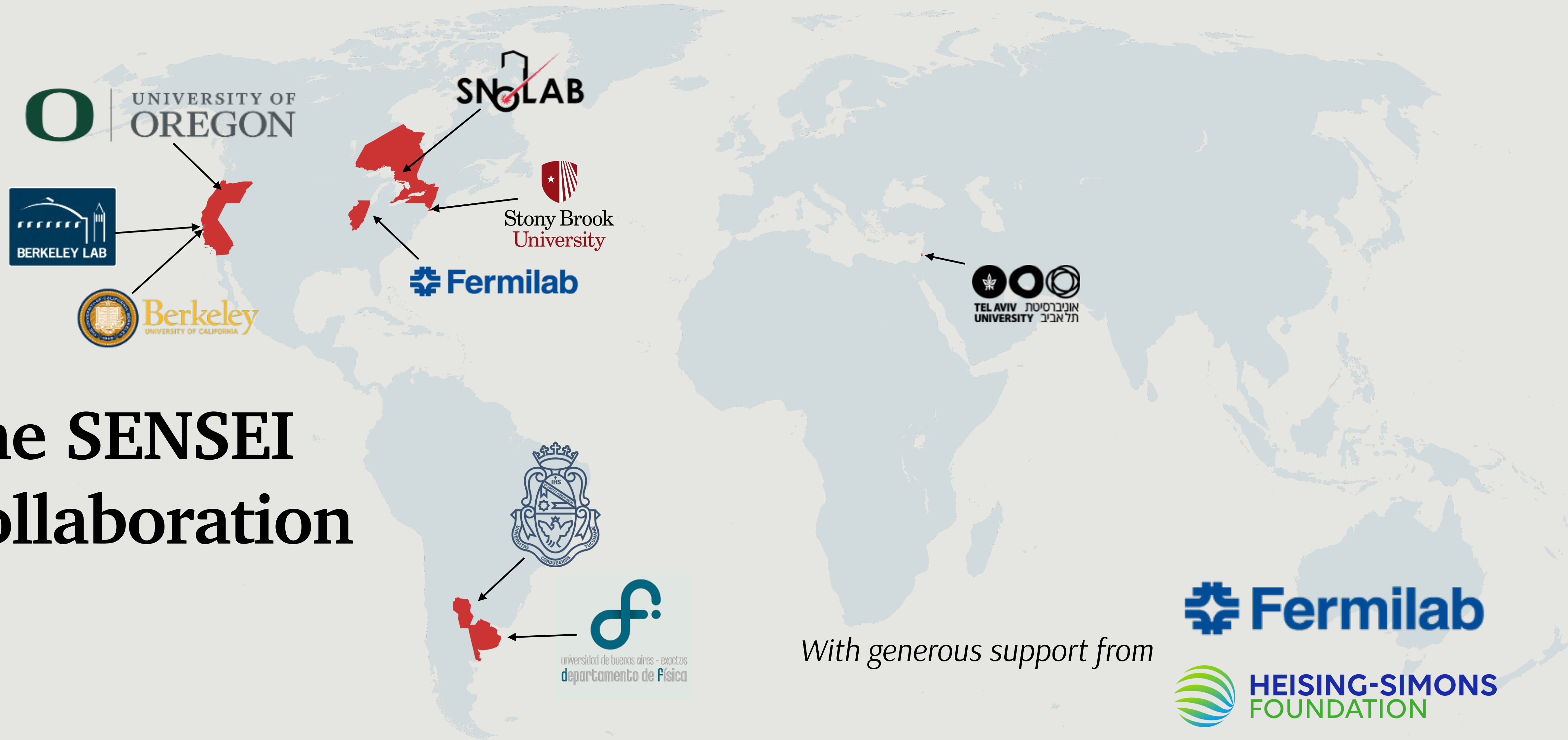


Latest Results and Prospects of the ensei Experiment

Ansh Desai

On Behalf of the SENSEI Collaboration

The SENSEI Collaboration



Sub-Electron Noise Skipper-CCD Experimental Instrument

The SENSEI Experiment

- * Next generation CCDs designed at LBNL and fabricated at Teledyne DALSA Semiconductor
- * Energy threshold **1.1 eV** (Si bandgap)
- * Sub-electron resolution ($\sim 0.1 e^-$) – **powerful for DM searches**

Goals:

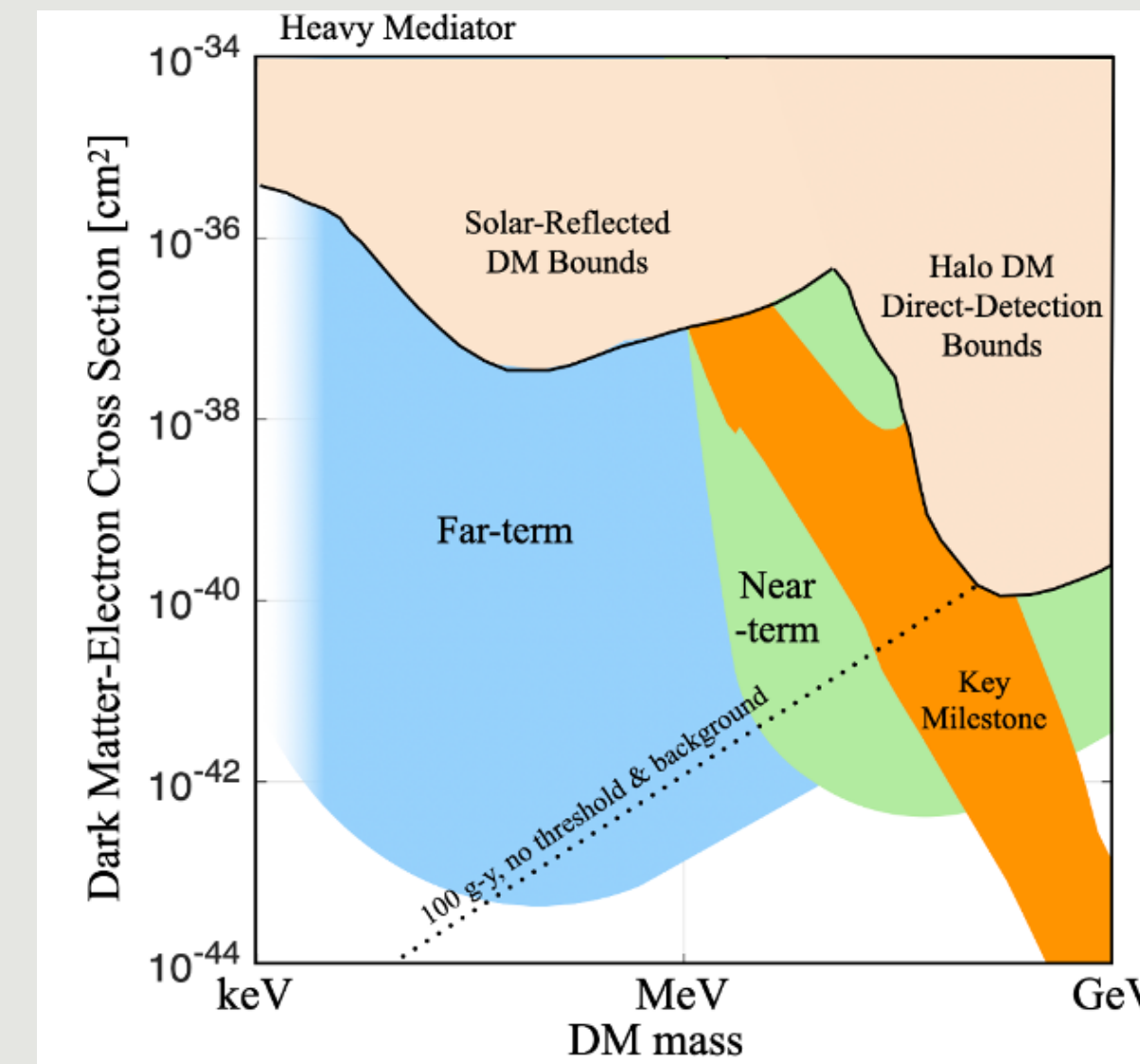
- * Validate Skipper Technology for DM and ν detection
- * Perform DM searches at MeV-scale (DM-electron scattering, DM-N scattering through Migdal Effect)
- * Perform DM searches at eV-scale through bosonic absorption (dark photons, axions)



Motivation

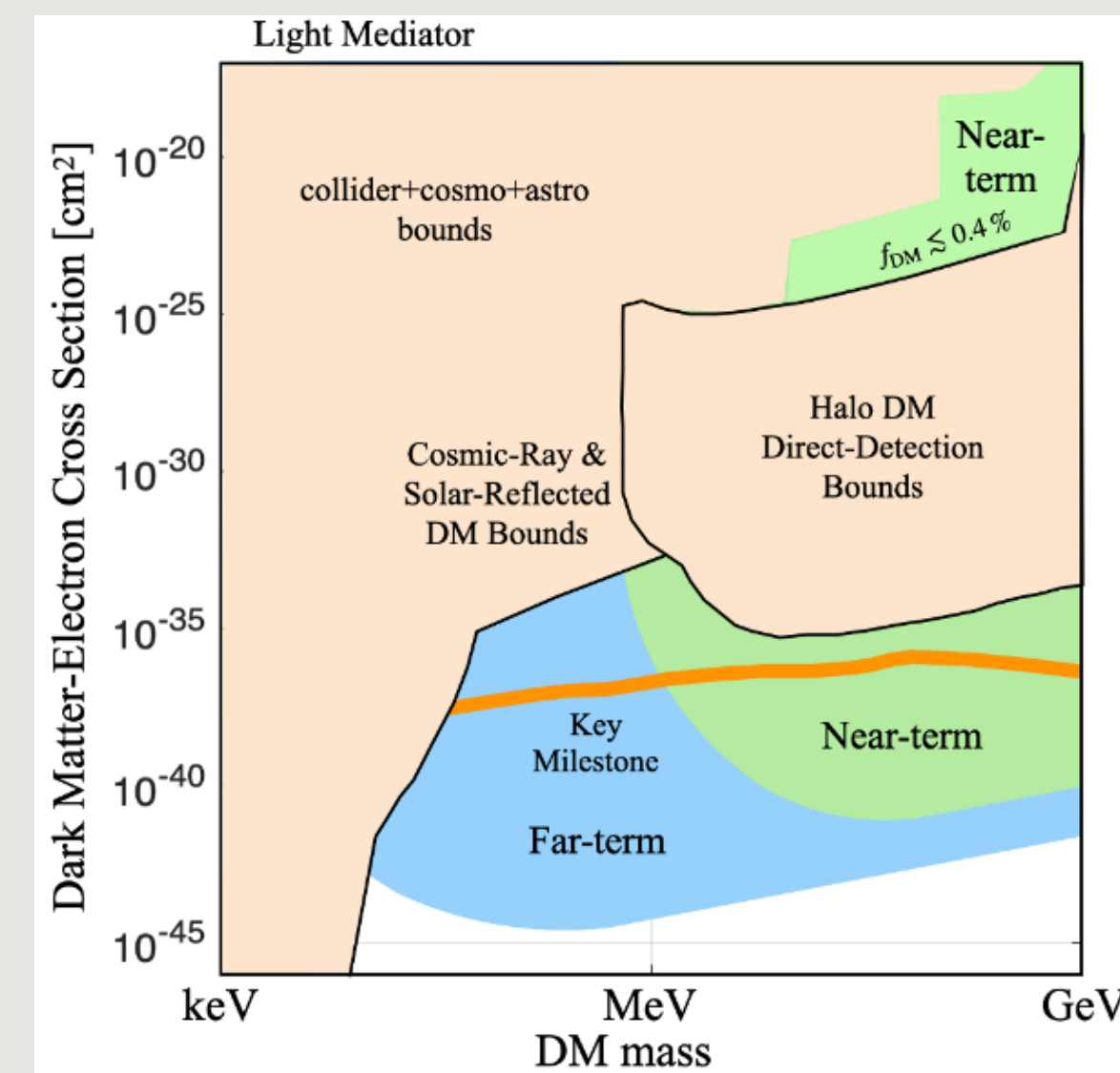
Light DM Benchmarks

- * Sub-GeV DM has a very rich phenomenology and the landscape is largely unexplored!
- * DM at this scale requires a dark sector, with new particles and forces
- * Many cosmologically motivated regions are accessible with today's detectors
- * Understanding our current detectors and sources of backgrounds is a key question to fully realize discovery potential



(Figure from Tien-Tien Yu [arXiv:2506.05234](https://arxiv.org/abs/2506.05234))

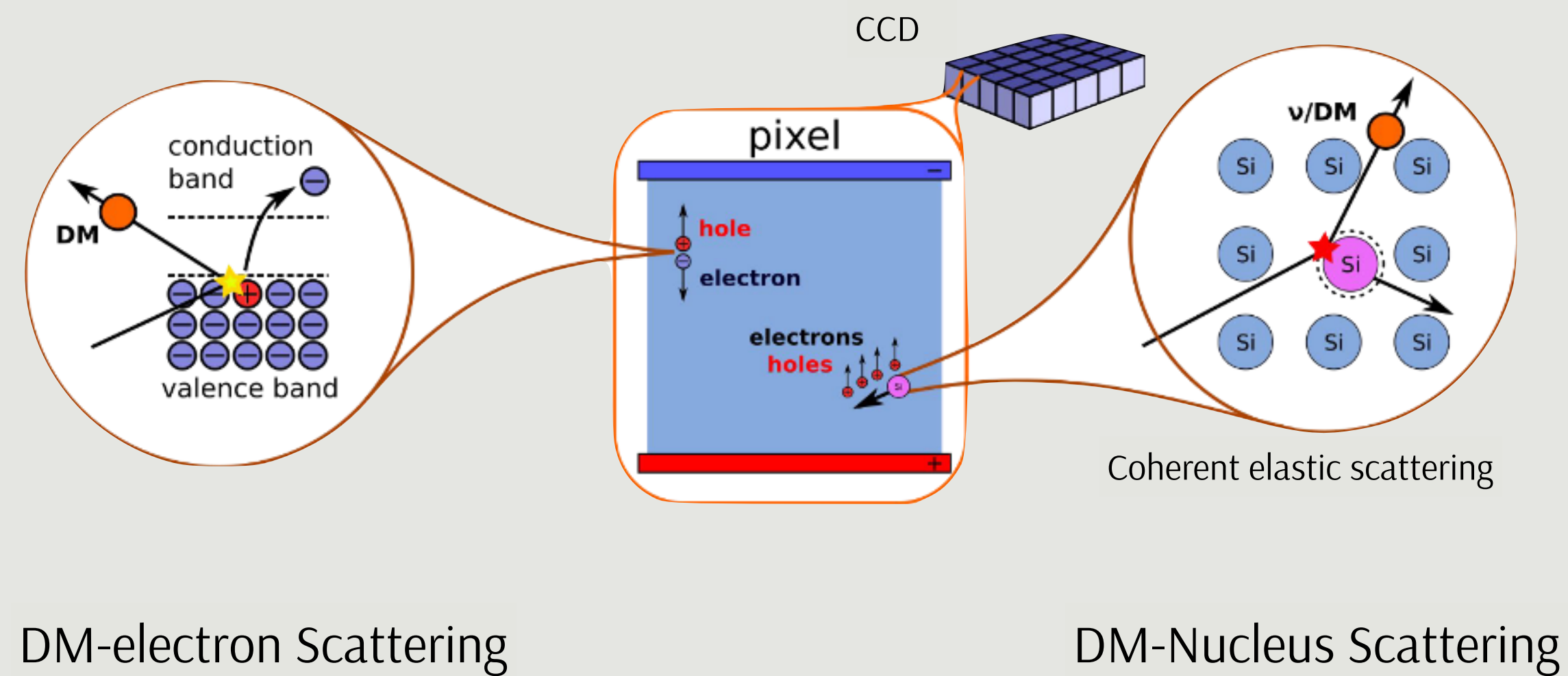
Heavy Mediator
 $F_{\text{DM}} = 1, m_{A'} \gtrsim 3 m_\chi$
 Relic density
 obtained through
 “freeze-out”



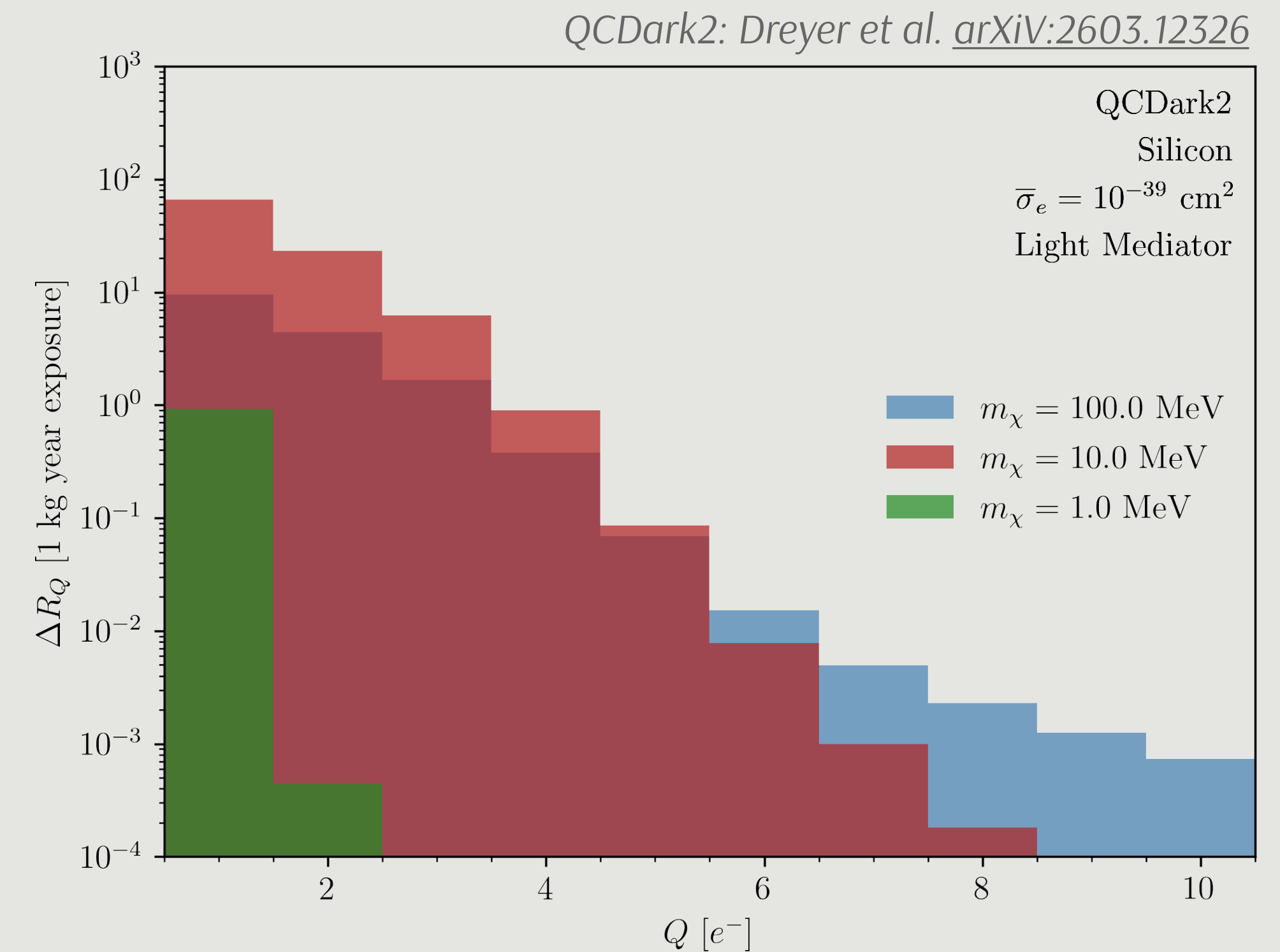
Ultralight Mediator
 $F_{\text{DM}} \propto 1/q^2, m_{A'} \ll m_\chi$
 Relic density
 obtained through
 “freeze-in”

The SENSEI Experiment

CCDs for Dark Matter



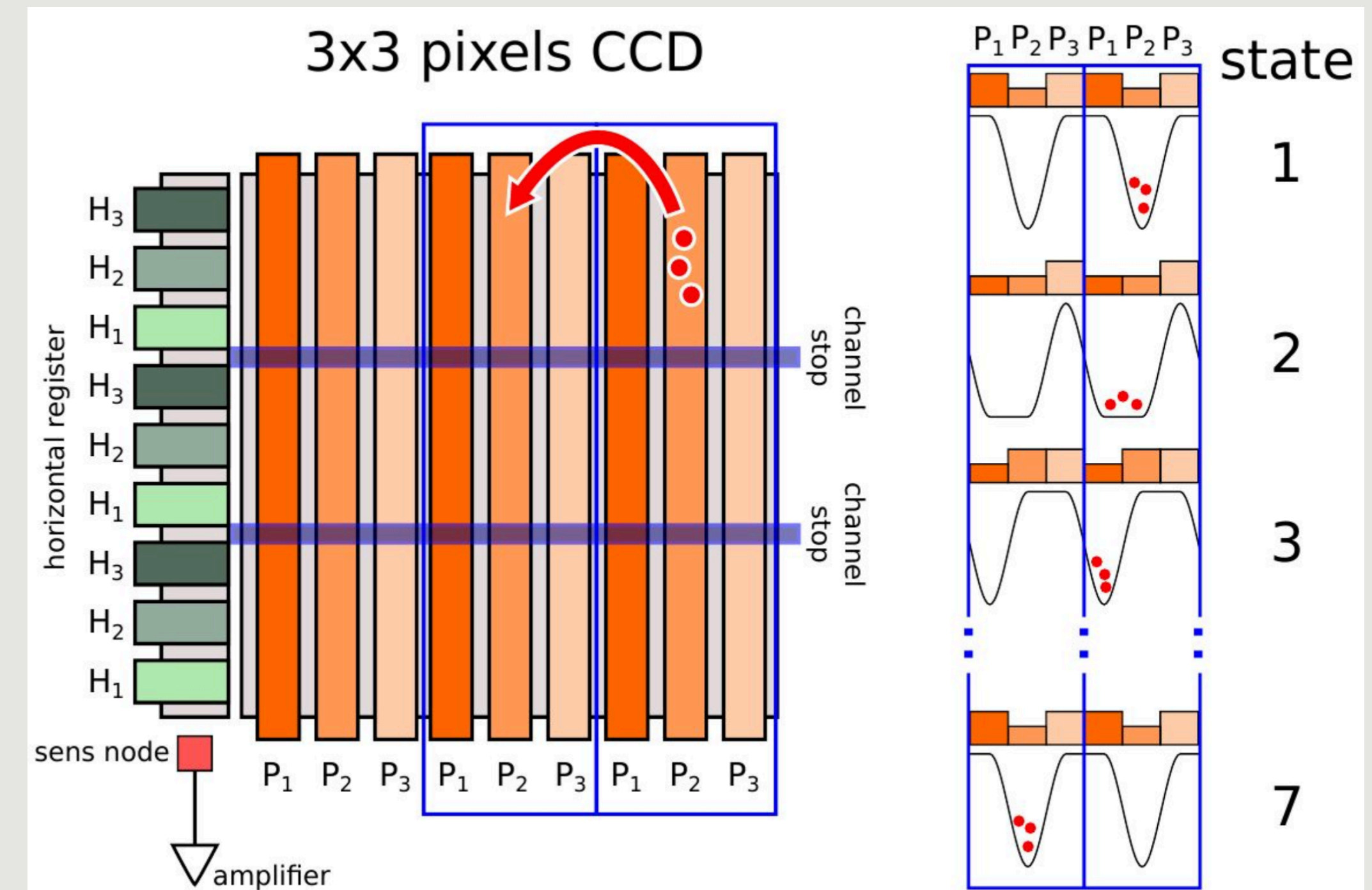
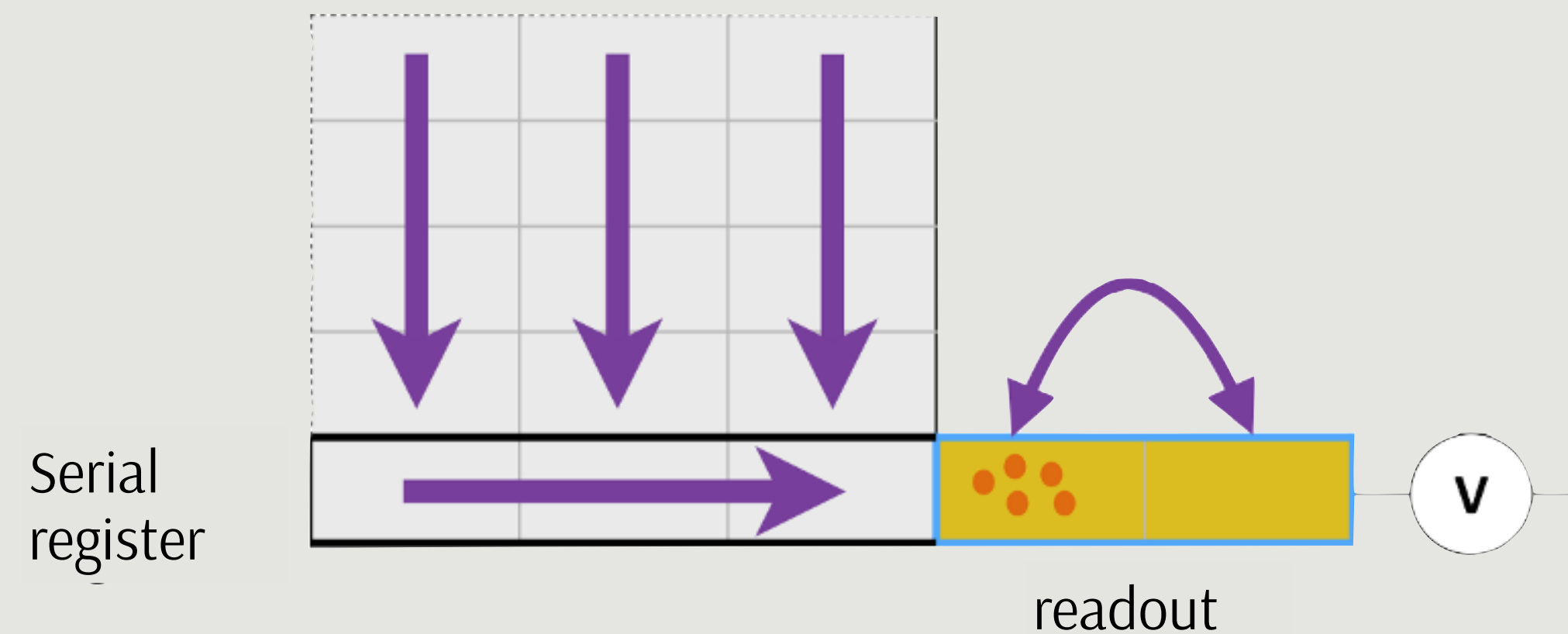
All signals are of order few e^- with a rapidly falling spectrum
Need an ultra sensitive detector!



The SENSEI Experiment

Skipper-CCDs

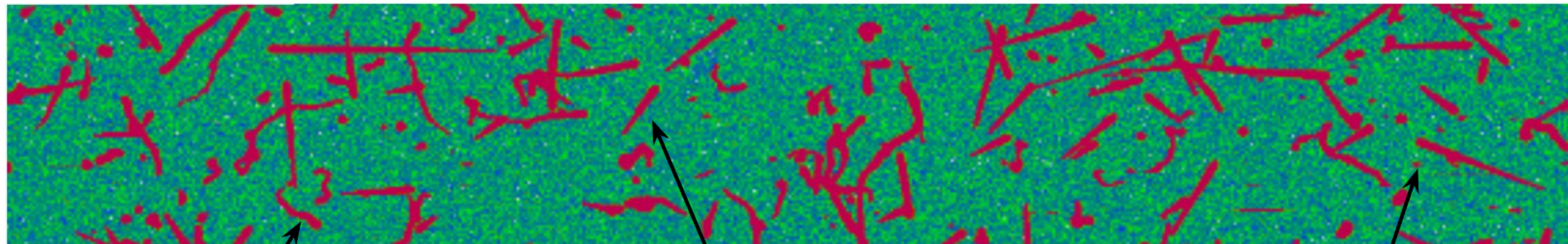
- * Skipper-CCDs allow for **reduction of both high and low frequency noise**
- * This is done through **repeated non-destructive measurements** at the sense node
- * All measurements averaged – gives **sub-electron resolution**



The SENSEI Experiment

Example Images

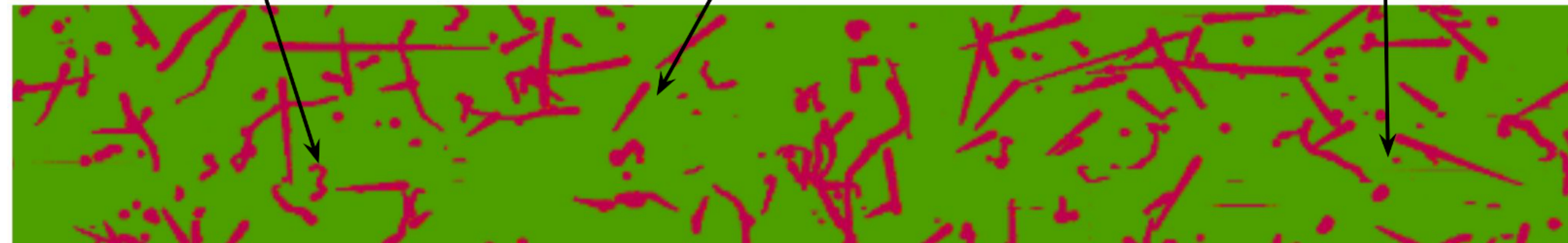
Traditional CCD



Electrons (curly tracks)

Muons (straight tracks)

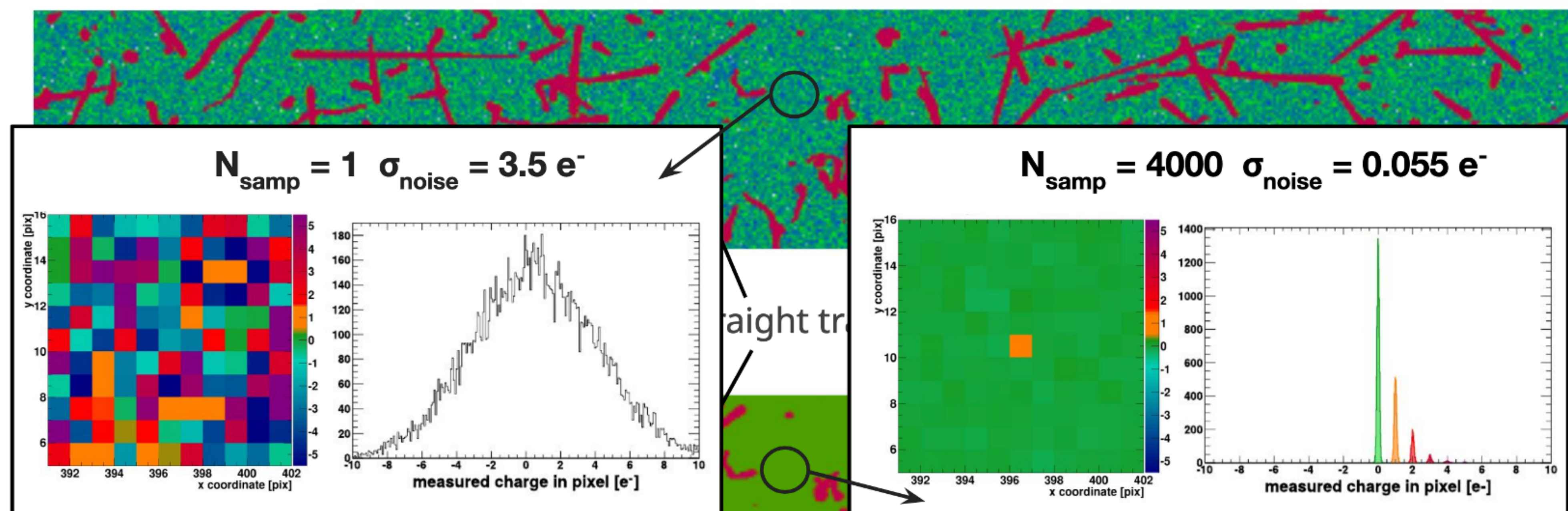
X-rays / γ -rays (point-like events)



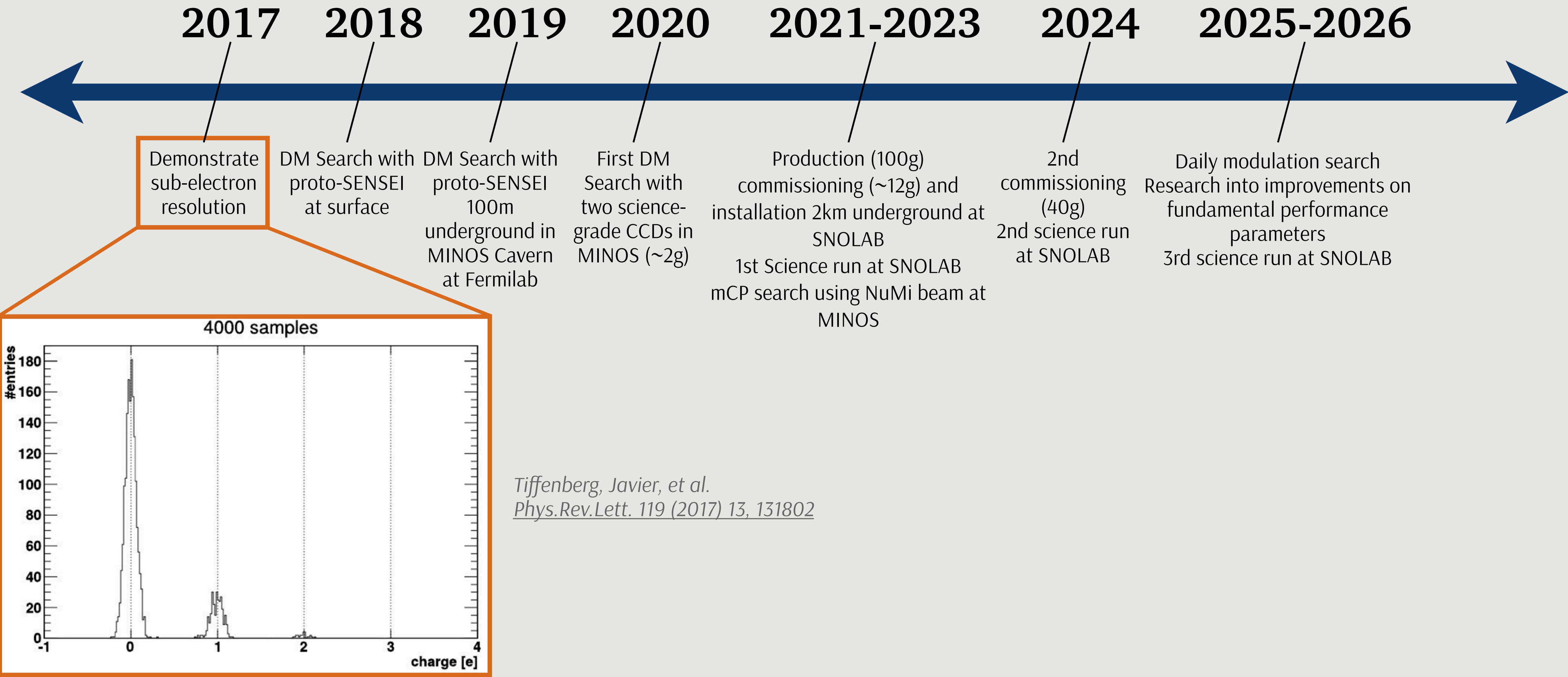
Skipper- CCD

The SENSEI Experiment

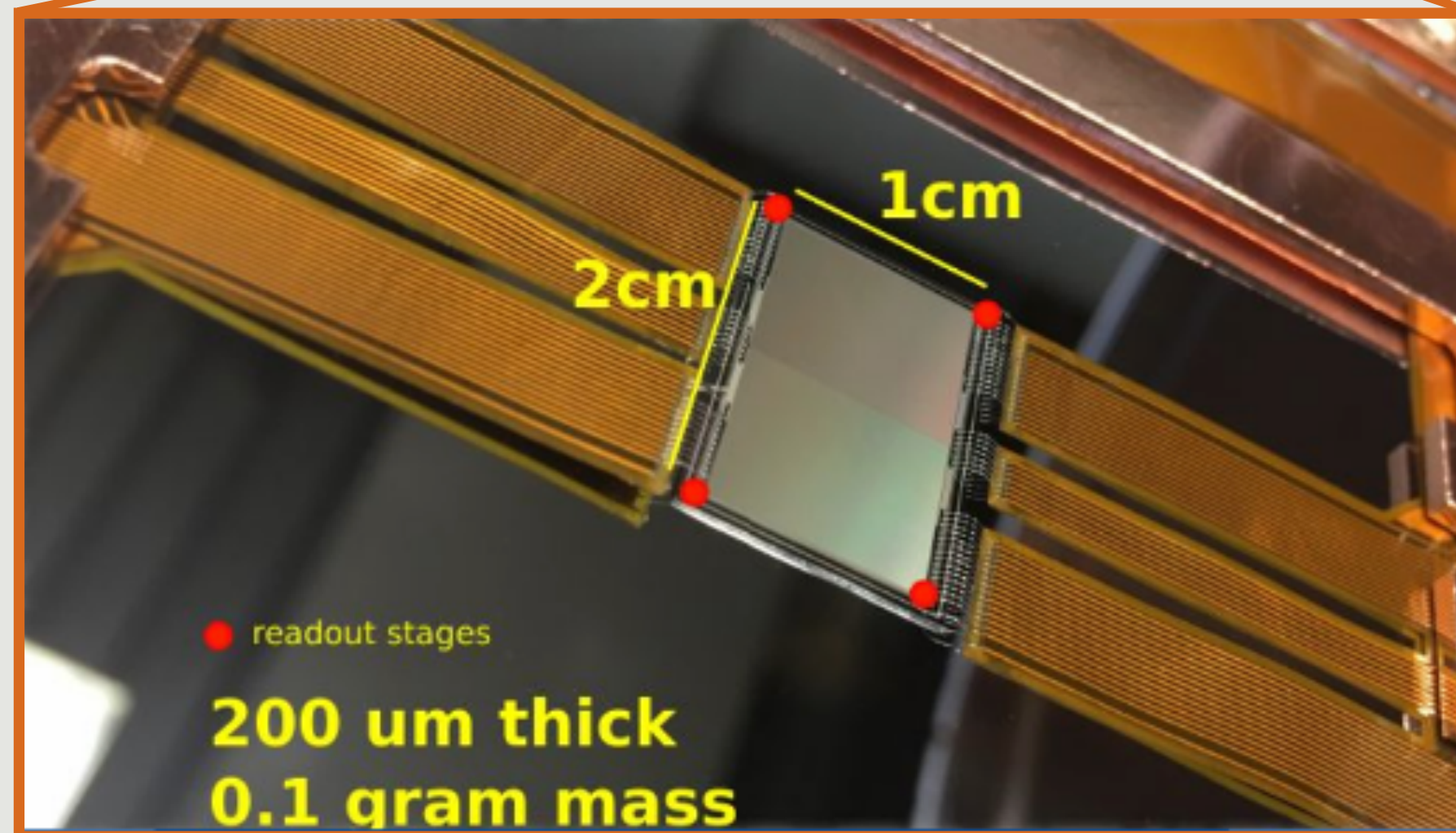
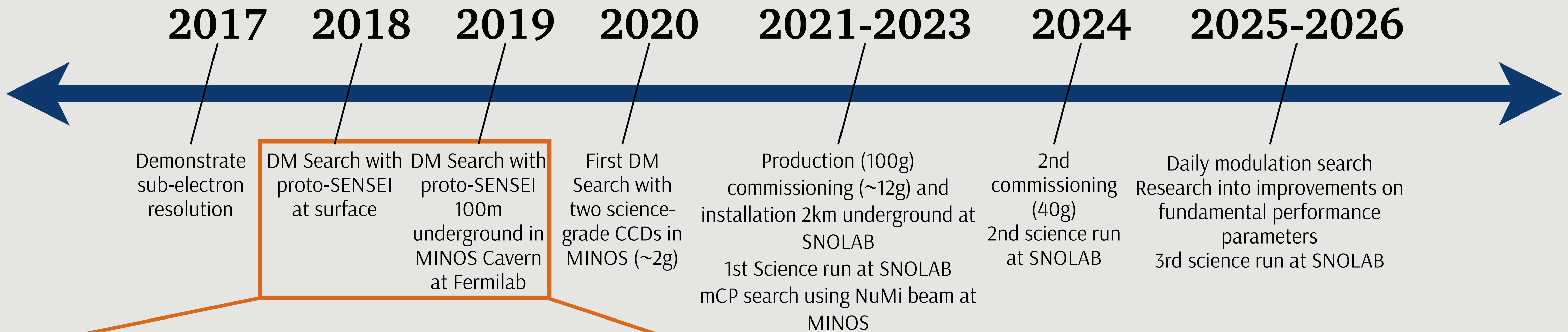
Example Images

Traditional CCD**Skipper- CCD**

The SENSEI Experiment Timeline



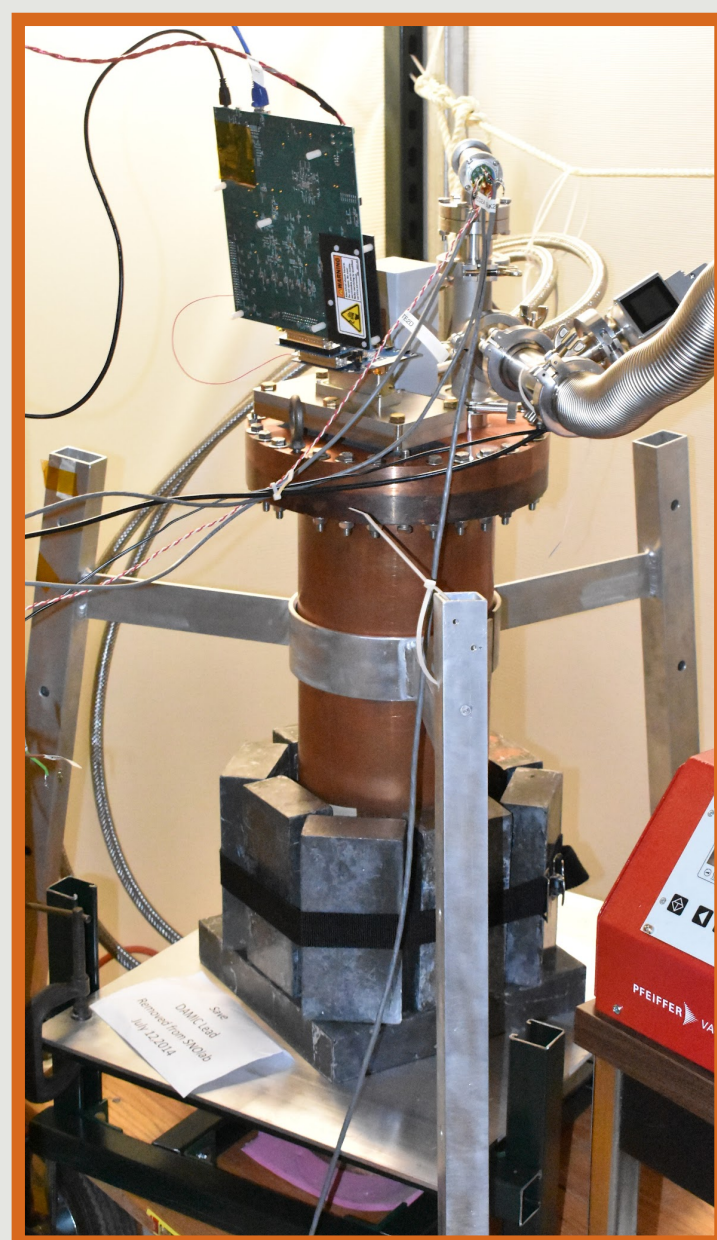
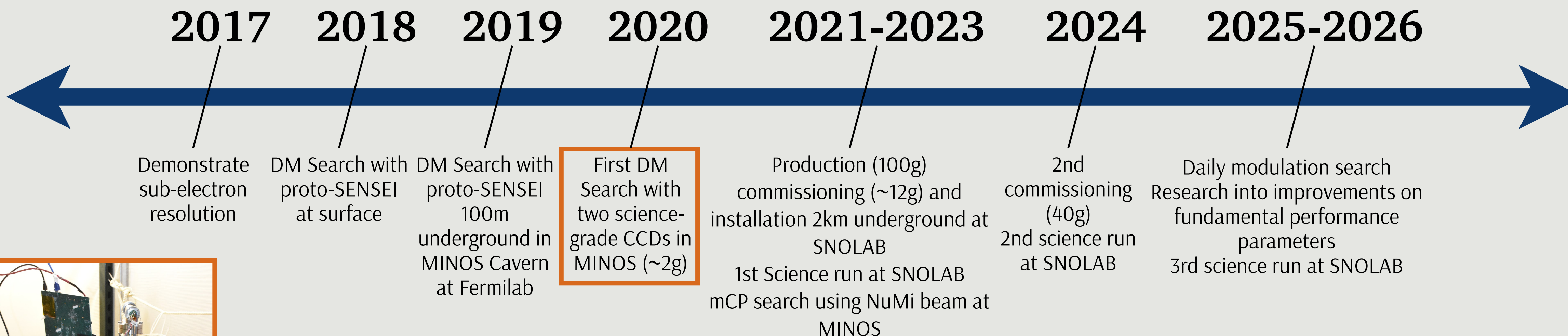
The SENSEI Experiment Timeline



The SENSEI Collaboration
Phys.Rev.Lett. 121 (2018) 6, 061803

The SENSEI Collaboration
Phys.Rev.Lett. 122 (2019) 16, 161801

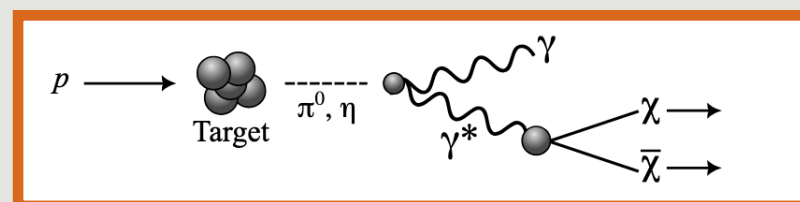
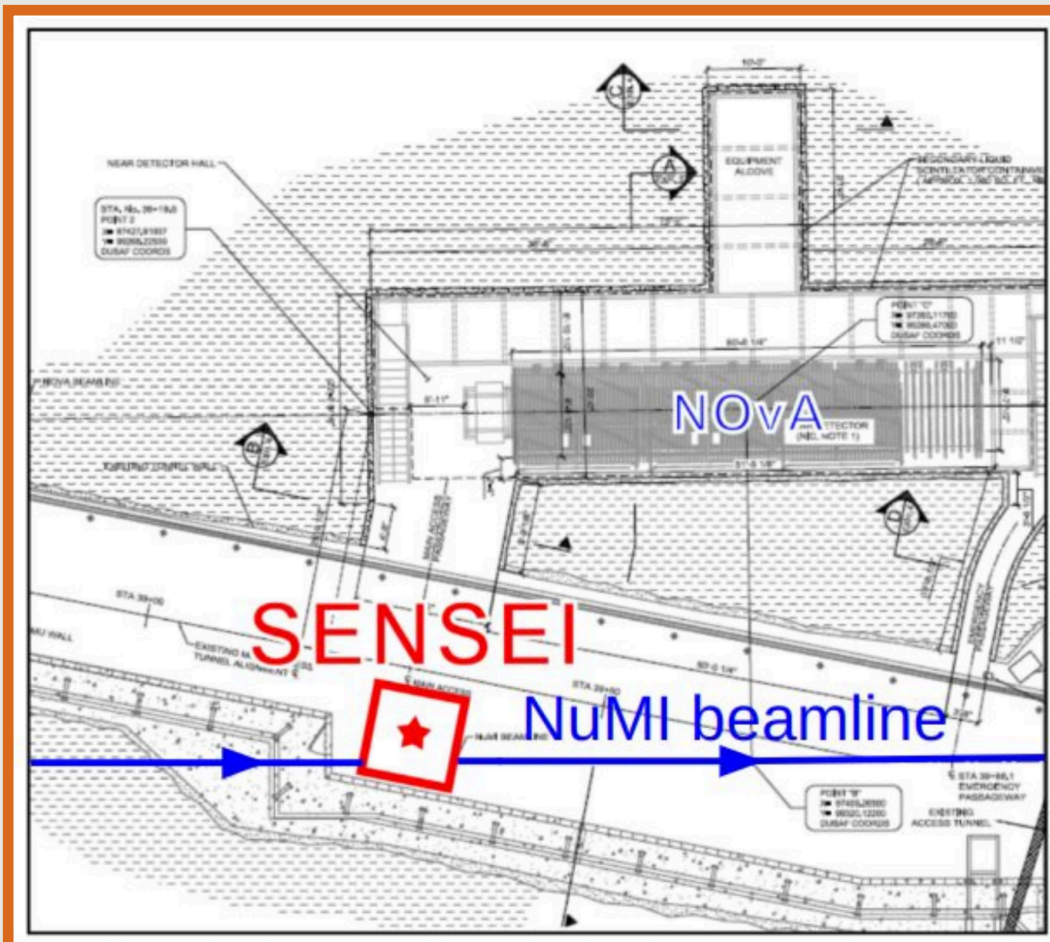
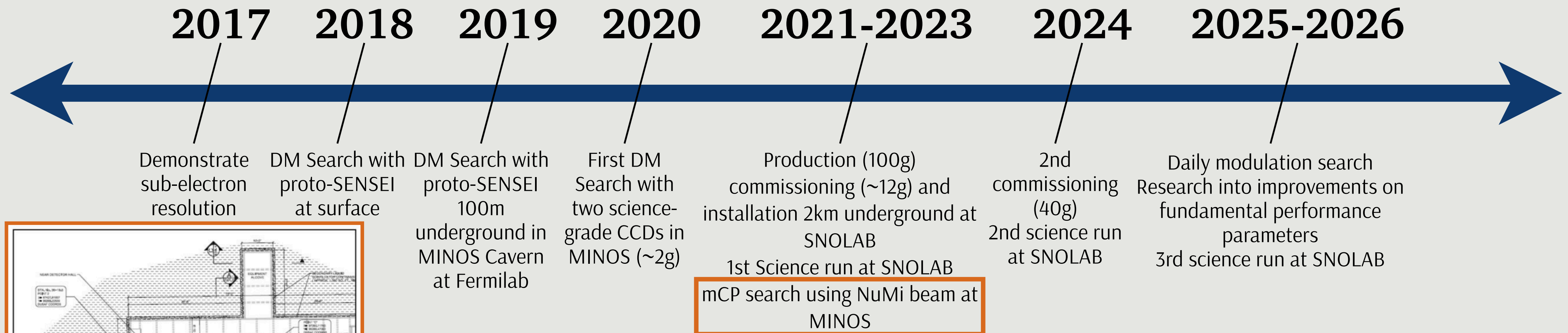
The SENSEI Experiment Timeline



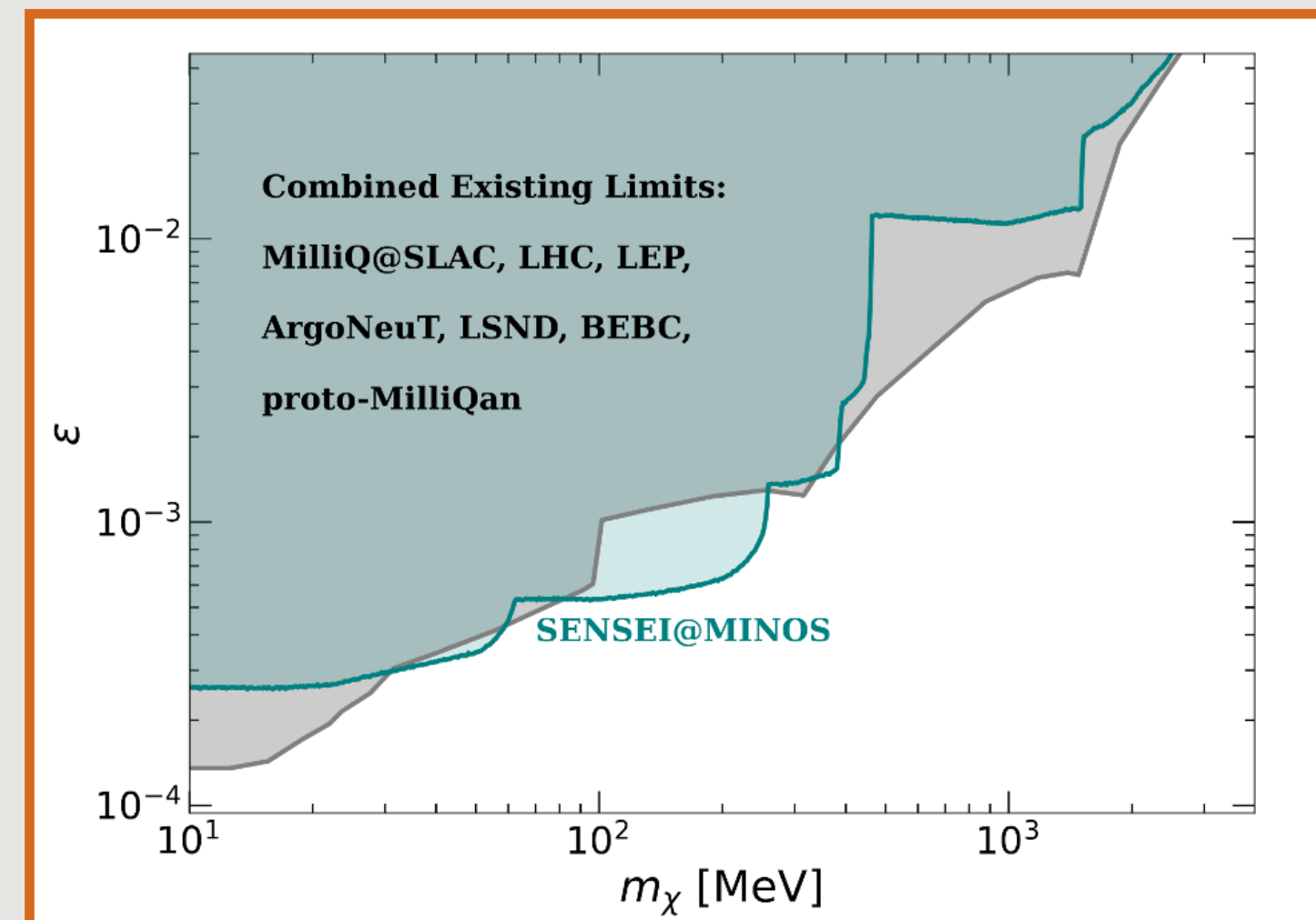
The SENSEI Collaboration
Phys.Rev.Lett. 125 (2020) 17, 171802

- * First science-grade CCD – designed by S. Holland at LBNL
- * 5.5 Mpix, 15 μm thick
- * 2g active mass
- * Data taken at ~135K at vacuum
- * Detector still operating with newer CCDs!

The SENSEI Experiment Timeline

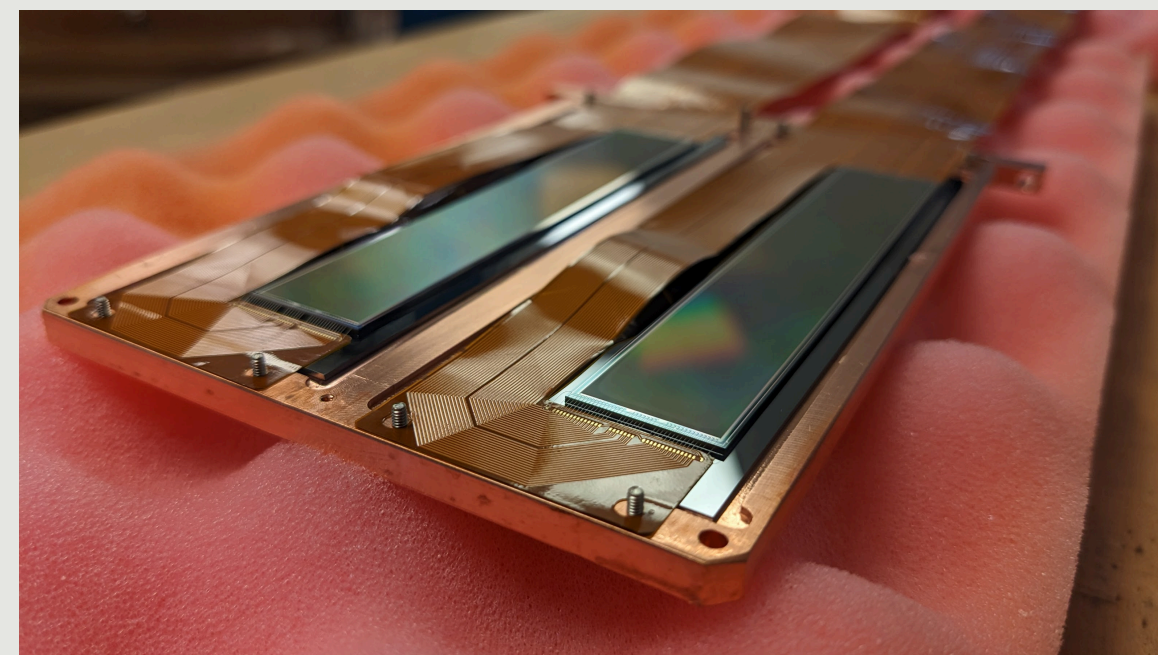
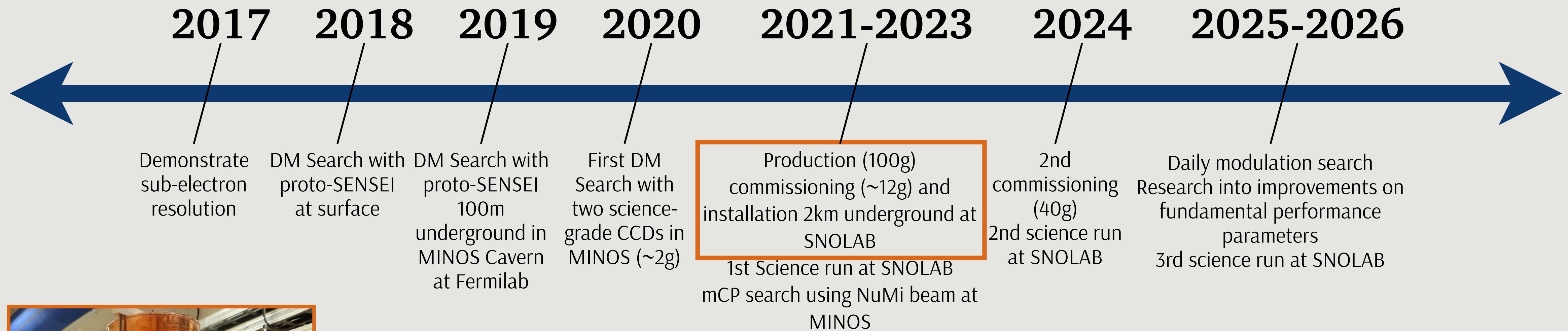


The SENSEI Collaboration
Phys.Rev.Lett. 133 (2024) 7, 071801



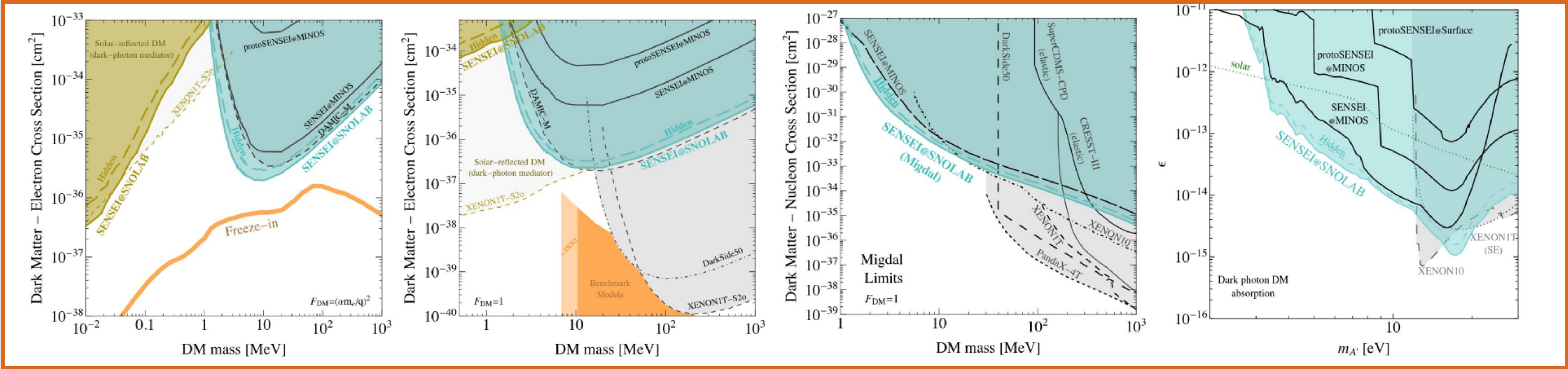
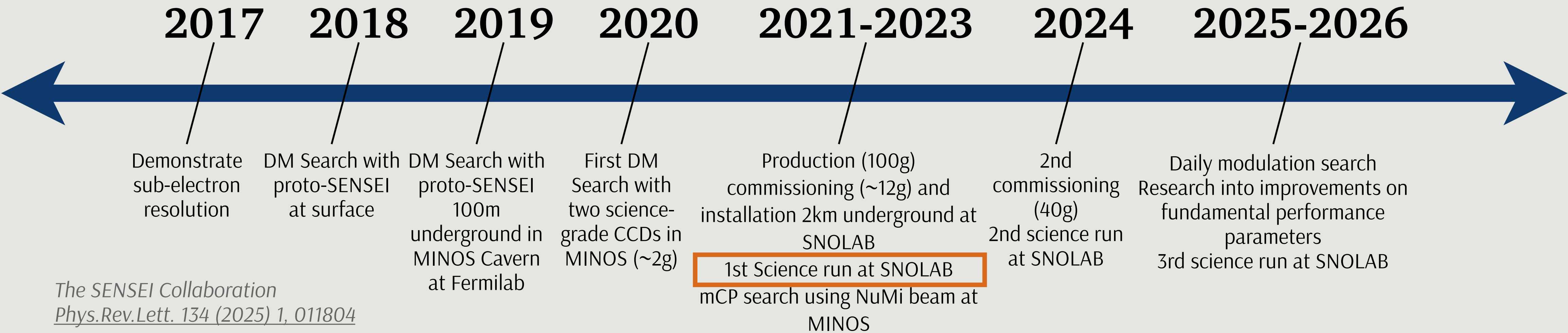
- * Proton collisions against a fixed target can produce mCPs collinear with the NuMI beam line
- * Reinterpretation of 2020 result with analysis using bins up to $6e^-$
- * World-leading constraints at 100 MeV!
- * Interest in developing bigger Skipper-CCD-based detectors to continue mCP searches – **see talk by B. Cervantes on Thursday!**

The SENSEI Experiment Timeline

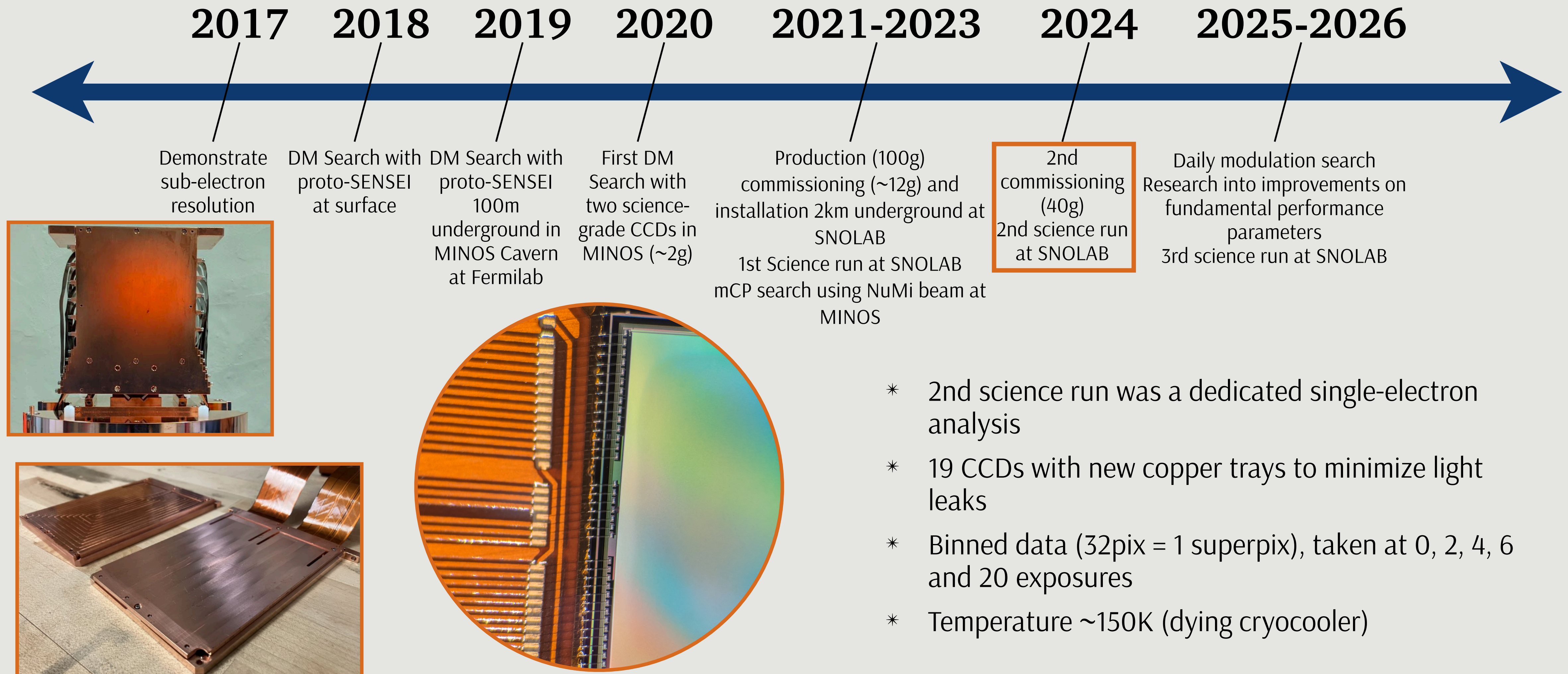


- * Cold copper box containing 12 copper trays, each can hold four 2g CCDs
- * Shielded by layers of copper, lead bricks, 42 inches of polyethylene+water
- * First science run data from 6 CCDs taken from Sep. 2022 – Apr. 2023
- * 20h exposures, 7.5h readout
- * Temperature goal 135K, in reality varied from 135-150K

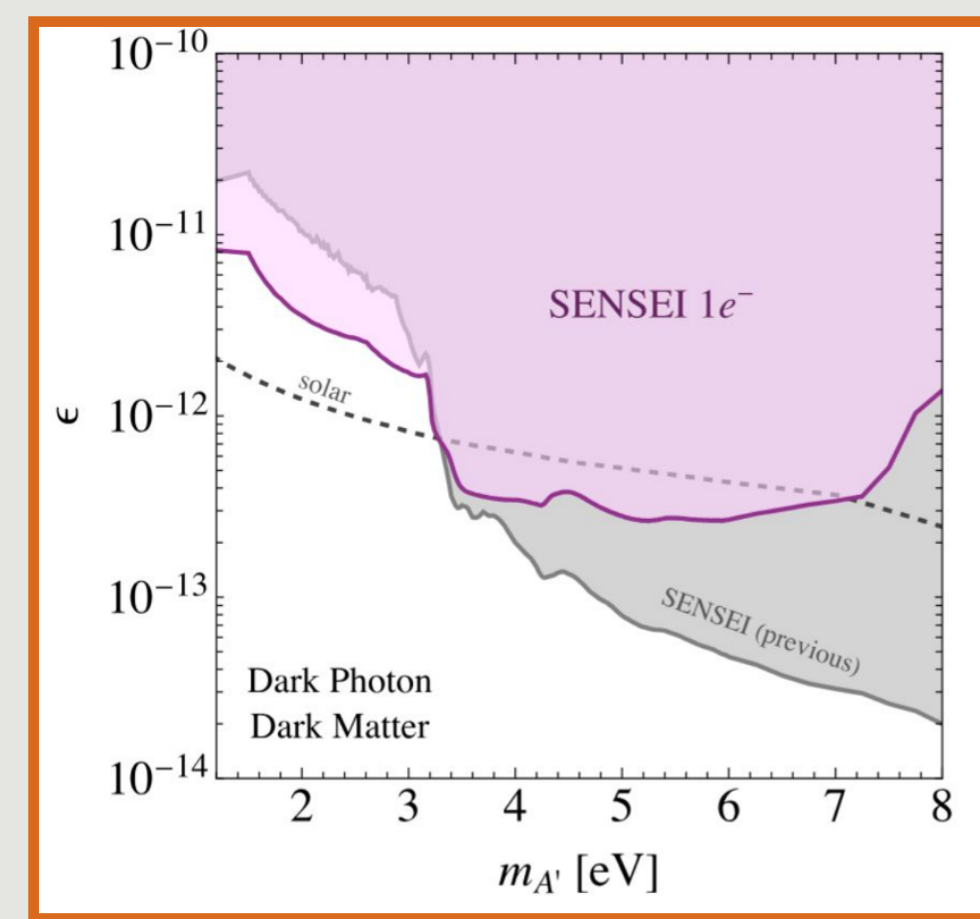
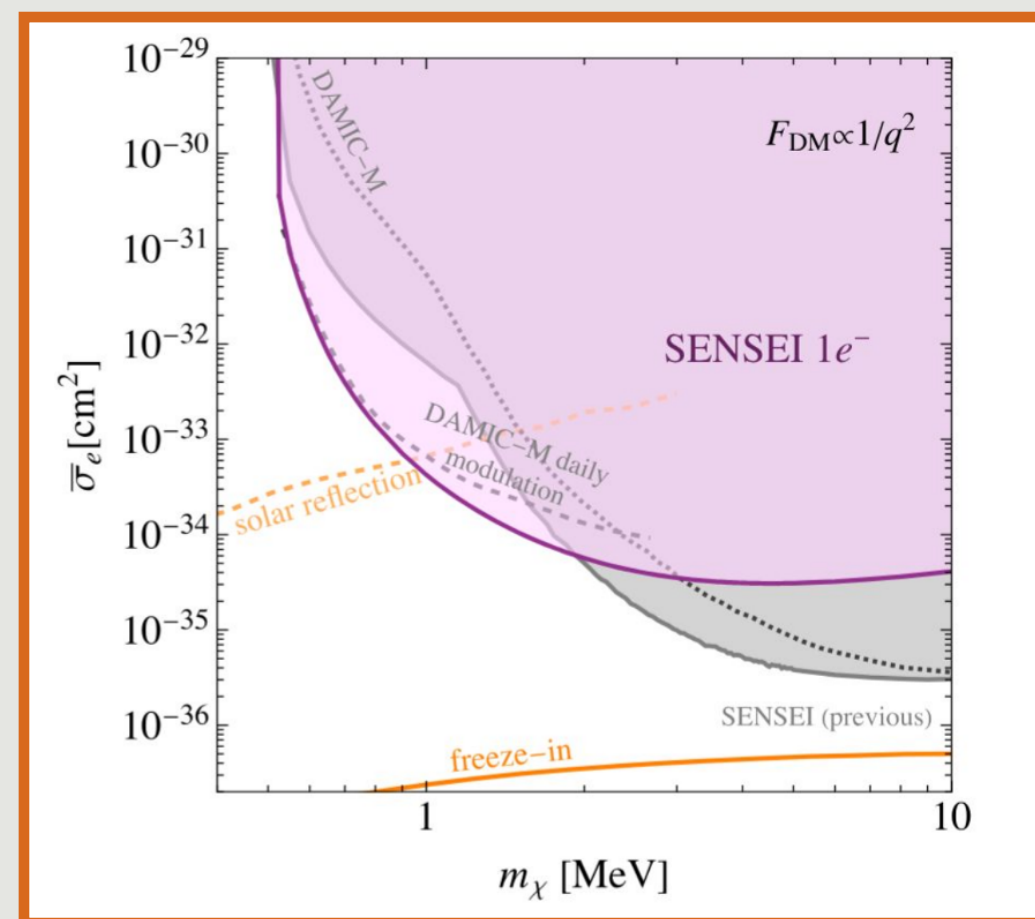
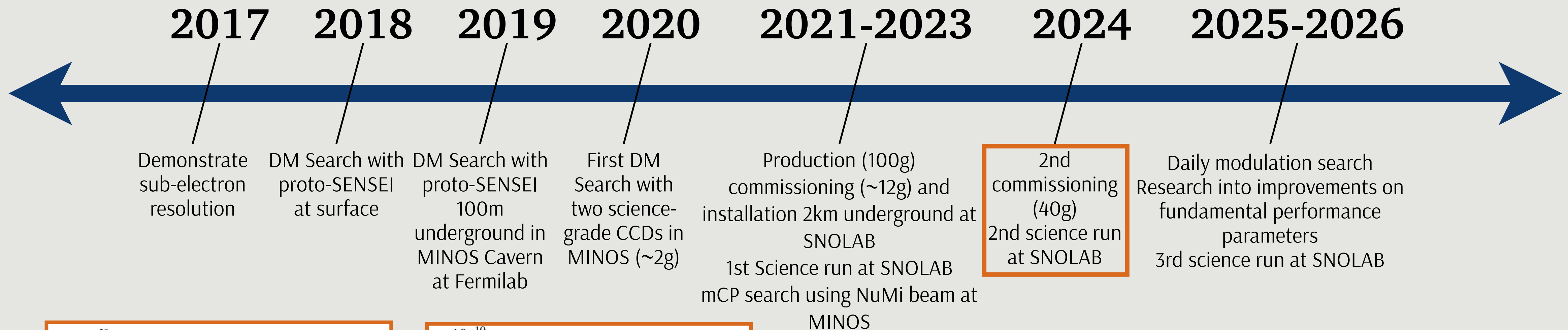
The SENSEI Experiment Timeline



The SENSEI Experiment Timeline



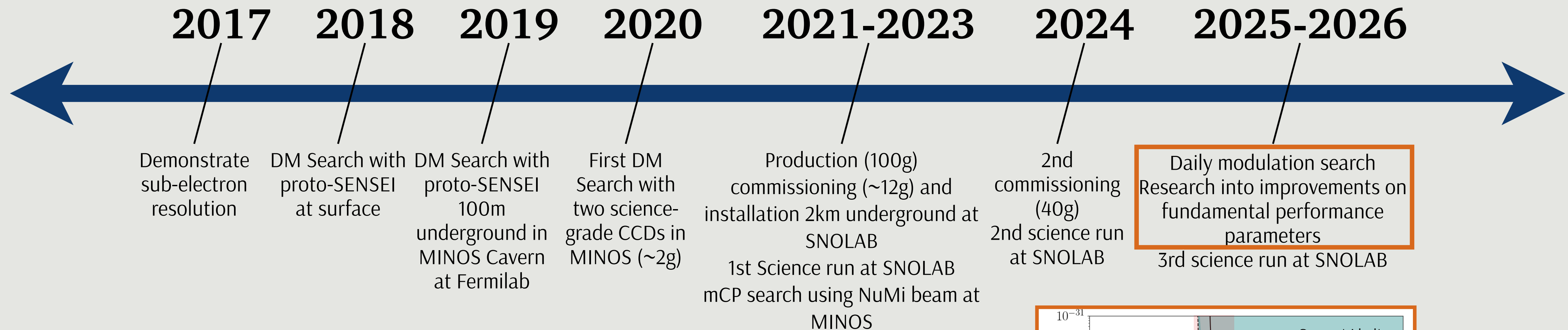
The SENSEI Experiment Timeline



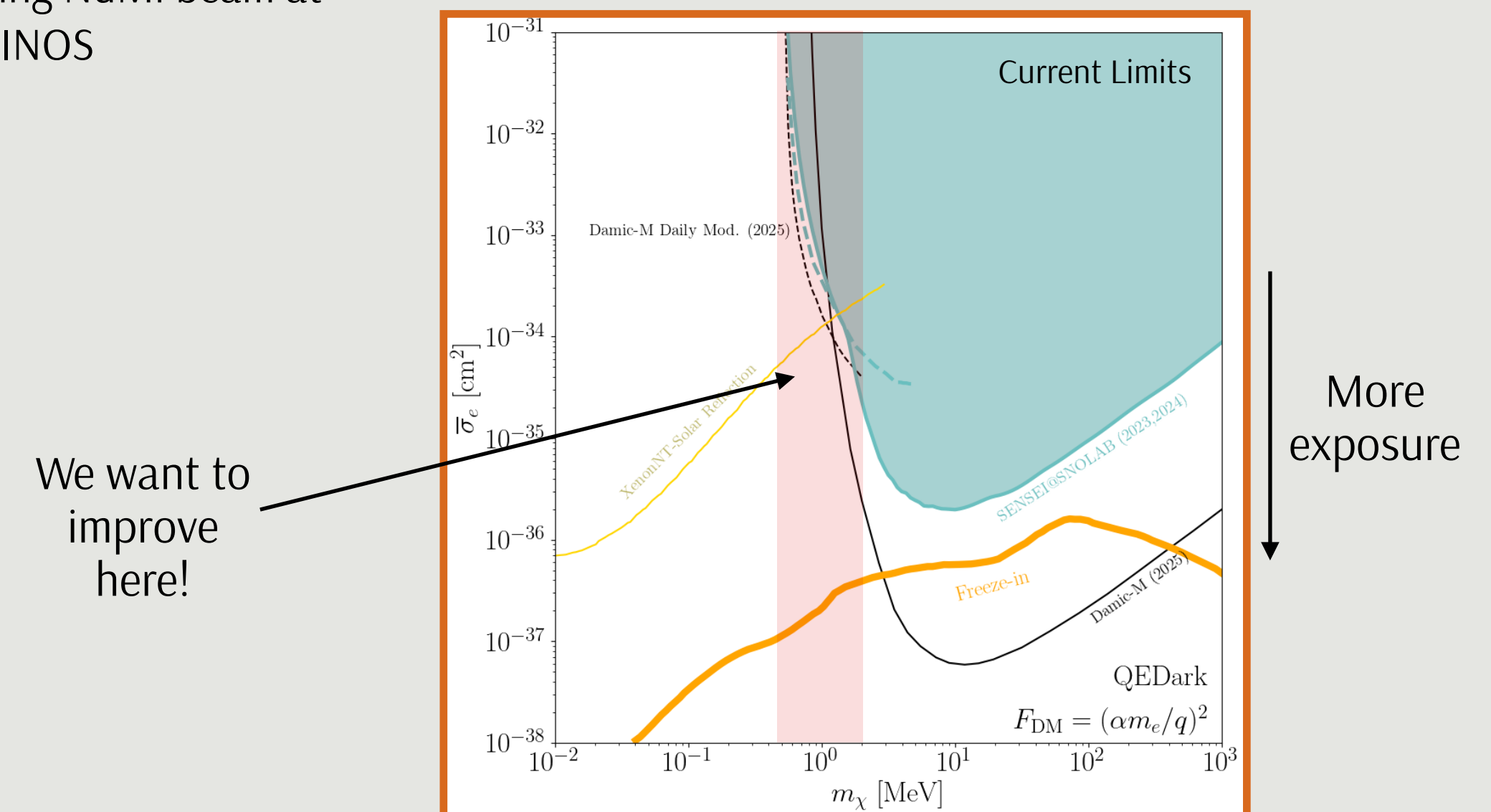
- * Result for best performing quadrant: $1.5 \times 10^{-5} e^-/\text{pix}/\text{day}$
- * Lowest ever single-electron rate in Silicon, very close to the original SENSEI goal of $1 \times 10^{-5} e^-/\text{pix}/\text{day}$
- * Set new constraints for DM Masses $< 3 \text{ MeV}$

The SENSEI Collaboration
Phys.Rev.Lett. 134 (2025) 16, 161002

The SENSEI Experiment Timeline



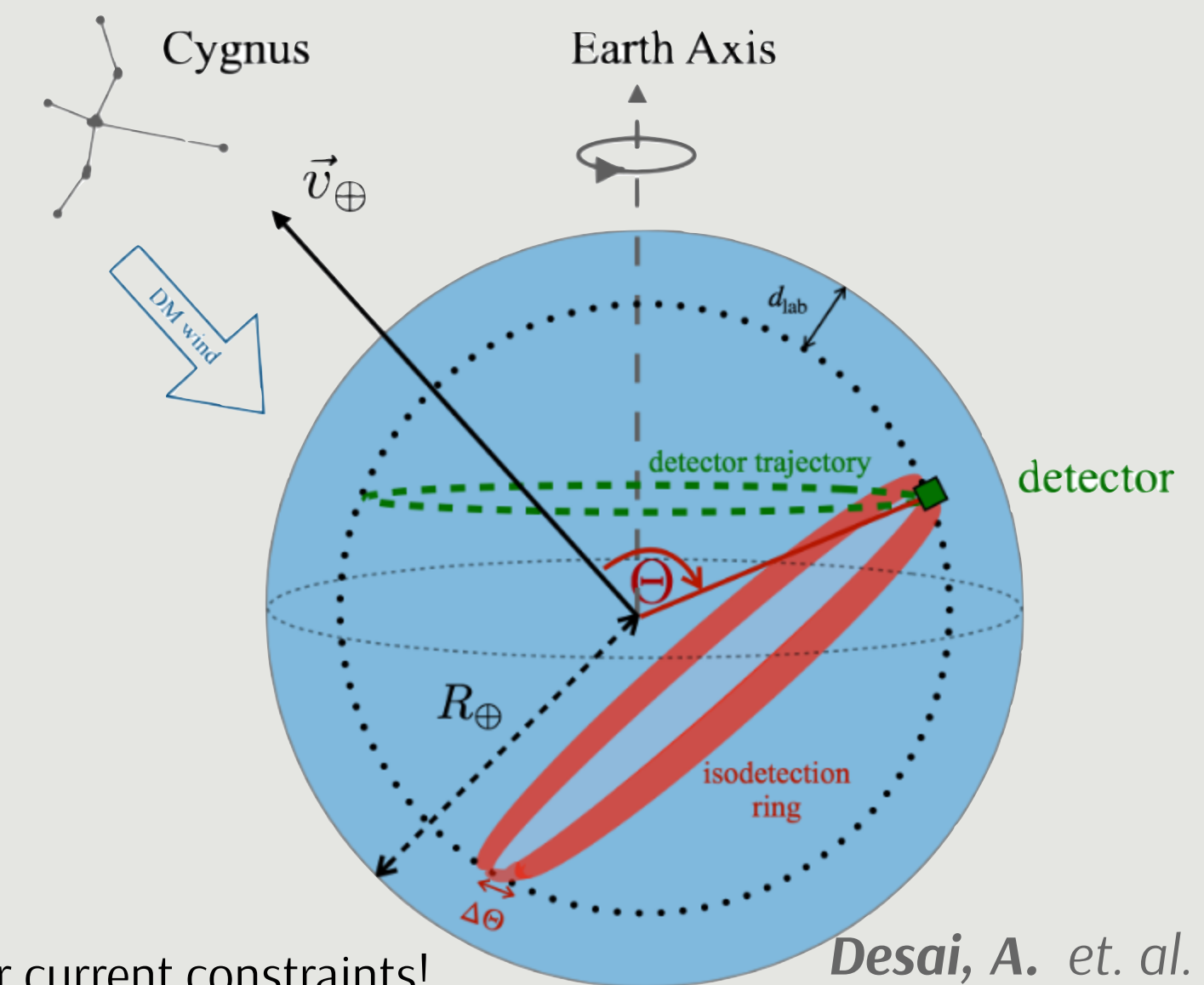
- * Skipper-CCDs are currently background free for $\geq 3e^- \rightarrow$ discovery potential increases with exposure
- * Our recent focus has been to use **new analysis techniques** and to **understand and reduce the single-electron background rate**
- * These both improve results for the $1e^-$ and $2e^-$ bins where the dominant background is single electron pileup
- * This improves sensitivity to lighter DM Masses



Recent and Upcoming Work

Diurnal Modulation

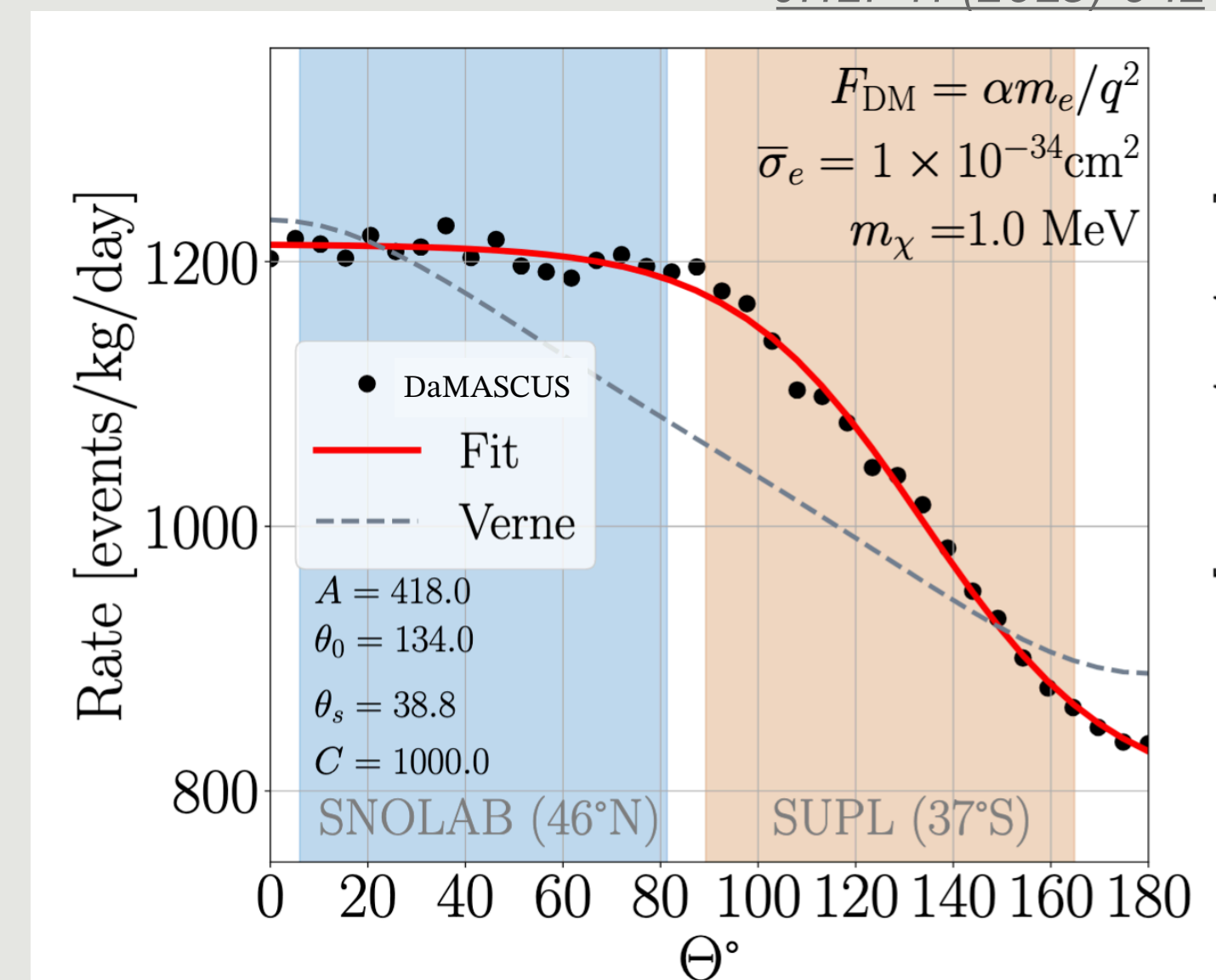
- * Modulation is a powerful tool to distinguish true signal from constant backgrounds, several possible sources for a DM signal to modulate
- * Earth-scattering induced modulation –DM interacts with nuclei inside the Earth → results in distortions of the velocity distribution seen at a detector, parametrized by isoangle
- * A detector on Earth will periodically move through a set of these isoangles and therefore will see a modulating signal with the period of a sidereal day
- * Software exists to calculate the velocity distributions of modulation: **Verne** (single scatter approximation, computationally cheap) and **DaMaSCUS** (more accurate full 3D Monte-Carlo, computationally expensive)
- * Combined with scattering rate calculation tools (QEDark, QCDark, etc)



A point near current constraints!

Desai, A. et. al.

JHEP 11 (2025) 042

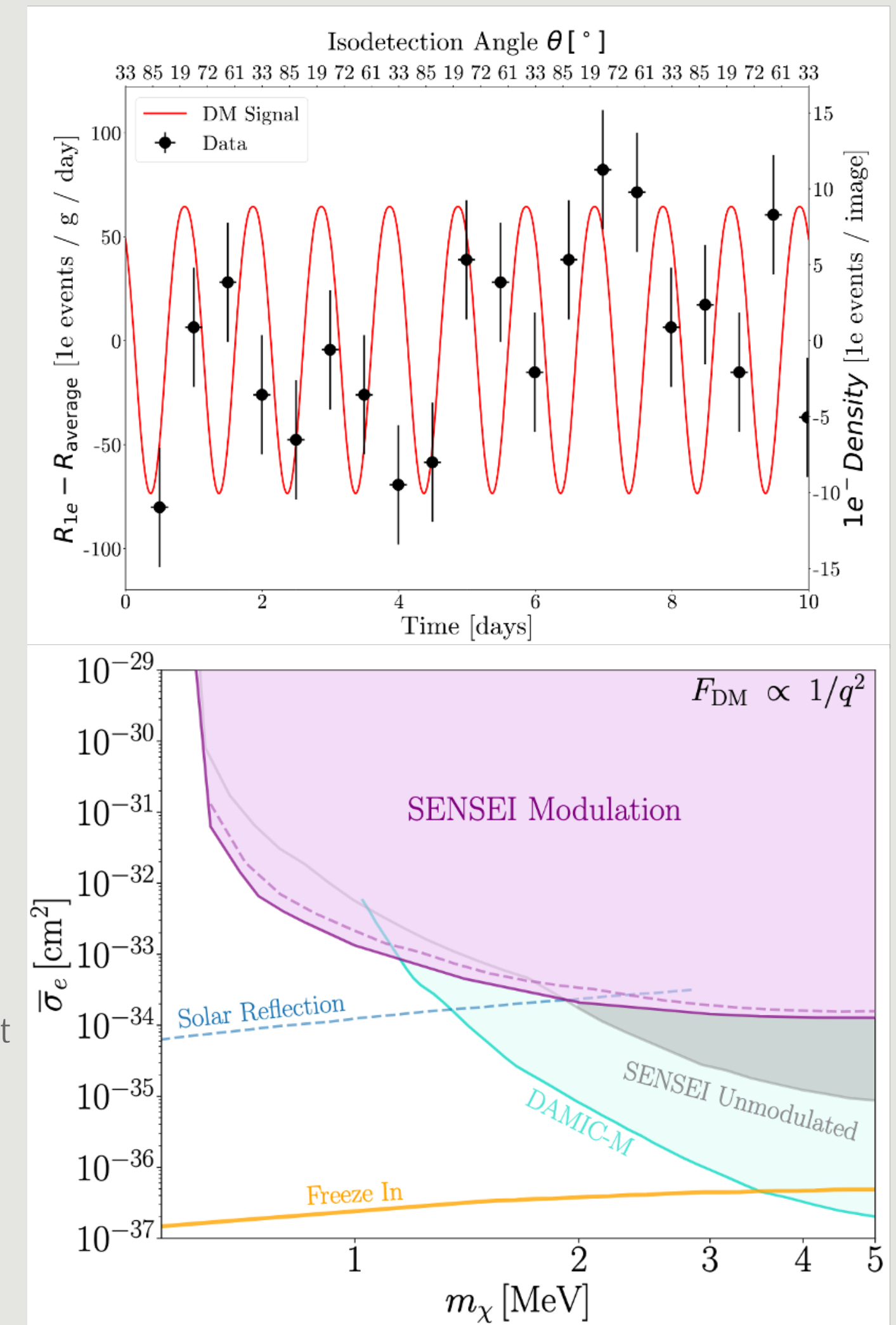


Recent and Upcoming Work

Diurnal Modulation

- * SENSEI Modulation data taken using 2 CCDs at MINOS from Feb – May 2024
- * Binned (1x32) images with 6h exposures, 23% of pixels removed with masking
- * Statistical analysis was general, considered both model dependent and model independent constraints
- * Order of magnitude improvement in constraints compared to SNOLAB Run 2 measurements
- * Daily modulation will remain a powerful analysis tool until background rates are significantly improved

The SENSEI Collaboration
Phys.Rev.Lett. 136 (2026) 21, 211001



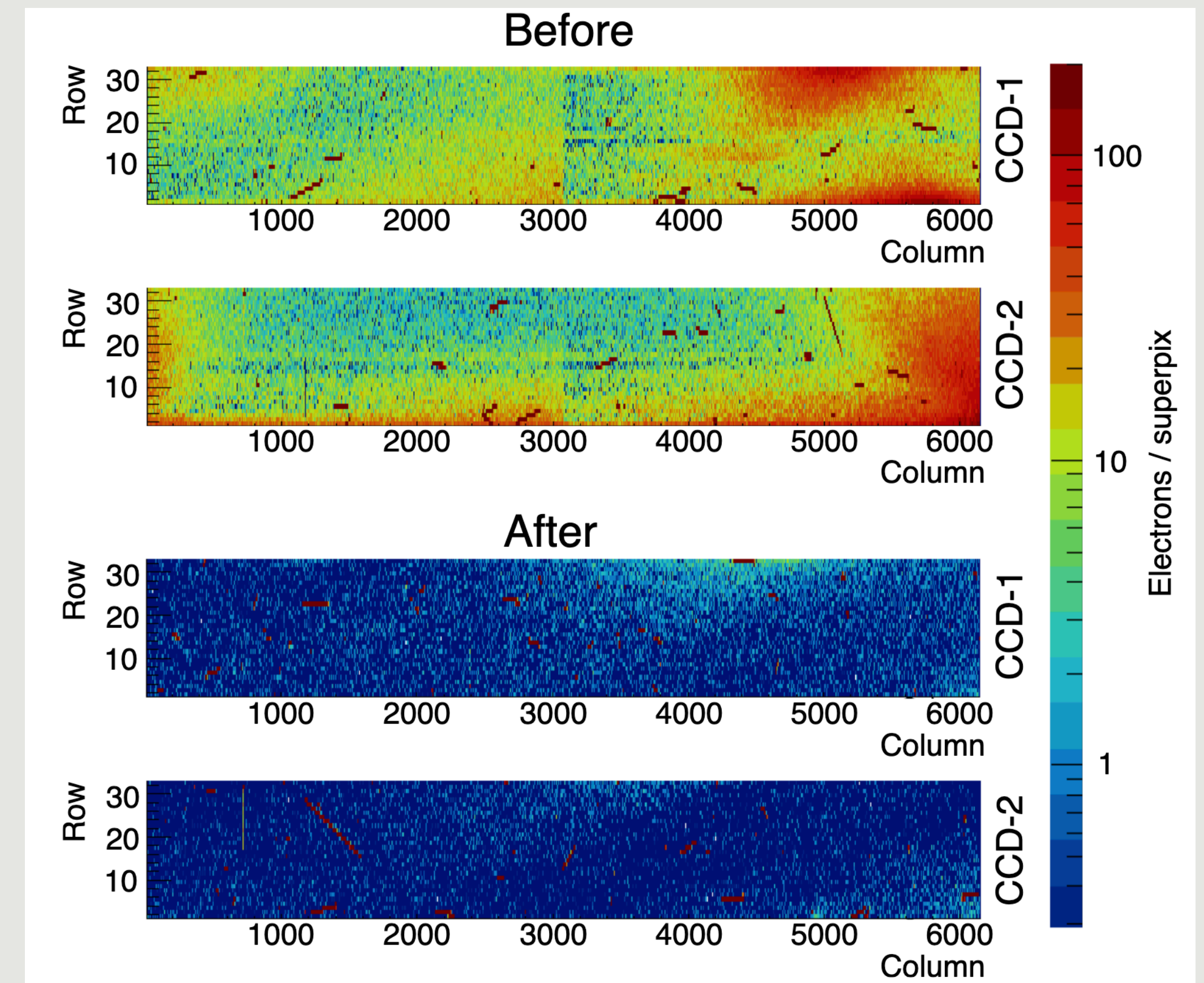
Does not
include newest
DAMIC-M result

Recent and Upcoming Work

Single-Electron Backgrounds

The SENSEI Collaboration
Phys.Rev.Lett. 134 (2025) 16, 161002

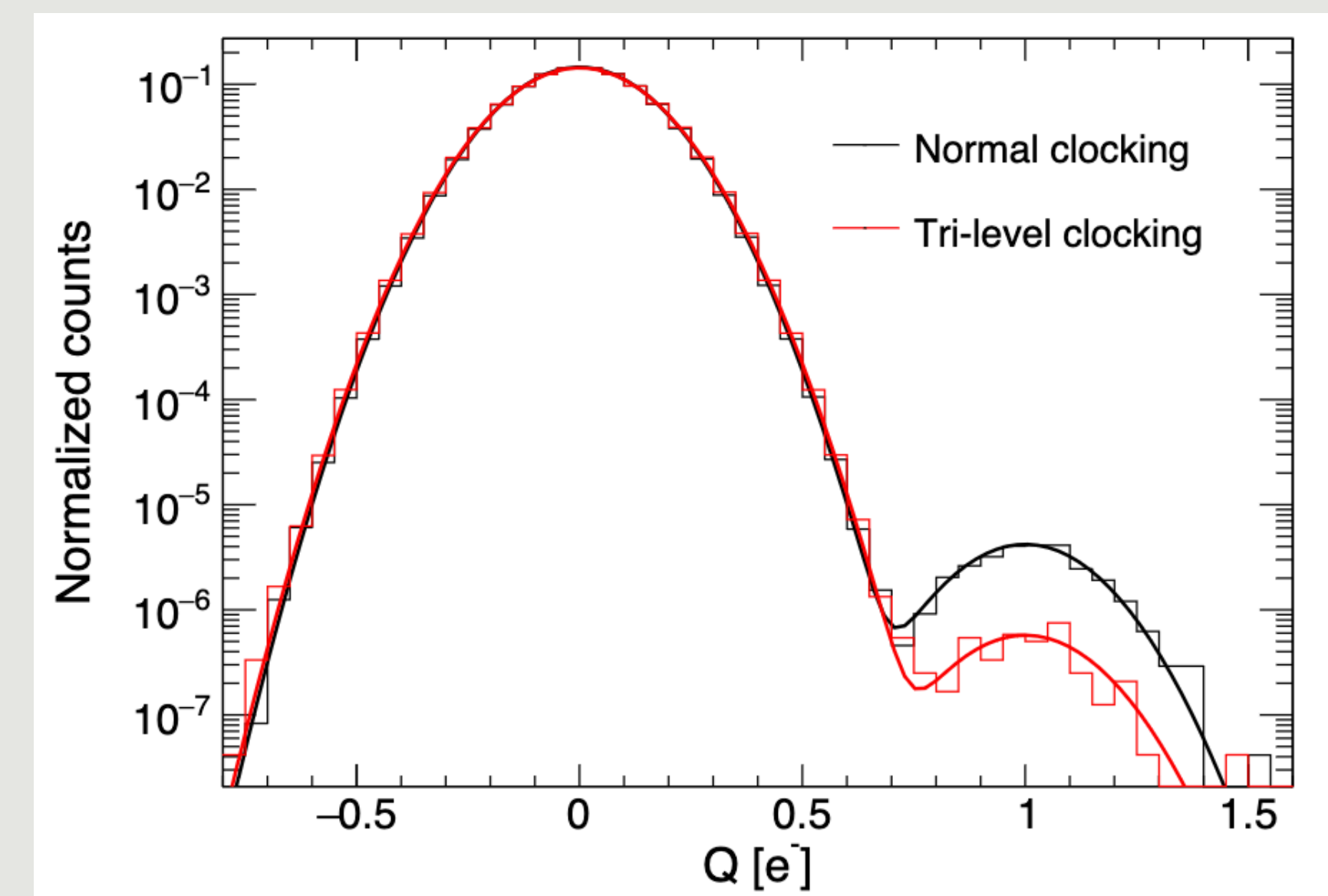
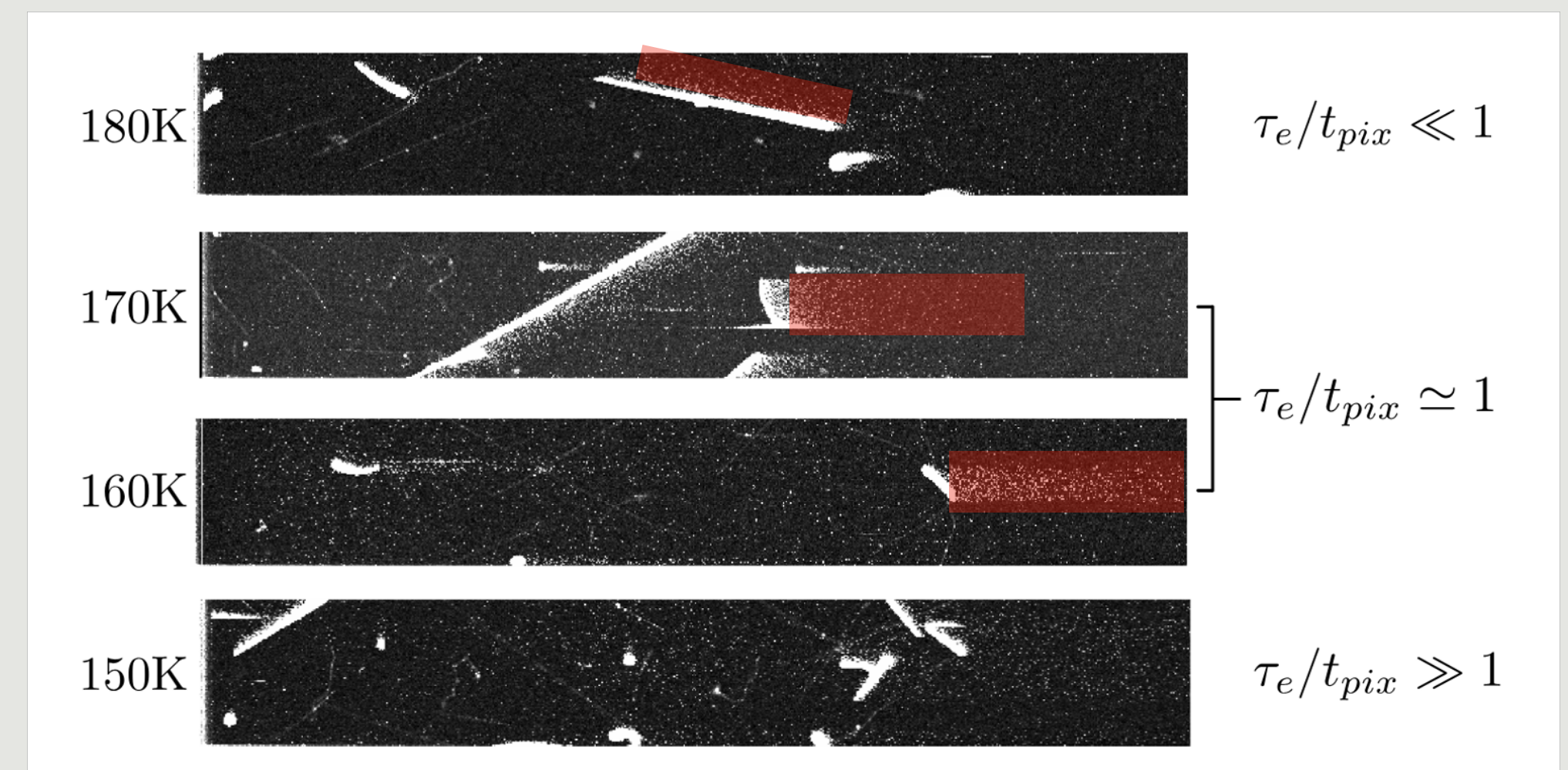
- * **Dark current** — de-trapping of electrons from thermal fluctuations, scales with exposure
- * **Light Leaks** — this was tested in a comparison run with MINOS during our dedicated single-electron run at SNOLAB
- * Hypothesis: blackbody radiation leaking onto the CCD as a possibility for the elevated single-electron rate
- * The SENSEI setup at SNOLAB has the CCD trays enclosed in a cold copper box, but the box has openings to room-temperature parts inside the vessel
- * Tested with an LED before and after replacing copper-tray design with an improved light-tight design — saw significant improvements



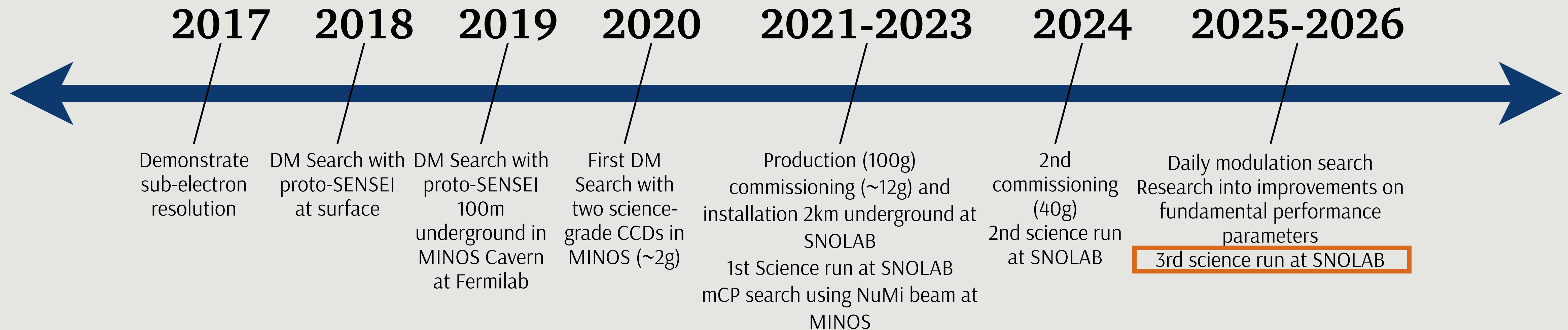
Recent and Upcoming Work

Single-Electron Backgrounds

- * **Dark current** – de-trapping of electrons from thermal fluctuations, scales with exposure
- * **Charge Traps** – backgrounds arising from defects in the silicon that can trap electrons from high energy events and release them hundreds of seconds to days later – producing uncorrelated single-electron events
 - * Recent and upcoming work understanding the effect of these at SENSEI operating temperatures
- * **Spurious charge** – impact ionization producing spurious electrons in bulk when shifting charge
- * Exposure independent, and can be improved by modifying measurement protocol
 - * Very recent paper working to characterize spurious charge in SENSEI CCDs
 - * New tri-level clocking technique to reduce single-electron backgrounds produced in serial register during skipper readout



Recent and Upcoming Work



- * We are currently taking unbinned data for our third science run, targeting $\geq 2e^-$ bins
- * Will take advantage of improved analysis strategies and background mitigation techniques
- * New cryocooler, should fix our temperature issues
- * Stay tuned for results!

Summary and Conclusion

- * SENSEI has pioneered Skipper-CCDs for exploring MeV-scale DM
- * We recently published our first daily modulation search, significantly improving our limits from 0.5–3 MeV
- * Recent work studying single-electron backgrounds in detail is in preparation
- * Using sophisticated analyses and careful background studies we are pushing for stronger sensitivity at the lightest masses
- * Science run 3 is ongoing, we should have exciting results soon!

Thank you for your attention!

Backup

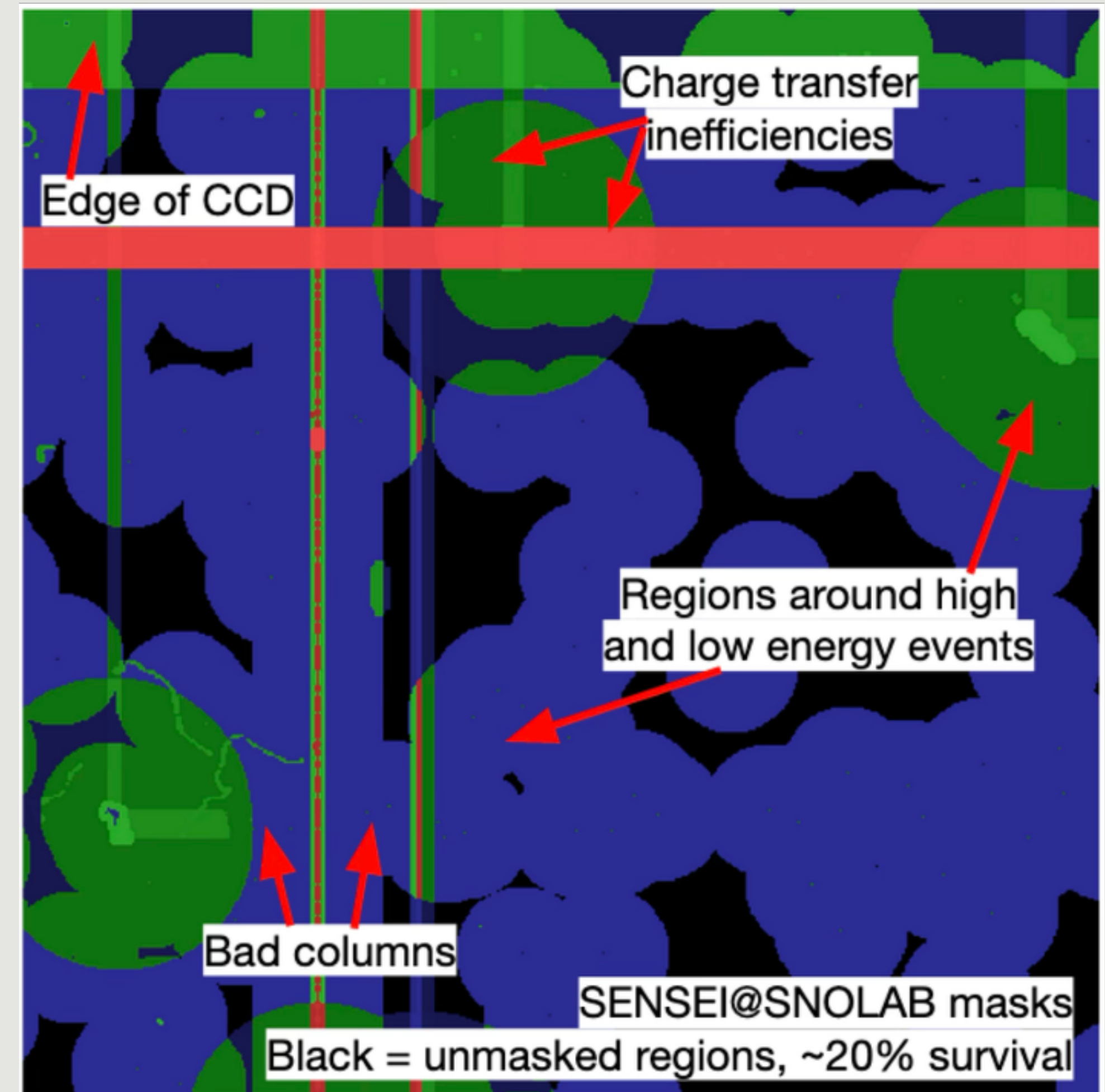


SENSEI Analysis

SENSEI @ SNOLAB Run 1

- * 45 commissioning images
- * 37 hidden images
- * $2e^-$ – $10e^-$ channels
- * Combined datasets: ~70 g-days per electron channel with cuts
- * Three limits: hidden dataset, commissioning dataset, and combined commissioning + hidden
- * Efficiency was ~20%

The SENSEI Collaboration
Phys.Rev.Lett. 134 (2025) 1, 011804



SENSEI Analysis

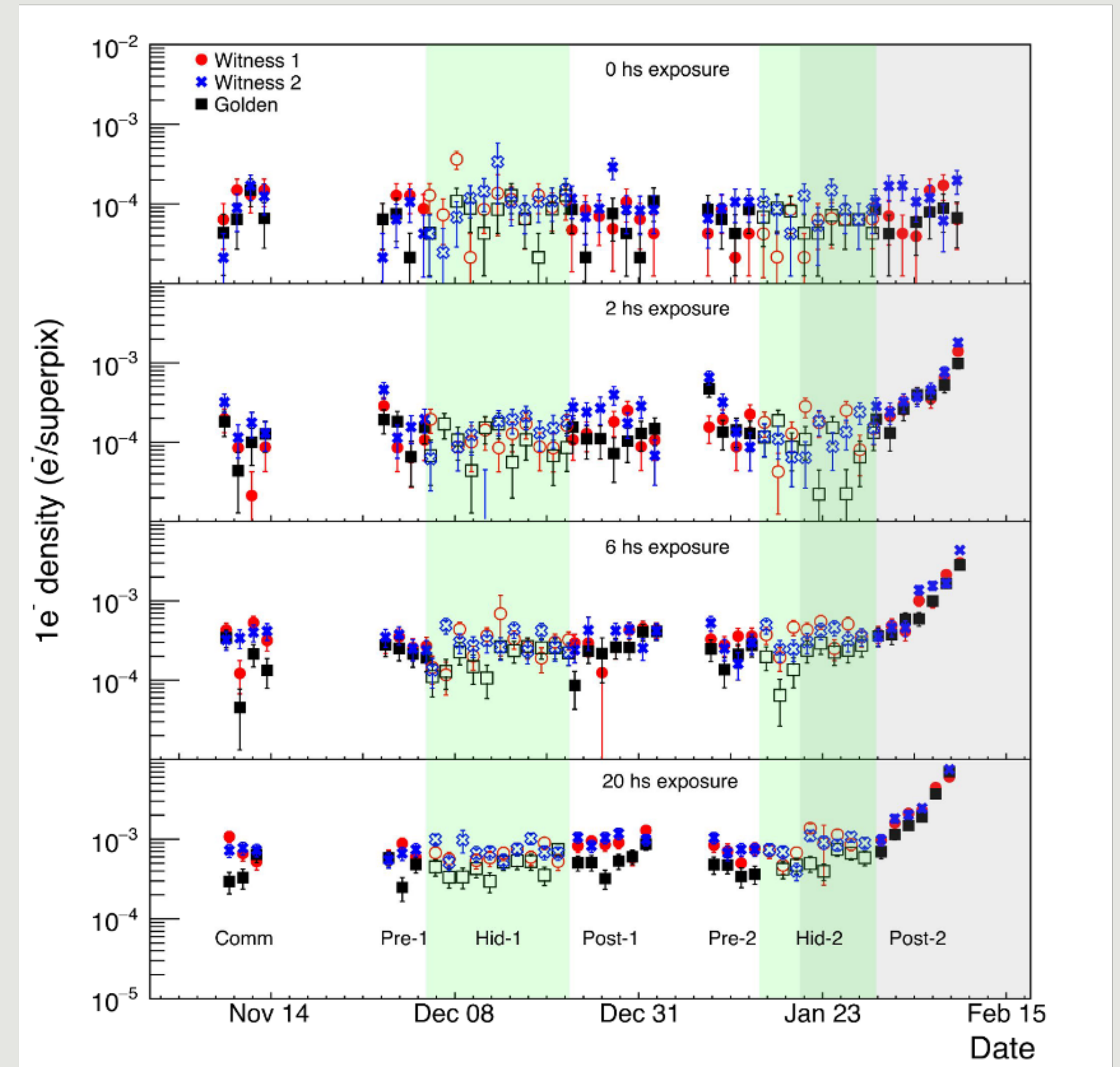
The SENSEI Collaboration
 Phys.Rev.Lett. 134 (2025) 16, 161002

SENSEI @ SNOLAB Run 2

1. Chose 1 Golden Quadrant
2. Quality cuts with commissioning data
 - * Electronic noise
 - * Cross talk
 - * Edges of CCDs
 - * Bad pixels and columns
 - * Hot image (3σ upper cut)
 - * Noisy image (refit after masking)
 - * Serial register events
 - * Charge transfer inefficiencies
 - * High energy events
3. Chose 2 Witness quadrants to assess cryocooler effect in hidden data

Detector effects

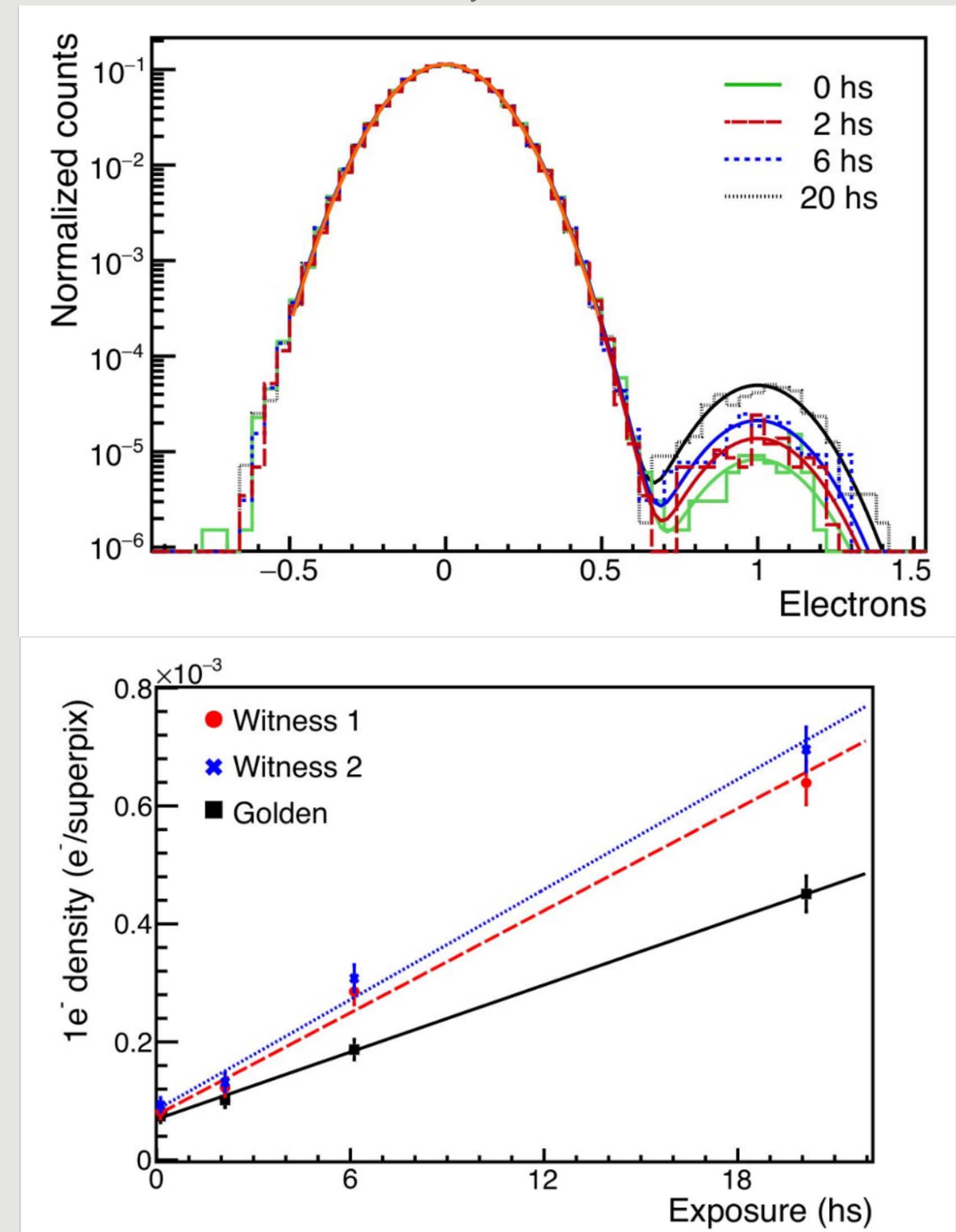
Environmental Background



SENSEI Analysis

SENSEI @ SNOLAB Run 2

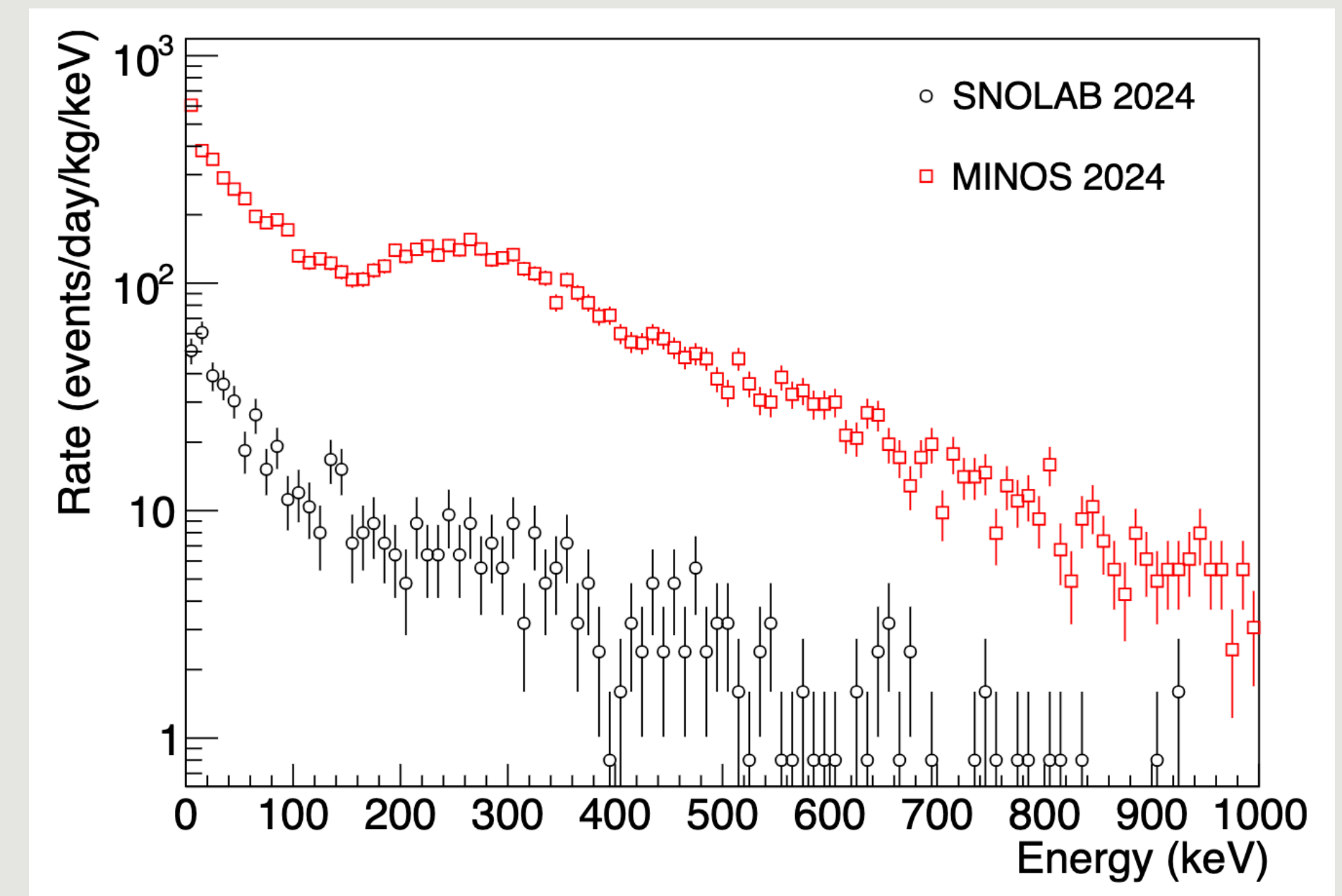
- * 19 hidden images selected, analysis on 3 quadrants, rest all kept hidden
- * Cut efficiencies at 85-97%
- * Backgrounds for the $1e^-$ rate are dark current (exposure dependent) and spurious charge (exposure independent)
- * Fitting double gaussian gives you $1e^-$ density for each exposure
- * Plotting $1e^-$ density as a function per exposure gives measurement of exposure dependent $1e^-$ rate
- * Open data – this analysis was released on github



SENSEI Analysis

Latest SENSEI High Energy Event Spectrum

- * Some masks applied here to remove instrumental effects
- * MINOS result here is shown after the new tray installation
- * No copper etching, which would further reduce this background



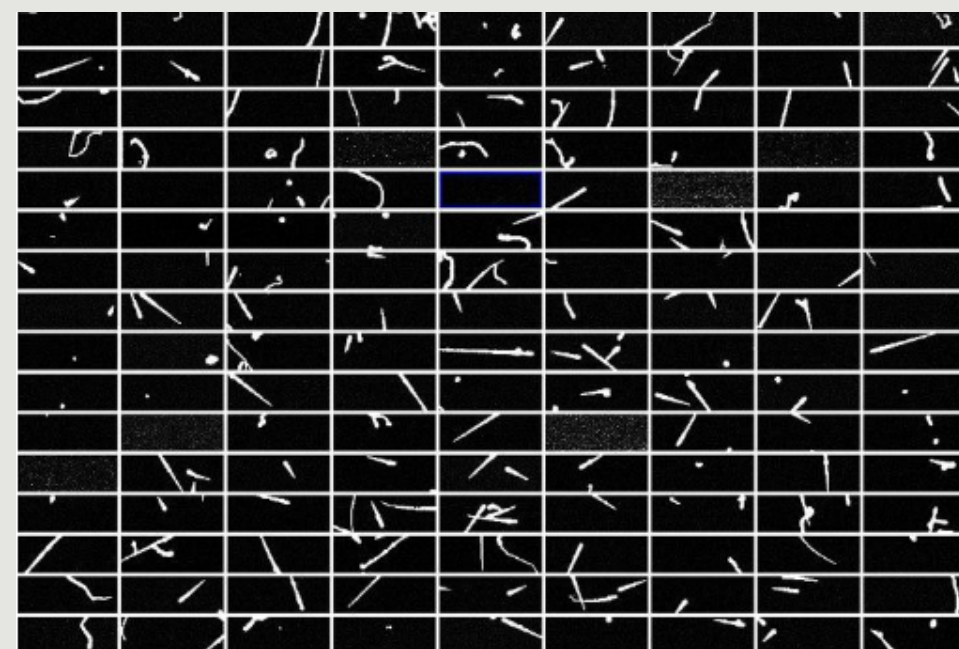
The SENSEI Experiment

The Future of Skipppers for Light DM

SENSEI (100g)

DAMIC-M (1kg)

OSCURA (10kg)



IEEE Transactions vol. 70, no. 6, pp. 2306-2316
 JINST 18 P01040
 JINST 16 P11012
 arXiv:2004.07599
 IEEE Sensors, 25, 5, 8813-8822

- * Leveraging DAMIC + SENSEI Expertise for OSCURA
- * 10% integration test (1kg) coming soon!
- * Currently OSCURA is the largest CCD camera (# of CCDs) in the world!

