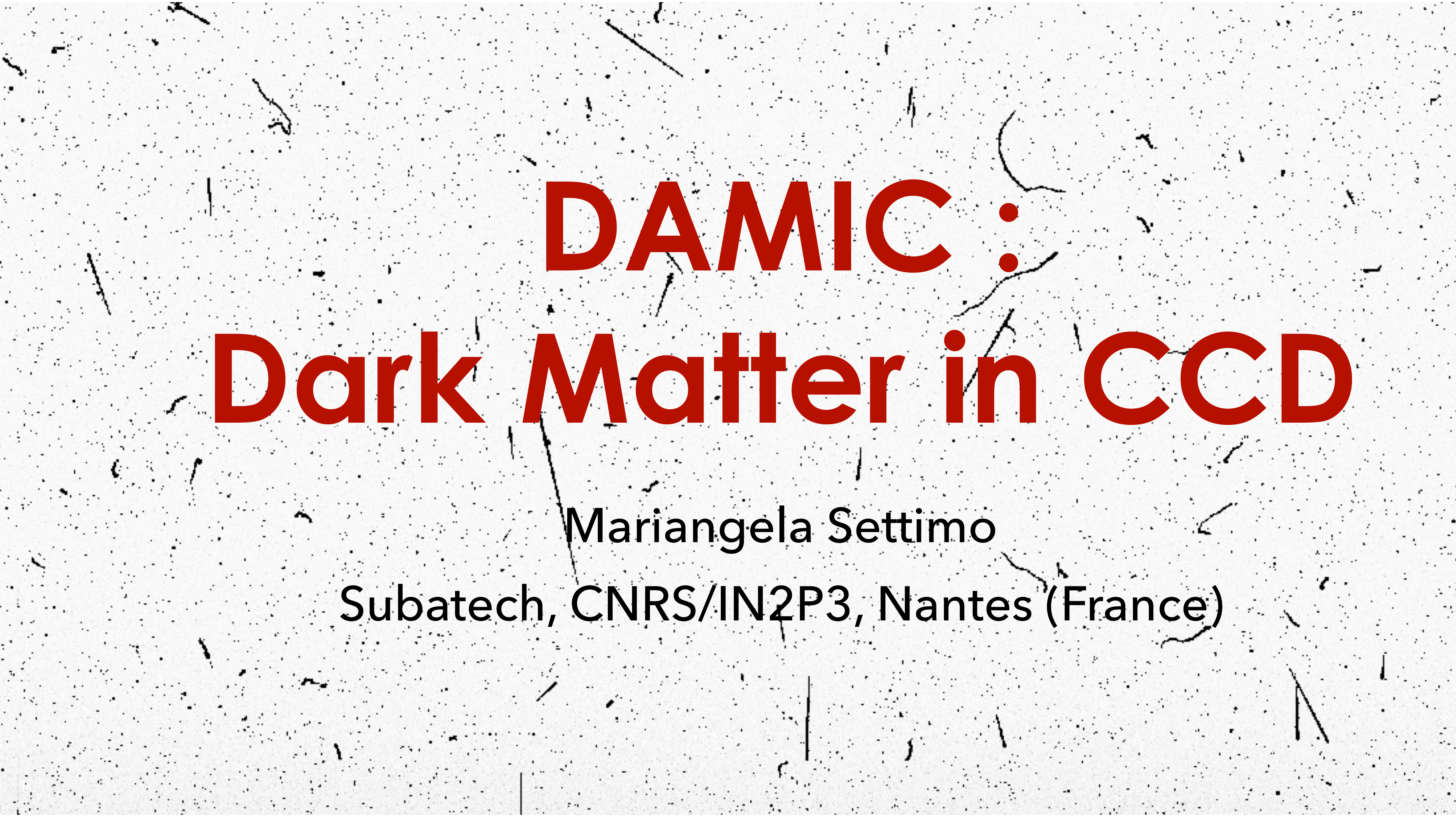


DAMIC : Dark Matter in CCD

Mariangela Settimo

Subatech, CNRS/IN2P3, Nantes (France)

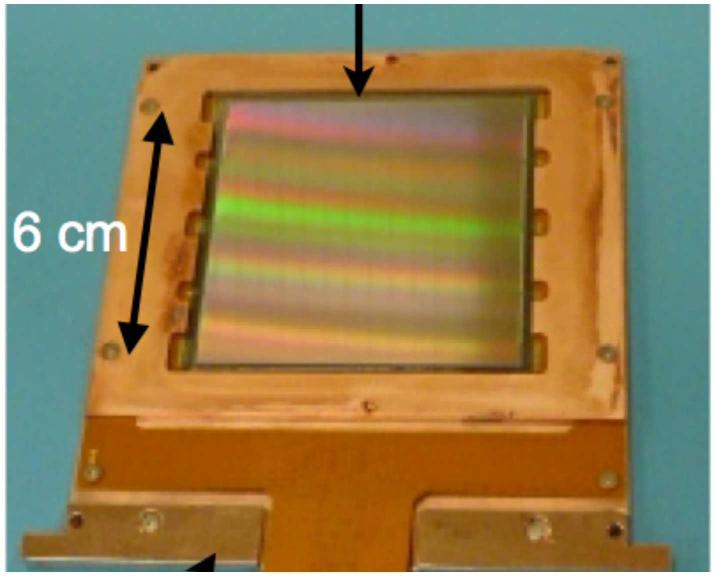
DArk **M**atter **I**n **C**CD

Charge-coupled device (CCD) as particle detectors

Conventional use: Light

Image sensors
~ 10-20 um thick CCD

Unconventional use: dark matter



Fully depleted, high-resistivity
16Mpix, 15 µm x15 µm,
650 µm thick, 5.9 g mass

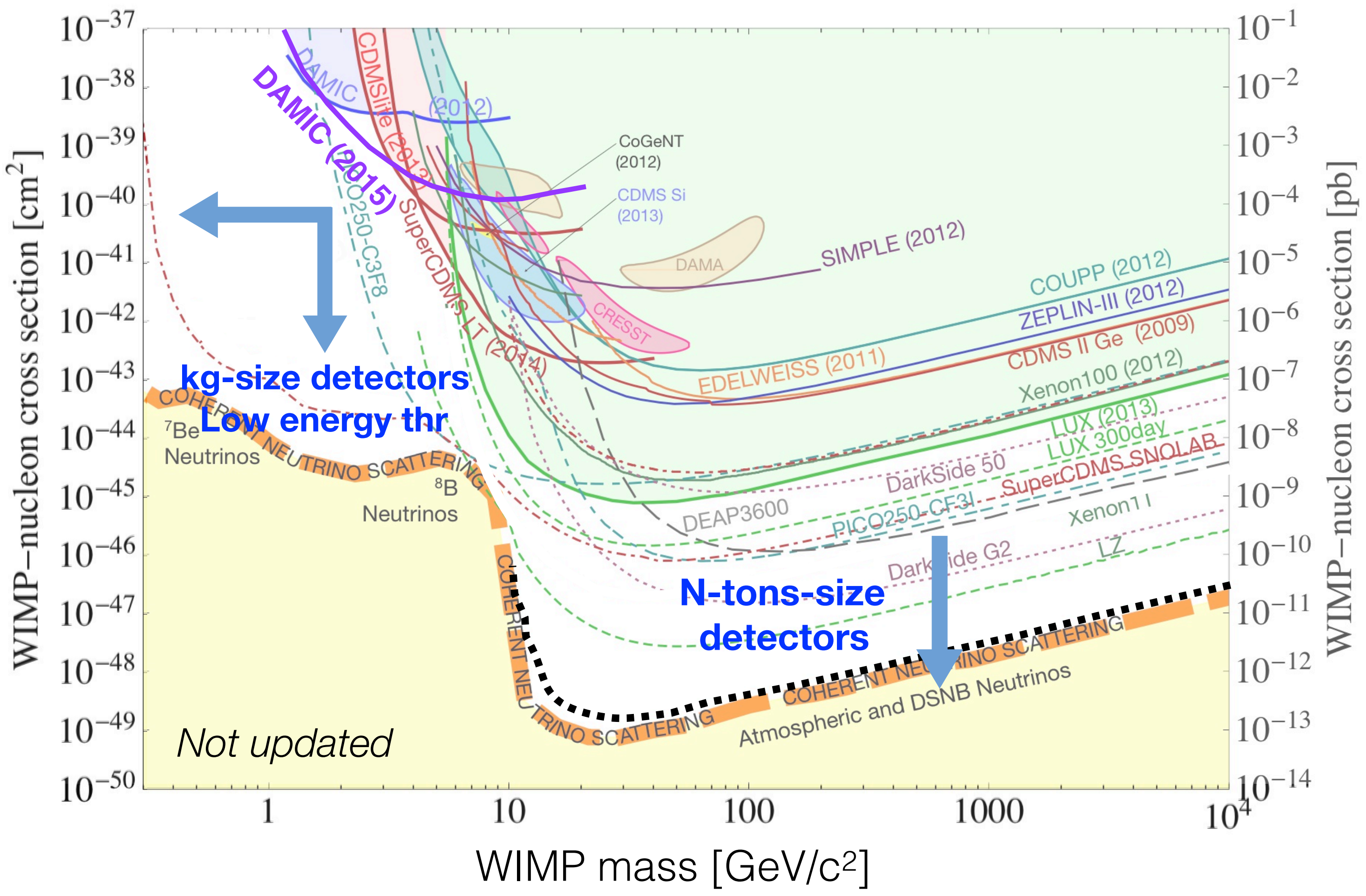
Dark matter candidates

- **DM constitutes 25% of our universe**
  Strong cosmological and astrophysical evidence

WIMPS very popular in the last decades
➡ large phase-space explored

Other searched-for candidates

- Axions & Axion-Like-Particles (ALPs)
- Sterile neutrinos
- Hidden photons (+ hidden sector)
- Millicharged (Lightly Ionizing) Particles



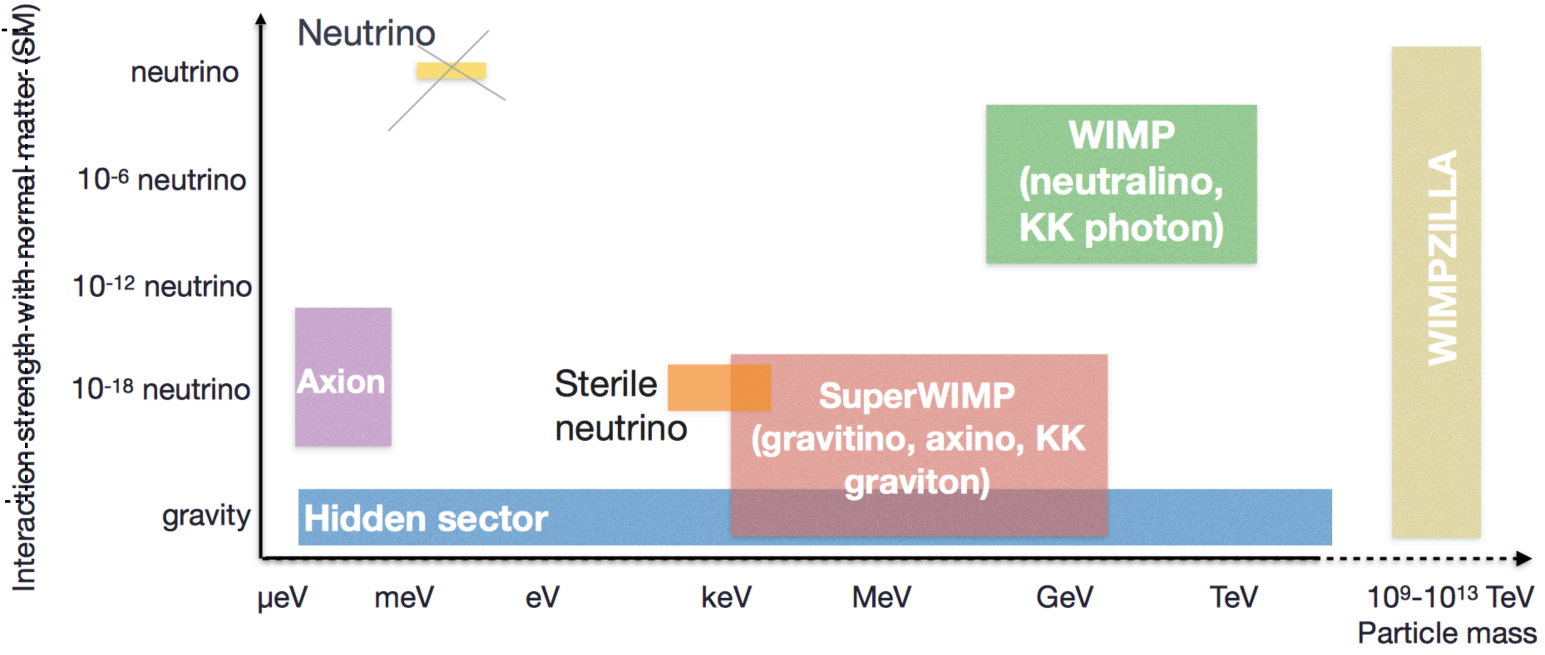
kg-size detectors
Low energy thr

N-tons-size detectors

Not updated

Detection through **nuclear and electron scattering** for DM particle :

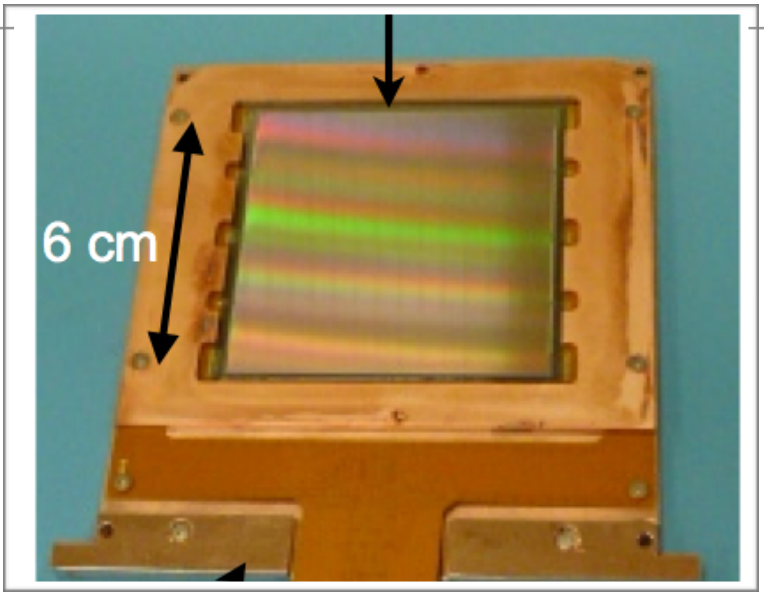
- Low-mass WIMPS (< 10 **GeV**)
- Hidden sector particles (**MeV scale**) and hidden photons (eV)



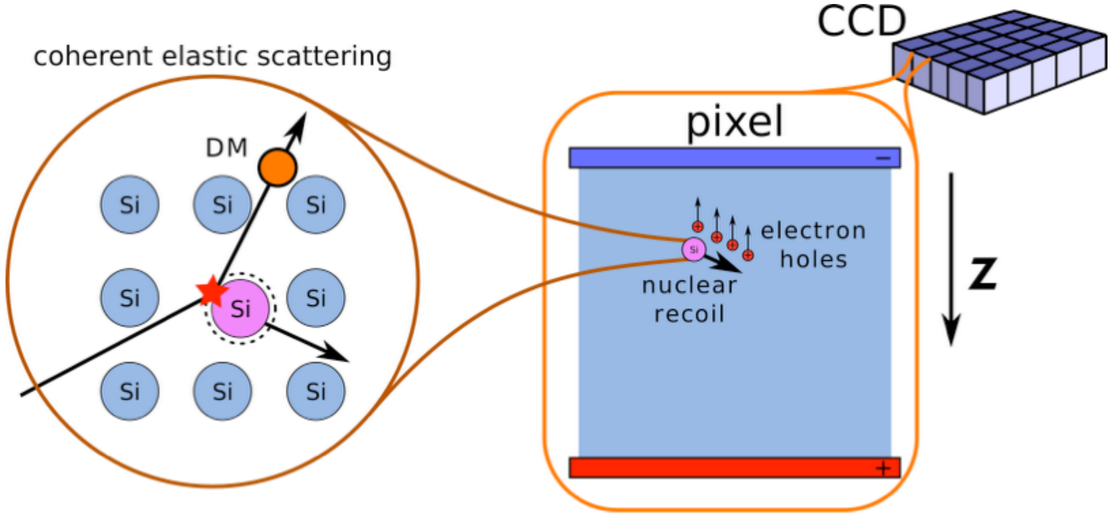
Why CCD for dark matter?

Detection of point-like energy deposit from nuclear recoils induced by WIMPS interactions in the bulk of CCDs.

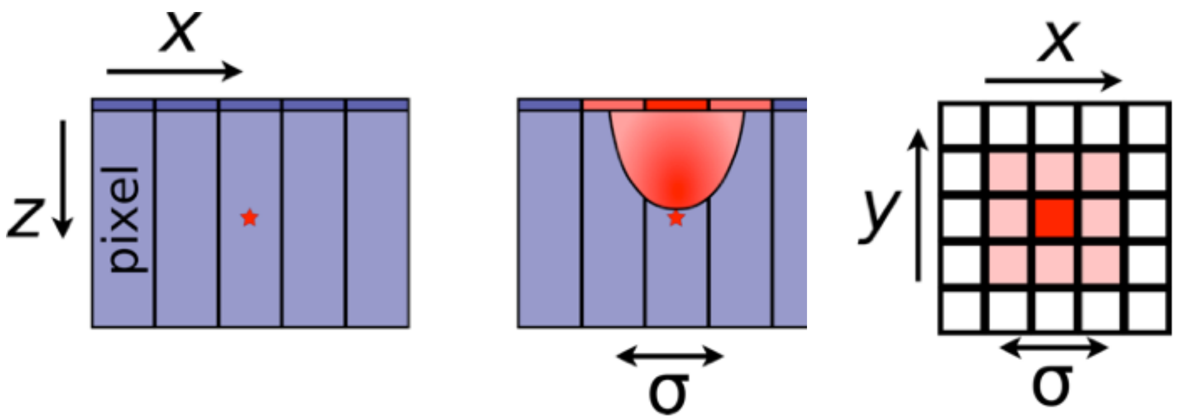
- Sensitivity to < 10 GeV WIMP masses (recoils ~ keV)



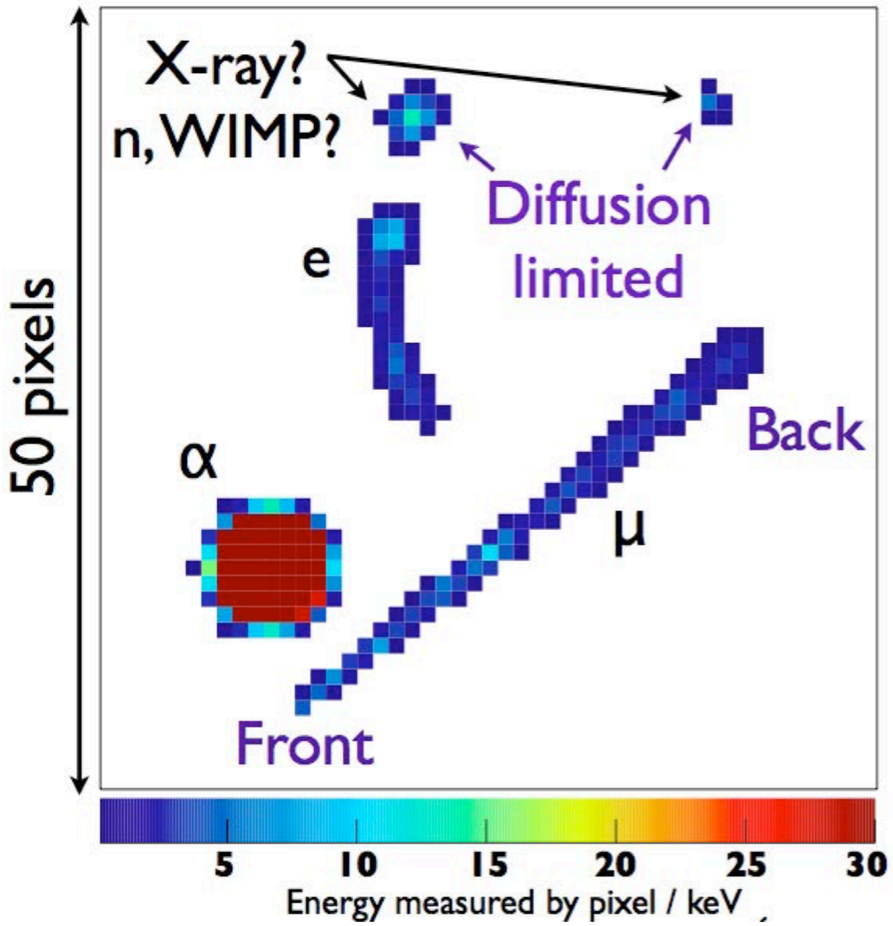
DAMIC Fully depleted CCD,
high-resistivity 16Mpix, 15 μm x15 μm,
650 μm thick, 5.9 g mass



3.7 eV to create e-h pair

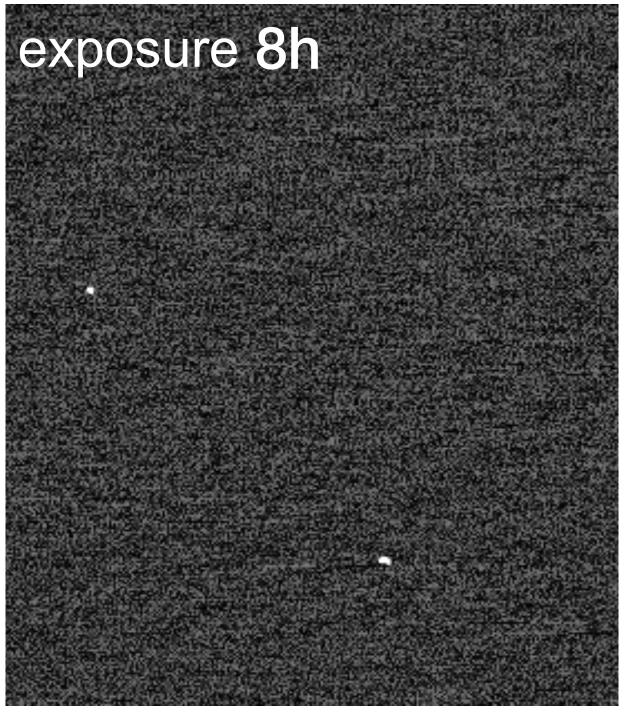


3D reconstruction and unique spacial resolution



Low energy threshold

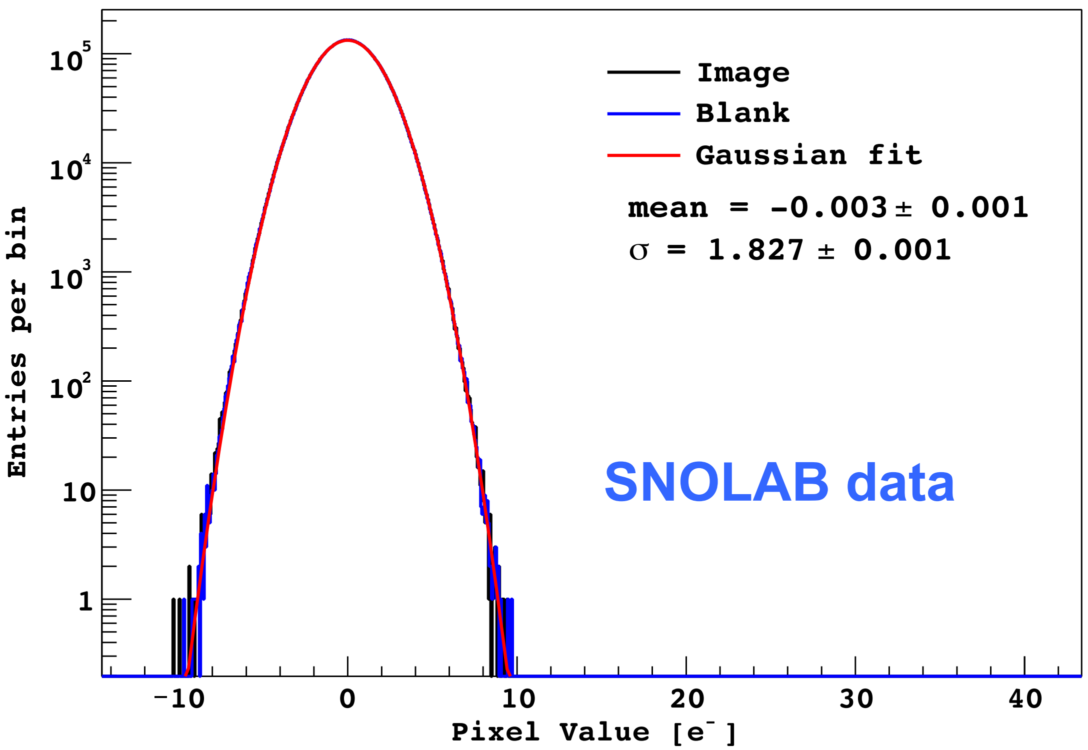
- Negligible noise contribution from dark current fluctuations (dark current < 0.001 e/pixel/day with CCD cooled at 120 K). Readout noise dominant contribution.



- A readout noise of ≈ 2 e- is achieved by slow CCD readout (≈ 10 min / 16 Mpix image).

3.6 eV to produce 1 e-hole pair

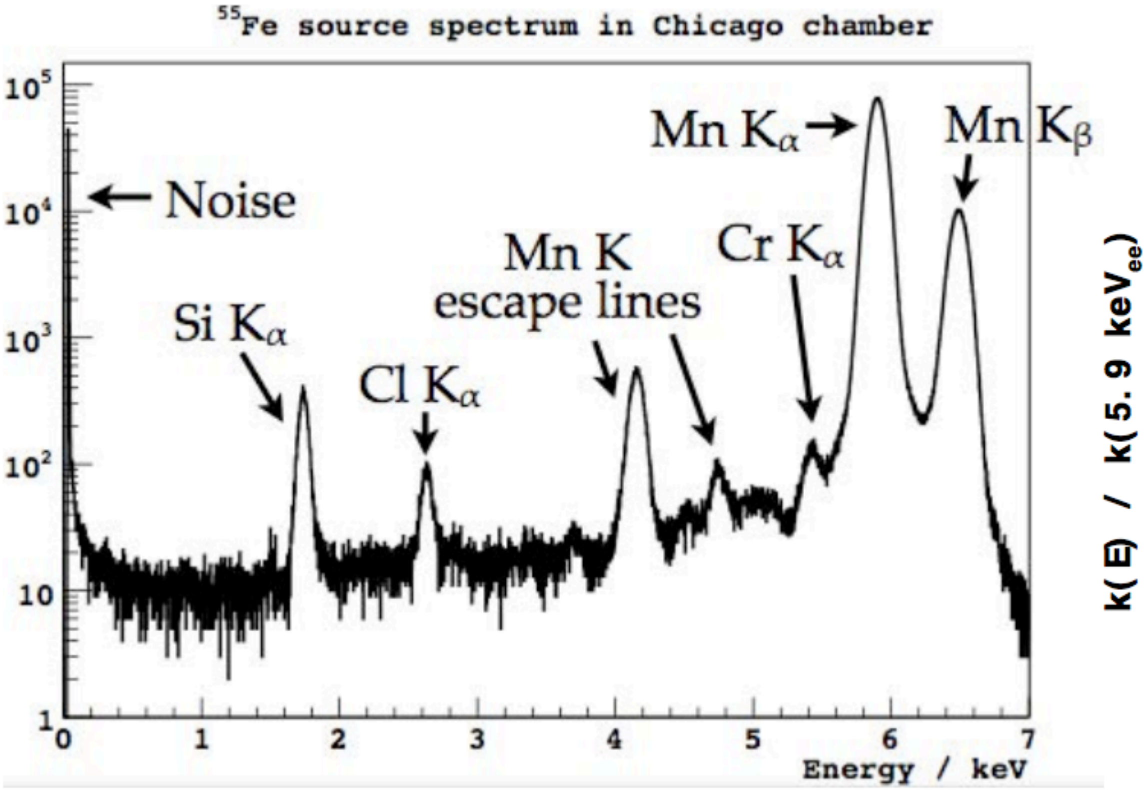
1.2 eV band gap



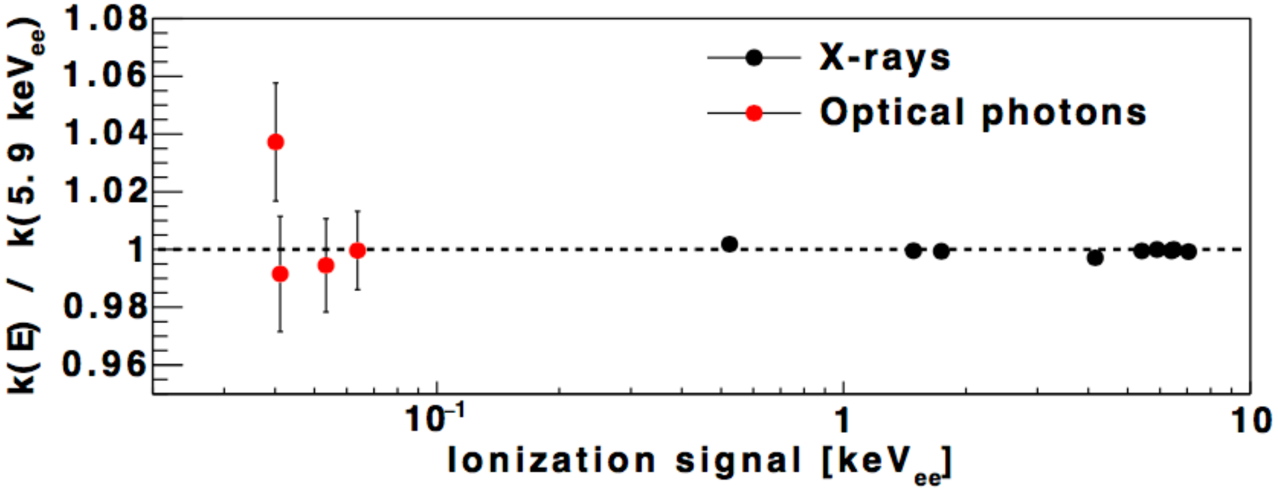
- Very long exposures (8 hours!) to minimize the n. of noise pixels above the energy threshold

Lower threshold, higher WIMP recoil rate (exponential), small mass detector competitive

Energy linearity and neutron recoil



Linearity demonstrated for signals <10 e^-



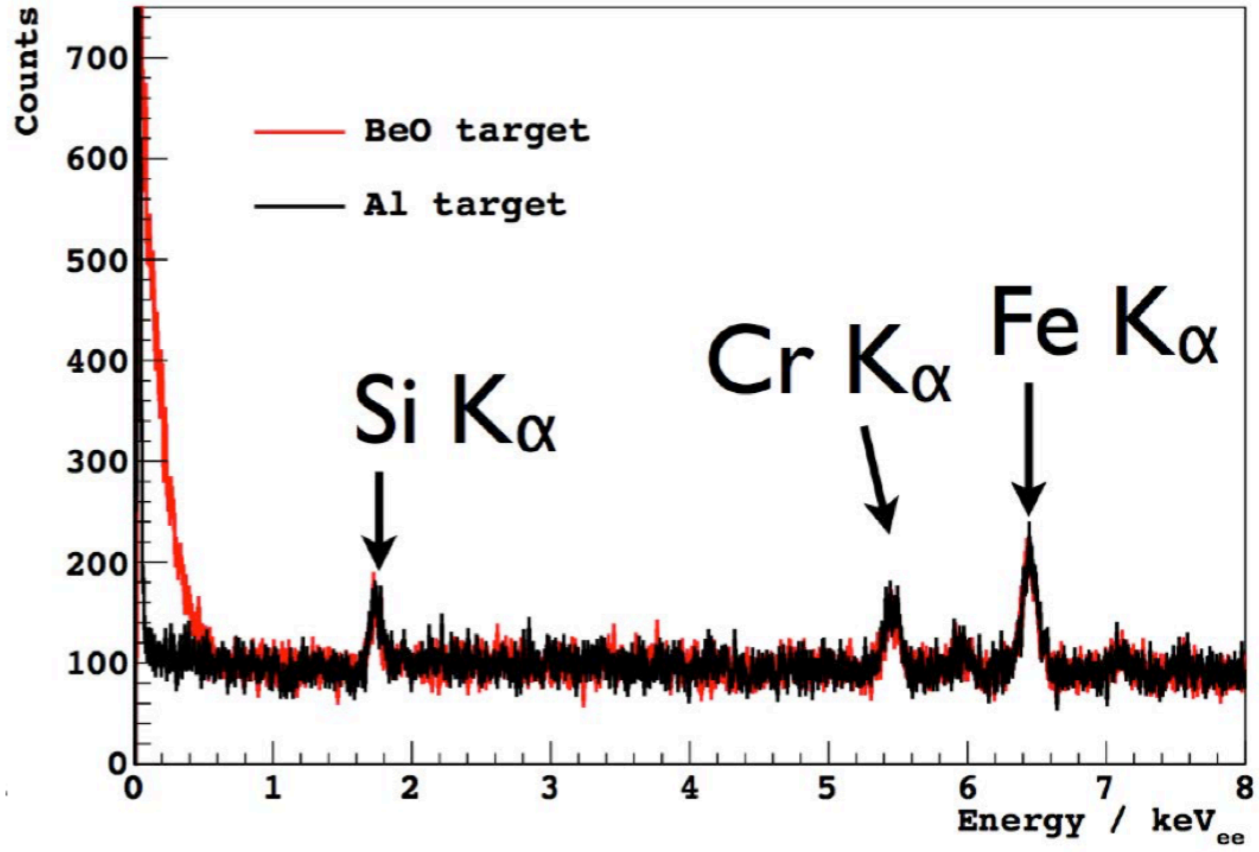
Antimony source with Be / Al cap

“Neutron-on” with BeO (n+γ)

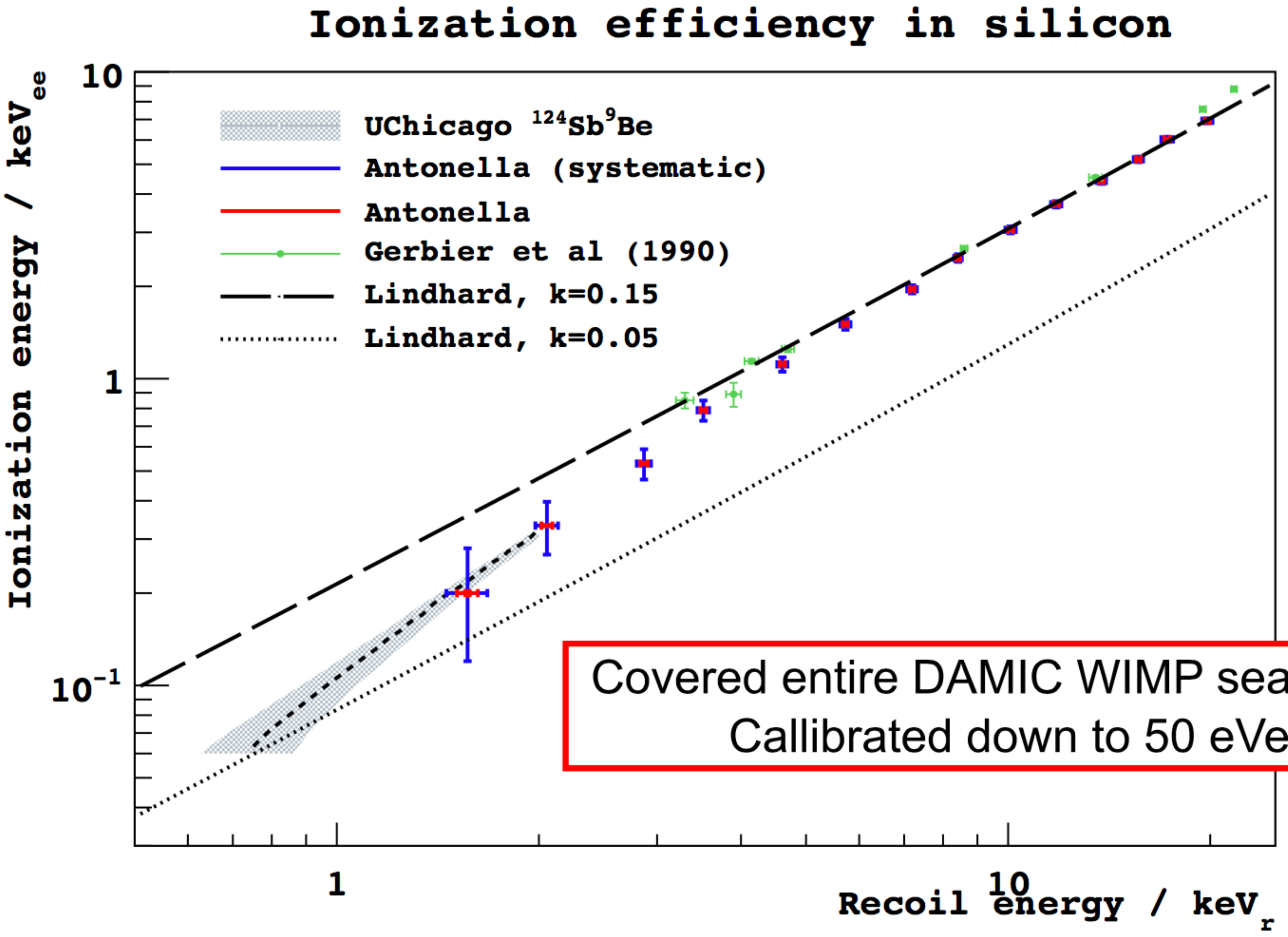
“neutron-off” with Al (only γ)

Clear signal from neutron-induced nuclear recoils

Nuclear recoil ionization efficiency from adjusting MC E_r to E_e spectrum



Nuclear-recoil Ionisation efficiency

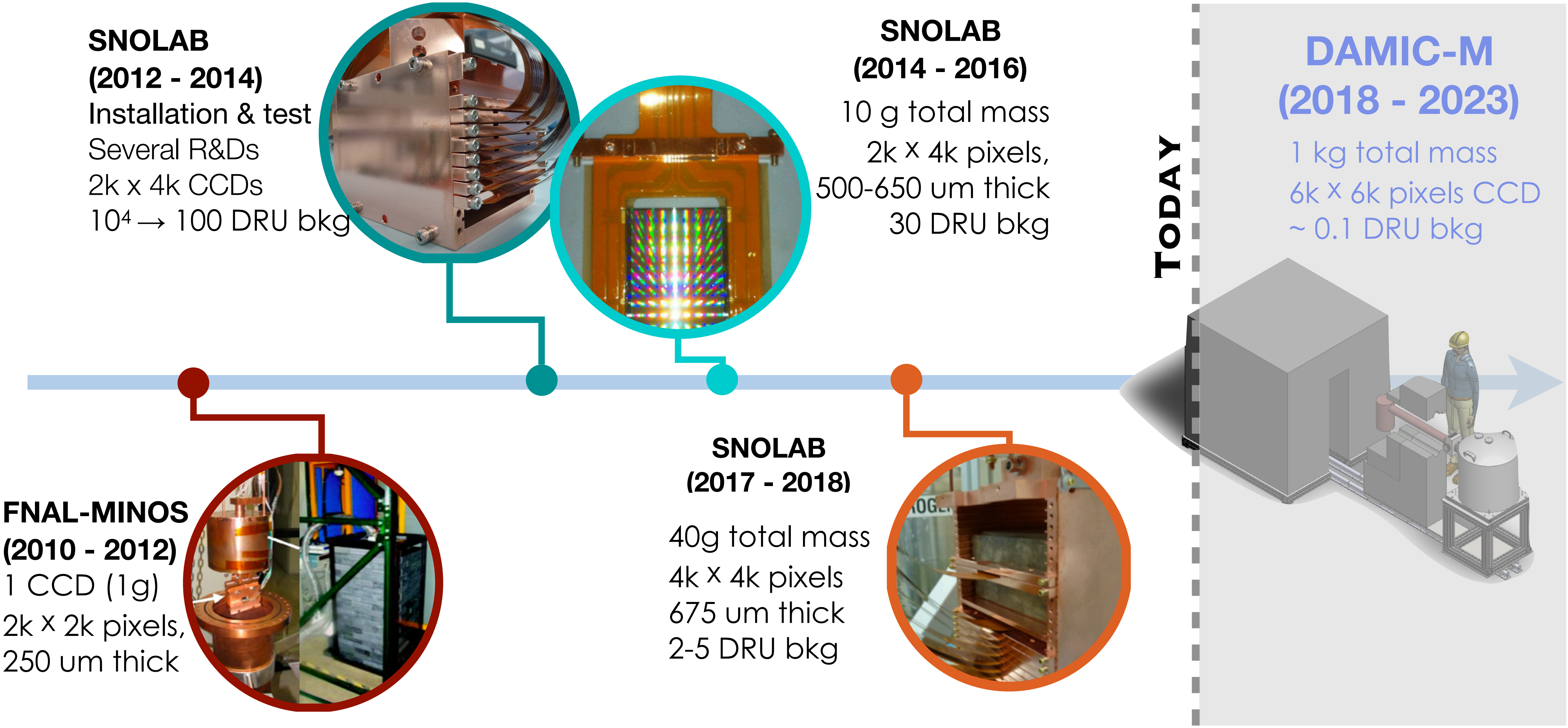


Covered entire DAMIC WIMP search ROI
Callibrated down to 50 eVee

Deviation from Lindhard theory below 5.5 keV,
crucial for low-mass WIMPs search in Si

PRD 94, 082007 (2016)

From DAMIC to DAMIC-M



FNAL-MINOS
(2010 - 2012)
1 CCD (1g)
2k x 2k pixels,
250 um thick

SNOLAB
(2012 - 2014)
Installation & test
Several R&Ds
2k x 4k CCDs
$10^4 \rightarrow$ 100 DRU bkg

SNOLAB
(2014 - 2016)
10 g total mass
2k x 4k pixels,
500-650 um thick
30 DRU bkg

SNOLAB
(2017 - 2018)
40g total mass
4k x 4k pixels
675 um thick
2-5 DRU bkg

DAMIC-M
(2018 - 2023)
1 kg total mass
6k x 6k pixels CCD
~ 0.1 DRU bkg

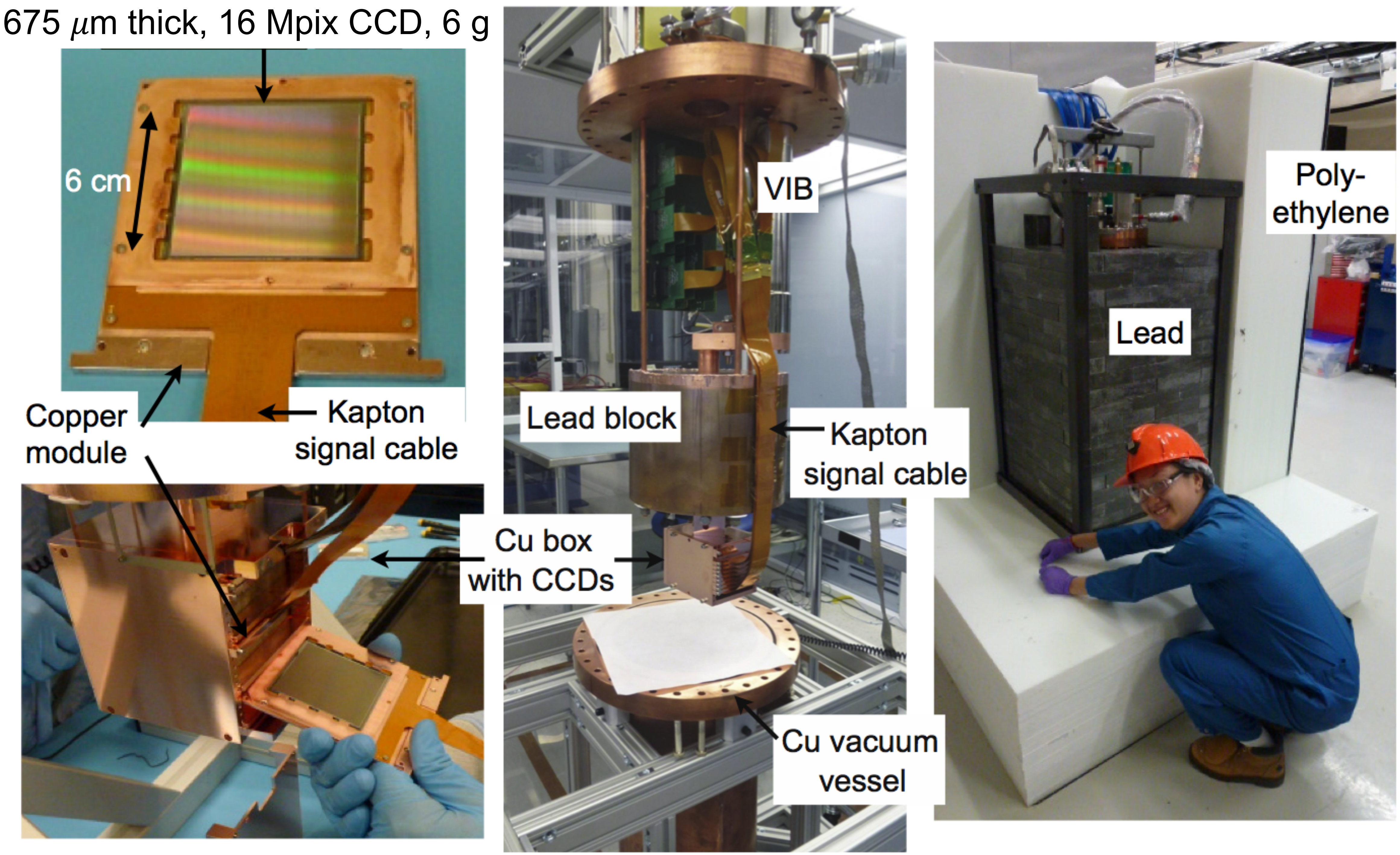
Differential rate unit (dru) = 1 event /keV/kg/day

Main Publications

Proof of concept : Phys. Lett. B 711 (2012)
Detector performances: arXiv:1407.0347
Radioactive background: JINST 10 (2015) P08014
Nuclear recoil ionisation: PRD 94, 082007 (2016)
JINST 12 P06014 (2017)

WIMPS search: Phys. Rev. D 94, 082006 (2016)
Compton scattering: Phys. Rev. D 96, 042002 (2017)
Hidden photons: Phys. Rev. Lett. 118, 141803 (2017)

DAMIC @ SNOLAB



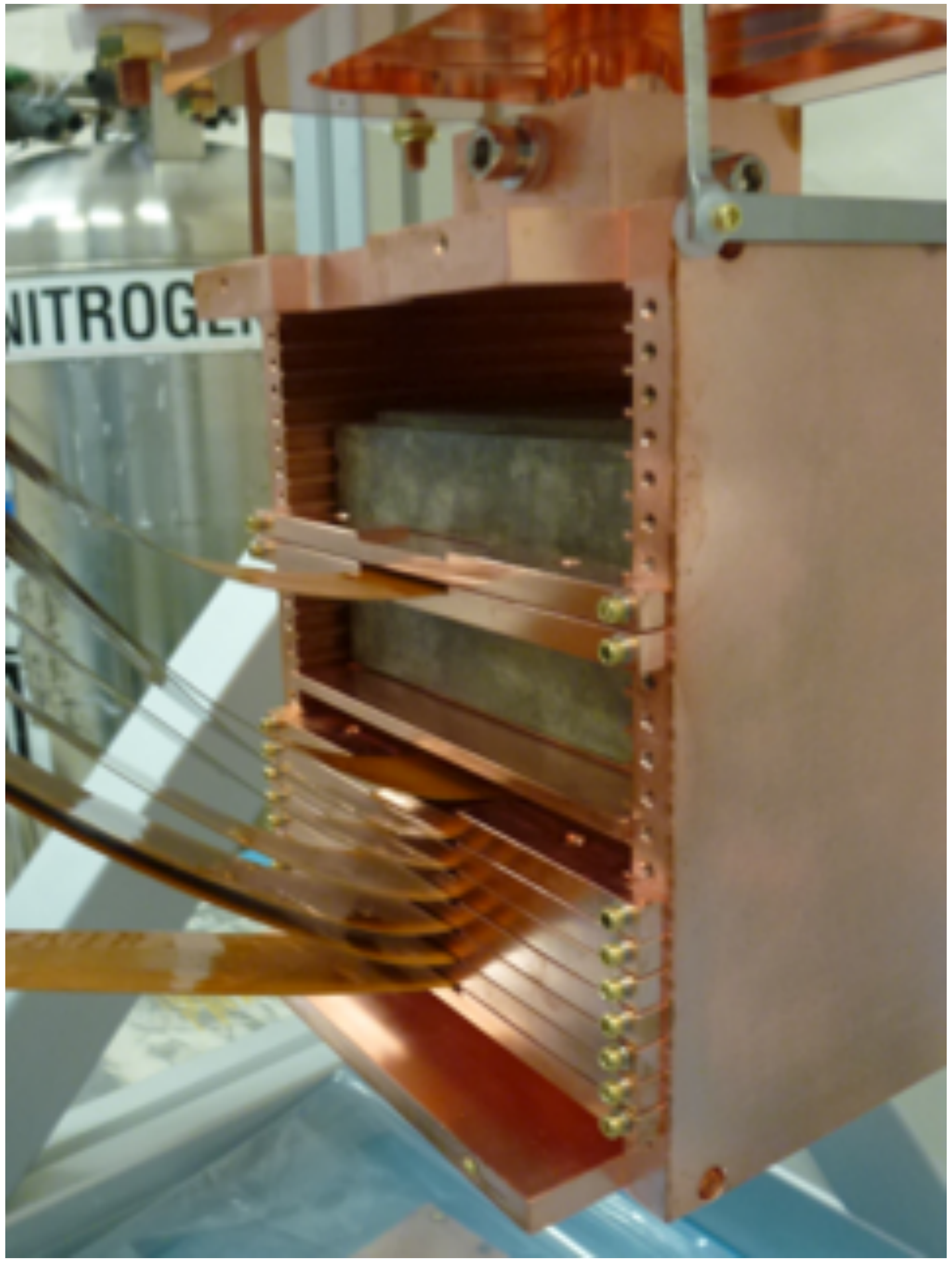
40g detector data taking 2017-2018 @ Snolab (2000 m underground)

Current detector configuration

- **7 CCDs** in stable data taking since 2017 (1 CCD sandwiched in ancient lead)
- **40 g detector mass**
- **Operating temperature of 140K**
- **Exposure for image : 8h and 24h**

(each image acquisition is followed by a “blank” whose exposure is the readout time)

- **7.6 kg day of data for background characterisation** (1x1 hardware binning)
- About **13 kg day of data collected for DM search** (in 1x100 hardware binning)



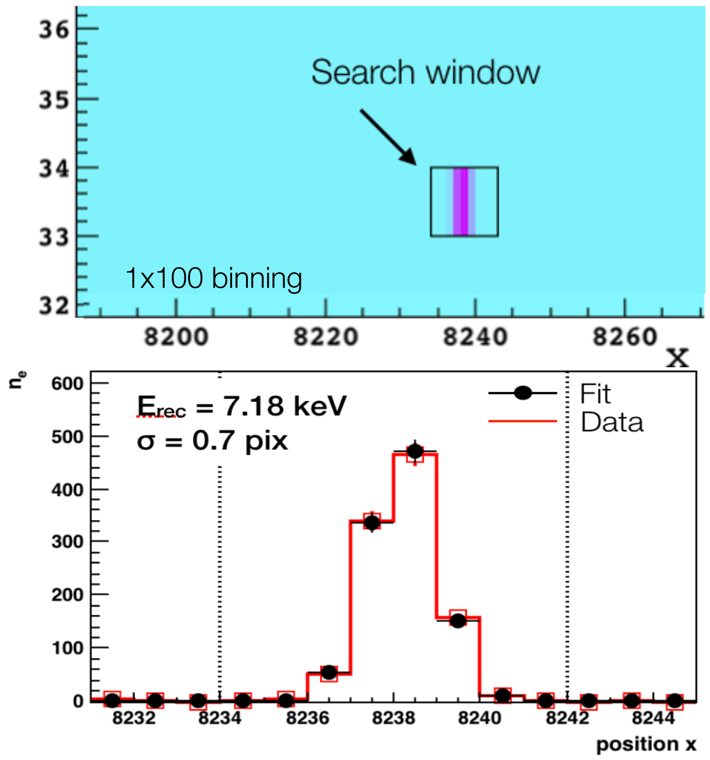
WIMPs search analysis

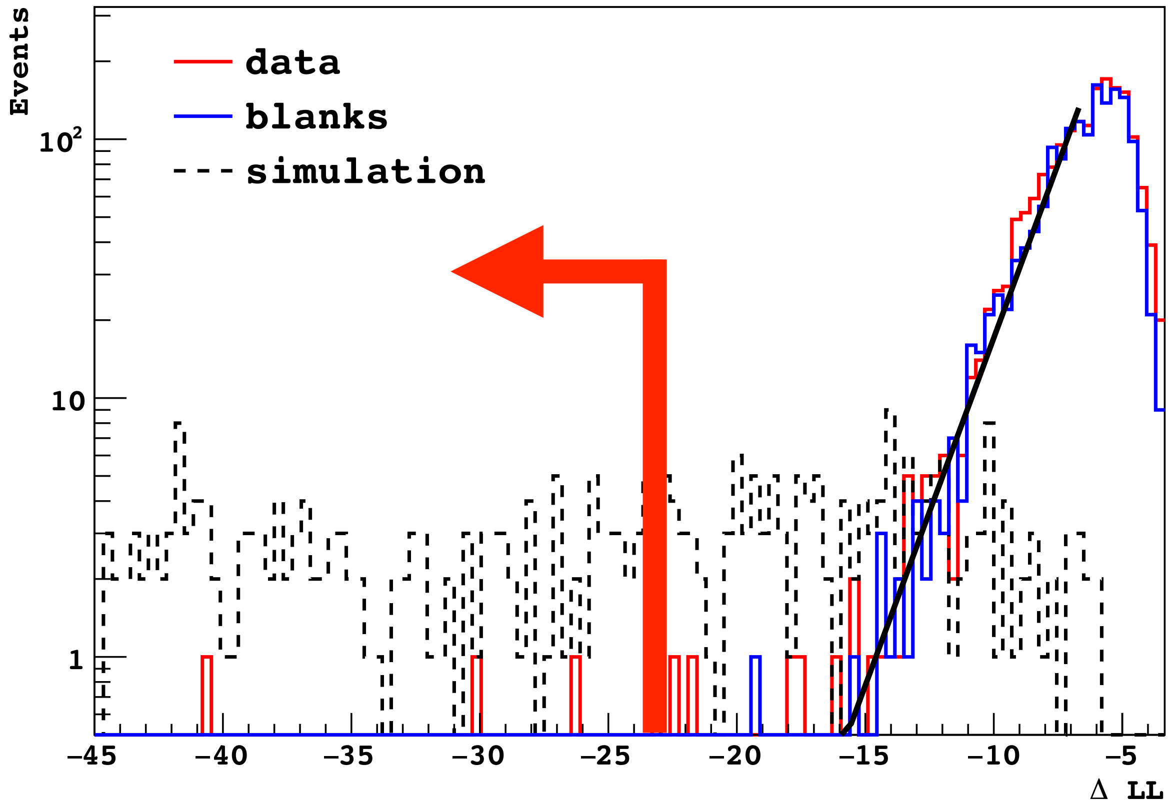
- Pedestal and correlated noise subtraction (hot pixels among several images masked)
- LL fit of the signal in a moving window across the image

$$\Delta LL = \mathscr{L}_n - \mathscr{L}_s$$

flat noise

Gaus signal + flat noise





DLL cut : < 0.001 bkg events from exponential fit of the "blanks" distrib

Background handling

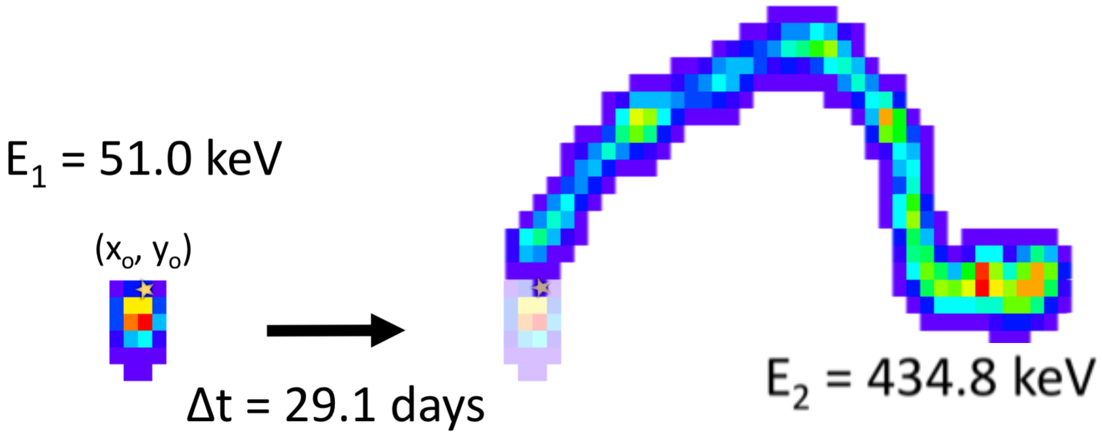
- **(a) Simple approach** : fiducial cut in depth to remove surface events
- **(b) Bkg model :** based on Geant4 simulations of isotopes in the CCD bulk and surrounding material: 2D binned LL fit to data

Background measurements

Bulk background (^{32}Si, tritium) and origin of surface background (^{210}Pb, U/Th chain) based on particle **identification and spatially correlated events (1x1 binning)**

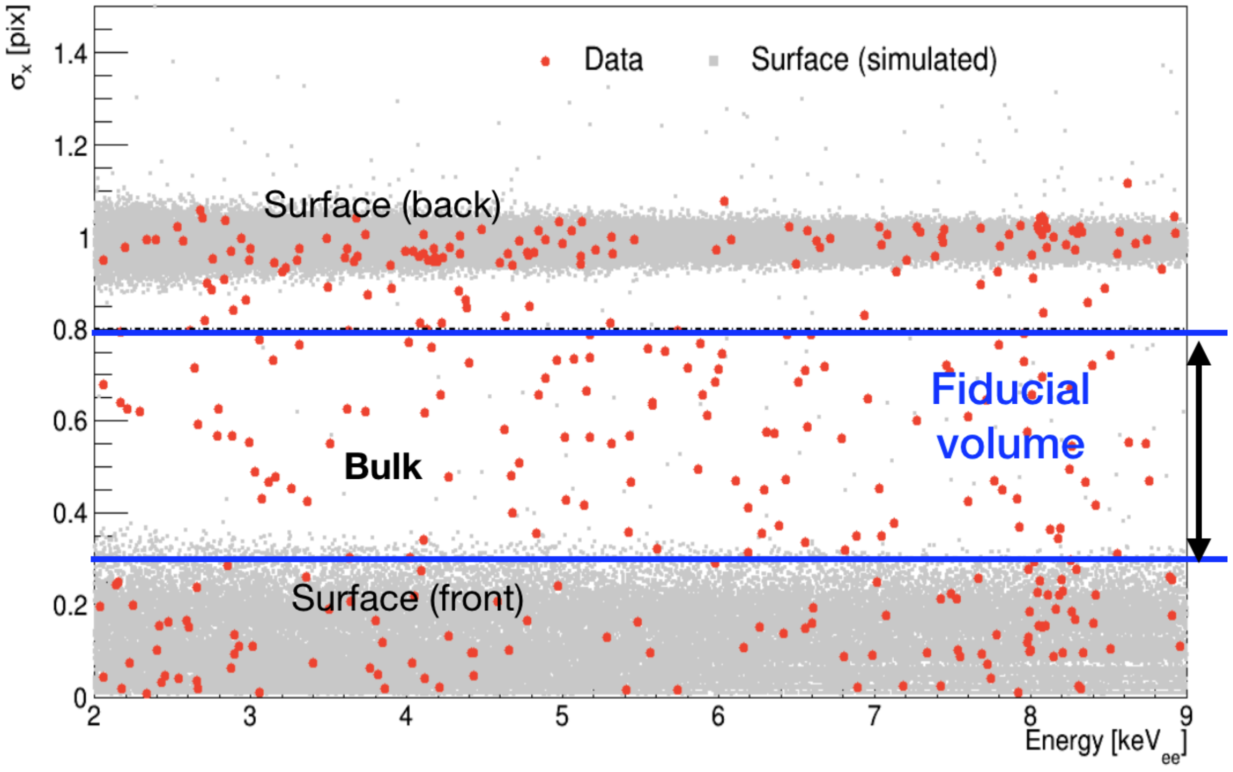
Spatial coincidence of two beta decays (^{32}Si)

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



Surface background rejection of diffuse limited clusters thanks to depth reconstruction, for any binning

(i.e. : depth cut or modelling of cluster-variance distribution from simulations)



Surface and background contamination

Measured contamination of ^{210}Pb and ^{32}Si
limits are placed on ^{238}U and ^{232}Th

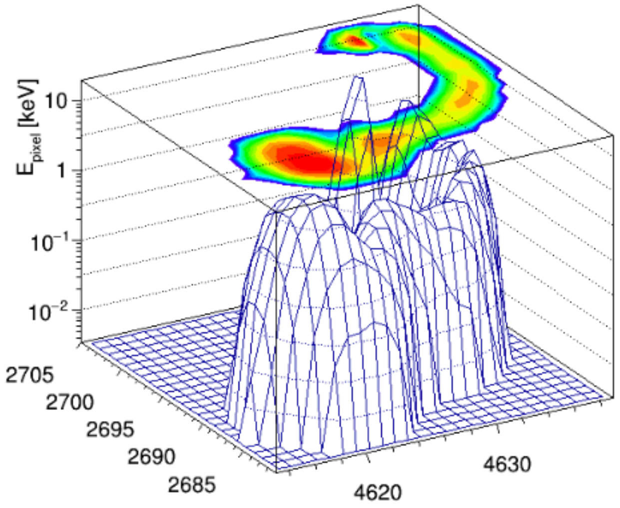
DAMIC 2019 analysis

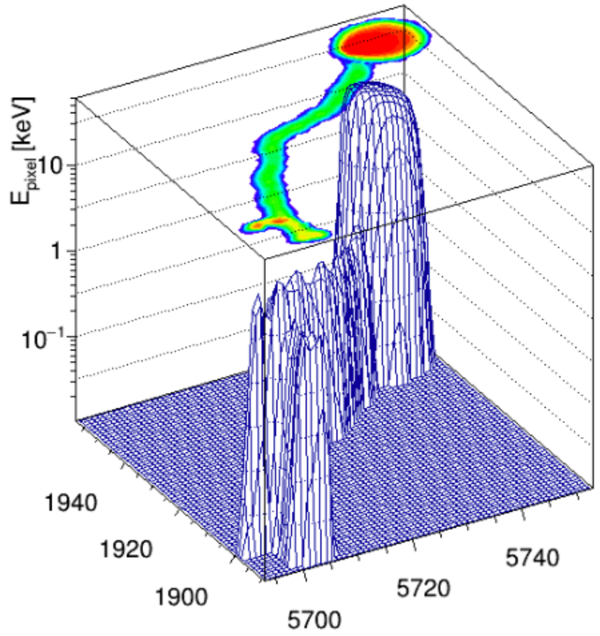
^{32}Si
- ➢ 133.3 ± 27.8 μBq/kg

^{210}Pb
- ➢ 83.1 ± 11.8 nBq/cm^2

^{238}U
- ➢ No α-β sequences
- ➢ Upper limit:
0.53/kg/day or 1.5 ppt [95%]

^{232}Th
- ➢ No α's with E = 18.7 MeV
- ➢ Upper limit:
0.35/kg/day or 1 ppt [95%]





DAMIC 2015 R&D result

^{32}Si
- ➢ 925.9 ± 1273 / 752 μBq/kg

^{210}Pb
- ➢ 902.8 ± 115.8 nBq/cm^2

^{238}U
- ➢ Upper limit: 5/kg/day [95%]

^{232}Th
- ➢ Upper limit: 15/kg/day [95%]

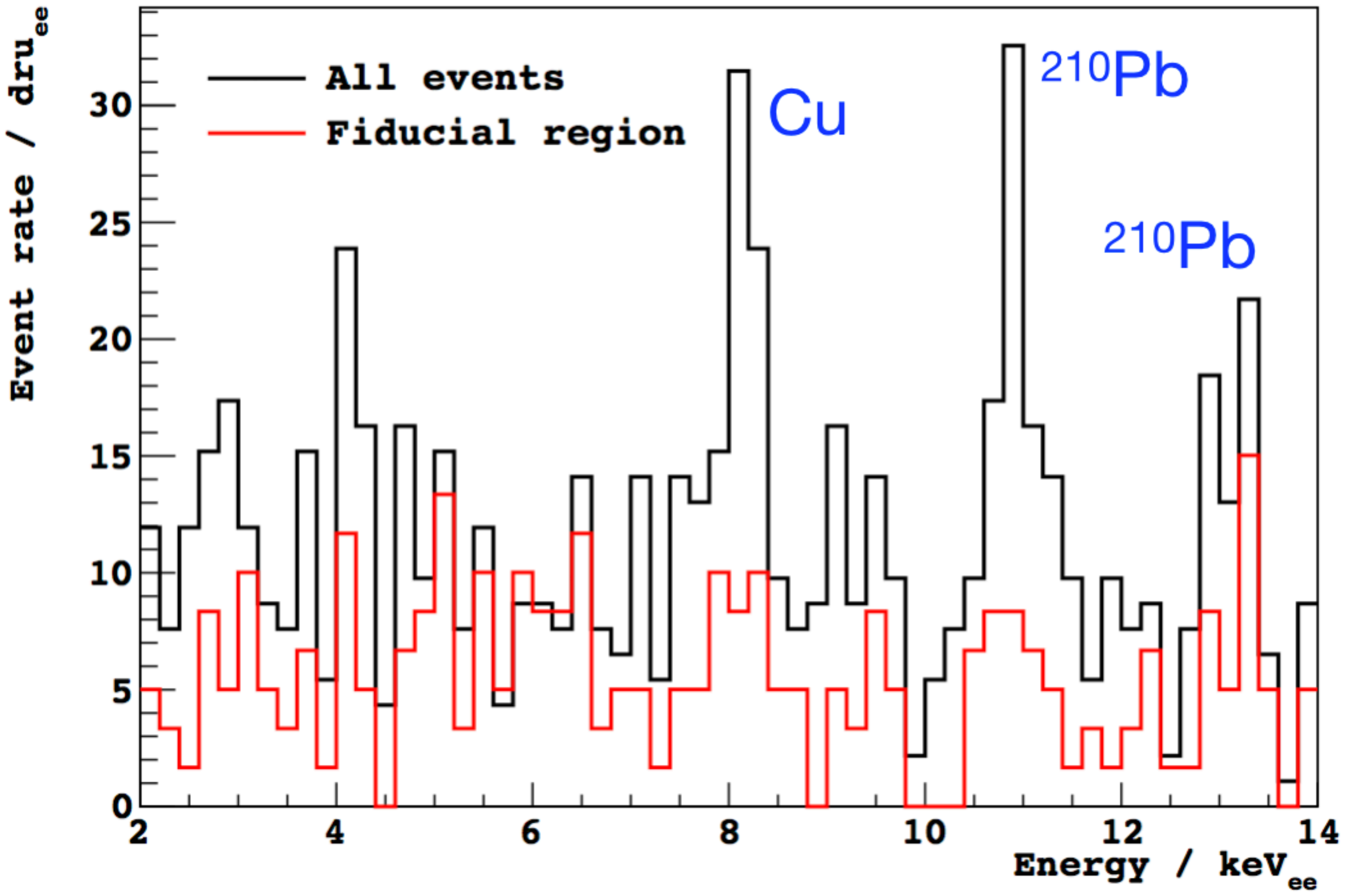
arXiv:1506.02562

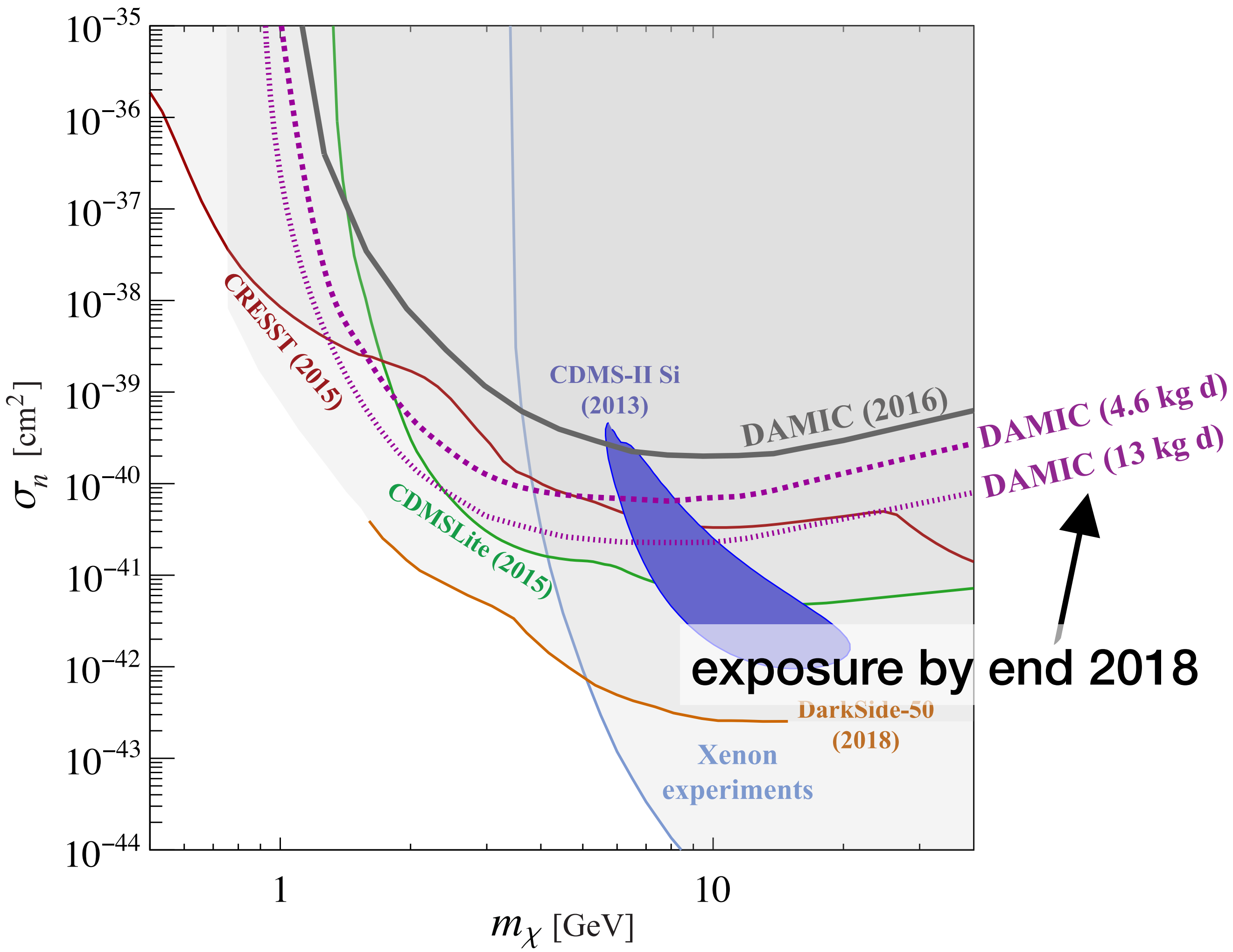
Difference (factor x7) in ^{32}Si

New data and sensitivity (2018)

40g detector commissioned in 2017

Energy spectrum above 2 keV





exposure by end 2018

≃ 5 dru in fiducial region, consistent between CCDs

a factor of ≃ 3-4 lower than our previous background level

≃ 2 dru for lead sandwiched CCD

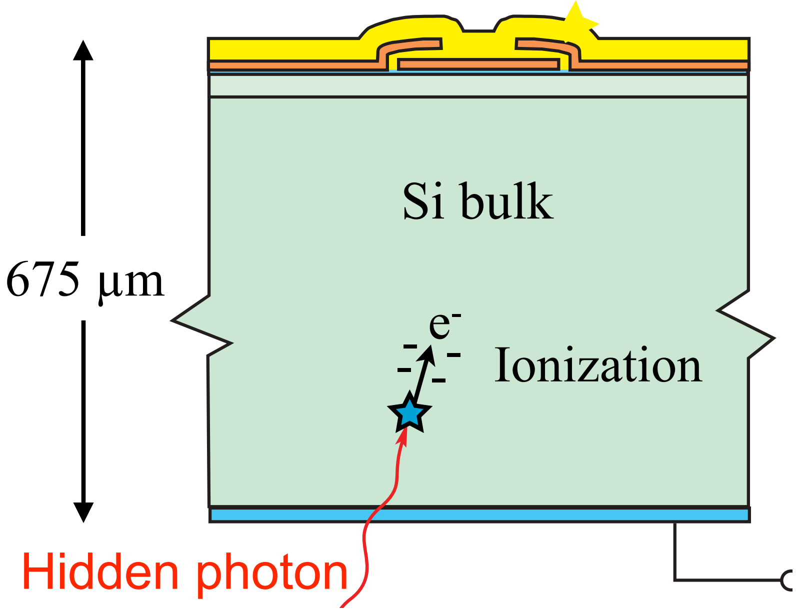
Differential rate unit (dru) = 1 event /keV/kg/day

Science-run data stopped in December
Finalising background model.

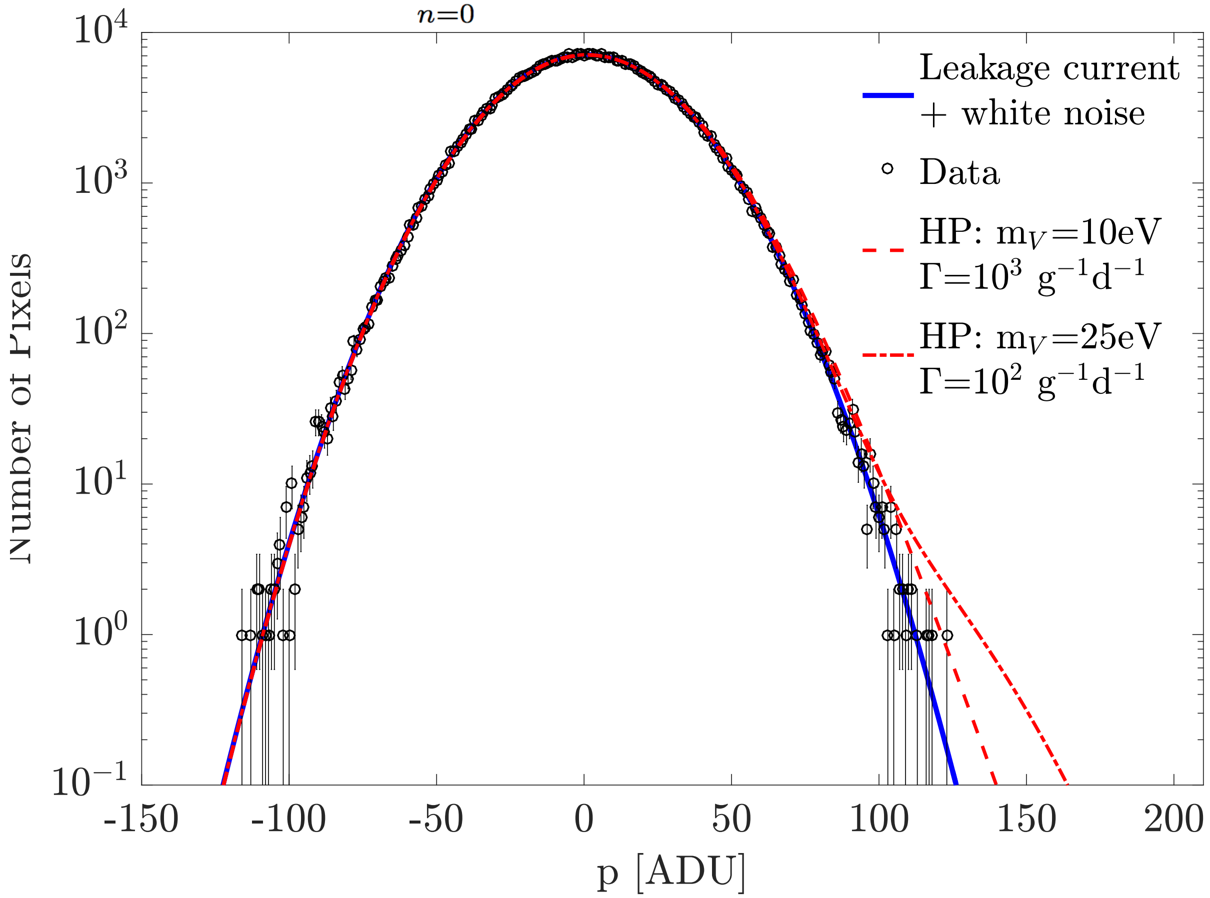
Full-data unblind and result release soon

Hidden photon search

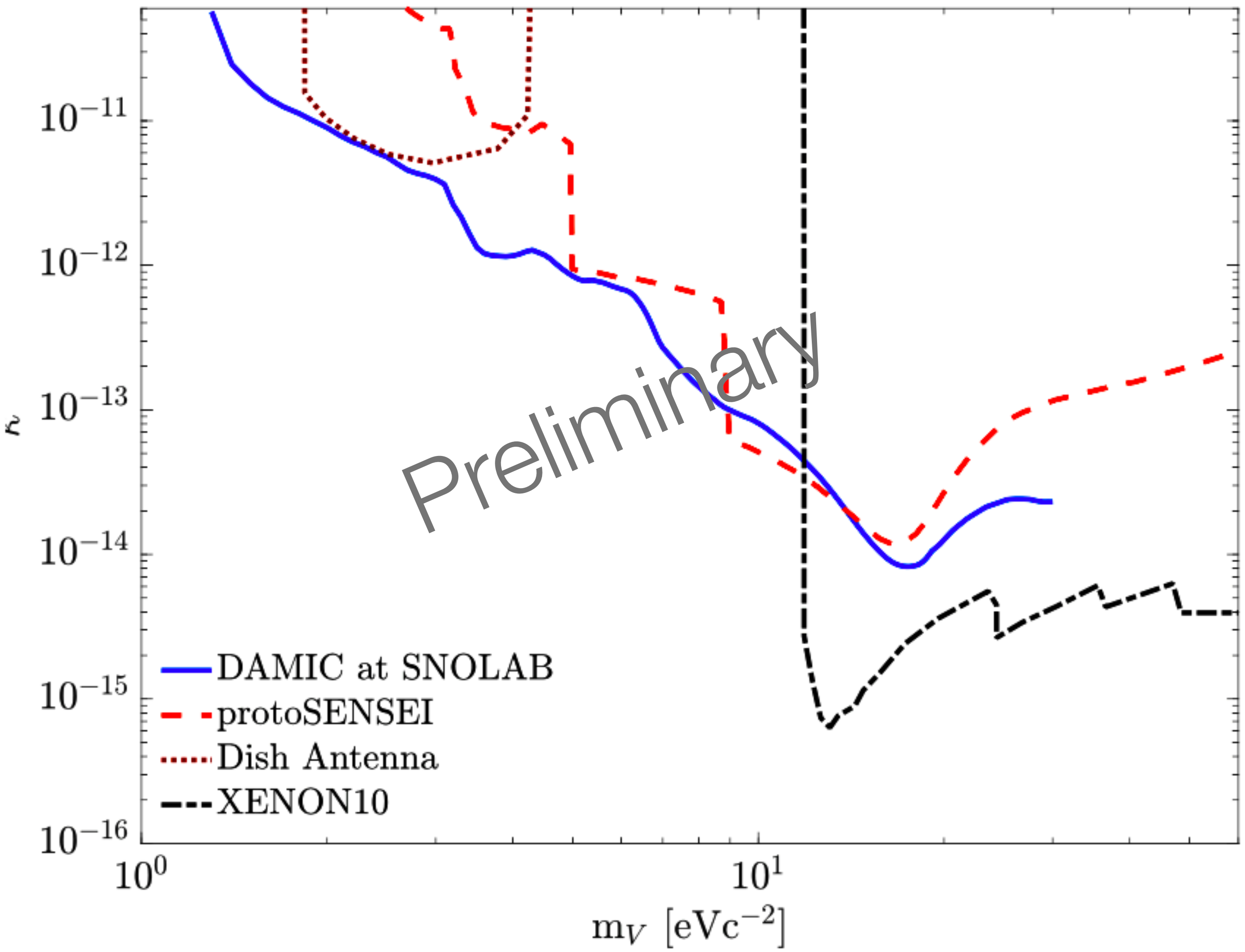
Absorption of hidden-photon dark matter.



$$f(p) = N \sum_{n=0}^{\infty} F(n|\lambda, \Gamma, m_V) \mathrm{Gaus}(\alpha p | n - \mu_0, \sigma_{\mathrm{pix}})$$



Update 2018, Exposure ~ 200 g day



Pixel distribution consistent with white noise + uniform leakage current.

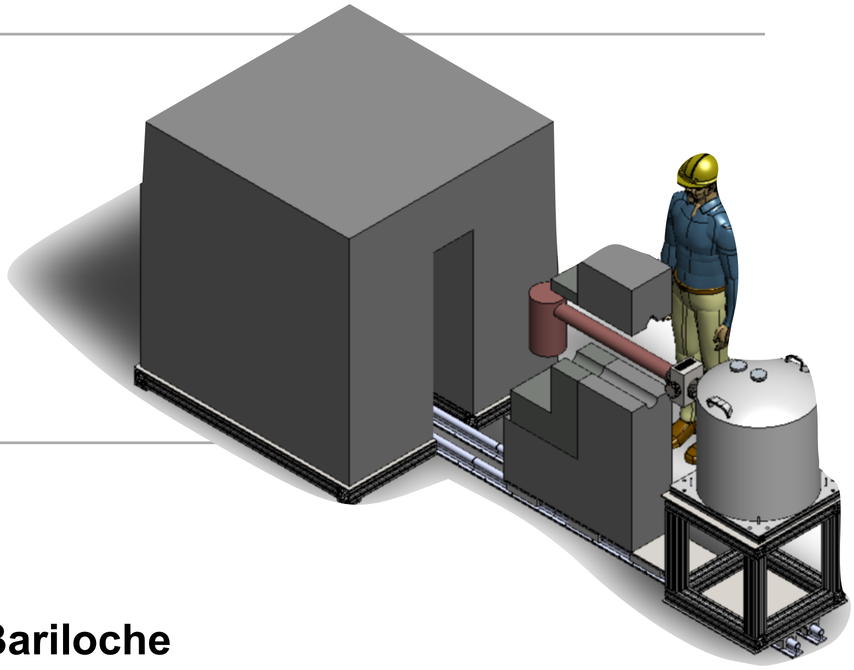
Similar analysis for DM-e scattering (soon)

Phys.Rev.Lett. 118 (2017) no.14, 141803

European Research Cour
Established by the European Commission

Next phase of DAMIC is started

DAMIC-M at Modane



France:
LPNHE - Paris *(ERC-host)*,
CENBG - Bordeaux
IPNO / LAL - Orsay
LSM, Modane
SUBATECH - Nantes

USA:
The University of **Chicago**,
University of **Washington**,
Pacific Northwest National Laboratory (**PNNL**)

Switzerland:
University of **Zurich**

Argentina:
Centro Atómico **Bariloche**

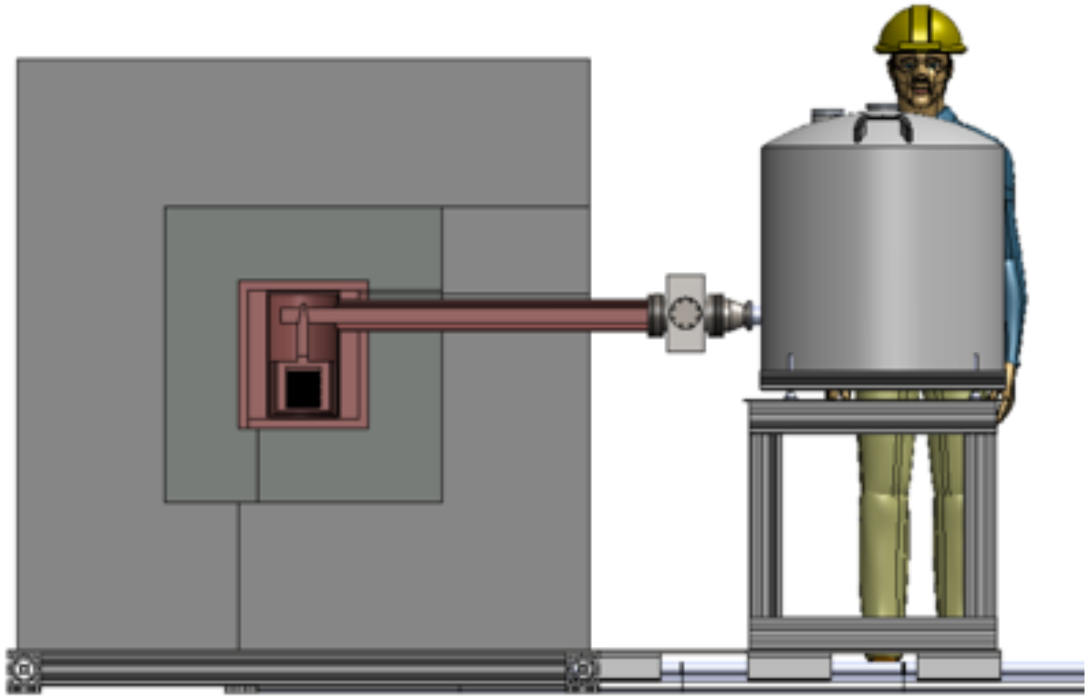
Brazil:
Universidad Federal do **Rio de Janeiro**

Canada:
SNOLAB**, Subdury**

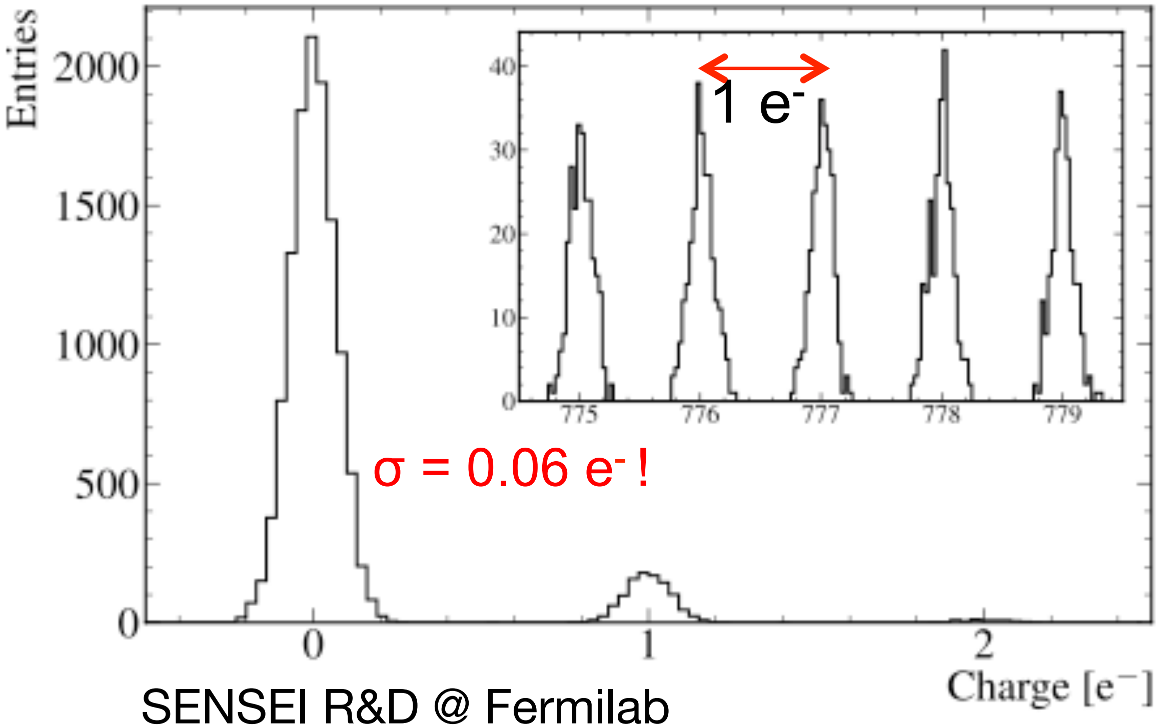
Denmark:
Niels Bohr Institute, **Copenaghen**
University of Southern Denmark, **Copenaghen**

Spain:
University of **Santander, Cantabria**

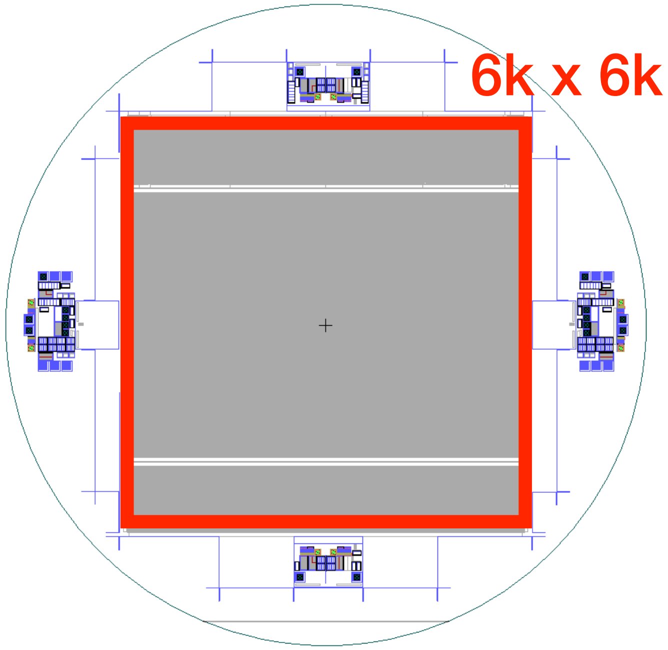
What's new in DAMIC-M



- 1 kg-size detector
  (6k x 6k x 0.7 mm, mass ~20 g)
- Skipper readout for sub-eV noise
  (energy threshold of few eV)
- Bkg reduction to a fraction of dru
  (improved design, materials, procedures)



SENSEI R&D @ Fermilab

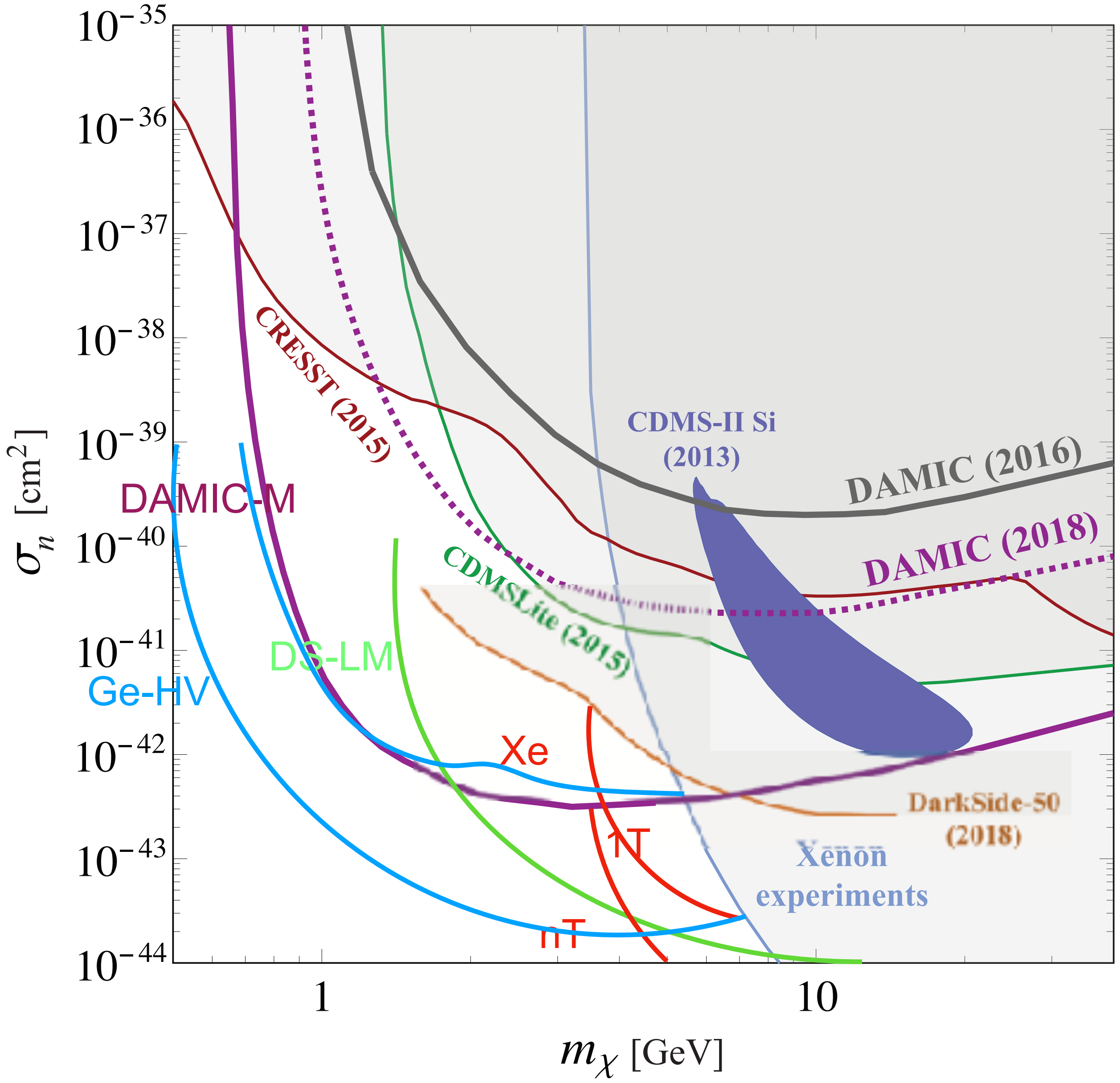


Wafer-layout by J.Holland (LNBL)

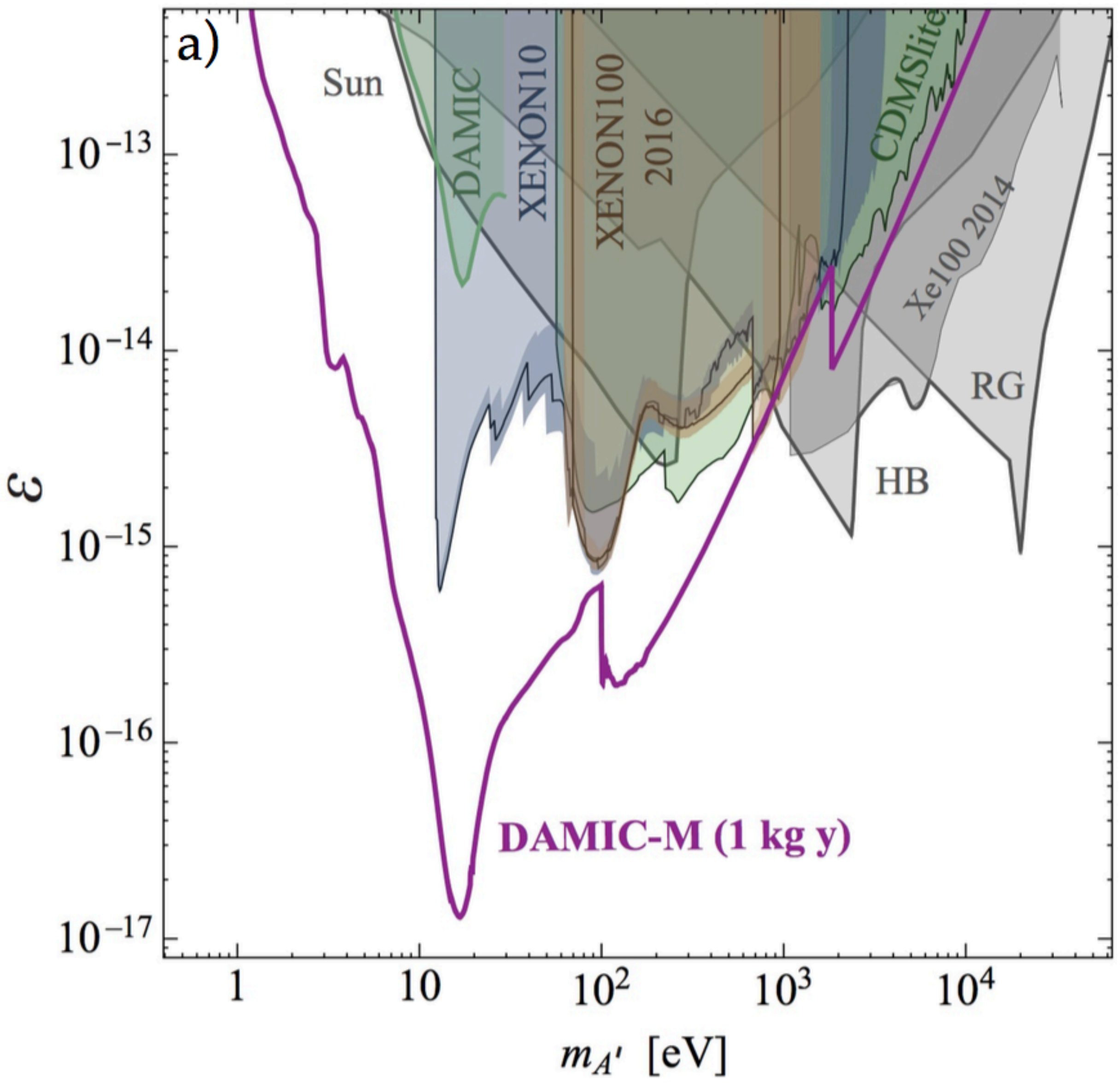
1st skipper CCDs received at UW!

DAMIC-M scientific goals (I)

Light-WIMP nuclear recoil

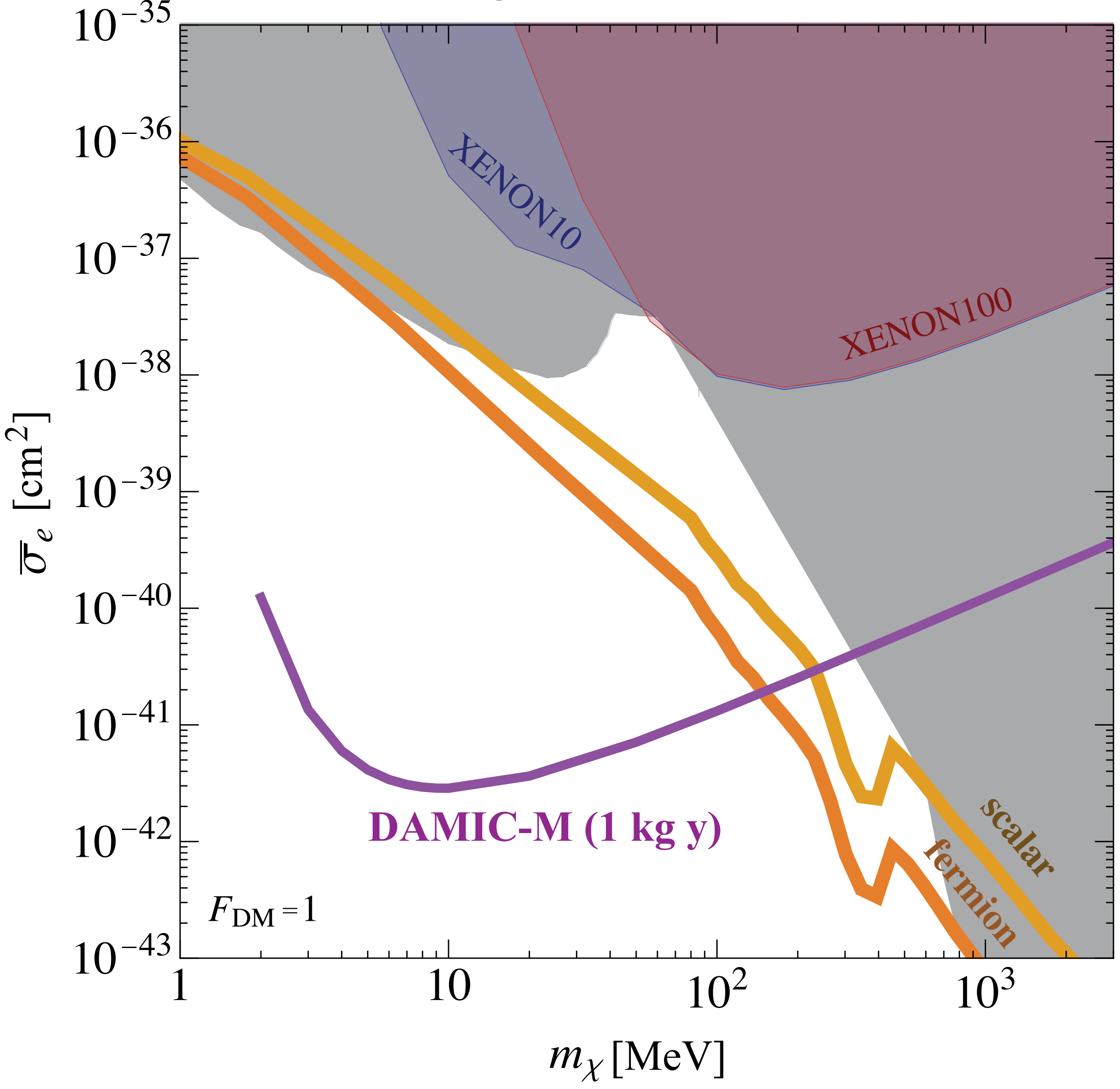


Hidden photon absorption

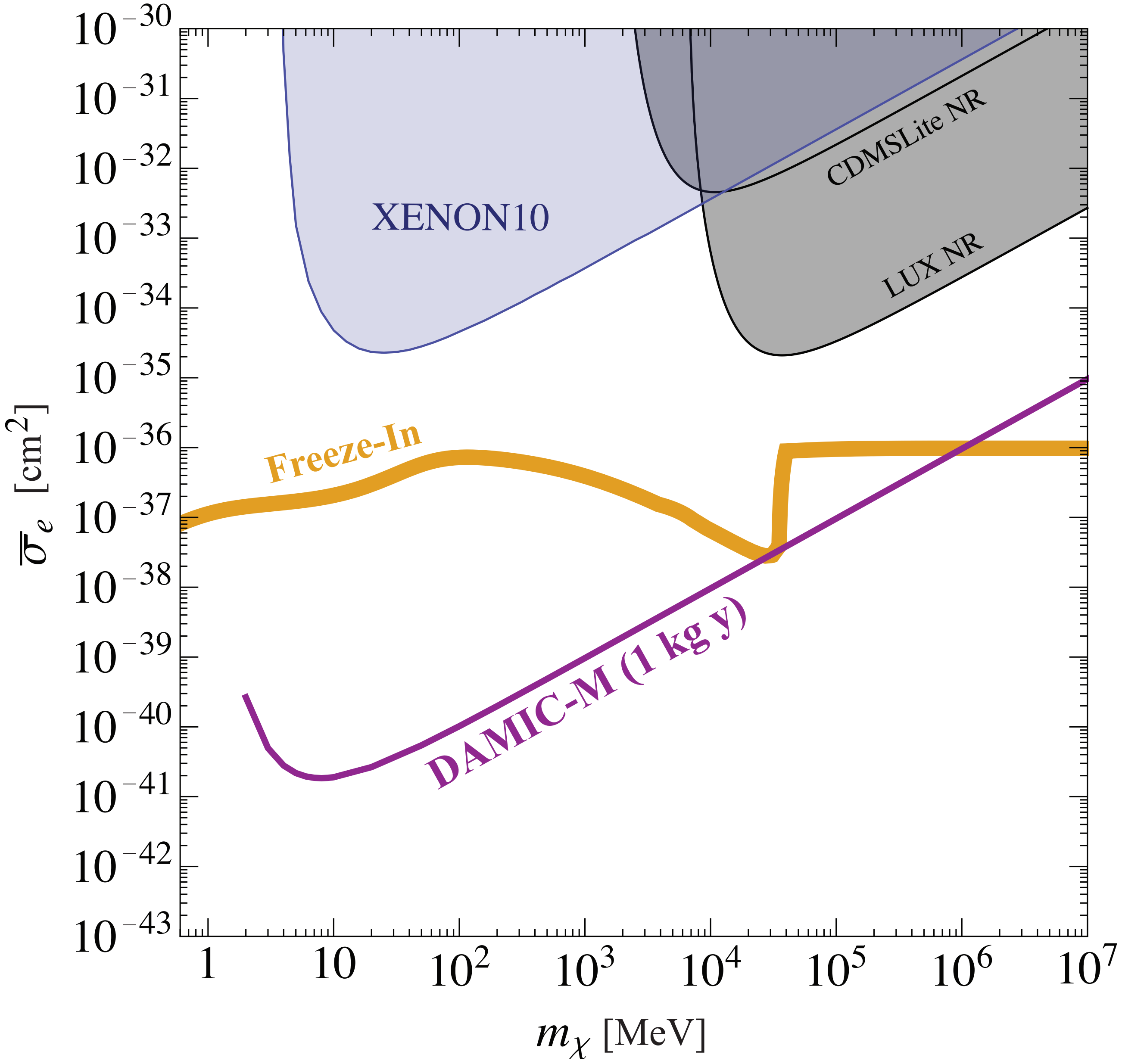


DAMIC-M scientific goals (I)

Light mediator

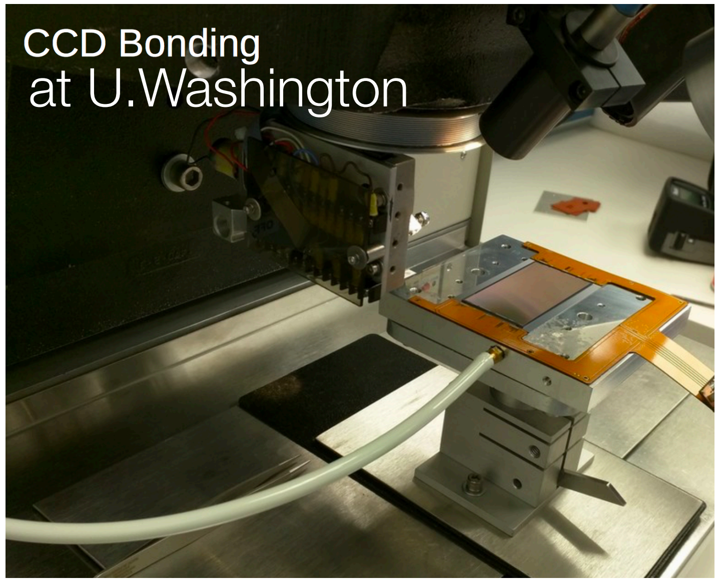


Heavy mediator



Current detector efforts…

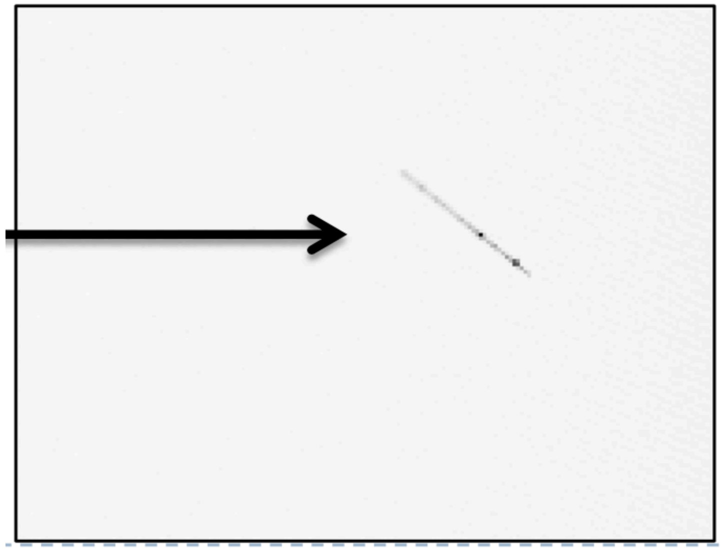
Officially started October 2018

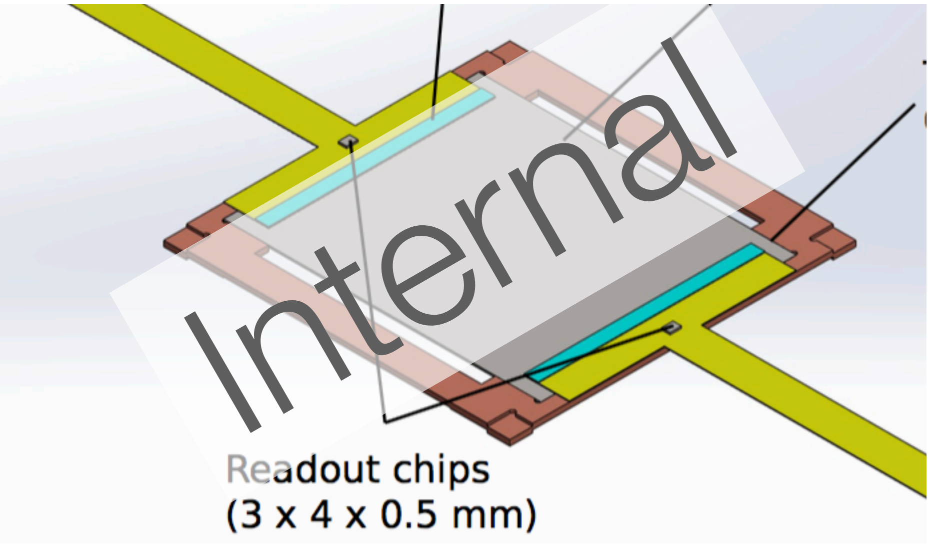


CCD PRODUCTION

- Silicon ingot provider identified
- procedure to reduce the exposure to cosmic rays (during wafering, production and transport)
- CCD packaging at UW
  - ➡ Operating 1st thick skipper CCDs (2k x 4k)

Image taken with DAMIC-M skipper CCD



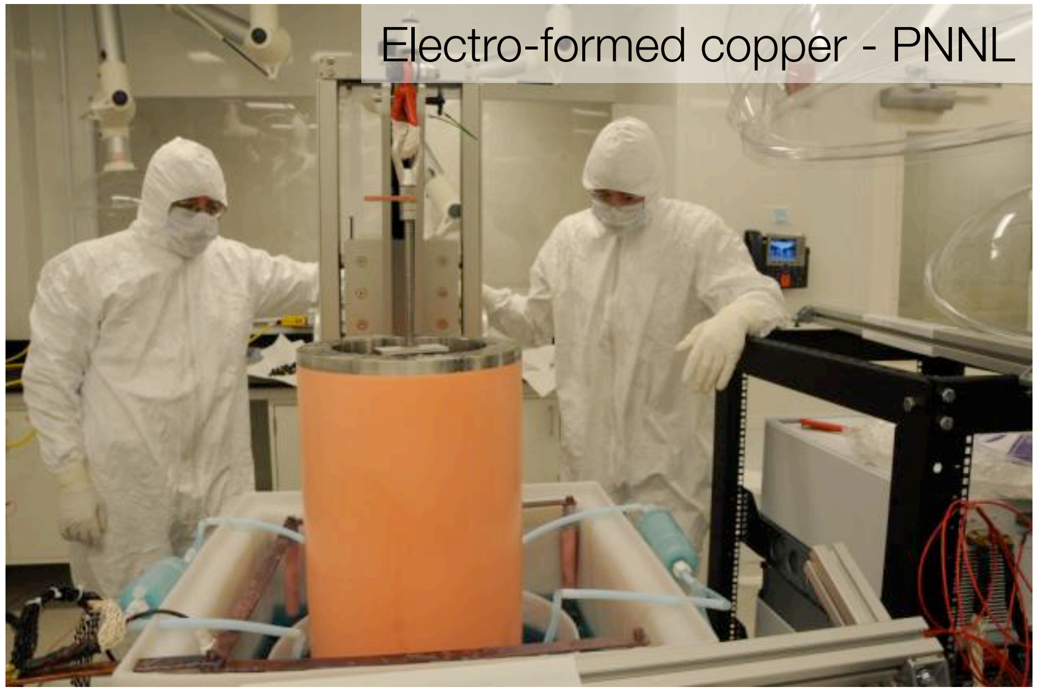


DETECTOR DESIGN

- Preliminary design of CCD frames and CCD stack (US), cryostat and shielding (FR)
- Electronics and cabling R&D (tests ongoing, FR):
- Material screening and selection (cables, electronics)

DAQ/DQM, SOFTWARE/SIMULATIONS

and background mitigation


Electro-formed copper - PNNL

Background (to be reduced to fraction of DRU)

- **External background:** better material selection and handling (e.g. electroformed copper, surface contamination, Rdn)
- **Bulk background:** ^{32}Si et tritium

Produced by cosmic rays on the Ar in atmosphere, it deposits on ground with precipitations (rain, snow,…)

Tritium: expected to be the dominant background for DAMIC-M

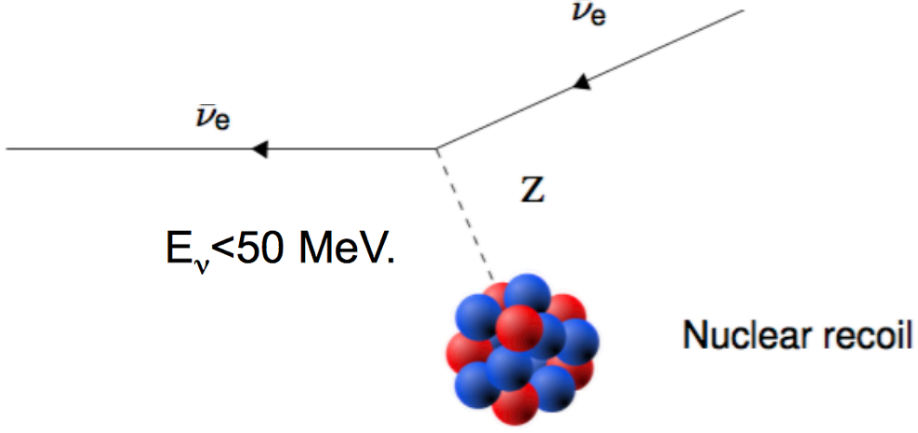
Produced by the cosmic neutrons and muon spallation in the Si bulk. production rate ~ 25 - 100/Kg/day (s.l.)

—> Minimize the time CCDs are exposed to cosmic rays (stock CCD underground, shielded container for transportation,…)

CCD Application to neutrinos

Coherent elastic ν-N scattering

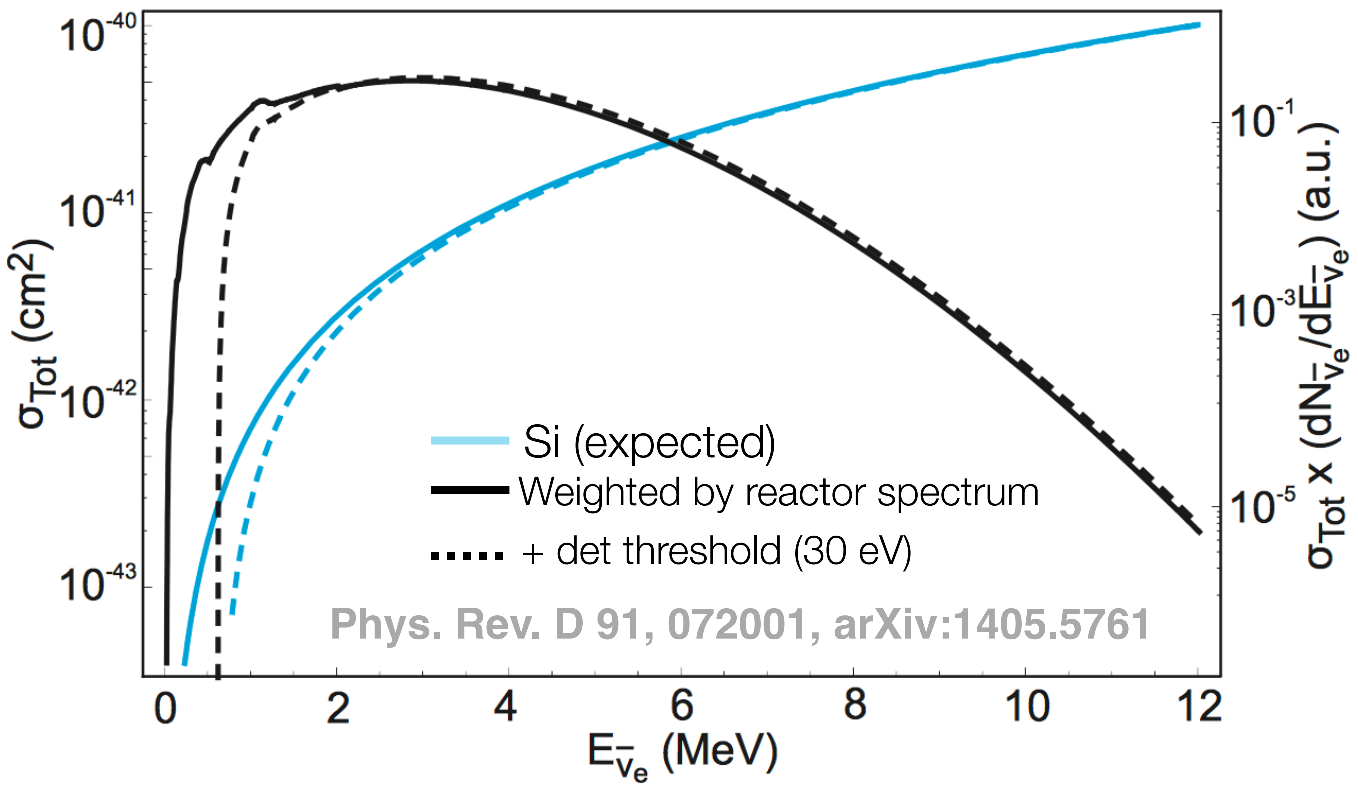
In Coherent Elastic Neutrino-Nucleus Scattering (CEνNS), the neutrino scatters off the nucleus as a whole.



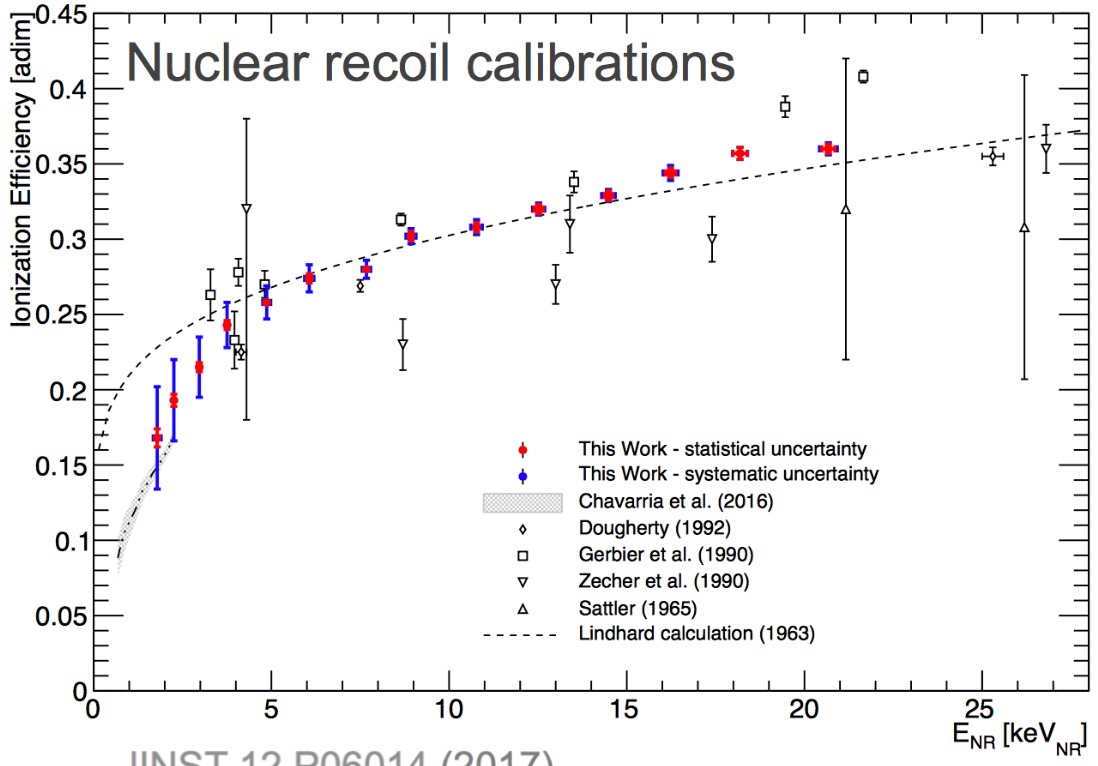
$$\frac{d\sigma}{dE_{\mathrm{rec}}}(E_{\bar\nu_e}, E_{\mathrm{rec}}) = \frac{G_F^2}{8\pi}[Z(4\sin^2\theta_W - 1)+N]^2 \times M(2 - \frac{E_{\mathrm{rec}}M}{E_{\bar\nu_e}{}^2})|f(q)|^2$$

The total cross-section is ≈ $4.22 \times 10^{-45} N^2 E_\nu{}^2$ cm^2 (N=14 for Si)

CONNIE experiment using CCD (same of DAMIC) at short distance from a nuclear reactor



Phys. Rev. D 91, 072001, arXiv:1405.5761



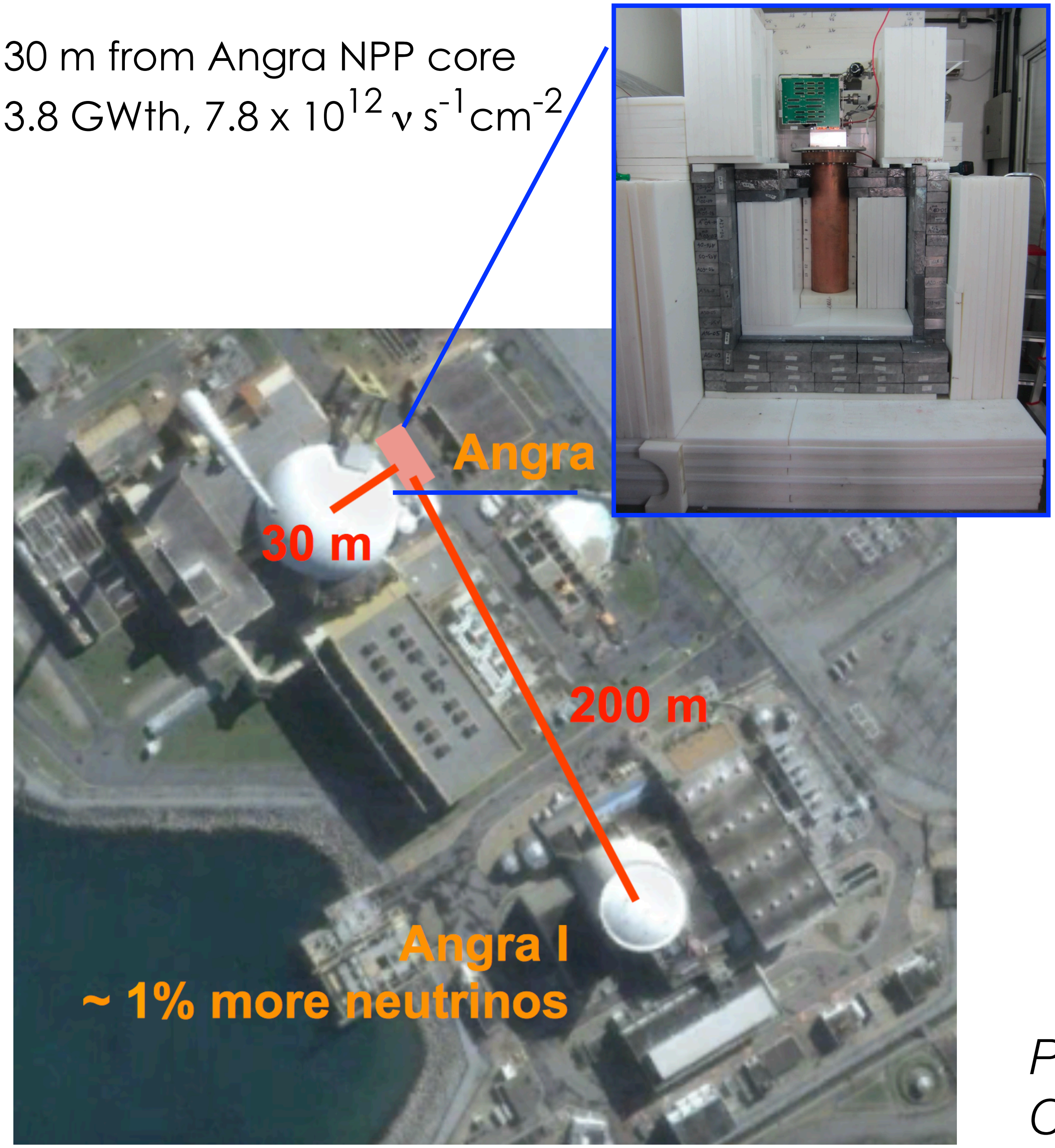
JINST 12 P06014 (2017)

CONNIE experiment @ Angra NPP

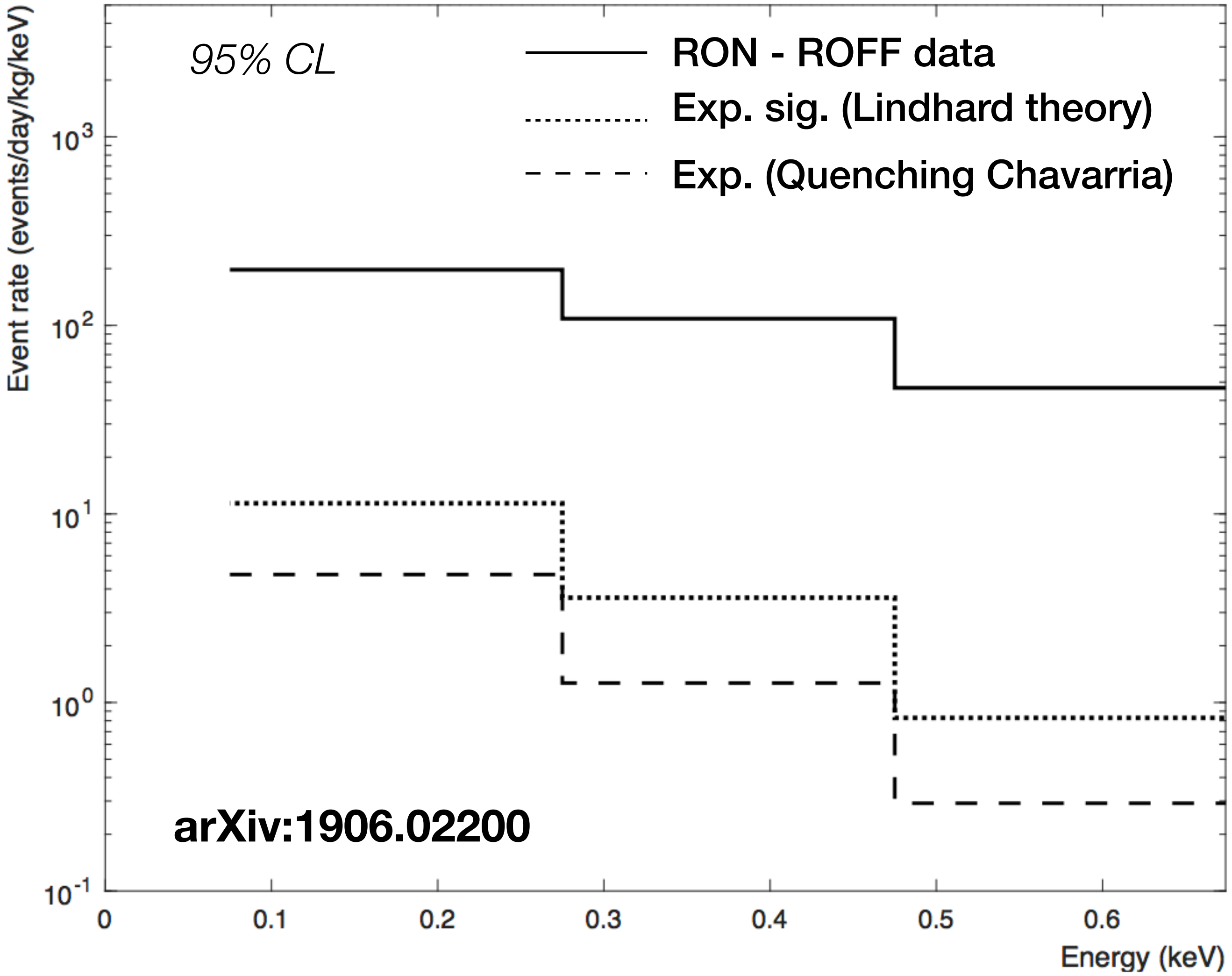
COherent **N**eutrino **N**ucleus **I**nteraction **E**xperiment

Detector Mass : 14 CCD (4k x 4k) ~ 80 gr
CCD design/performance as in DAMIC

30 m from Angra NPP core
3.8 GWth, 7.8 x 10^{12} ν $s^{-1}$$cm^{-2}$



Principle : Detect the coherent neutrino-nucleus interactions by measuring the ionisation of nuclear recoils



arXiv:1906.02200

3.7 kg-days: 2.1 kg-days reactor ON
1.6 kg-days reactor OFF

Planned future improvements include installing skipper CCDs to lower the threshold by a factor of 10.

Summary

DAMIC has proved the CCD technology as a competitive technique for the low-mass DM search

- Features : **unique spatial resolution, single electron resolution, extremely low noise (readout dominated), energy threshold ~ 40eV**
- Essential information for the next generation of Si detectors (DAMIC-M, SuperCDMS)

Next stage : a kg size detector at Modane

- Goals : enhanced sensibility for **WIMPS at low energy** and search in the **hidden sector**.
- new readout for **sub-electron resolutions, Extremely low background** (fraction of DRU) and 1kg mass are the main novelties

CCD as particle detector : DAMIC (for dark matter),
CONNIE (neutrino)

Thank you for your attention!

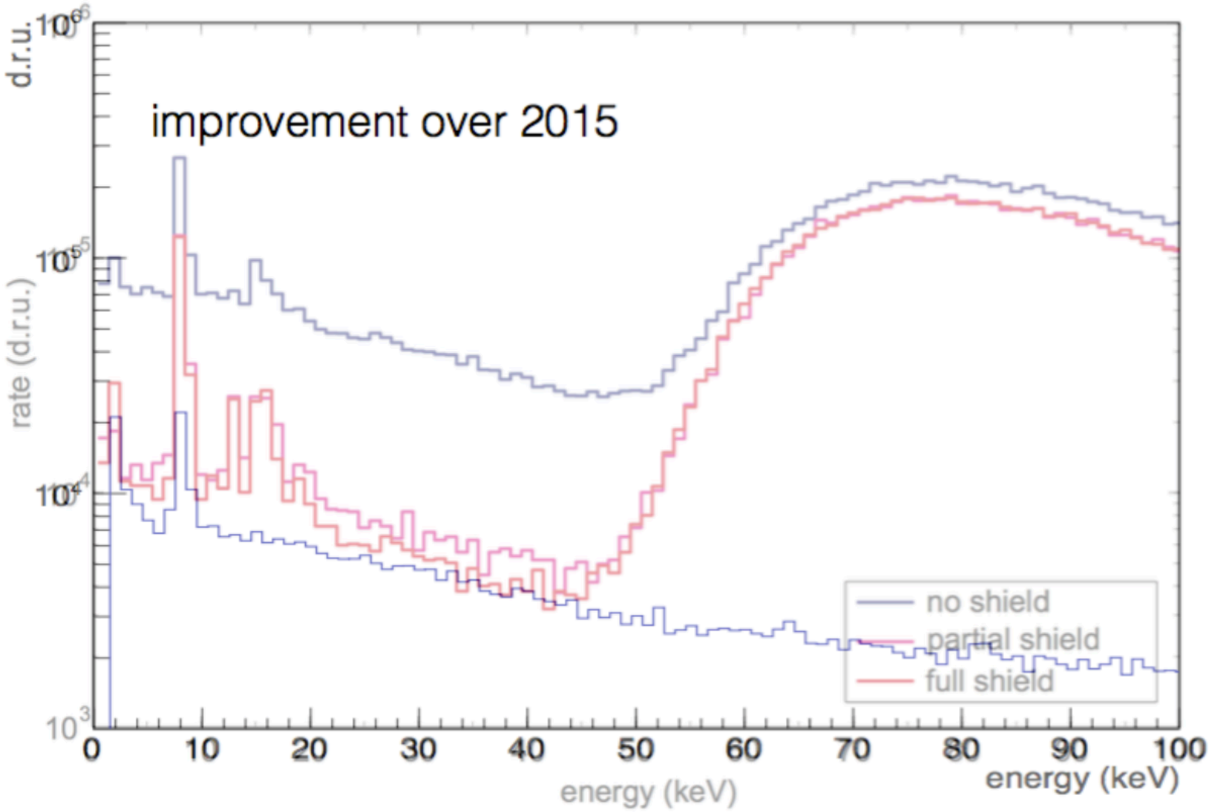
PhD fellowship CNRS - U.Chicago open @ Nantes
(Starting in October 2019)

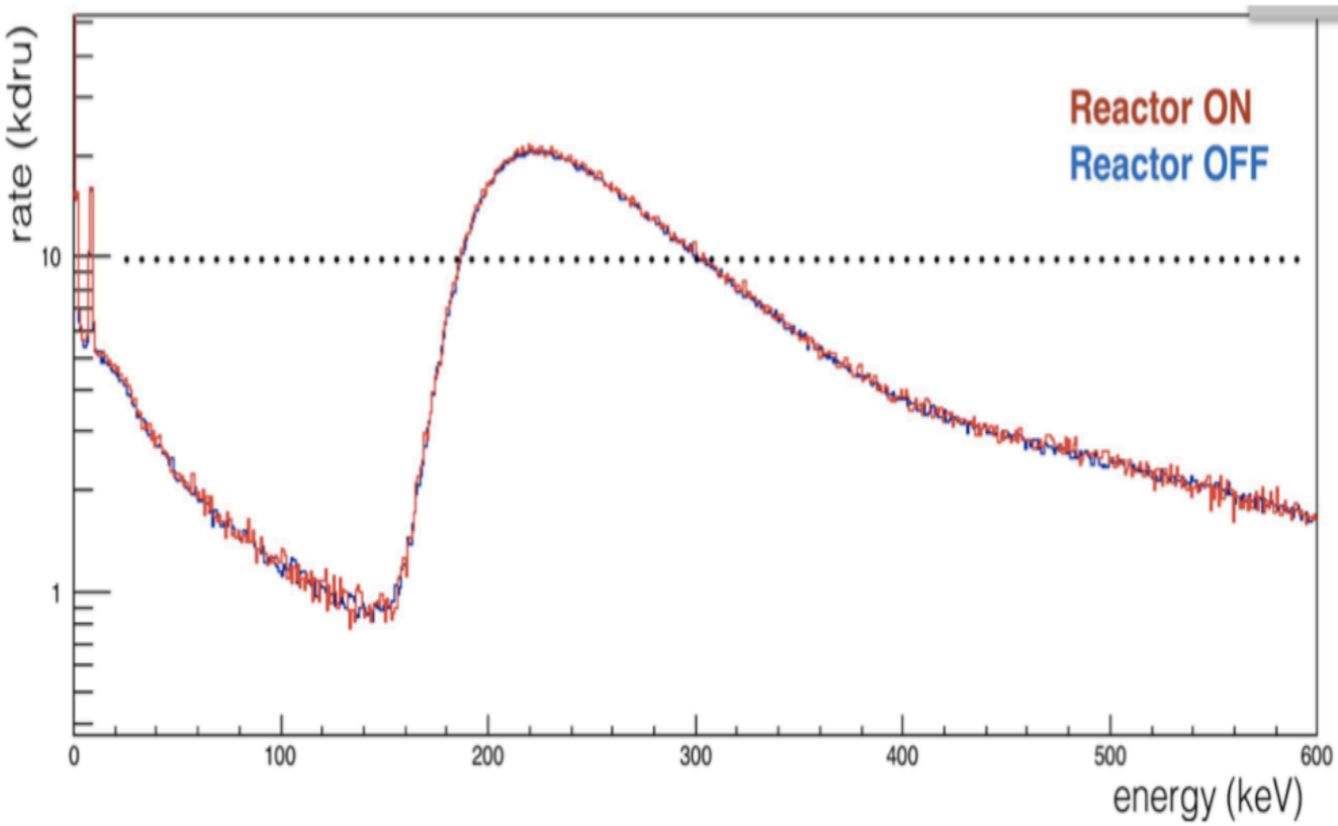
Application on the CNRS portail
https://emploi.cnrs.fr

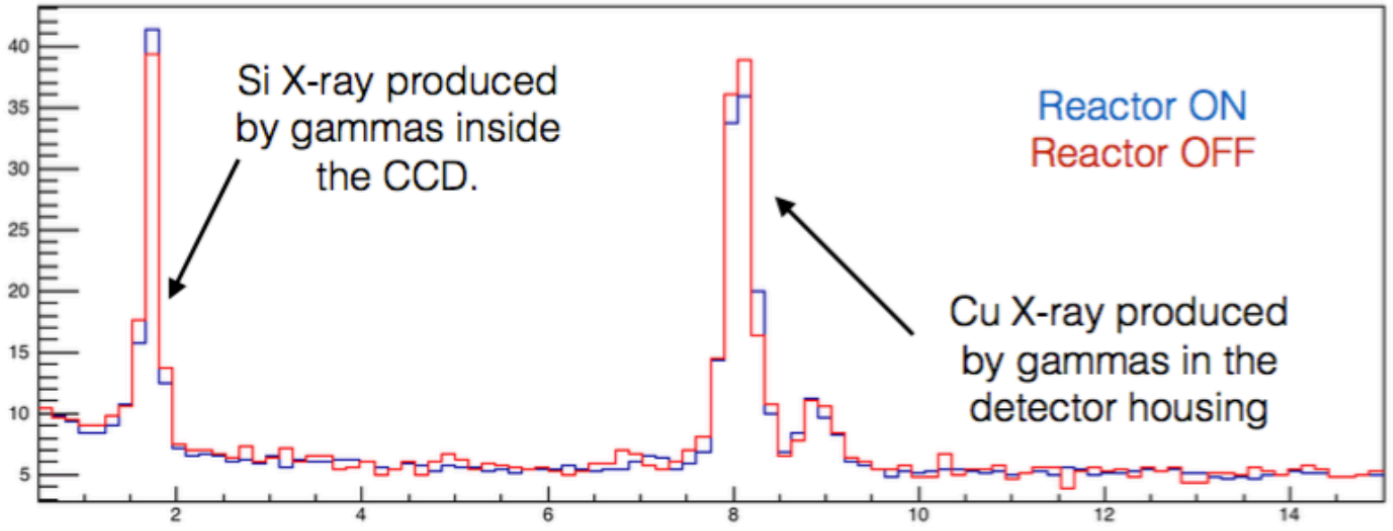
For information:
DAMIC.PhD2019@subatech.in2p3.fr

Backup

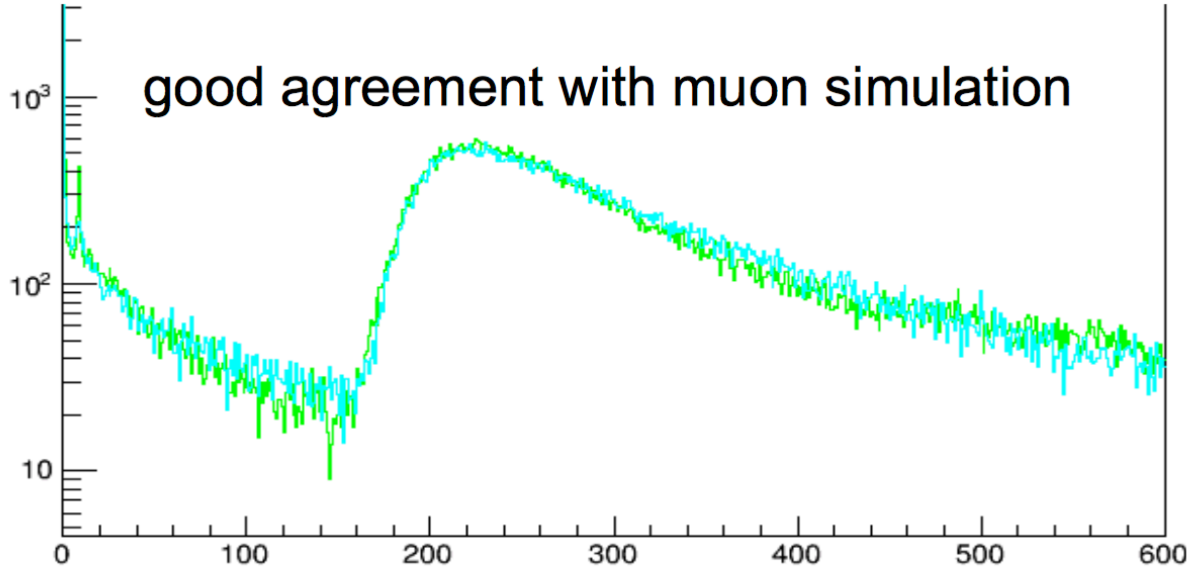
- Background reduction in 2016-2017 compared to 2015.
- Stability of muon and fluorescence x-ray rates between reactor ON-OFF.


improvement over 2015



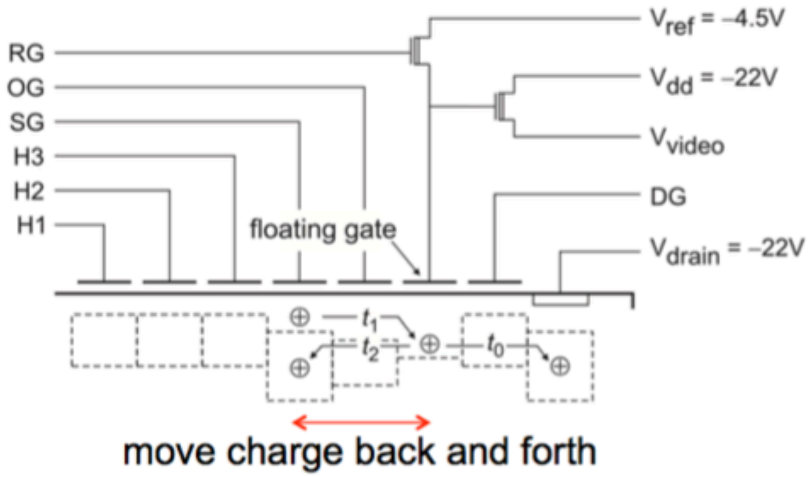

Si X-ray produced by gammas inside the CCD.

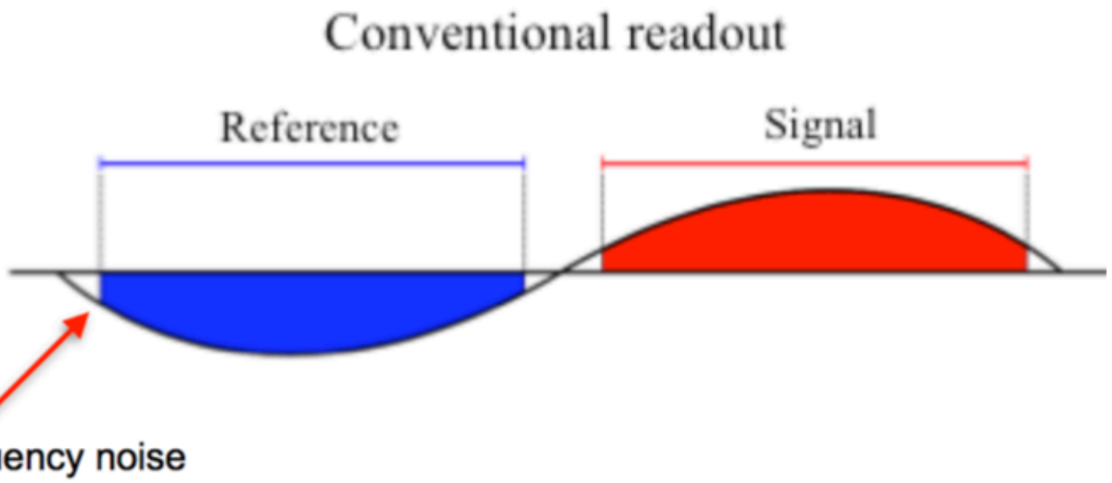
Cu X-ray produced by gammas in the detector housing


good agreement with muon simulation

DAMIC-1K sub-e^- noise

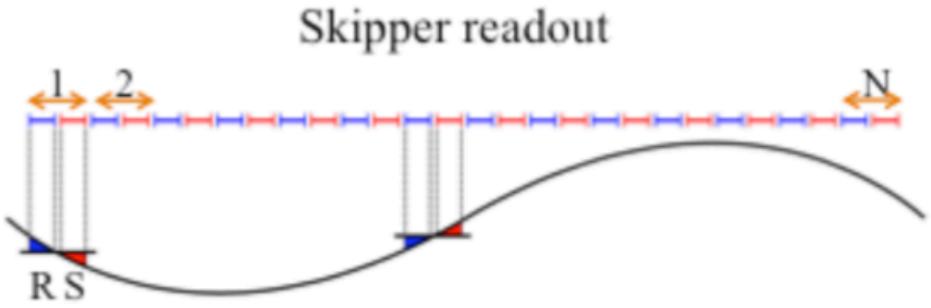
- **Skipper readout** a novel charge readout approach which results in *single electron resolution*





Non-destructive measurement of the charge!

Measure the charge fast (kill 1/f noise) and N times (noise ≈ 1/√N)



SENSEI R&D Fermilab

ββ coincidences

$$^{210}\mathrm{Pb} \xrightarrow{64\ \mathrm{keV}} {}^{210}\mathrm{Bi} \xrightarrow{1.2\ \mathrm{MeV}} {}^{210}\mathrm{Po}$$

$$\tau_{1/2} = 5\ \mathrm{d}$$

$$^{32}\mathrm{Si} \xrightarrow{0.22\ \mathrm{MeV}} {}^{32}\mathrm{P} \xrightarrow{1.7\ \mathrm{MeV}} {}^{32}\mathrm{S}$$

$$\tau_{1/2} = 14\ \mathrm{d}$$

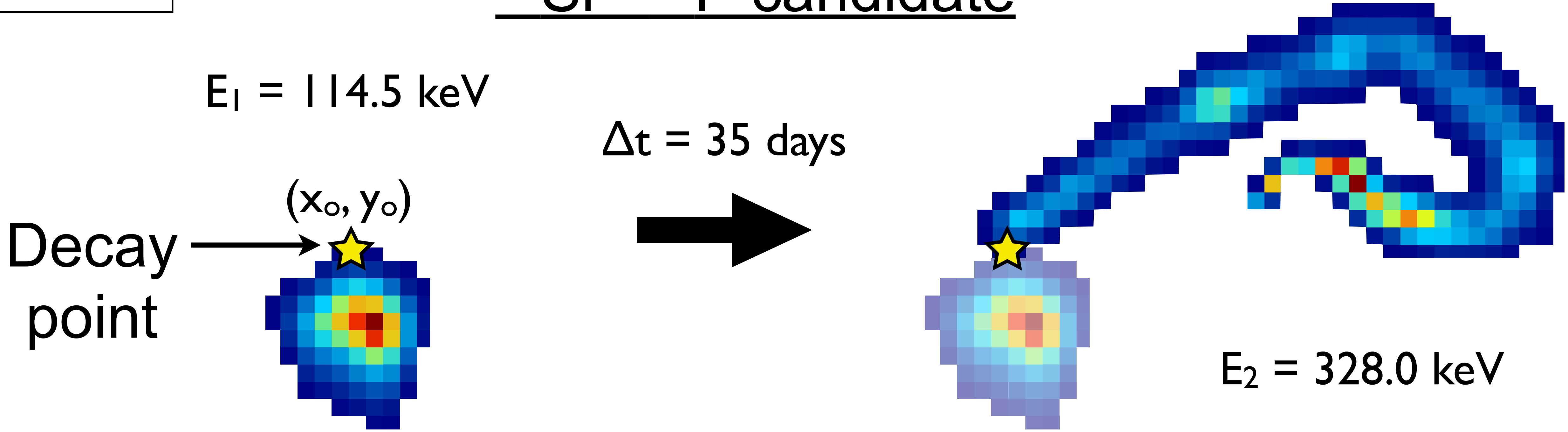
57 days of data in 1 CCD:

$^{210}\mathbf{Pb} < 37\ \mathrm{kg}^{-1}\mathrm{d}^{-1}$
(95% C.L.)

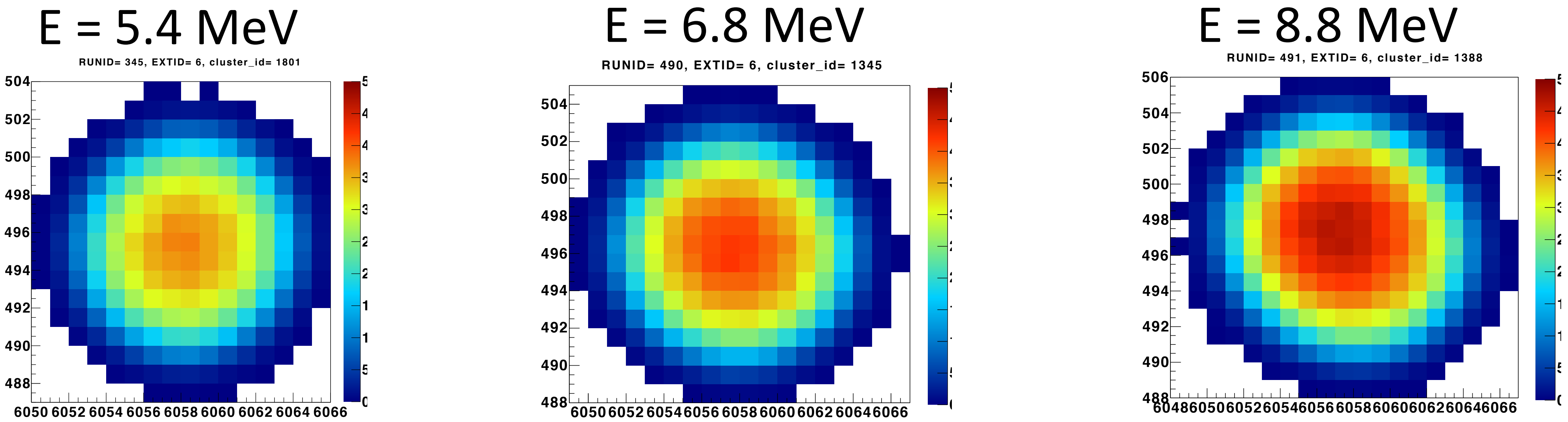
$^{32}\mathbf{Si} = 80^{+110}_{-65}\ \mathrm{kg}^{-1}\mathrm{d}^{-1}$
(95% C.L.)

JINST 10 P08014

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



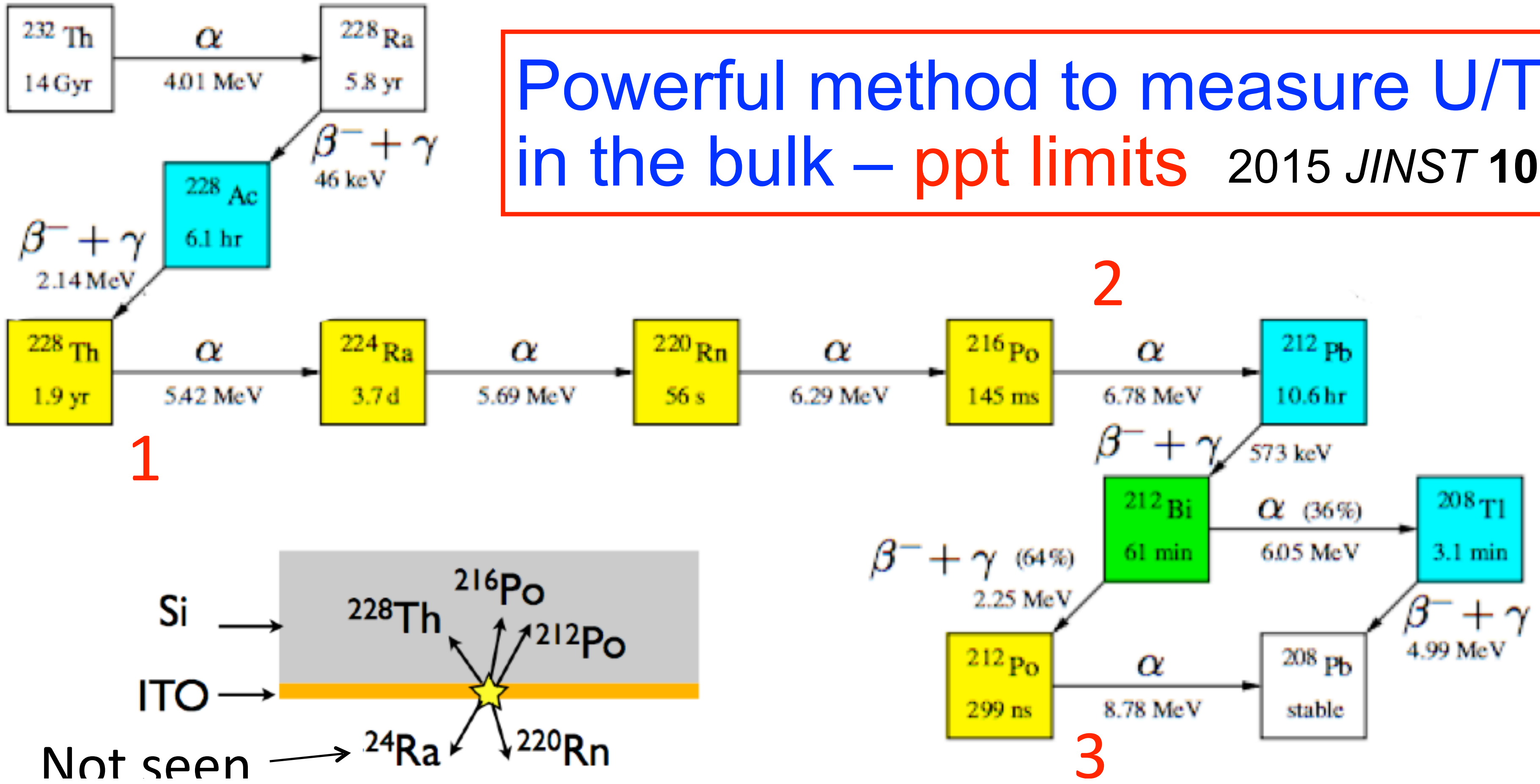
DAMIC background characterization



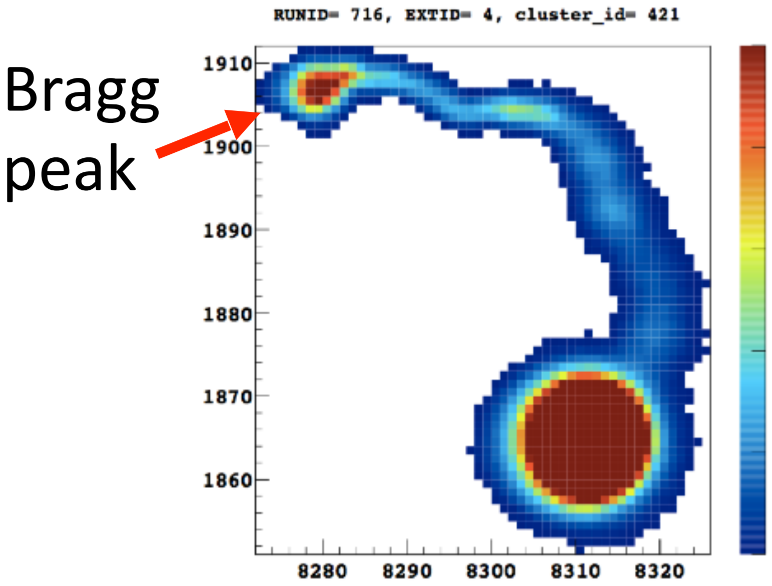
1 Δt = 17.8 d 2 Δt = 5.5 h 3

Three α at the same location!

Powerful method to measure U/Th bkg in the bulk – ppt limits 2015 *JINST* **10** P08014



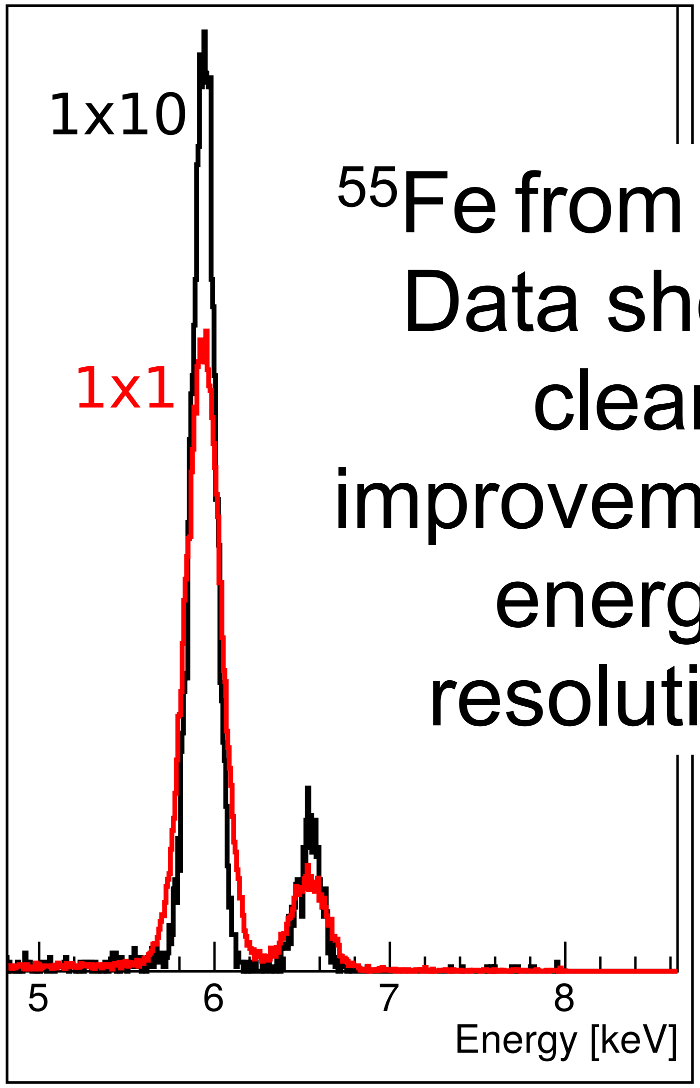
Example of α + β



Flexibility in readout

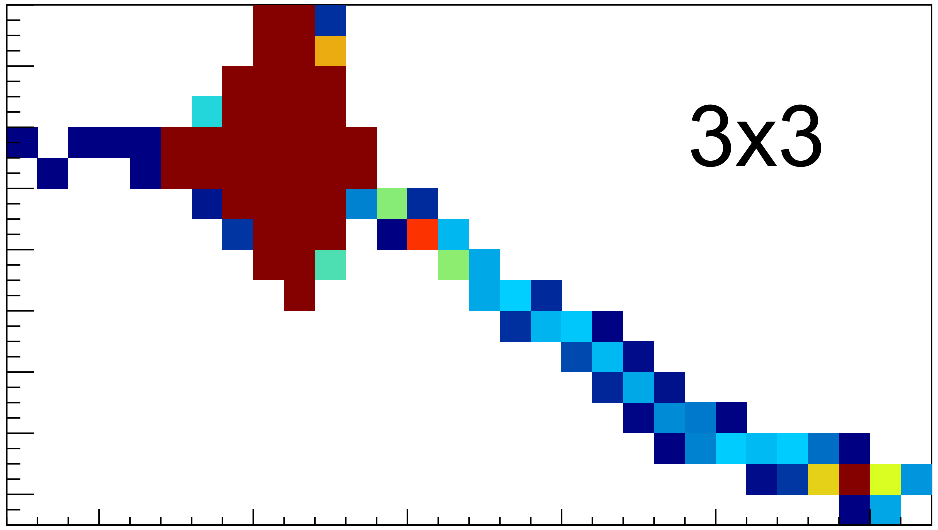
Pixels can be readout in “groups” and the total charge estimated in a single measurement.

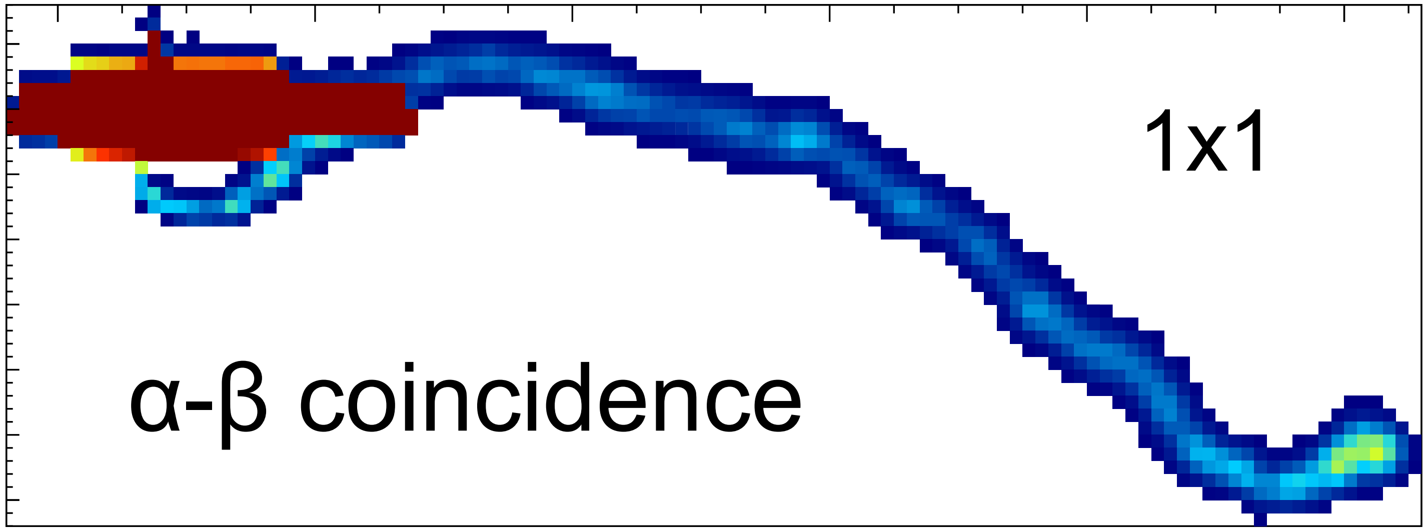
Less pixels but same noise *per* pixel!



^{55}Fe from back: Data shows clear improvement in energy resolution.

Loss of x, y and z information

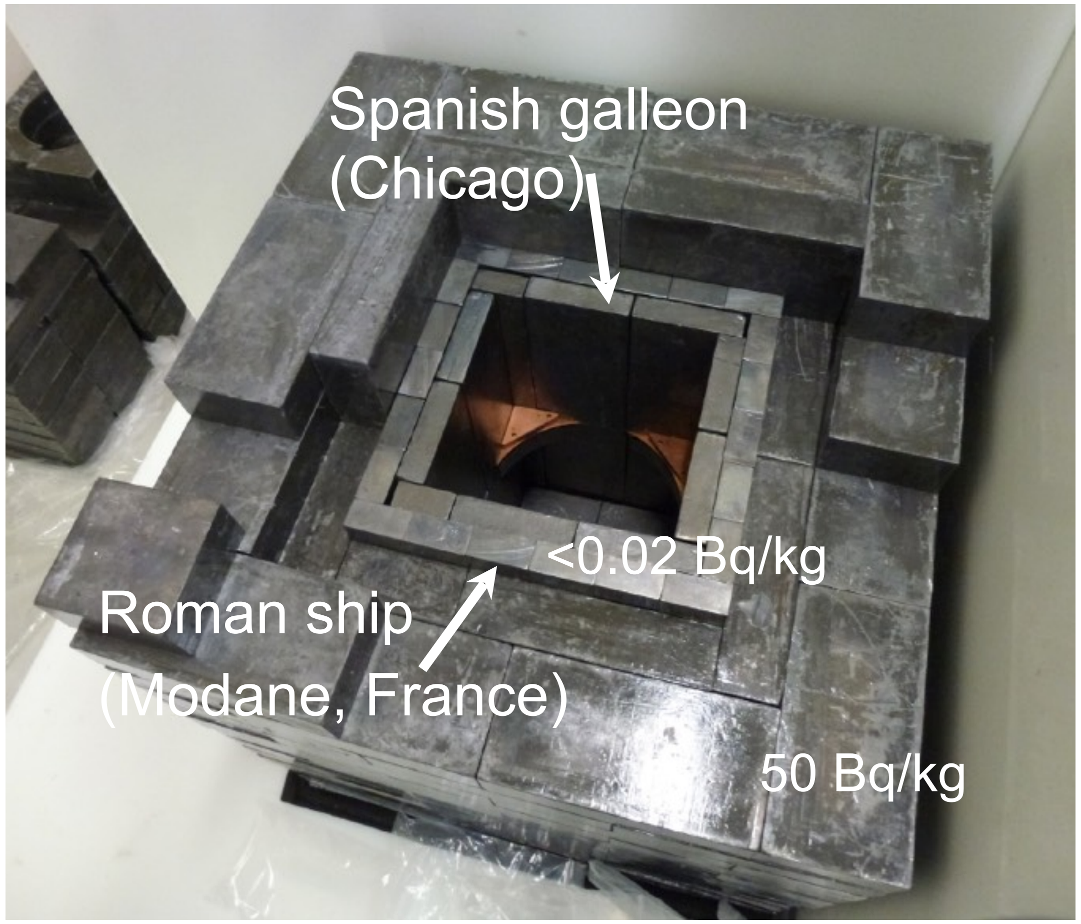




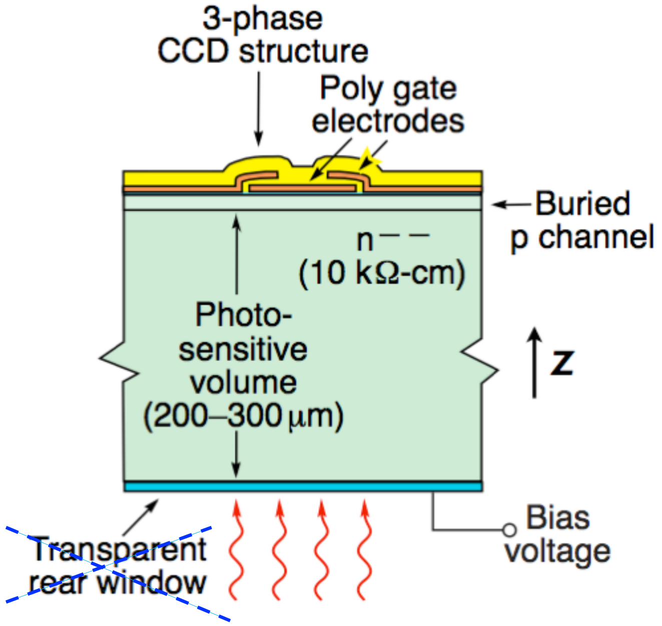
α-β coincidence

- **Lead shielding** to stop environmental γ rays

Inner 2” shielding made of ancient lead to avoid bremmstrahlung γs from ^{210}Pb β-decay (22 yrs half-life)



- **Material selection and cleaning:** copper machining, “secret” recipe etching (surface bkg)



Radioactive!

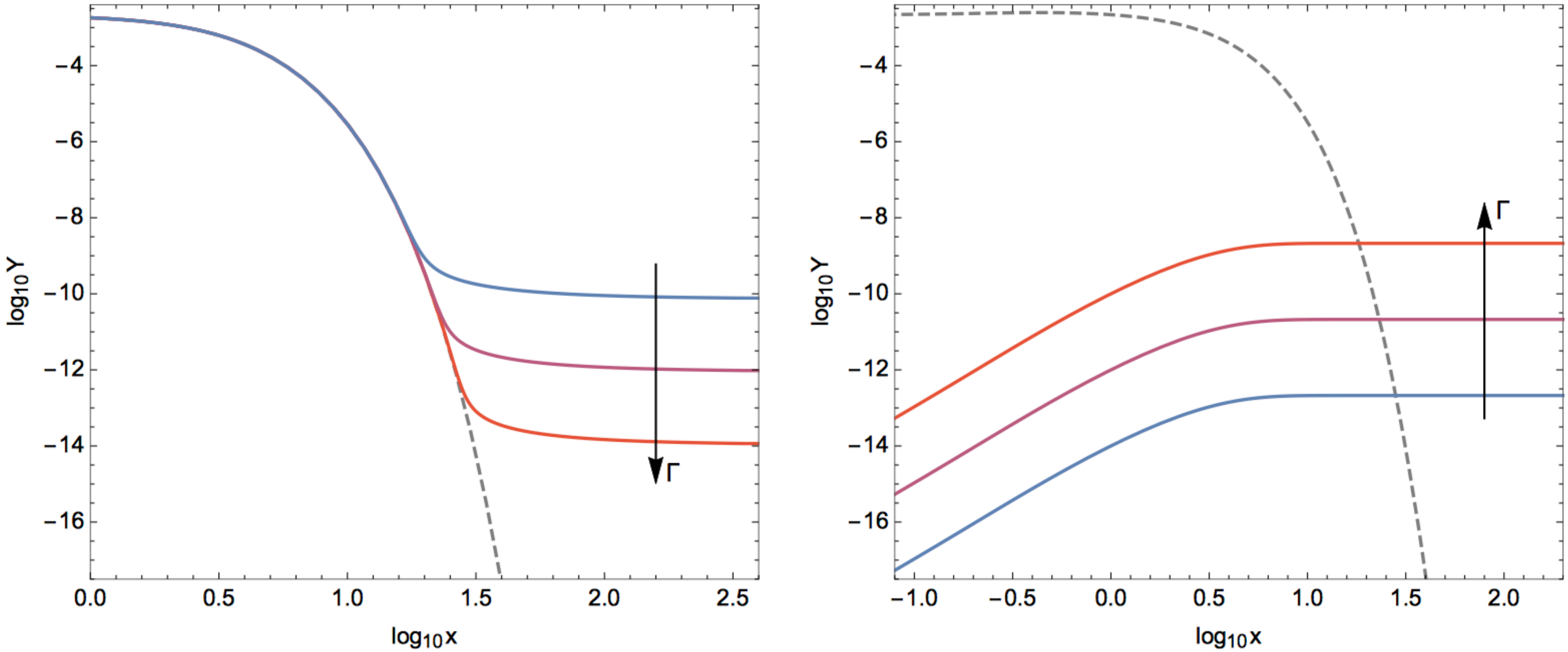


Figure 2. The two basic mechanisms for DM production: the freeze-out (left panel) and freeze-in (right panel), for three different values of the interaction rate between the visible sector and DM particles χ in each case. The arrows indicate the effect of increasing the rate Γ of the two processes. In the left panel $x = m_\chi/T$ and gray dashed line shows the equilibrium density of DM particles. In the right panel $x = m_\sigma/T$, where σ denotes the particle decaying into DM, and the gray dashed line shows the equilibrium density of σ. In both panels $Y = n_\chi/s$, where s is the entropy density of the baryon-photon fluid.