The SENSEI Experiment

dark-matter searches with Skipper-CCDs

A. M. Botti* for the SENSEI† collaboration
KEK IPNS-IMSS-QUP Joint workshop 2022
February 8-10, 2022

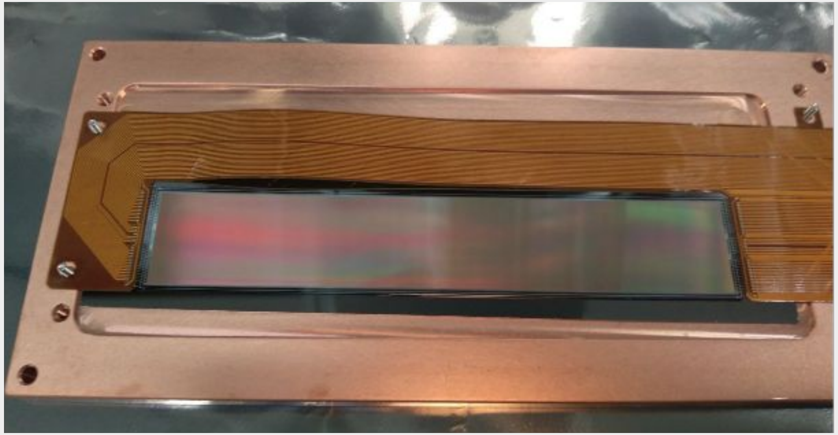


Image: SENSEI sensor

* Fermi National Accelerator Laboratory · abotti@fnal.gov
† Sub-Electron-Noise Skipper-CCD Experimental Instrument · https://sensei-skipper.github.io

Outline

1. Dark matter evidence, detection, candidates, and experiments
2. The sensei experiment
3. Skipper-CCDs
4. ProtoSENSEI
5. First scientific-grade skipper-CCD
6. Prospects

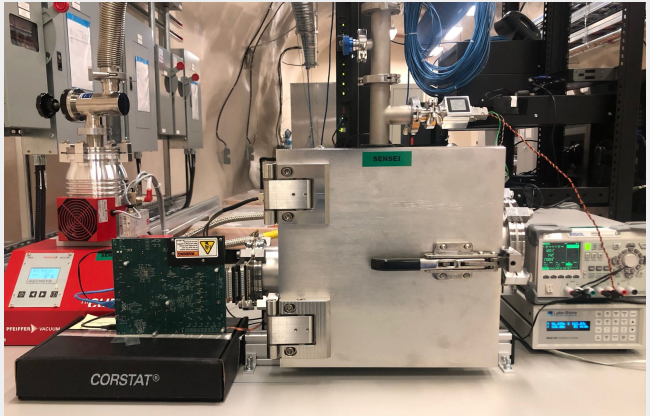
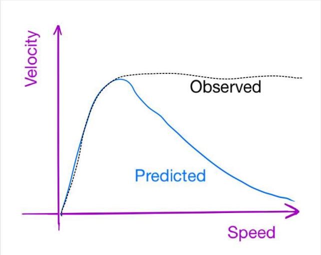
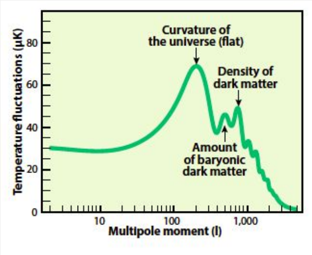


Image: Skipper-CCD testing setup

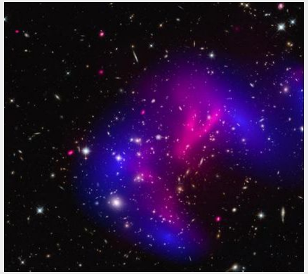
Dark-matter evidence

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

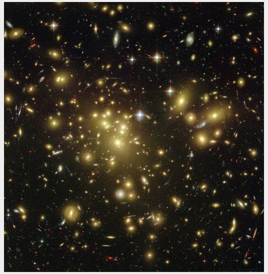




Astronomy: Roen Kelly, after Wayne Hu



NASA, ESA, STScI, CXC.



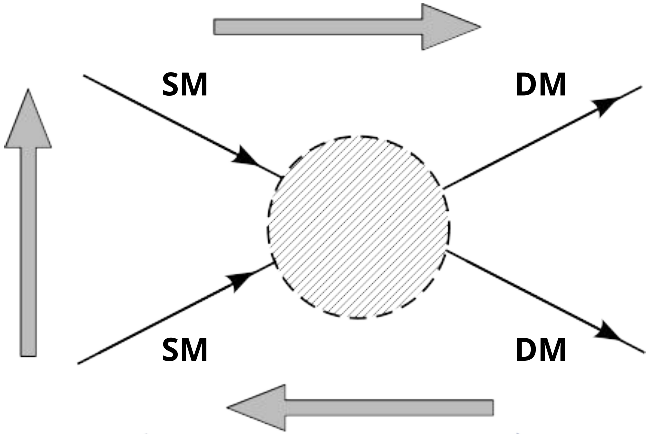
Hubble space telescope

Dark-matter detection

Colliders

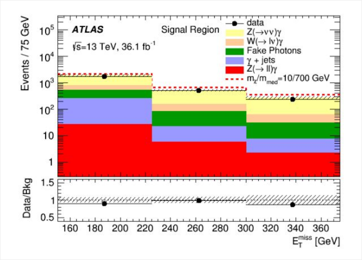
Direct detection

(This talk)

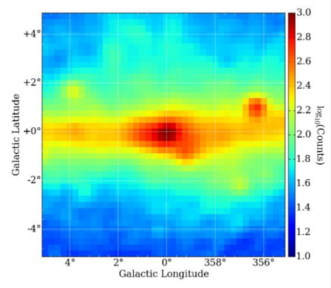


Indirect detection

(Gammas, neutrino, and cosmic rays)

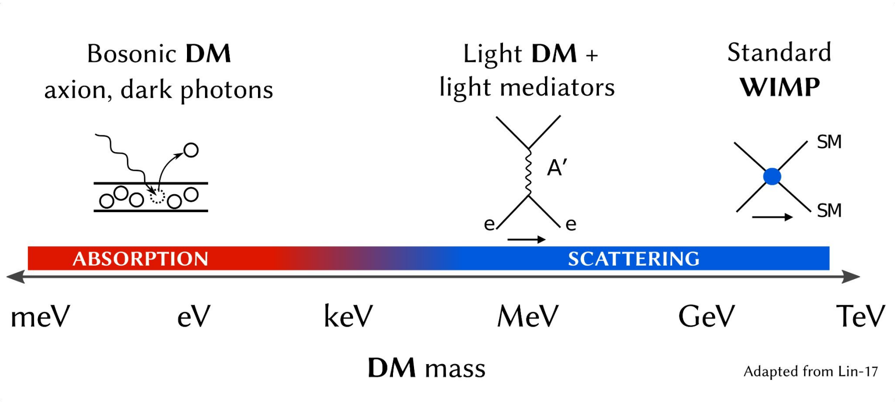


The ATLAS Collaboration. Eur. Phys. J. C 77, 393 (2017)



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

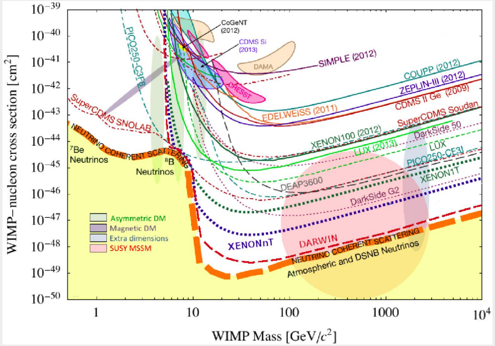
Dark-matter candidates



Field like

Particle like

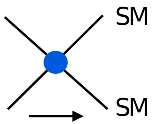
WIMPs favoured by ΛCDM



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

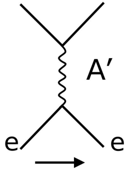
Detecting dark-matter candidates

Standard
WIMP

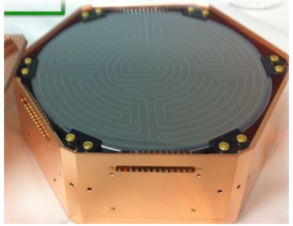


XENON Collaboration

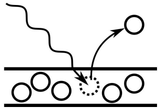
Light **DM** +
light mediators



SuperCDMS Collaboration



Bosonic **DM**
axion, dark photons



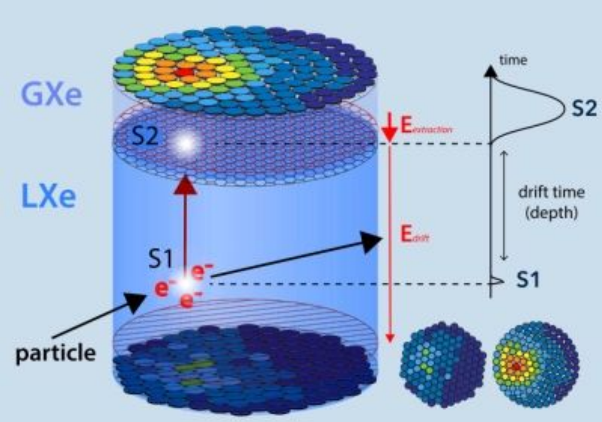
ADMX Collaboration

- ➔ 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

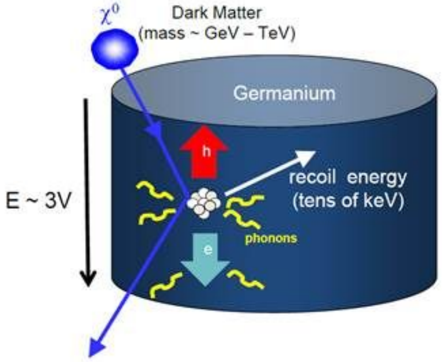
- ➔ Photon mixing, photoelectric absorption
- ➔ Targets: resonant cavities, semiconductors.

Experimental examples



Xenon 1T (nobel Gas/Liquid):

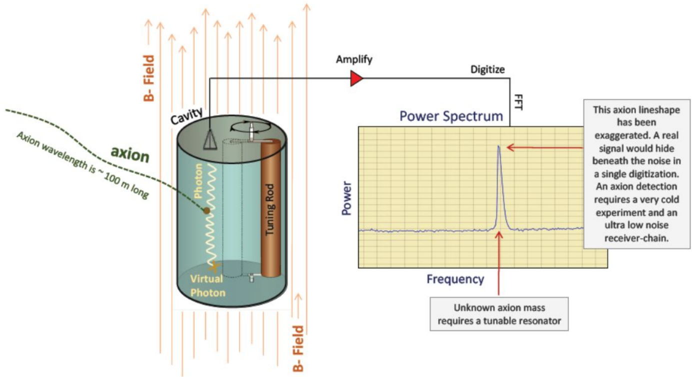
- ➔ dual-phase TPC with Xe at T ~ 170 K
- ➔ 2016-2018 at LNGS (3600 mwe)
- ➔ Nucleus recoil: no evidence of WIMPs
- ➔ Electron recoil: 3.5 σ excess at about 1~7 keV



SuperCDMS SNOLAB (cryogenic):

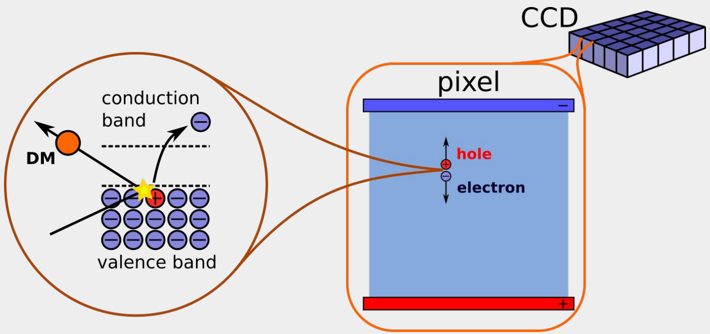
- ➔ SuperCDMS SOUDAN (2012 – 2015) sucesor.
- ➔ 40 kg Ge/Si solid-state detectors at T ~ mK.
- ➔ Beginning 2021 at SNOLAB (6000 mwe).
- ➔ Leading limits on low-mass WIMPs

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.



SENSEI (Skipper-CCD):

- ➔ 1st DM experiment with skipper-CCD.
- ➔ 100 g Si at T ~ 140 K.
- ➔ Beginning ~ 2021 at SNOLAB (6000 mwe).
- ➔ Best limits on e-/nucleus scattering (Migdal effect) and absorption with commissioning data < 10 MeV, 0.6~5 MeV, and 1.2~12.8 eV.

The SENSEI Collaboration

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

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& leveraging R&D support from Fermilab

The Sensei Experiment

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

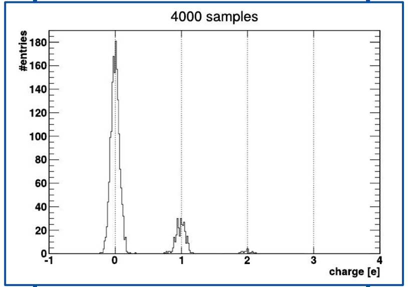
New generation Charge Couple Devices **(CCD)**
LBNL MicroSystems Lab Energy threshold **~ 1.1 eV**
(Si bandgap) and readout noise **~ 0.1 e^-**

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

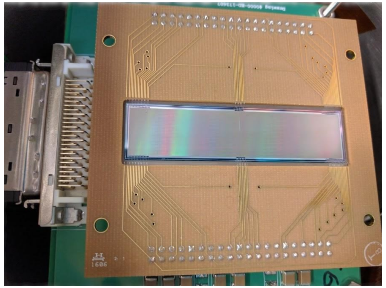
2017	2018	2019	2020	Ongoing
Demonstrate sub-electron resolution	DM search with **proto-SENSEI** (0.1 g) at **surface**	DM search with **proto-SENSEI** at **MINOS** (230 m.w.e.)	DM search with **science grade** (~2 g) at **MINOS**	**Production** (100g) + commissioning at **SNOLAB** (6000 m.w.e.)



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

First Skipper-CCD prototypes

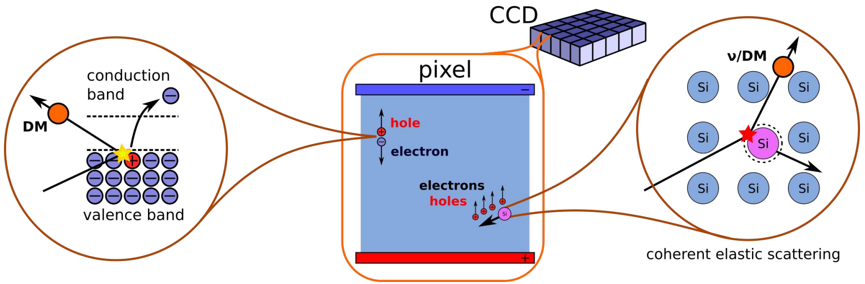
- Prototype designed at LBNL MSL
- 200 & 250 μm thick, 15 μm pixel size
- Two sizes 4k × 1k (0.5gr) & 1.2k × 0.7k pixels
- Parasitic run, optic coating and Si resistivity ~10kΩ
- 4 amplifiers per CCD, three different RO stage designs



Instrument:

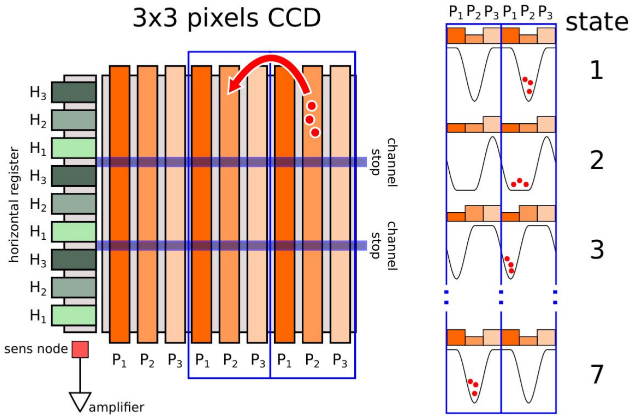
- System integration done at Fermilab
- Custom cold electronics
- Firmware and image processing software
- Optimization of operation parameters

Charge-coupled devices (CCD)



DM-electron scattering

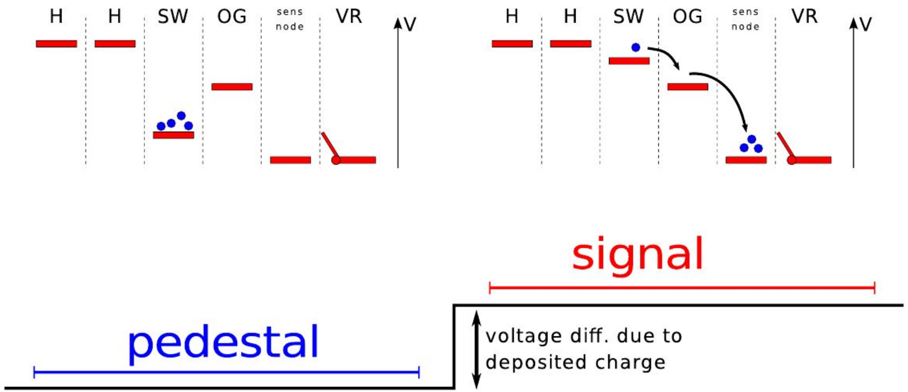
DM-Nucleus scattering



CCD read-out

Charge estimation:

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

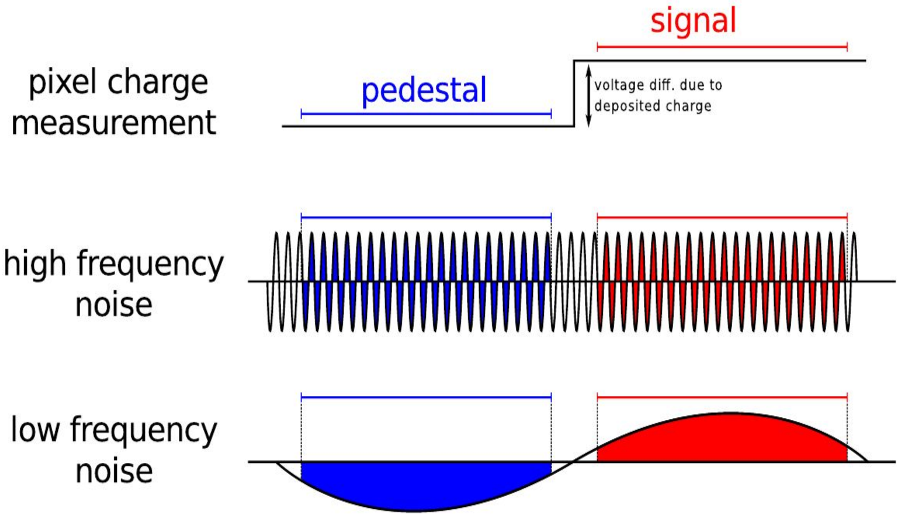


CCD read-out noise

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

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

But not **low frequency**…

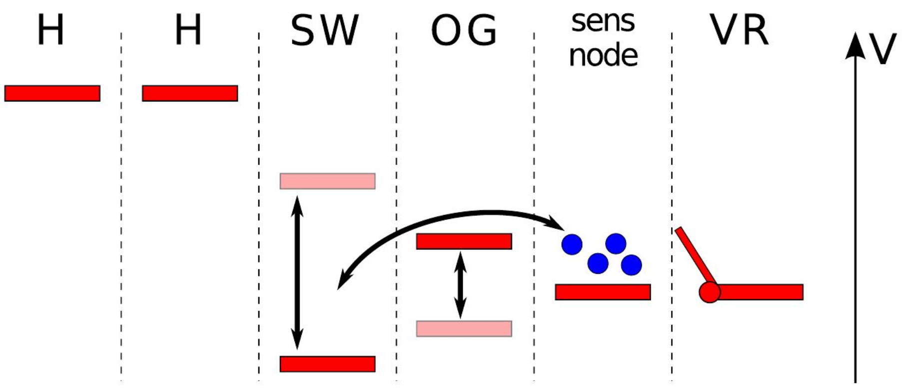


Skipper CCD read-out

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

Pixel value = **average** of all samples

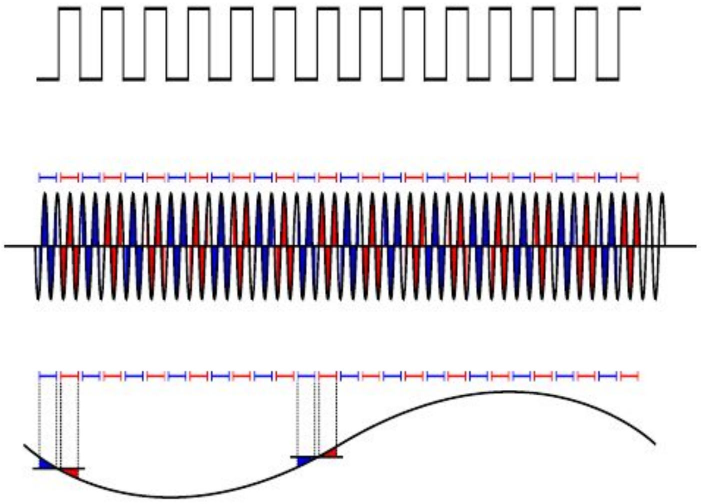
Suggested in **1990** by Janesick et al. (doi:10.1117/12.19452)



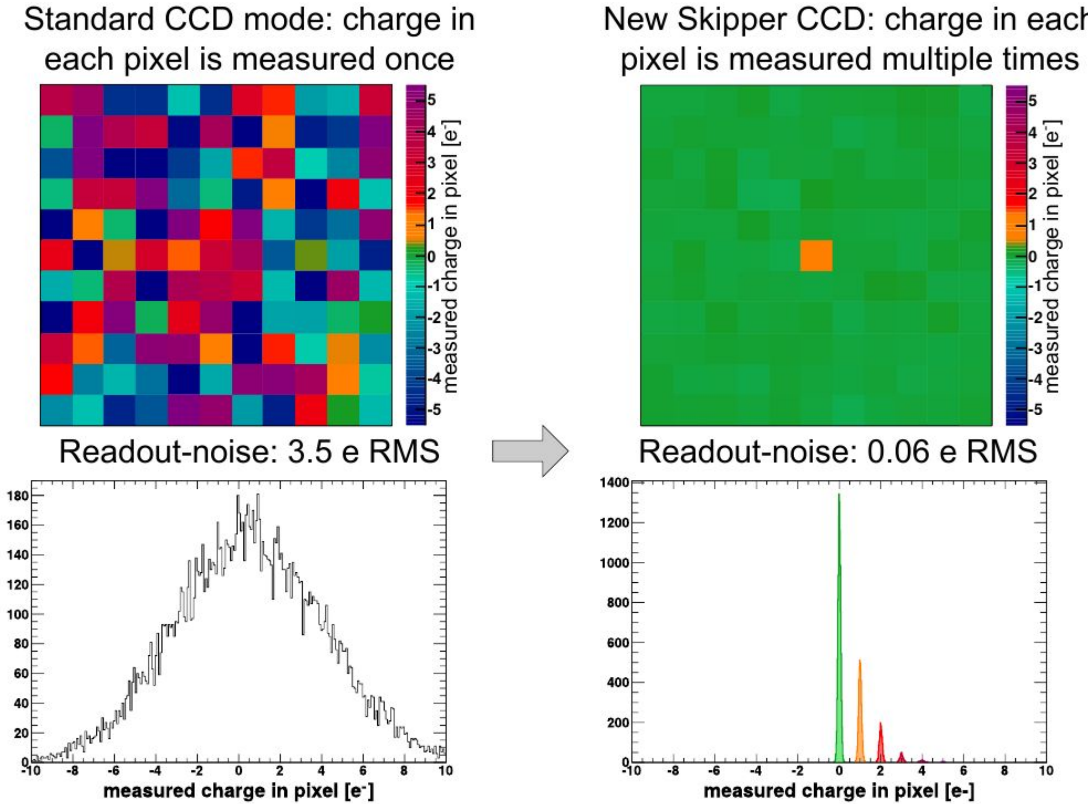
Skipper CCD read-out

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

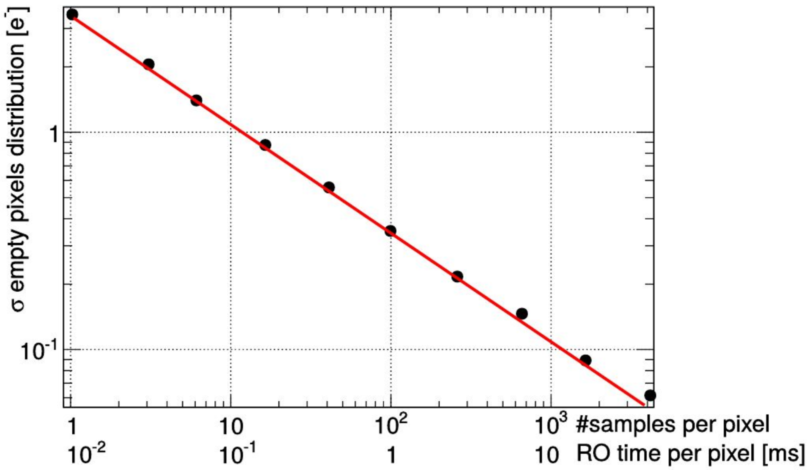
Then, the low-frequency noise is reduced

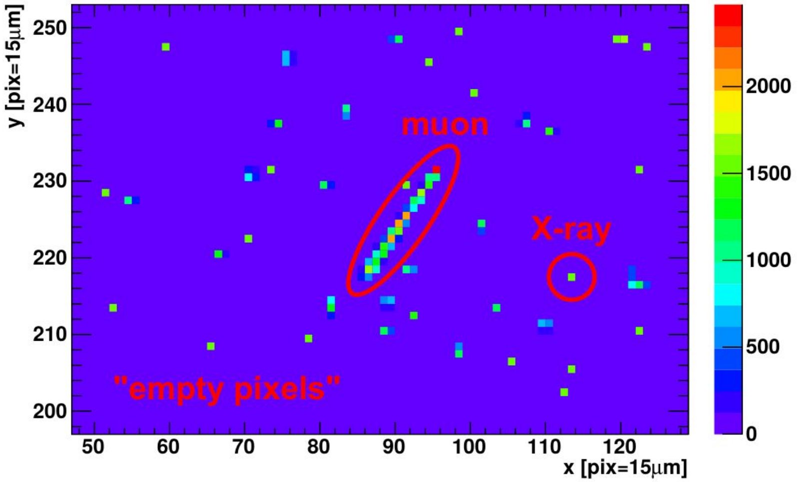


Skipper-CCD read-out noise

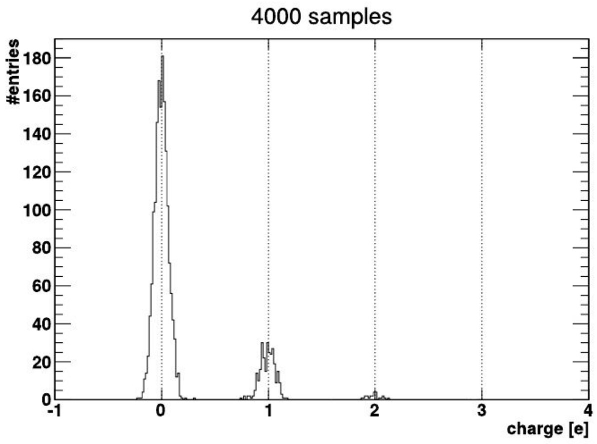


Skipper-CCD read-out noise

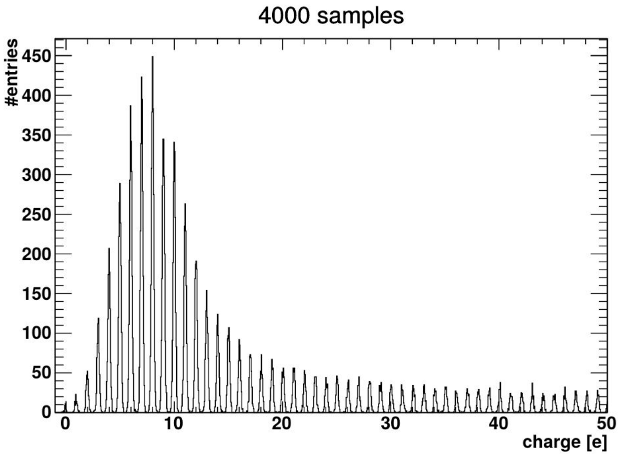




Skipper-CCD resolution



(Almost) Empty CCD



Front-illuminated CCD

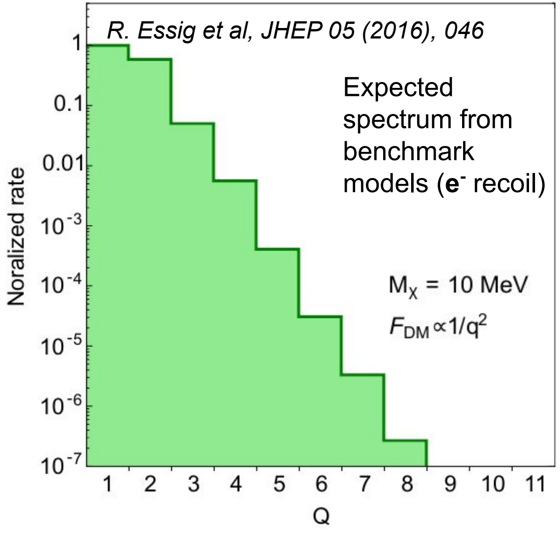
Skipper-CCDs for dark matter

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

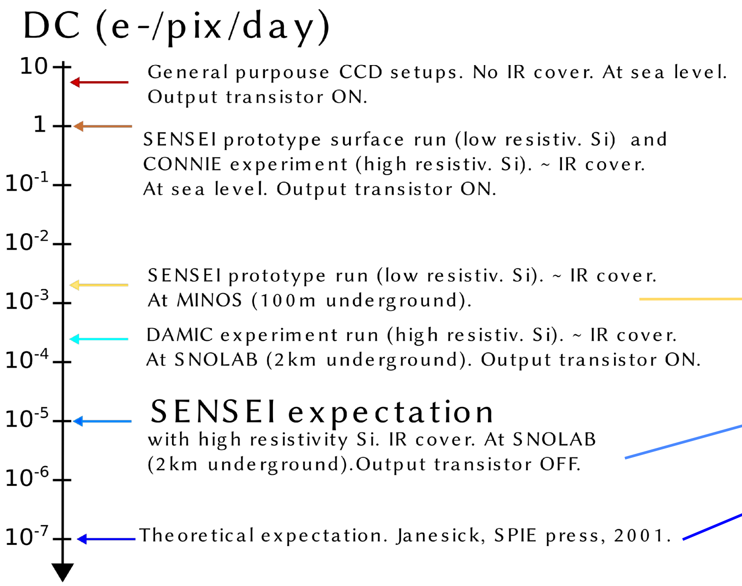
Sensitivity to **1,2,3 e**$^-$ signals needed: **Skippers** can do this!
But only if we understand and control **backgrounds**

Environmental background:
- Air-shower **muons** → go **underground**
- **Soil** radioactivity/environmental **radiation** → **shielding**

Detector noise:
- Dark counts → CCD **operation**
- Defects in crystal lattice → quality **cuts**
- Other spurious charge → CCD **operation** + quality **cuts**



Expected background



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

Expected background (detector)

Contribution (e^-/pix)		Time dependence: Linear – Exposure	Time dependence: Linear – Readout	Time dependence: Independent	Spatial distribution
Dark current	Intrinsic	$\lambda_{DC}\ t_{EXP}$	$\frac{\lambda_{DC}}{2}\ t_{RO}$	-	Uniform
	Extrinsic				Uniform
Amplifier-light current		-	$\lambda_{AL}\ t_{RO}$	-	Localized
Spurious charge		-	-	μ_{SC}	Uniform

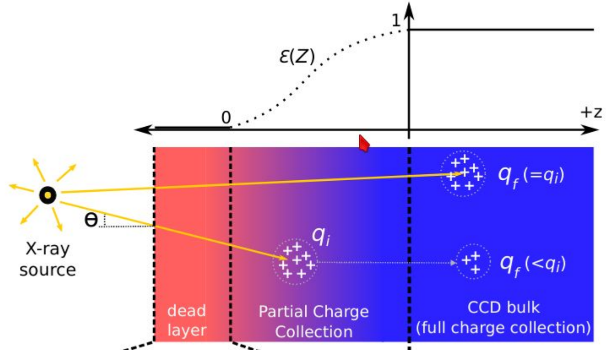
The SENSEI Collaboration. Phys. Rev. Applied 17, 014022 (2022)

Single electron rate reduced by optimizing operation parameters

- Read-out mode: continuous vs expose
- Voltage configuration
- Amplifier off while not reading

Expected background (environment)

- High-energy events (muons, electrons, etc).
- Halo and transfer inefficiency from high-energy events
- Interactions in partial charge collection layer
- Compton scattering

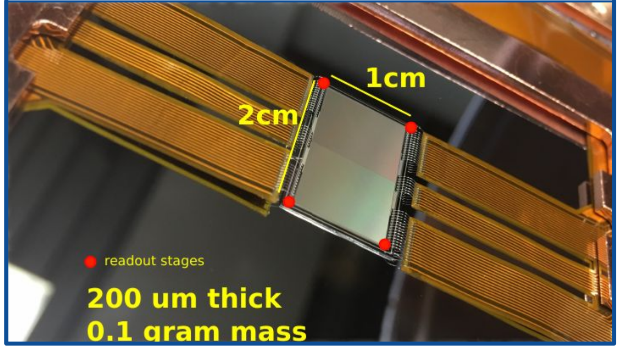


Unthinned CCD-A	2.2µm SiO_2	[0, ?] Si	~670µm Si
Thinned CCD-B	0.1 +0.04+0.02µm SiO_2+ZrO_2+In	[0, ?] Si	~200µm Si

G. Fernandez Moroni, Phys. Rev. Applied 15, 064026 (2021)

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.

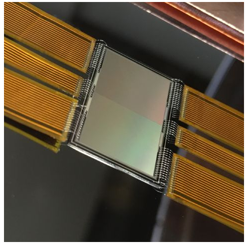
The SENSEI Collaboration
Physical review letters 122.16 (2019): 161801.

proto-SENSEI

R&D sensor:

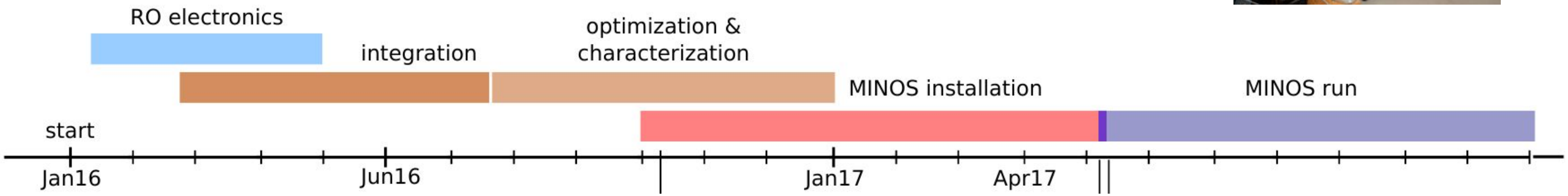
- **optimize** operation parameters
- develop **packaging** and **shielding**
- Characterize **background/noise**
- first physics **results**!

New package Commissioned at surface



Underground clean room

Deploy at MINOS + data taking



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

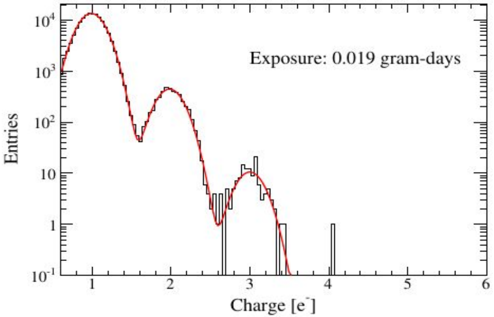
Device:

- 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

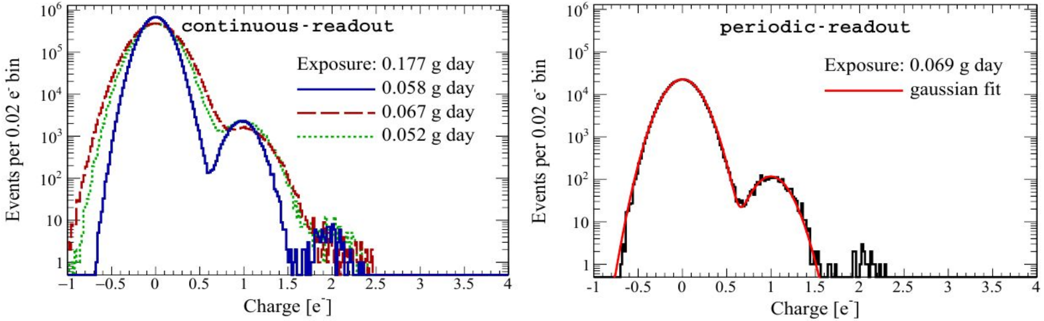
Cuts \ $N_{e,\text{min}}$	1	2	3	4	5
1. DM within a single pixel	1	0.62	0.48	0.41	0.37
2. Nearest Neighbor	0.8	0.8	0.8	0.8	0.8
3. Noise	0.88	0.88	0.88	0.88	0.88
4. Bleeding	0.95	0.95	0.95	0.95	0.95
Total	0.67	0.41	0.32	0.27	0.24
Number of events	140,302	4,676	131	1	0

Surface run

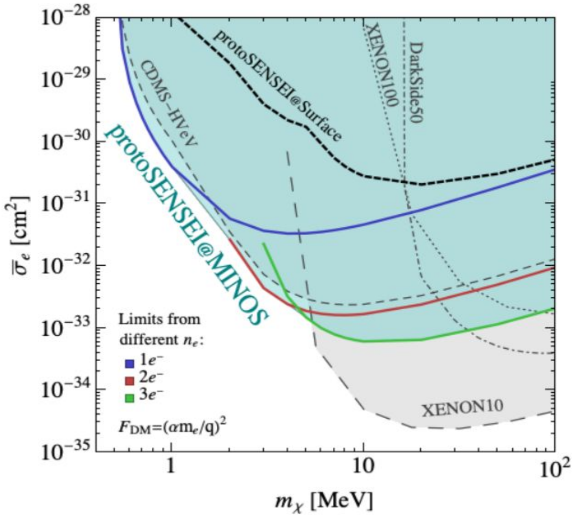


Cuts \ N_e	periodic			continuous		
	1	2	3	3	4	5
1. DM in single pixel	1	0.62	0.48	0.48	0.41	0.36
2. Nearest Neighbour	0.92			0.96		
3. Electronic Noise	1			~1		
4. Edge	0.92			0.88		
5. Bleeding	0.71			0.98		
6. Halo	0.80			0.99		
7. Cross-talk	0.99			~1		
8. Bad columns	0.80			0.94		
Total Efficiency	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

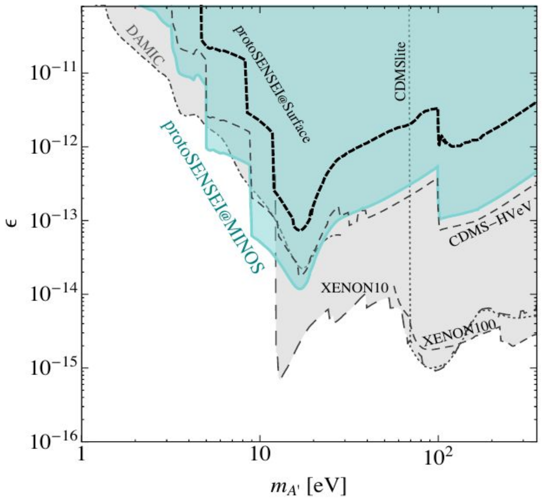
MINOS run



Proto-SENSEI results



***Ultralight** mediator*



Absorption

The Sensei Experiment

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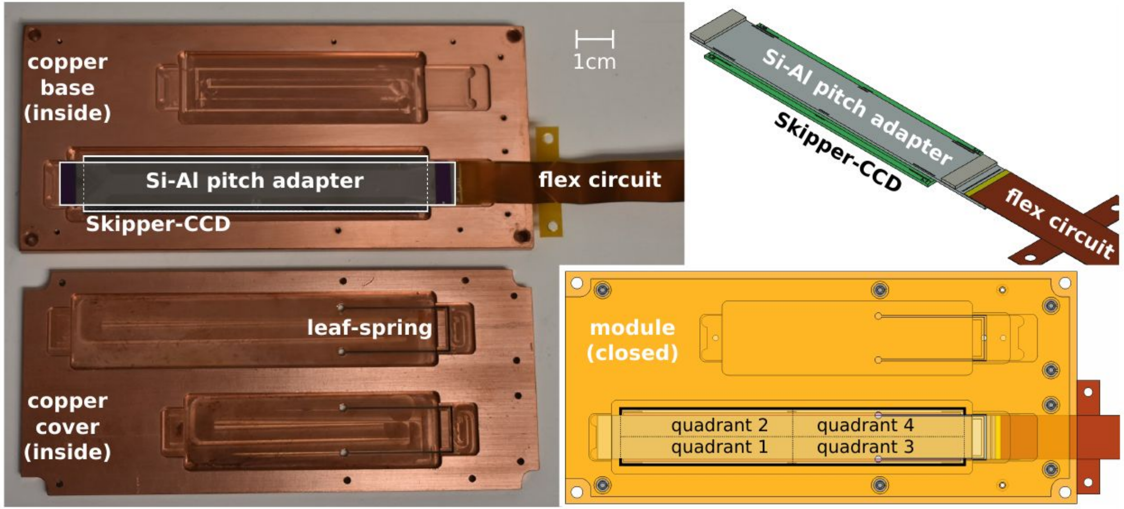
The SENSEI Collaboration
Phys. Rev. Lett. 125, 171802 (2020)

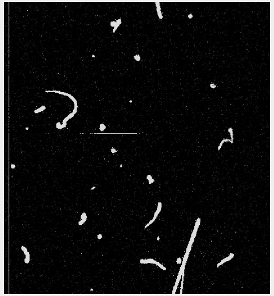
New device

- 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

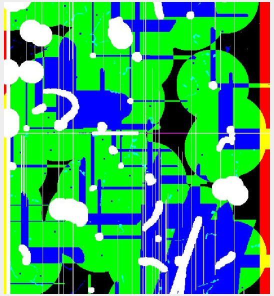


Quality cuts

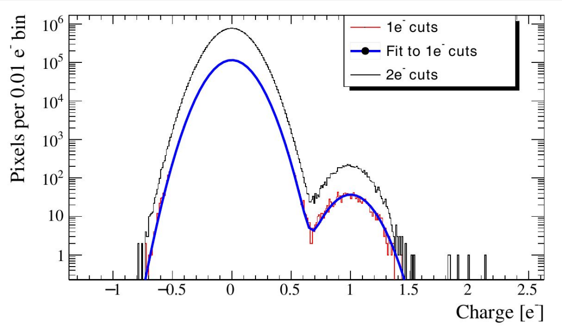
Cuts \ N_e	1		2		3		4	
1. Charge Diffusion	1.0		0.228		0.761		0.778	
	Eff.	#Ev	Eff.	#Ev	Eff.	#Ev	Eff.	#Ev
2. Readout Noise	1	$> 10^5$	1	58547	1	327	1	155
3. Crosstalk	0.99	$> 10^5$	0.99	58004	0.99	314	0.99	153
4. Serial Register	~ 1	$> 10^5$	~ 1	57250	~ 1	201	~ 1	81
5. Low-E Cluster	0.94	42284	0.94	301	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	



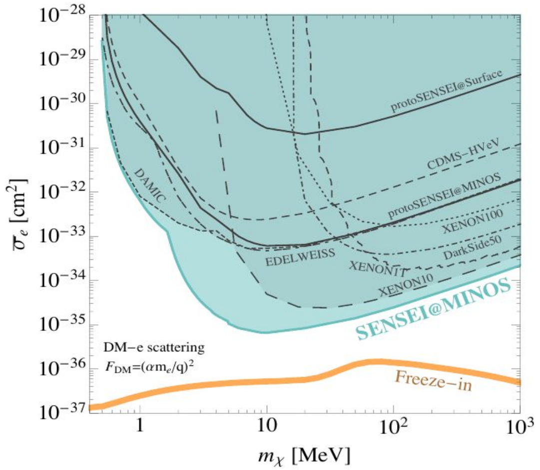
Example image



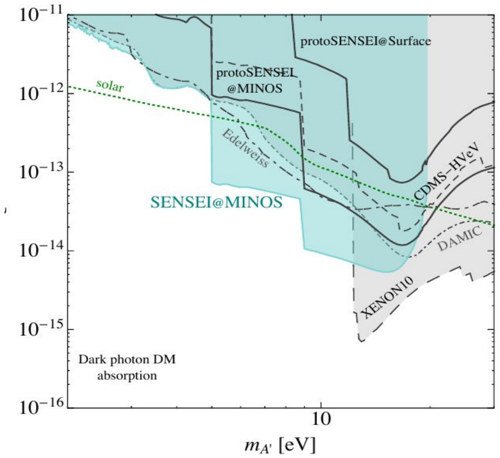
Masking



Latest results

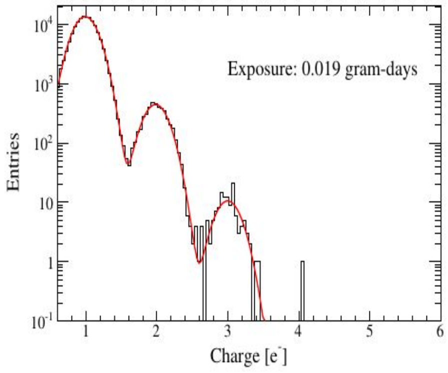


Light mediator
e^- scattering

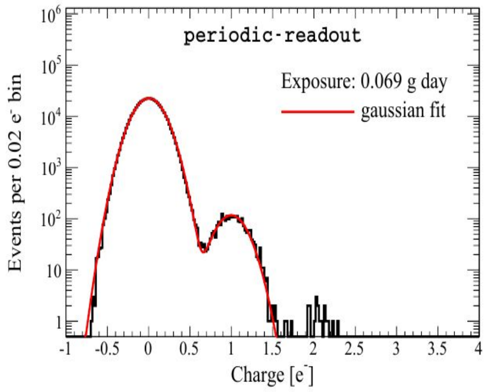


Absorption

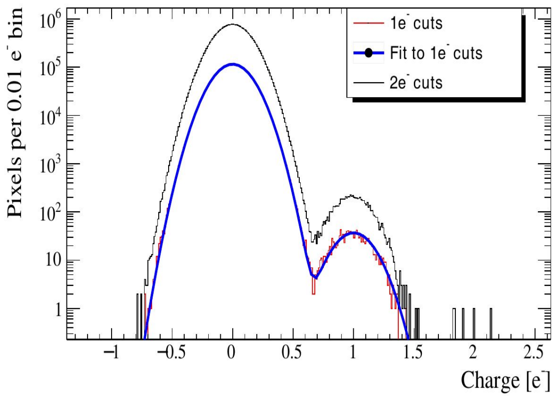
Summary: from prototype to science grade



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



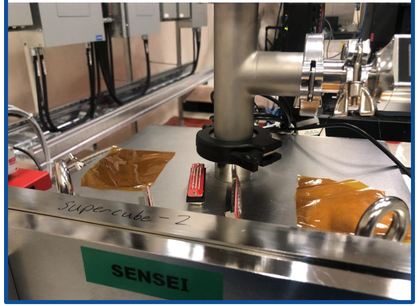
Active mass ~ **0.1 g**
0.069 gram-day exposure
0.14 e- RO noise
(**800** samples)
SEE ~ **0.005 e-/pix/day**



Active mass ~ **2 g**
19.926 gram-day exposure
0.14 e- RO noise
(**300** samples)
DC ~ **$1.6x10^{-4}$ e-/pix/day**

The SENSEI Experiment

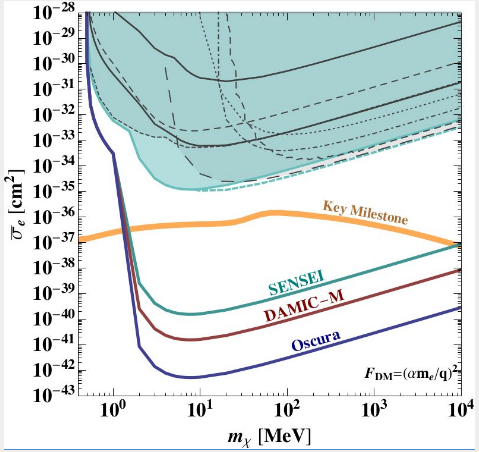
2017	2018	2019	2020	Ongoing
Demonstrate sub-electron resolution	DM search with **proto-SENSEI** (0.1 g) at **surface**	DM search with **proto-SENSEI** at **MINOS** (230 m.w.e.)	DM search with **science grade** (~2 g) at **MINOS**	**Production** (100g) + commissioning at **SNOLAB** (6000 m.w.e.)

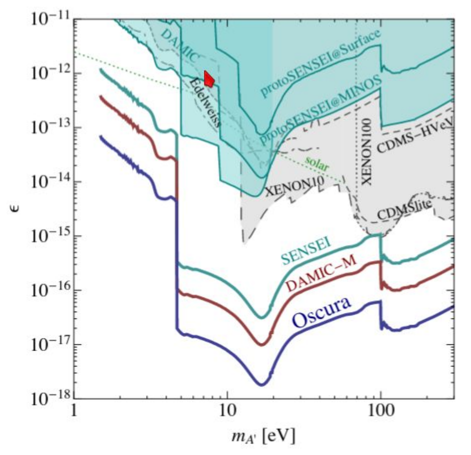


Perspectives: beyond SENSEI

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

Snowmass 2021, OSCURA LOI, J. Estrada et al.



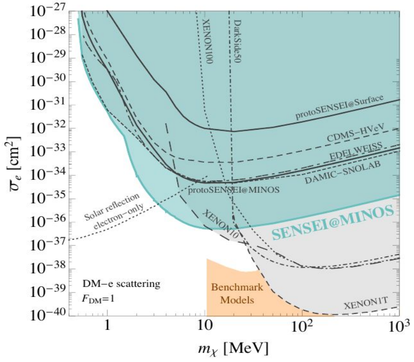


Summary

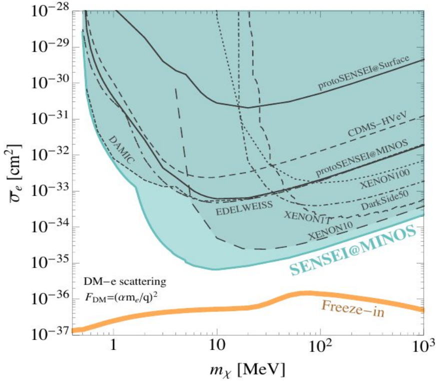
- **SENSEI**: first dedicated experiment searching for **e-DM** interactions.
- **protoSENSEI** at the **surface** and **MINOS** produced first physics.
- First **scientific grade skipper-CCD** achieved.
- Best constraints on **DM-e-** scattering for light mediator and heavy mediator, up to **10 MeV**.
- Best constraints for **Nucleus recoil** (Migdal Effect) for light mediator with **0.6~5 MeV**.

- Best constraints for **DM absorption** on electrons for mass **1.2~12.8 eV**.
- **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 DM searches in the next ~ 7 years

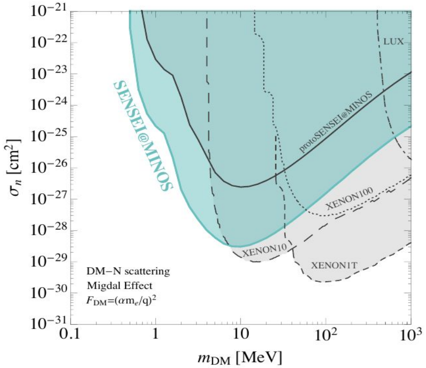
Latest results



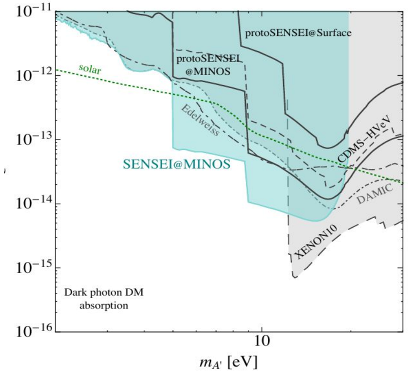
***Heavy** mediator*
***e$^-$** scattering*



***Light** mediator*
***e$^-$** scattering*



***Light** mediator*
***Nucleus** scattering*

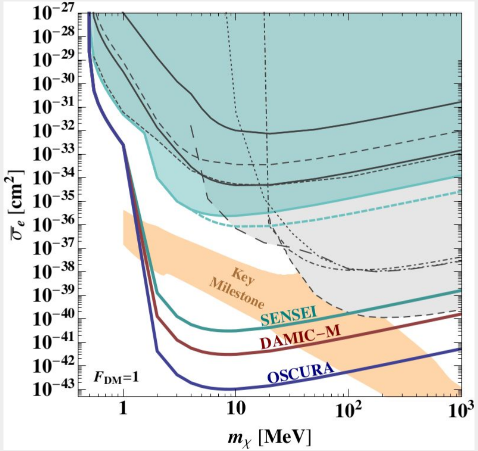


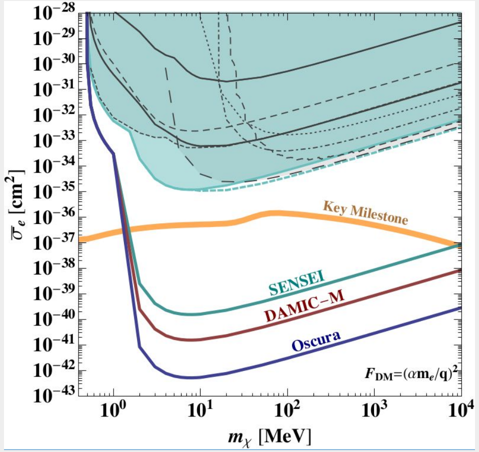
Absorption

Perspectives: beyond SENSEI

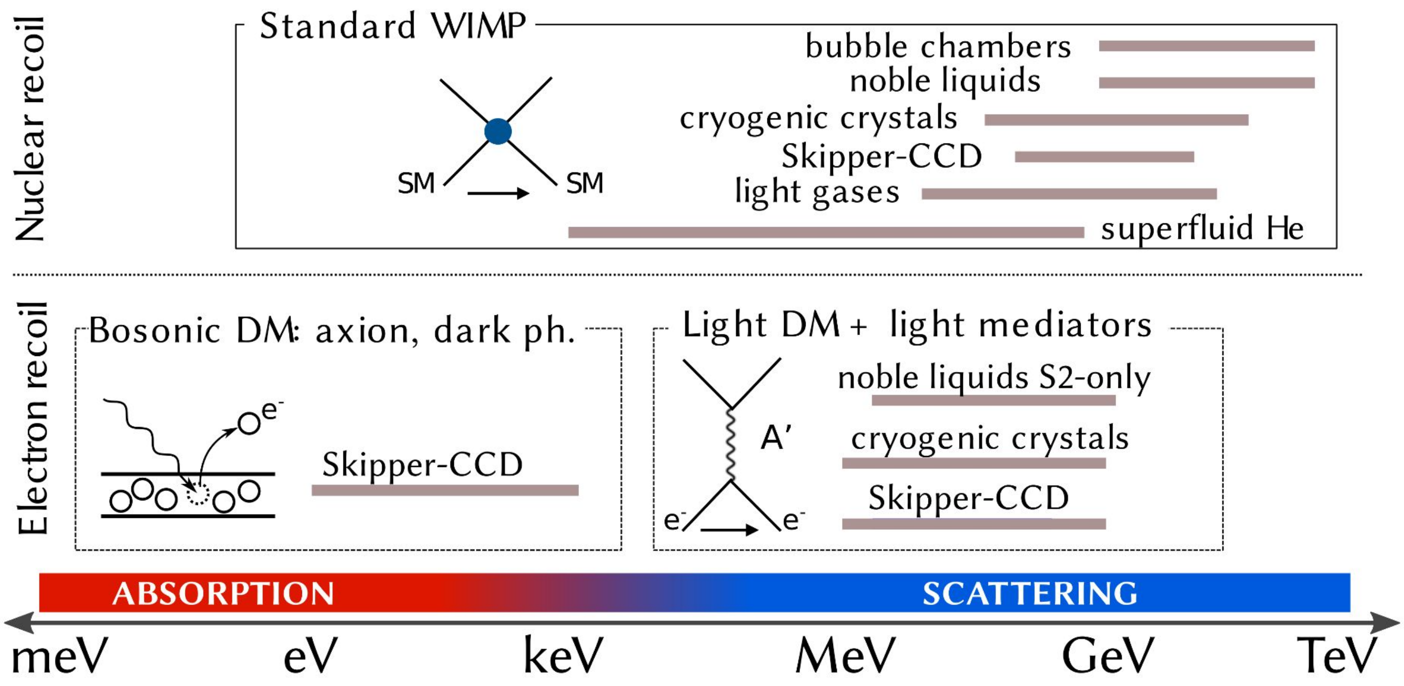
2021	2024	2027
SENSEI 100g	DAMIC-M 1kg	OSCURA 10kg

Snowmass 2021, OSCURA LOI, J. Estrada et al.





Experimental approach



Skipper-CCD single electron events

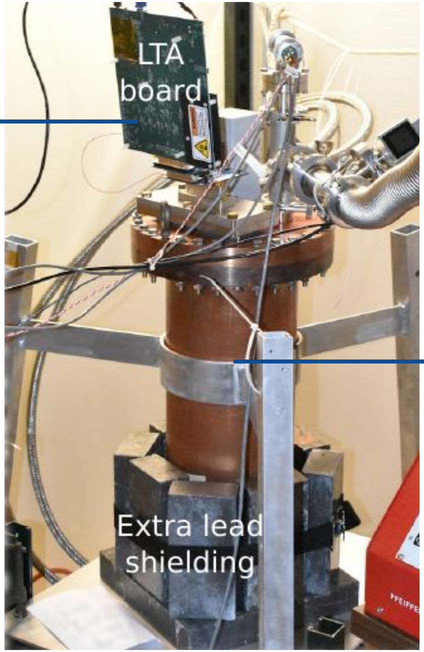
Contribution (e^-/pix)		Time dependence: Linear, Exposure	Time dependence: Linear, Readout	Time dependence: Independent	Spatial distribution
Dark current	Intrinsic	$\lambda_{DC}\, t_{EXP}$	$\frac{\lambda_{DC}}{2}\, t_{RO}$	-	Uniform
	Extrinsic				Uniform
Amplifier-light current		-	$\lambda_{AL}\, t_{RO}$	-	Localized
Spurious charge		-	-	μ_{SC}	Uniform

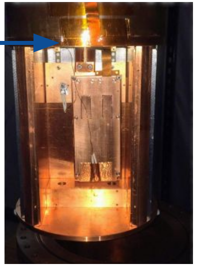
Single electron rate reduced by optimizing operation parameters

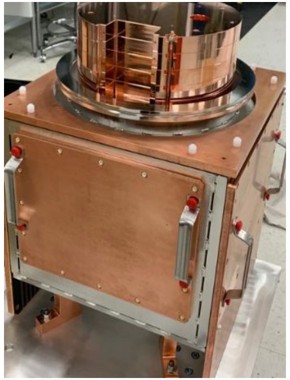
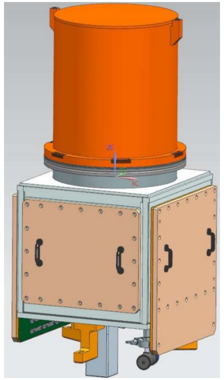
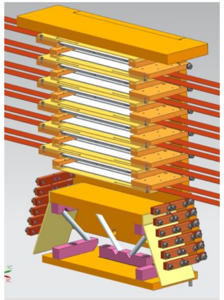
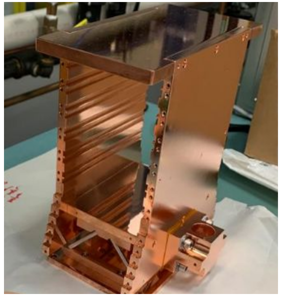
- Read-out mode: continuous vs expose
- Voltage configuration

Setup @ MINOS

- 230 m.w.e.
- Previous vessel + extra shielding
- T ~ 135 K + vacuum
- LTA board





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