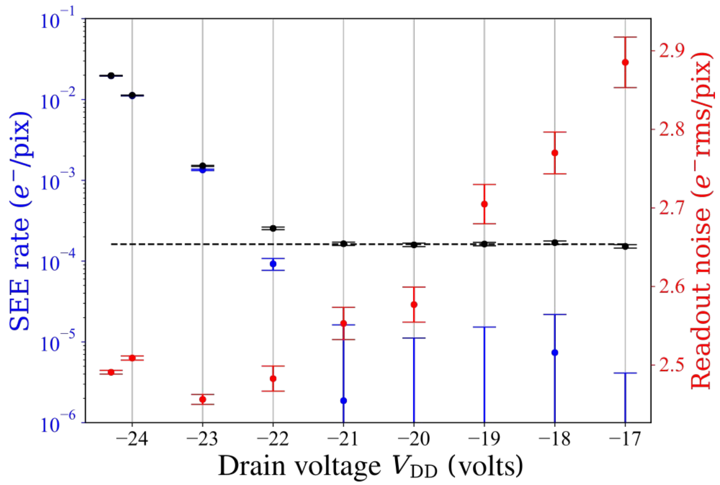
- Spurious charge (10^{-2} to 10^{-5} e^-/pix/image)
- Amplifier light (10^{-1} to 10^{-5} e^-/pix/image)
-

Exposure dependent

- Dark current (10^{-5} e^-/pix/day at 135 K)
- Light leaks

Single electron rate reduced by optimizing operation parameters

- Read-out mode: continuous vs expose
- Voltage configuration
- Amplifier off while exposure



The SENSEI Collaboration. Phys. Rev. Applied 17, 014022 (2022)

Background sources: environment

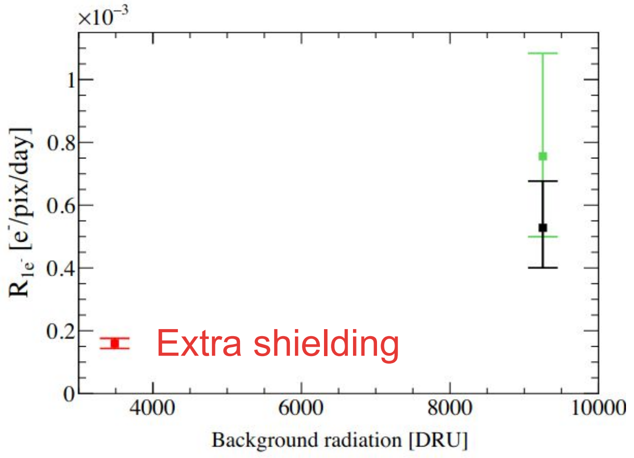
High-energy:

- Air shower muons
- Nuclear decays
- x/ɣ-rays

Low-energy:

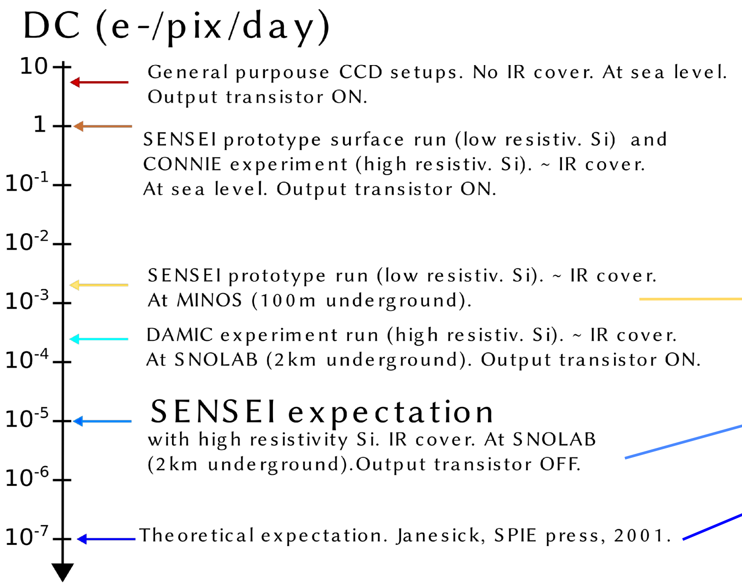
- IR photons
- Halo and transfer inefficiency
- Compton scattering
- Charge collection inefficiency

Environmental background is reduced with shielding, and removed from data with quality cuts



The SENSEI Collaboration - Phys. Rev. Lett. 125, 171802 (2020)

Background goal



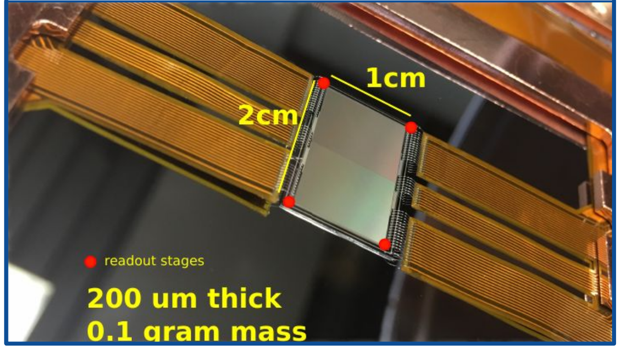
Dark Current $[e^- pix^{-1} day^{-1}]$	$\geq 1e^-$ [pix]	$\geq 2e^-$ [pix]	$\geq 3e^-$ [pix]
10^{-3}	1×10^8	3×10^3	7×10^{-2}
10^{-5}	1×10^6	3×10^{-1}	7×10^{-8}
10^{-7}	1×10^4	3×10^{-5}	7×10^{-14}

Background estimations for 1 year and 100 g.

Blue: discovery channel (background free)
Red: modulation or limits

The SENSEI Experiment

2017	2018	2019	2020	Ongoing
Demonstrate sub-electron resolution	DM search with **proto-SENSEI** (0.1 g) at **surface**	DM search with **proto-SENSEI** at **MINOS** (230 m.w.e.)	DM search with **science grade** (~2 g) at **MINOS**	**Production** (100g) + commissioning at **SNOLAB** (6000 m.w.e.)



The SENSEI Collaboration
Physical Review Letters 121.6 (2018): 061803.

The SENSEI Collaboration
Physical review letters 122.16 (2019): 161801.

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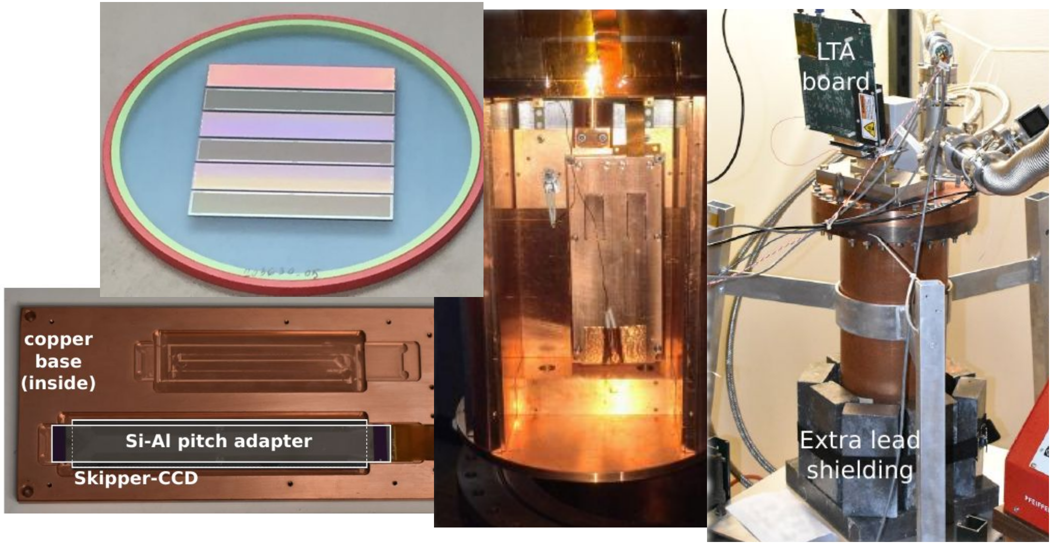
The SENSEI Collaboration Phys. Rev. Lett. 125, 171802 (2020)

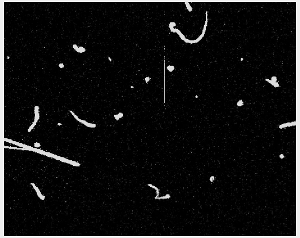
New device @ MINOS

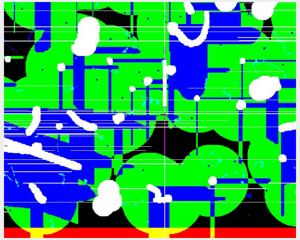
- First skipper-CCD optimized for DM detection
- 5.5 Mpix of 15 μm
- 675 μm thick
- Active mass ~ 2 g
- 20 kΩ
- 4 amplifiers
- T ~ 135 K + vacuum

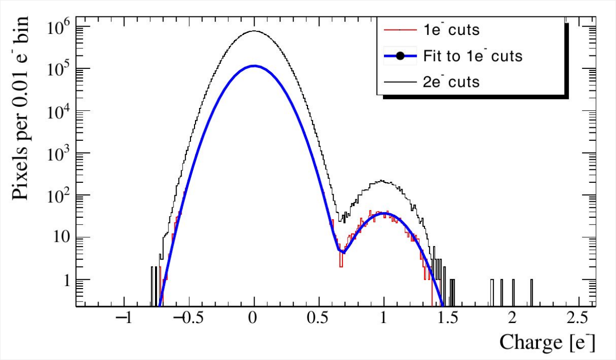


Quality cuts

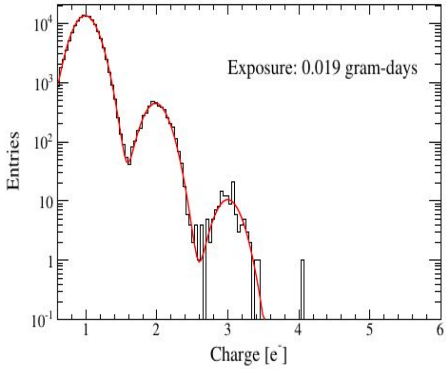
Cuts \ N_e	1		2		3		4	
1. Charge Diffusion	1.0		0.228		0.761		0.778	
	Eff.	#Ev	Eff.	#Ev	Eff.	#Ev	Eff.	#Ev
2. Readout Noise	1	$> 10^5$	1	58547	1	327	1	155
3. Crosstalk	0.99	$> 10^5$	0.99	58004	0.99	314	0.99	153
4. Serial Register	~ 1	$> 10^5$	~ 1	57250	~ 1	201	~ 1	81
5. Low-E Cluster	0.94	42284	0.94	301	0.69	35	0.69	7
6. Edge	0.70	25585	0.90	70	0.93	8	0.93	2
7. Bleeding Zone	0.60	11317	0.79	36	0.87	7	0.87	2
8. Bad Pixel/Col.	0.98	10711	0.98	24	0.98	2	0.98	0
9. Halo	0.18	1335	0.81	11	~ 1	2	~ 1	0
10. Loose Cluster	N/A		0.89	5	0.84	0	0.84	0
11. Neighbor	~ 1	1329	~ 1	5	N/A			
Total Efficiency	0.069		0.105		0.341		0.349	
Eff. Efficiency	0.069		0.105		0.325		0.327	
Eff. Exp. [g-day]	1.38		2.09		9.03		9.10	
Observed Events	1311.7(*)		5		0		0	
90%CL $[\text{g-day}]^{-1}$	525.2(*)		4.449		0.255		0.253	

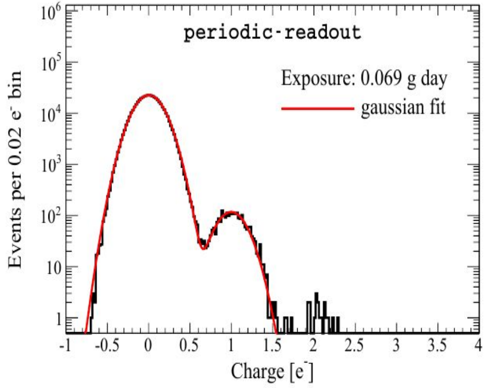

Example image

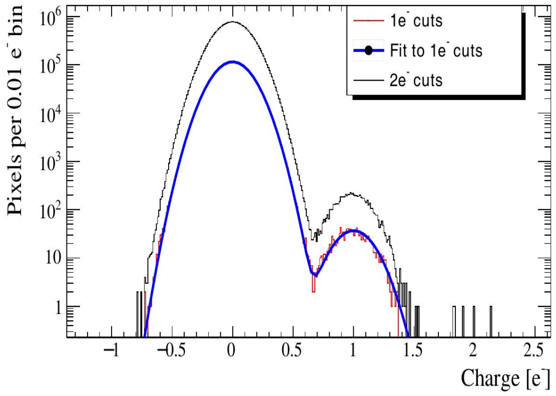

Masking



Summary: from prototype to science grade





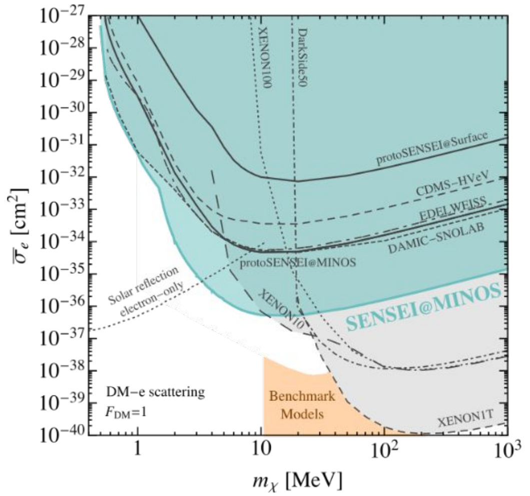


Active mass ~ **0.1 g**
0.019 gram-day exposure
0.14 e- RO noise
(**800** samples)
SEE ~ **1.14 e-/pixel/day**

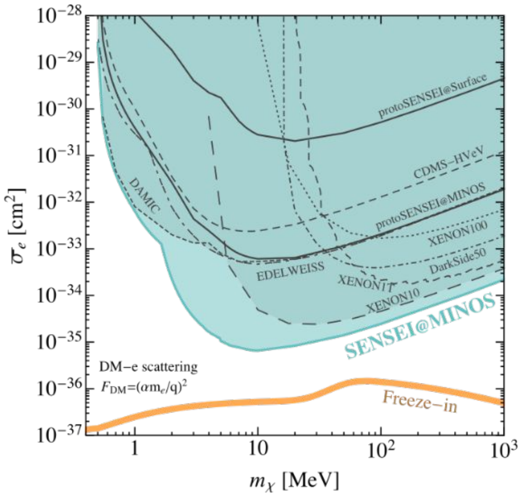
Active mass ~ **0.1 g**
0.069 gram-day exposure
0.14 e- RO noise
(**800** samples)
SEE ~ **0.005 e-/pix/day**

Active mass ~ **2 g**
19.926 gram-day exposure
0.14 e- RO noise
(**300** samples)
SEE ~ **1.6×10^{-4} e-/pix/day**

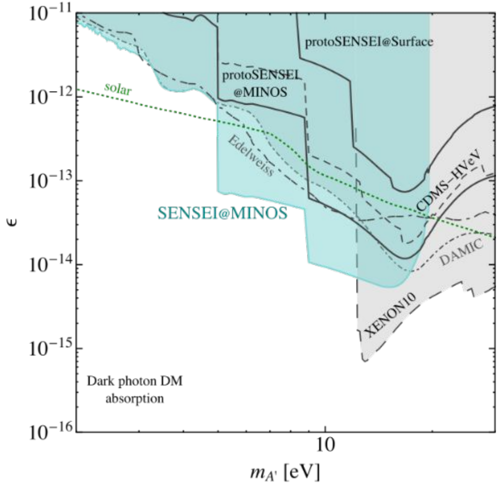
Results 2020



***Heavy** mediator*
e⁻ scattering



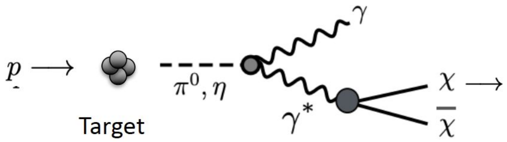
***Light** mediator*
e⁻ scattering



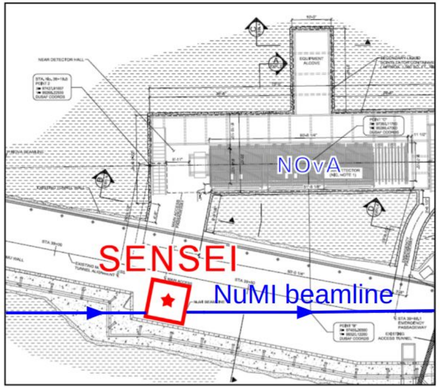
Absorption

2023: Milli-charged particles @ MINOS

Proton collisions w/ fixed target -> mCPs collinear w/ NuMI beamline:

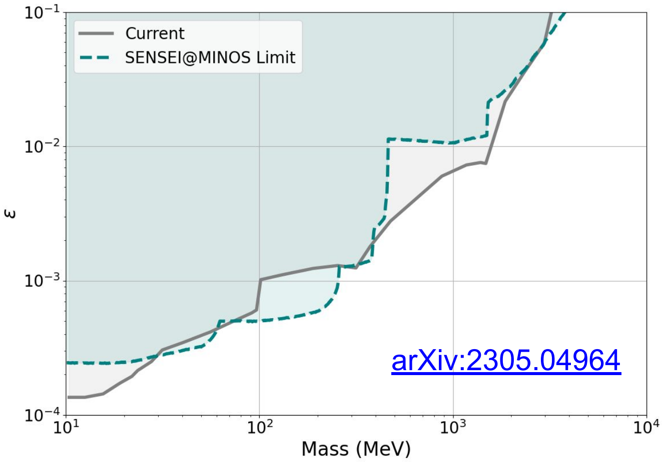


arXiV:1902.03246



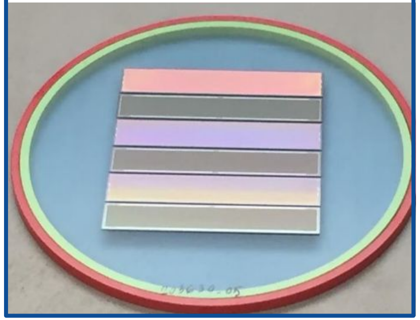
Extension of previous analysis to 6e-

	$1e^-$	$2e^-$	$3e^-$	$4e^-$	$5e^-$	$6e^-$
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



The Sensei Experiment

2017	2018	2019	2020	Ongoing
Demonstrate sub-electron resolution	DM search with **proto-SENSEI** (0.1 g) at **surface**	DM search with **proto-SENSEI** at **MINOS** (230 m.w.e.)	DM search with **science grade** (~2 g) at **MINOS**	**Production** (100g) + commissioning at **SNOLAB** (6000 m.w.e.)



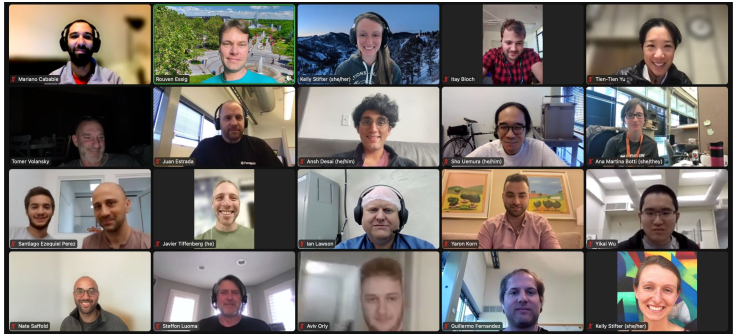
SENSEI @ SNOLAB

Towards a **100 g** science grade skipper-CCD detector:

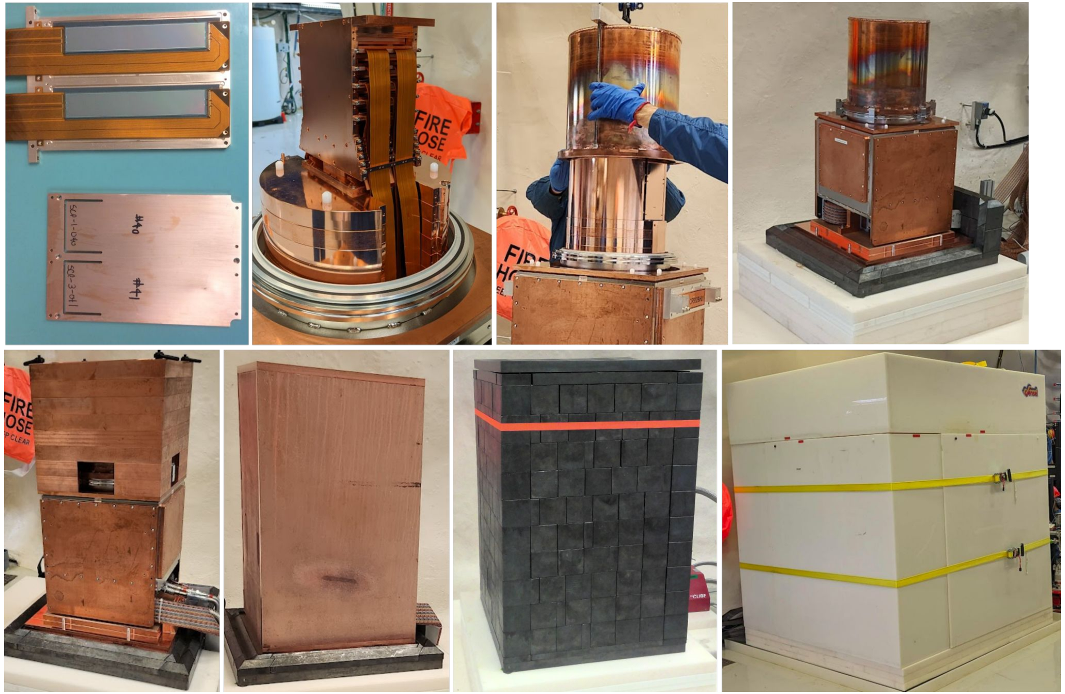
- Produce ~ **50** devices
- **Packaging** at Fermilab
- **Testing**
- Deliver and deploy at **SNOLAB** (6000 m.w.e.)

Vessel deployed during the pandemic by SNOLAB staff

→ **10000** dru (MINOS standard shield): proto-SENSEI
→ **3000** dru (MINOS extra shield): first science grade skipper
→ **5 (ultimate goal)** dru (SNOLAB): SENSEI 100 g



SENSEI @ SNOLAB: Setup



Setup:

- Copper box for 12 copper tray
- Each tray for 2 (4) ~2g CCDs.
- Cold copper box
- 6-in copper bricks and hat inner shield
- Vacuum pump (< 2x10^-4 mbar)
- Cryocooler + heater (~140 K)
- 2 layer of copper outer shield
- 3-in lead
- 42-inch polyethylene and water shield

SENSEI @ SNOLAB: First science run

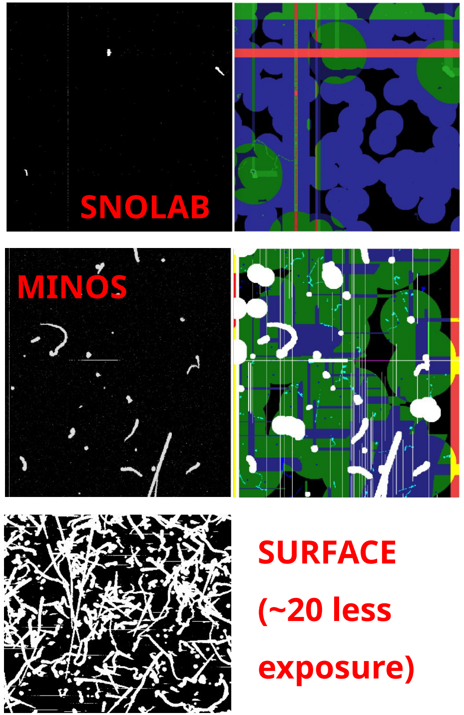
Setup:

- 6 CCDs (~13 g),
- 6144 × 1024 pixels
- 15 μm pitch, 675 μm thick
- Installation: 4-7/2021
- Commissioning: 10/2021-8/2022
- Science: 9/2022-4/2023

Operations:

- 20 hour exposures
- 129 images (~50% blinded)
- 7.3 hours readout, noise of ~0.14 e-
- Temperature variations of 135 K-155 K
- 1 e- density (after cuts): ~2 x 10-4 e-/pixel

SENSEI @ SNOLAB: First images



1. Data quality cuts to remove anomalous images

2. Cluster any contiguous pixels ≥1 e-

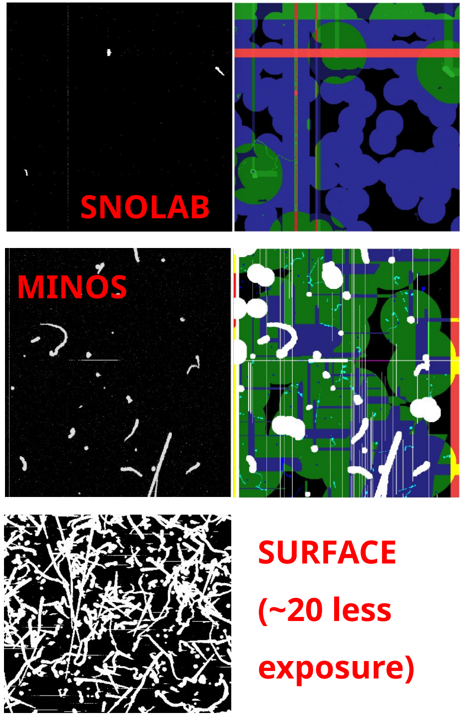
3. Apply masks to images to remove:

- Electronic noise
- Cross-talk
- Edges of CCDs
- Bad pixels and columns
- Serial register events
- Charge transfer inefficiencies
- Region surrounding any ≥1e- pixels

4. Remove clusters with any pixels overlapping a mask

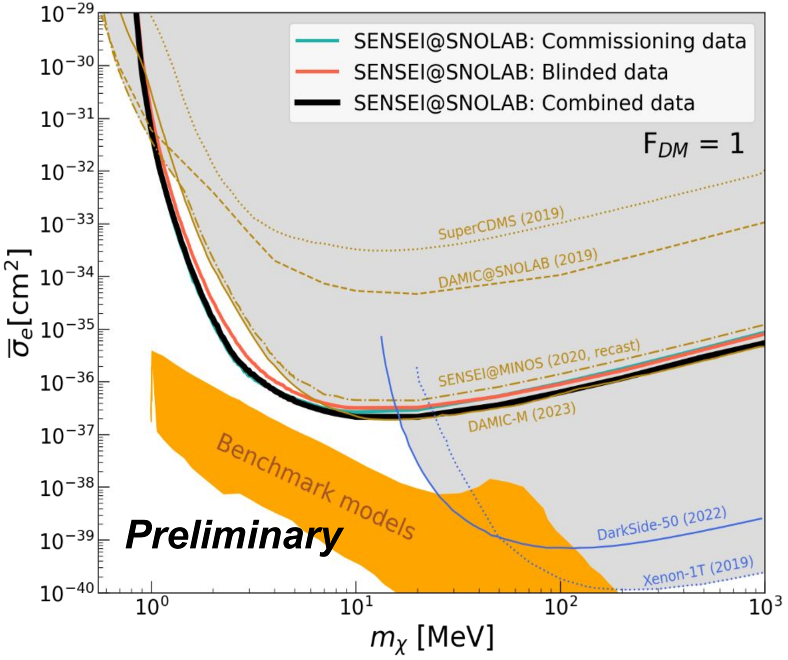
5. Remove individual high-background cluster shapes

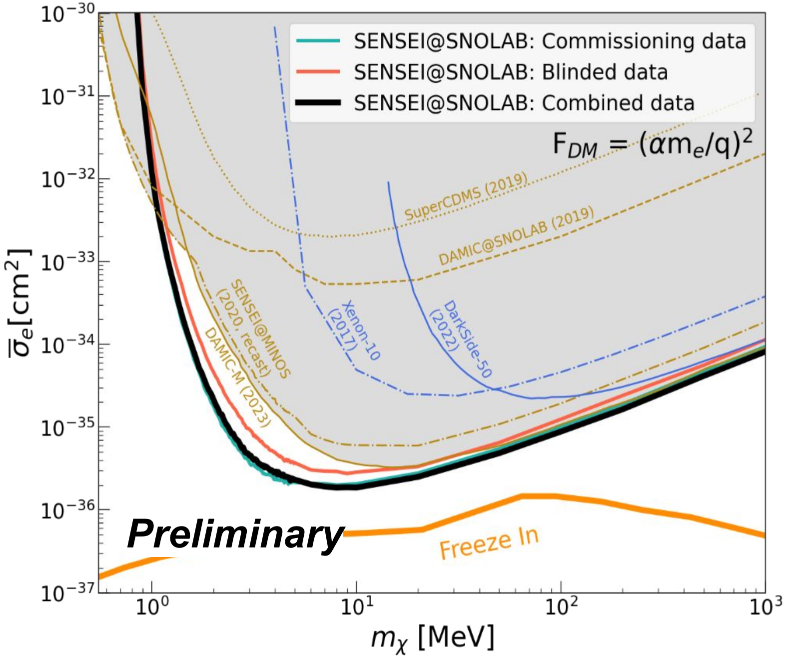
SENSEI @ SNOLAB: quality cuts



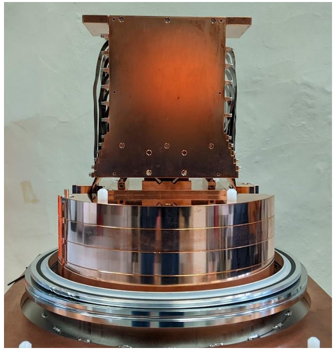
- 45 unblinded commissioning images,
- 37 blinded images
- 2-10 e- channels
- Combined datasets: ~70 g-days per electron channel with cuts
- Three limits: blinded dataset, commissioning dataset, and combined commissioning + blinded exposure

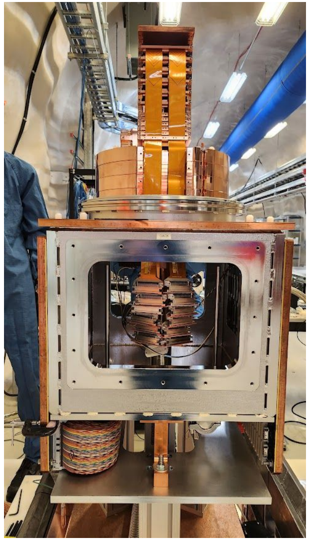
SENSEI @ SNOLAB: First results

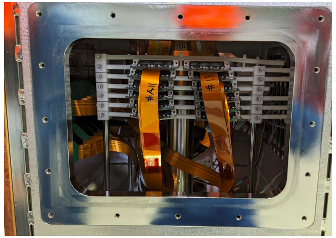




SENSEI @ SNOLAB: Second science run



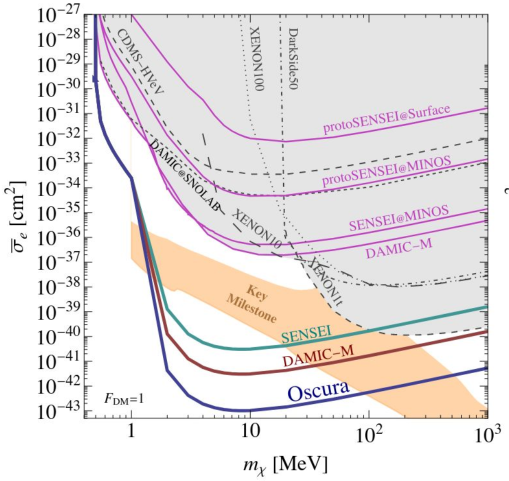


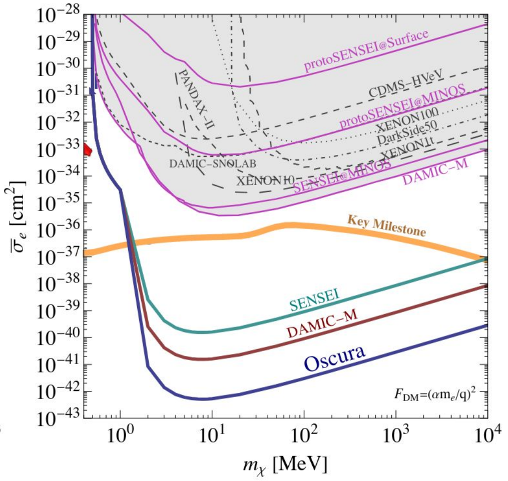


- 19 CCDs (~ 40 g)
- Improved support
- Shield fully deployed
- Improved support
- Data acquisition starting soon

Perspectives DM with skippers

SENSEI 100g	DAMIC-M 1kg	OSCURA 10kg
2021	2024	2027





arXiv: 2304.04401

THE UNIVERSITY OF CHICAGO Fermilab sensei

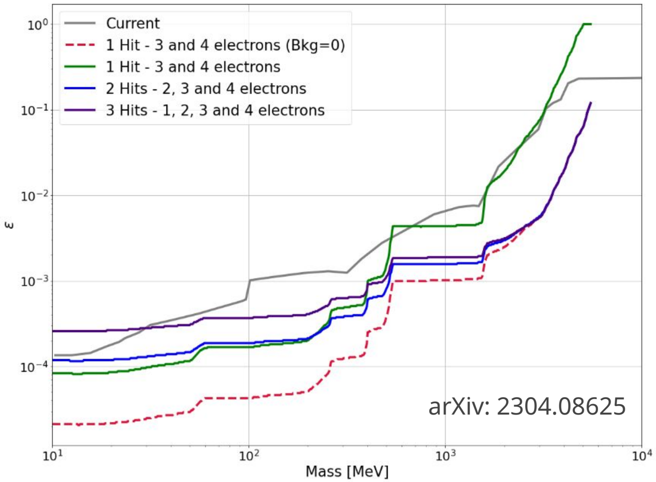
Perspectives mCP with skippers

SENSEI 100g — 2021

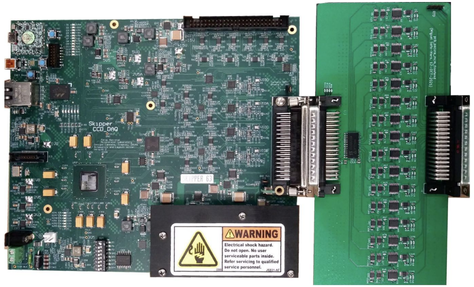
DAMIC-M 1kg — 2024

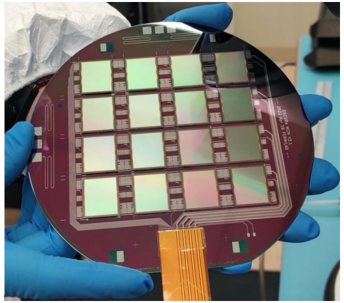
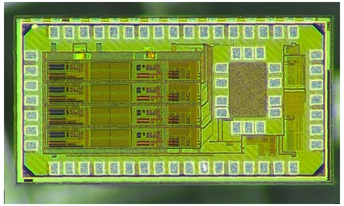
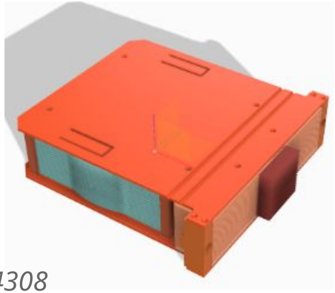
OSCURA IT 1kg

OSCURA 10kg — 2027



OSCURA



C. Chavez et al. Sensors 22 (2022) 11, 4308
F. Chierchie et al. arXiv:2210.16418
B. Cervantes, et al. 2304.04401

10 kg skipper-CCDs:

- ➔ 24000 channels/devices (28 GPix)
- ➔ 1500 multi-chip modules (MCM) with 16 CCDs each
- ➔ 94 super modules with 16 MCMs each

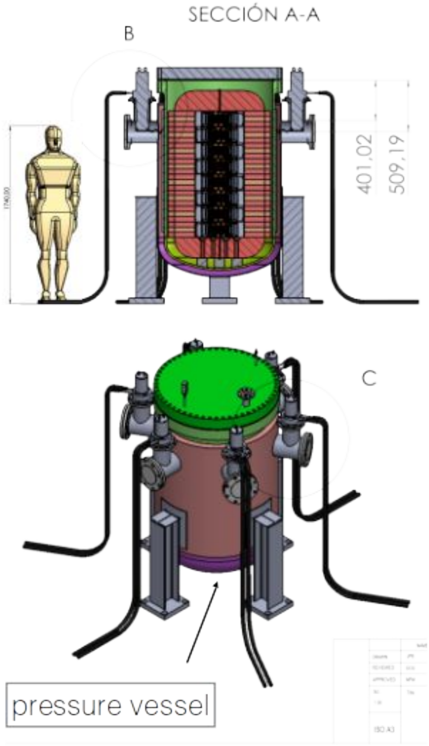
Read-out:

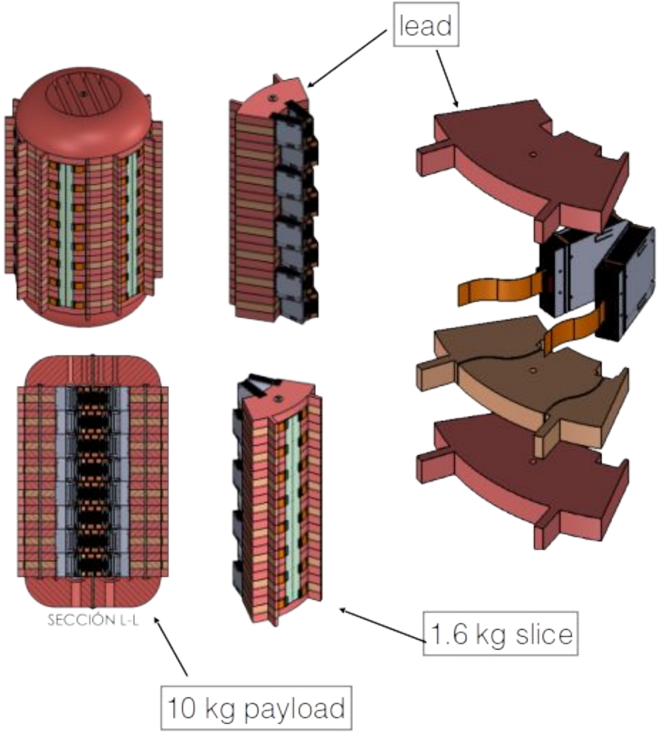
- ➔ High-density package
- ➔ Multiplexer + SENSEI electronics
- ➔ ASICs

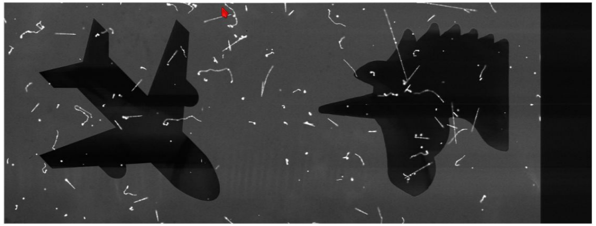
Background goal (0.01 dru):

- ➔ Silicon based pitch adapter
- ➔ Aluminum shielding
- ➔ Low-background materials

OSCURA configuration







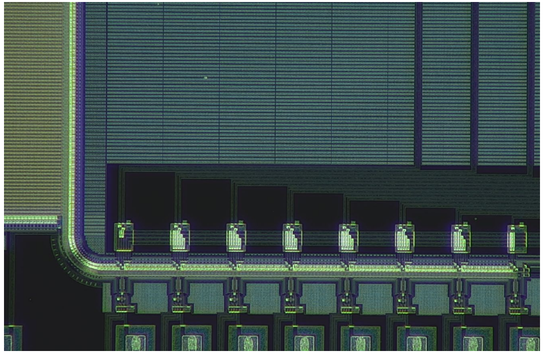
Summary

- **DM** is an exciting field with a lot of **instrumental challenges**
- **SENSEI**: first dedicated experiment searching for **e-DM** interactions with skipper-CCDs.
- **protoSENSEI** at the **surface** and **MINOS** produced first physics.
- First **scientific grade skipper-CCD** achieved.
- New limit with MINOS data for **mCP**. Best constraints around **100 MeV**
- Best constraints on **DM-e-** scattering for light mediator (**1-1000 MeV)** and heavy mediator (**1-10 MeV)**
- **Absorption** and **Migdal** limits coming

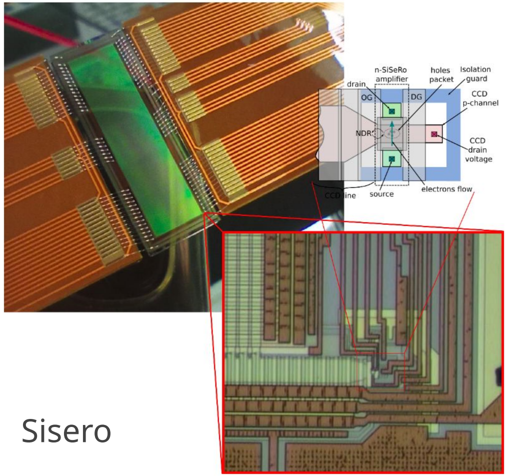
- **Production** of full **100 g** detector fully funded and ongoing.
- **SENSEI** experiment will collect almost **2 million** times the exposure of the first run in ~ **2-3 years**, probing large regions of uncharted territory populated by popular models
- **generations** of **skipper-CCD** experiments foreseen for cosmic DM searches in the next ~ 7 years
- **New efforts** to build particle **trackers** at **beams** for **mCPs**

New generations with faster read-out @ FNAL

MAS Skipper-CCD



https://arxiv.org/abs/2308.09822

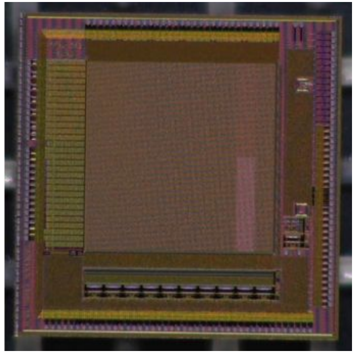


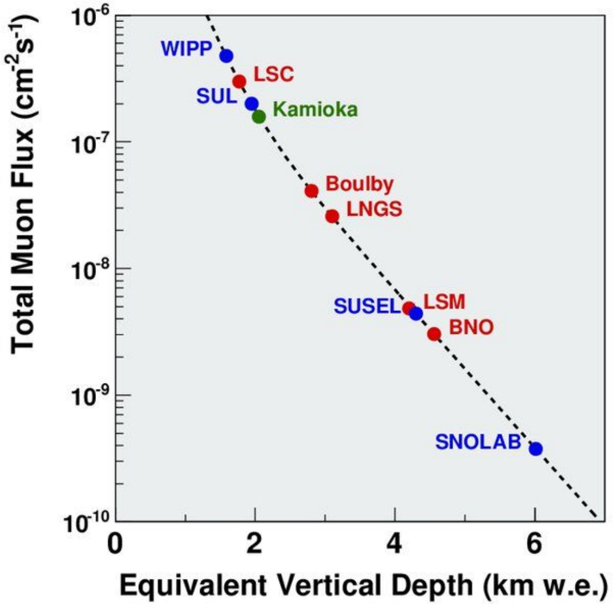
Sisero

5x2.5 μm

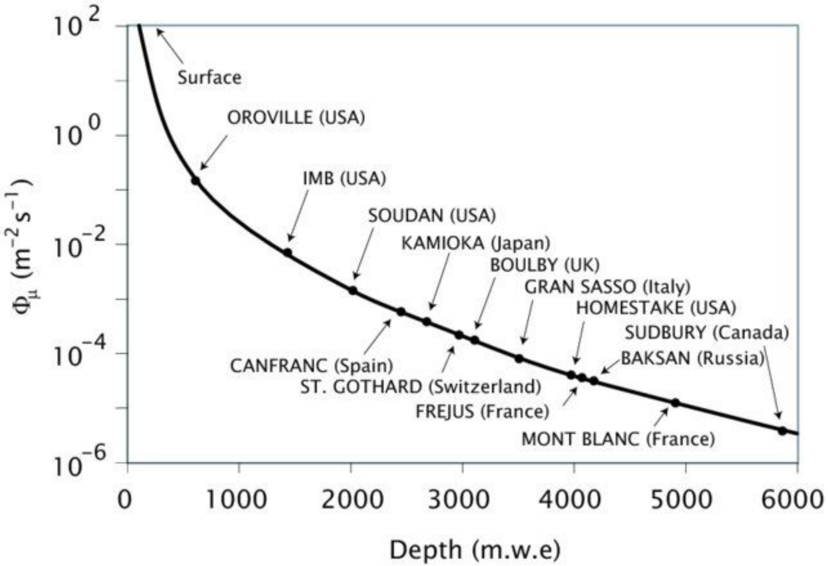
https://arxiv.org/pdf/2310.13644.pdf

Skipper-CMOS



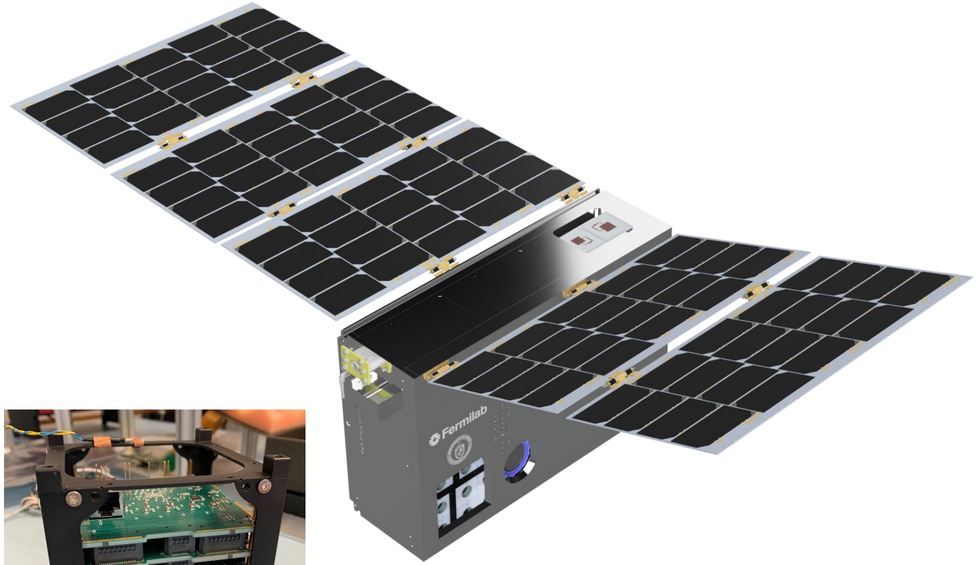


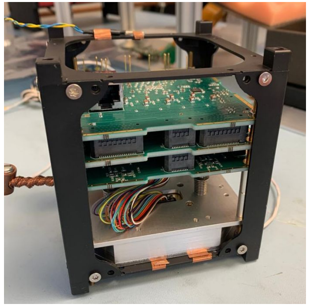
The search for neutrinoless double beta decay. La Rivista del Nuovo Cimento 35(2)

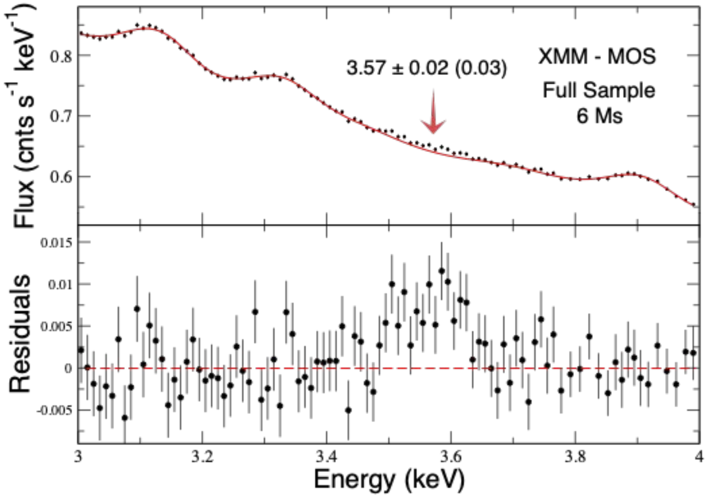


The Canfranc Underground Laboratory. Present and Future. Igor G. Irastorza

And more: DarkNESS



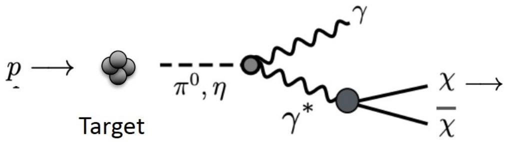




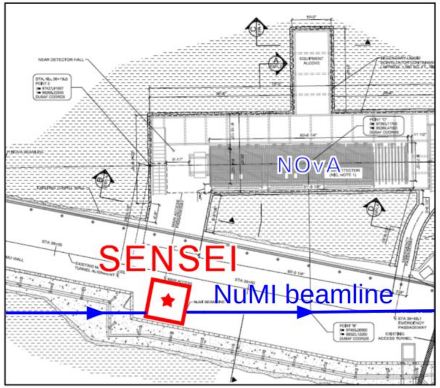
Bubul et al 2014 observed this line at 3.5 keV in galaxy clusters using X-ray telescope.

Going back to Milli-charged particles @ MINOS

Proton collisions w/ fixed target -> mCPs collinear w/ NuMI beamline:



arXiV:1902.03246



Extension of previous analysis to 6e-

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Efficiency	0.069	0.105	0.325	0.327	0.331	0.338
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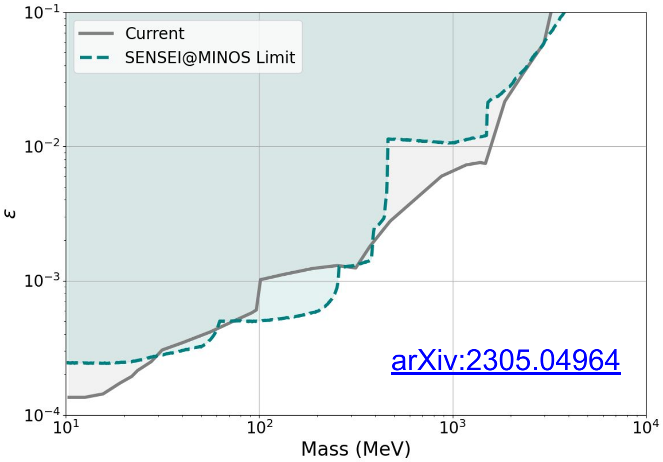
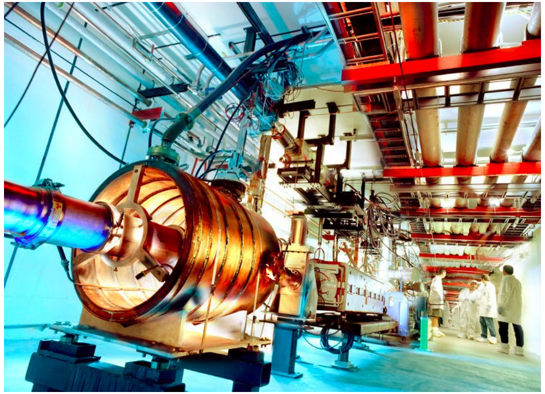
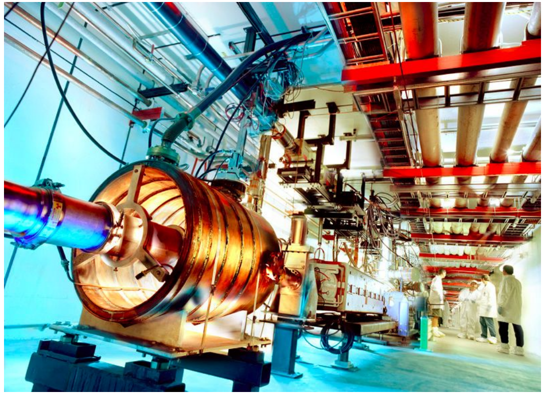


NuMI



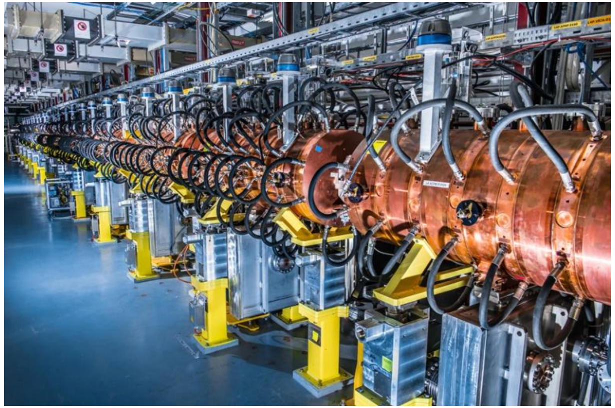
Magnetic focusing "horn" at NuMI beam.

NuMI



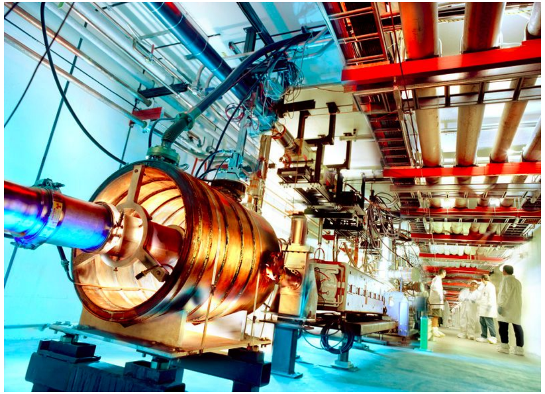
Magnetic focusing "horn" at NuMI beam.

PIP-II

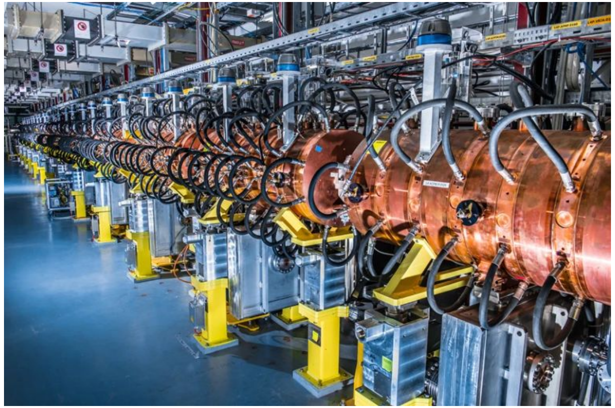


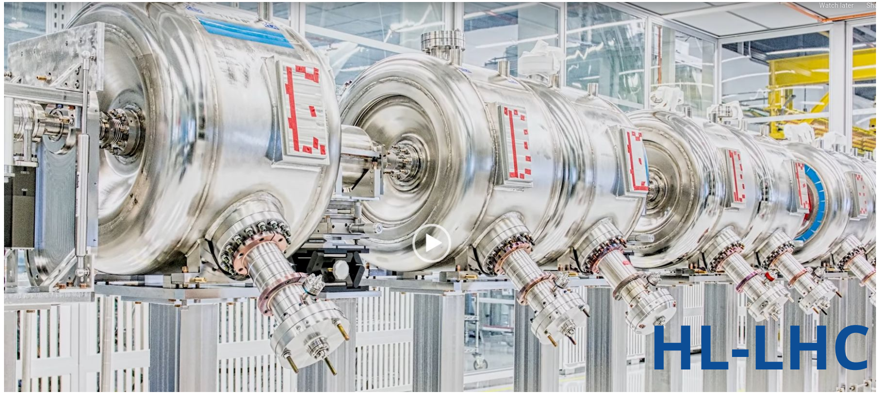
PIP-II 325 MHz spoke resonator cavity string

NuMI


Magnetic focusing "horn" at NuMI beam.

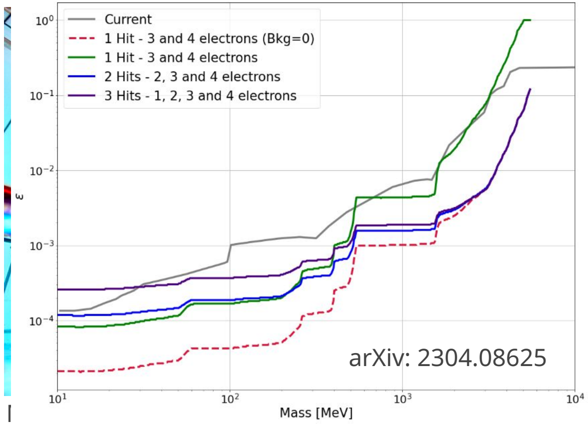
PIP-II


PIP-II 325 MHz spoke resonator cavity string

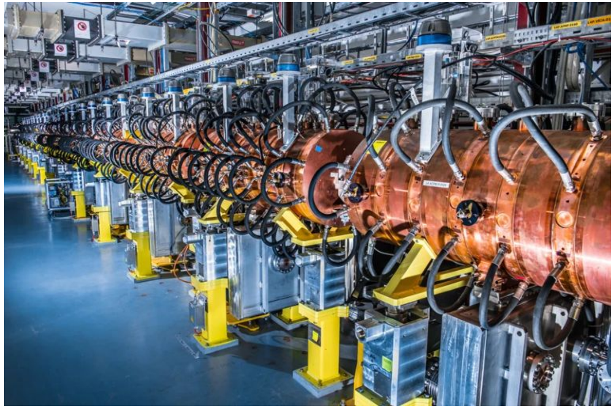


CERN's 86-metre long Linac4 accelerator, which produces proton beams for the Large Hadron Collider. Credit: Robert Hradil, Monika Majer/ProStudio22.ch/CERN

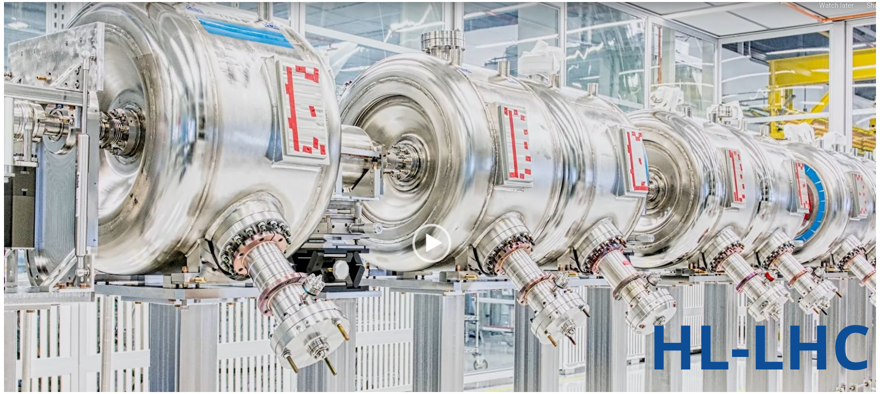
NuMI



PIP-II



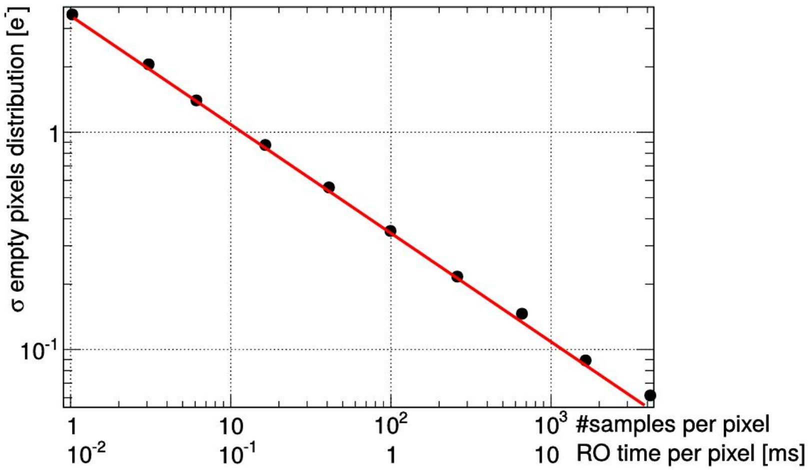
PIP-II 325 MHz spoke resonator cavity string

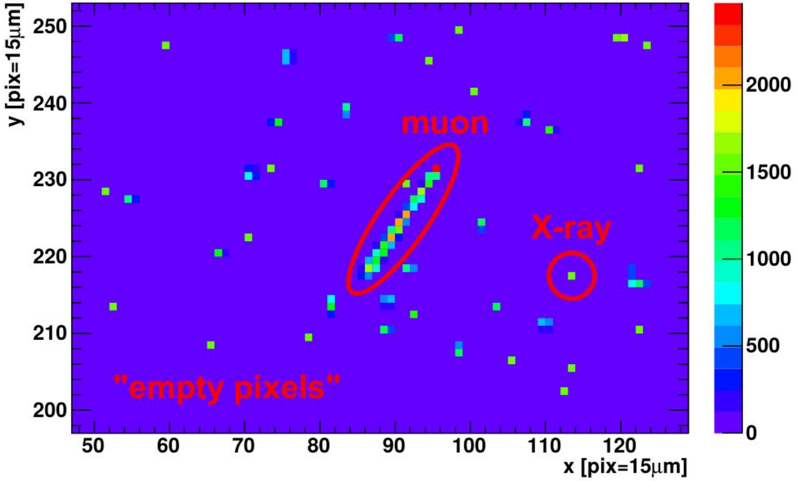


HL-LHC

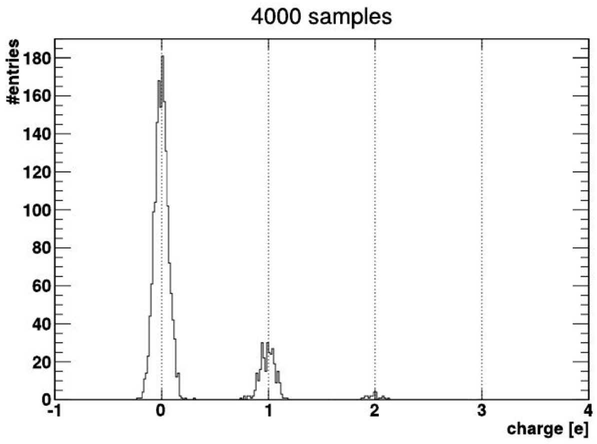
CERN’s 86-metre long Linac4 accelerator, which produces proton beams for the Large Hadron Collider. Credit: Robert Hradil, Monika Majer/ProStudio22.ch/CERN

Skipper-CCD read-out noise

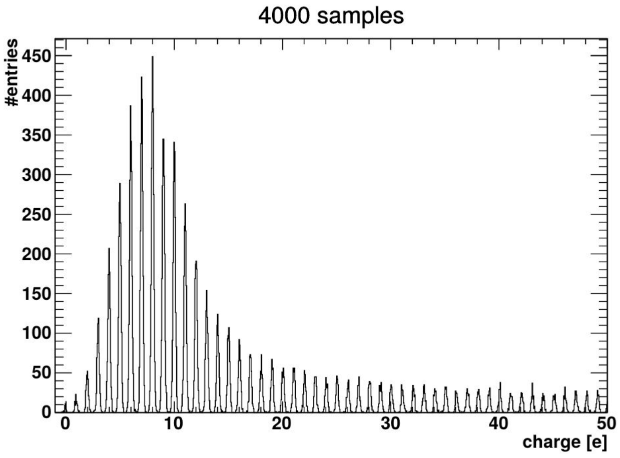




Skipper-CCD resolution



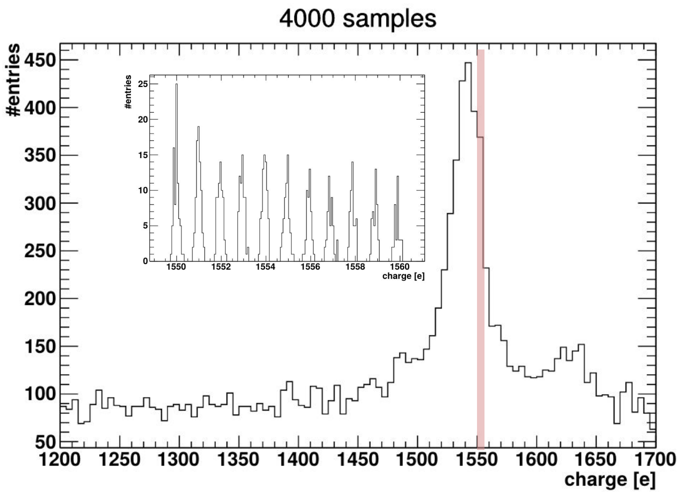
(Almost) Empty CCD



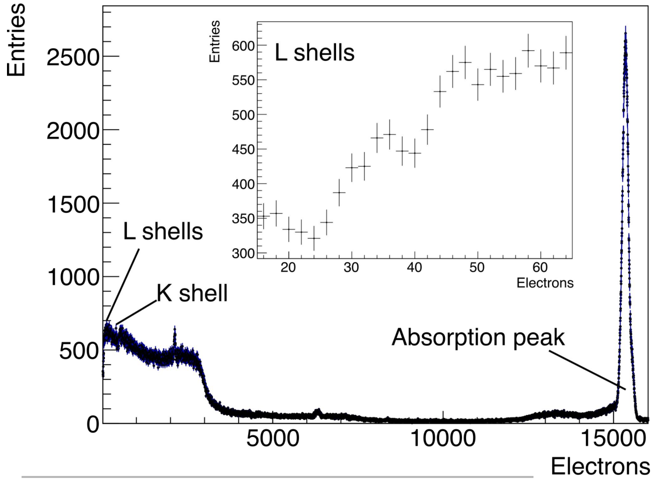
Front-illuminated CCD

Skipper-CCD for photo detection

D. Rodrigues et al., NIMA A 1010 165511

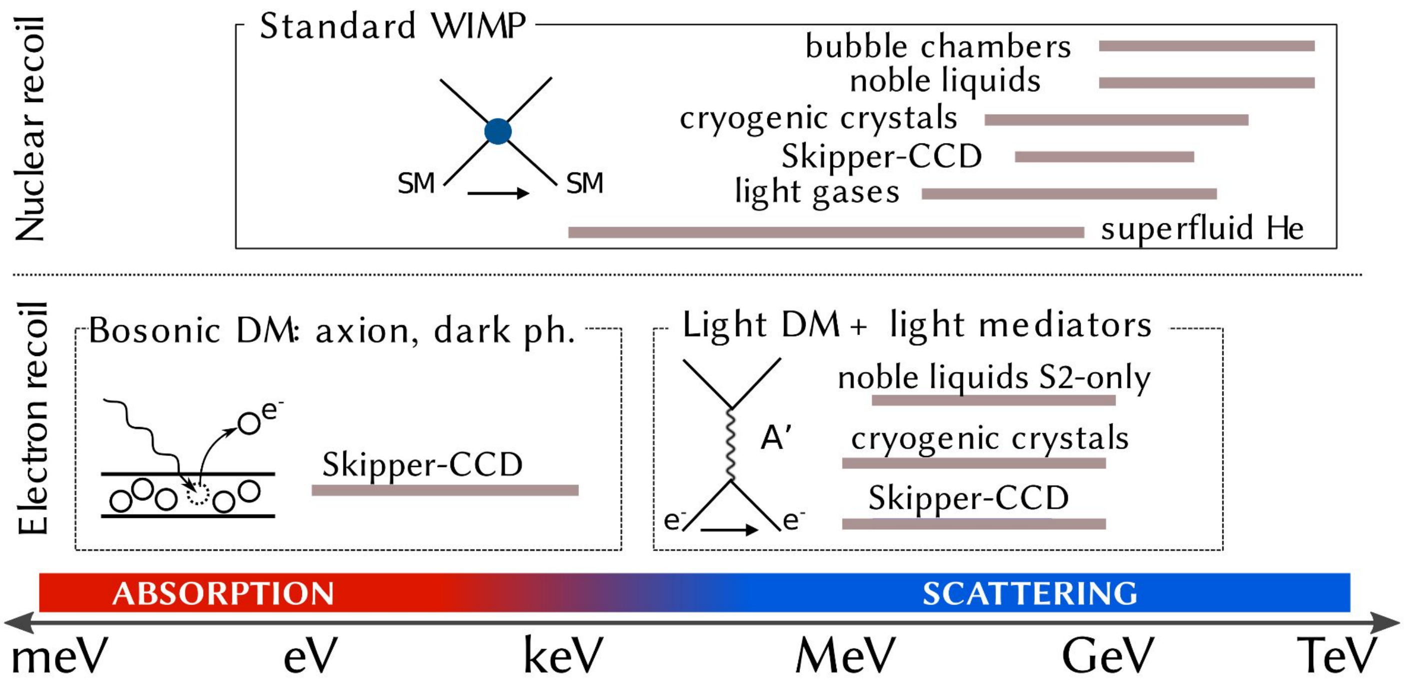


Charge per event for 55Fe x-ray source



Compton scattering spectrum in Silicon with 241Am γ-ray source

Experimental approach



Proto-SENSEI runs

@ **surface**:

- Data from May 2017
- Sea level
- 3 mm copper shielding
- 18 images **continuous read**
- DC **1.14 e-/pixel/day**
- **0.019 gram-day** total exposure

@ **MINOS**:

- Data from 2018
- 230 m.w.e.
- **Cylindrical vacuum vessel** with 2” lead.
- Two readout modes (continuous & **periodic**)
- Single-electrons events **0.1~0.005 events/pix/day**
- **0.177 ~ 0.069 gram-day** total exposure

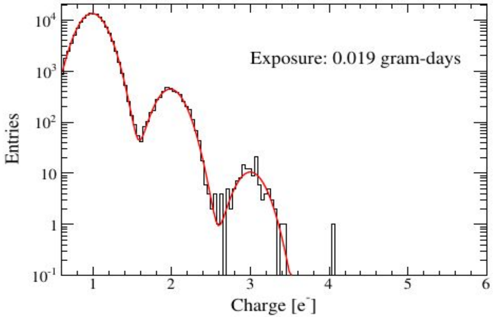
Device:

- 0.9 Mpix of 15 μm and 200 μm thick
- Active mass ~ 0.1 g
- 10 kΩ
- T ~ 130 K + vacuum
- 4 amplifiers
- 0.14 e- RO noise (800 samples)
- Operated with LTA board

Proto-SENSEI cuts

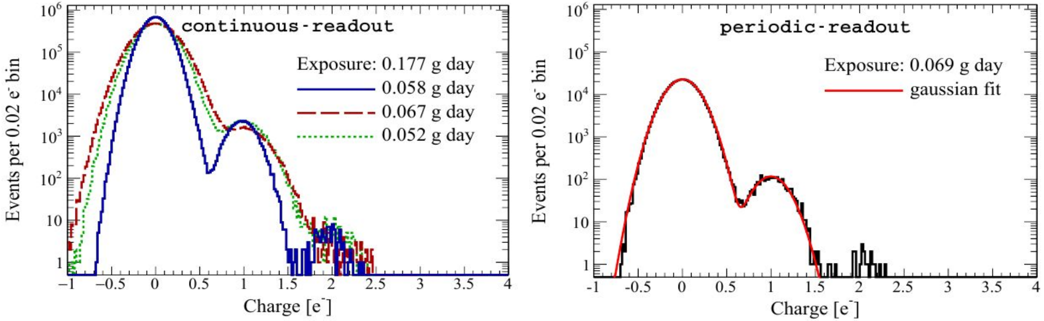
Cuts \ $N_{e,\min}$	1	2	3	4	5
1. DM within a single pixel	1	0.62	0.48	0.41	0.37
2. Nearest Neighbor	0.8	0.8	0.8	0.8	0.8
3. Noise	0.88	0.88	0.88	0.88	0.88
4. Bleeding	0.95	0.95	0.95	0.95	0.95
Total	0.67	0.41	0.32	0.27	0.24
Number of events	140,302	4,676	131	1	0

Surface run

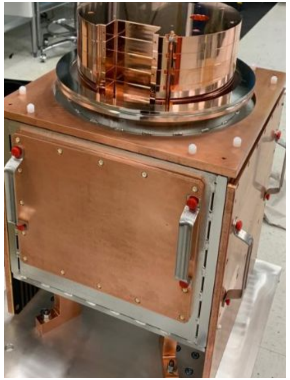


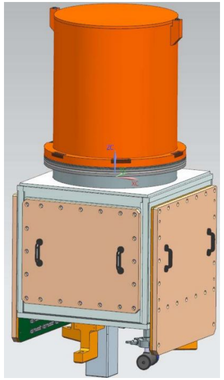
Cuts \ N_e	periodic			continuous		
	1	2	3	3	4	5
1. DM in single pixel	1	0.62	0.48	0.48	0.41	0.36
2. Nearest Neighbour	0.92			0.96		
3. Electronic Noise	1			~1		
4. Edge	0.92			0.88		
5. Bleeding	0.71			0.98		
6. Halo	0.80			0.99		
7. Cross-talk	0.99			~1		
8. Bad columns	0.80			0.94		
Total Efficiency	0.38	0.24	0.18	0.37	0.31	0.28
Eff. Expo. [g day]	0.069	0.043	0.033	0.085	0.073	0.064
Number of events	2353	21	0	0	0	0

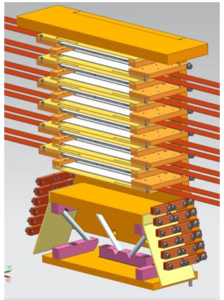
MINOS run

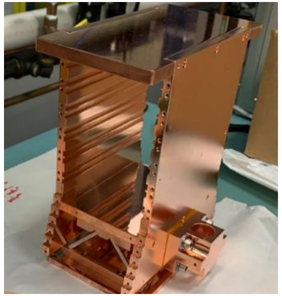


Perspectives @ SNOLAB









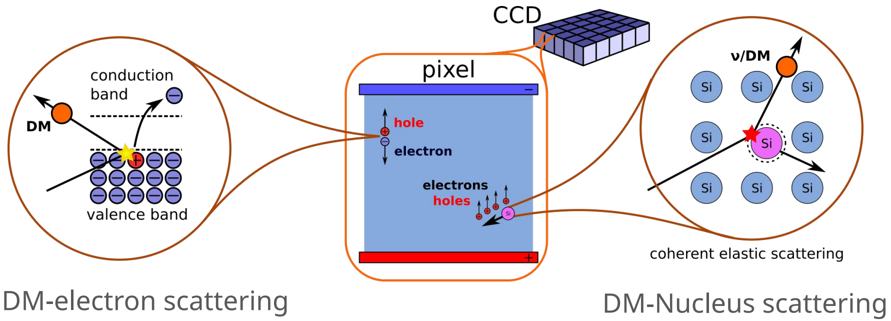
- Science-grade skipper-CCDs achieved
- Packaging and electronics also achieved
- Phase 1 system @ SNOLAB
- Vessel delivered to SNOLAB
- First CCDs deployed

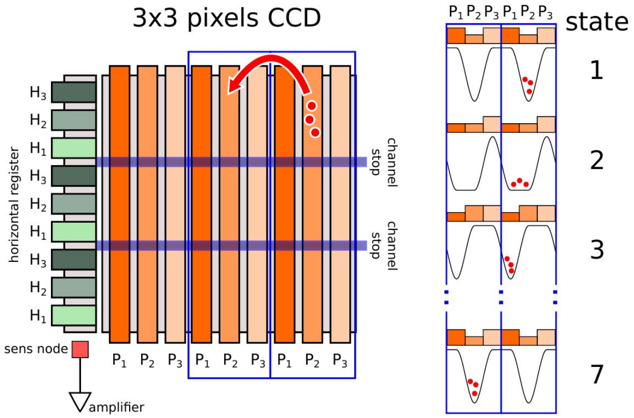
Towards a **100 g** skipper-CCD detector:

- Produce ~ **50** devices
- **Packaging** at Fermilab
- **Testing**
- Deliver and deploy at **SNOLAB**
- Status of Vessel?

➔ **10000** dru (MINOS standard shield): proto-SENSEI
➔ **3000** dru (MINOS extra shield): first science grade skipper
➔ **5** dru (SNOLAB): SENSEI 100 g

Charge-coupled devices (CCD)

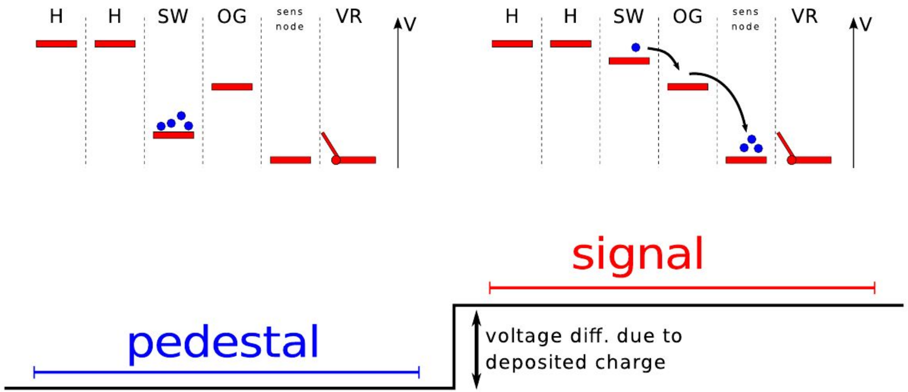




CCD read-out

Charge estimation:

1. **pedestal** integration
2. **signal** integration
3. **charge** = **signal** - **pedestal**

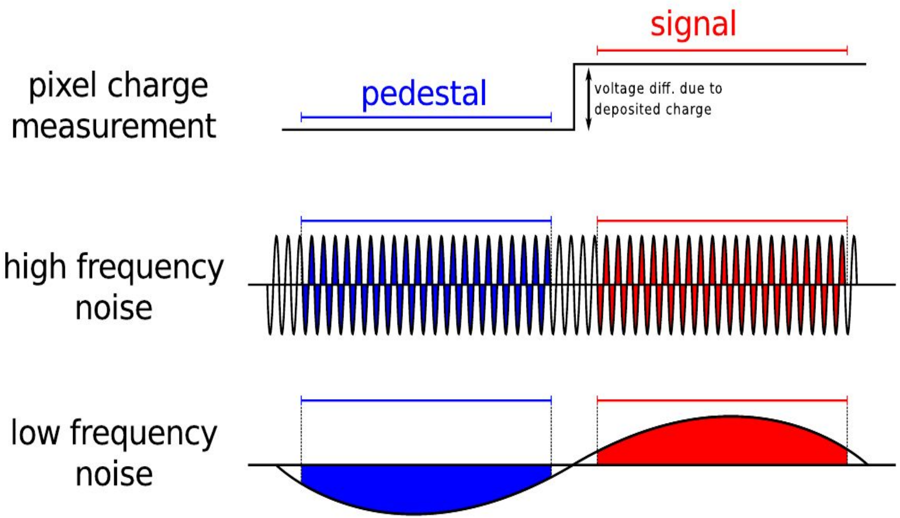


CCD read-out noise

Traditional **CCD**: **charge** transferred to sense node and read **once**

Pedestal and **signal** integration reduces **high-frequency** noise.

But not **low frequency**...

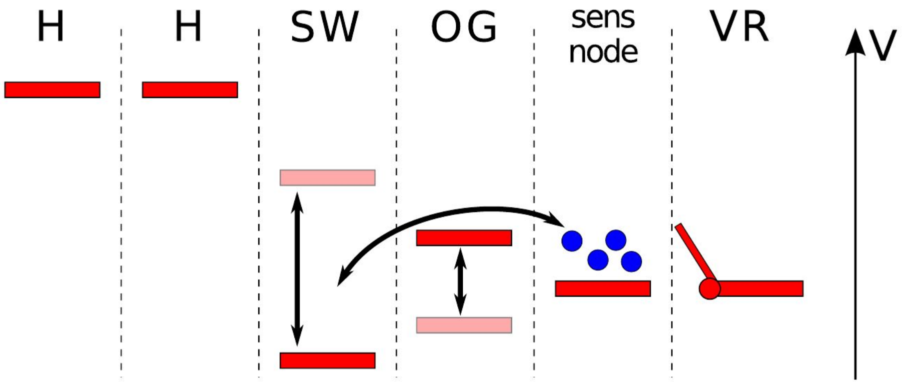


Skipper CCD read-out

Multiple sampling of same pixel without corrupting the **charge** packet.

Pixel value = **average** of all samples

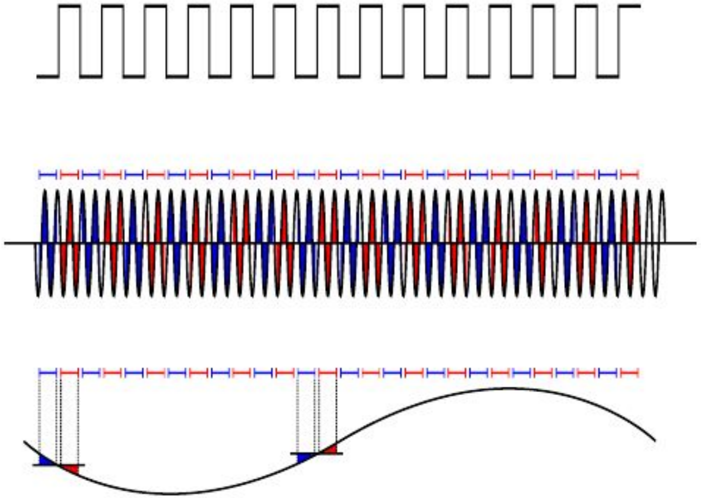
Suggested in **1990** by Janesick et al. (doi:10.1117/12.19452)



Skipper CCD read-out

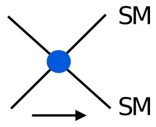
1. **pedestal** integration.
2. **signal** integration.
3. **charge** = **signal** – **pedestal**.
4. **Repeat** N times.
5. **Average** all samples.

Then, the low-frequency noise is reduced



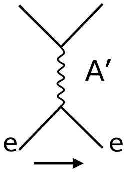
Detecting dark-matter candidates

Standard
WIMP

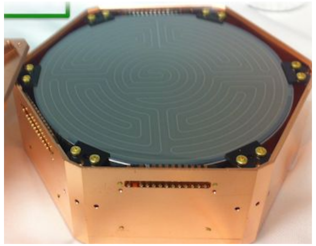


XENON Collaboration

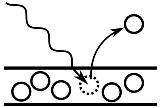
Light **DM** +
light mediators



SuperCDMS Collaboration



Bosonic **DM**
axion, dark photons



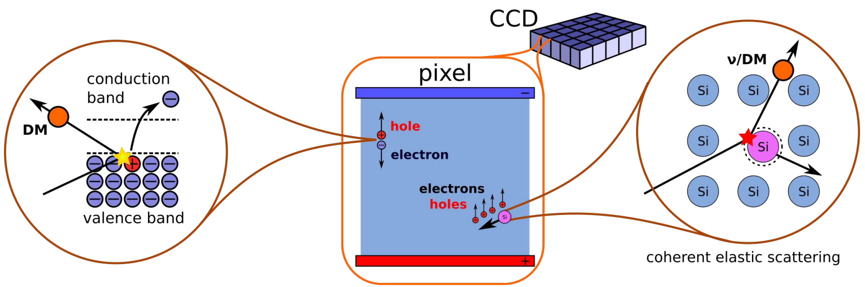
ADMX Collaboration

- ➔ Coherent nucleus interaction $\sigma_{n\text{-}DM}$
- ➔ Nucleus / electron interactions
- ➔ Light nuclei for mDM << 10 GeV
- ➔ Targets: noble gases / liquids, cryogenic crystals , semiconductors, scintillators

- ➔ Electron interactions
- ➔ Targets: noble gases / liquids, cryogenic crystals , semiconductors, scintillators

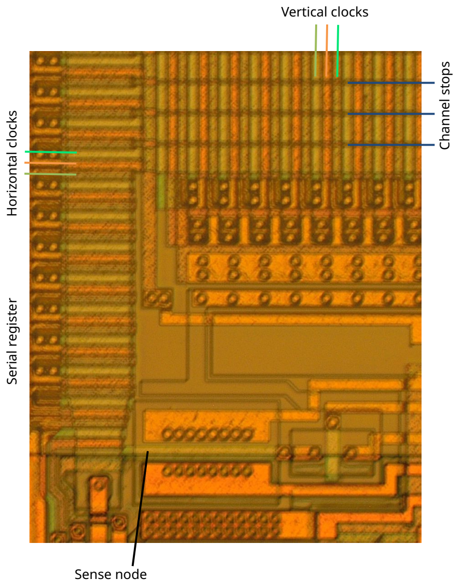
- ➔ Photon mixing, photoelectric absorption
- ➔ Targets: resonant cavities, semiconductors.

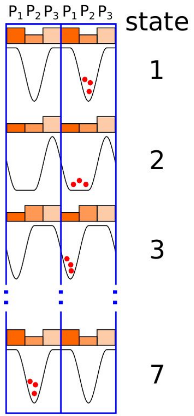
Charge-coupled devices (CCD)



DM-electron scattering

DM-Nucleus scattering





SENSEI @ SNOLAB






Cambiar imagenes

Towards a **100 g** science grade skipper-CCD detector:

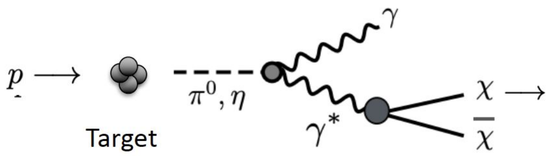
- Produce ~ **50** devices
- **Packaging** at Fermilab
- **Testing**
- Deliver and deploy at **SNOLAB** (6000 m.w.e.)

Vessel deployed during the pandemic by SNOLAB stuff

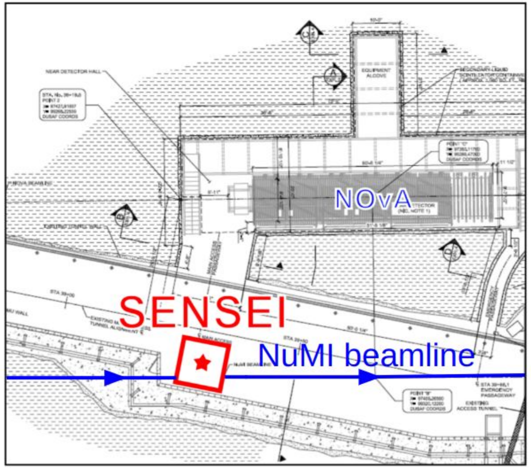
→ **10000** dru (MINOS standard shield): proto-SENSEI
→ **3000** dru (MINOS extra shield): first science grade skipper
→ **5 (ultimate goal)** dru (SNOLAB): SENSEI 100 g

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

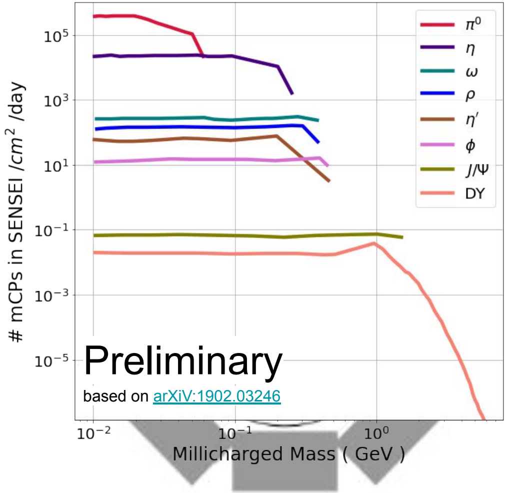
Proton collisions w/ fixed target can produce mCPs collinear w/ NuMI beamline:



arXiV:1902.03246



Using production rates accepted by SENSEI@MINOS…



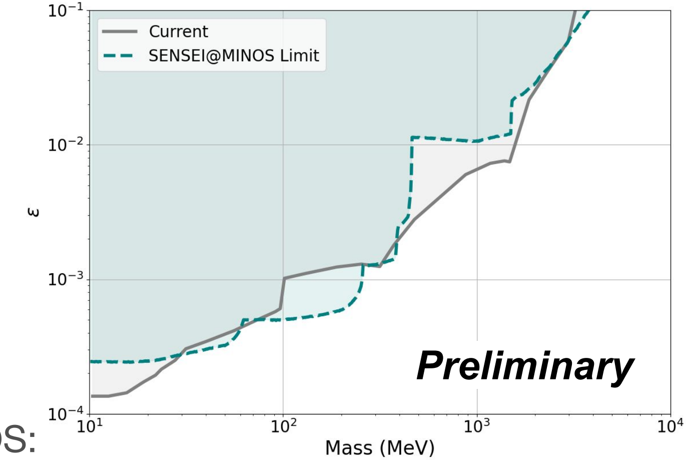
… and data from SENSEI@MINOS:

	$1e^-$	$2e^-$	$3e^-$	$4e^-$	$5e^-$	$6e^-$
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 $6e^-$ (PRELIMINARY)

Paper forthcoming!

World-leading limits around 100 MeV:



Significant potential for future mCP searches with CCDs!