LDMA'19

DAMIC-M: search for light dark matter with CCDs

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KICP

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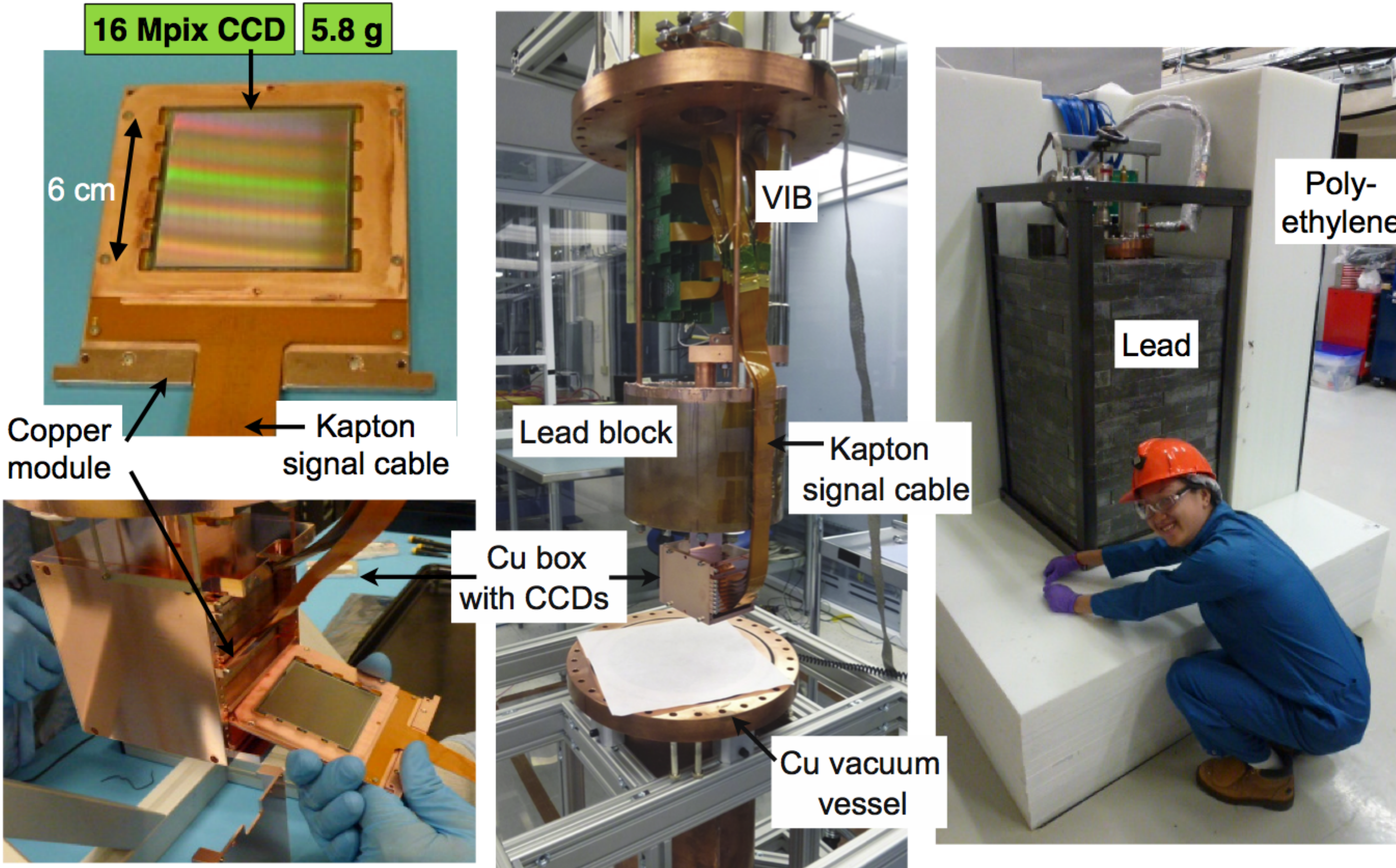
(Photo image: particle tracks in a DAMIC CCD)

Dark Matter in CCDs @ SNOLAB

15 μm x 15 μm pixel, 675 μm thick

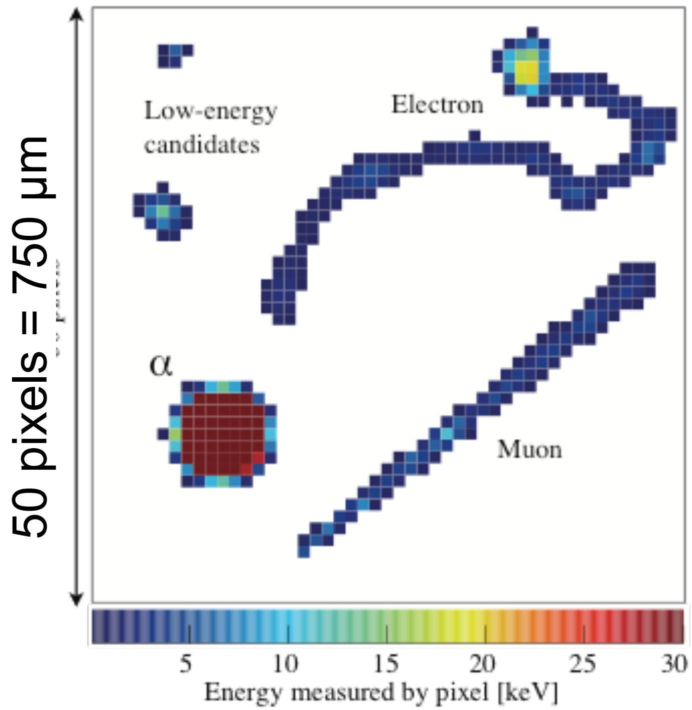


DAMIC-M (DAMIC at Modane) builds on the experience of DAMIC at SNOLAB

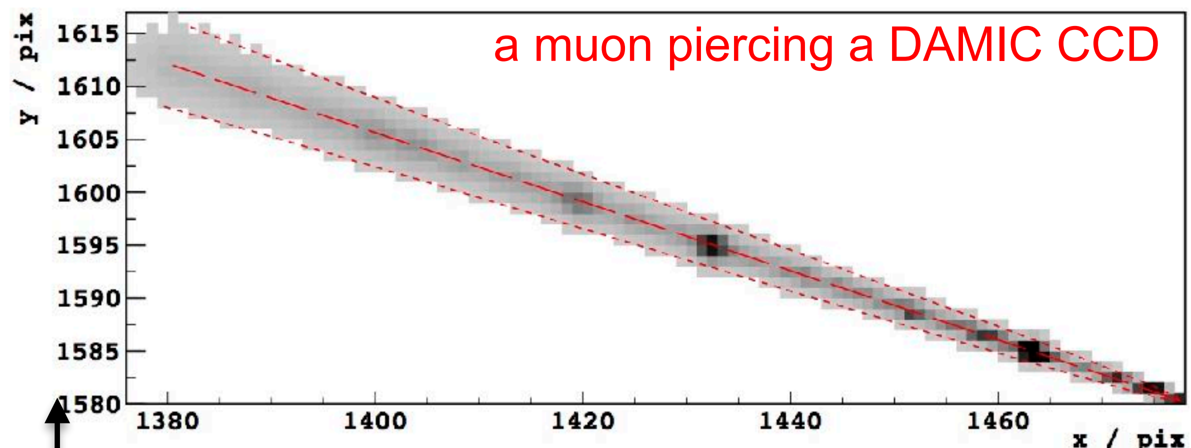
DAMIC CCDs

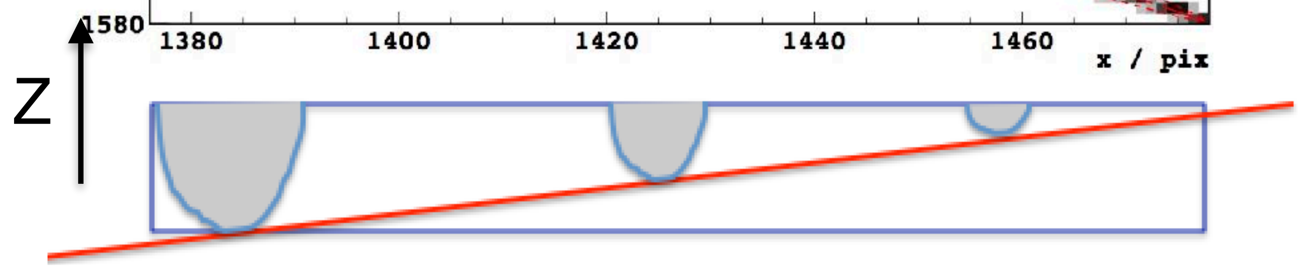
Exquisite spatial resolution

Allows for unique particle identification and background characterization



3D reconstruction of energy deposit within the silicon bulk using charge diffusion





$\sigma_{xy} \approx Z$: fiducial volume definition

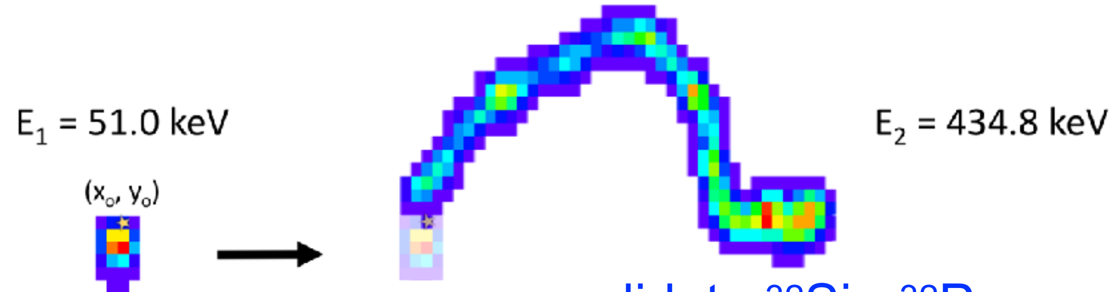
- Cosmogenic ^{32}Si

Unique capability to characterize (and reject) backgrounds

Produced by cosmic rays in the atmosphere, ends up in the silica sand.

Search for spatially correlated beta decays. Sensitivity with current data is few Bq/kg

^{32}Si ($T_{1/2}$= 150 y, β) ➔ ^{32}P ($T_{1/2}$= 14 days, β)



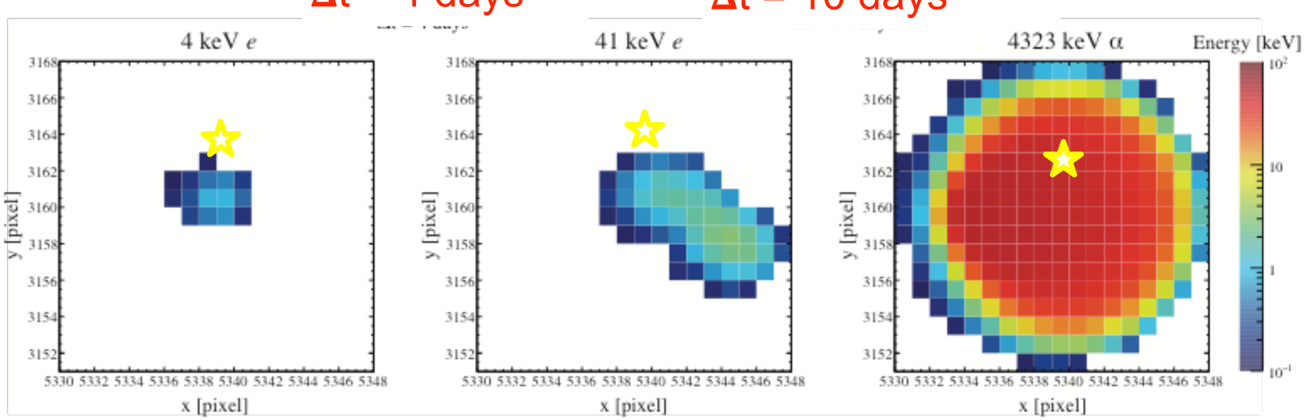
Δt = 29.1 days

candidate ^{32}Si - ^{32}P

- Bulk and surface radiogenic backgrounds

Δt = 4 days

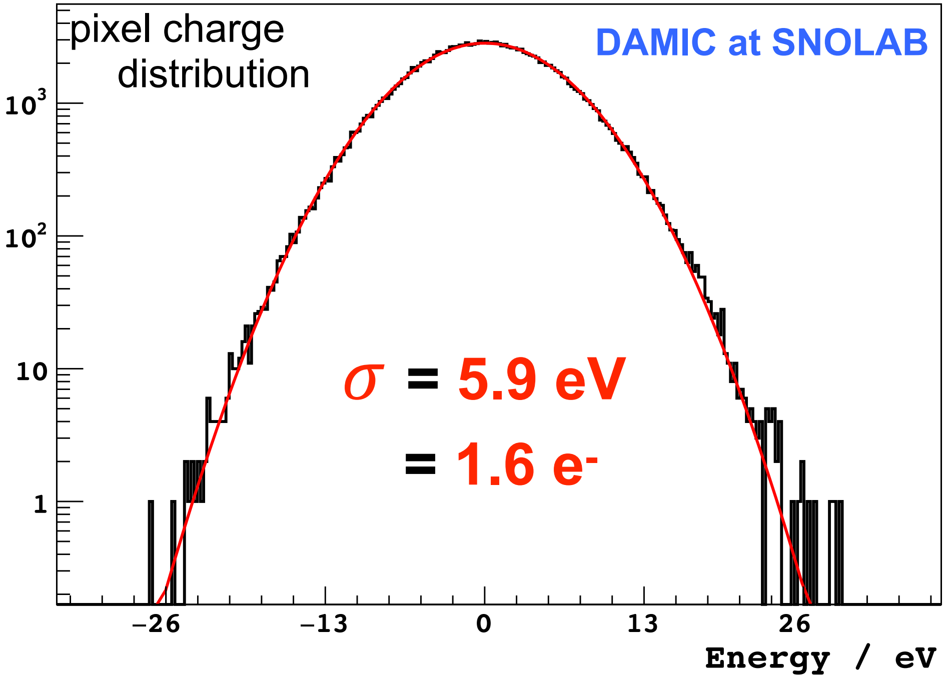
Δt = 10 days



candidate ^{210}Pb decay chain

sub-ppt levels sensitivity to bulk contamination

^{210}Pb ($T_{1/2}$= 22.3 y, β) ➔ ^{210}Bi ($T_{1/2}$=5.0 days, β) ➔ ^{210}Po ($T_{1/2}$= 138 days, α)



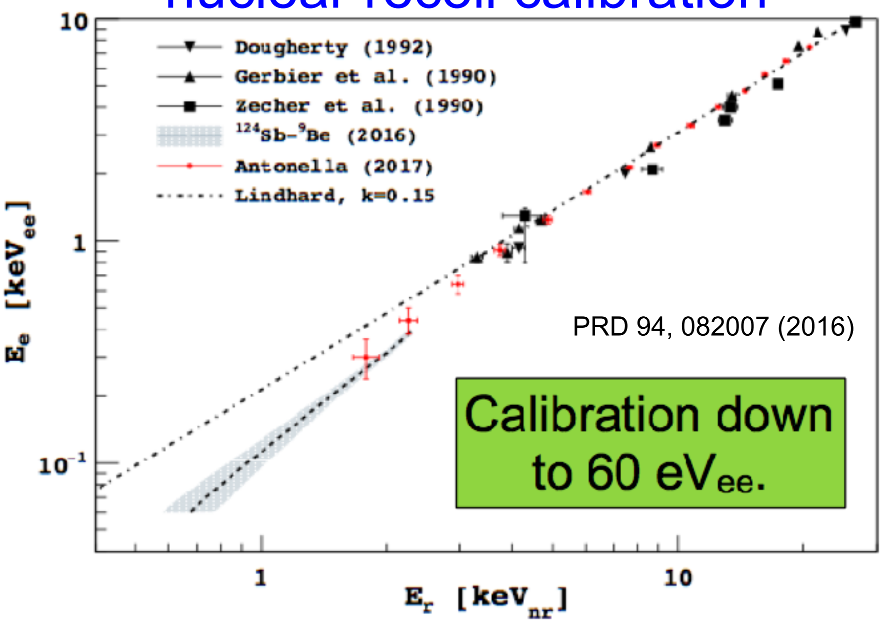
extremely low noise and dark current

lowest dark current ever measured in a silicon detector:

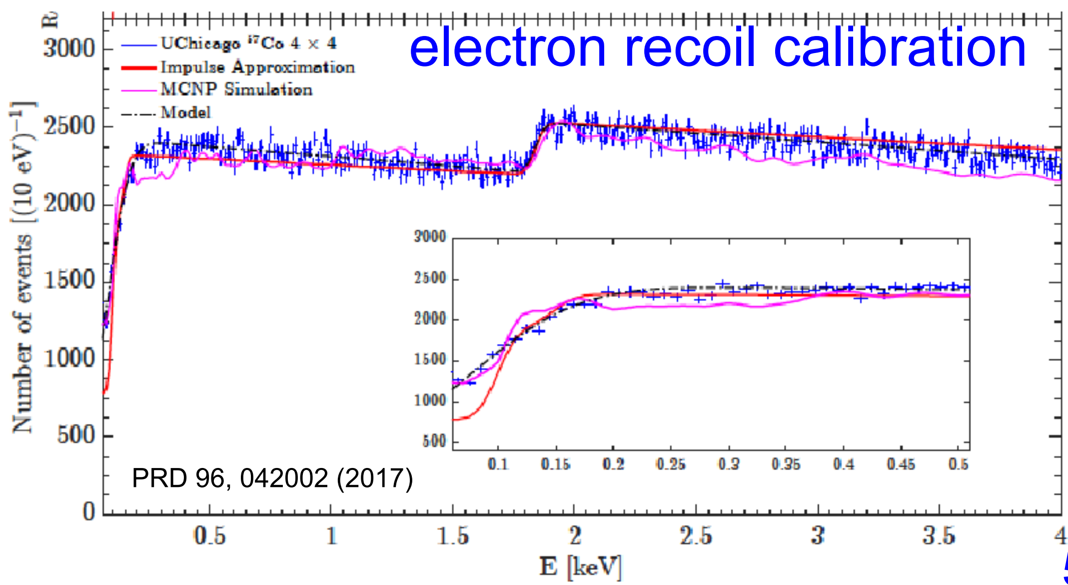
2×10^{-22} A/cm^2 (at 140 K)

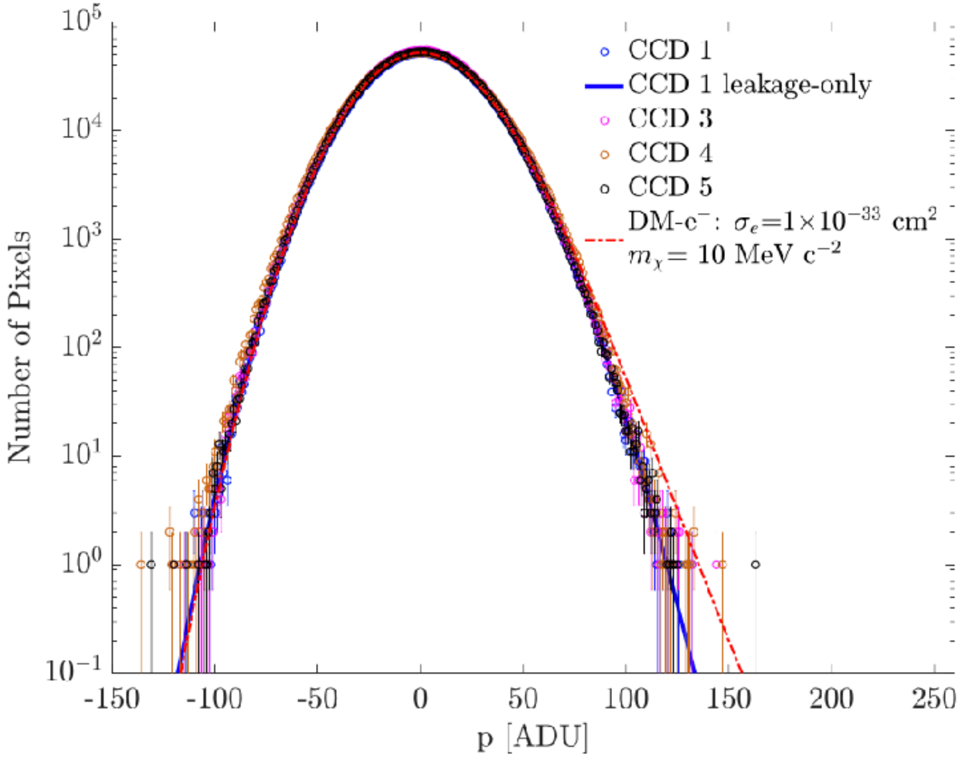
calibrated down to threshold

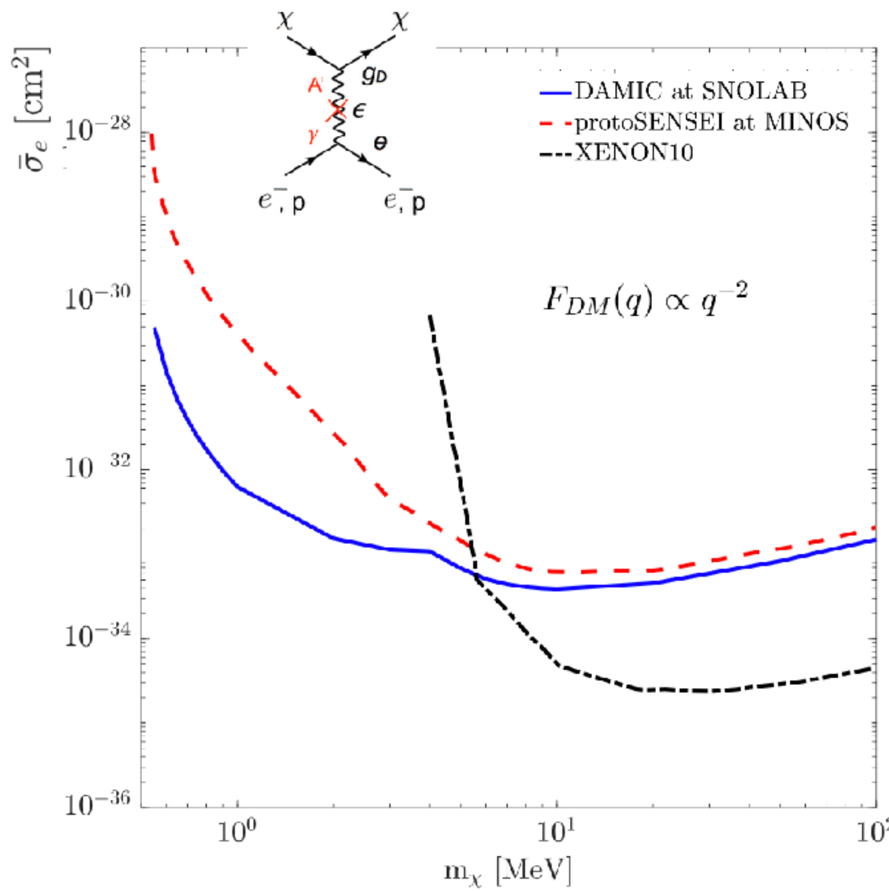
nuclear recoil calibration

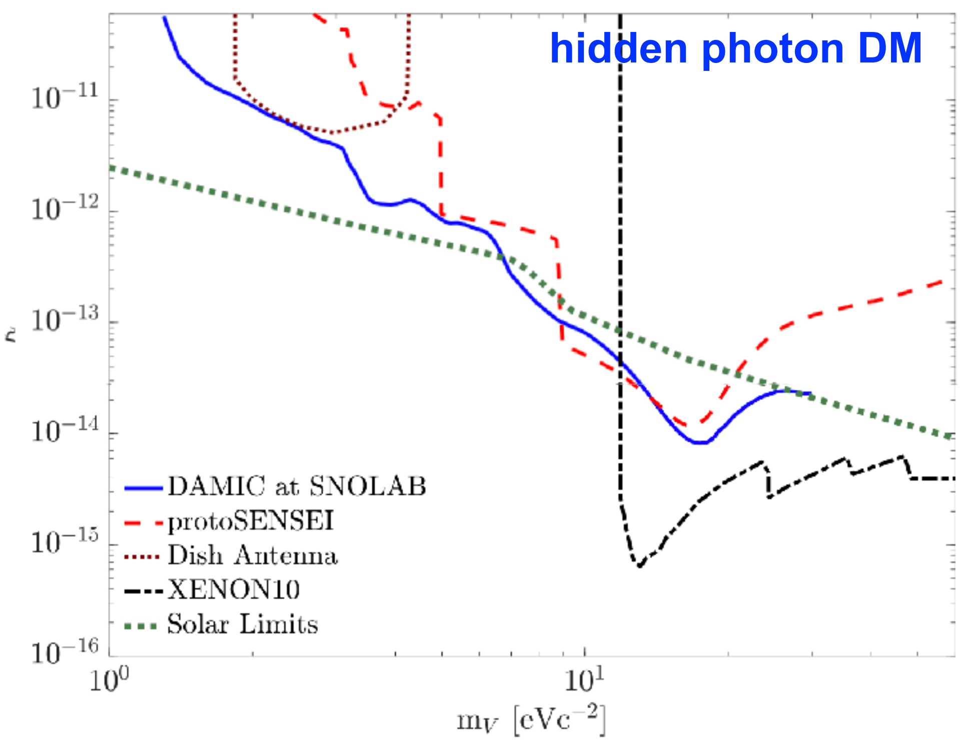


electron recoil calibration









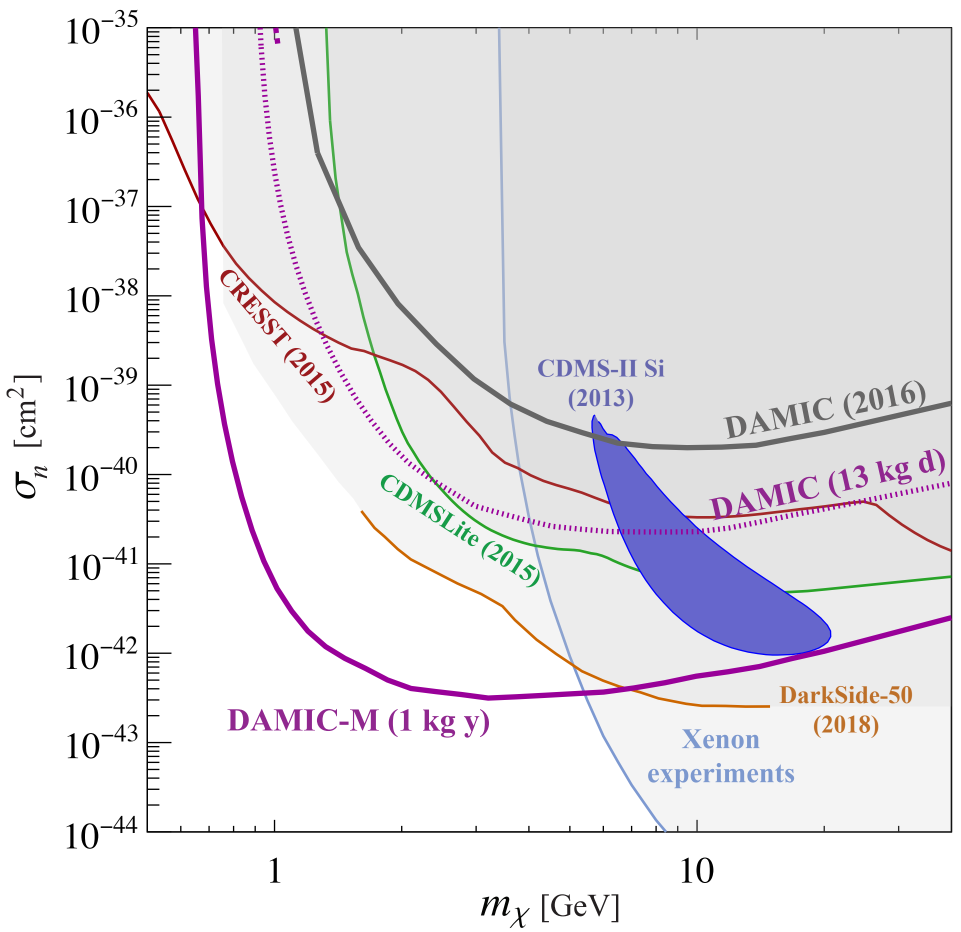
Phys. Rev. Lett. 123, 181802 (2019)

DM-electron limits

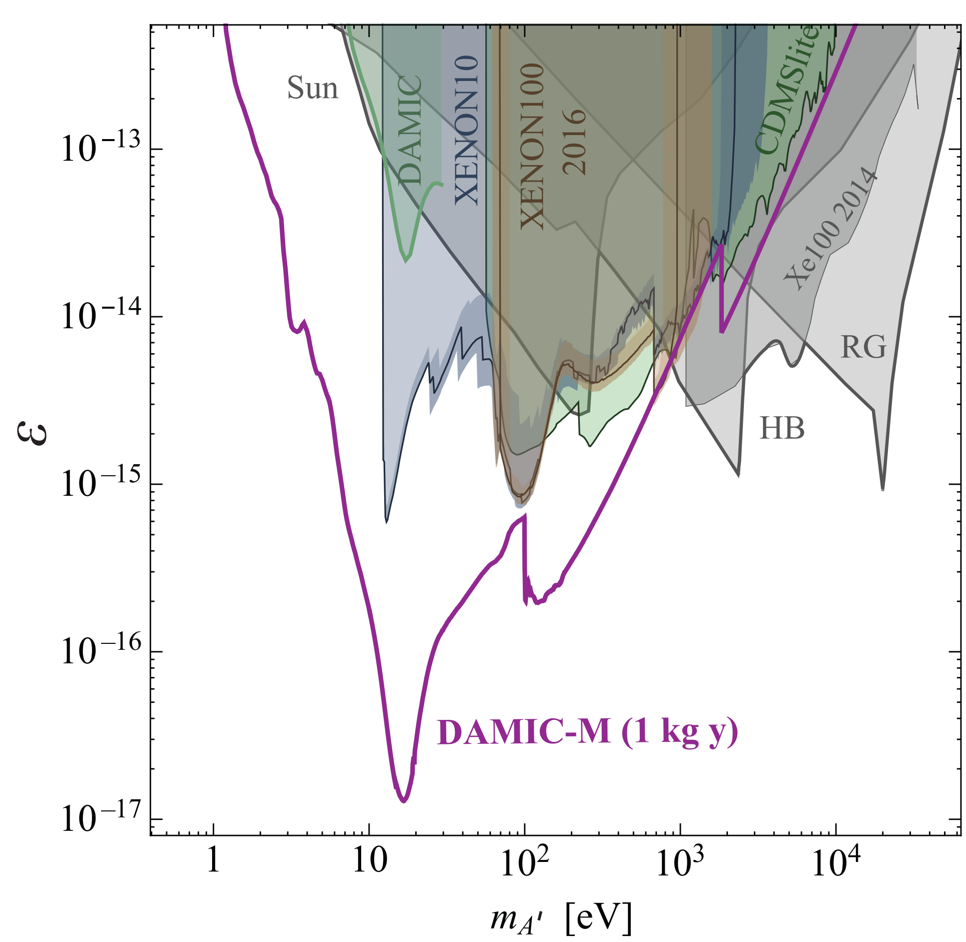
DAMIC@SNOLAB has established world-best limits thanks to the extremely low dark current and threshold

Scientific reach

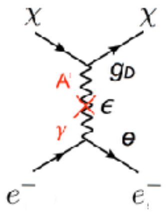
WIMP nuclear recoil search



Hidden photon search

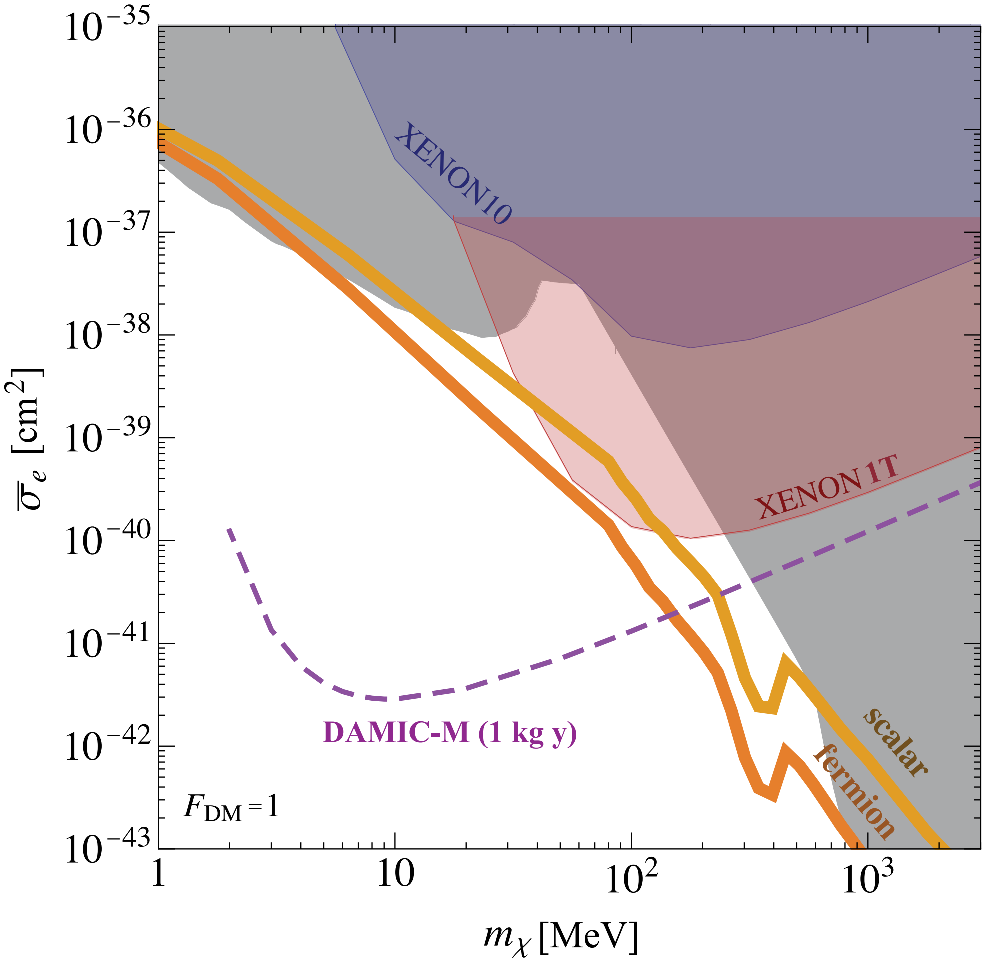


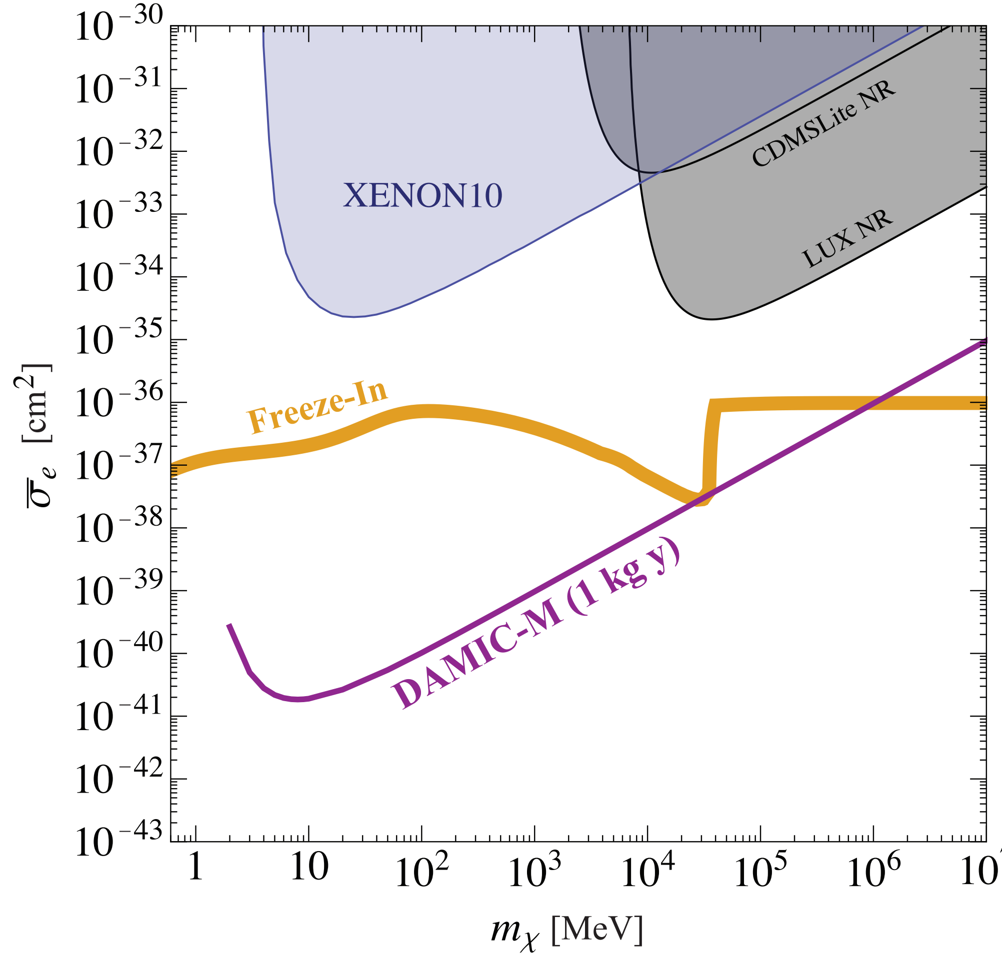
DAMIC-M will feature <u>single electron</u> resolution allowing for detection thresholds of 2-3 e-



Scientific reach

Heavy mediator | **Light dark matter - electron scattering** | **Light mediator**



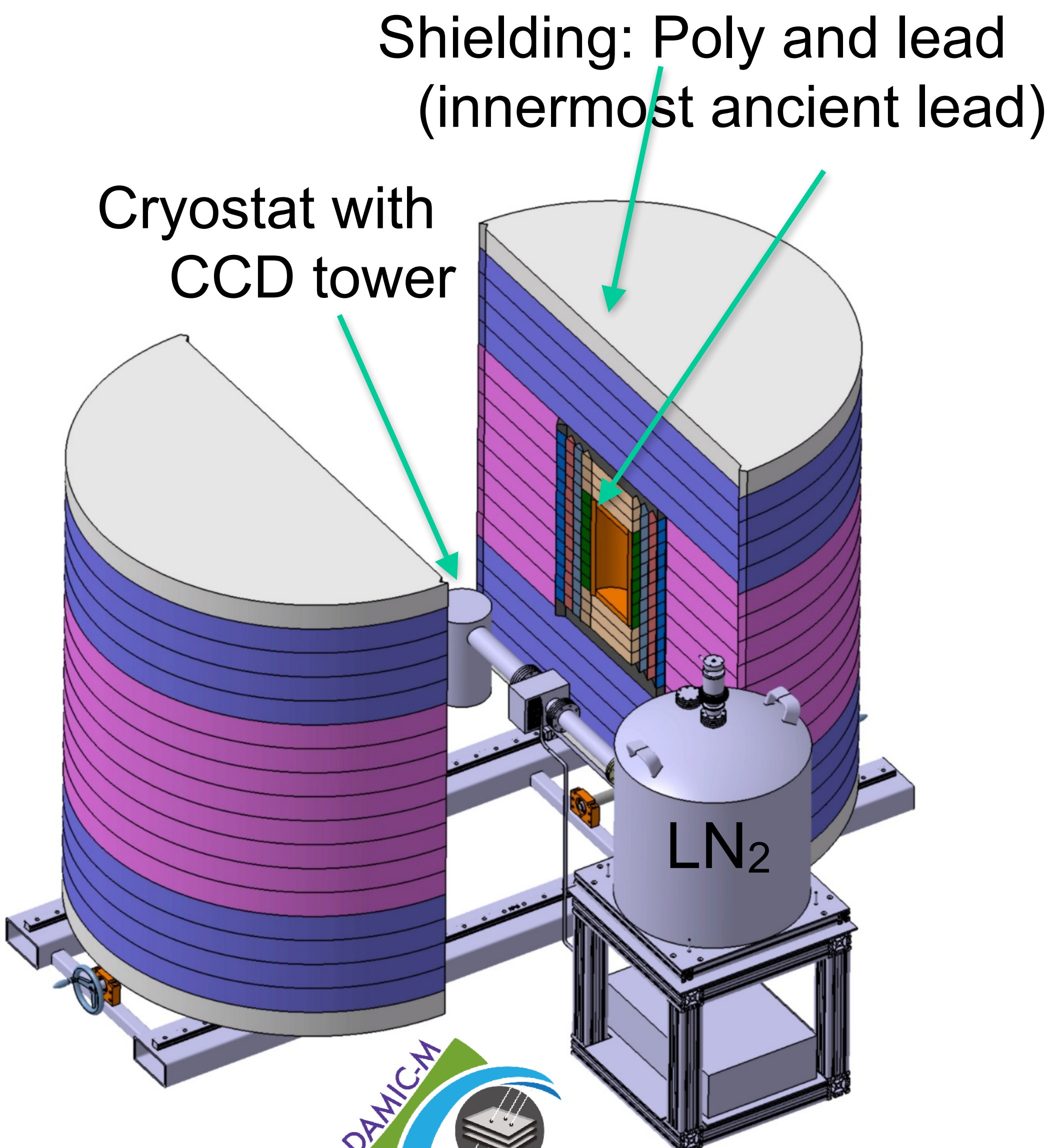


DAMIC-M will be sensitive to light dark matter even if these candidates constitute only a small fraction of the total DM in the universe

DAMIC-M

DAMIC at Laboratoire Souterrain de Modane

- 50 CCDs (kg-size target mass)
- Most massive CCDs ever built (>10 g each)
- **Single electron resolution** with "skipper" readout (demonstrated by Fermilab SENSEI group)
- A fraction of dru background
- "Classical" design (Ge detectors and DAMIC at SNOLAB)
- R&D and design up to 2021
- Construction 2022
- Installation in 2023



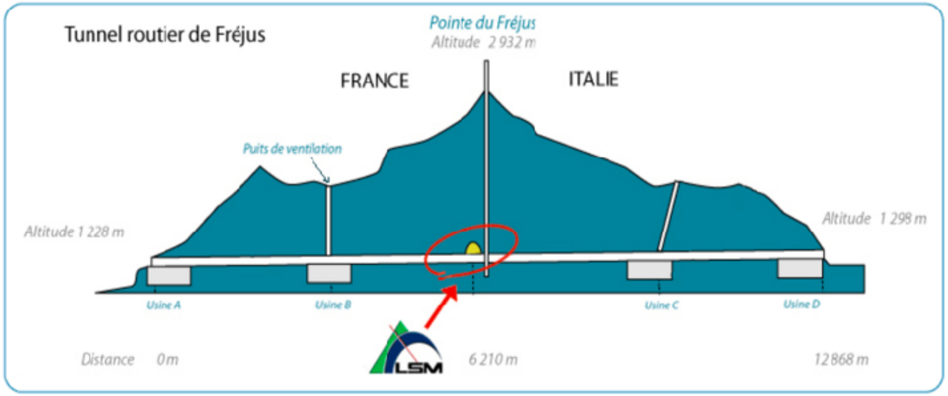
DAMIC-M

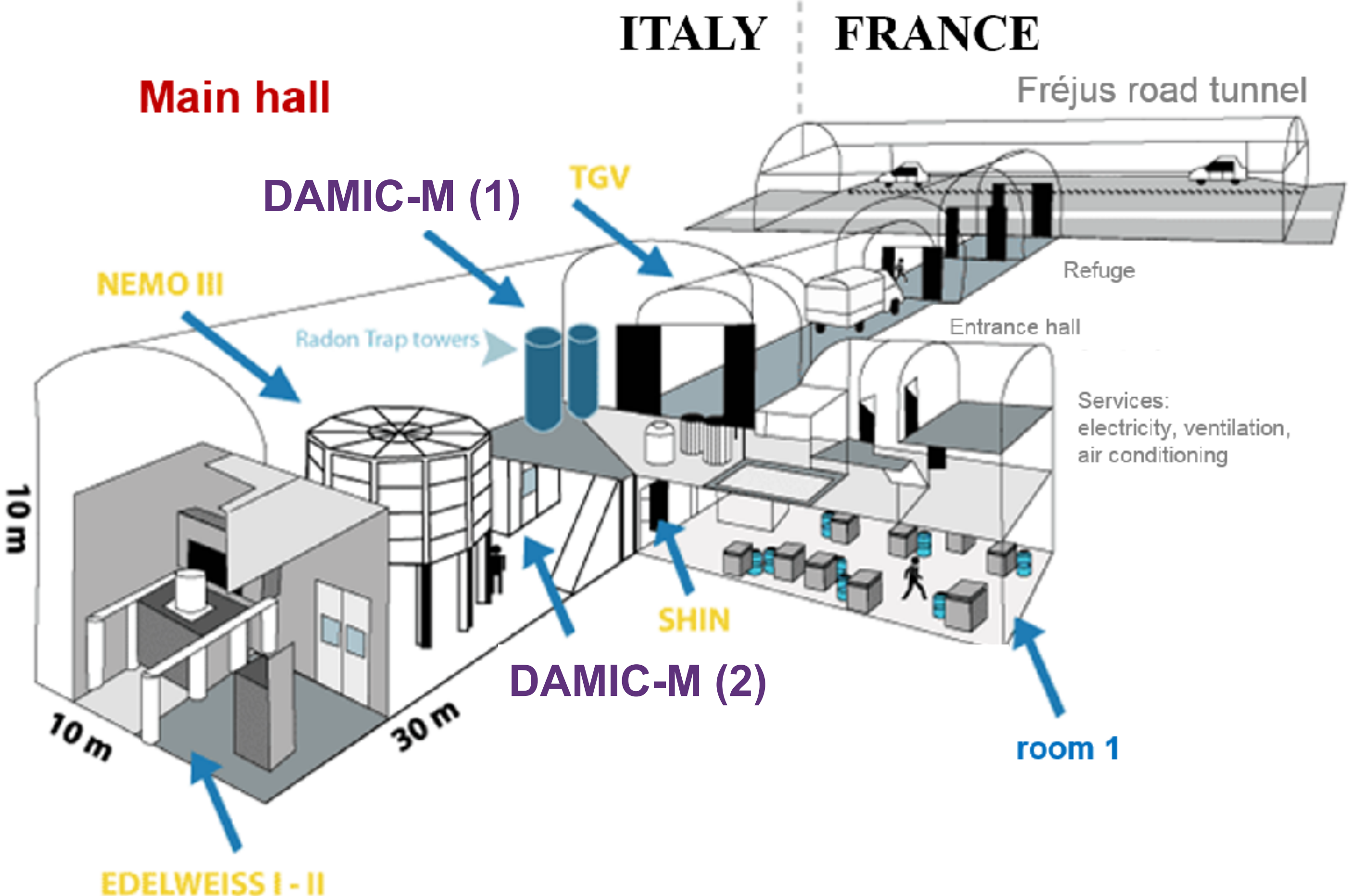
European Research Council

The National Science Foundation

FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

The Laboratoire Souterrain de Modane

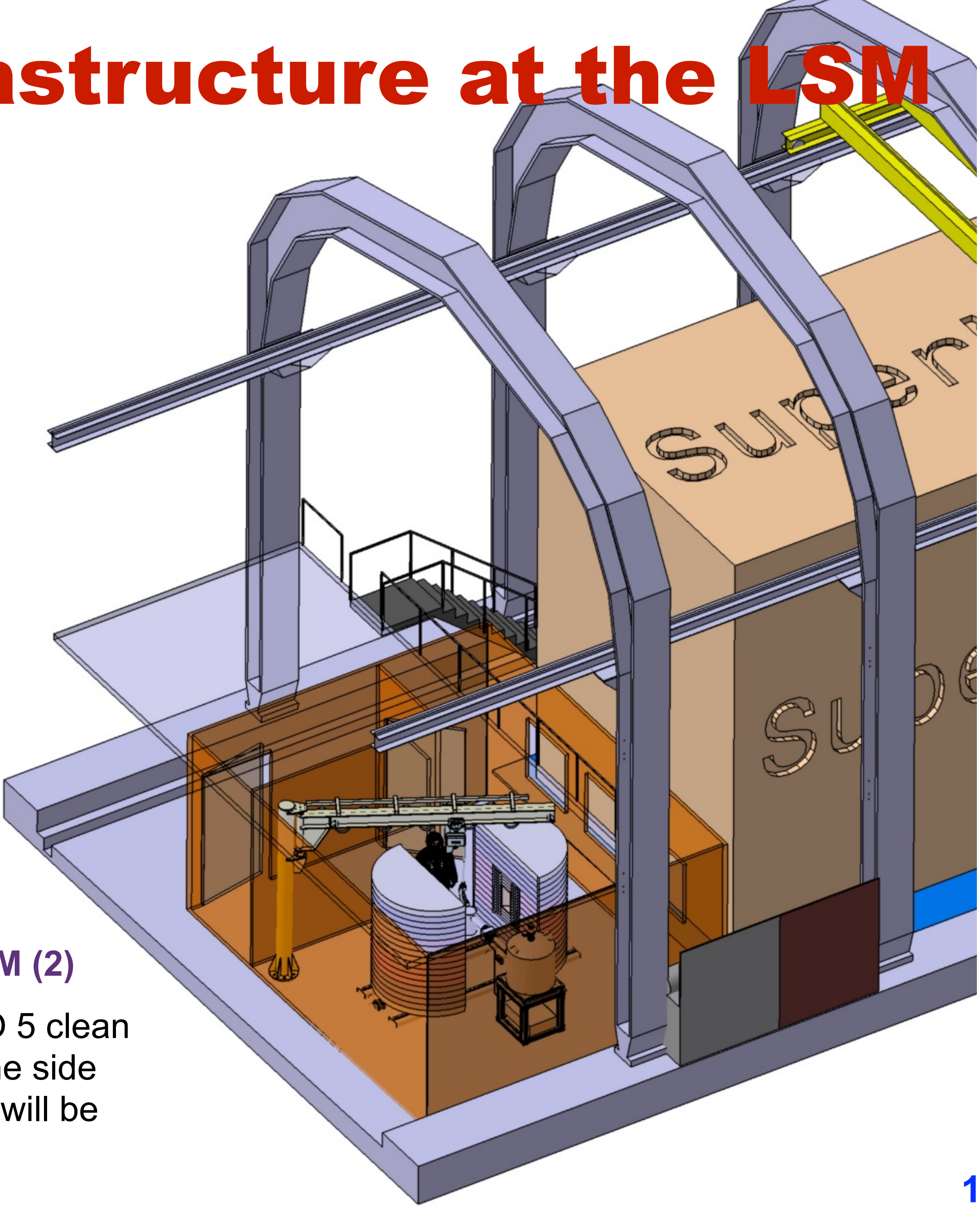




DAMIC-M infrastructure at the LSM

DAMIC-M (1)

On the upper floor an ISO 5, radon-free clean room will host the CCD packaging and test facilities



DAMIC-M (2)

The detector will be installed in an ISO 5 clean room located on the ground floor on the side of SuperNemo. DAMIC-M clean room will be installed by the end of 2019

The journey has begun!

Silicon Ingot production by TOPSIL, Frederikssund, Denmark

Float Zone mono pulling	21/08/2019 23:00 -> 22/08/2019 11:15
Crystal splitting into ingot sections and mono test	22/08/2019 11:15 -> 22/08/2019 13:00
Ingot surface grinding	22/08/2019 13:00 -> 22/08/2019 15:00
Ingot electrical tests	22/08/2019 15:00 -> 23/08/2019 11:30
Package and invoicing	23/08/2019 11:30 -> 23/08/2019 14:30
Ingot shipped (picked up by car).	23/08/2019 14:30

Now at Boulby, waiting for wafering by Shin-Etsu Handotai Europe (Livingston, Scotland)

(DAMIC at SNOLAB wafers were produced in in China, with ingot and wafers shipped by airplane.

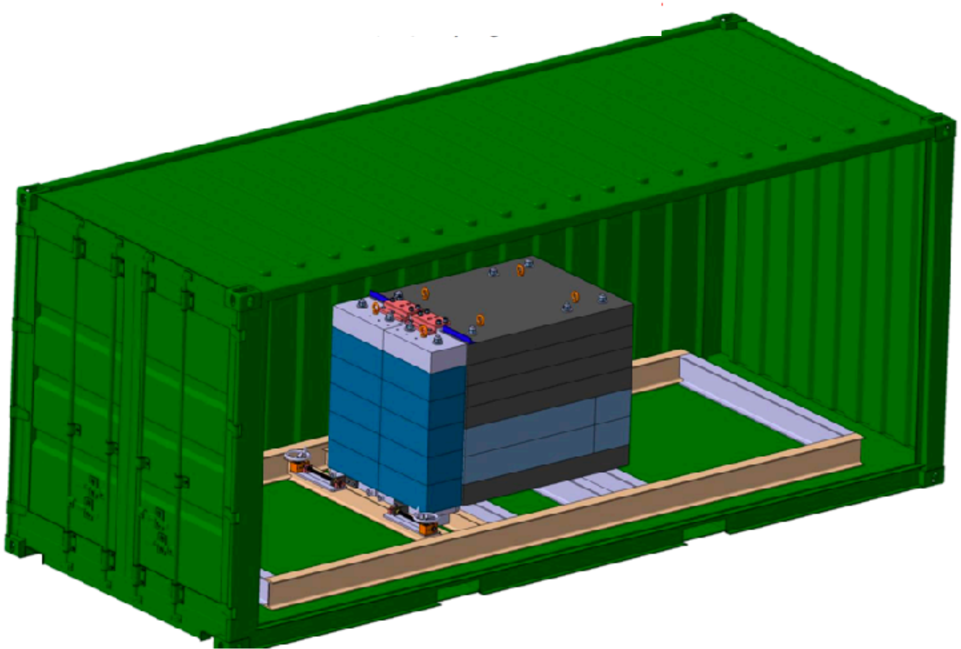
One air flight is equivalent to several months of cosmic ray exposure on surface)

and will continue!

DAMIC-M CCDs are fabricated by Teledyne DALSA in Canada

The wafers and CCDs will be shipped by sea in a custom-made shielded container

(8-15 days transatlantic journey)



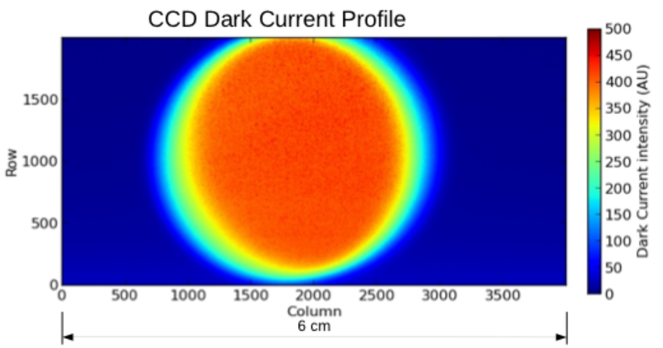
A 20' standard dry container with a ≈ 15 t iron shielding. A cavity 50 cm x 40 cm x 110 cm large enough for the CCD packages and the electroformed copper cryostat

The shielding reduces tritium cosmogenic activation by a factor ≈ 25

Underground storage at SNOLAB for wafers/ CCDs while in North America

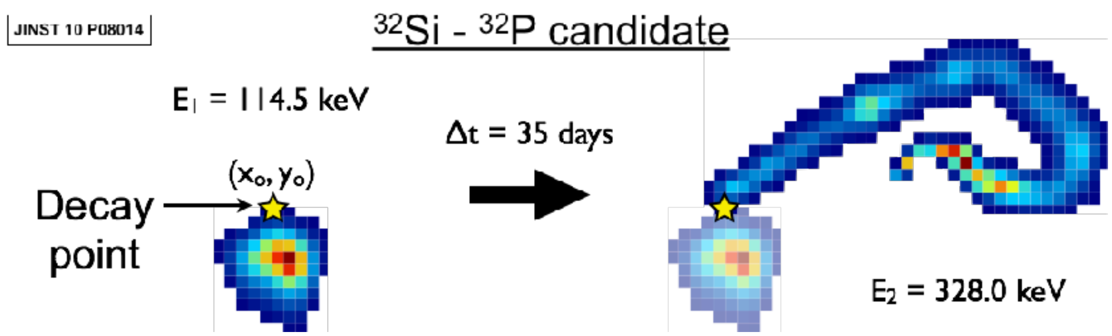
DAMIC-M Backgrounds

- Most relevant backgrounds identified by DAMIC at SNOLAB
- Cosmogenic tritium: minimize exposure to cosmic rays with shielding during transport/fabrication; CCD packaging and test underground at LSM. Also, R&D ongoing to evaluate tritium removal by wafers/CCDs baking.



Activation of a DAMIC CCD at the LANSCE neutron beam. Tritium clearly detected; rate measurement being finalized.

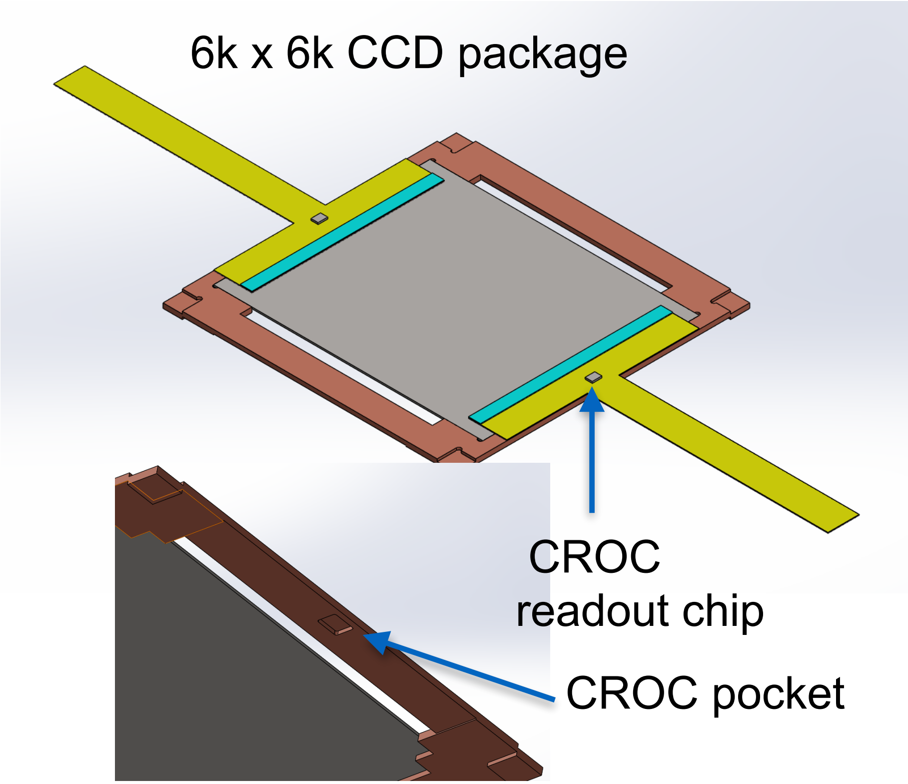
- Cosmogenic ^{32}Si: spatial correlations

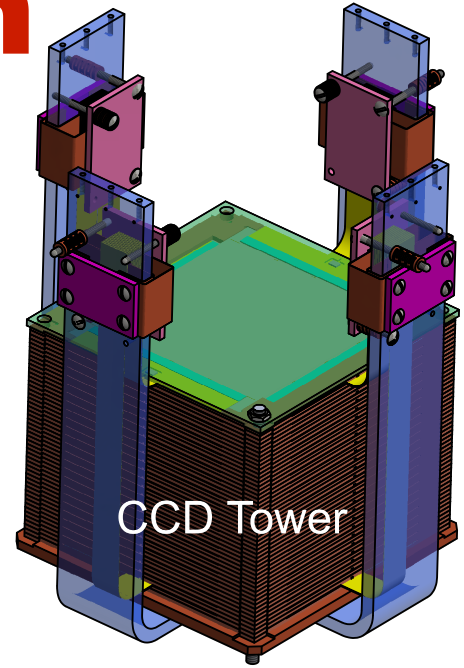


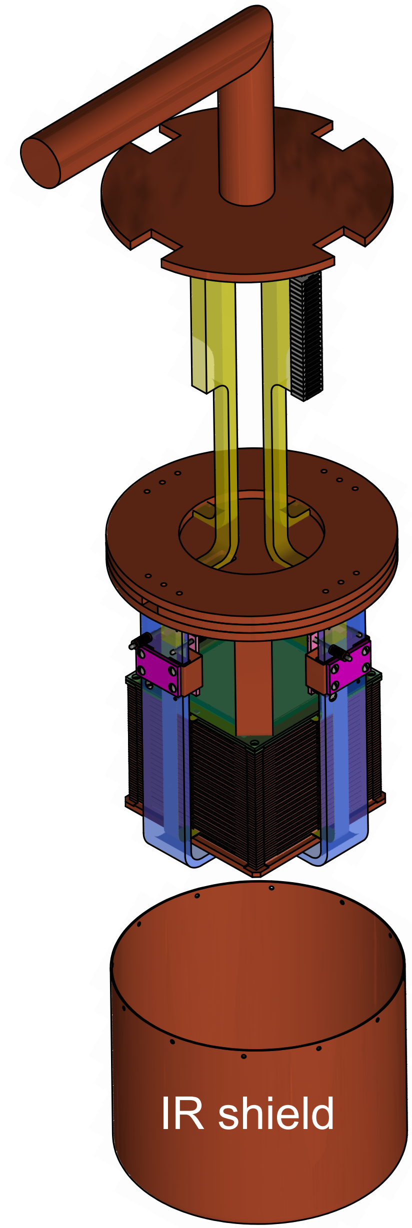
- Surface ^{210}Pb: minimize exposure to radon (radon-free clean room at LSM for CCD packaging/test; installation in radon-free tent)
- Radiogenic background: material selection and electro formed copper

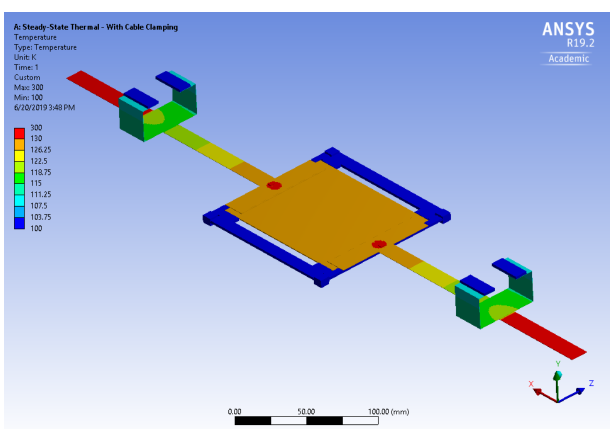
Challenging goal: 0.1 dru

Detector Design







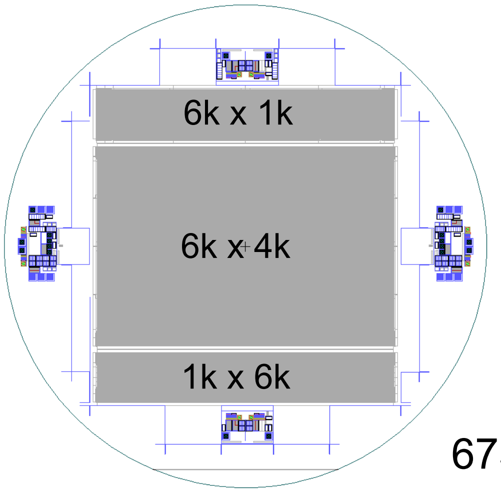


thermal modeling

Design will continue through 2021

DAMIC-M CCDs

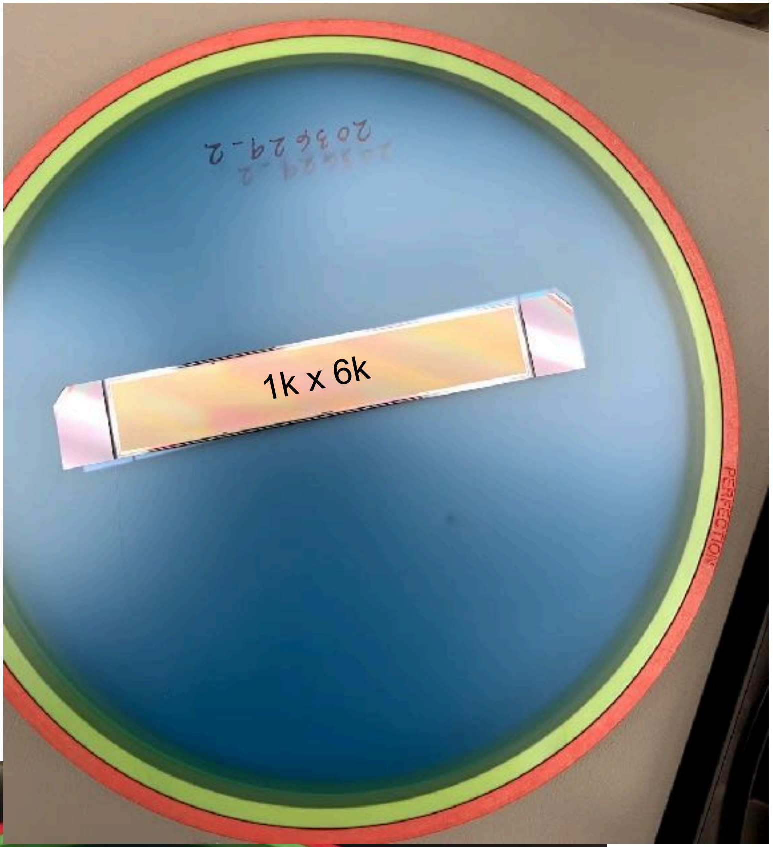
design by S. Holland (LBNL), fabricated by Teledyne/DALSA



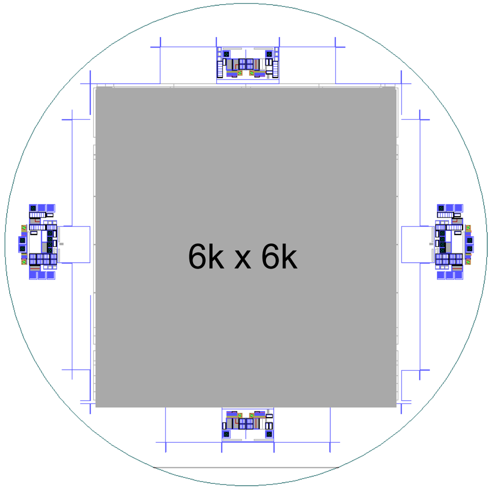
DAMIC-M prototype skipper CCDs

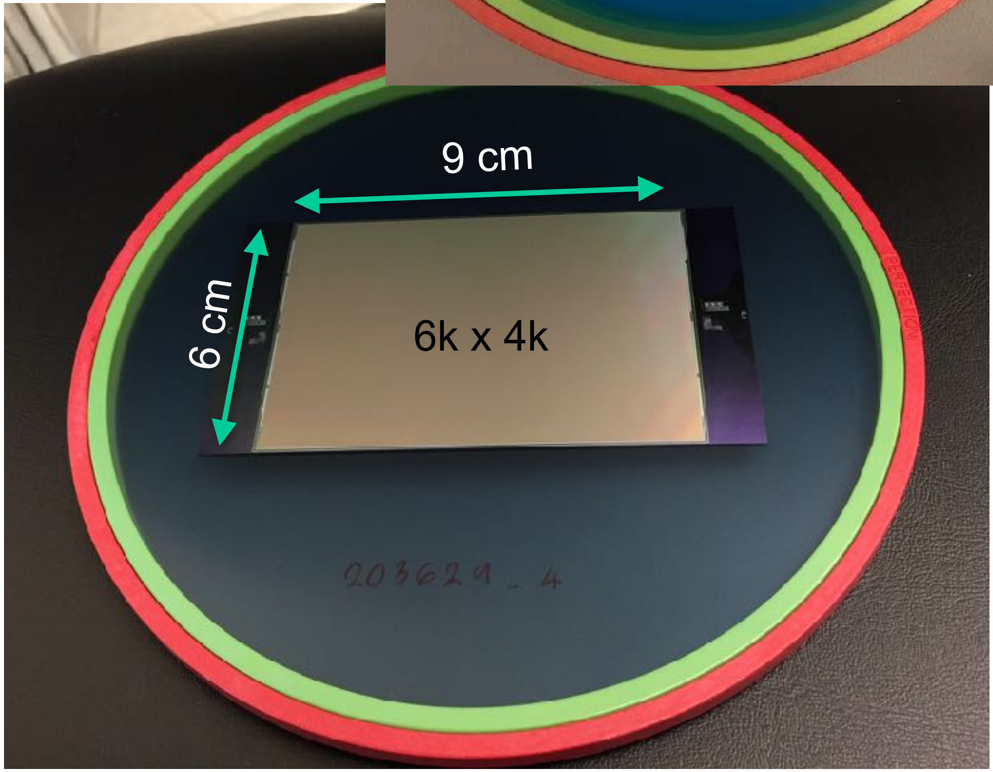
Three CCDs per 6” wafer to test different skipper readout amplifier design.

675 μm thick



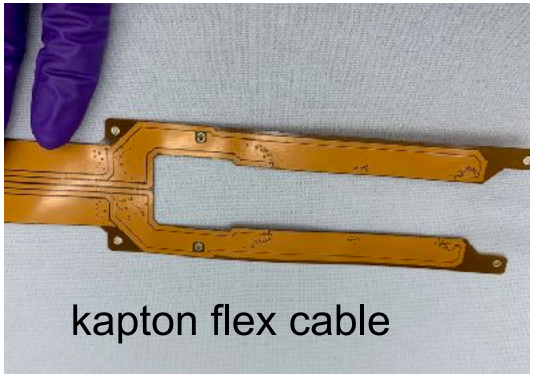
DAMIC-M production skipper CCD design
9 cm x 9 cm

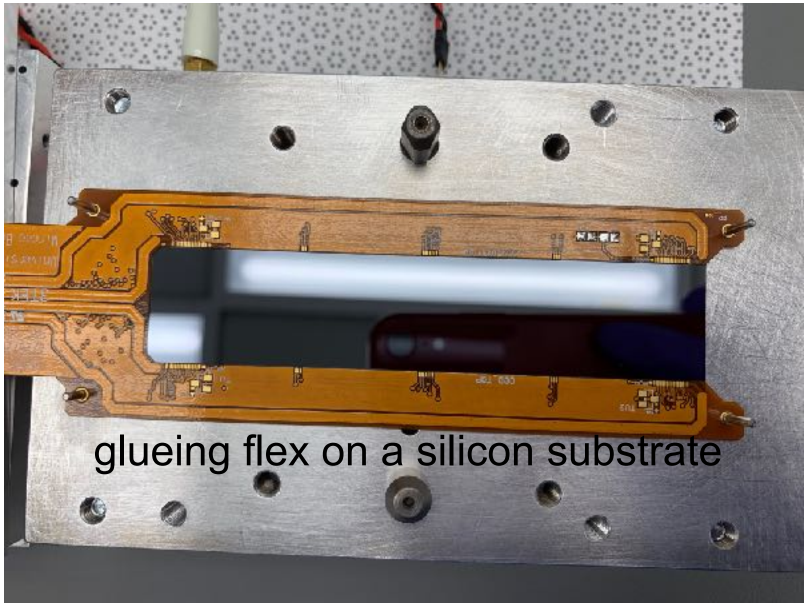


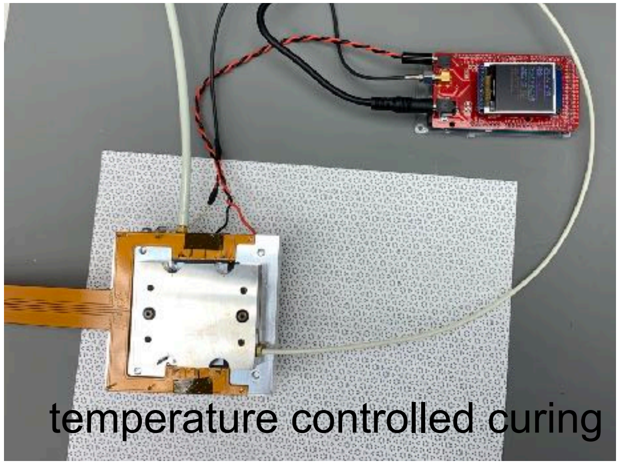


CCD Packaging

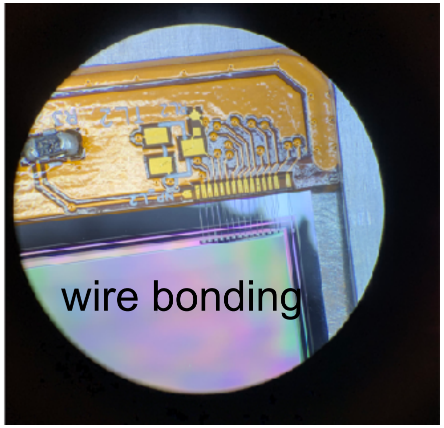
1k x 6k DAMIC-M prototype CCDs

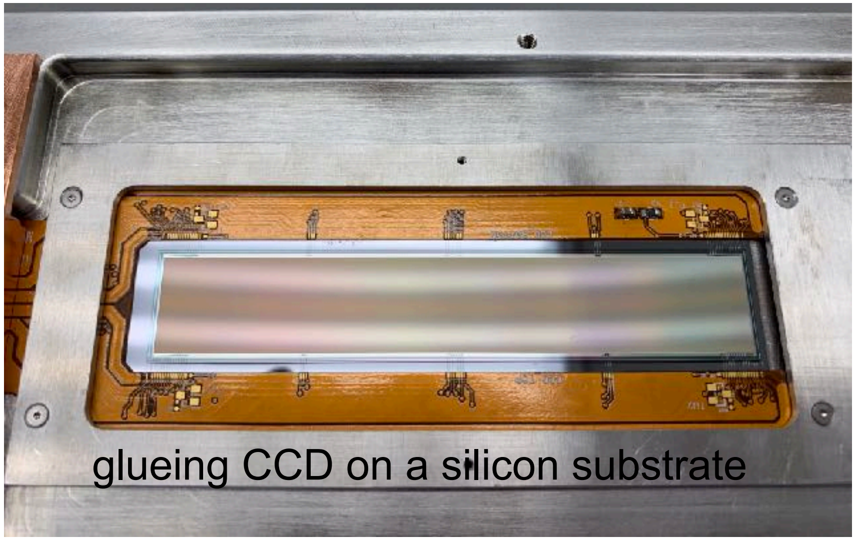

kapton flex cable


glueing flex on a silicon substrate


temperature controlled curing

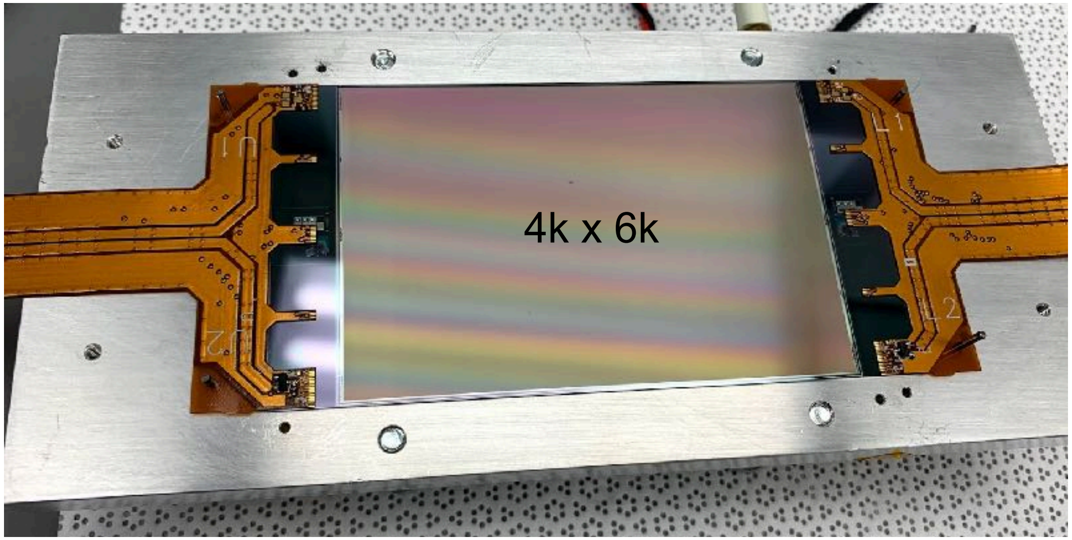
Improvement of packaging procedures originally developed for DAMIC at SNOLAB, notably by reducing the curing (and potential exposure of CCDs to radon) from a day to few hours


wire bonding


glueing CCD on a silicon substrate

Low background procedures will be implemented for the pre-production and production CCDs (the main objective of the DAMIC-M CCD prototypes is demonstrating single-electron resolution and selection of best skipper amplifiers for the production)

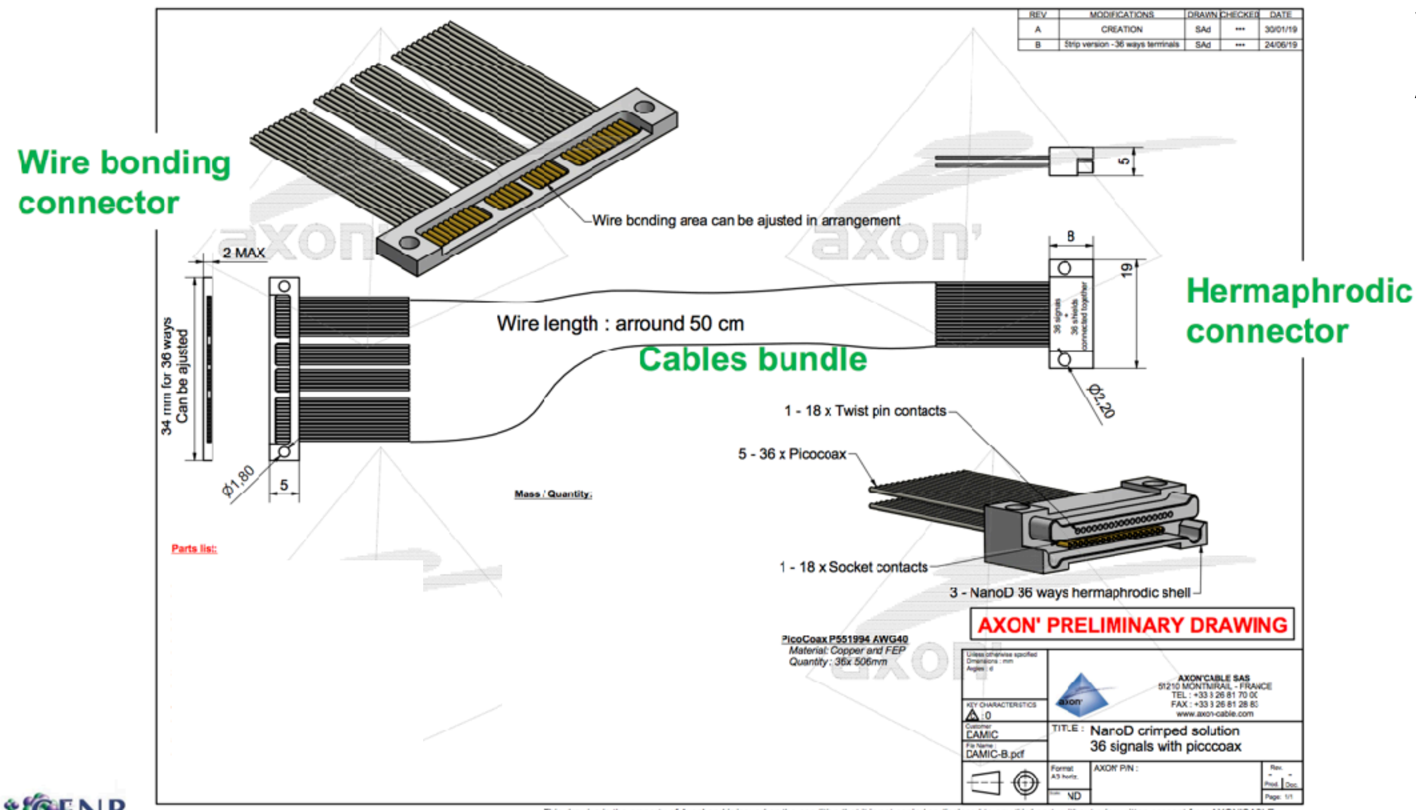
Low-background cables



Flex cable R&D:

minimize mass close to CCD;

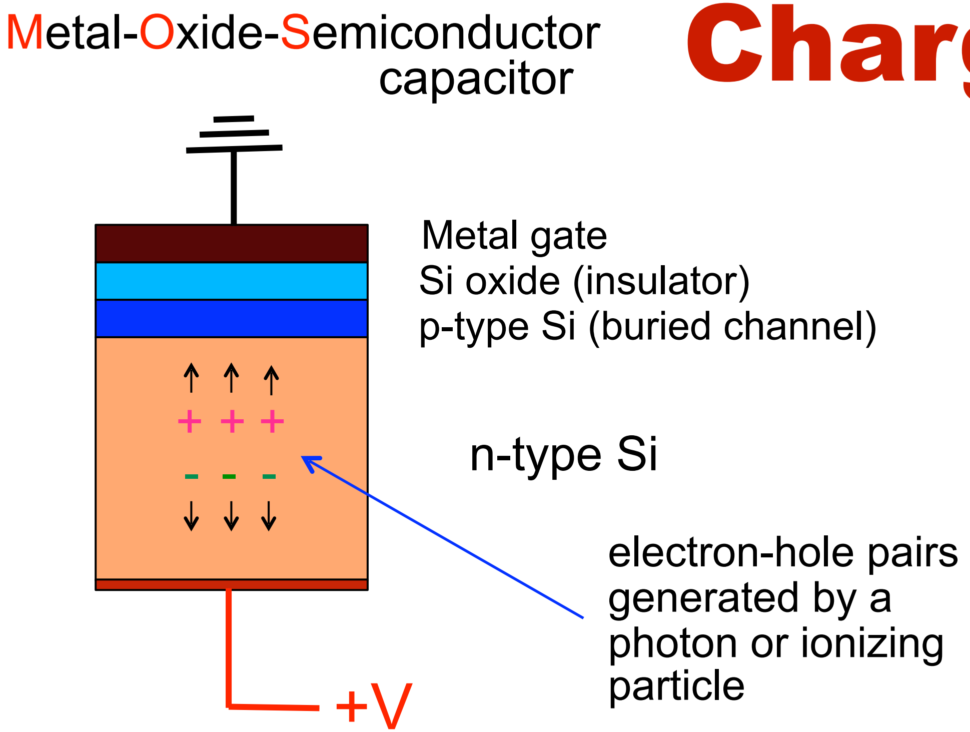
develop clean fabrication procedures for multilayer flex (PNNL)

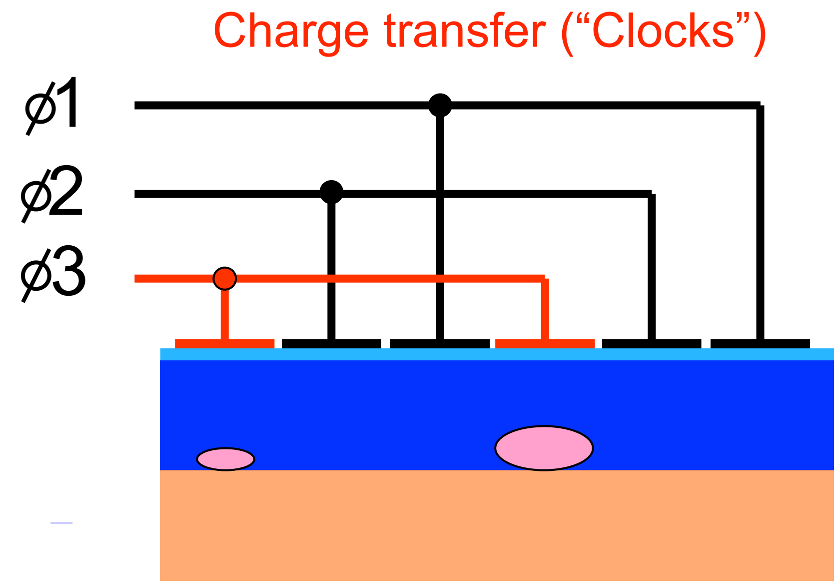


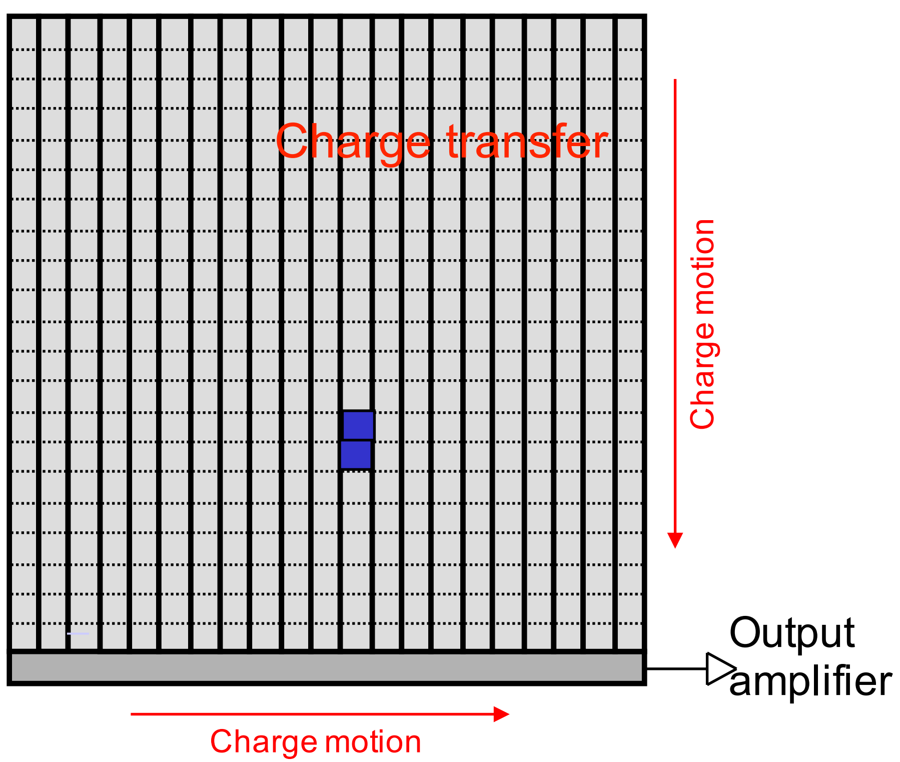
We are also pursuing with AXON a solution employing picocoaxial cables (low-background demonstrated by MAJORANA)

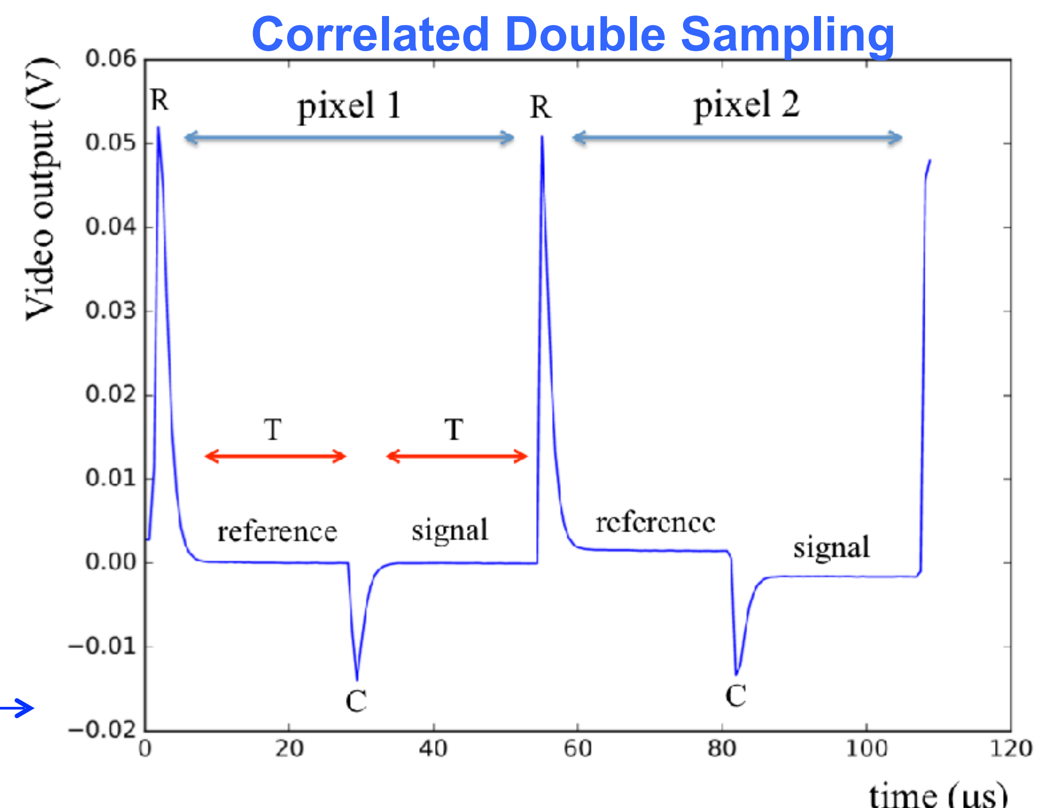
Both would fulfill our requirements for cables' radio purity

Charge Coupled Device



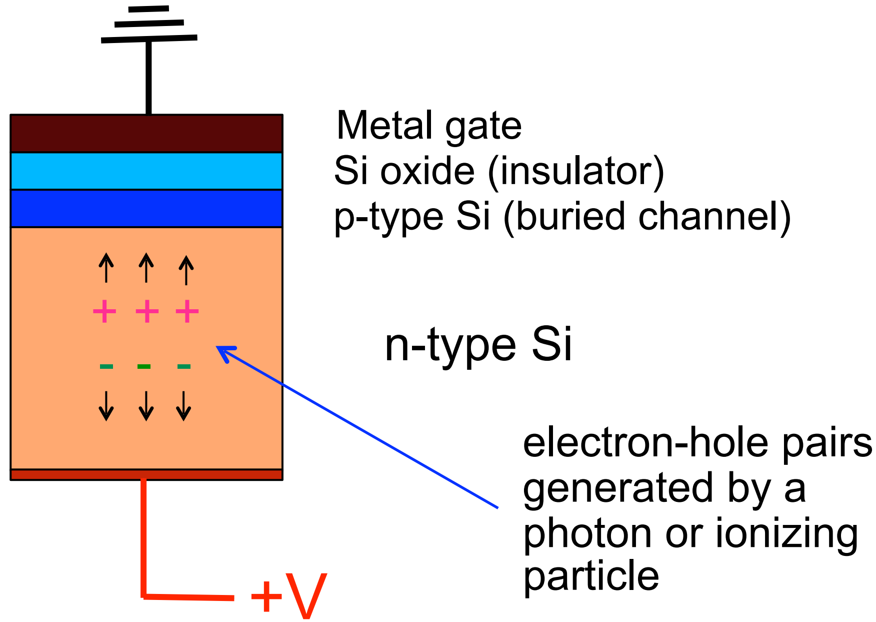




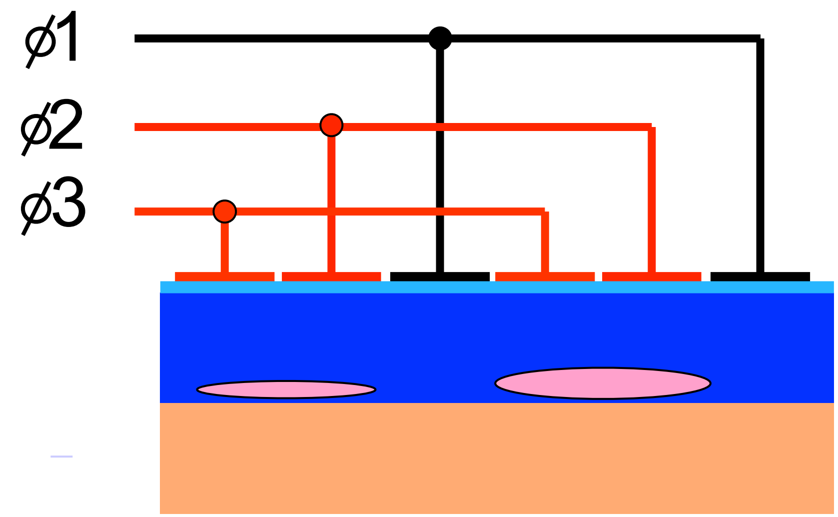


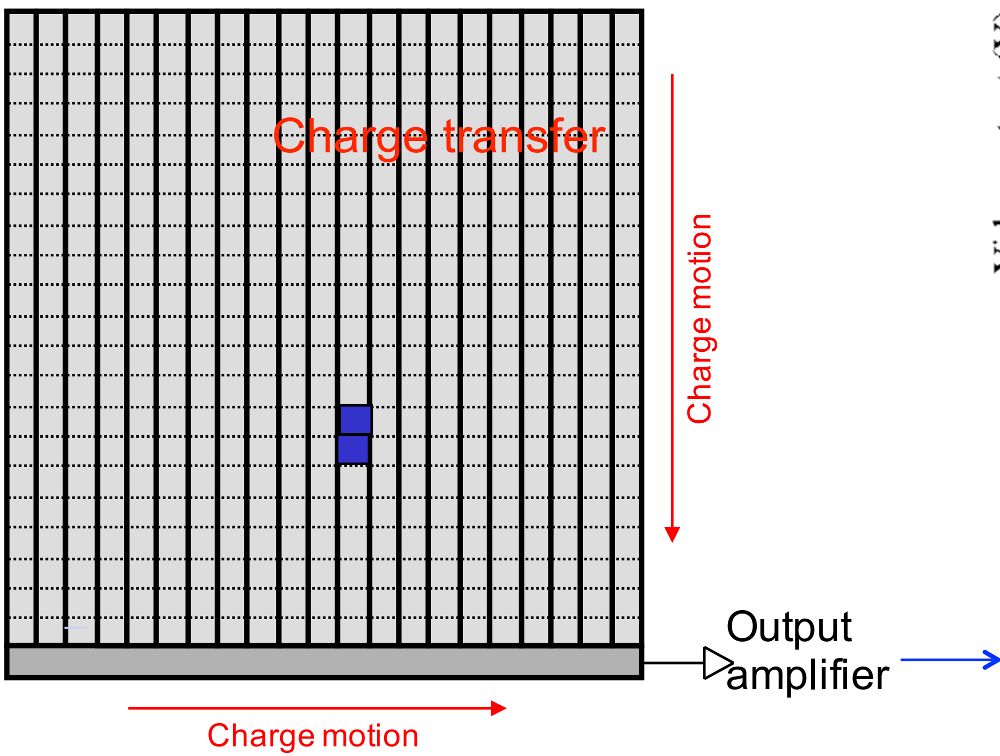
Charge Coupled Device

Metal-Oxide-Semiconductor capacitor

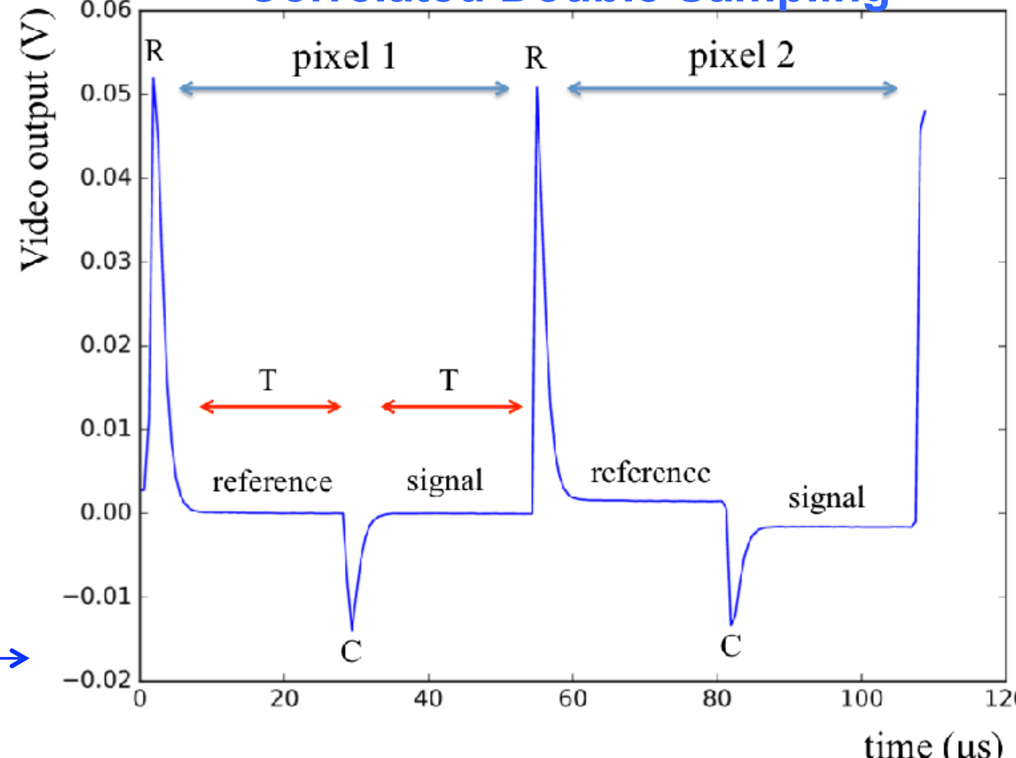


Charge transfer ("Clocks")



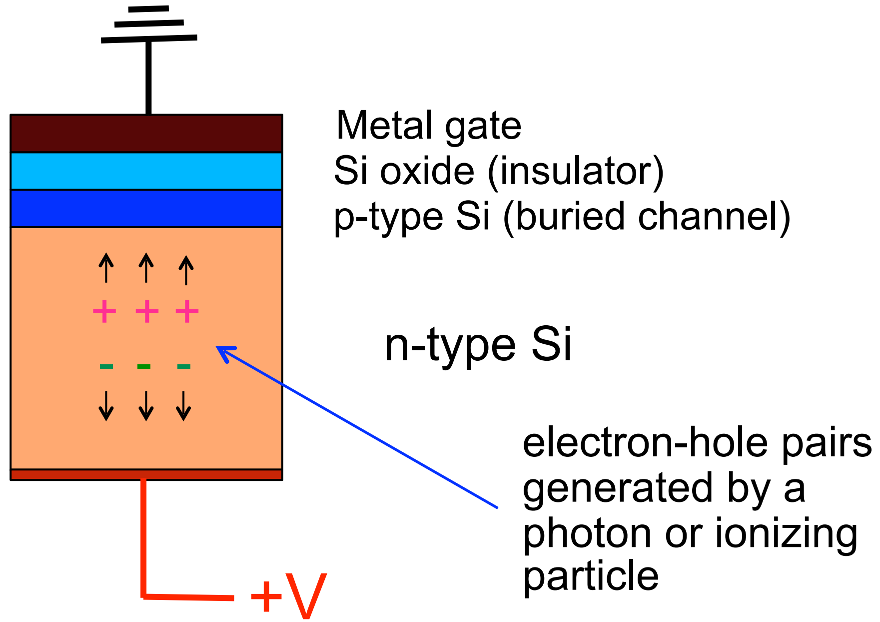


Correlated Double Sampling



Charge Coupled Device

Metal-Oxide-Semiconductor capacitor



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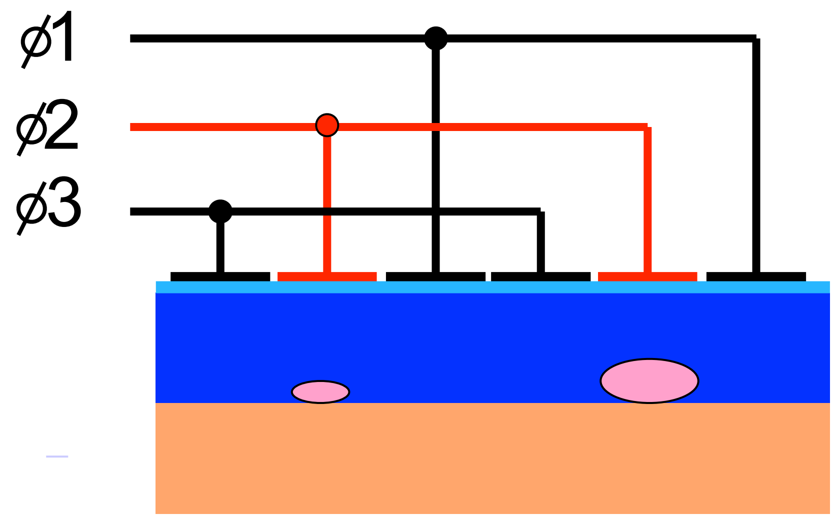

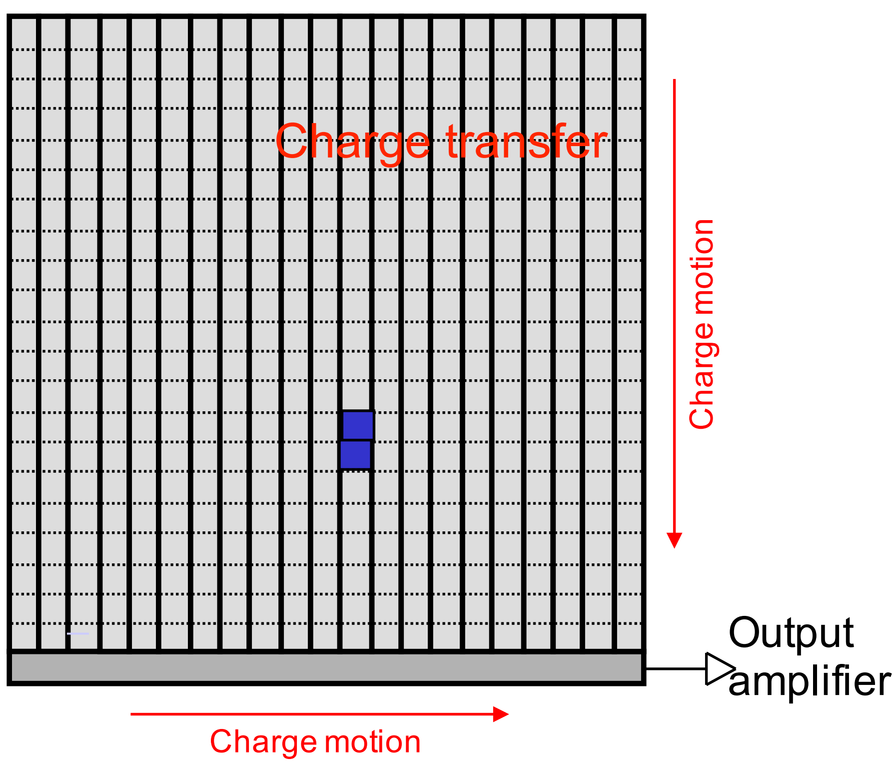

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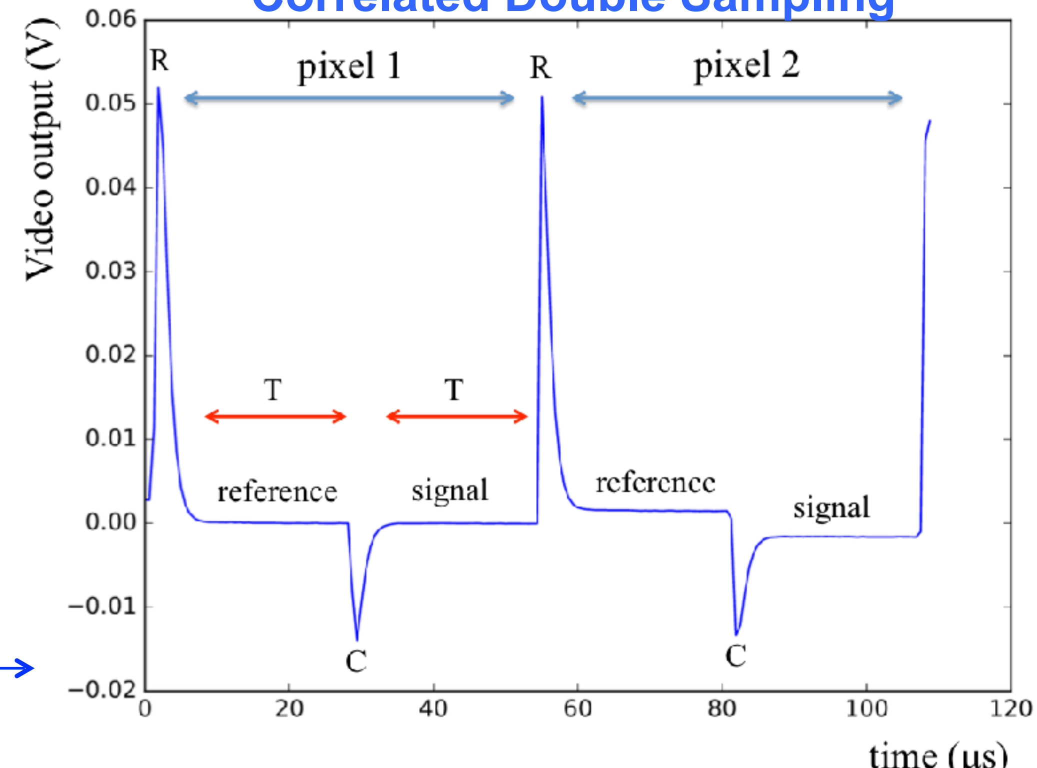
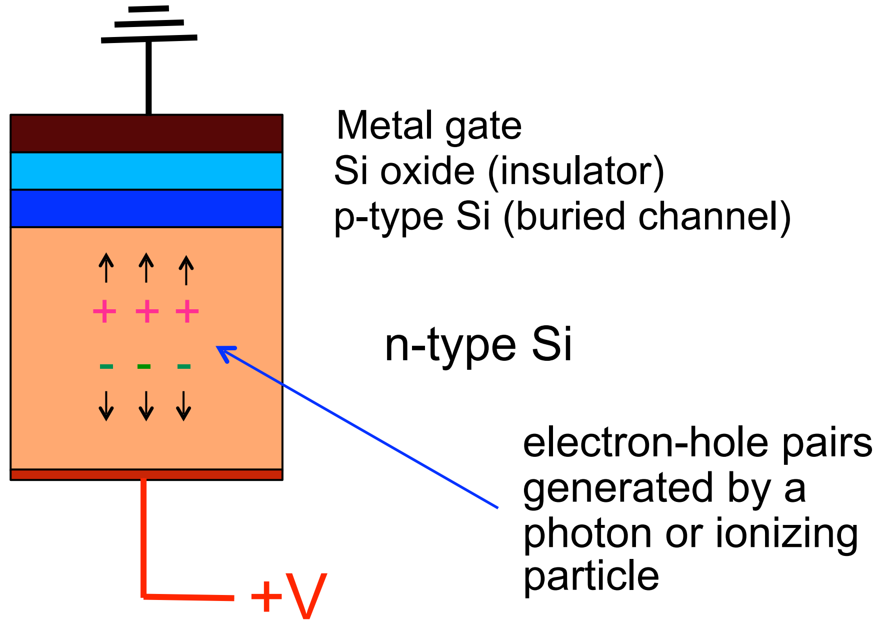


Charge Coupled Device

Metal-Oxide-Semiconductor capacitor



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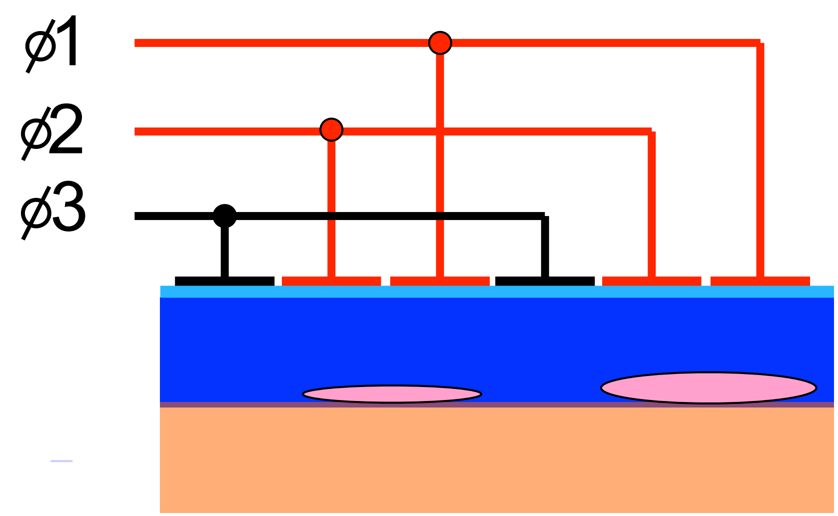

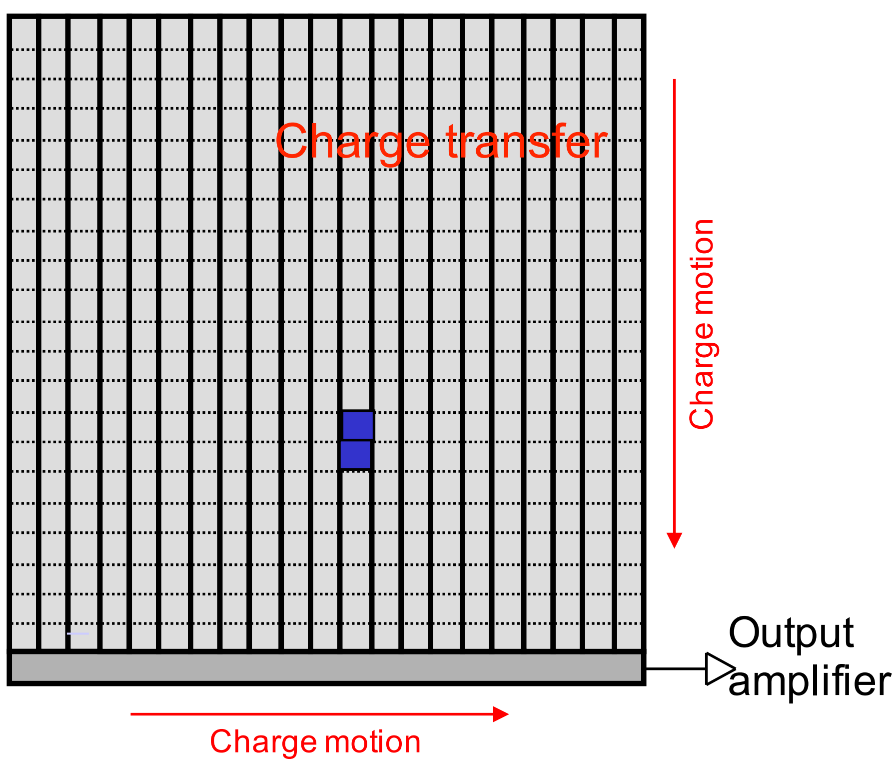

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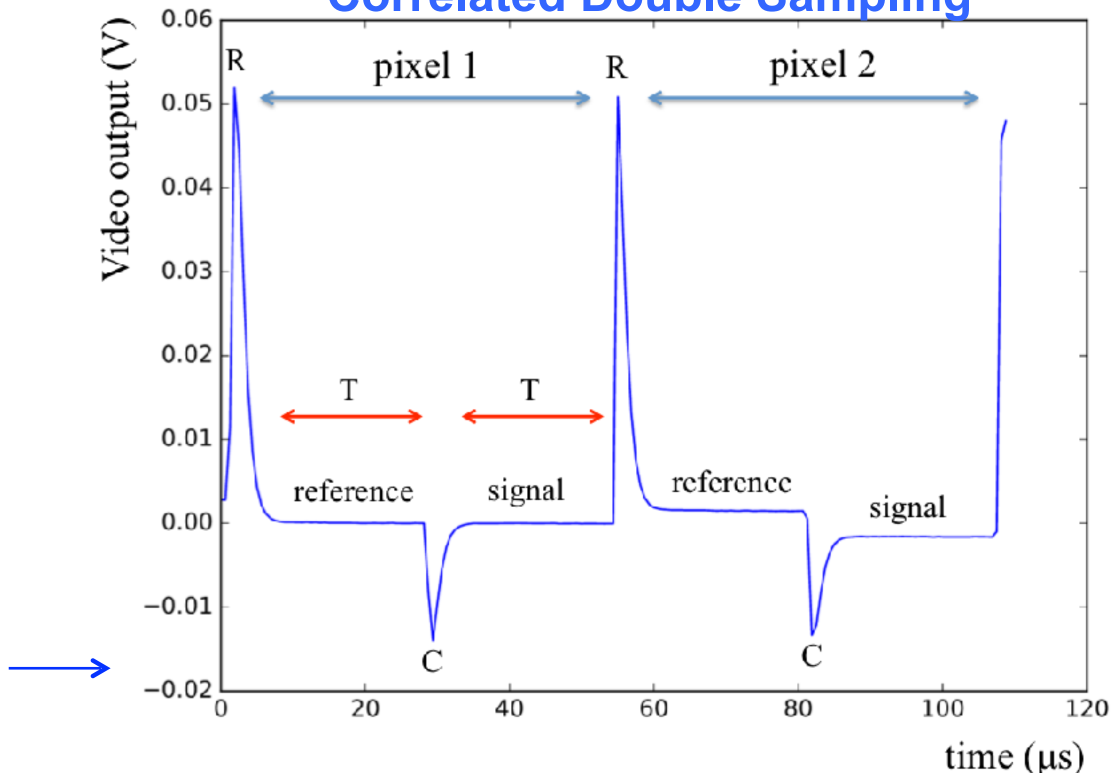
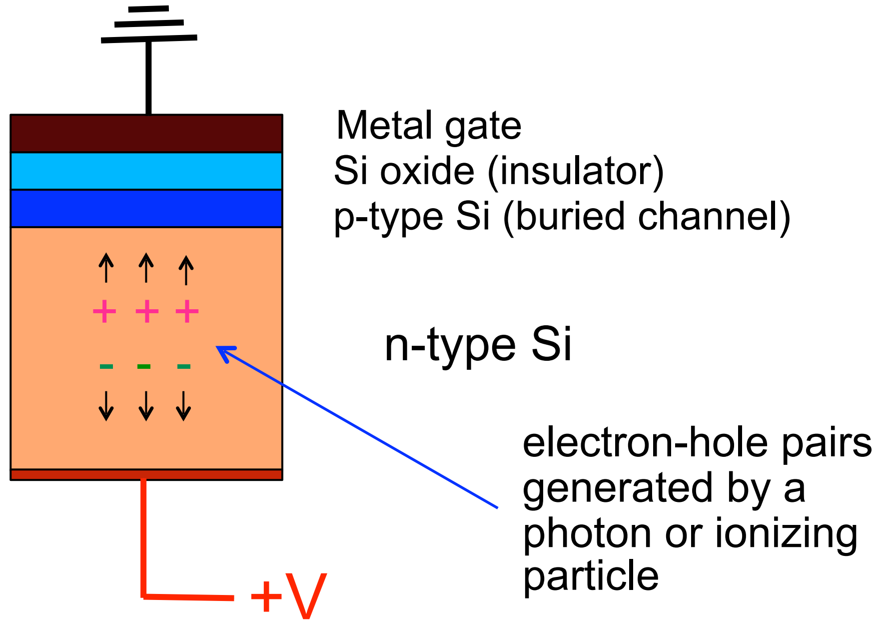


Charge Coupled Device

Metal-Oxide-Semiconductor capacitor



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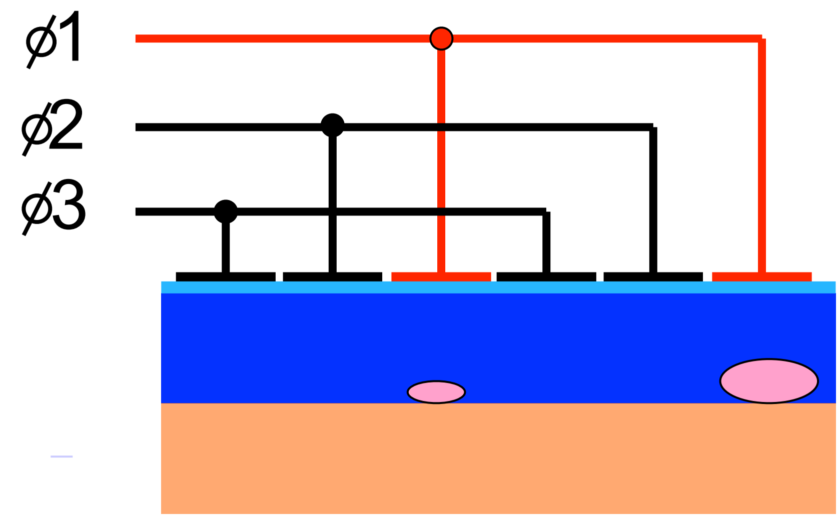
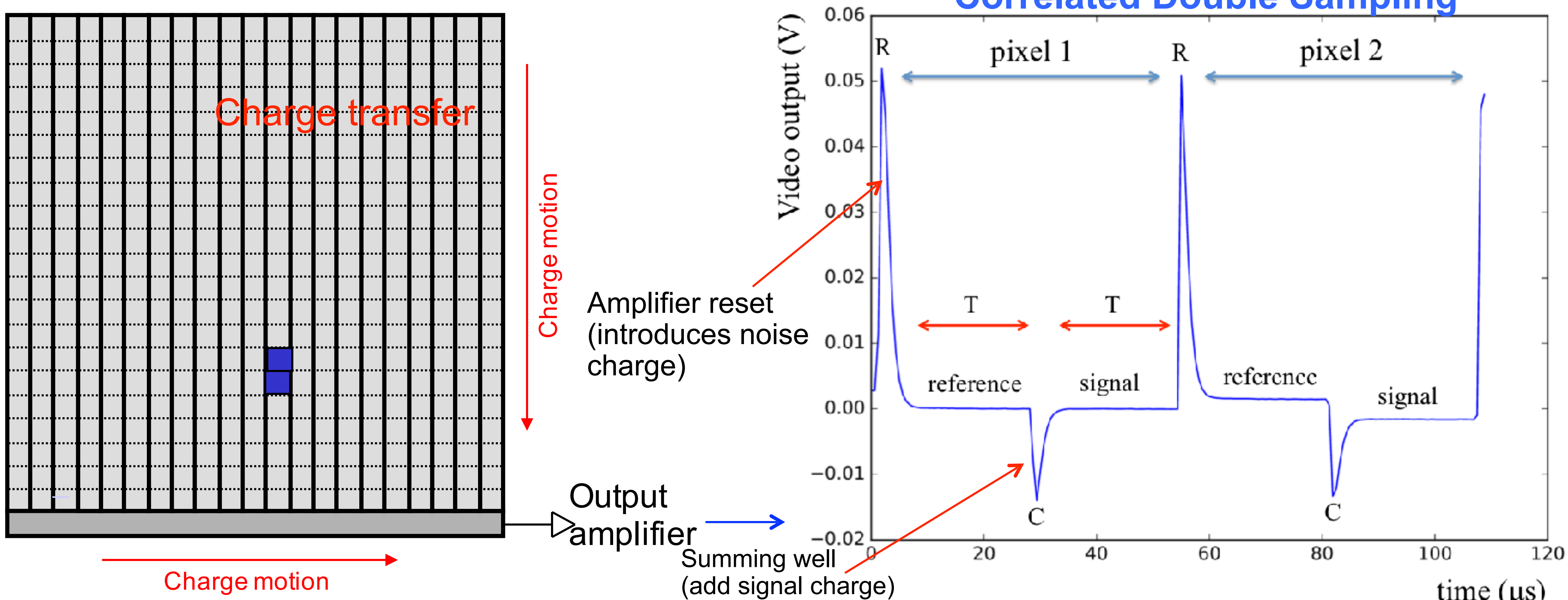
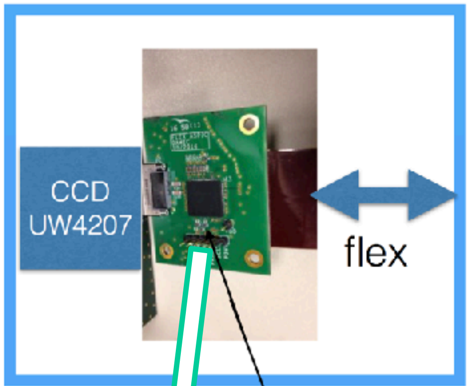


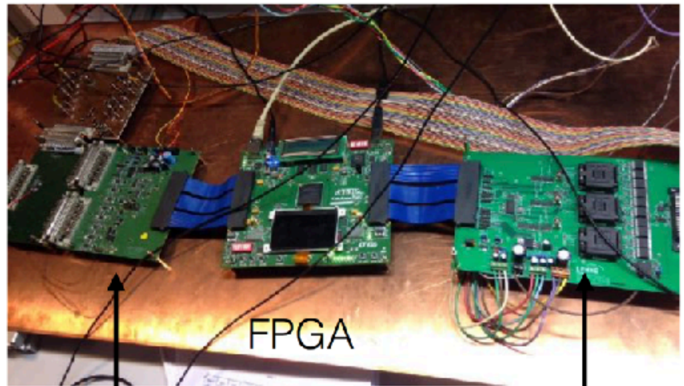
Correlated Double Sampling



Electronics

Dewar





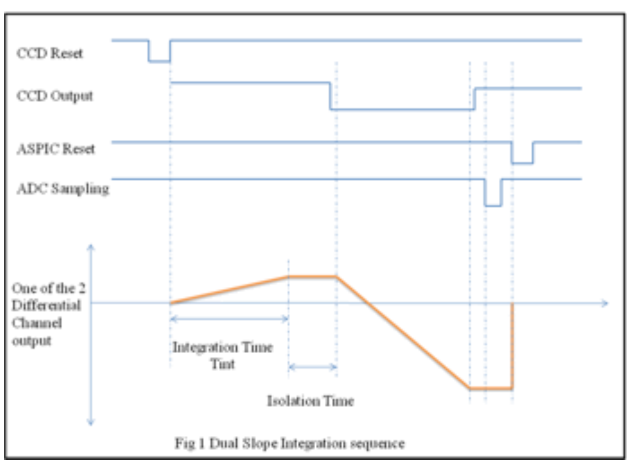
ASPIC (LSST)

BEB3 (ADC)

3CABAC board (CCD Clocks)

successful test of CCD Controller components (CABAC ASIC for clocks, ADC, ASPIC chip for CDS)

delivered, under test

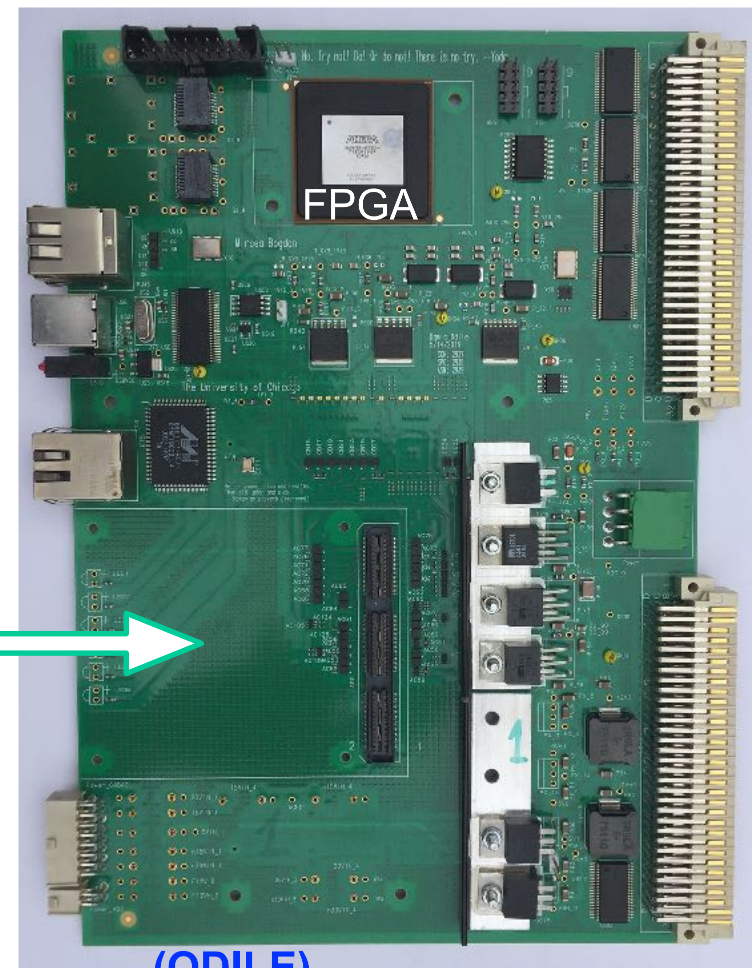


now integrated in a single controller board, one CCD per board

ADC daughter board

Two ADC being evaluated
20 bit 1.6 MHz
18 bit 15 MHz

CCD Controller Mother Board



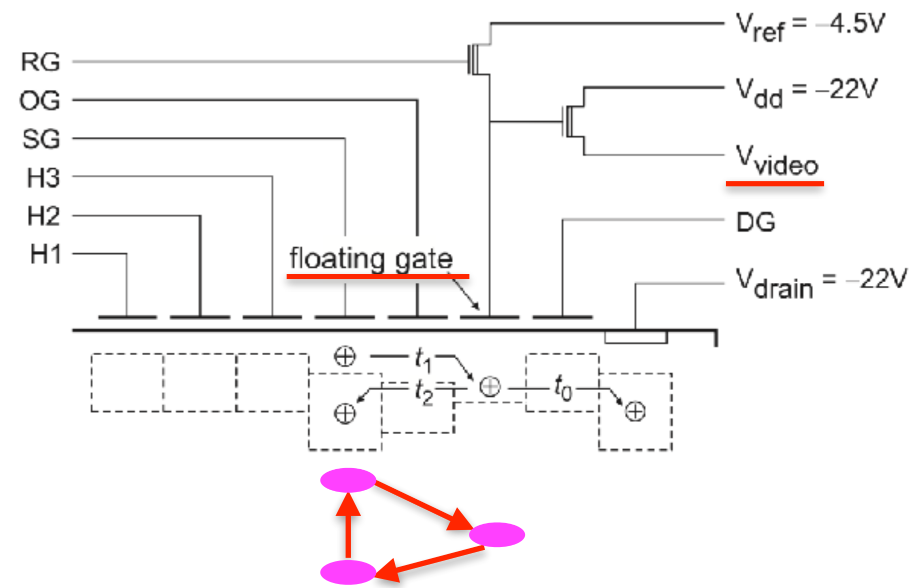
(ODILE)

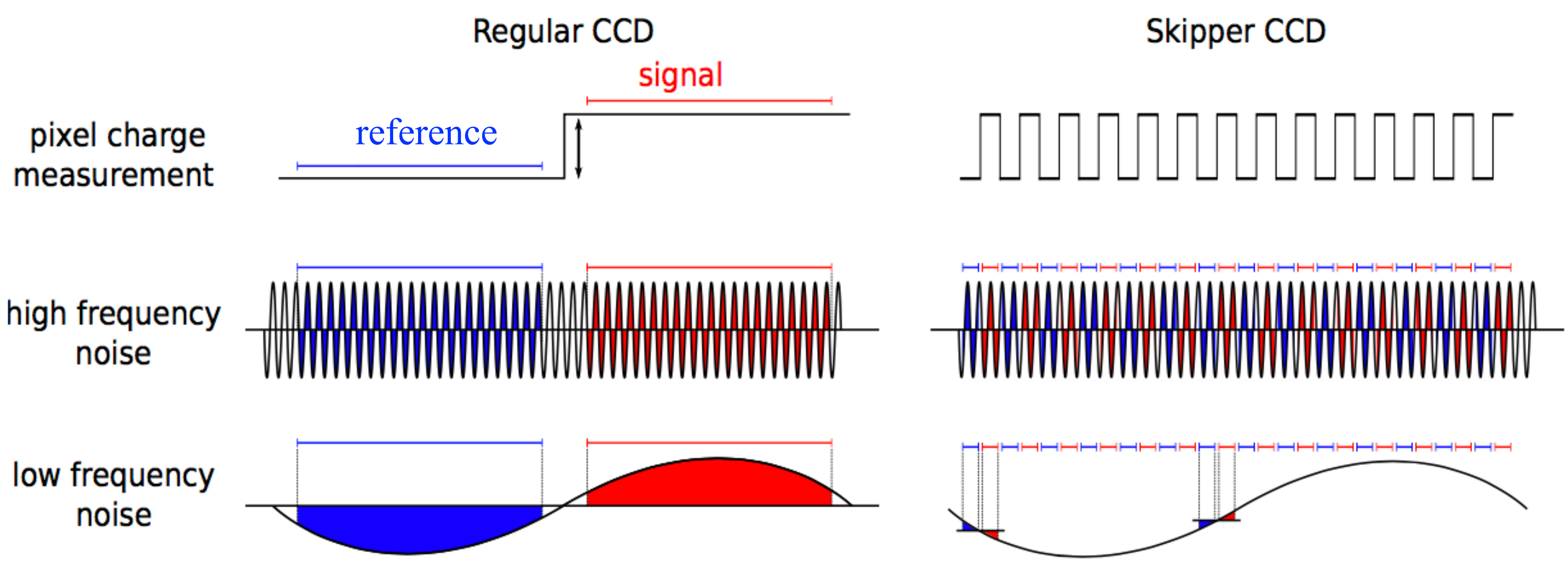
Skipper CCD readout

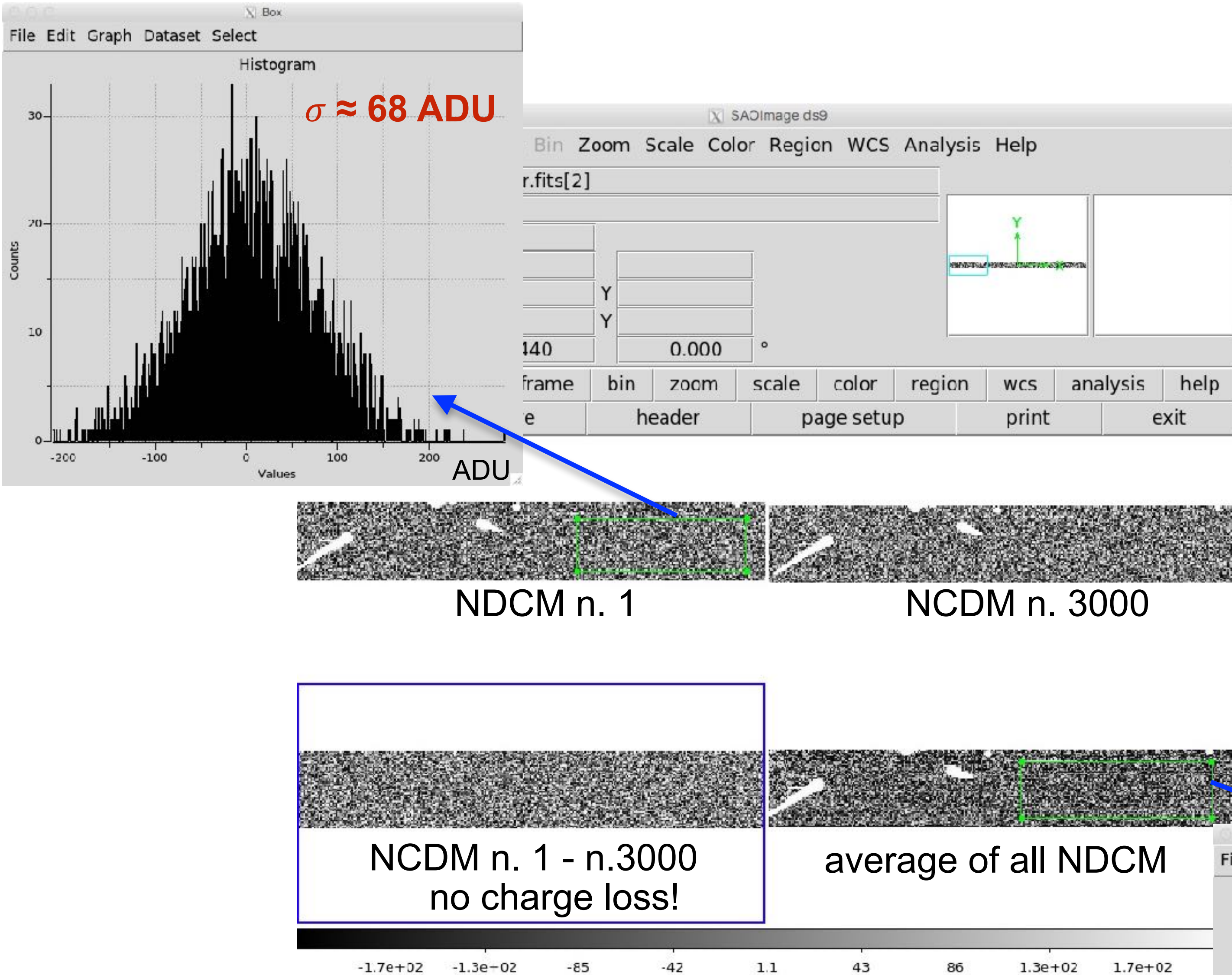
Noise in a regular CCD is dominated by the 1/f low frequency noise of the output amplifier

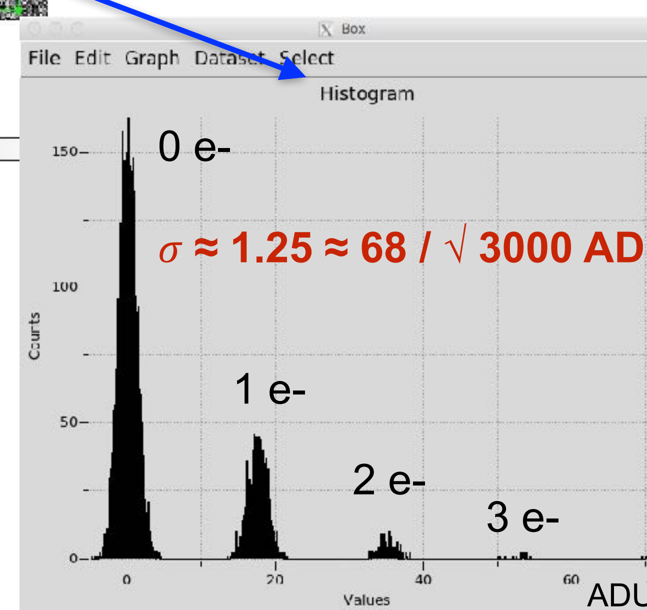
Non-destructive charge measurement! (NDCM)

Measure the charge fast (kill 1/f noise) and N times (noise ≈ $1/\sqrt{N}$)







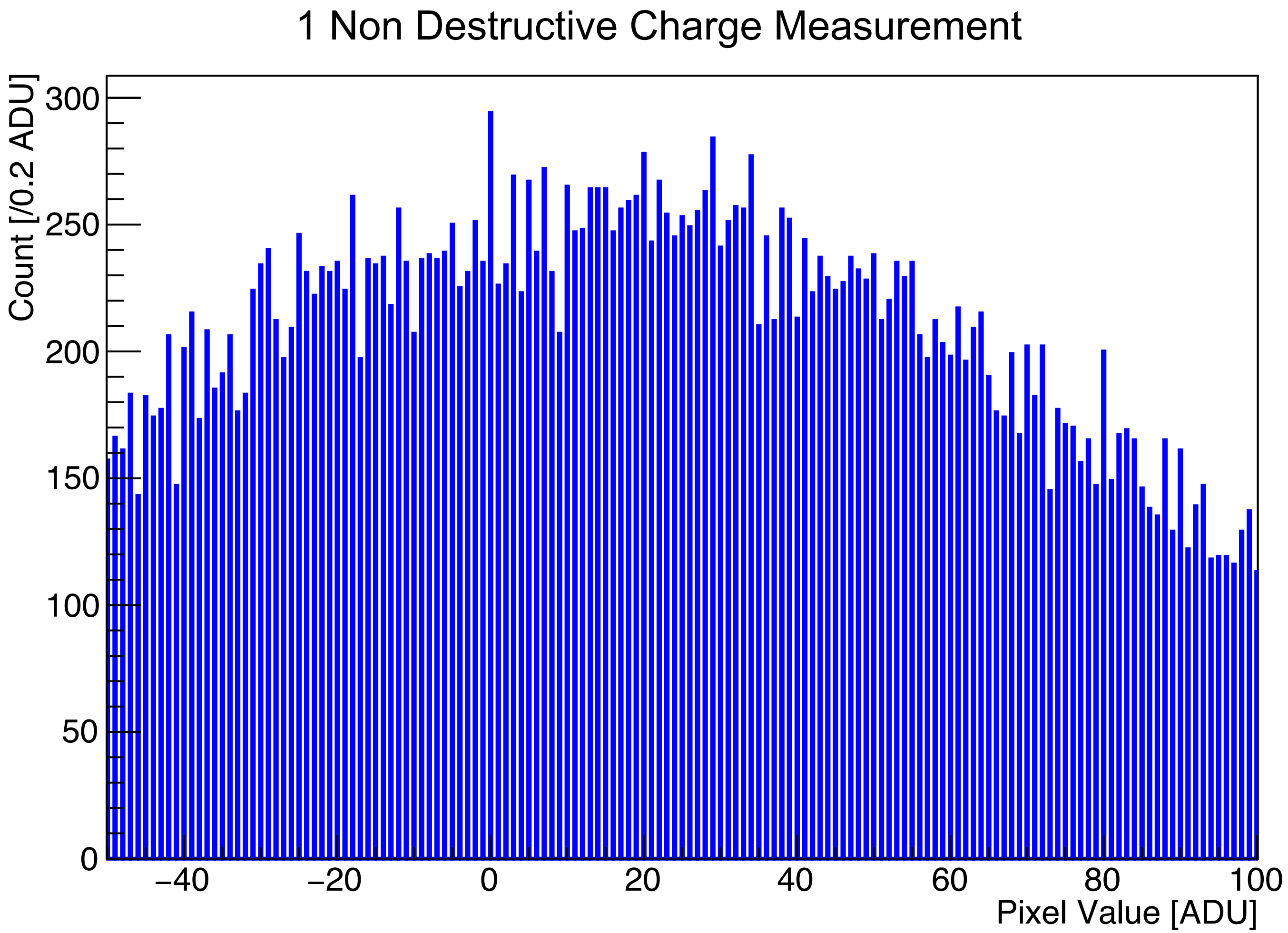


DAMIC-M prototype skipper CCDs

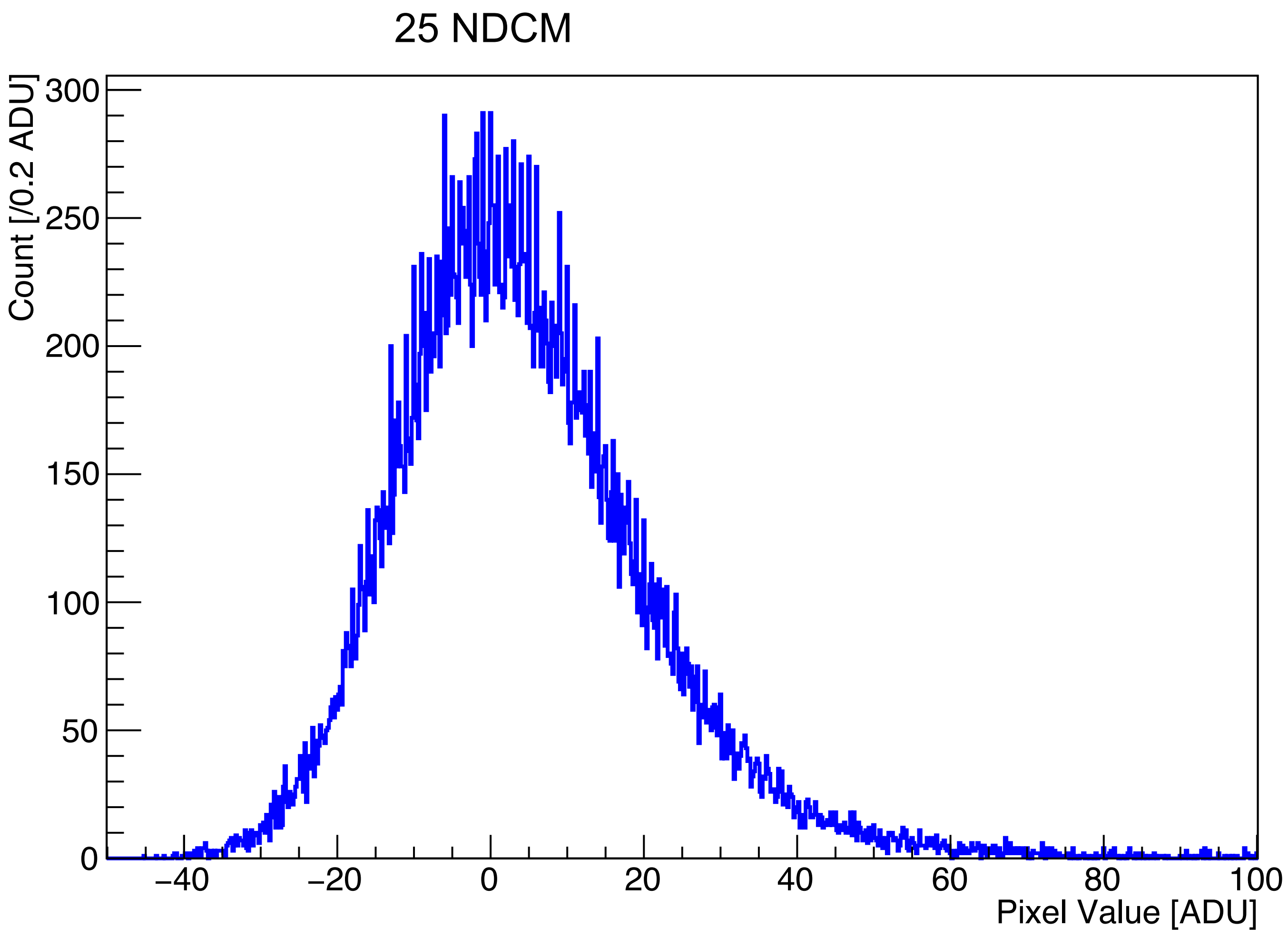
RAW DATA!

Single electron charge resolution

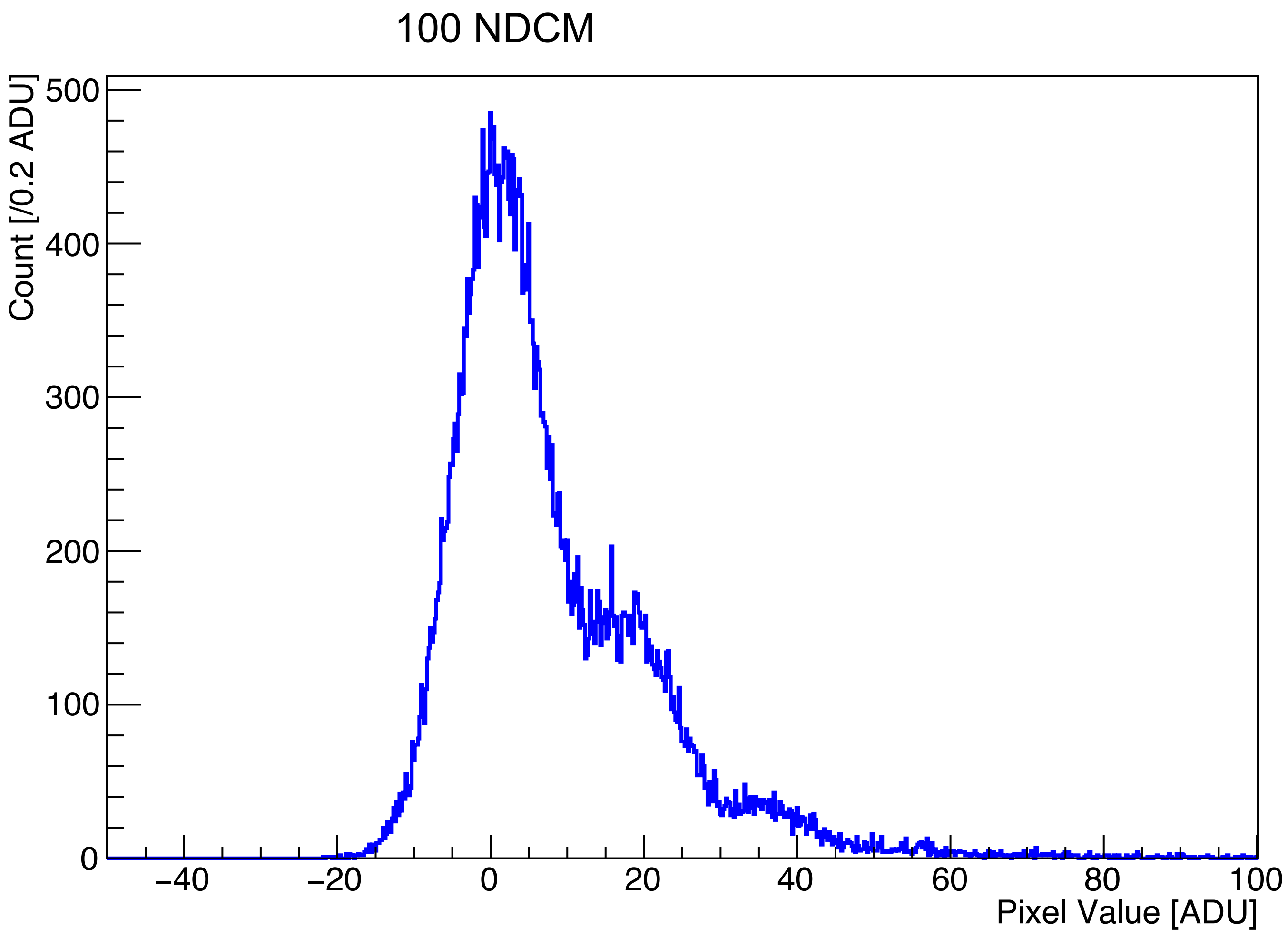
DAMIC-M Skipper charge resolution



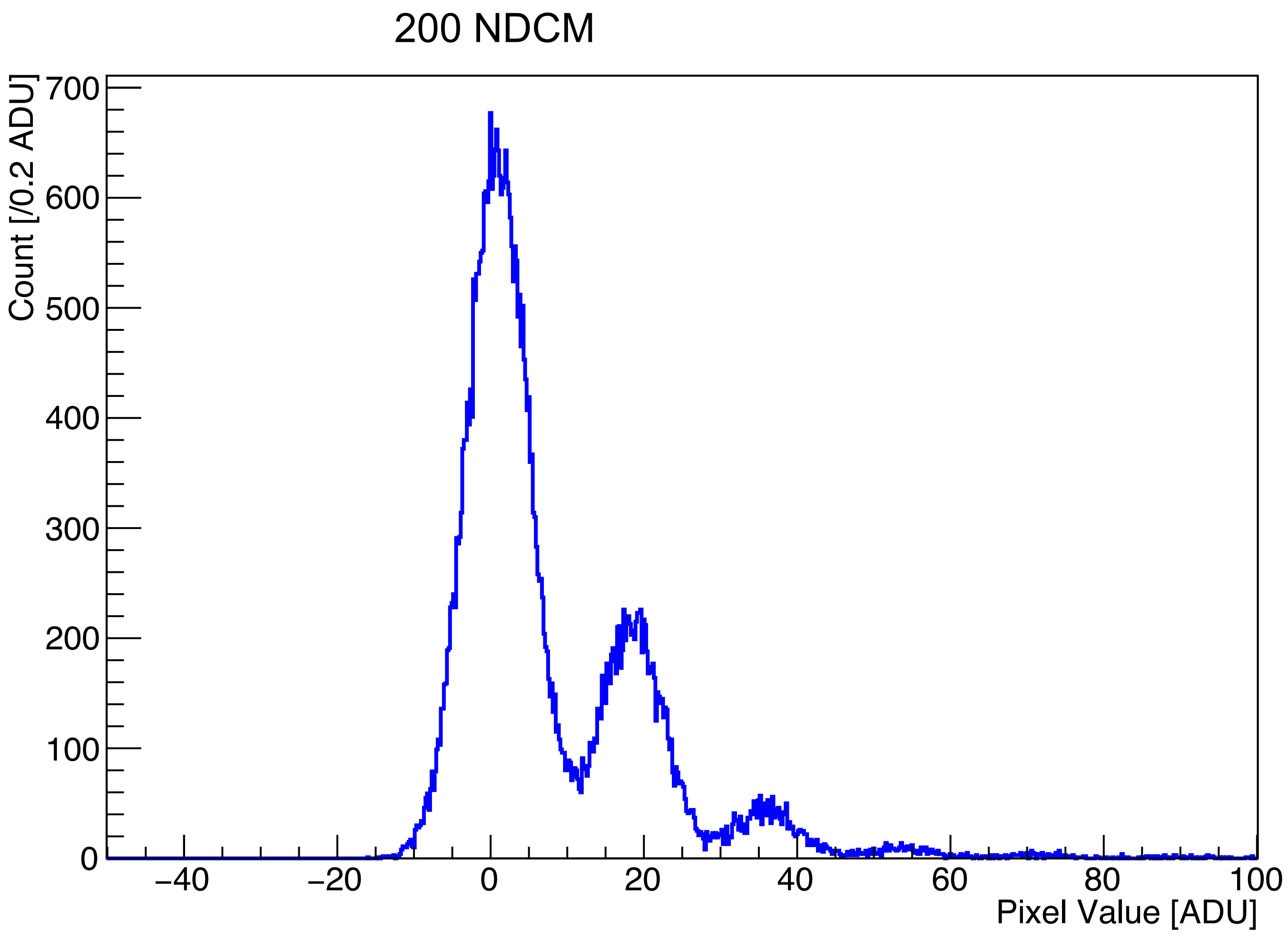
DAMIC-M Skipper charge resolution



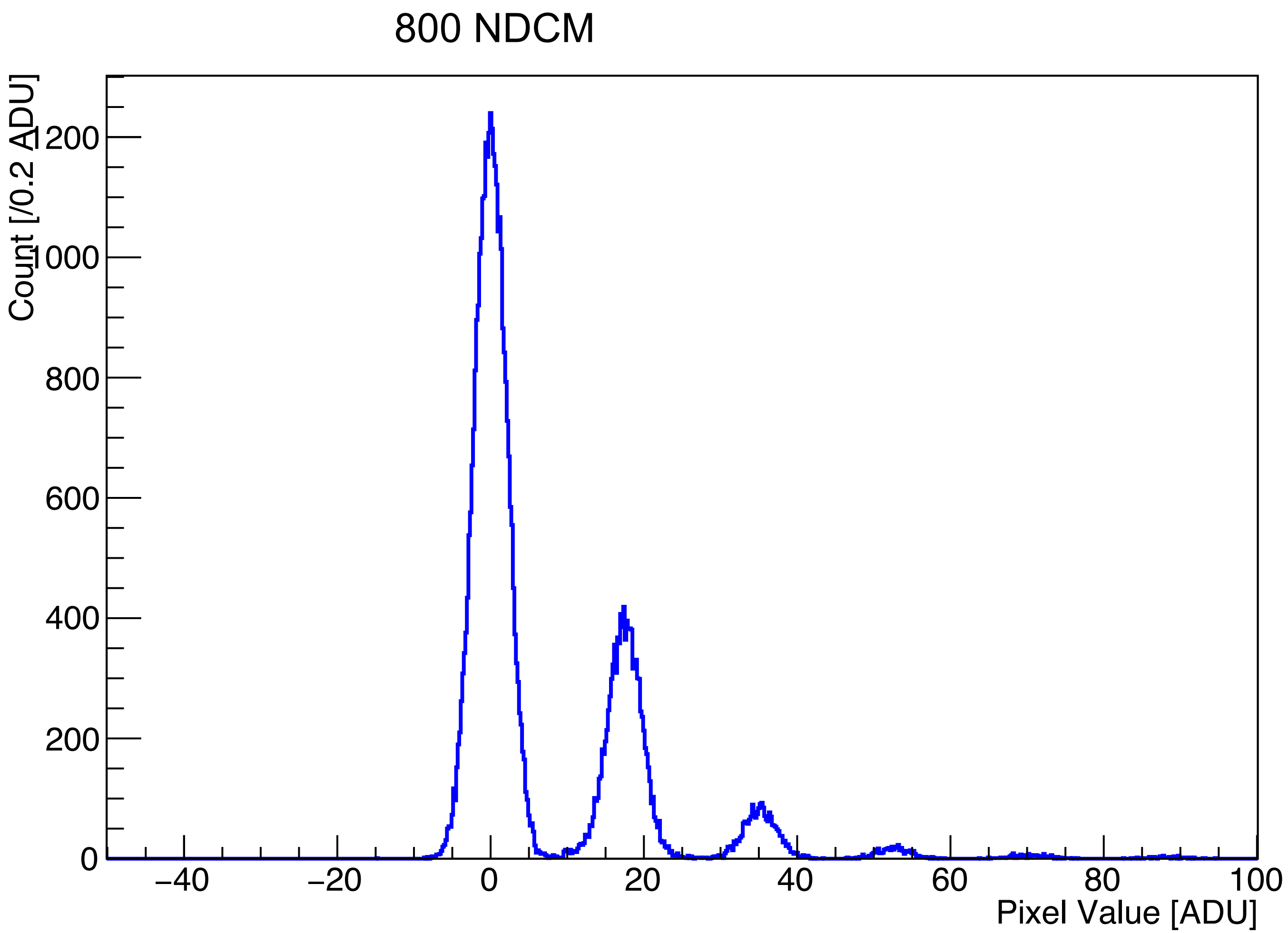
DAMIC-M Skipper charge resolution



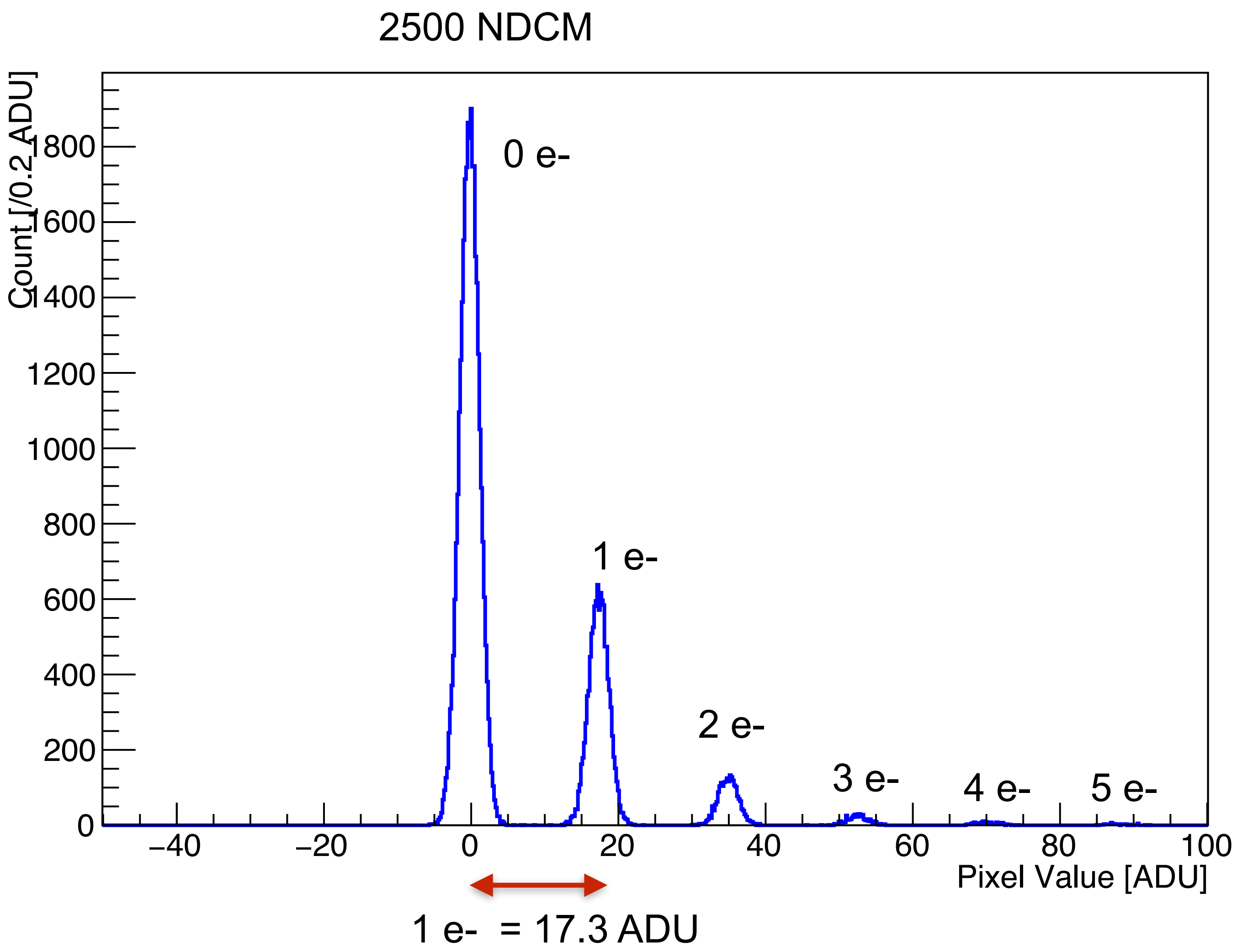
DAMIC-M Skipper charge resolution



DAMIC-M Skipper charge resolution

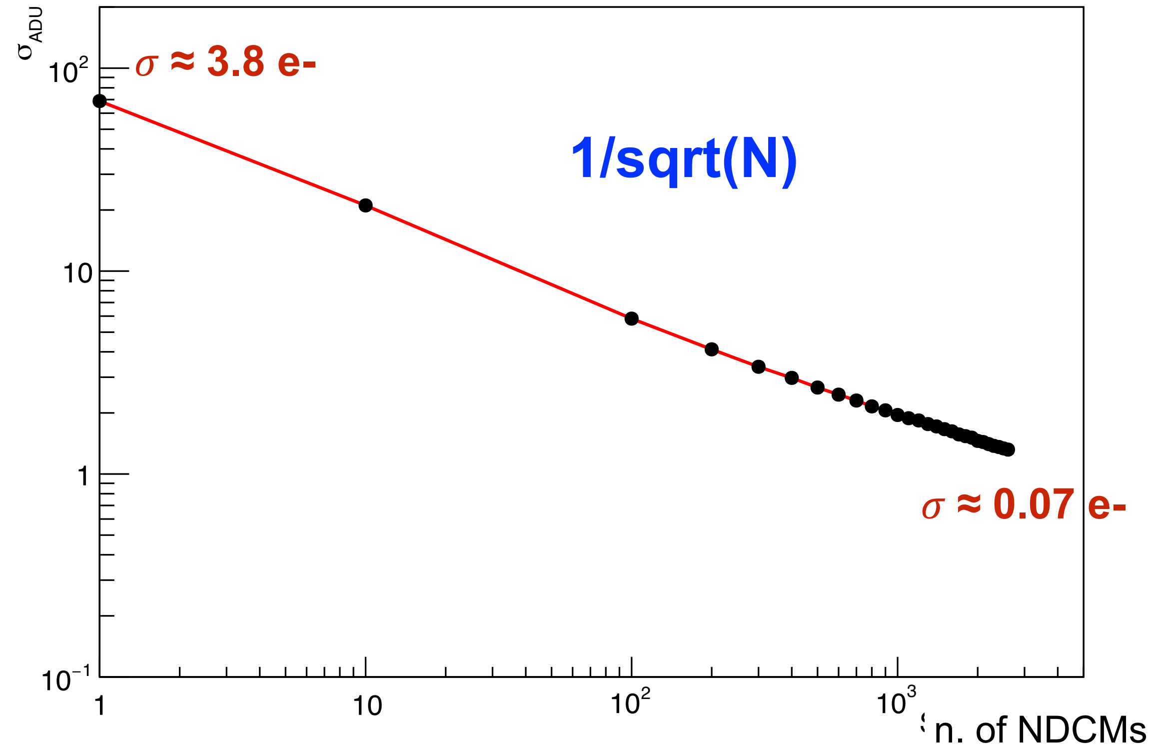


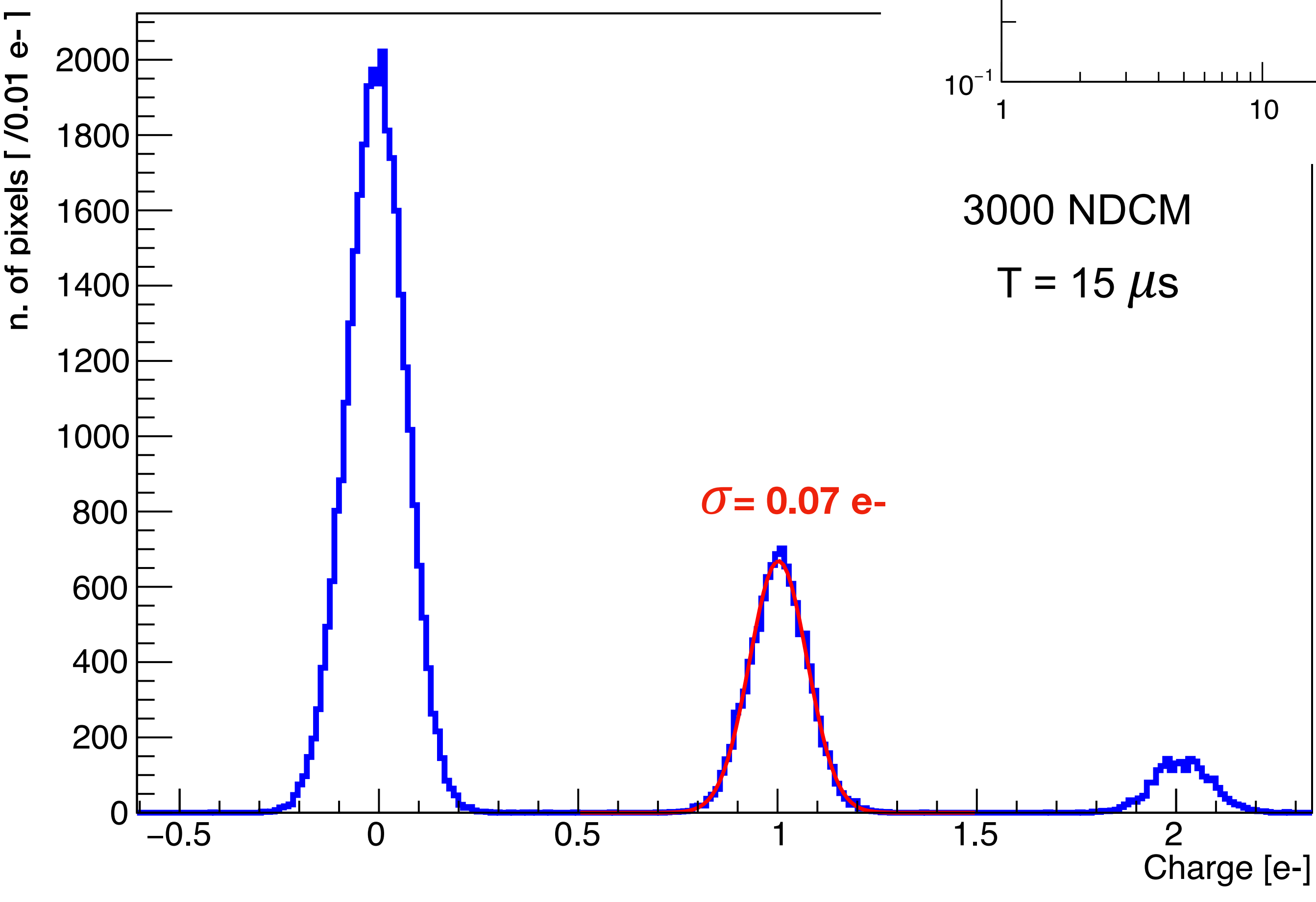
DAMIC-M Skipper charge resolution



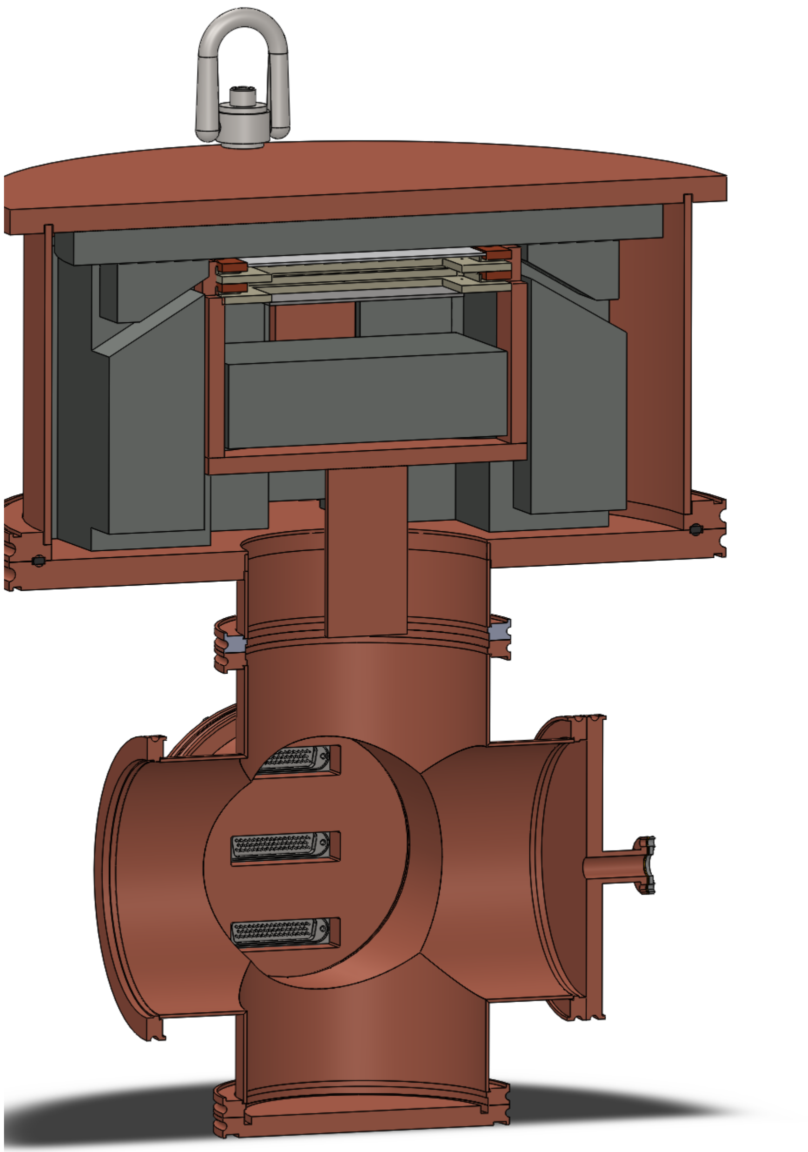
direct calibration of ADU to charge
(cross checked with ^{57}Co source)

Single electron resolution obtained for a wide range of integration times (T = 2 - 20 μs) allowing optimization with respect to electronics noise





Low Background Chamber



- A low-background chamber (background level ≈ dru) is in preparation
- Main objectives:
  - characterization of DAMIC-M CCDs in low-bkg environment: dark current; ^{32}Si rate; ^{210}Pb surface bkg; CCD packaging
  - first science results with a few CCDs
- Installation at LSM beginning of 2020

Outlook

- DAMIC-M is pushing to a kg-size detector the high-resistivity, fully-depleted CCD technology pioneered at SNOLAB
- The experiment is in its design phase. Progress on all aspects: detector design, electronics, low-background
- Major milestones accomplished: silicon ingot production; demonstration of single electron resolution with large-size, thick CCDs implementing skipper design
- We are moving fast. Before the end of this year, installation of DAMIC-M clean room at LSM and CCD pre-production. CCD production scheduled for next year.
- A low-background chamber will be installed at the LSM beginning of 2020 to characterize DAMIC-M skipper CCDs underground in a low background environment. Early science results with a few CCDs are foreseen.
- We are already thinking about next step: R&D for a 10-kg detector based on the skipper technology has recently been funded by DOE (FOA *Dark Matter New Initiatives*; DAMIC-M and SENSEI US groups joined effort)

DAMIC-M Collaboration

DAMIC-M

CENPA
Center for Experimental Nuclear Physics and Astrophysics
UNIVERSITY of WASHINGTON

SNOLAB

Pacific Northwest
NATIONAL LABORATORY

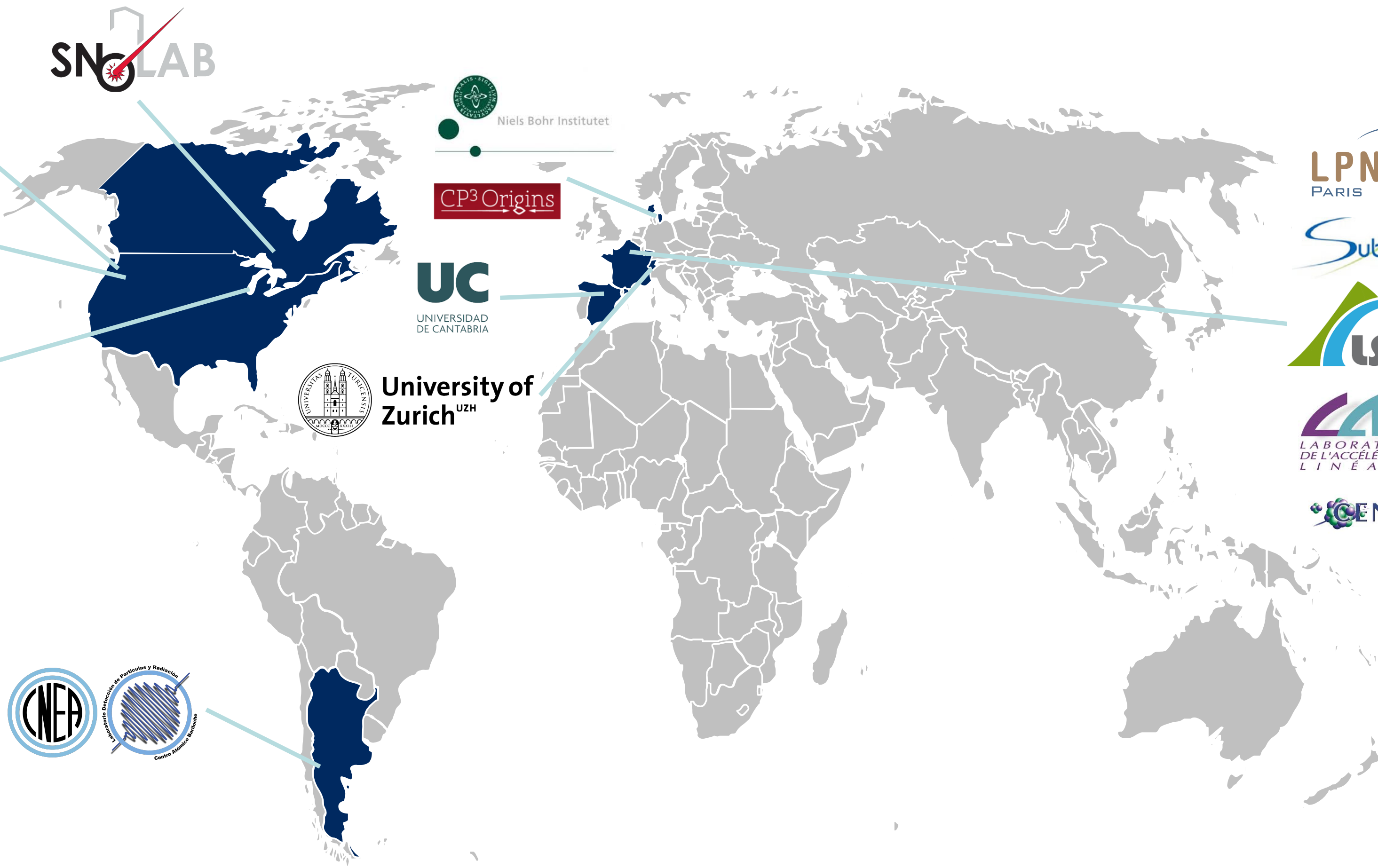
Kavli Institute
for Cosmological Physics
at The University of Chicago

Niels Bohr Institutet

CP³ Origins

UC
UNIVERSIDAD DE CANTABRIA

University of Zurich[UZH]



LPNHE
PARIS

Subatech

LSM

LAL
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

CENBG

CNEA

Laboratorio Detección de Partículas y Radiación
Centro Atómico Bariloche

erc
European Research Council
established by the European Commission

NSF The National Science Foundation

FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION