DM searches with **DAMIC** (**DA**rk **M**atter **I**n **C**CD)

Romain Gaïor for the DAMIC collaboration

ICRR Tokyo 26 December 2019

Outline

Motivations / Background

Dark Matter in CCD

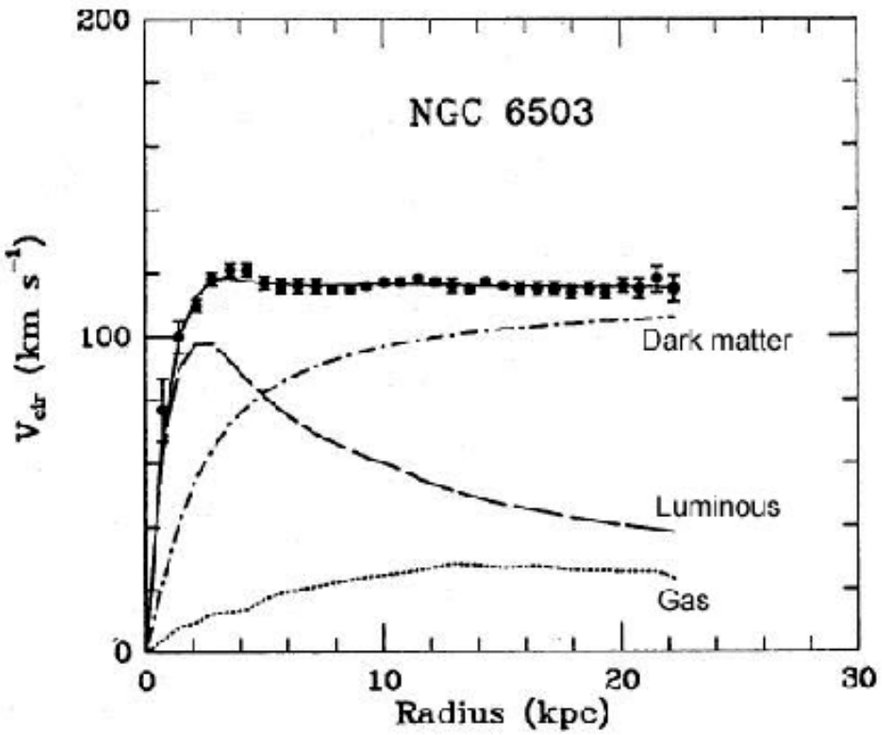
DAMIC at Snolab

DAMIC-M

Motivations

Observations pointing to DM

- Astrophysical observations:
  Galaxy rotation curves



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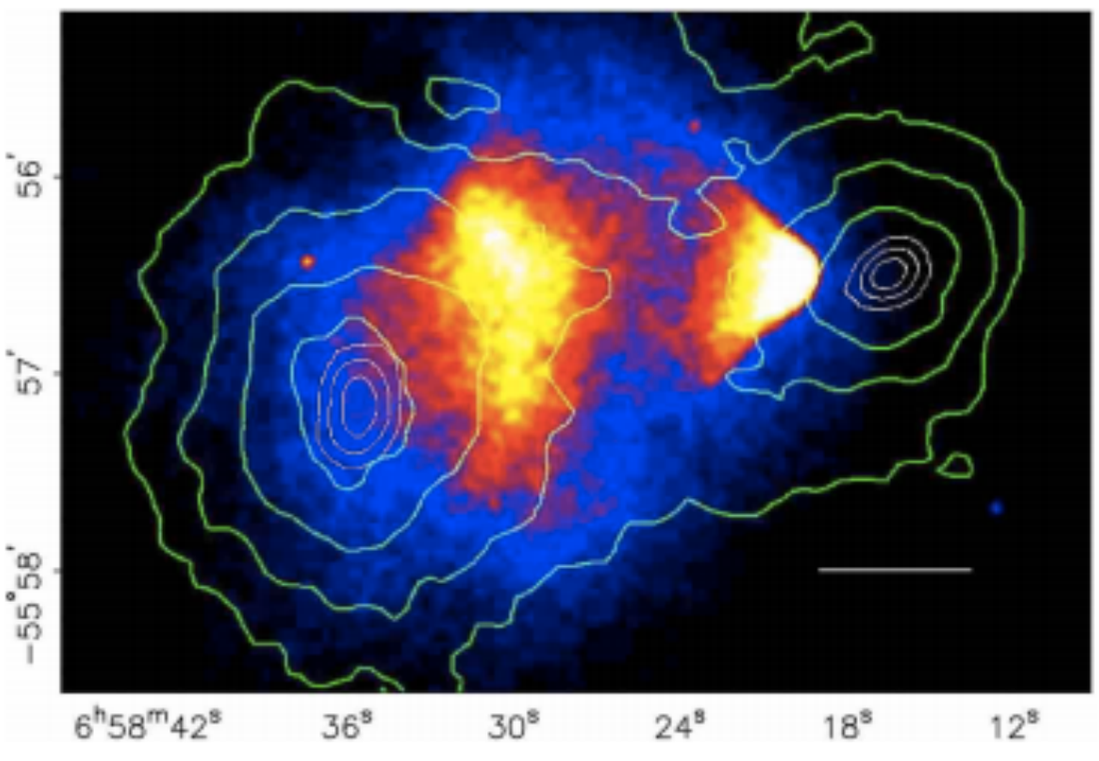

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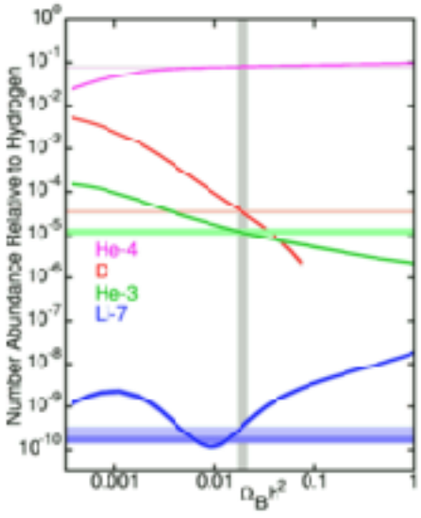
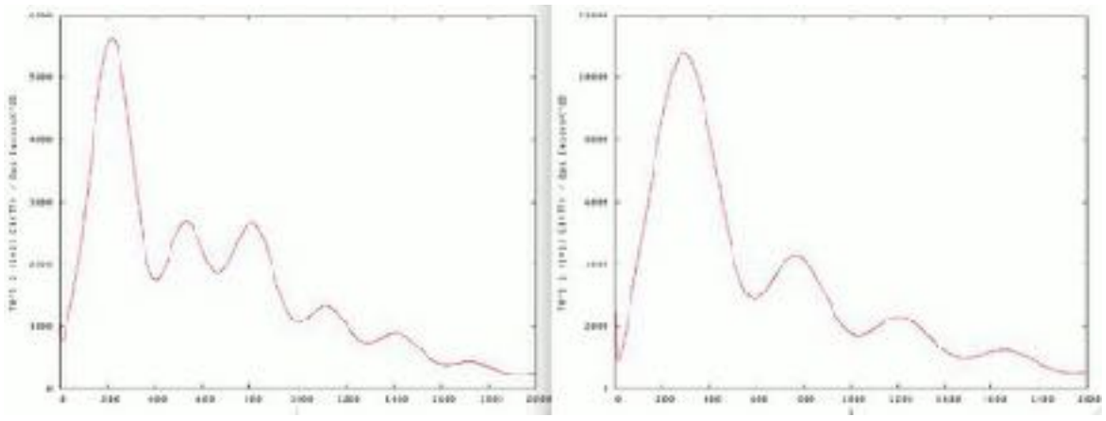
- Cosmological
  CMB spectrum
  Big bang nucleosynthesis





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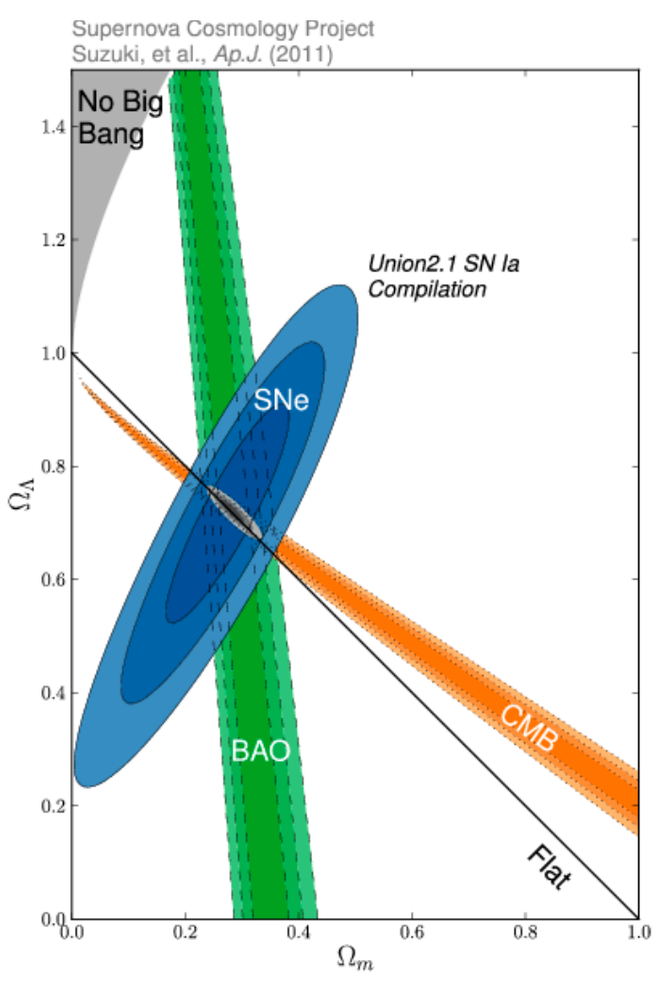
Current picture

- In Universe:
  - ~70% Dark Energy + 30% Matter
  - 80% of matter is Dark !



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Observations pointing to DM

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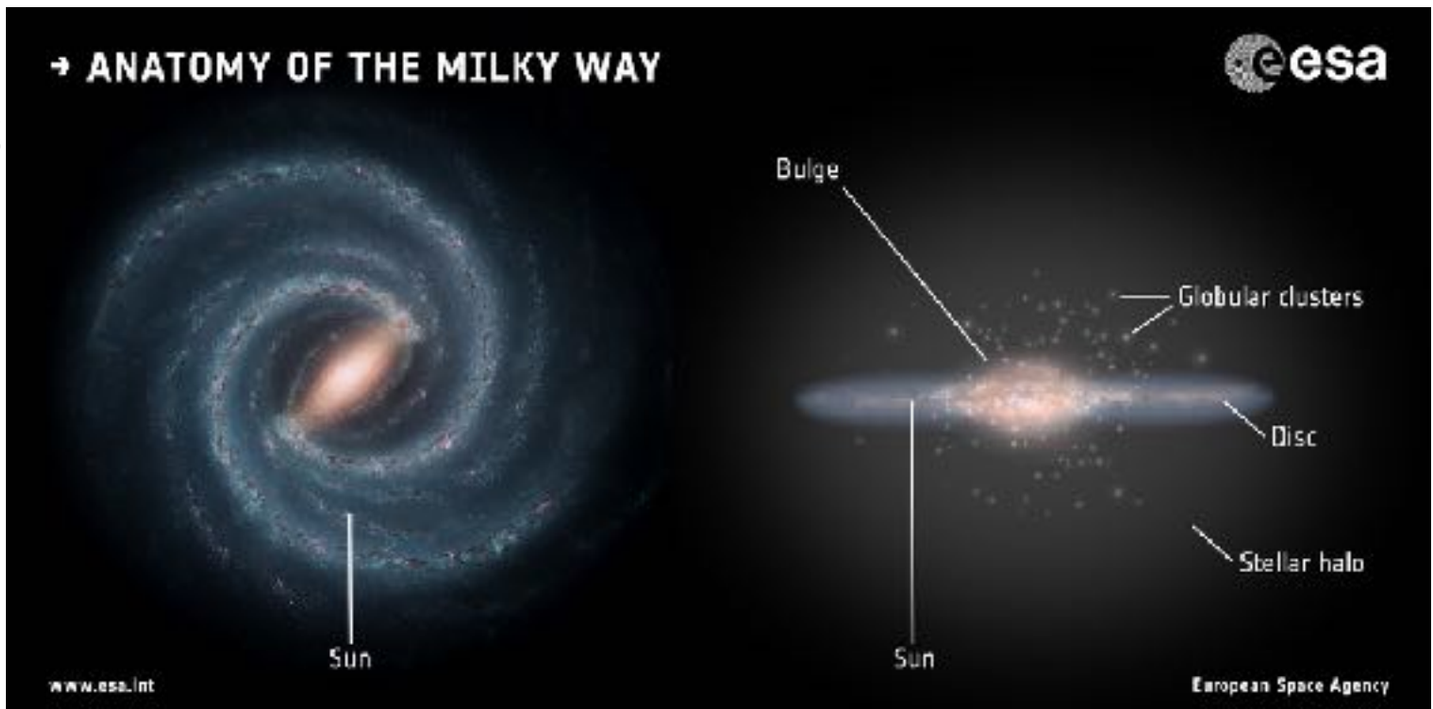
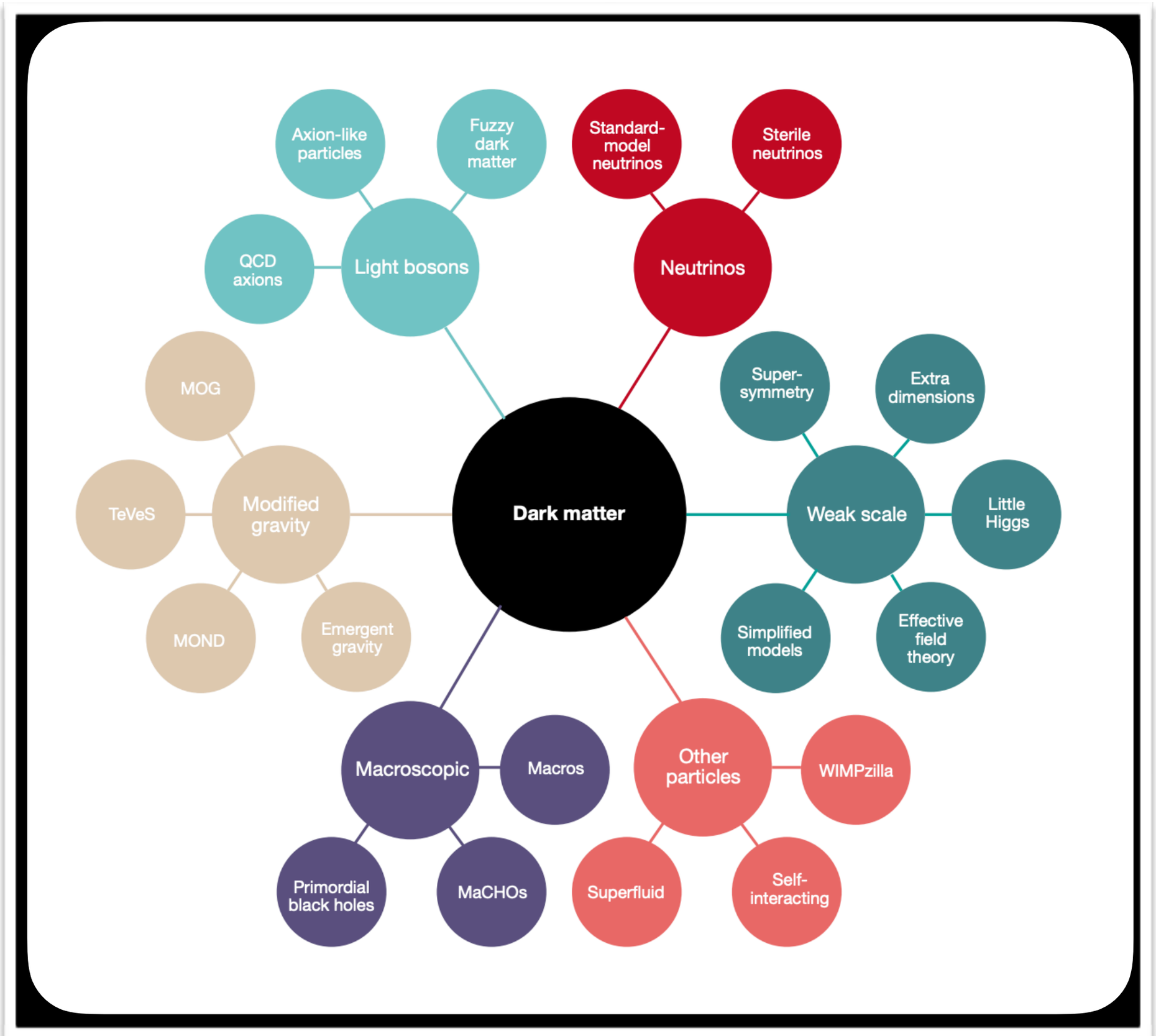
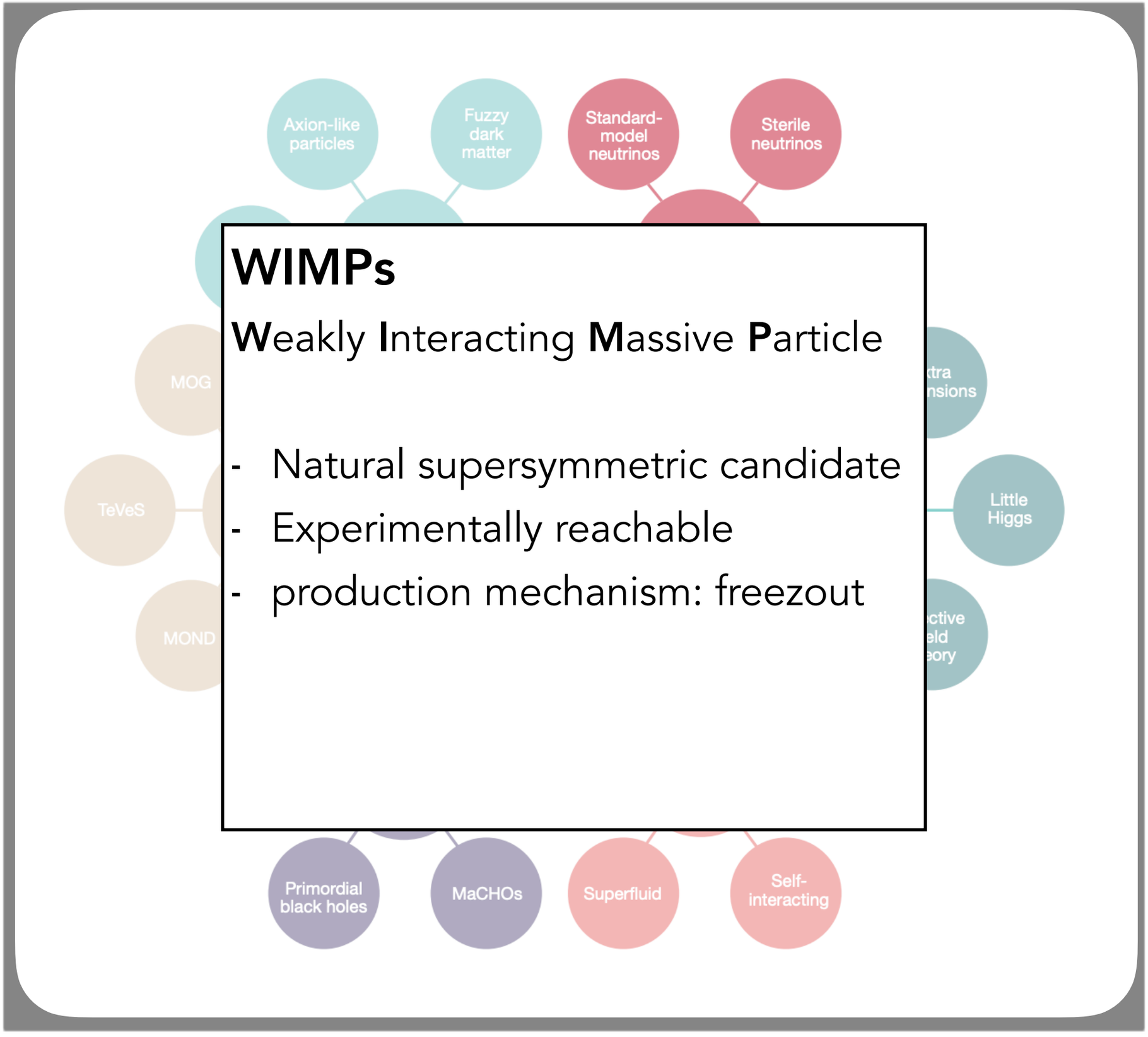
Current picture

- In Universe:
  - ~70% Dark Energy + 30% Matter
  - 80% of matter is Dark !
- In our galaxy:
  - ~0.3 GeV/c^2
  - v_c ~220km.s^{-2}





Bertone, Tait Nature (2018) 1810.1668



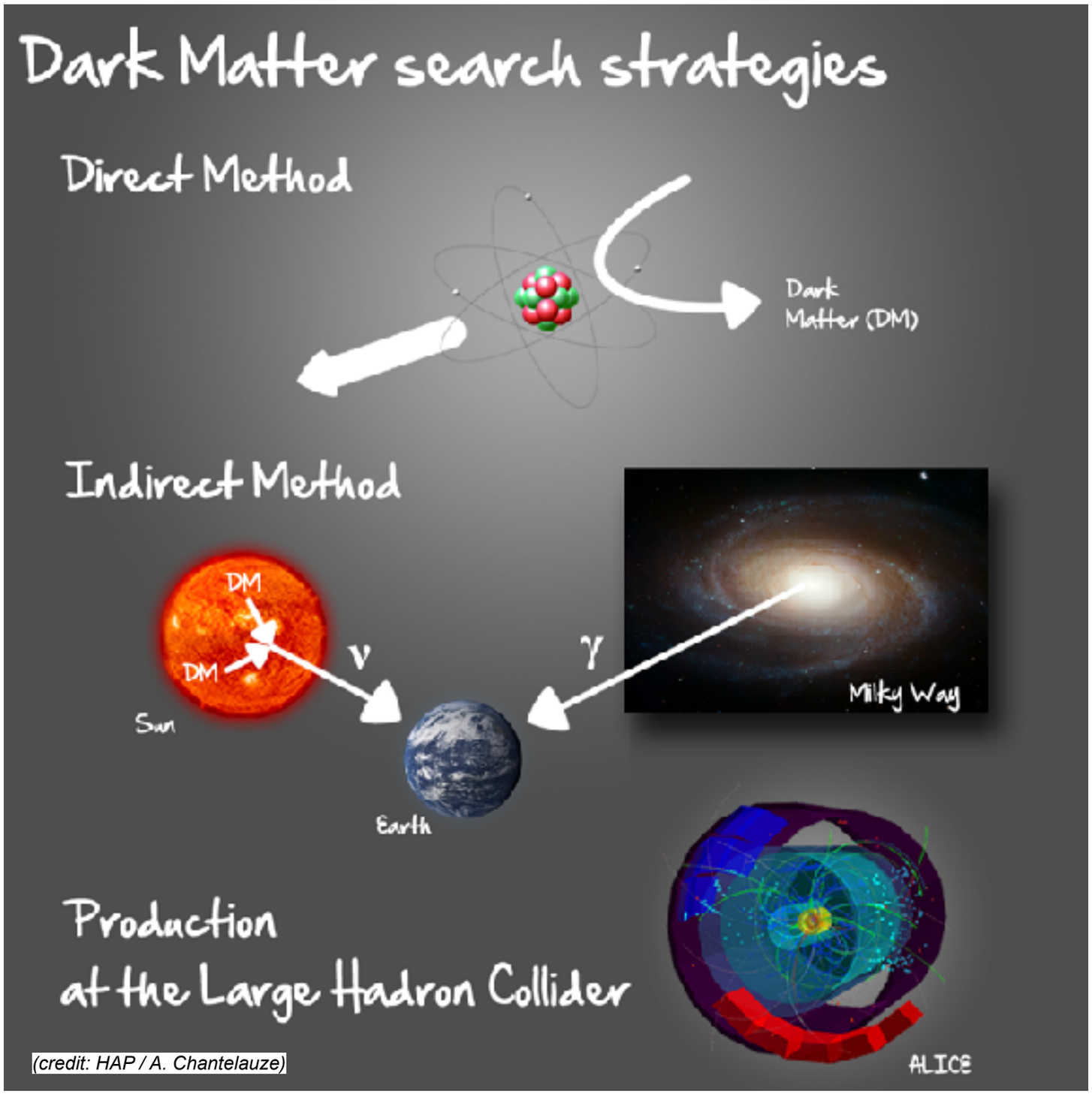
WIMPs

Weakly **I**nteracting **M**assive **P**article

- Natural supersymmetric candidate
- Experimentally reachable
- production mechanism: freezout

Bertone, Tait Nature (2018) 1810.1668

Detection methods



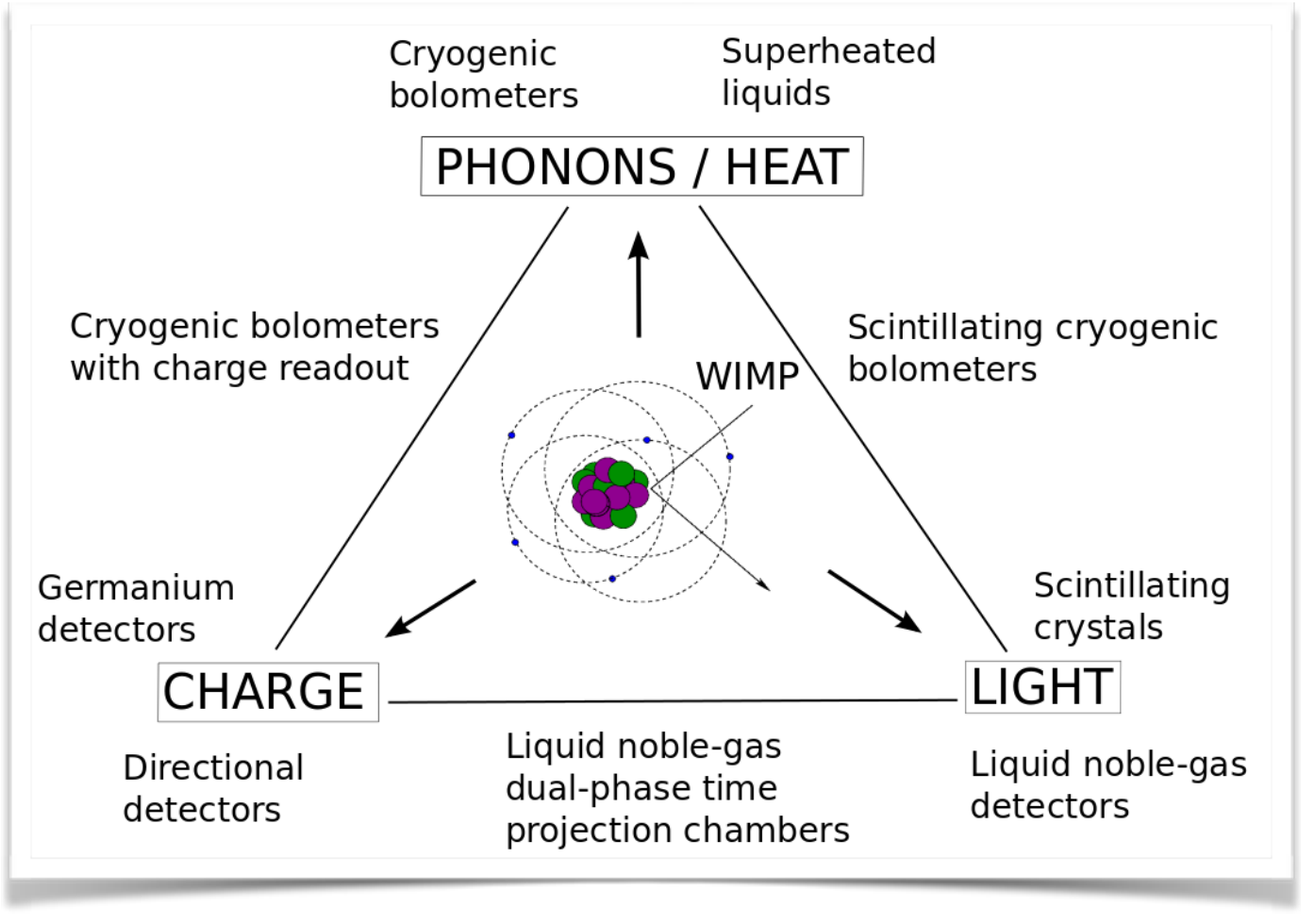
(credit: HAP / A. Chantelauze)

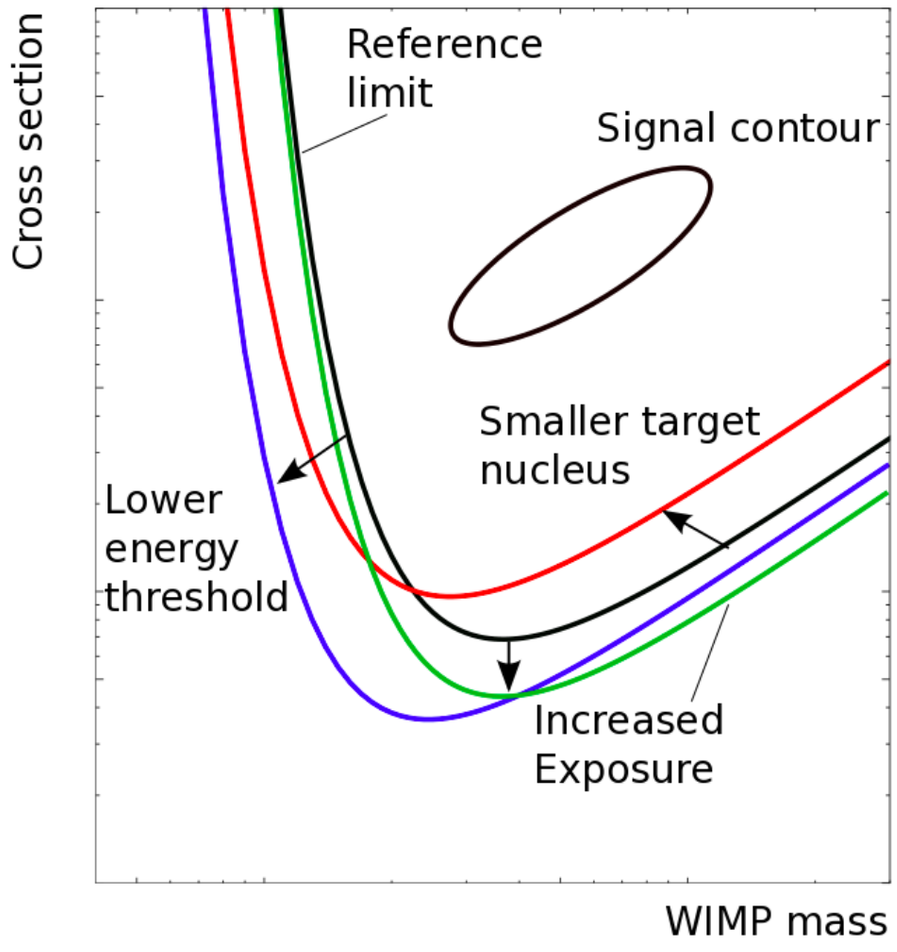
Direct searches

- m_x = 100GeV m_N = 130 GeV
  —> $\langle E_r \rangle$ ~ 13keV
- m_x = 5GeV m_N = 28 GeV
  —> $\langle E_r \rangle$ ~ 0.3keV

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{2\mu_A^2 \cdot m_\chi} \cdot \sigma_0 \cdot A^2 \cdot F^2 \int_{v_{min}}^{v_{esc}} \frac{f(\mathbf{v},t)}{v}\, \mathrm{d}^3 v,$$

$$v_{min} = \sqrt{\frac{m_A \cdot E_{thr}}{2\mu_A^2}}.$$





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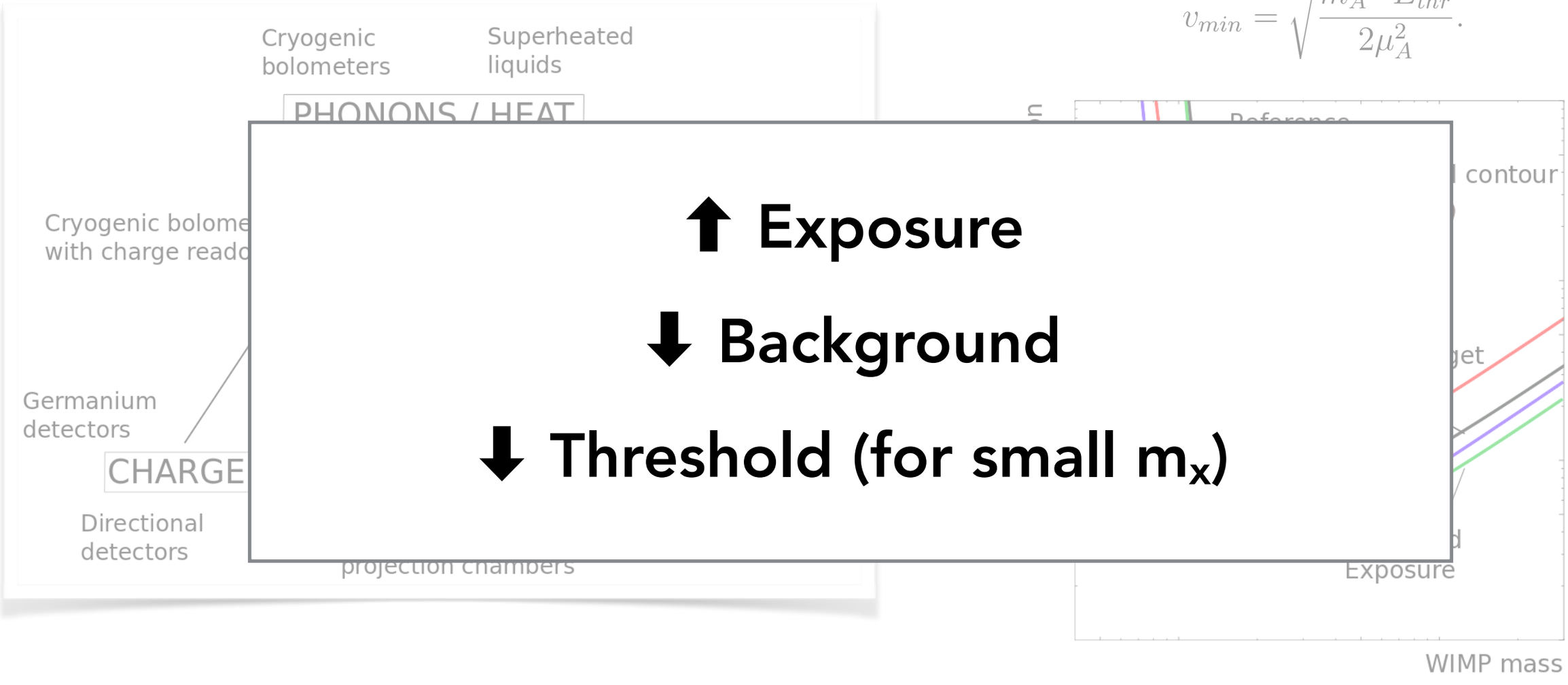
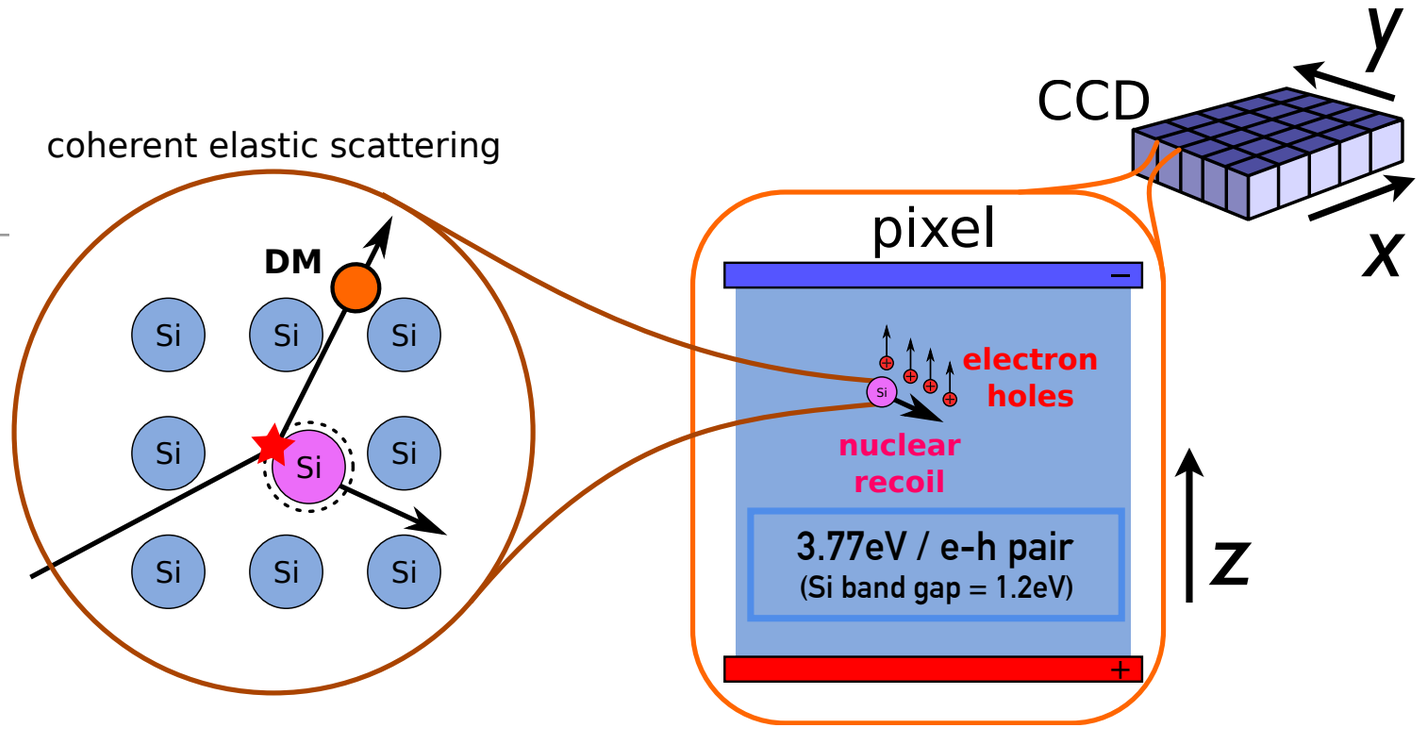


⬆ Exposure

⬇ Background

⬇ Threshold (for small m_x)

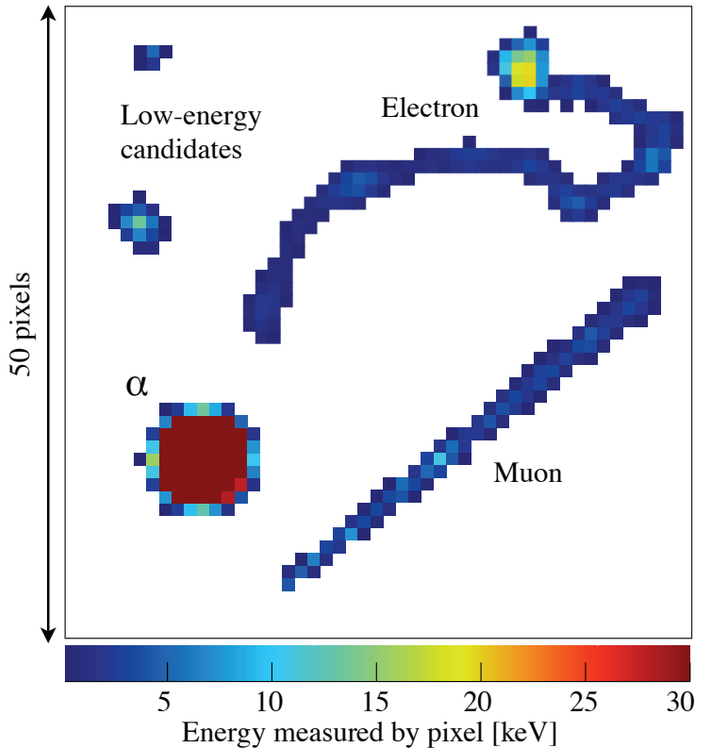
Dark Matter in CCD ?



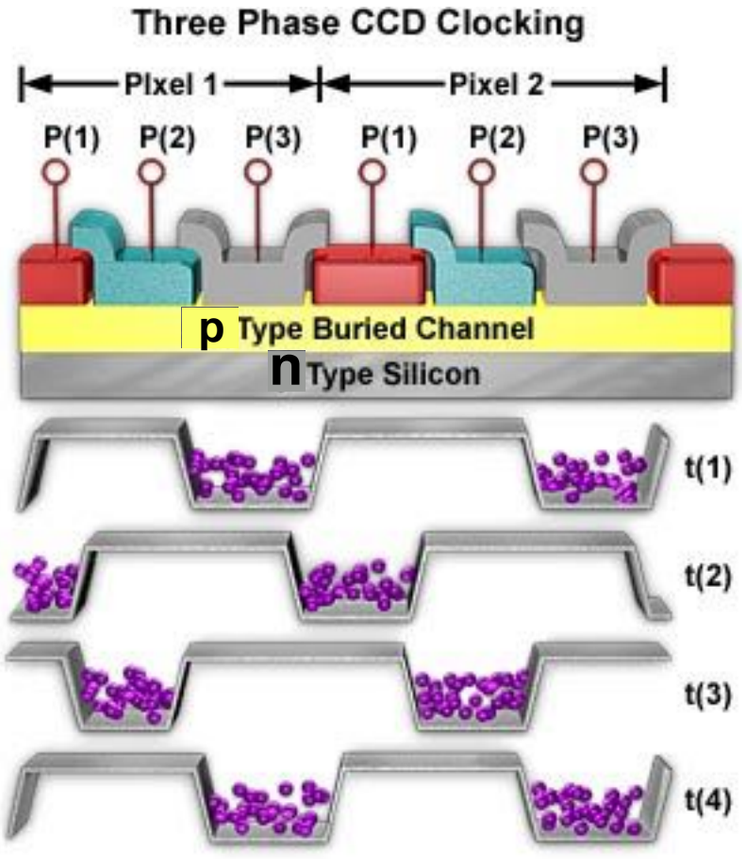
- low energy **threshold**
  (low mass WIMP)
  band gap in Si = 1.2 eV

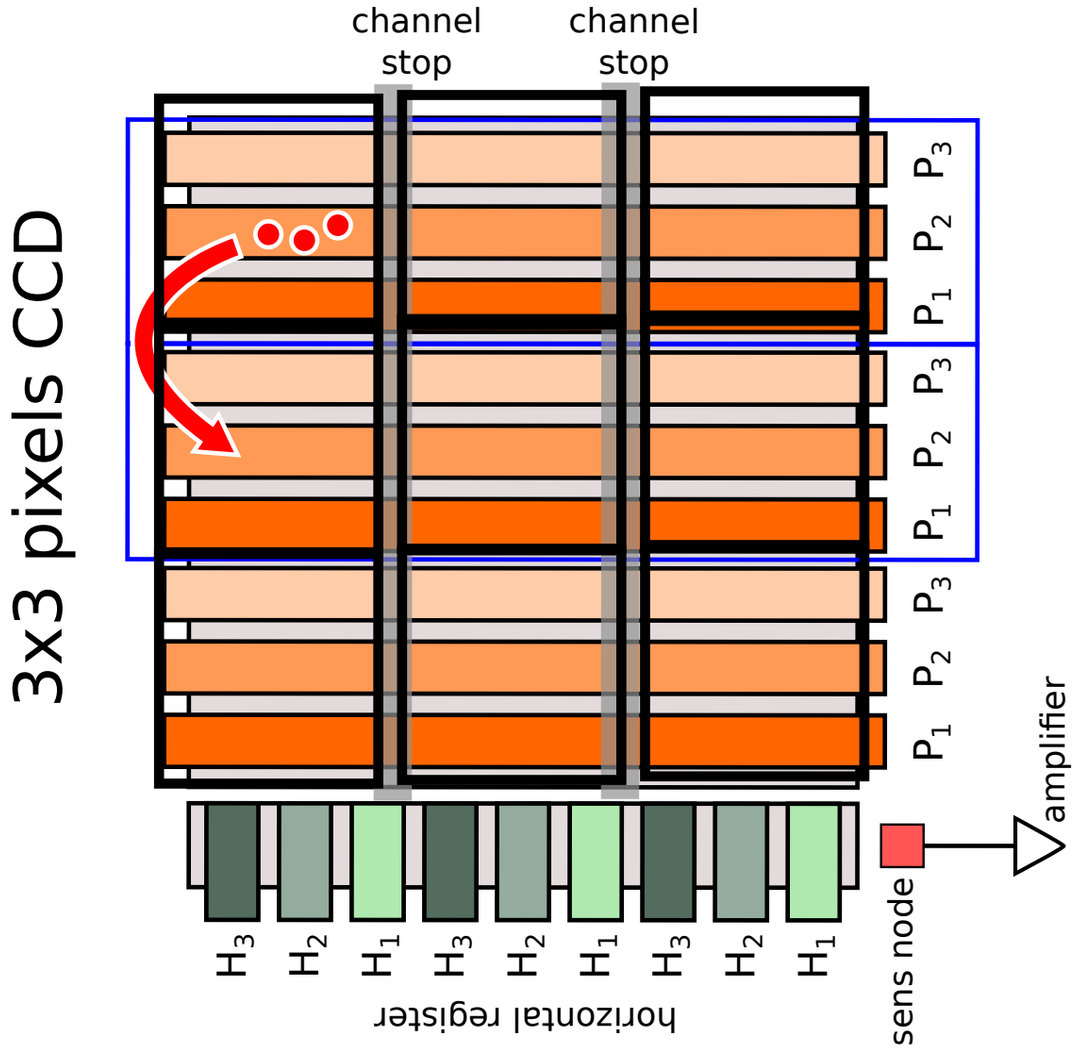
- high **granularity**
  3D information

- **Thick** CCDs
  675um, high resistivity



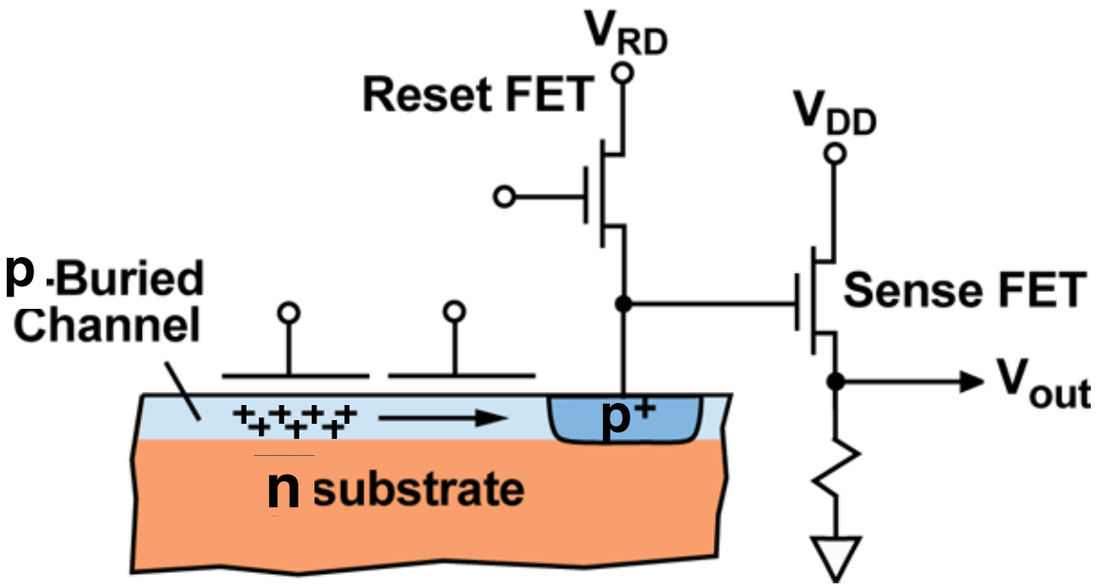
CCD operation basics: **Clocking**

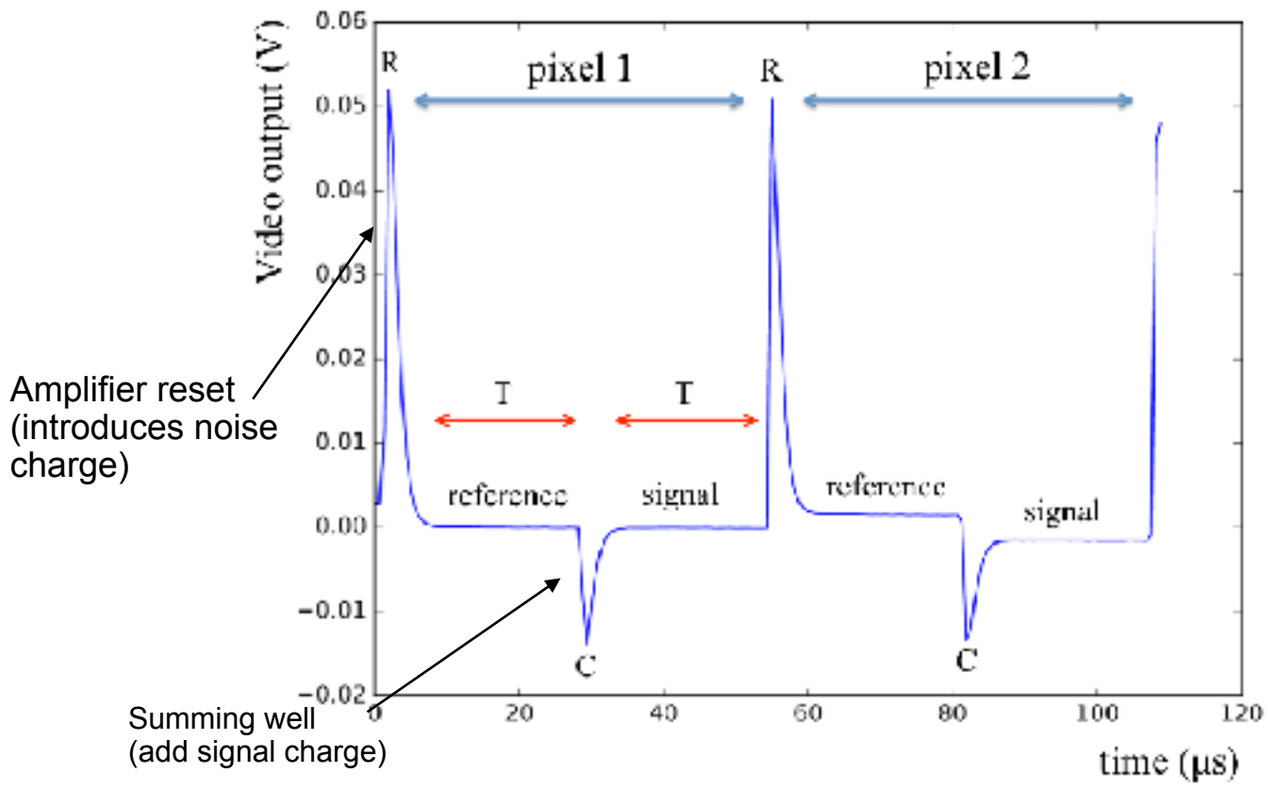




https://hamamatsu.magnet.fsu.edu/articles/threephase.html

CCD operation basics: **Readout**





1. Reset the sense node
2. Measure the reference level
3. Inject the charge on the sense node through the summing well
4. Measure the signal level

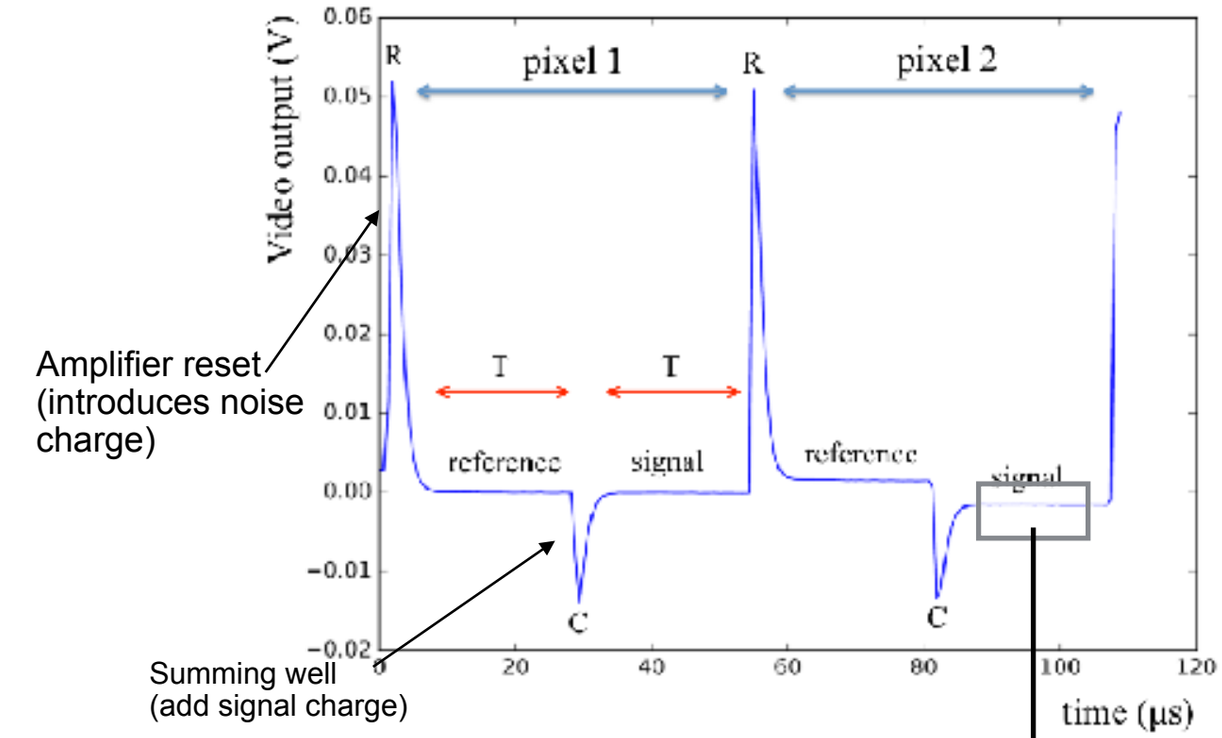
—> You get a voltage proportional to the pixel charge content

Noise

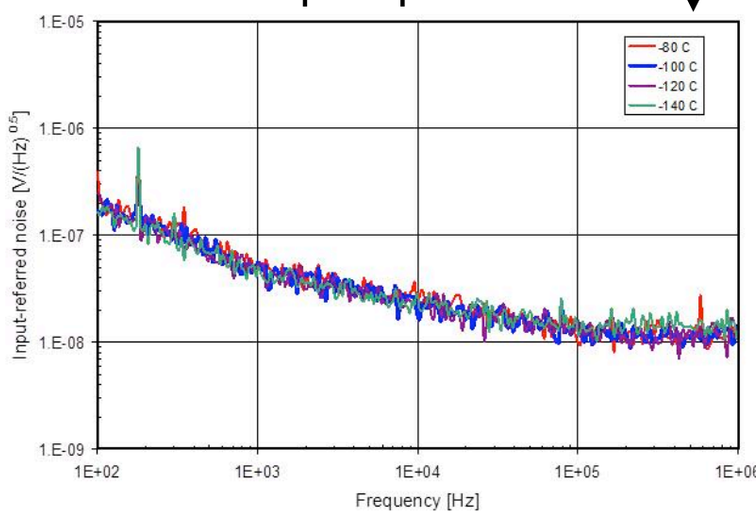
- Correlated noise:
  Suppressed with Image processing

- Readout: Dual Slope integration with integration time of 40µs
  —> noise ~ **1.6e$^-$**

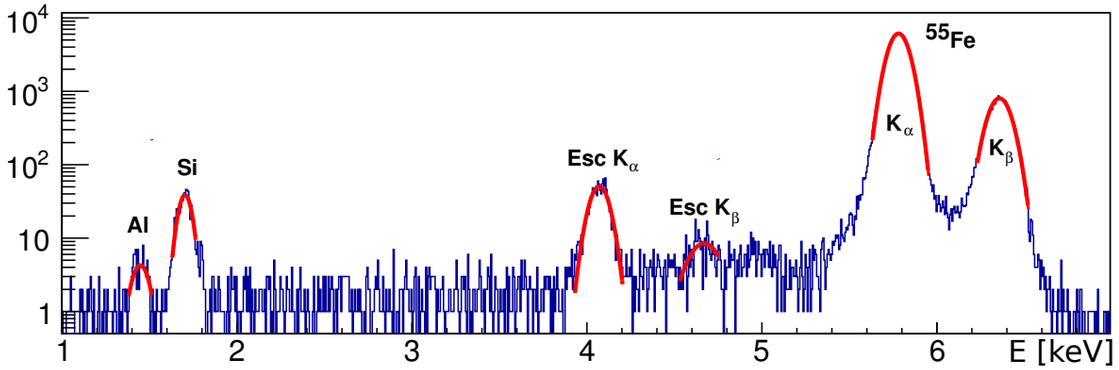
- **low leakage current**:
  ~10 e$^-$ / mm^2 / day



Freq. Spectrum



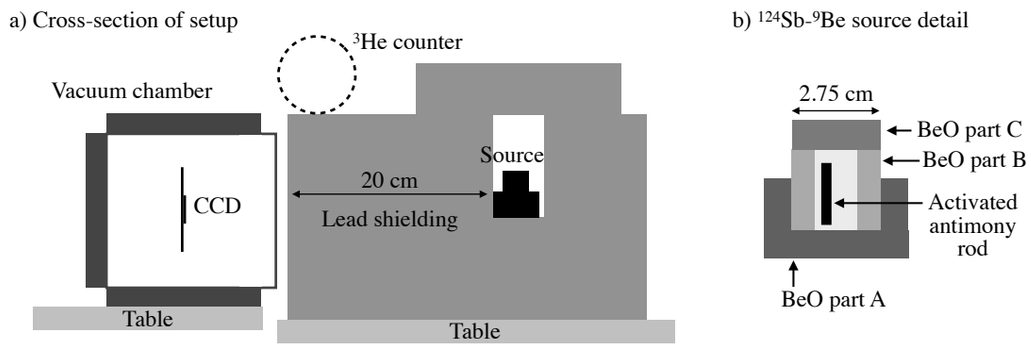
Calibration

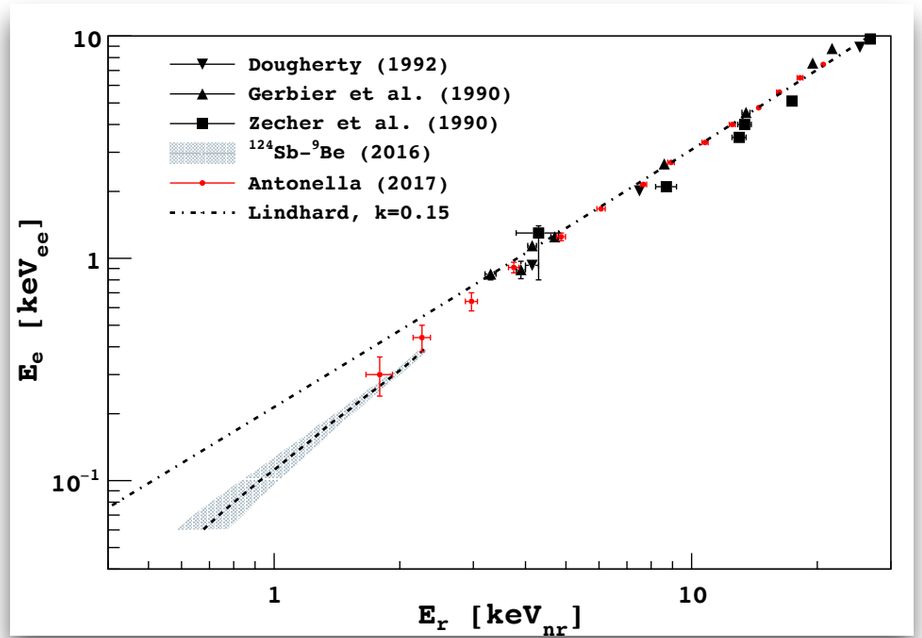


- ionisation in Si
  - fluorescence line (down to 1keV)
  - LED (40eV - 80 eV)
  - Compton spectrum
  - **Linearity** <5%

Compton:arXiv:1706.06053 Phys.Rev. D96 (2017) no.4, 042002

NR: IOP June 2017 Vol 12 P06014; Phys. Rev. D 94, 082007,

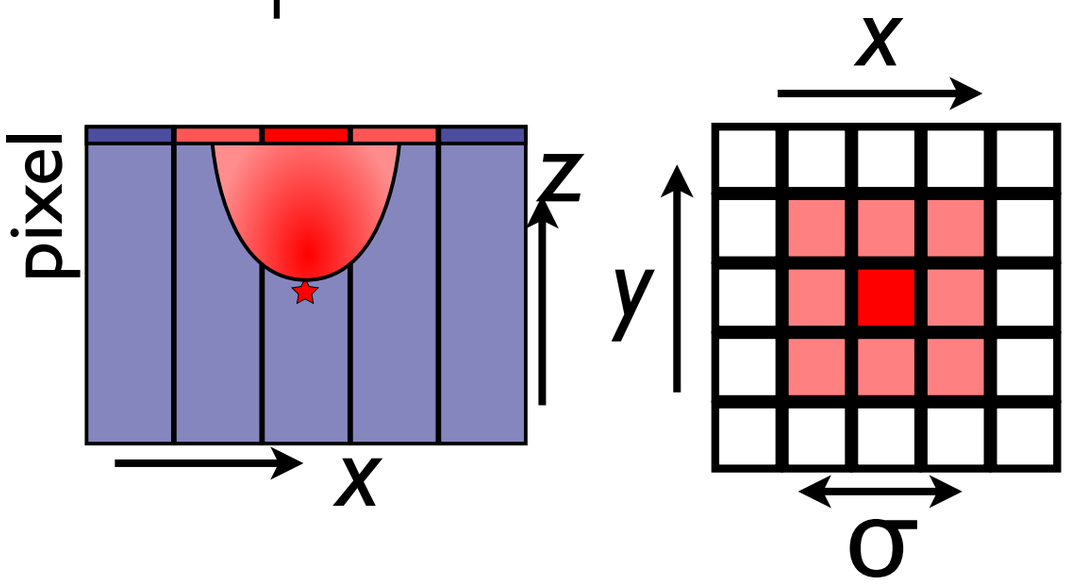




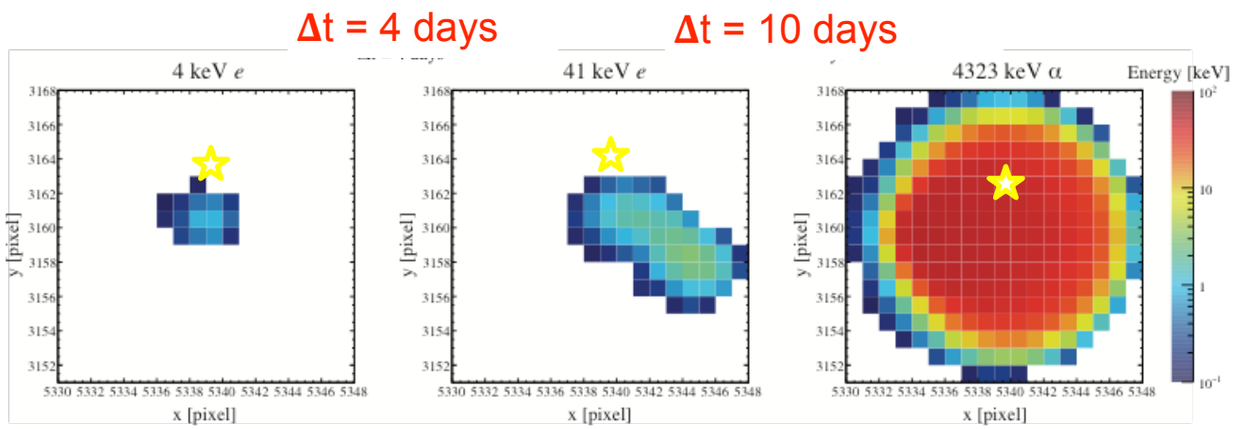
- Nuclear recoil:
  -**Quenching factor** measured in Si down to 60eV$_{ee}$
  - Deviation from Lindard model

Radioactive background discrimination

Depth information

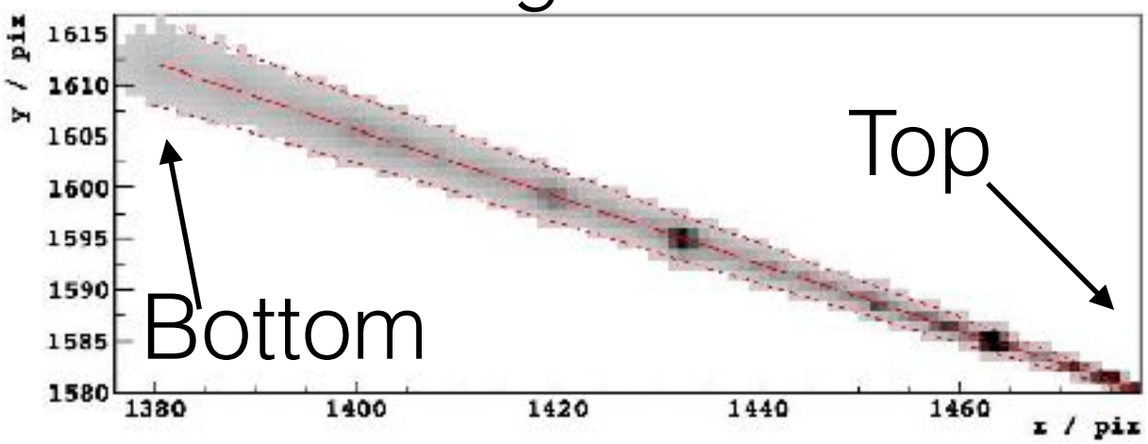


Pb210 Candidate



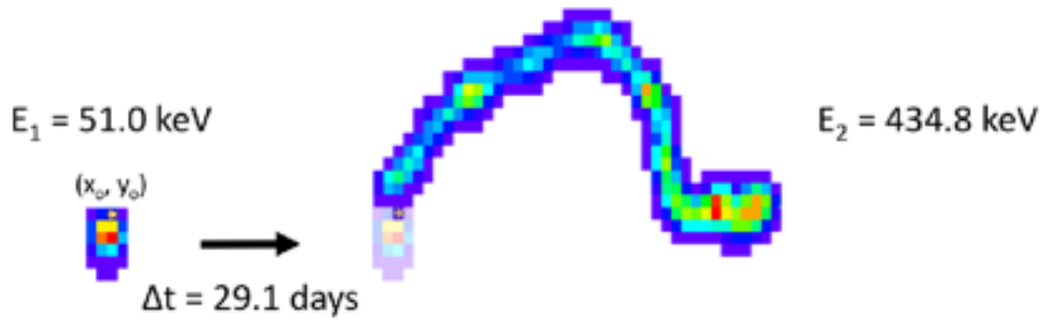
^{210}Pb ($T_{1/2}$= 22.3 y, β) ➔ ^{210}Bi ($T_{1/2}$=5.0 days, β) ➔ ^{210}Po ($T_{1/2}$= 138 days, α)

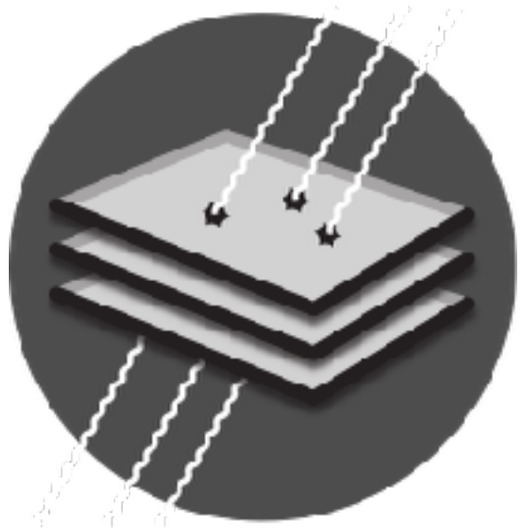
Piercing muon



Si32 Candidate

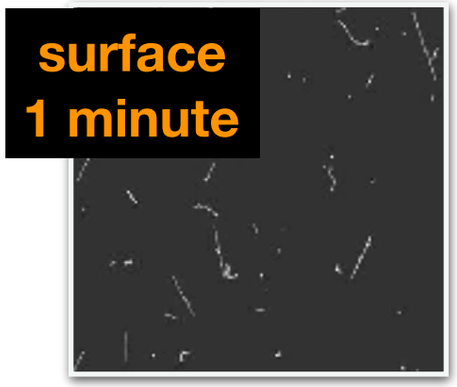
^{32}Si ($T_{1/2}$= 150 y, β) ➔ ^{32}P ($T_{1/2}$= 14 days, β)

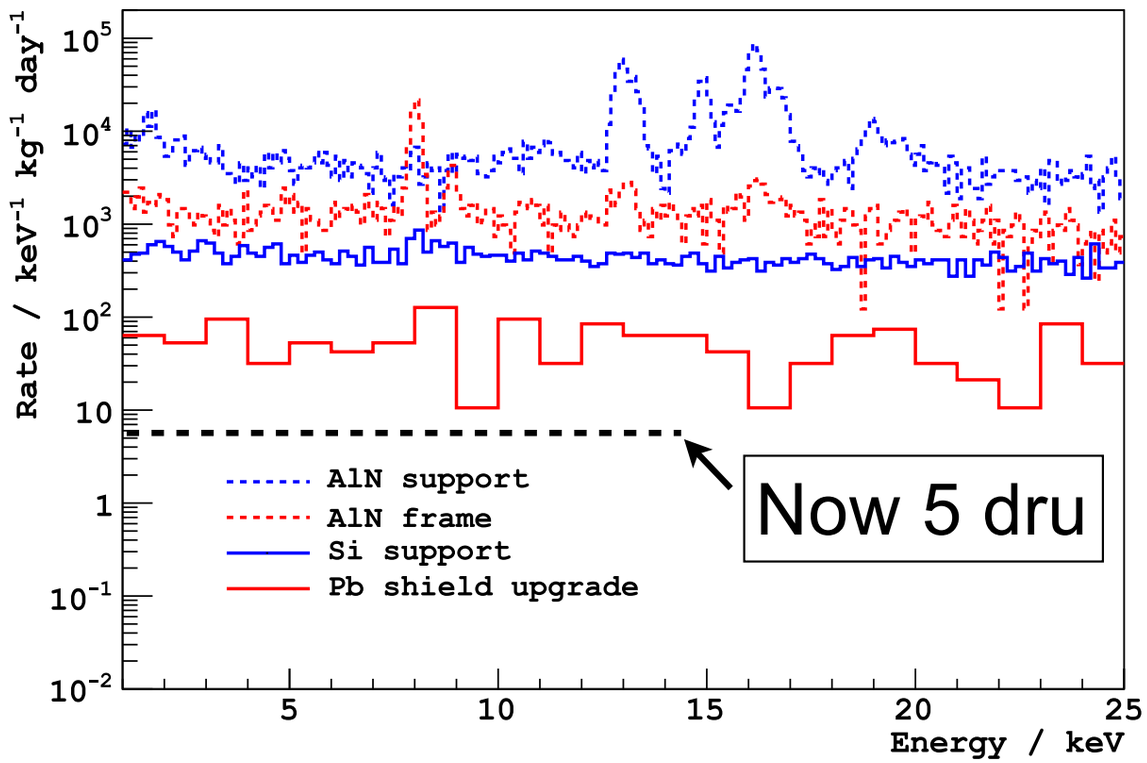


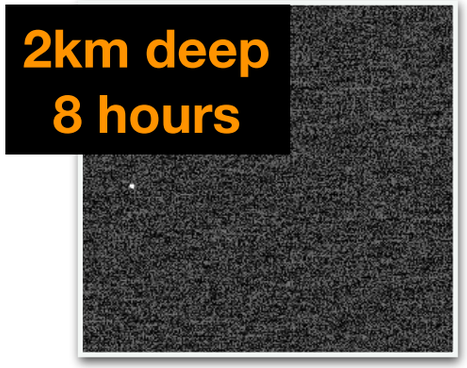


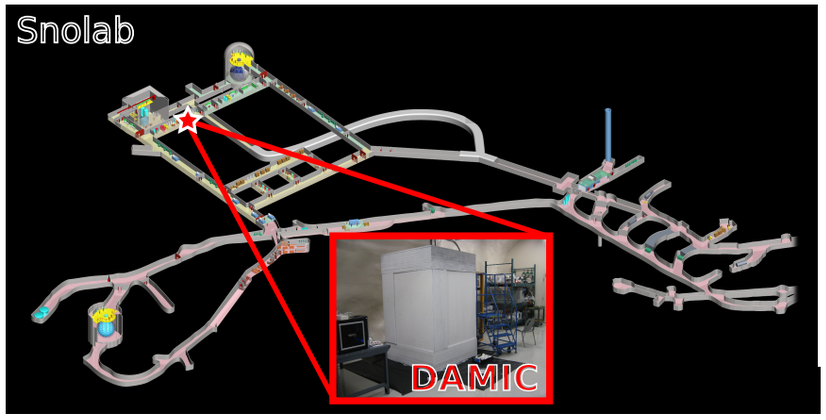
DAMIC at SNOLAB: 2012 - now

DAMIC at SNOLAB





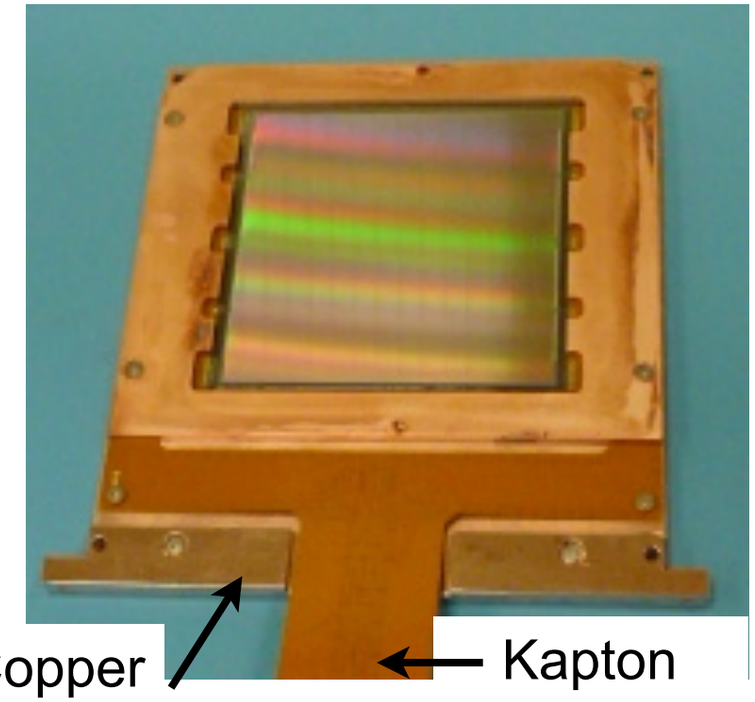


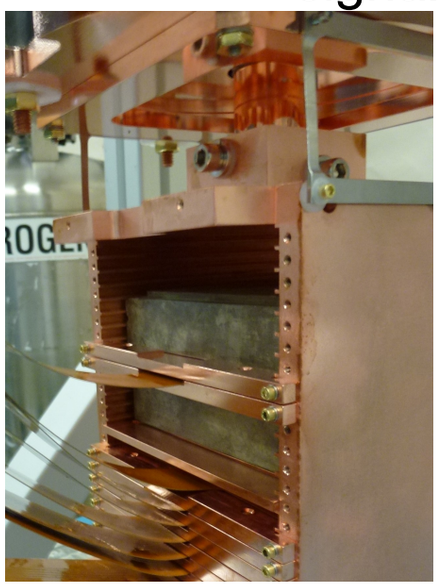


- In a (active) mine **2km** (6000m.w.e.) below surface (1μ / m^2 / 3 days)
  https://www.youtube.com/watch?v=sZPLcv-ASwc

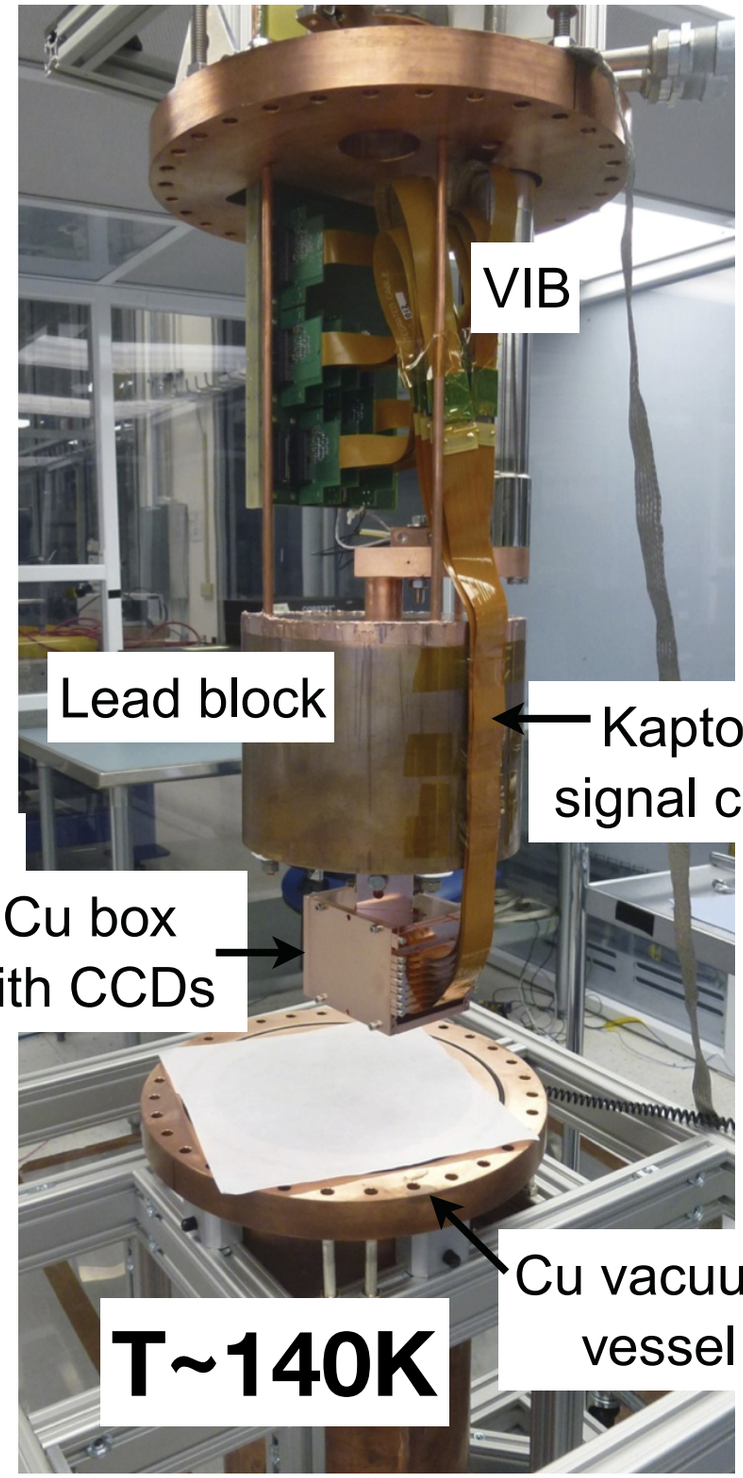
- Many improvements over the years in **background mitigation**

DAMIC detector

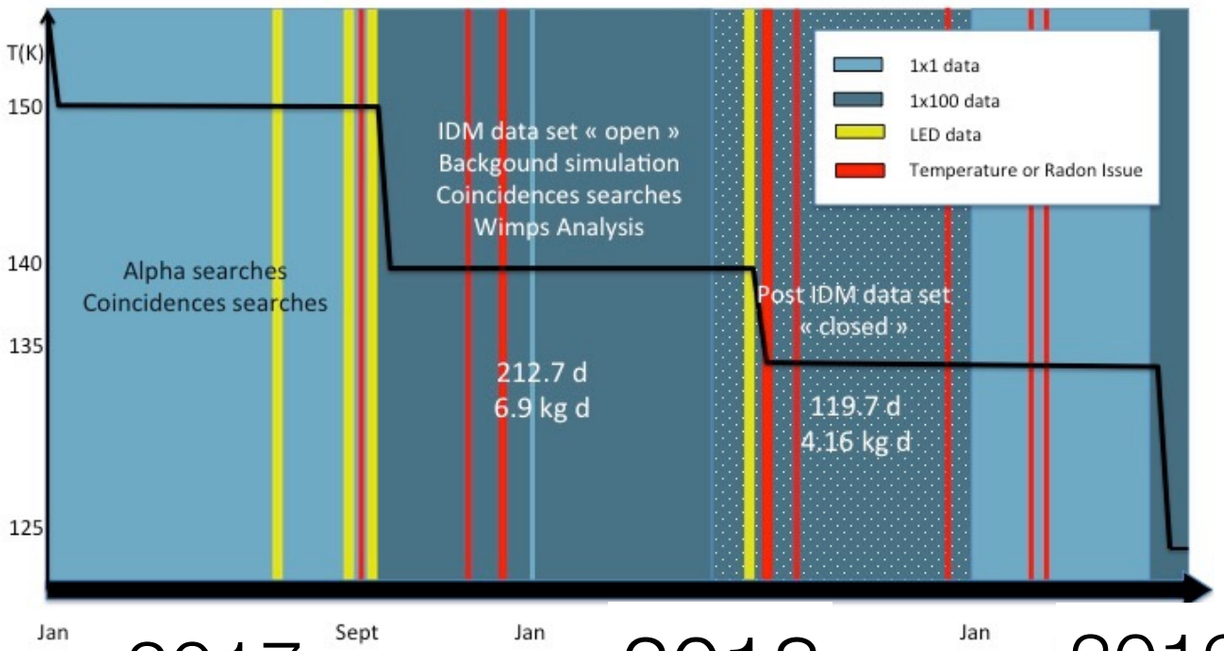


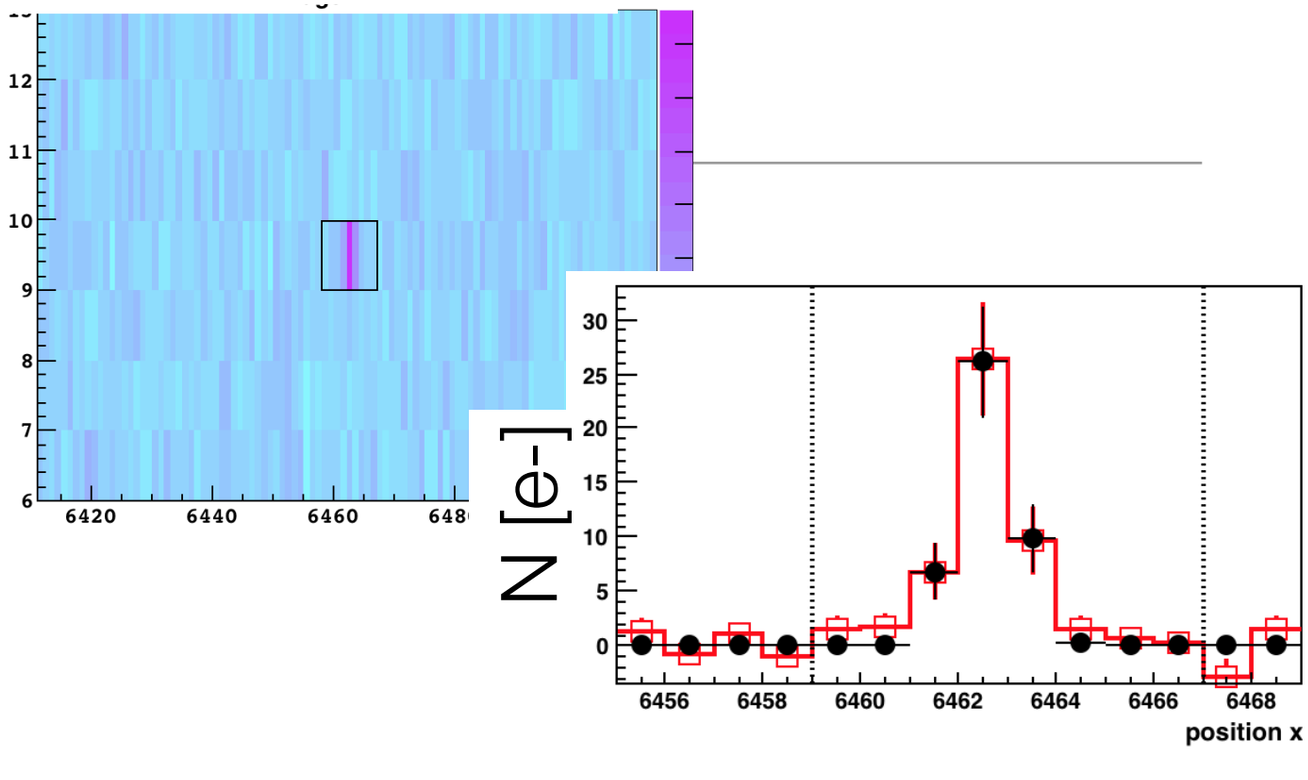


7 CCDs ~ 40g



WIMP search





Data set

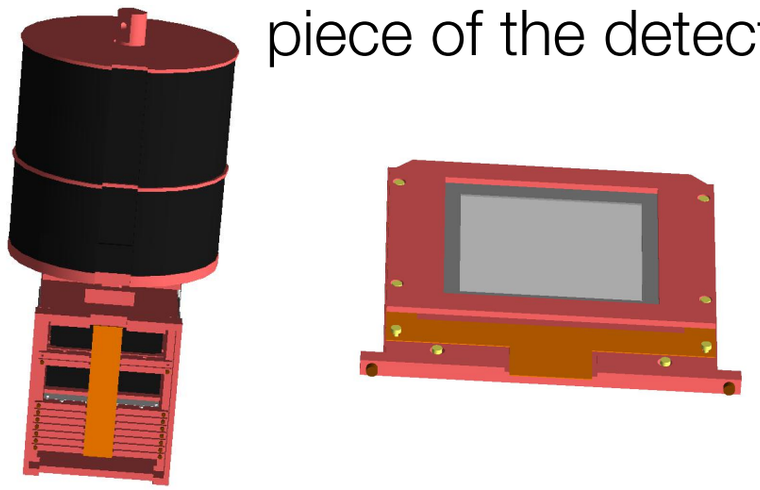
- **1x100 binning** (15 x1500um pixels)
- Data set of 864x7 images (8h or 24h exposure)
- Low radon && Low leakage current && quality cuts
- **~11 kg.day**
  (previous publication 0.6 kg.day:
  arXiv:1607.07410 Phys. Rev. D 94, 082006 (2016))

Analysis steps

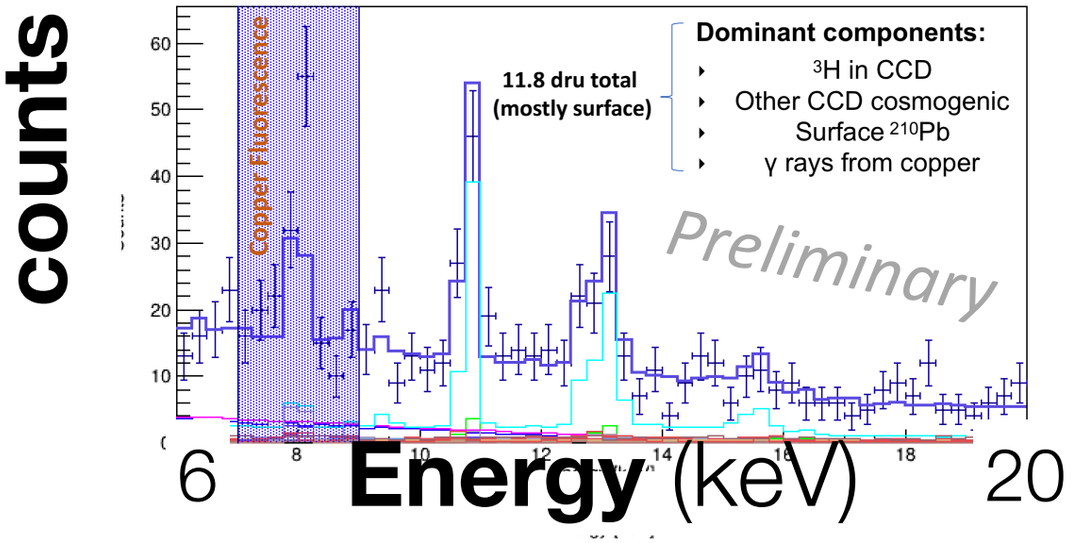
- Geant4 Simulation of the radioactive contaminations
- Build a background model in a test region
- Search for low energy deposition (~50ev - 20keV)
- Compare data / model in region of interest —> Discovery (or limits…)

Background model

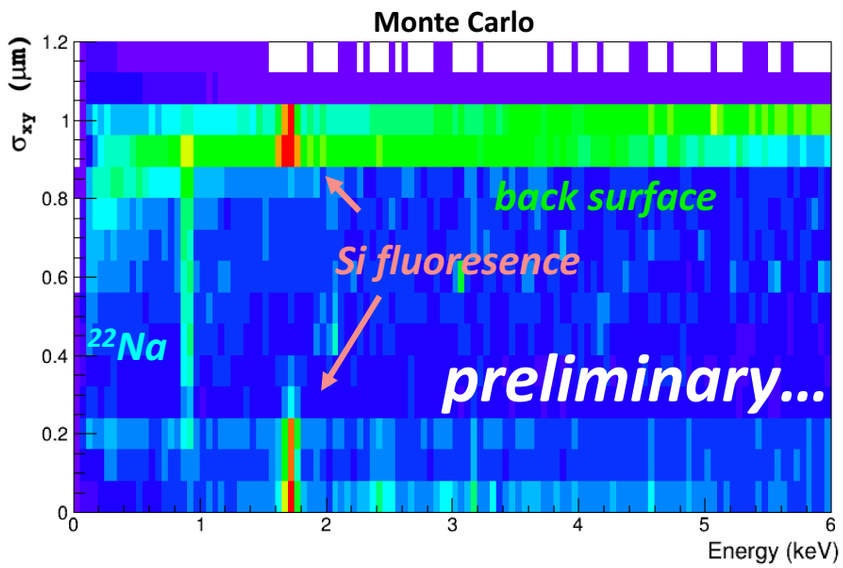
1 **GEANT4 Simulation** of relevant decay chains in each piece of the detector



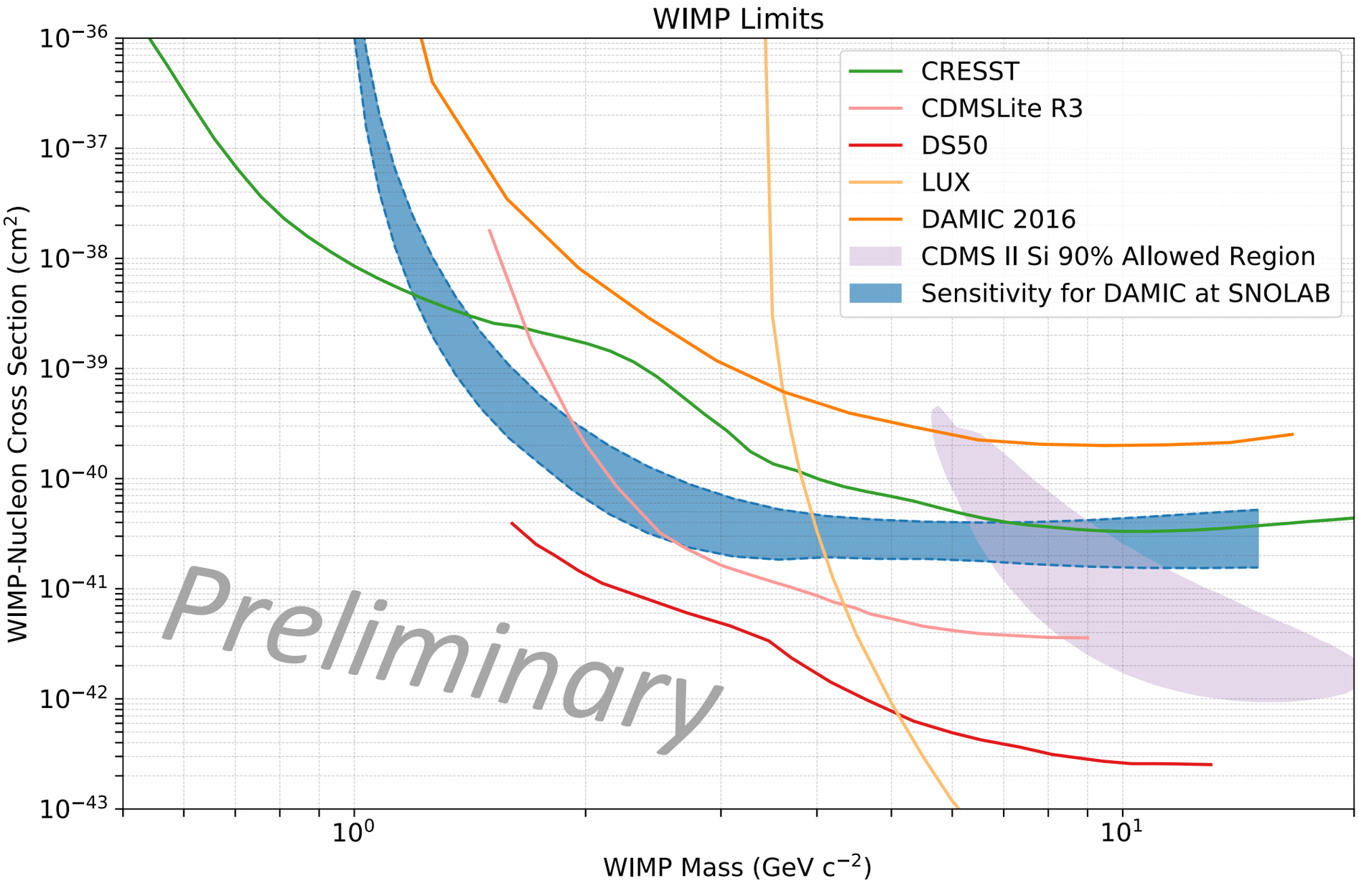
2 **2D fit** in the plane Energy-Depth at **E > 6keV** (constrained with assay value)



3 Background Model **in ROI**



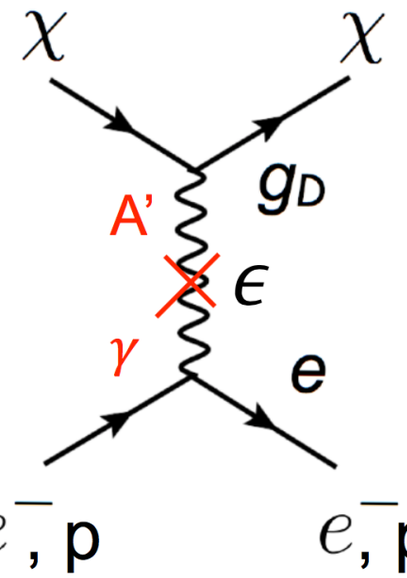
Sensitivity to WIMP with 11kg.day



Light dark matter - DM-e scattering

- Light dark matter (keV- GeV) appear in hidden sector scenarios

- elastic scattering with e- or absorption of dark photon
  —> Deposited energy large enough to directly ionise atom
  (in crystal excite from valence to conduction band)



Simulation in DAMIC detector

- indefinite momentum and band structure—> need specific treatment
  see arxiv:1509.01598 (Essig et al)

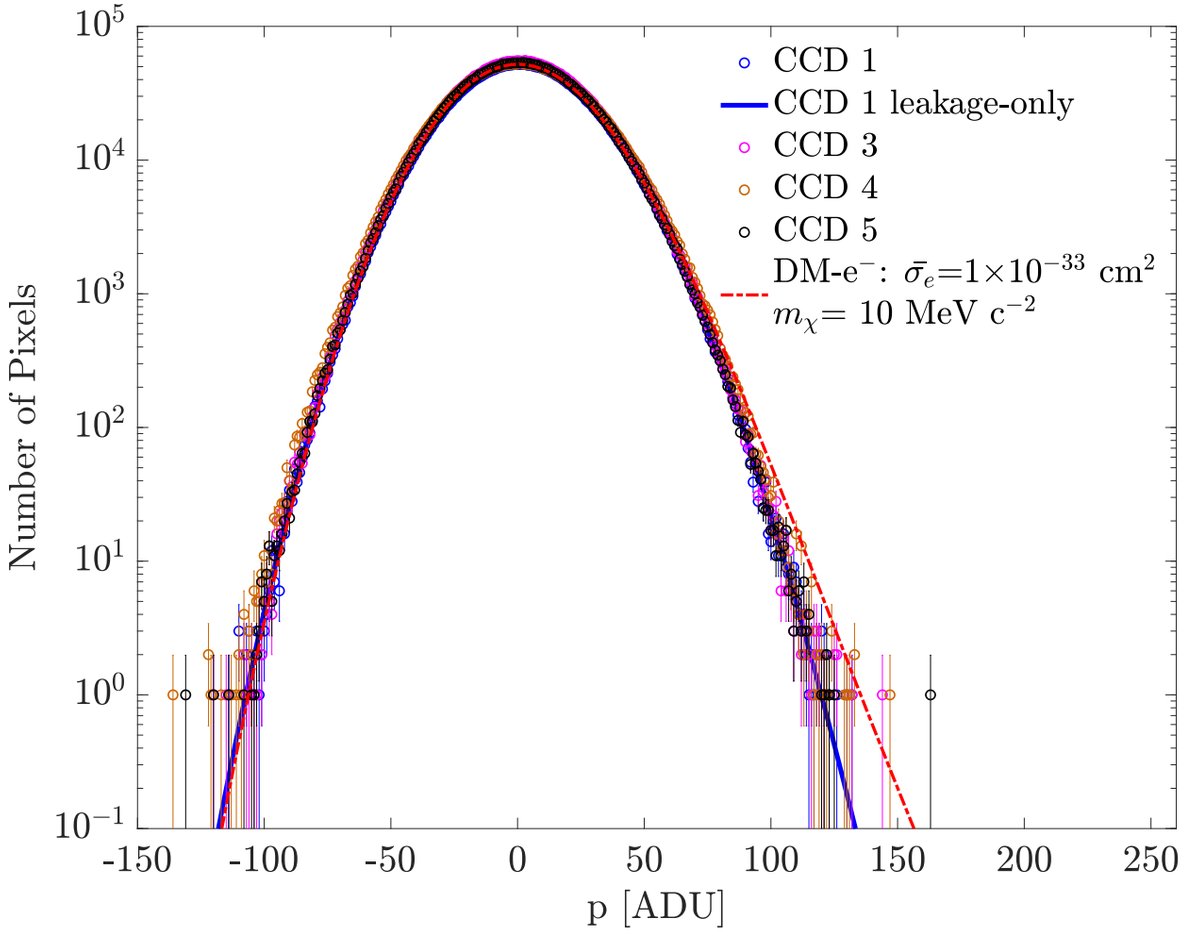
DM flux parameters *crystal form factor*

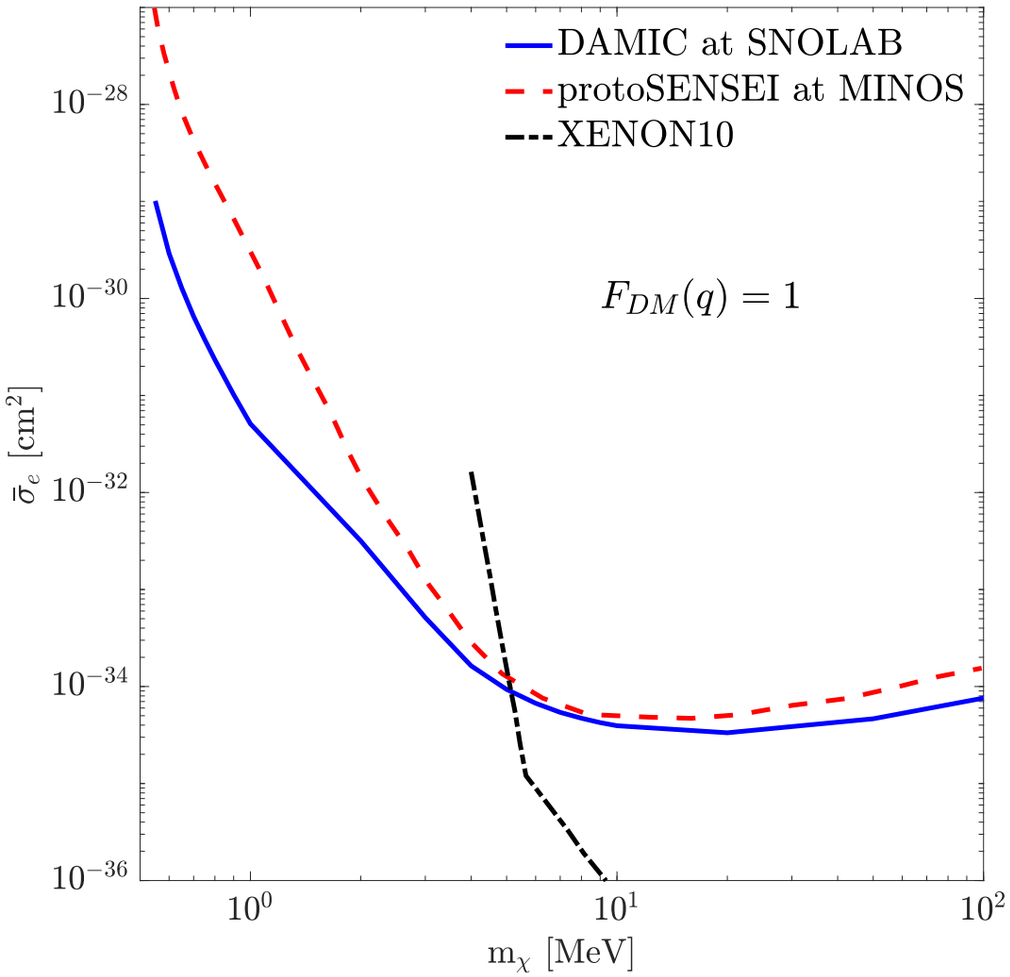
$$\frac{dR}{dE_e} \propto \bar{\sigma}_e \int \frac{dq}{q^2}\, \eta(m_\chi, q, E_e) |F_{DM}(q)|^2 |f_c(q, E_e)|^2$$

reference X section

$F_{DM} = (\alpha m_e)/q^n \ \{n = 0, 1, 2\}$
depends on interaction

DAMIC DM-electron limits: arXiv:1907.12628

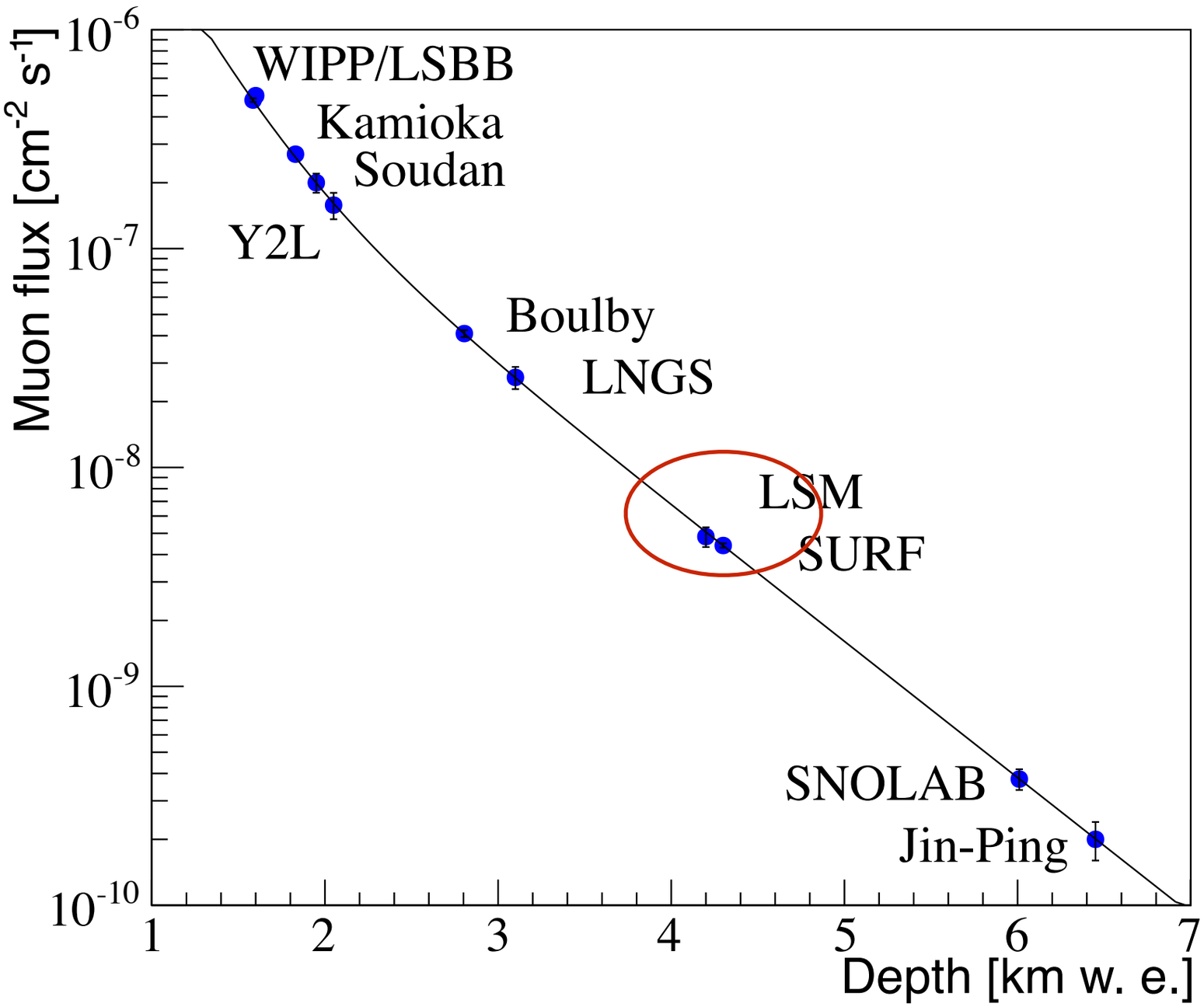




- **Selection of images** with the lowest leakage current (1-3 e- / mm2 / day)
- **Fit the pixel distribution** with electronics, leakage current, signal components
- **extract limit** on σ_e (for various interaction assomptions)

—> **Lowering the threshold to ~ 1 e-** would change the game…

Toward the next steps



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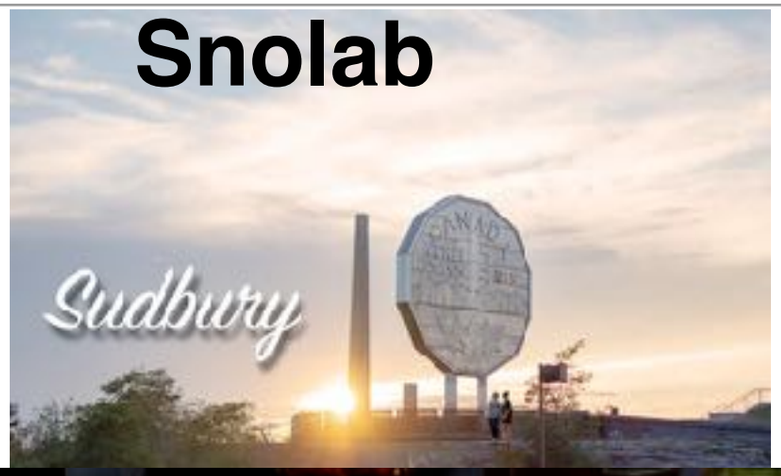
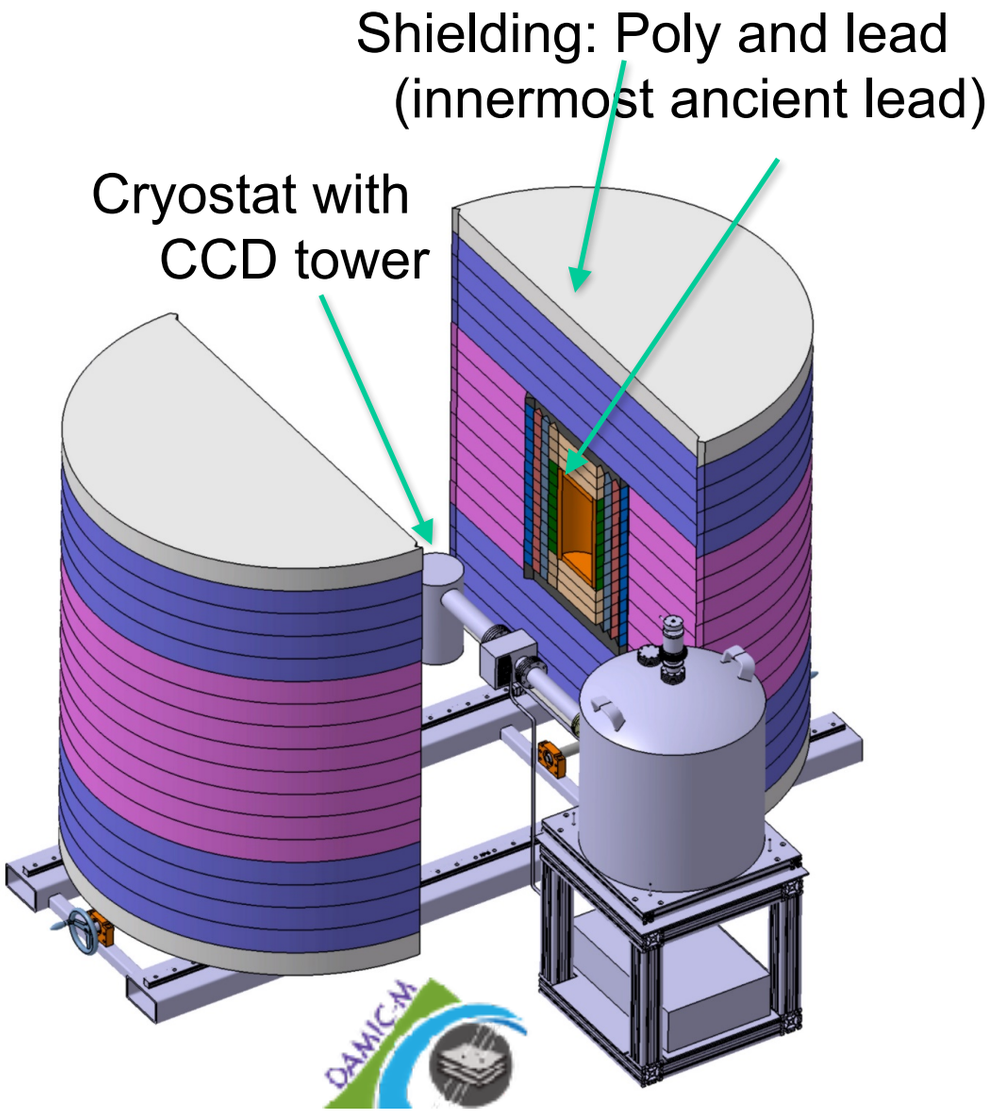


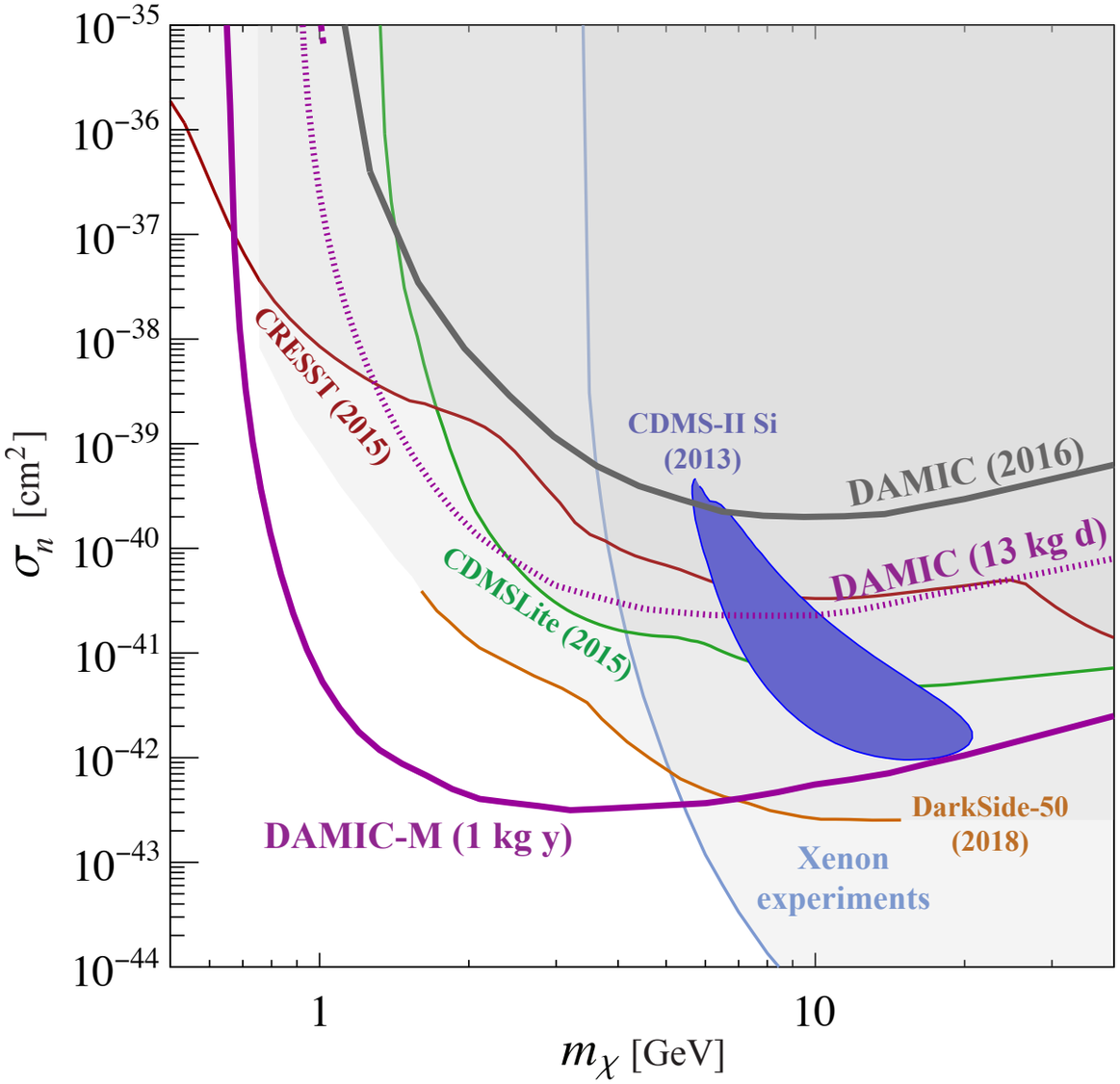
DAMIC-M in a nutshell



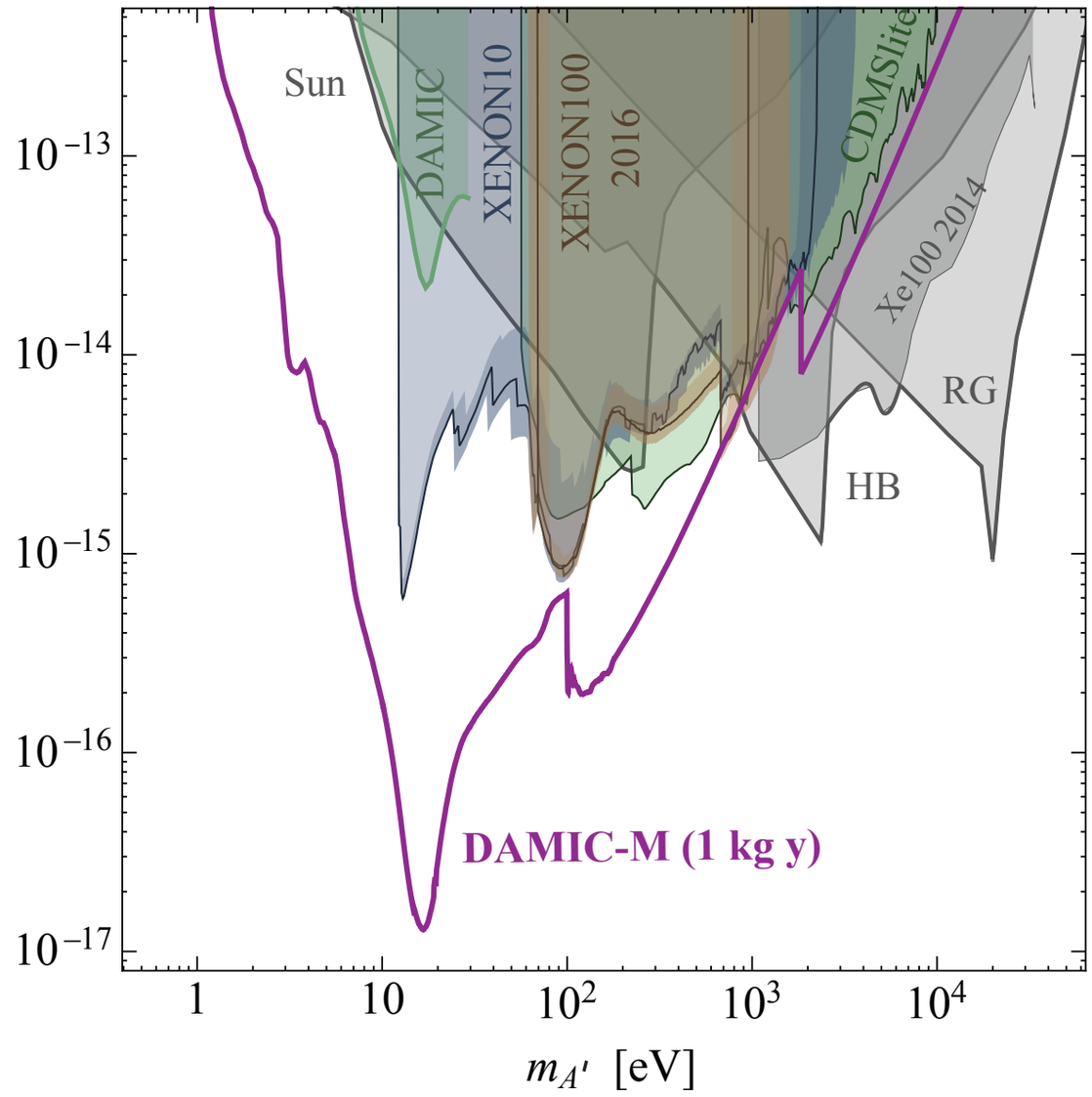
- Snolab —> **Modane**
- mass: 40g —> **1kg**
  more + larger CCDs
- Background: 5 —> **0.1 d.r.u**
  Very thorough component choice, gained experience
- Threshold: 10e- —> **1e-**
  Use of skipper CCD, integrated electronics

Scientific reach

WIMP nuclear recoil search

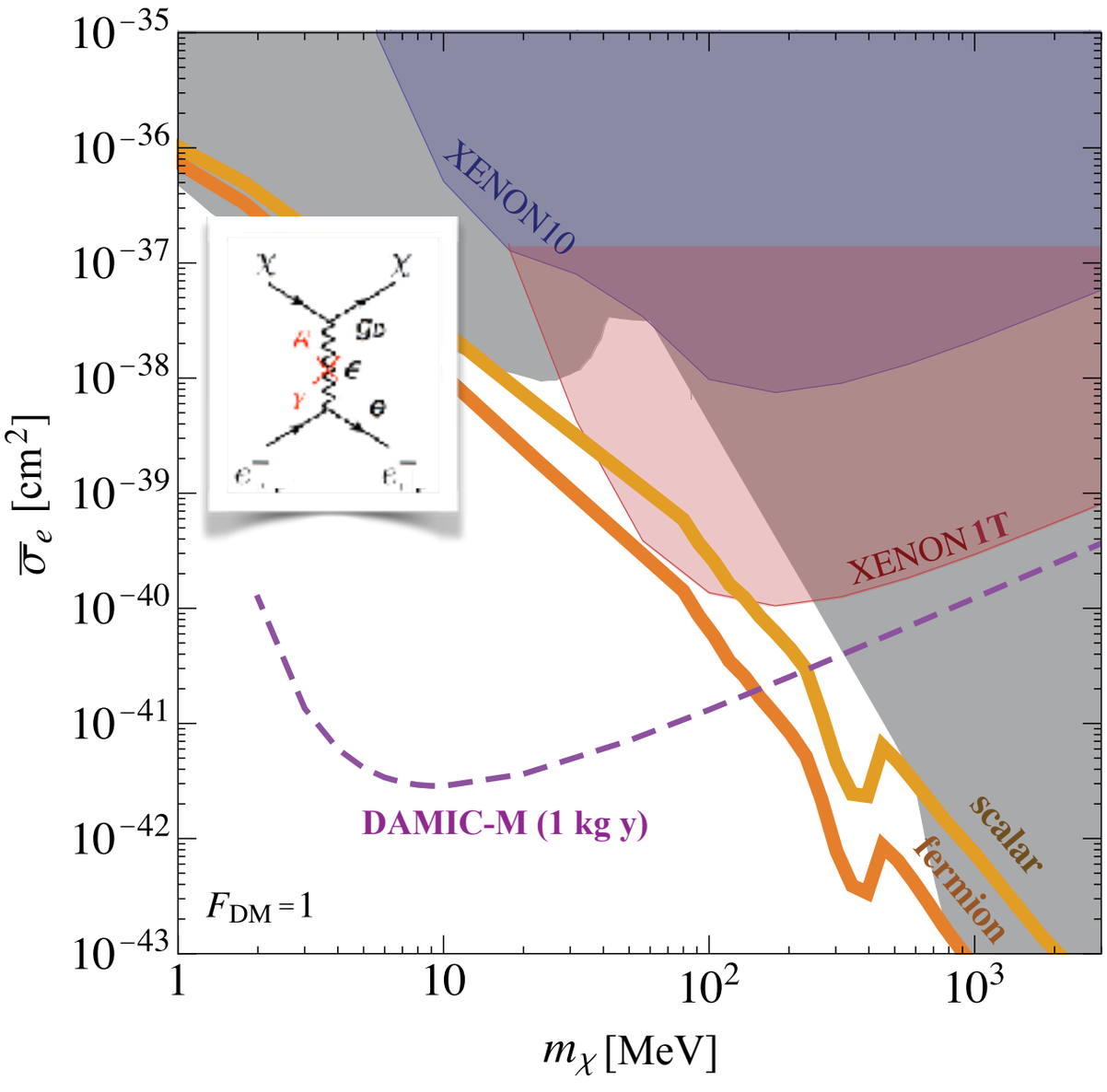


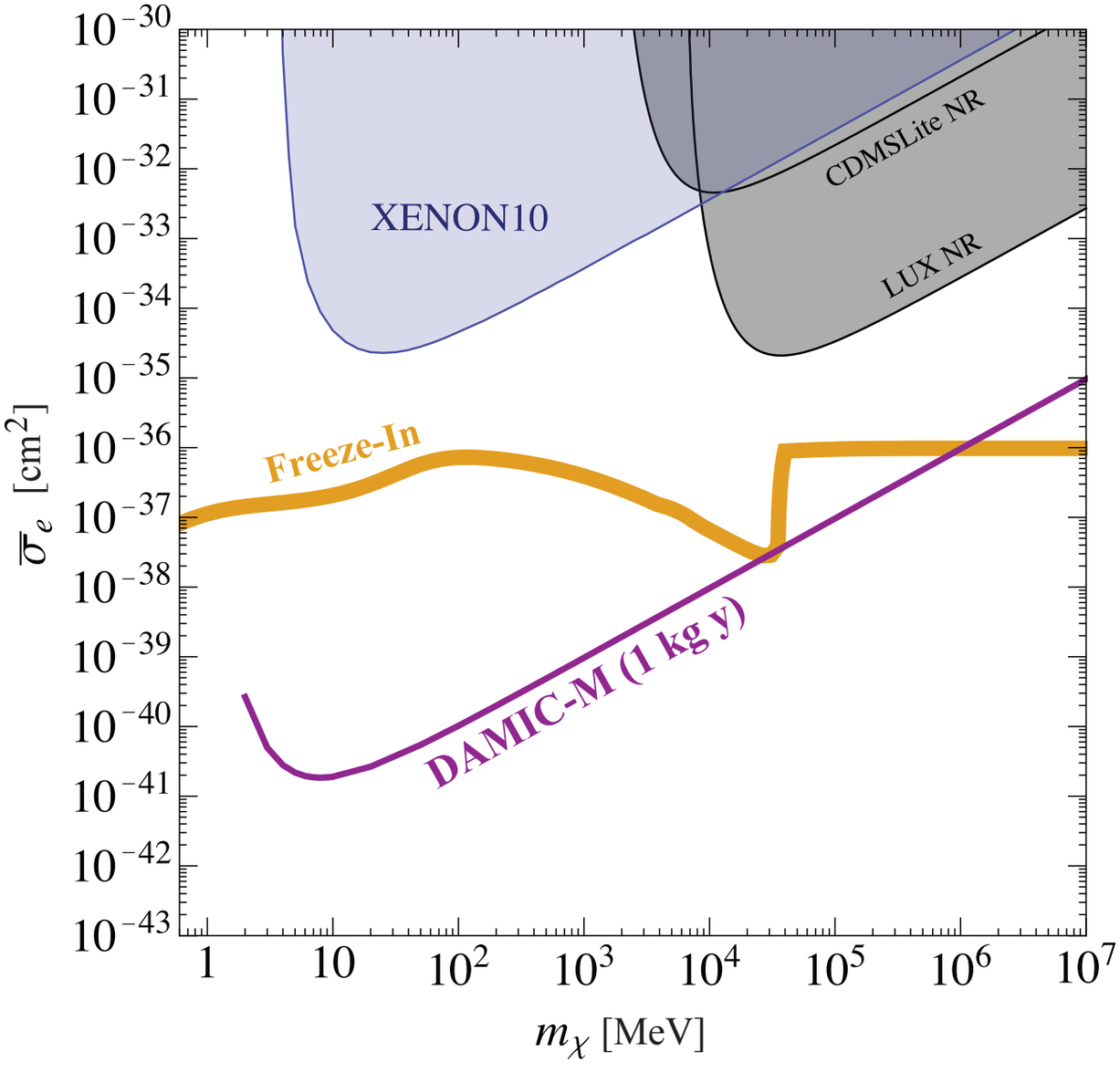
Hidden photon search



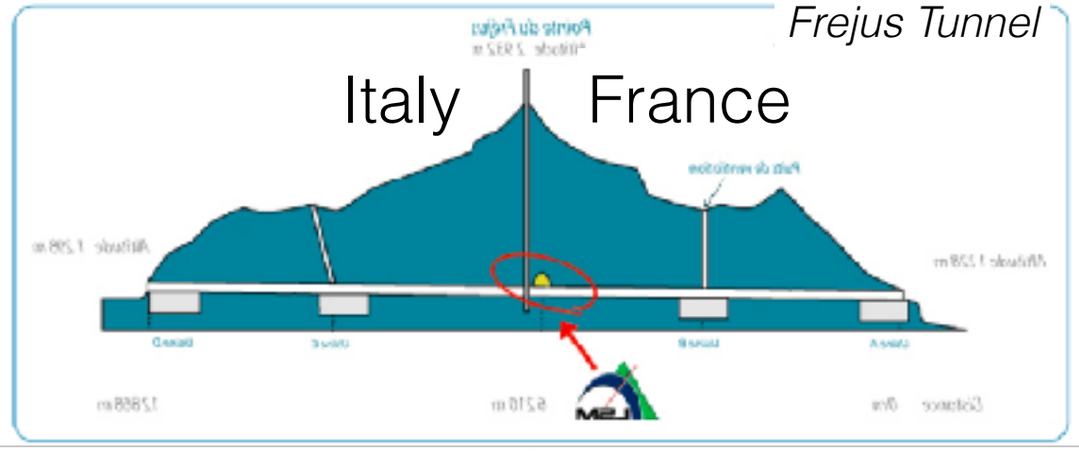
Scientific reach

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

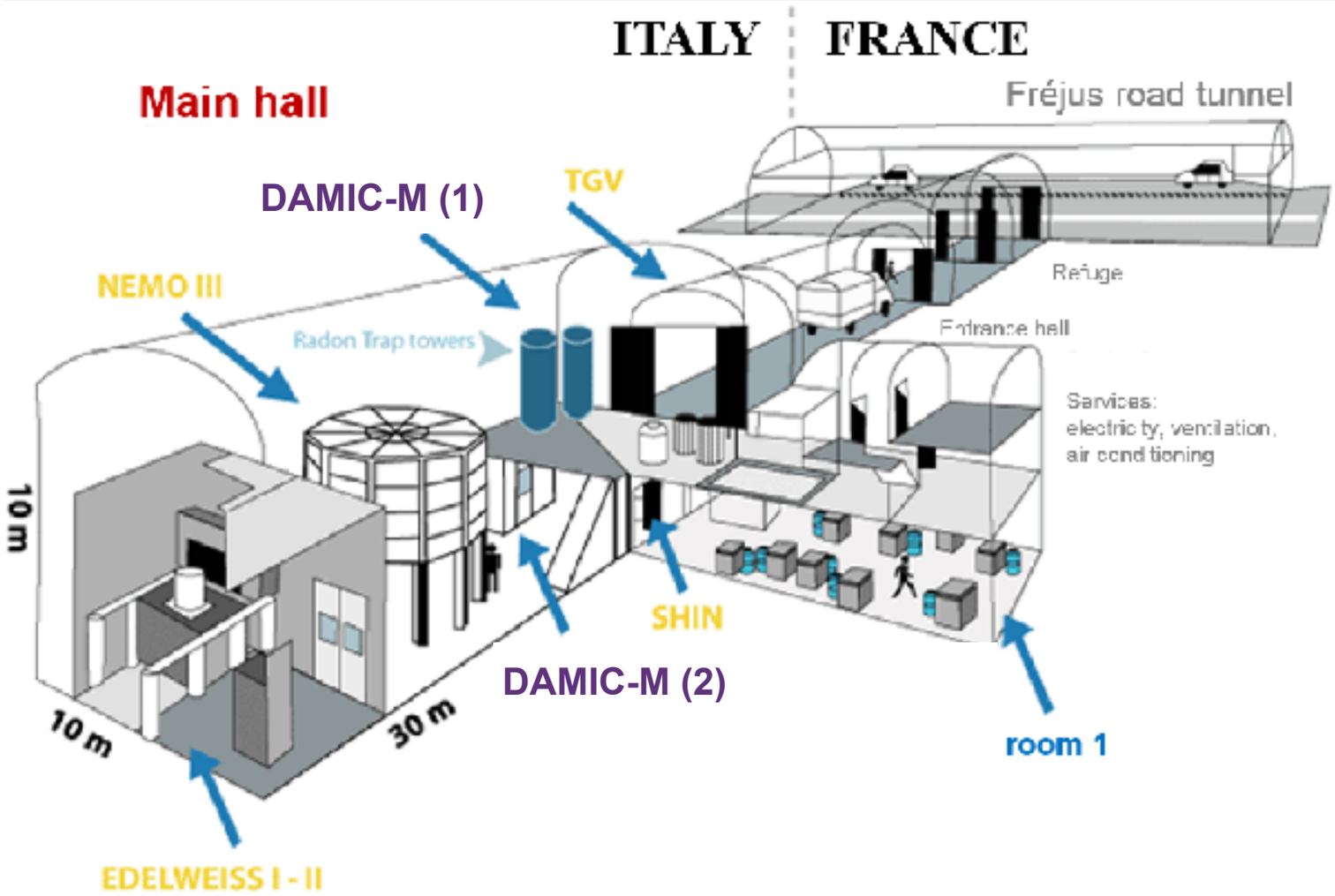




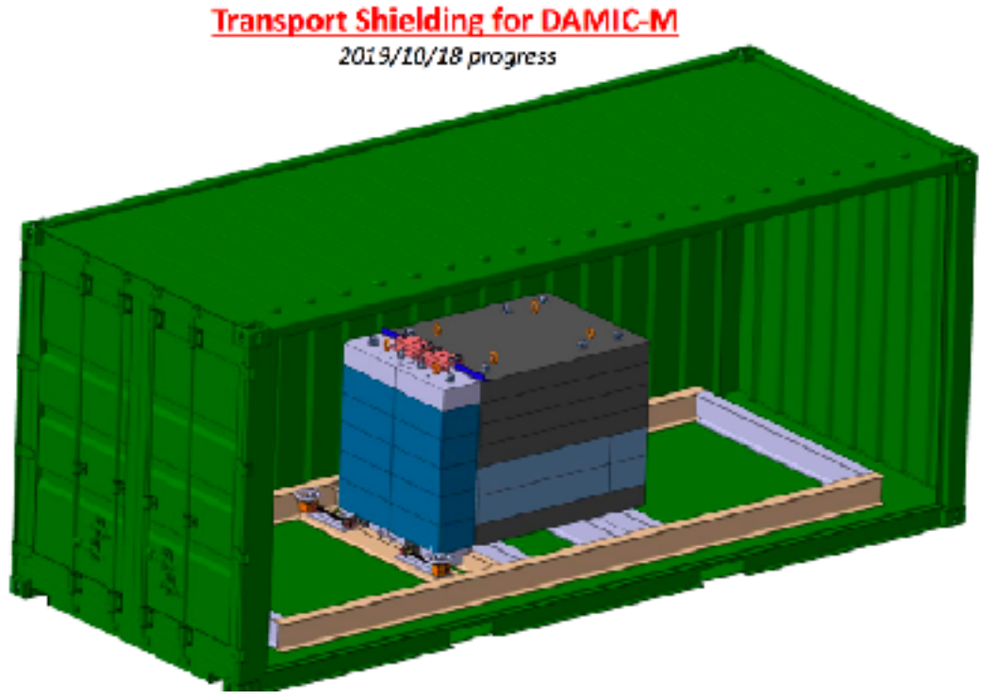
Laboratoire Souterrain de Modane



Frejus Tunnel



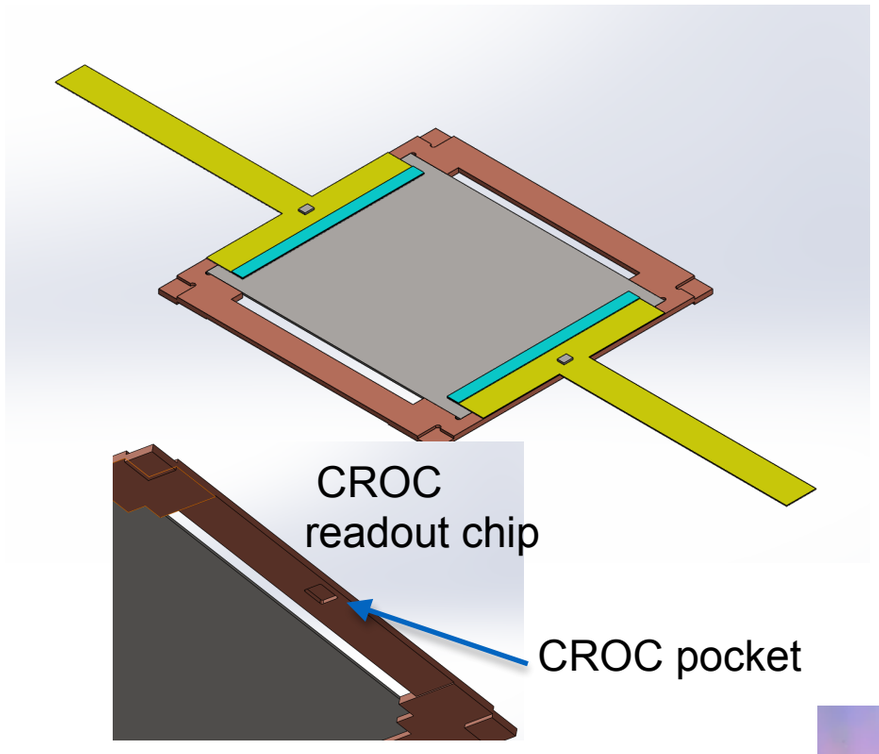
The precious ingot…

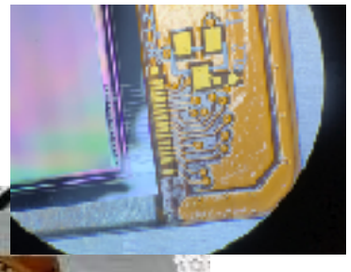


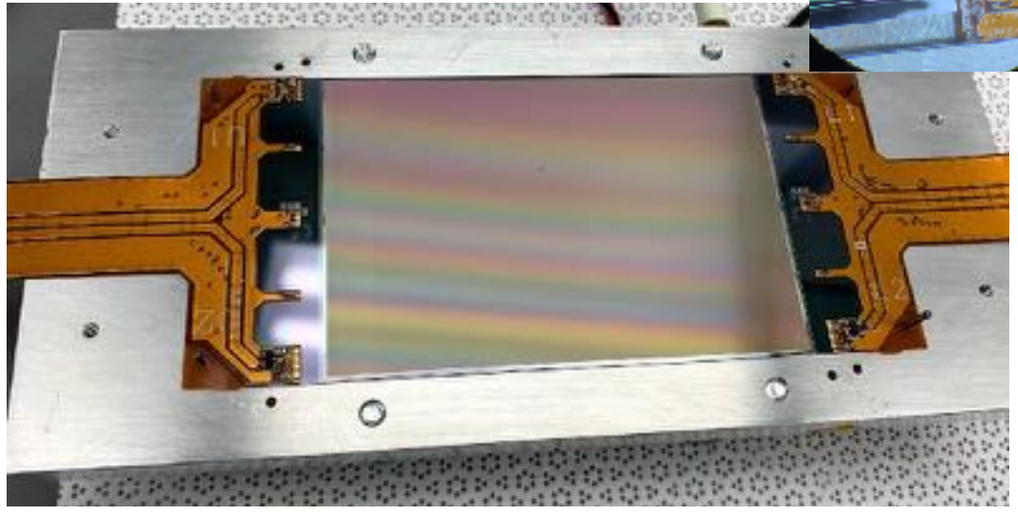
The whole history of the CCD is controlled
Cosmic ray and Radon are the ennemies !

Detector design

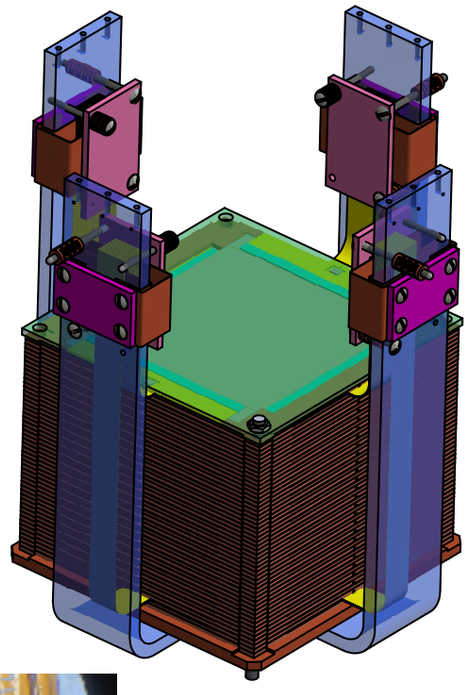
CCD + frame + flex

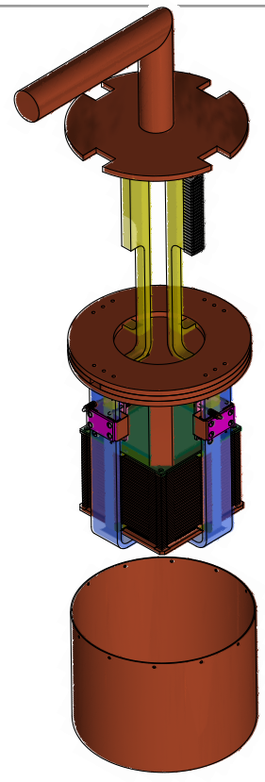






CCD tower



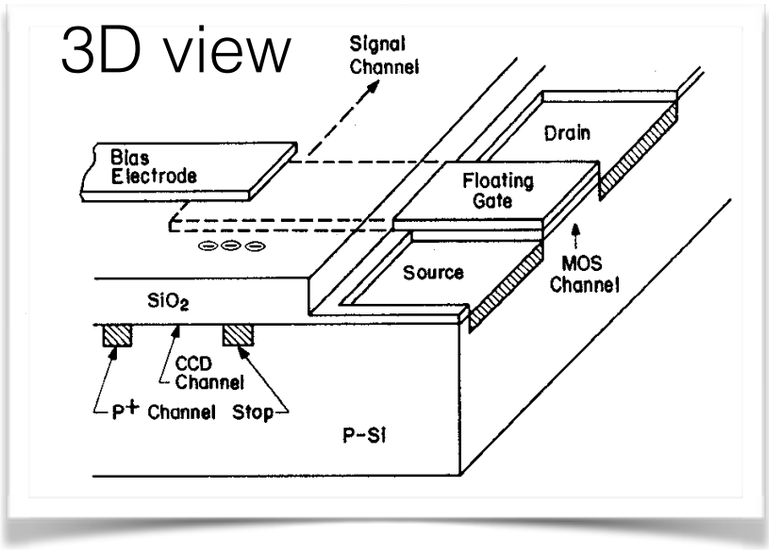


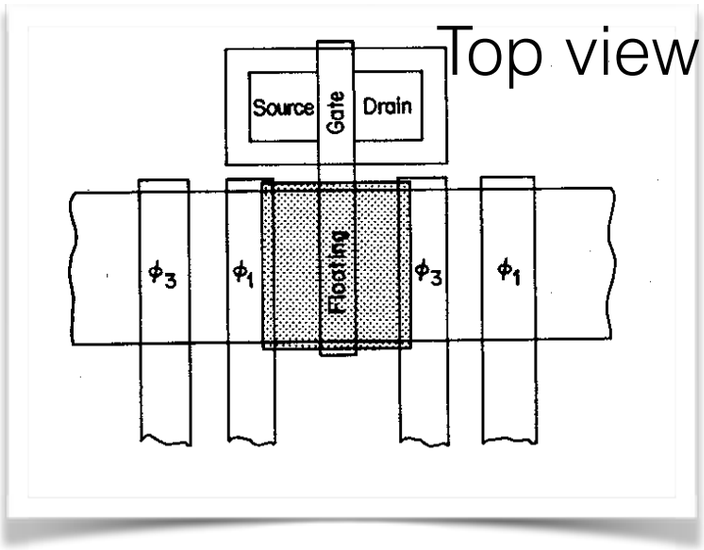
electro formed
copper at PNNL

- Design in fast progress
- CCD packaging improved for shorter CR exposition
- Choice of the cable (Kapton vs Coaxial) still under review

Skipper CCD

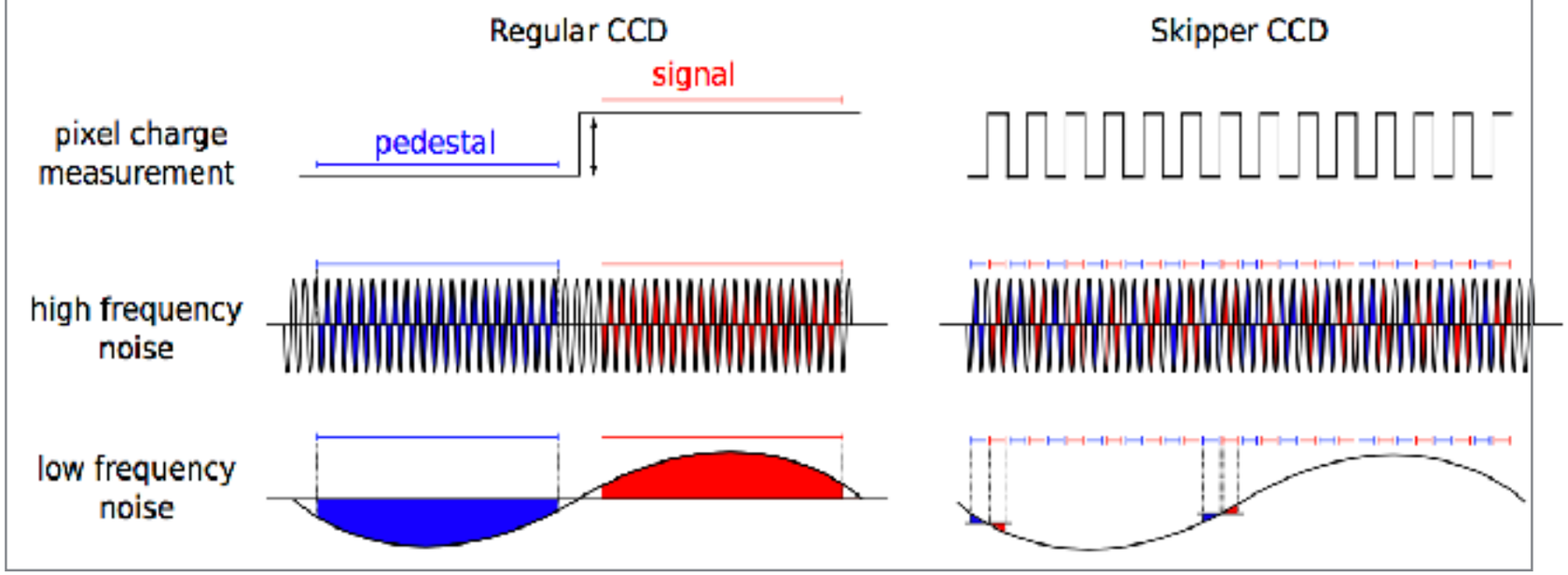
Floating gate amplifier



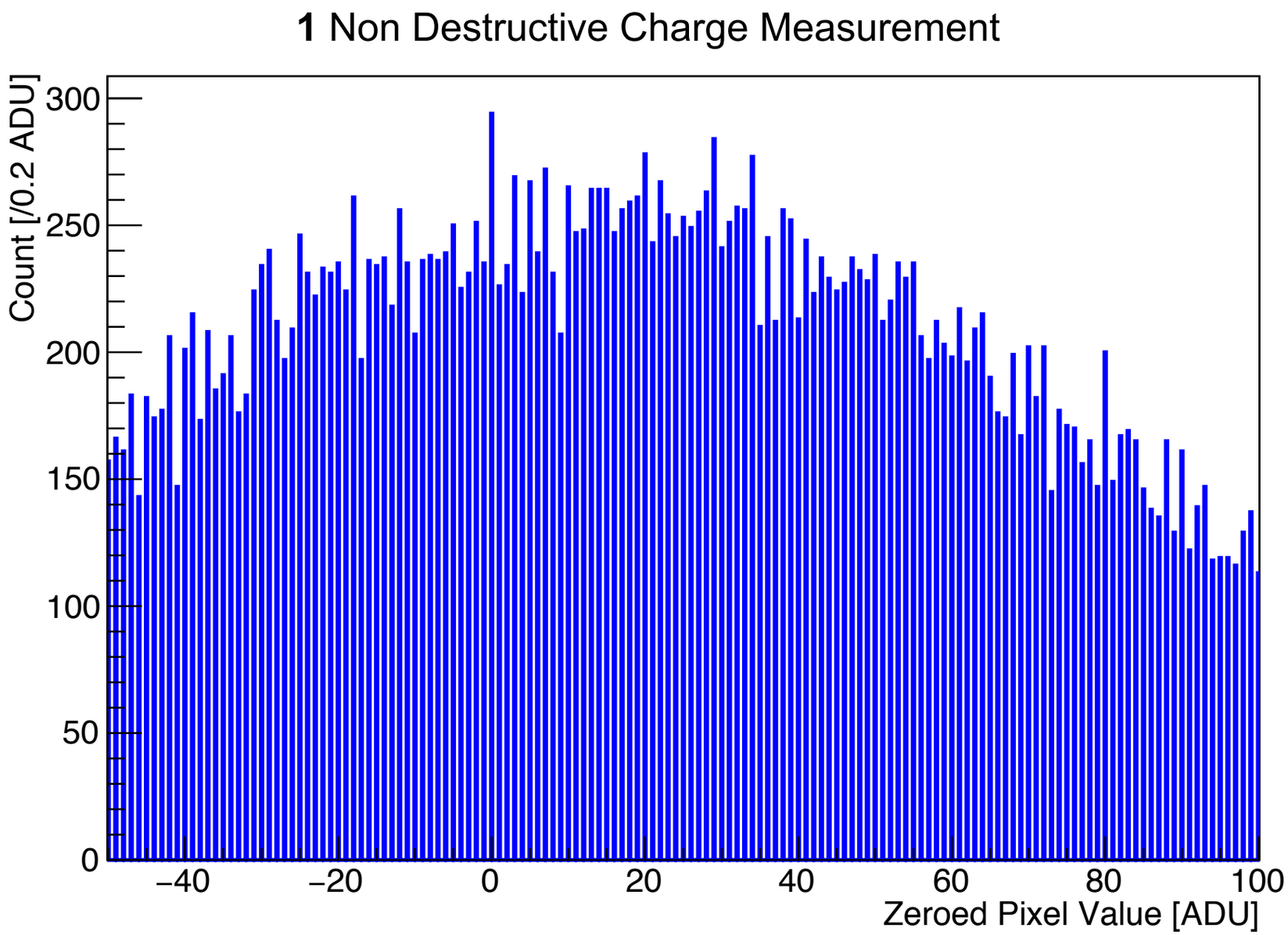


- Replace floating diffusion amplifier with floating gate *(Wen 1974)*
- Allows a *non destructive charge reading*
- **Kills white and 1/f noise**
- Successfully operated in 2017 *(Tieffenberg et al 2017)*
- Now also operated by DAMIC-M teams !!!

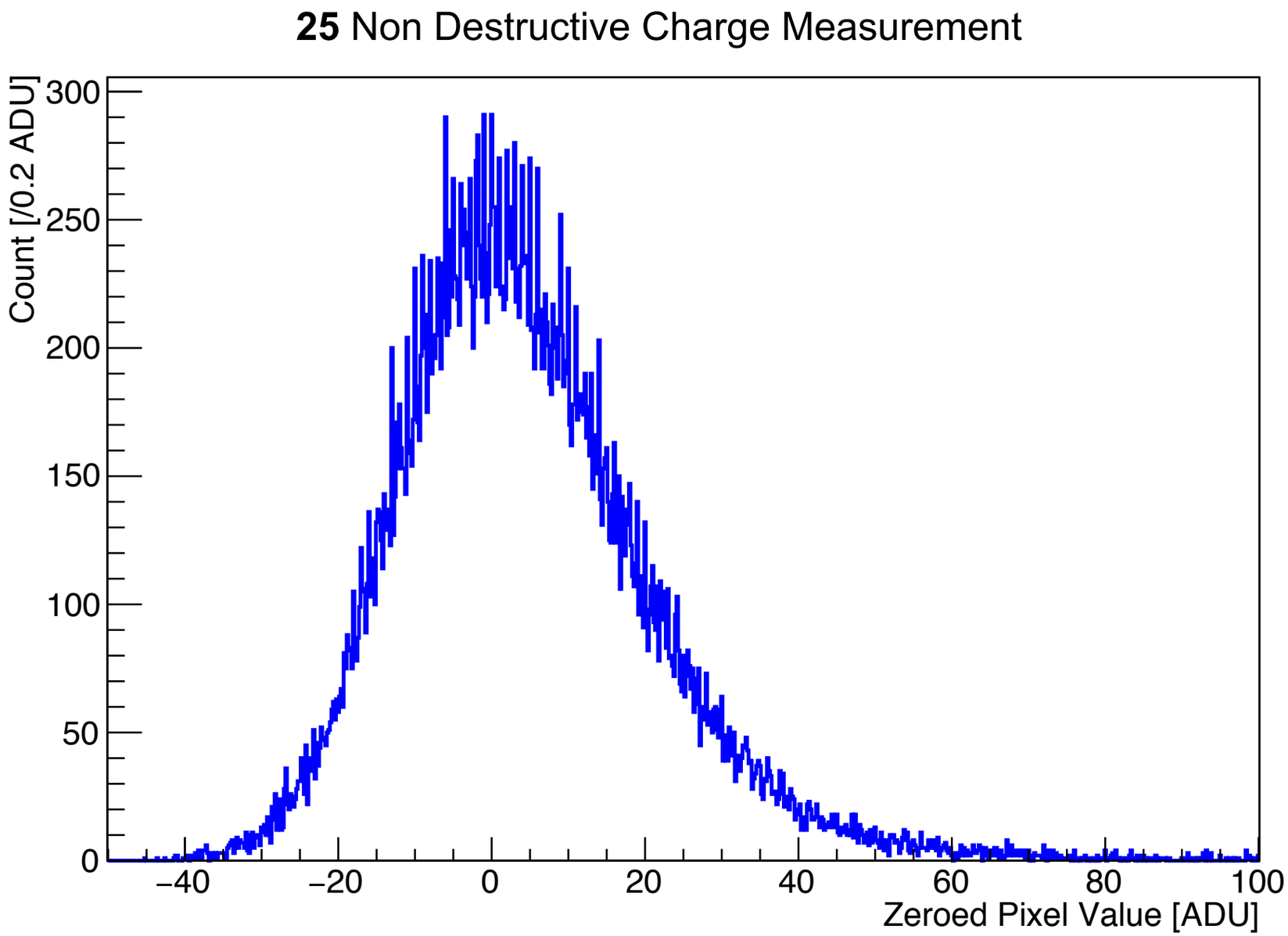
Comparison with regular CCD



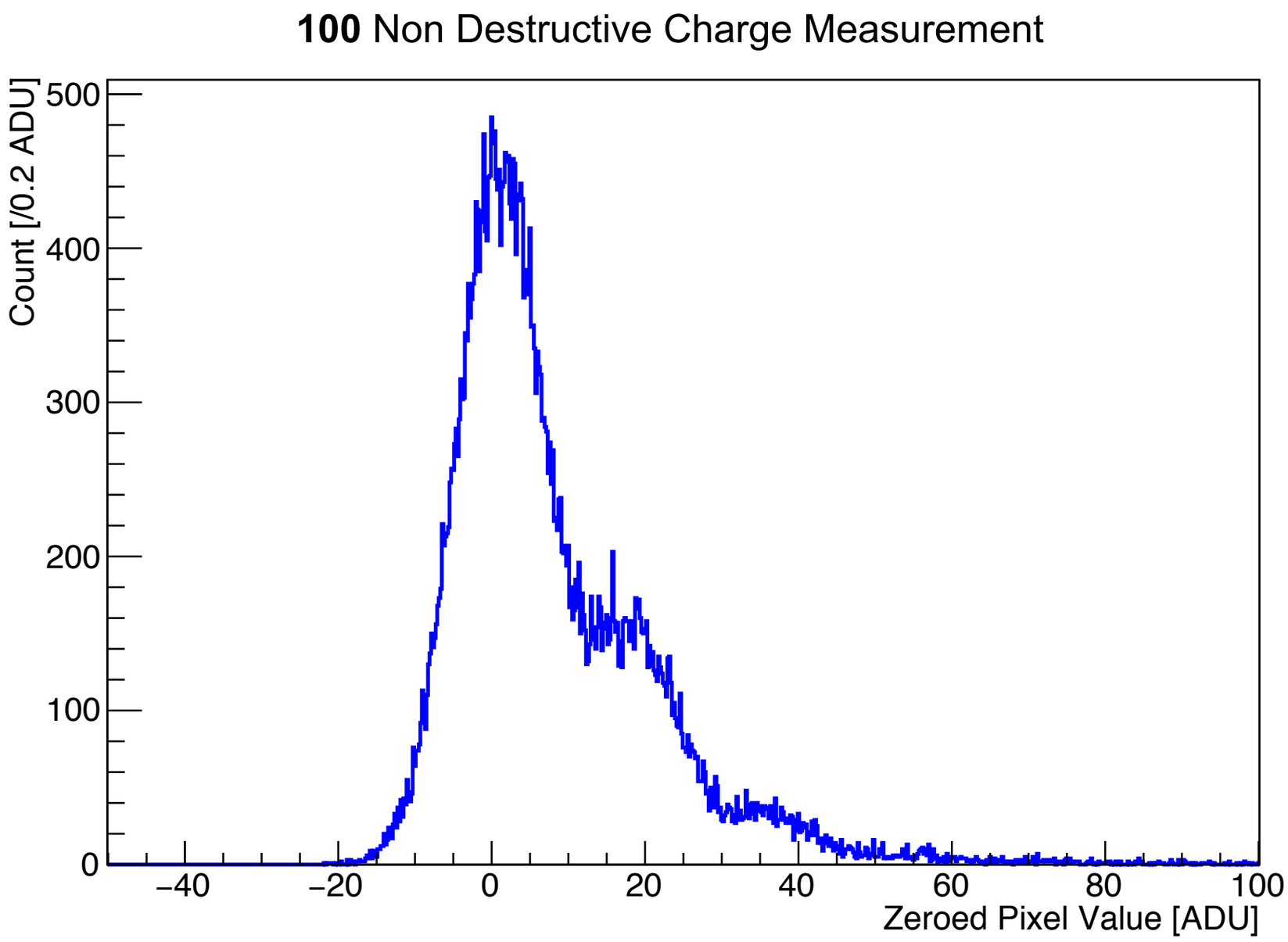
Skipper CCD charge resolution



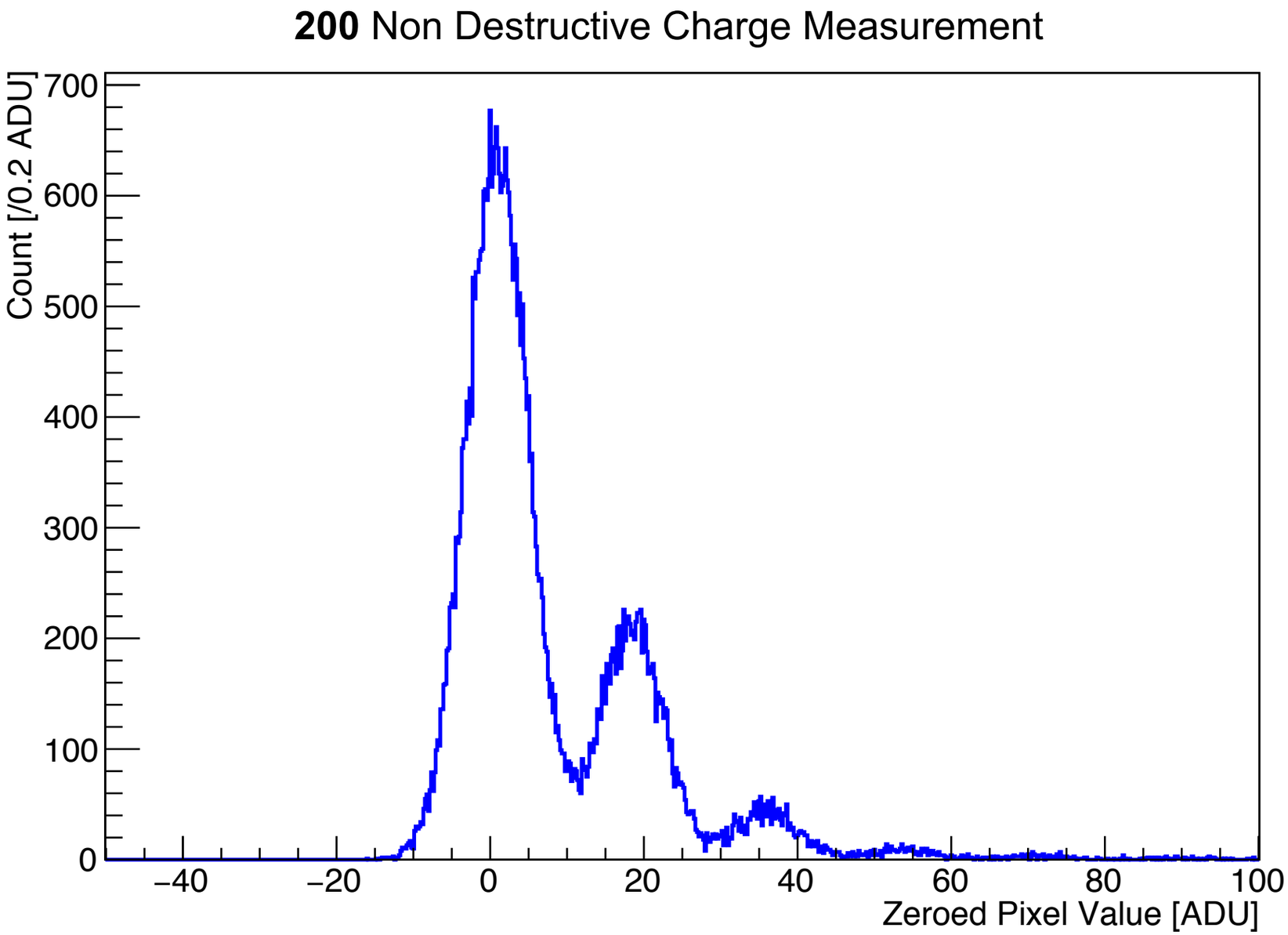
Skipper CCD charge resolution



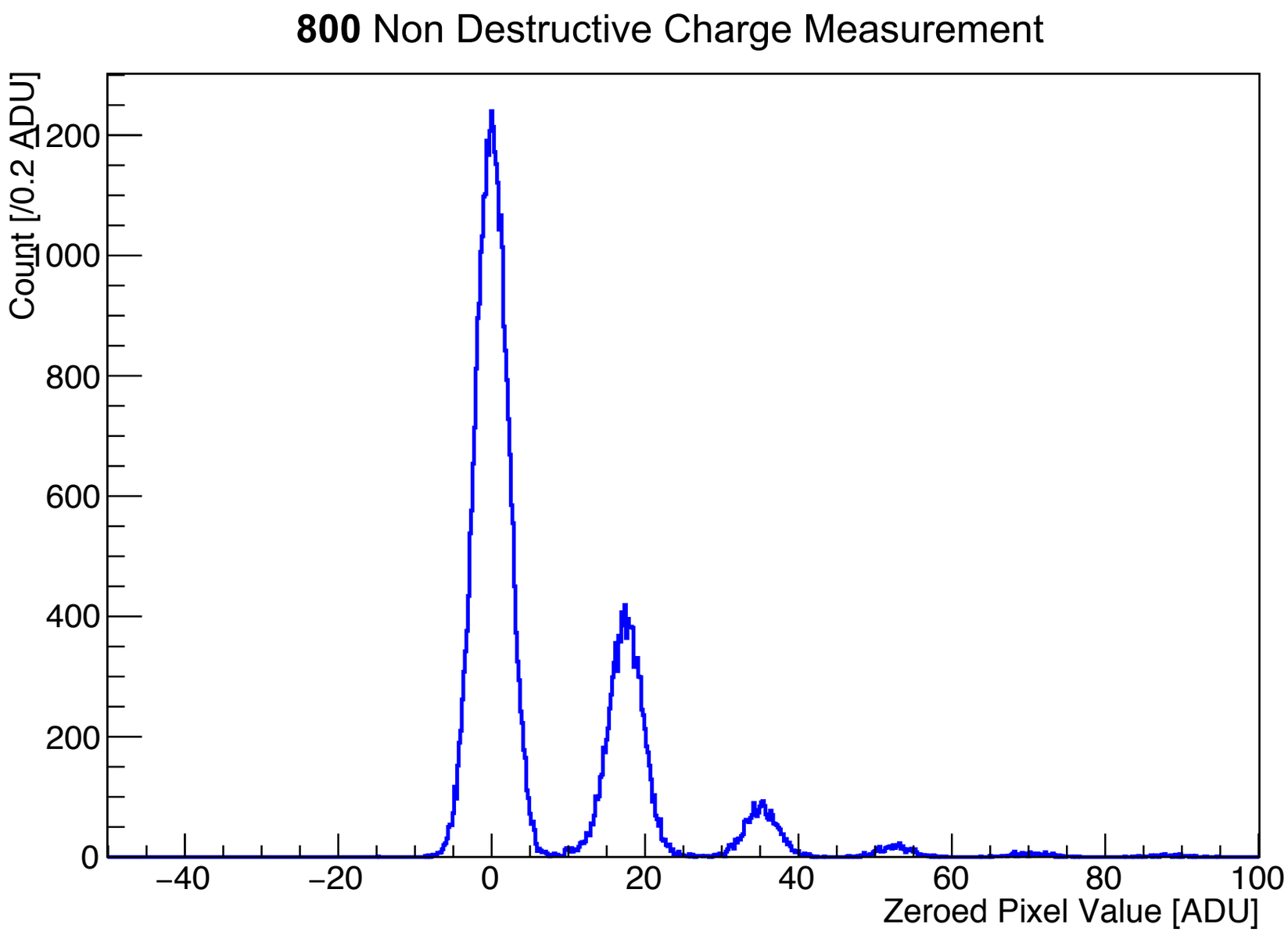
Skipper CCD charge resolution



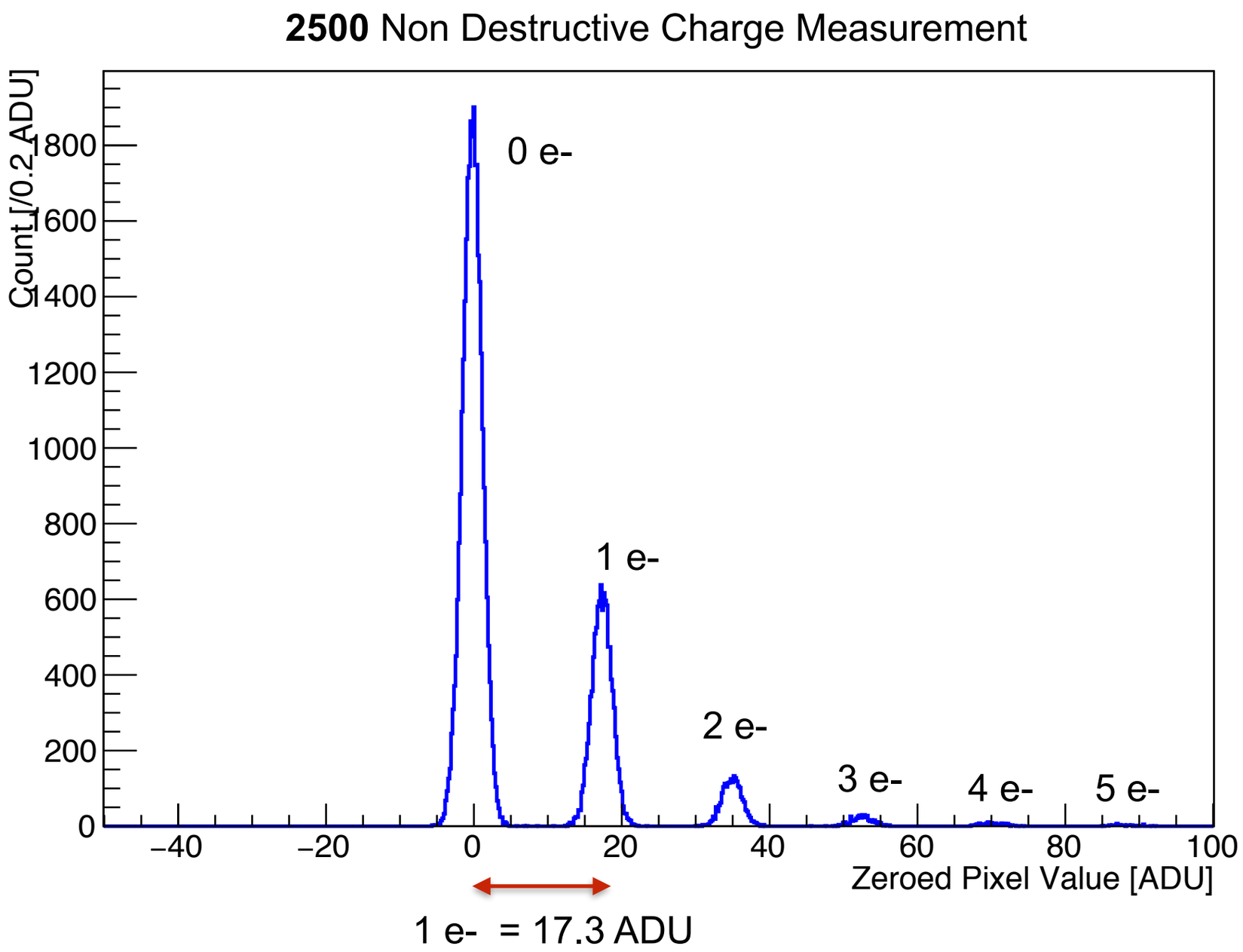
Skipper CCD charge resolution



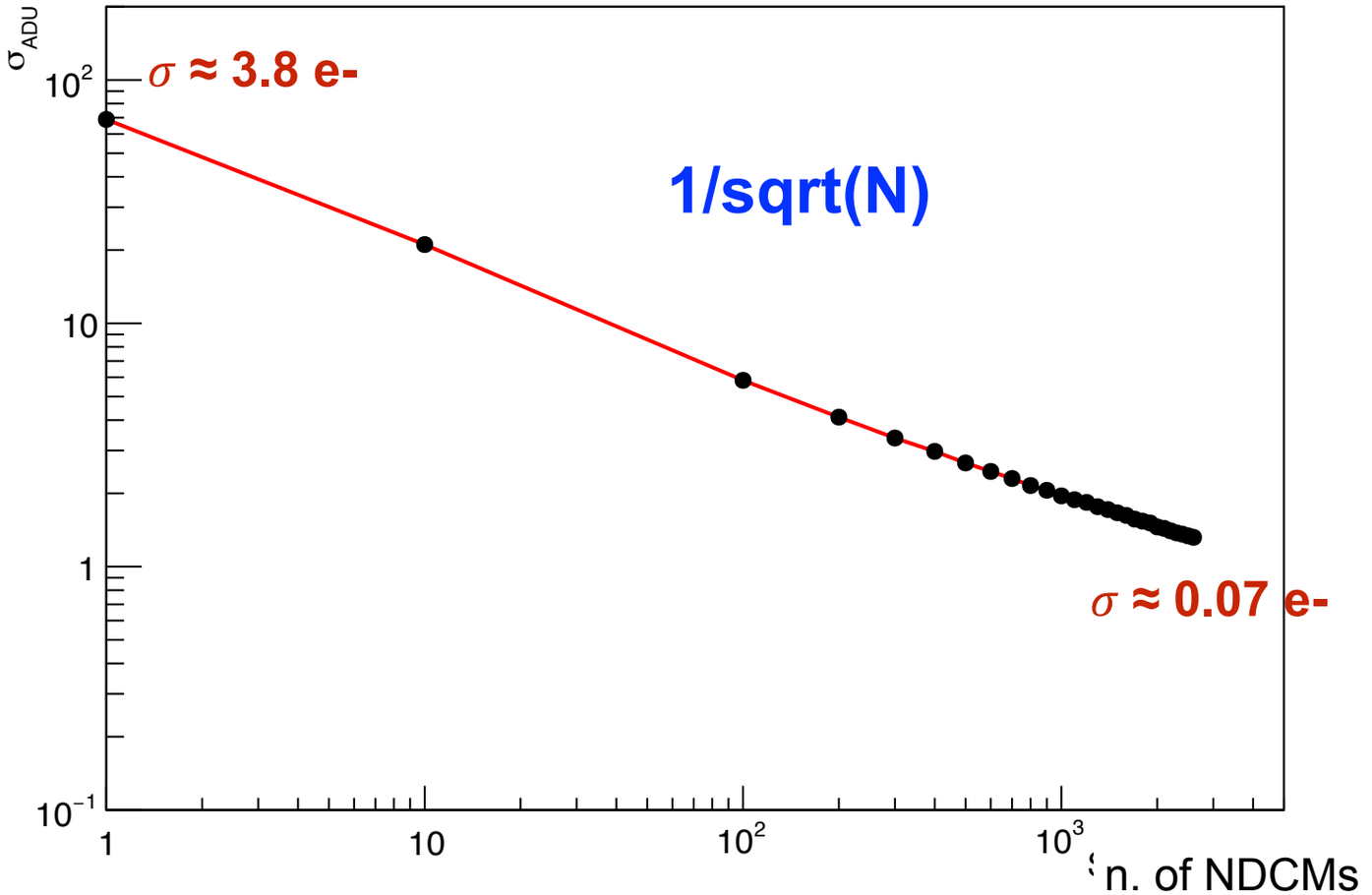
Skipper CCD charge resolution

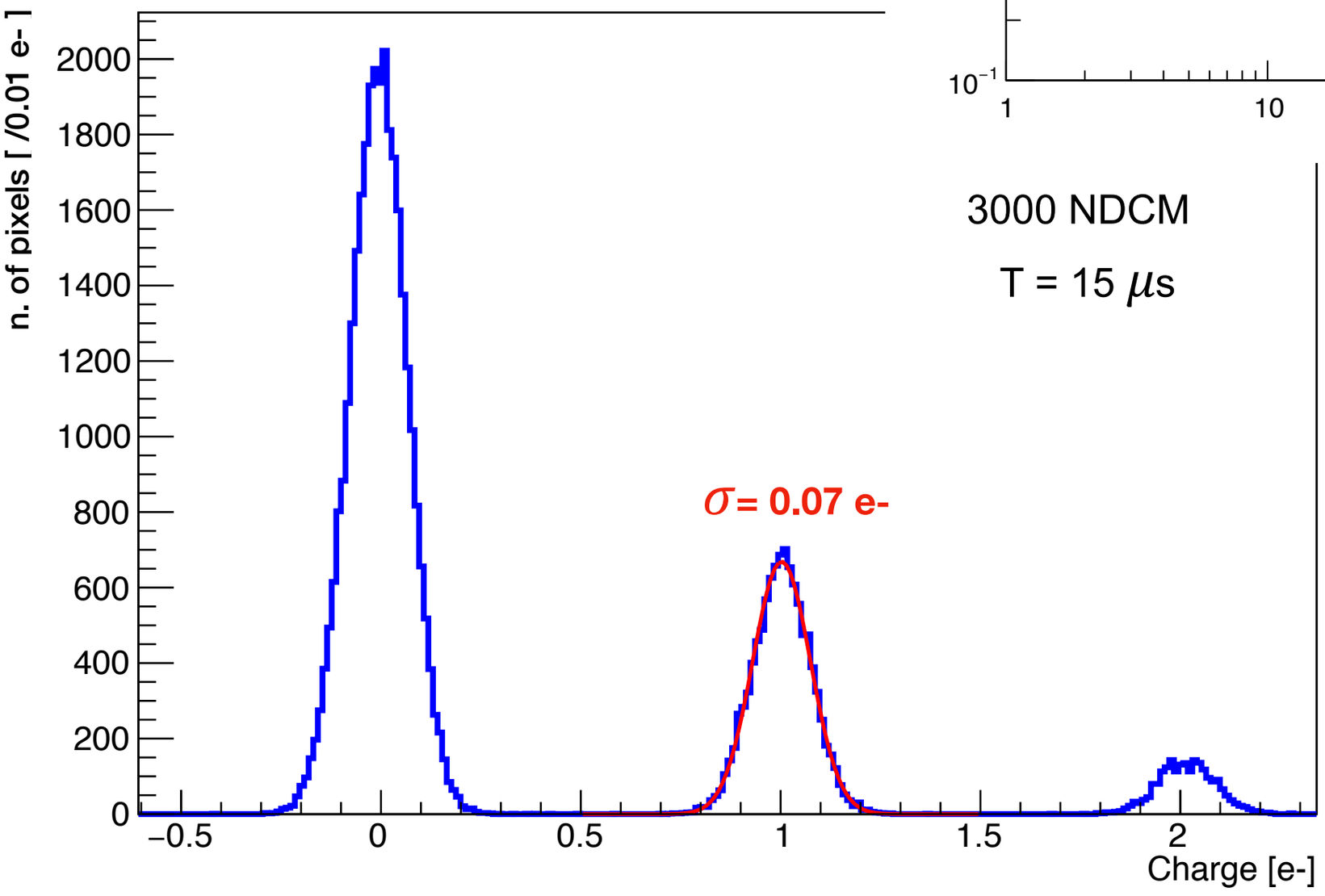


Skipper CCD charge resolution

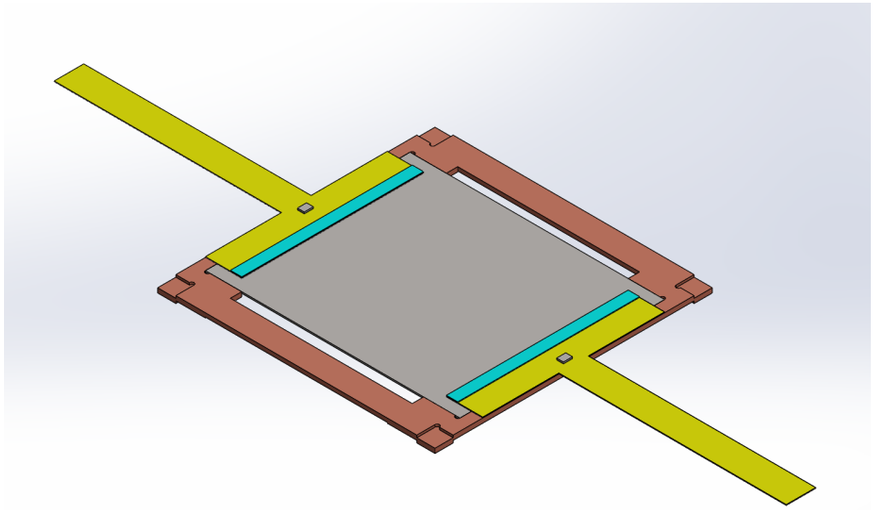


Single electron resolution obtained for a wide range of integration times (T = 2 - 20 μs) allowing optimization with respect to electronics noise





DAMIC-M electronics

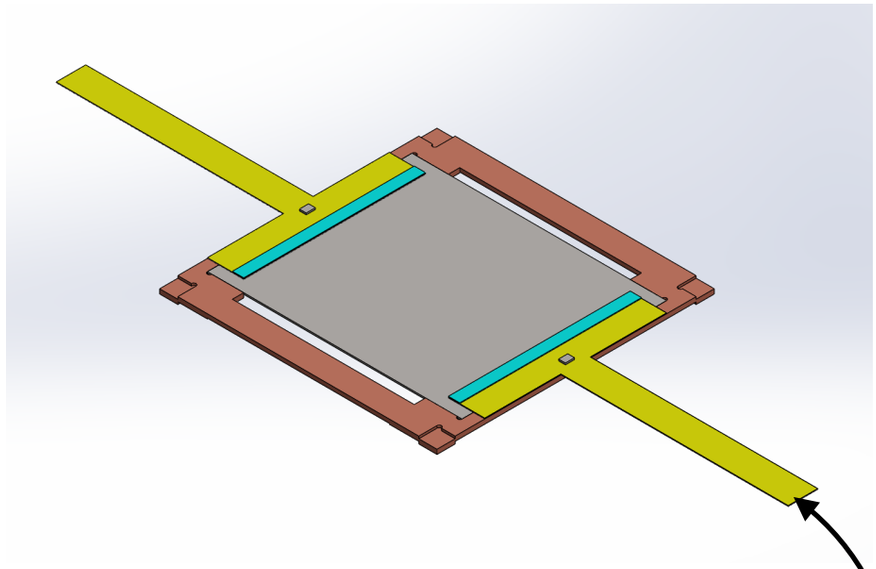


- Current electronics is commercial is:
  - physically big
  - not easily customisable
  - ~ 20k per CCD…

  (I let you multiply by 50)

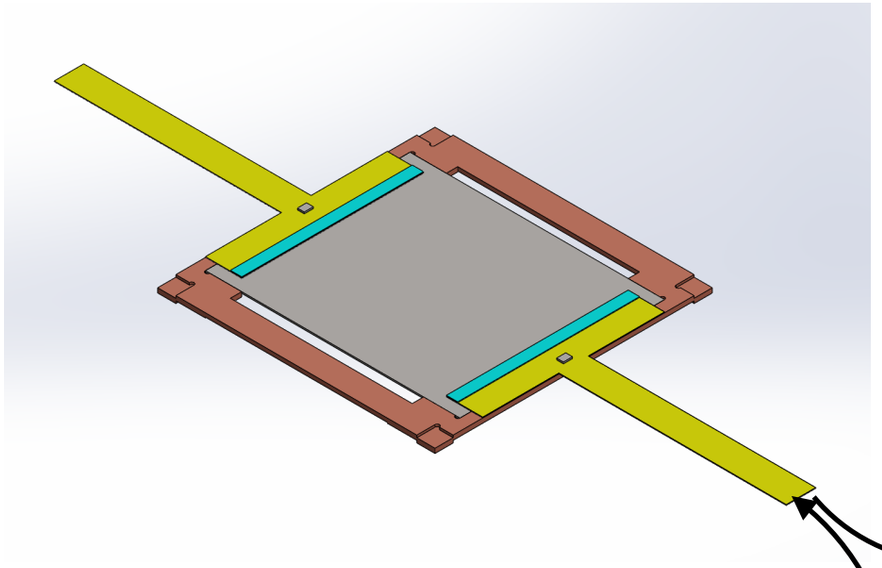
- LPNHE (Paris) has experience in the CCD electronics
  - ASPIC chip in LSST
  - CABAC chip (designed for LSST but didn’t make it to the final detector)
  - CCD testing

DAMIC-M electronics



<u>Clocking</u>:
Charge transfer
Amplifier sequence timing
CABAC chip

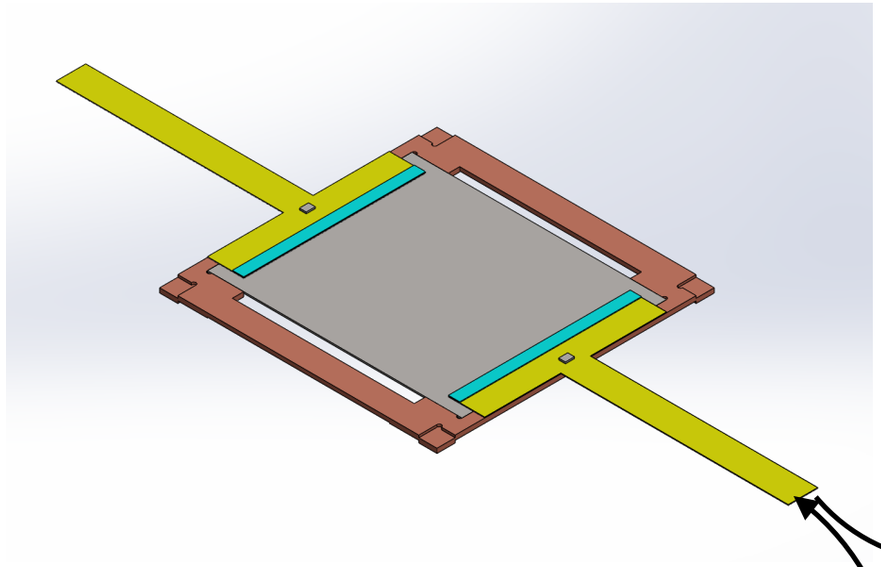
DAMIC-M electronics



<u>Readout:</u>
Amplification
Dual slope integration
CROC chip

<u>Clocking</u>:
Charge transfer
Amplifier sequence timing
CABAC chip

DAMIC-M electronics

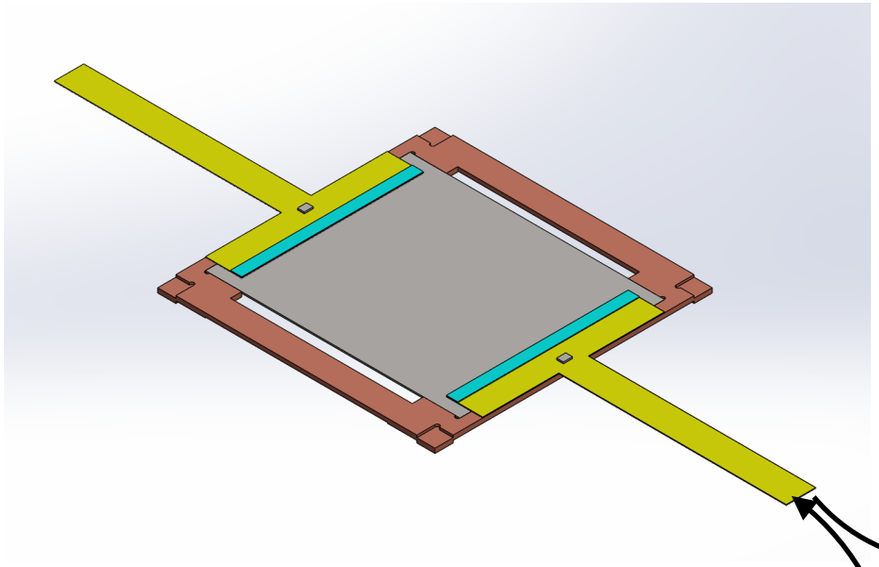


<u>Readout:</u>
Amplification
Dual slope integration
CROC chip

<u>Clocking</u>:
Charge transfer
Amplifier sequence timing
CABAC chip

<u>ADC</u>
Sample each charge meas.
(16bits 1MS/s)
or
Oversample each charge meas. (18bits 15MS/s)

DAMIC-M electronics



<u>Readout:</u>
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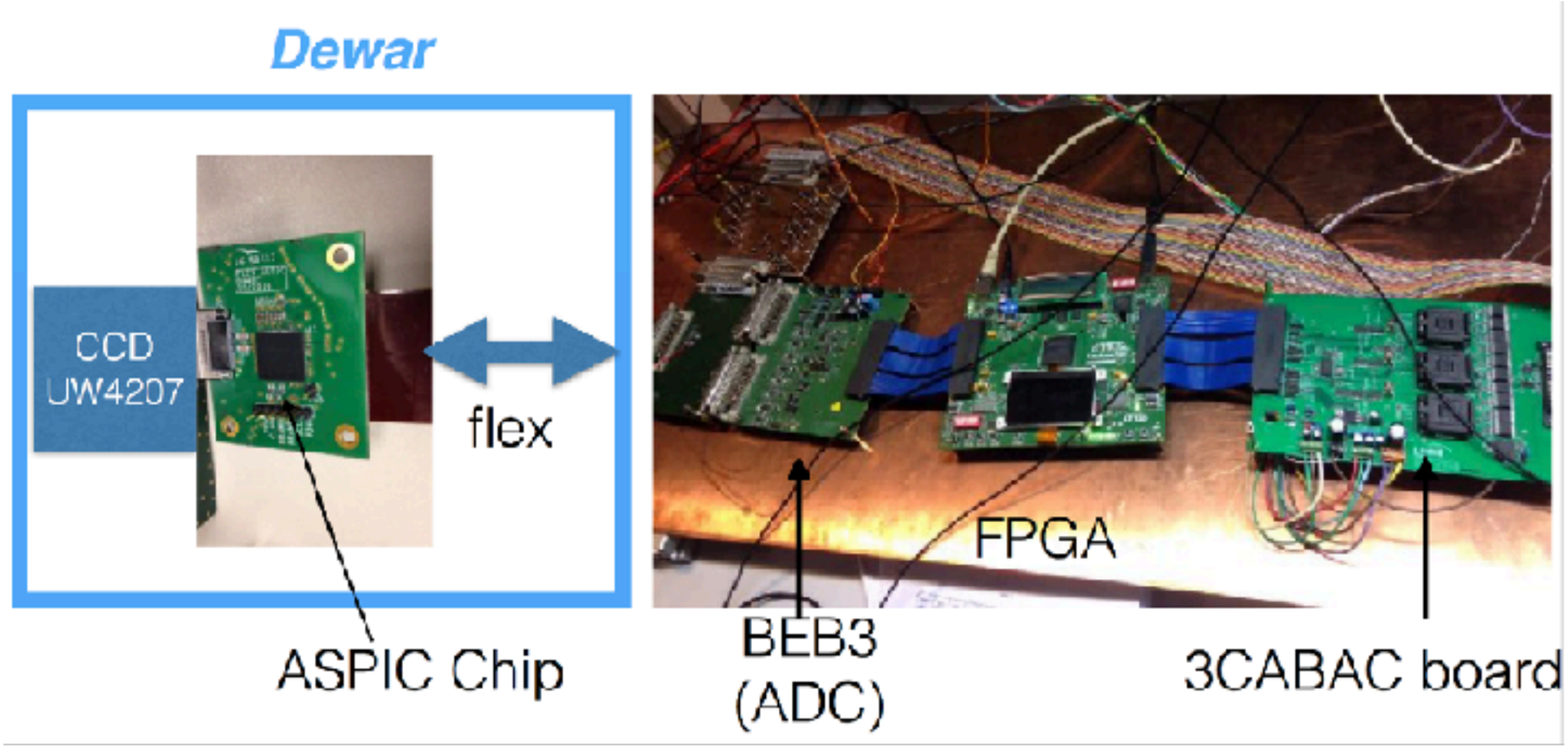
Charge transfer
Amplifier sequence timing
CABAC chip

<u>ADC</u>
Sample each charge meas.
(16bits 1MS/s)
or
Oversample each charge meas. (18bits 15MS/s)

Mother board: *ODILE*

DAMIC-M electronics

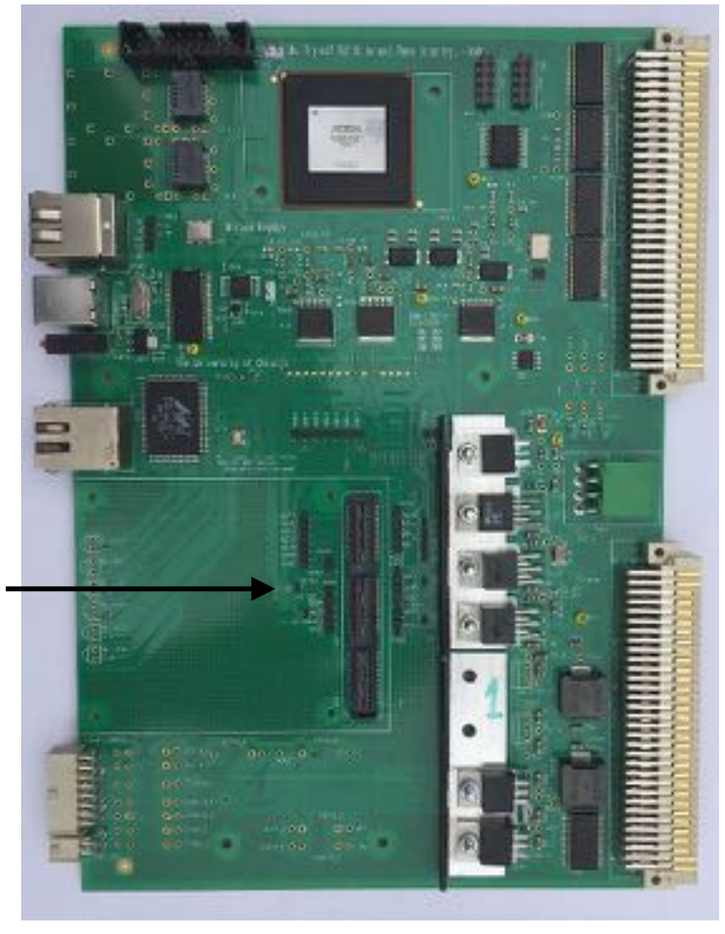


- A first version of the integrated electronics has operated successfully !!!
- …it was with previously developed elements (readout chip and ADC)
- New version will be operating in 2 months gurai

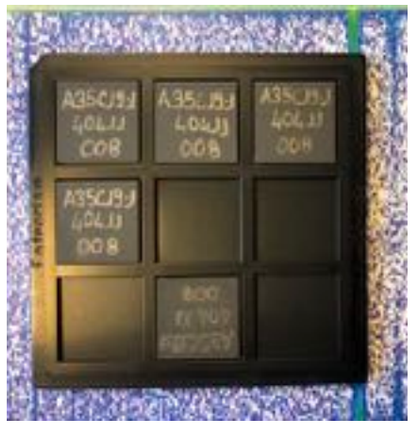
DAMIC-M electronics

ADC

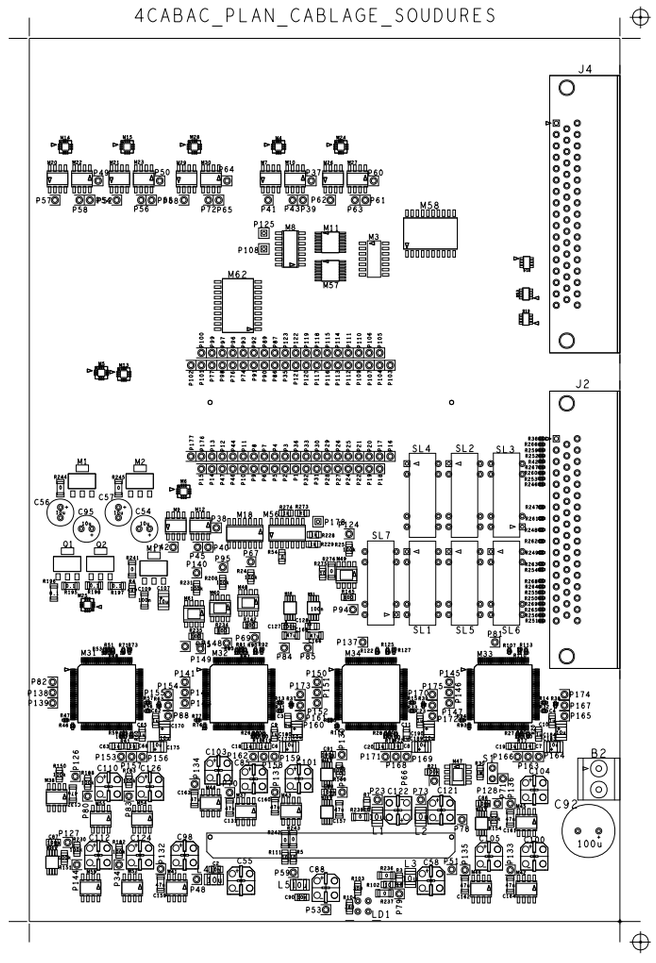
Odile (Mother Board)



CROC



4CABAC



- Very exciting phase where things come together ! Lot of work ahead !
- New version of the CROC, Fast ADC will also come next year

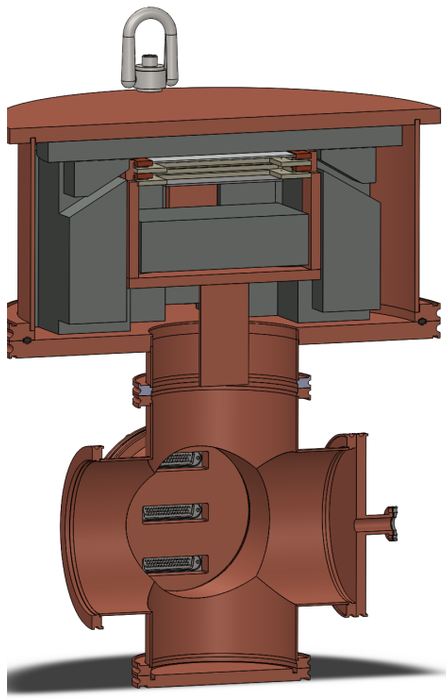
DAMIC-M timeline

R & D / optimisation

Construction

Installation

2020 2021 2022 2023



- 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

Conclusions

- **CCD are innovative DM detector**

- **DAMIC at Snolab** ends its science data taking and will release result soon: background studies / WIMP search

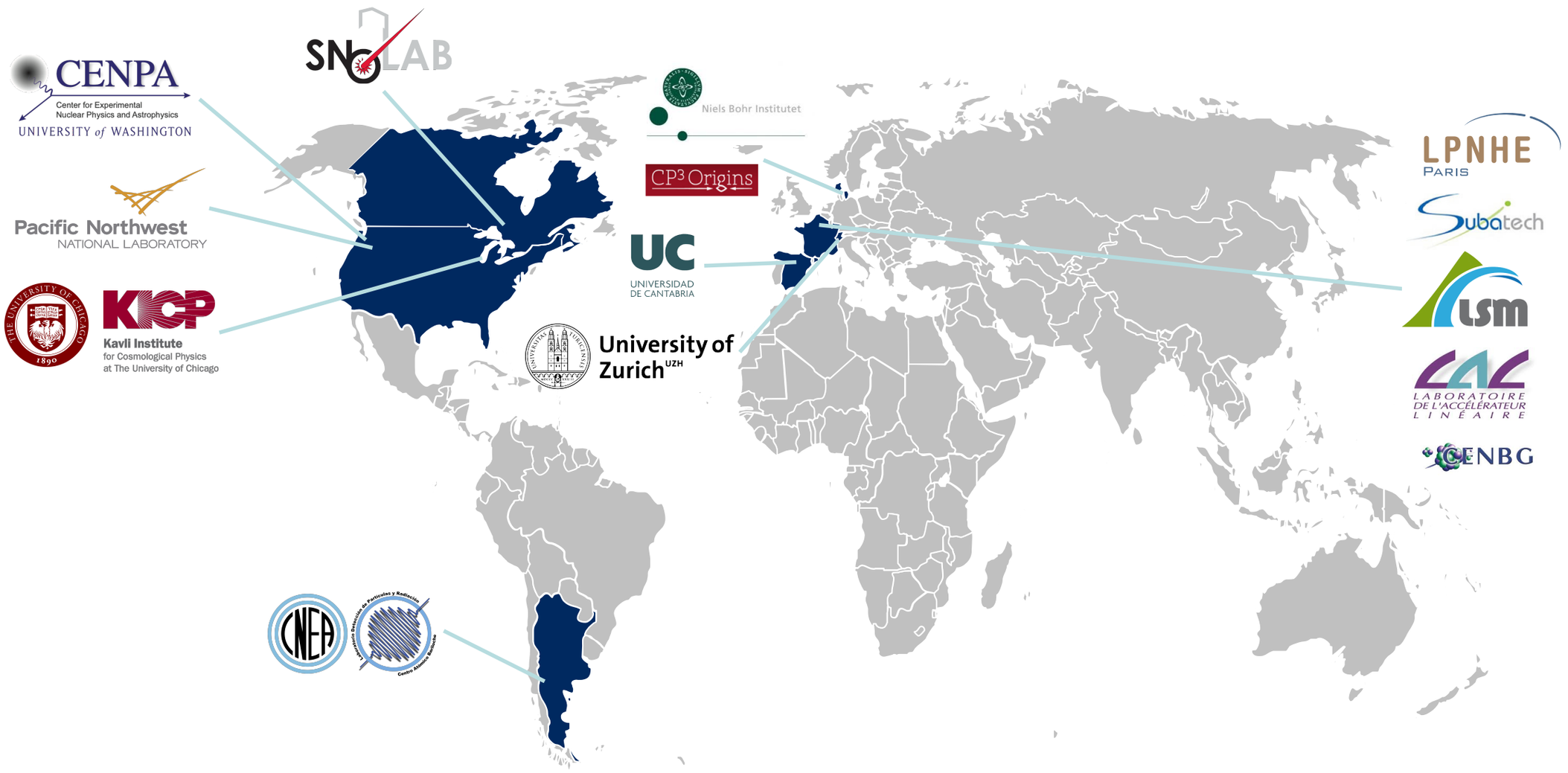
- **DAMIC-M:**

  - Major milestone: Ingot production, single electron resolution on large CCD

  - Many Progresses in: detector design, electronics, low background

  - in 2020: Clean room installation in LSM, CCD pre-production, installation of a test low background chamber

DAMIC-M Collaboration



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