GDR DUPhy, 29th November - 1st December 2021, Paris

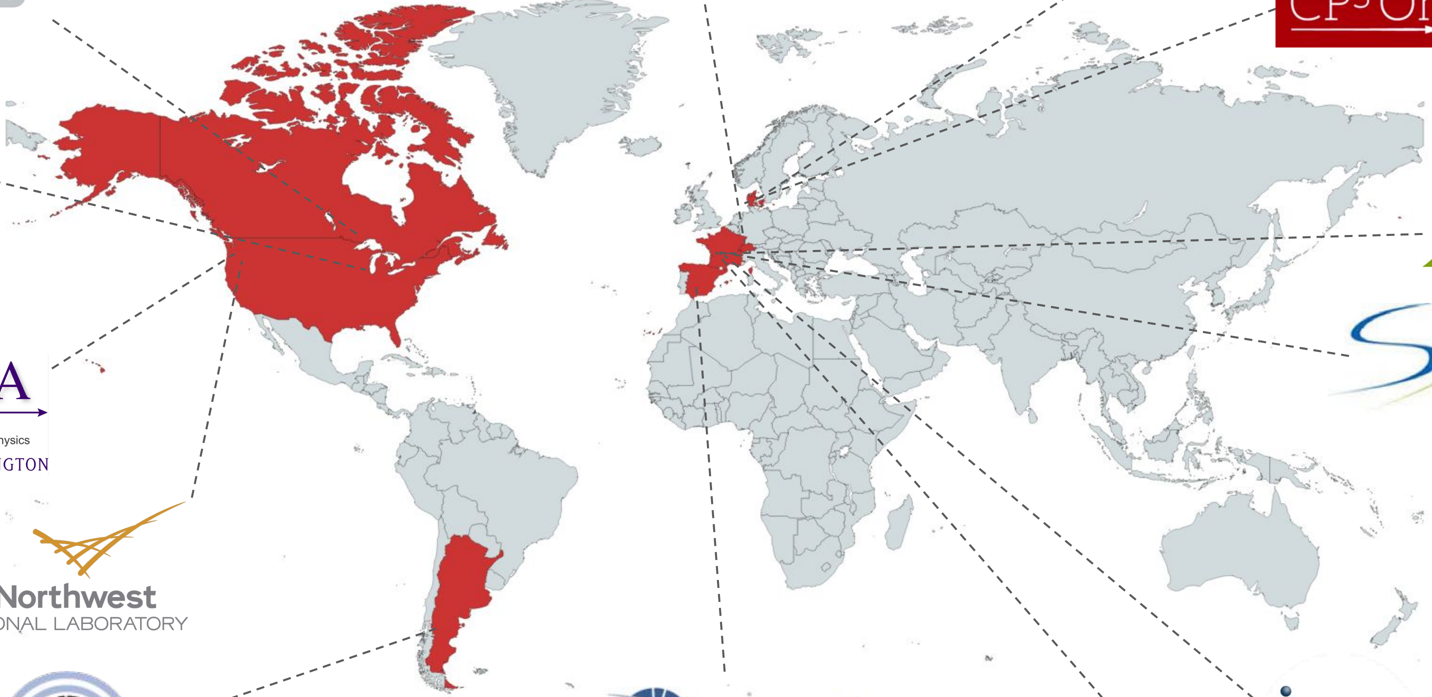
Search for Light Dark Matter with DAMIC-M

Claudia De Dominicis on behalf of the DAMIC-M Collaboration
SUBATECH, CNRS, IMT Atlantique, Nantes

Outline

- The DAMIC-M experiment
- DAMIC-M design and simulations
- Low Background Chamber prototype

The DAMIC-M Collaboration



SNOLAB

The University of Chicago 1890

CENPA
Center for Experimental Nuclear Physics and Astrophysics
UNIVERSITY of WASHINGTON

Pacific Northwest NATIONAL LABORATORY

CNEA

University of Zurich[UZH]

Niels Bohr Institutet

CP3 Origins

LSM

Subatech

IFCA Instituto de Física de Cantabria

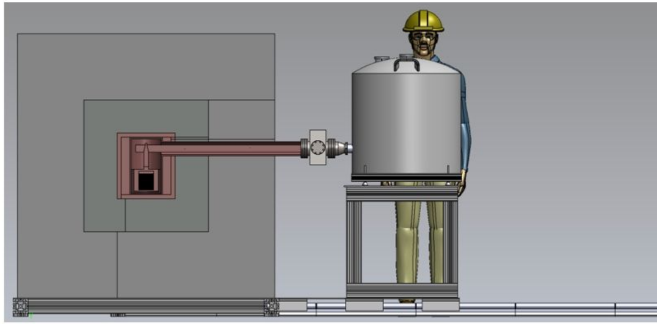
LPNHE PARIS

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

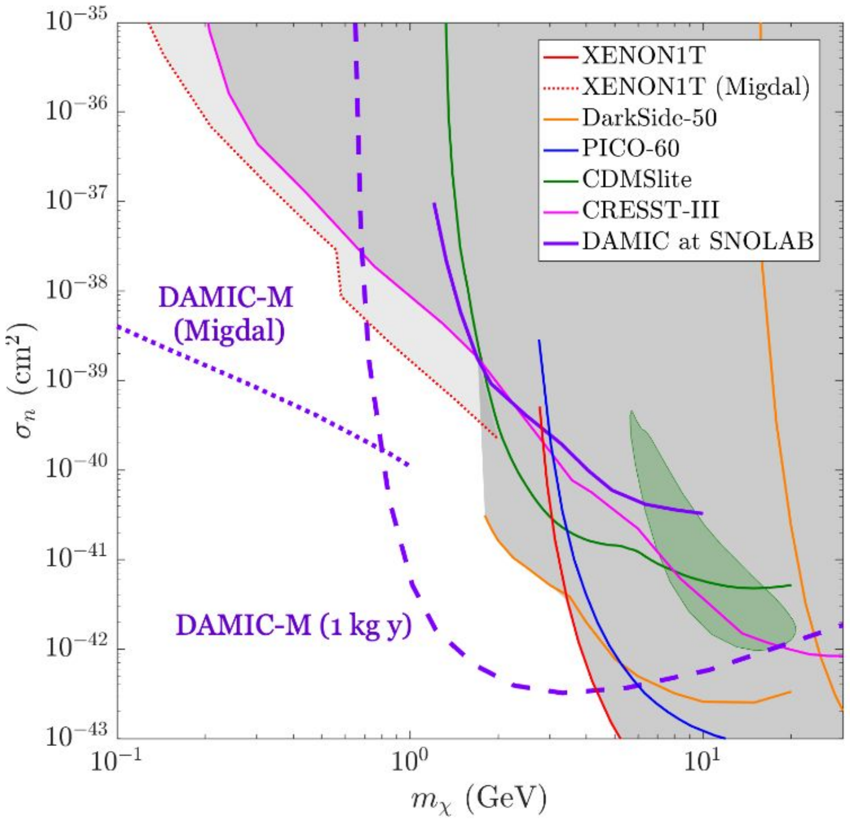
DArk Matter In CCDs at Modane: DAMIC-M

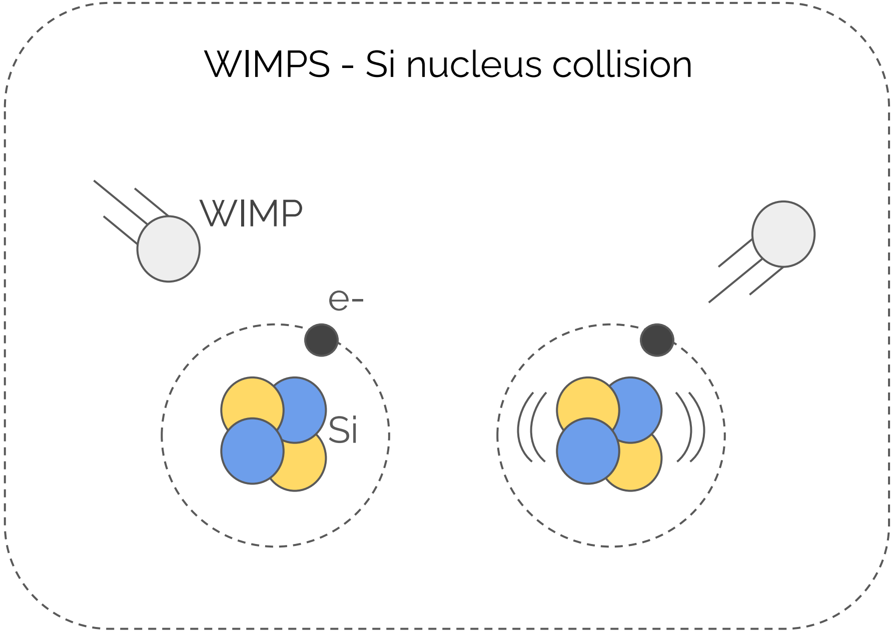
- Predecessor: DAMIC@SNOLAB
  See contribution by Michelangelo Traina
- Location: LSM Laboratoire Souterrain de Modane (under 1700m of rock)
- Aim: detect Light DM (WIMP, Hidden Sector) signals

  via interaction with Si e- or nucleus in bulk of CCDs
- Detector features:
  - ~200 CCDs 6000 pix x 1500 pix
  - ~1 kg size
  - Sub-electron resolution
  - Temperature: 140 K → Dark current: 0.001 e-/pixel/day
  - Background: fraction of decays/keV/day/kg (d.r.u)

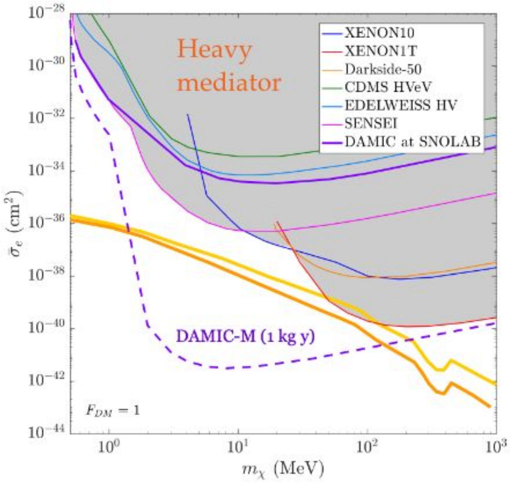


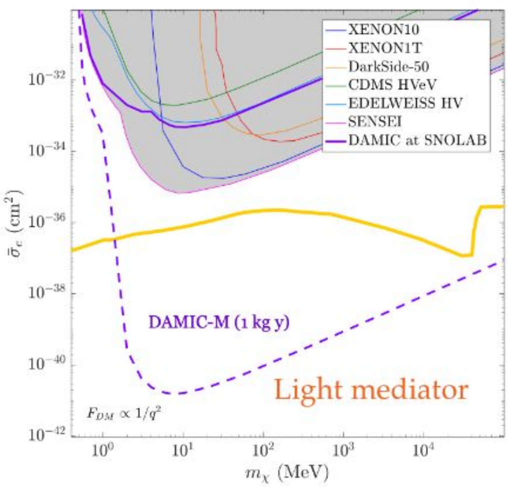
Physics reach - Light WIMPS



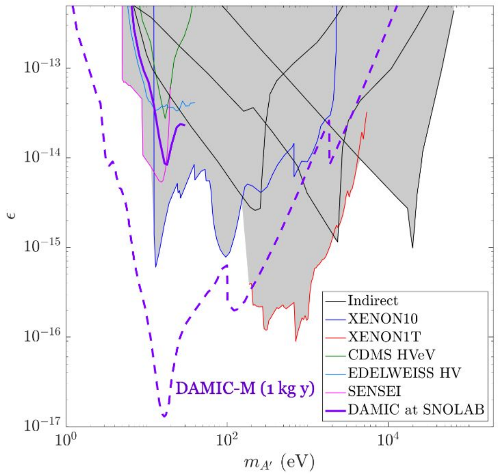


Physics reach - Hidden sector

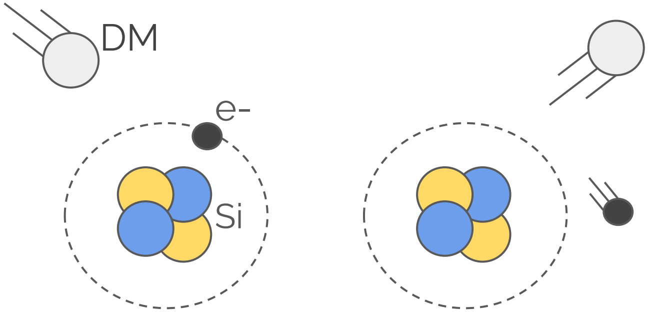




Hidden dark photon

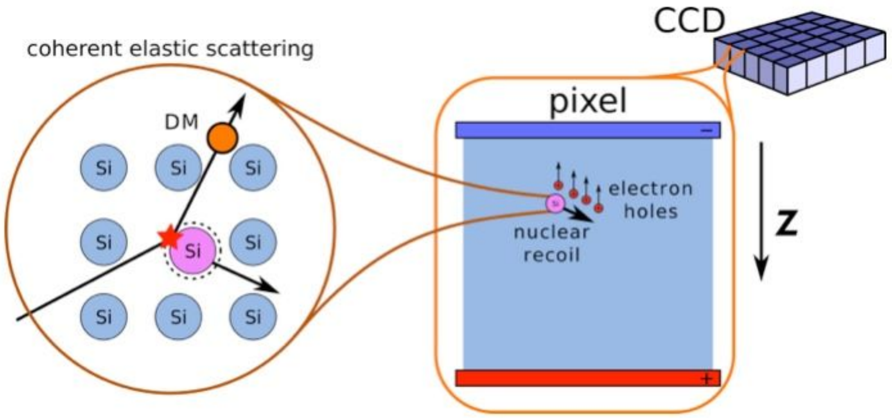


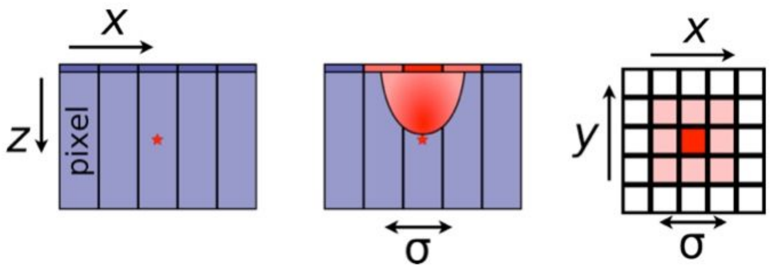
DM - valence e- collision



CCDs operation and 3D reconstruction

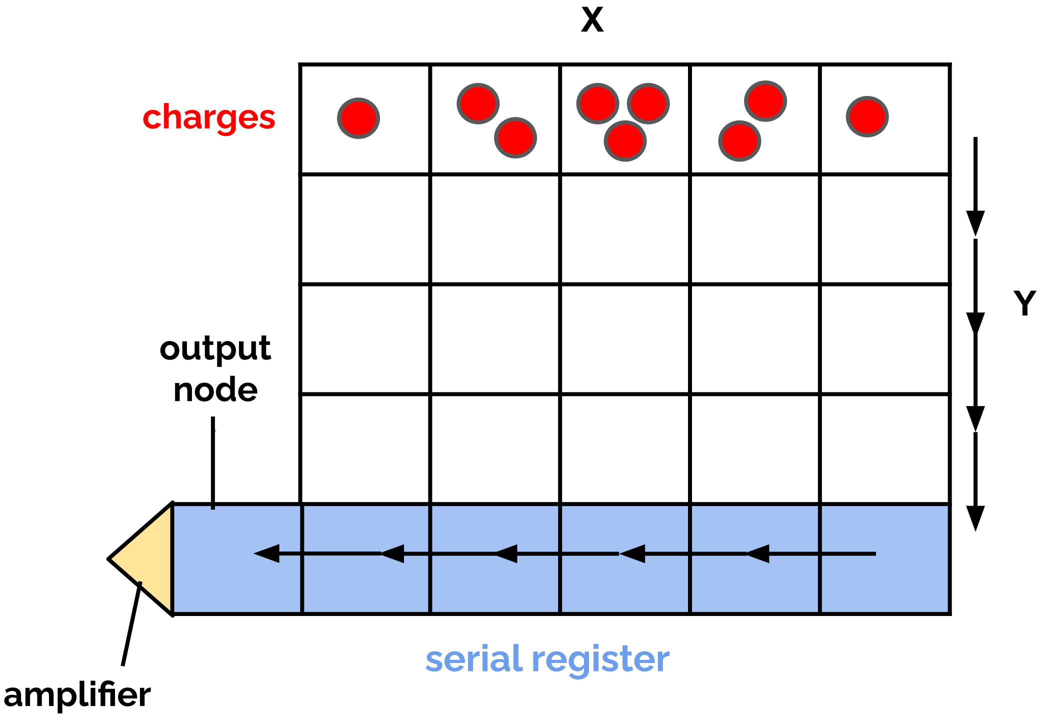
- CCD: n-type silicon (thickness: 0.675 mm)
- Creation of a depletion region (active volume) in the CCD (full depletion)
- DM interaction causes creation of e-/h pair (3.77 eV required on average) in depletion region
- 3D reconstruction:
  - z position: diffusion of charges during drift
  - x-y position: Precise spatial resolution (0.015 mm x 0.015 mm pixels)





CCDs readout

- charges in a row moved in the following row
- charges in serial register moved pixels by pixels in X direction
- charges in output node read by amplifier
- In DAMIC-M: Skipper Amplifier

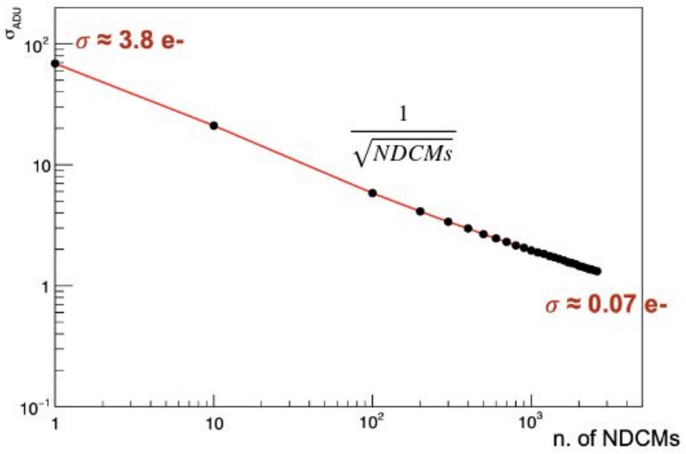


Skipper CCDs for sub-electron resolution

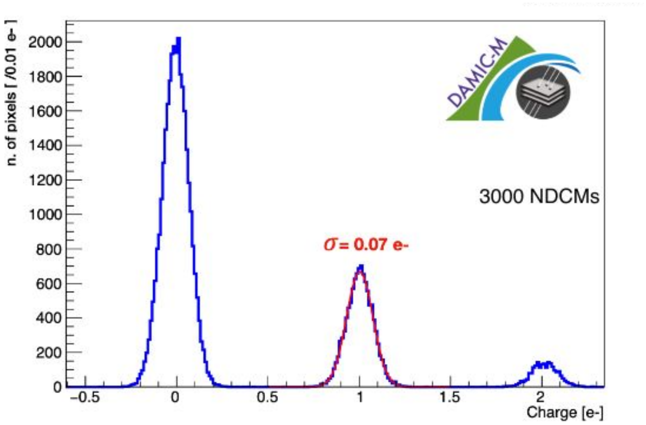
Skips = Non Destructive Repetitive Charge Measurements (NDCMs)

Charges in output node read by amplifier N times

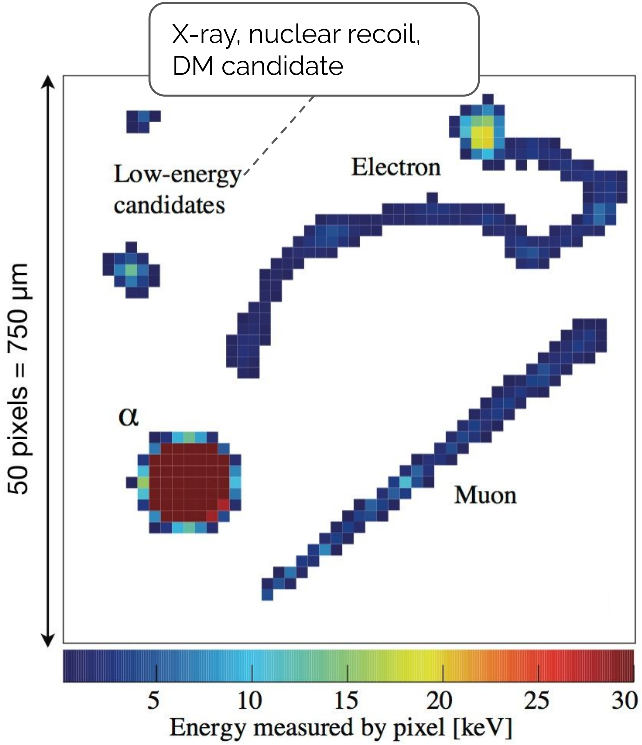
Readout noise decrease by a factor 1/sqrt(N)



Single electron resolution

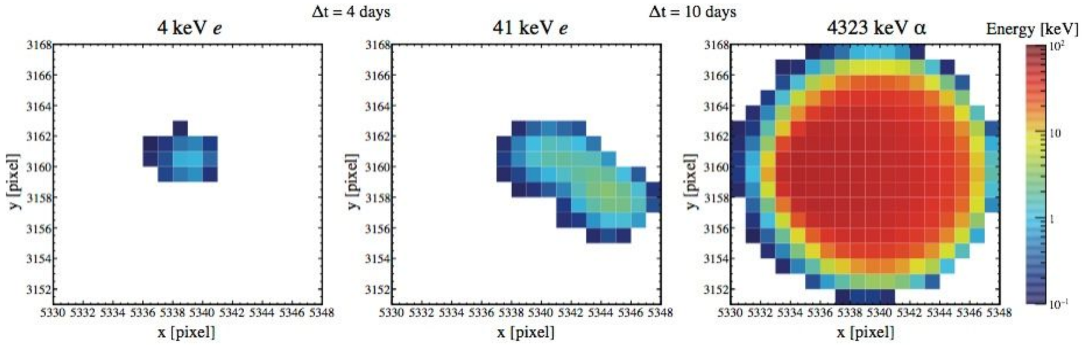


Particle identification



Signatures of different ionizing particles in a CCD

Identification decay chains



Decay chain of a ^{210}Pb nucleus on the CCD surface [1]:

Pb210 → Bi210 + e- with t1/2= 22y, Q-value = 63.5 keV
Bi210 → Po210 + e- with t1/2= 5d, Q-value = 1.16 MeV
Po210 → Pb206 + α with t1/2 = 138 d, Q-value = 5.41 MeV

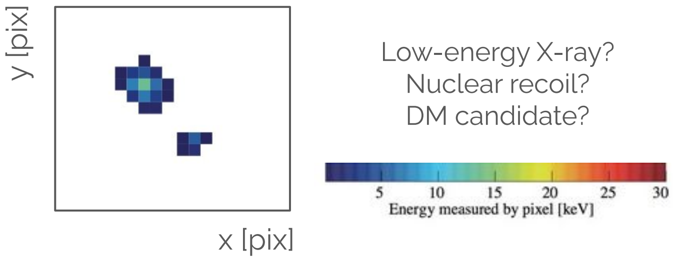
[1] A. Aguilar-Arevalo et al. [DAMIC], Measurement of radioactive contamination in the high-resistivity silicon CCDs of the DAMIC experiment, JINST **10** (2015) no.08, P08014, [arXiv:1506.02562 [astro-ph.IM]].

Challenges of DAMIC-M

Background goal: < 1 d.r.u

How to distinguish signal from background?

Main sources of background: e- , gammas, neutrons



Techniques to reduce background:

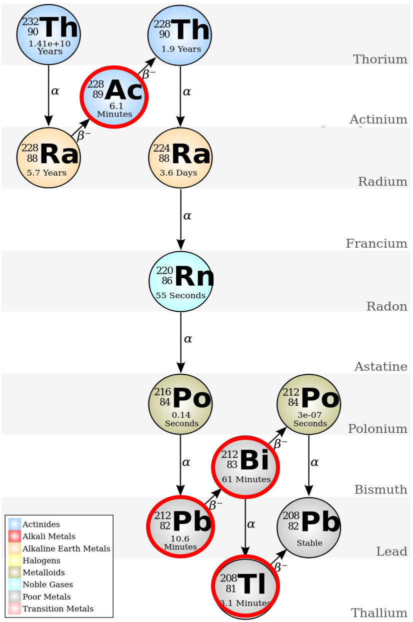
- radiogenic contamination:
  - use ultra pure materials
  - chemical treatment
- cosmogenic activation:
  - limit exposure time on surface
  - underground storage
  - shielded material transportation
- cosmic rays:
  - detector underground
- external gamma & neutrons:
  - ancient lead and polyethylene shield

Techniques to distinguish bkg/signal

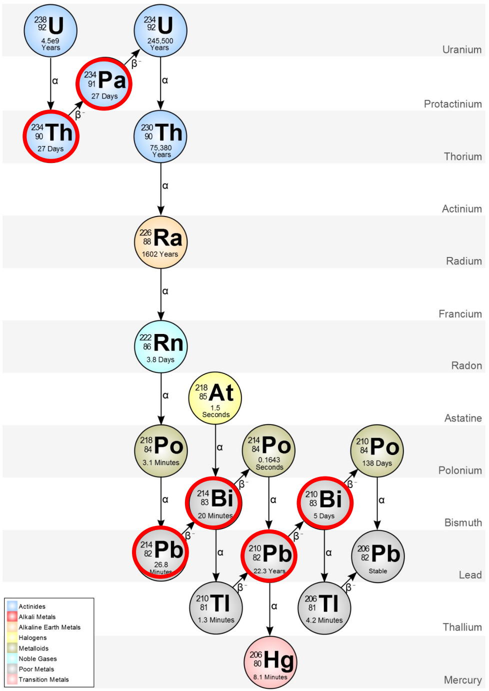
- analysis techniques:
  - fiducial cuts
  - particle identification
  - modelling the background

Background: problematic isotopes for DAMIC-M

Th232 Chain



U238 Chain



Cosmogenic isotopes

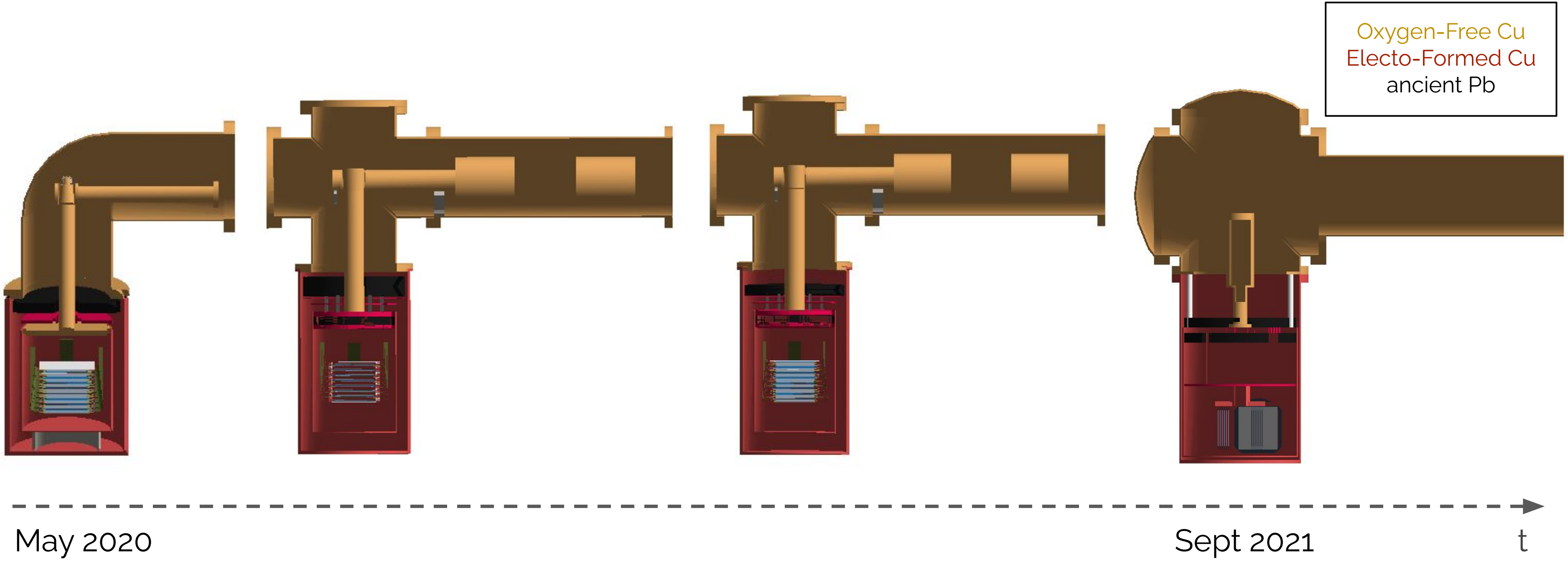
- Co56 (in Cu)
- Co57 (in Cu)
- Co58 (in Cu)
- Co60 (in Cu)
- Mn54 (in Cu)
- Fe59 (in Cu)
- Sc46 (in Cu)
- Si32 (in Si)
- Na32 (in Si)
- H3 (in Si)

Others

- K40 (in Epoxy)
- Rb87 (in Cu and Epoxy)

DAMIC-M design evolution

An extensive campaign of innovation of the detector's technology and design is ongoing

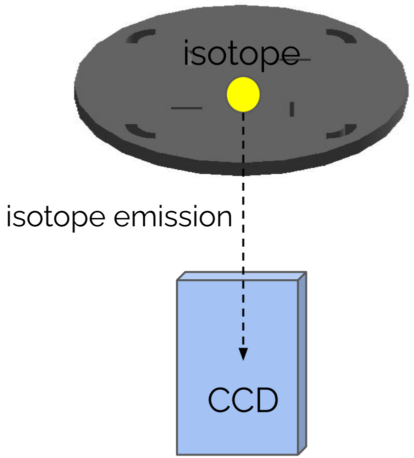


DAMIC-M simulation chain

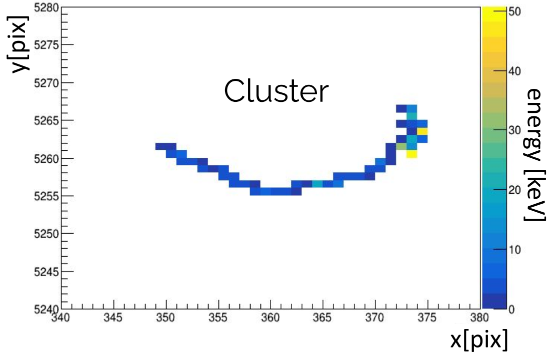
Simulations exploited to estimate the background level, optimize the detector design, drive the material selection and handling.

Geant4	Python code	Personal script
simulate the interactions of the isotopes in detector components	mimic CCD response	background estimation

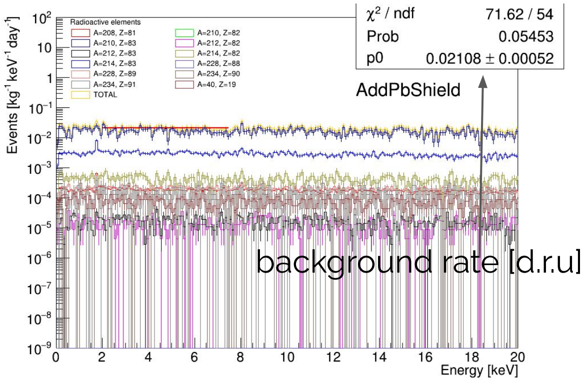
Detector component: Pb Shield



Pixelization and clusterization processes

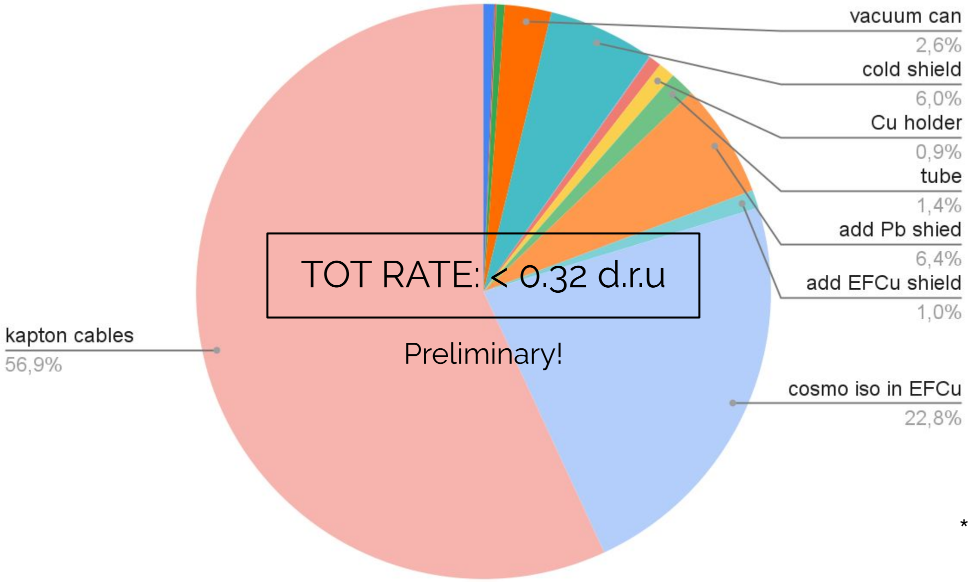


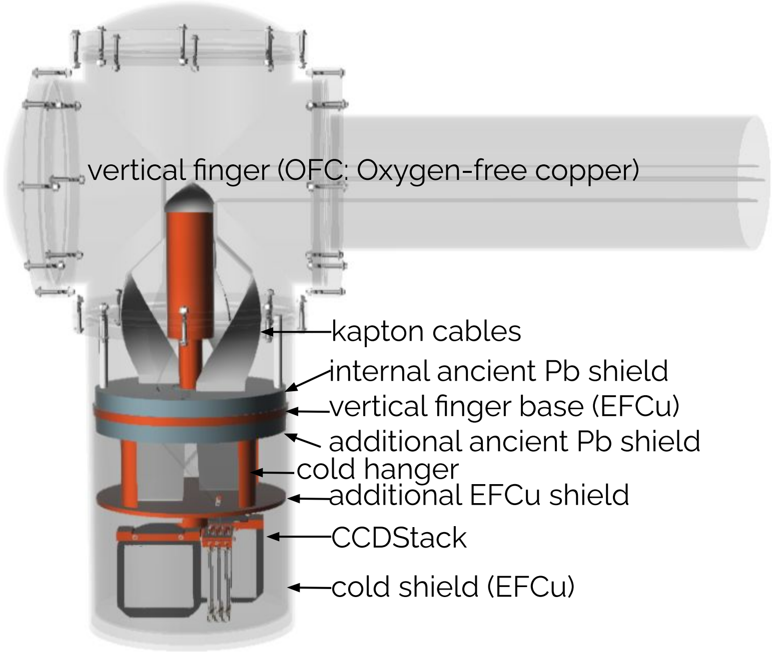
Clusters Energy Spectrum

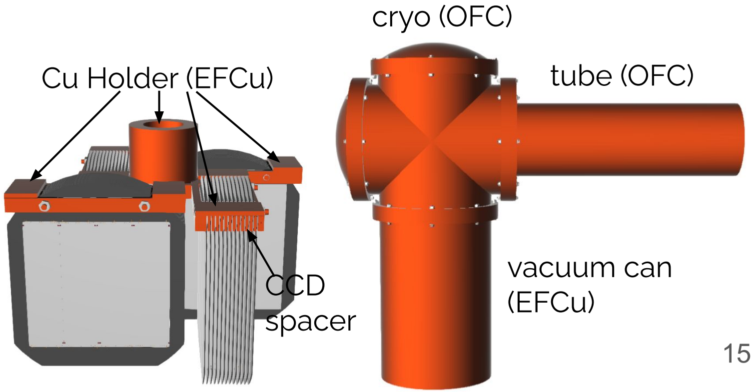


*Normalization factor: isotope activity * component mass/(detector mass * number simulated evts)*

DAMIC- M design simulations







(*) cosmogenic isotopes in electro-formed Cu materials with exposure time= 10d, cooling time underground before data taking = 6m, experiment running time=1y

With external lead shield: bkg rate <0.6 d.r.u, external shield to be optimized

DAMIC-M Timeline

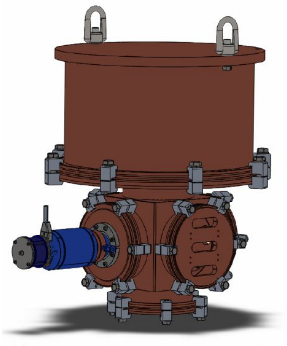
2021	2022	2023

Finalization DAMIC-M design

CCD production and testing

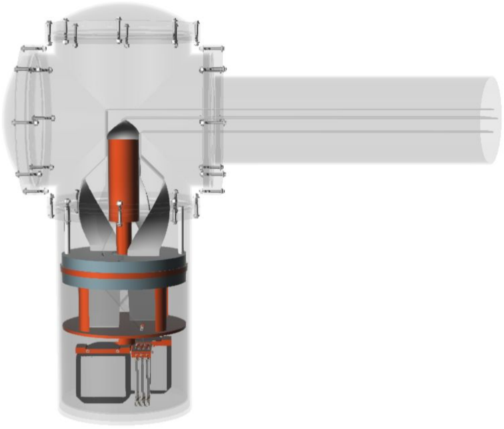
LBC (Low Background Chamber):

- being installed now, data by the end of 2021



DAMIC-M

- Installation & data



Status of DAMIC-M

1) CCD production, packaging ongoing

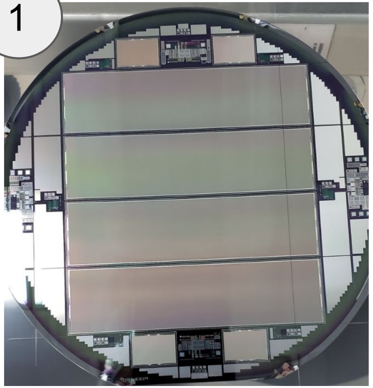
2) CCD testing ongoing

3) Electronics designed, under tests.

4) Calibration with radioactive sources ongoing.

Detector design to be finalized in the next months; Installation at LSM in 2023.

1



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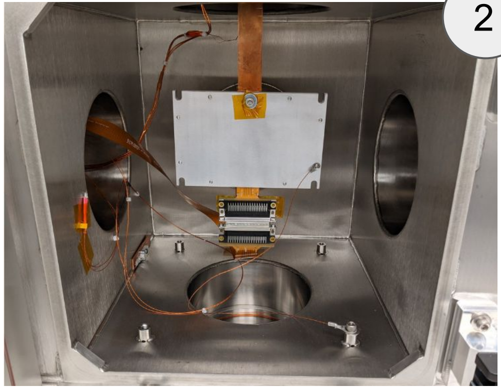

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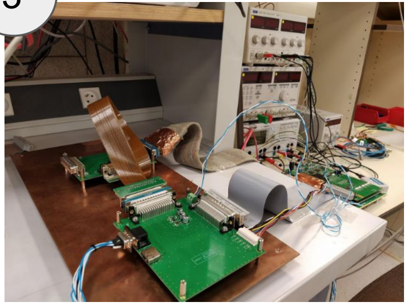

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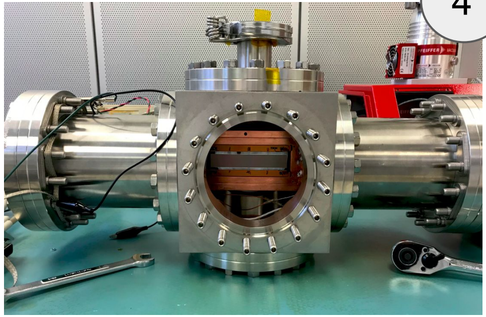
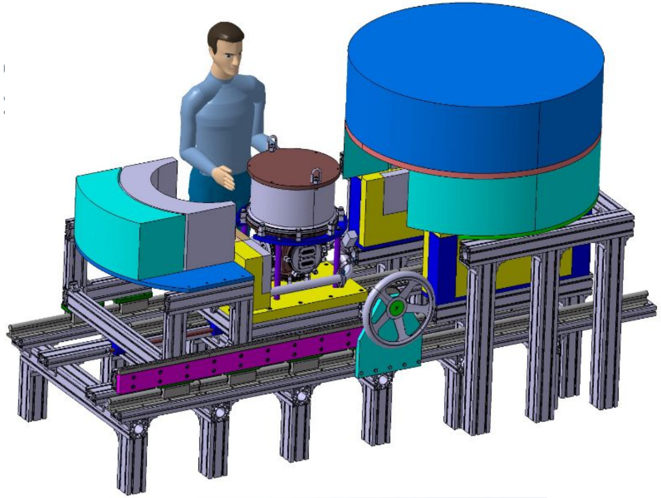
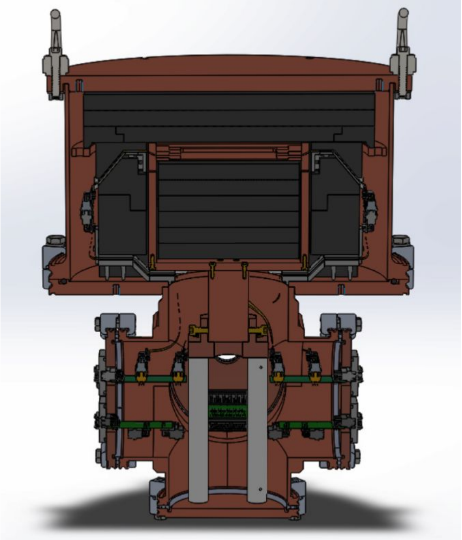


LBC Prototype

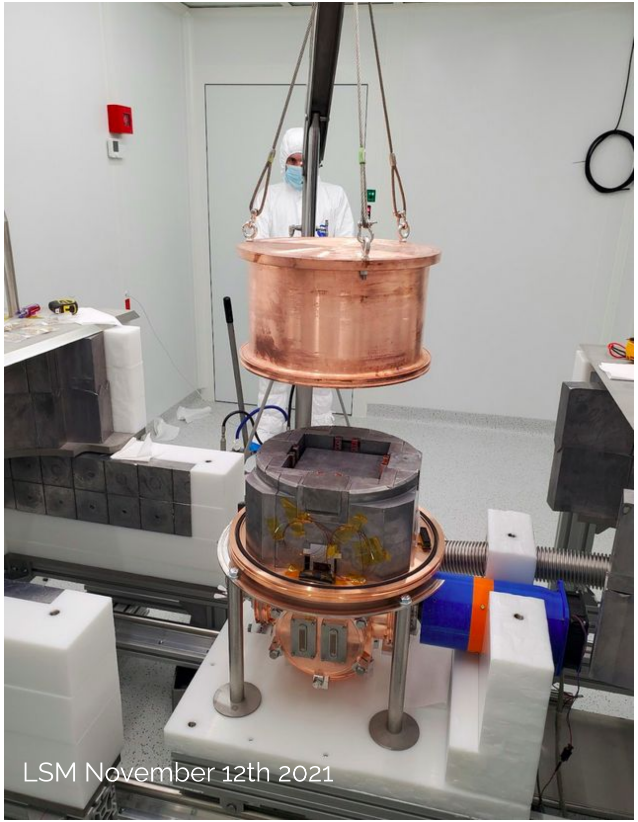
- Detector consists of:
  - Two 6000 x 4000 pix skipper CCDs
  - Cryostat (copper) and inner shielding (ancient Pb)
  - An outer shielding (Pb + Polyethylene)
- Aim:
  - Demonstrate the ability to control backgrounds for DAMIC-M
  - first dark matter search
  - integration/operation of DAMIC-M electronics
- Target:
  - 1 kg-day exposure
  - O(1) dru background
- Timeline:
  - Installation on going
  - testing with CCDs in the next days,
  - Data run 2022





LBC Status

LBC is being installed at the LSM Laboratory



Conclusion

- On our way towards DAMIC-M:
  - CCDs are being fabricated and tested right now!
  - calibration ongoing: compton measurements
  - design optimization ongoing
  - electronics designed
  - development analysis techniques to further reduce the background

- Low Background Chamber:
  - DAMIC-M prototype, first physics results
  - Data: end of 2021 - 2022

DAMIC-M

Thank you for the attention!

Subatech

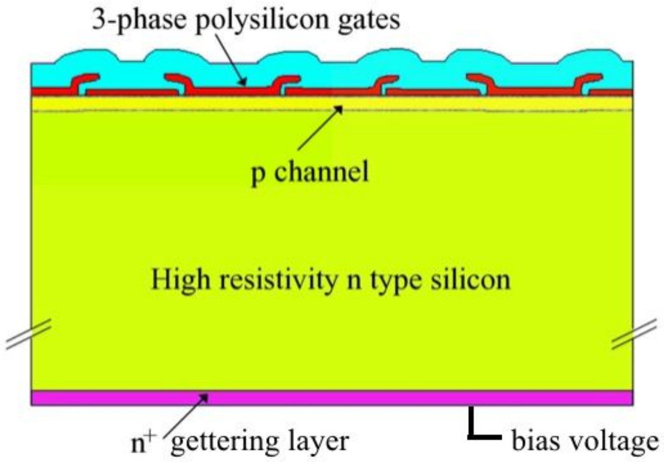
IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

cnrs

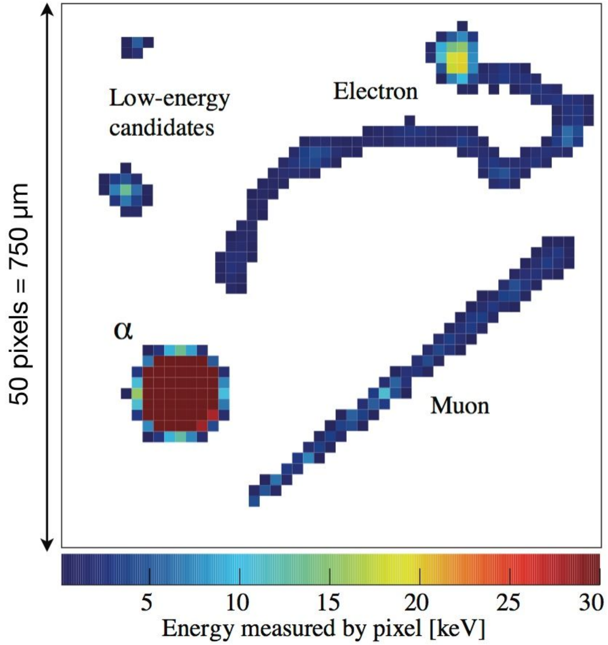
Backup

CCD properties

pixel structure



tracks in the CCD



Diffusion and z reconstruction

$$\sigma_{xy}^2 = -A \ln|1 - bz|.$$

$$A = \frac{\epsilon}{\rho_n} \frac{2k_B T}{e},$$

$$b = \left(\frac{\epsilon}{\rho_n} \frac{V_b}{z_D} + \frac{z_D}{2}\right)^{-1}$$

ϵ permittivity of silicon,
ρ_n : donor charge density in the substrate
k_B: Boltzmann's constant
T: operating temperature (120 K in DAMIC)
e: electron's charge
V_b: bias applied across the substrate (40V in DAMIC)
z_D: thickness of the device

IN DAMIC: σ_{max}=(21±1)μm≈1.4 pix.

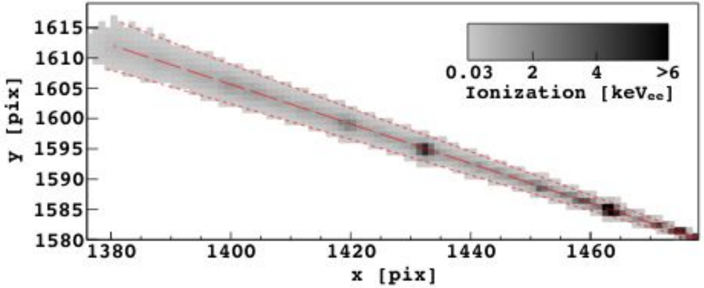


FIG. 4. A MIP observed in cosmic ray background data acquired on the surface. Only pixels whose values are above the noise in the image are colored. The large area of diffusion on the top left corner of the image is where the MIP crosses the back of the CCD. Conversely, the narrow end on the bottom right corner is where the MIP crosses the front of the device. The reconstructed track is shown by the long-dashed line. The short-dashed lines show the 3 σ band of the charge distribution according to the best-fit diffusion model.

Search for low-mass WIMPs in a 0.6 kg day exposure of the DAMIC experiment at SNOLAB;
Phys. Rev. D 94, 082006 (2016)
DAMIC Collaboration (A. Aguilar-Arevalo et al.)

Background isotopes

Parent Chain	Isotope	Q value
^{238}U	^{234}Th	274 keV
	^{234m}Pa	2.27 MeV
^{226}Ra	^{214}Pb	1.02 MeV
	^{214}Bi	3.27 MeV
^{210}Pb	^{210}Pb	63.5 keV
	^{210}Bi	1.16 MeV
^{232}Th	^{228}Ra	45.5 keV
	^{228}Ac	2.12 MeV
	^{212}Pb	569 keV
	^{212}Bi	2.25 MeV
	^{208}Tl	5.00 MeV
^{40}K	^{40}K	1.31 MeV
Copper Activation	^{60}Co	2.82 MeV
	^{59}Fe	1.56 MeV
	^{58}Co	2.31 MeV
	^{57}Co	836 keV
	^{56}Co	4.57 MeV
	^{54}Mn	1.38 MeV
	^{46}Sc	2.37 MeV
^{32}Si	^{32}Si	227 keV
	^{32}P	1.71 MeV
Silicon Activation	^{22}Na	2.84 MeV
	^{3}H	18.6 keV

TABLE II. Isotopes considered for the background model grouped by parent decay chain classification. Q values are provided for convenience from Ref. [54, 55].

Characterization of the background spectrum in DAMIC at SNOLAB:

https://arxiv.org/abs/2110.13133

Isotope	Half-life [yrs]	Decay mode	Q-value [keV]
^{3}H	12.32 ± 0.02	β-	18.591 ± 0.003
^{7}Be	0.1457 ± 0.0020	EC	861.82 ± 0.02
^{10}Be	$(1.51 \pm 0.06) \times 10^6$	β-	556.0 ± 0.6
^{14}C	5700 ± 30	β-	156.475 ± 0.004
^{22}Na	2.6018 ± 0.0022	β+	2842.2 ± 0.2
^{26}Al	$(7.17 \pm 0.24) \times 10^5$	EC	4004.14 ± 6.00

TABLE I. List of all radioisotopes with half-lives > 30 days that can be produced by cosmogenic interactions with natural silicon. All data is taken from NNDC databases [14]. [a]

[a] Unless stated otherwise, all uncertainties quoted in this paper are at 1σ (68.3%) confidence.

Cosmogenic activation of silicon

https://arxiv.org/abs/2007.10584

Compton setup

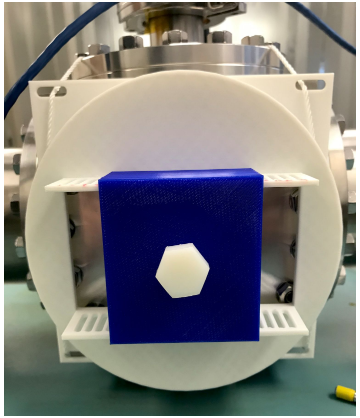
- Stainless-steel vacuum chamber
- Temperature: 126 K
- sources Am241 & Co57
- 6k x 1k pixels CCD

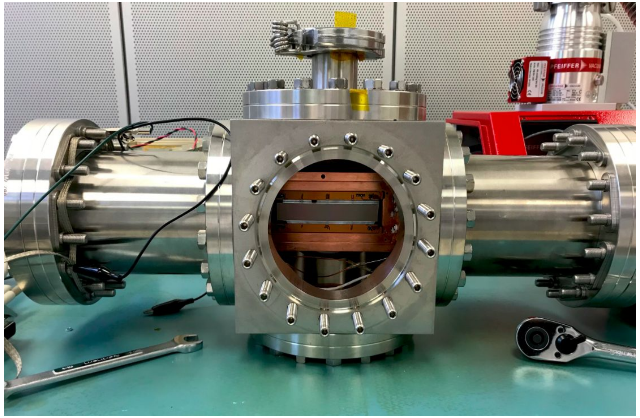
Readout:

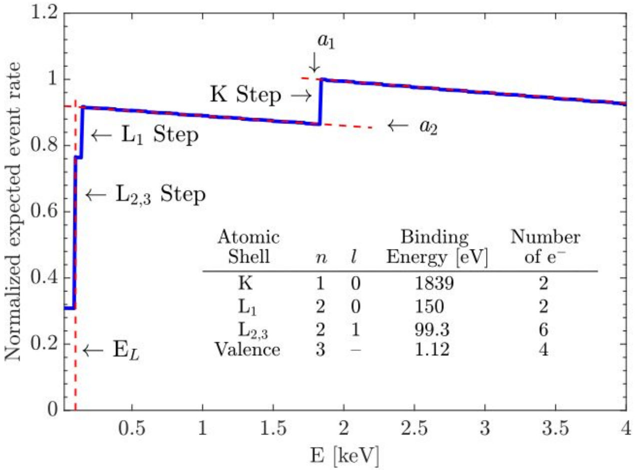
- 64 skips
- 0.6 e- readout noise (2.3 eV)

Aim:

- Parametrization Compton spectrum at low energy (main source of background)
- Resolve L Steps



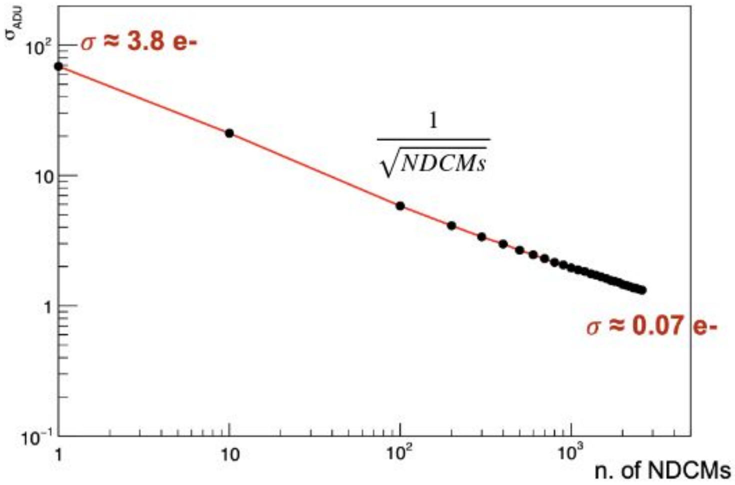


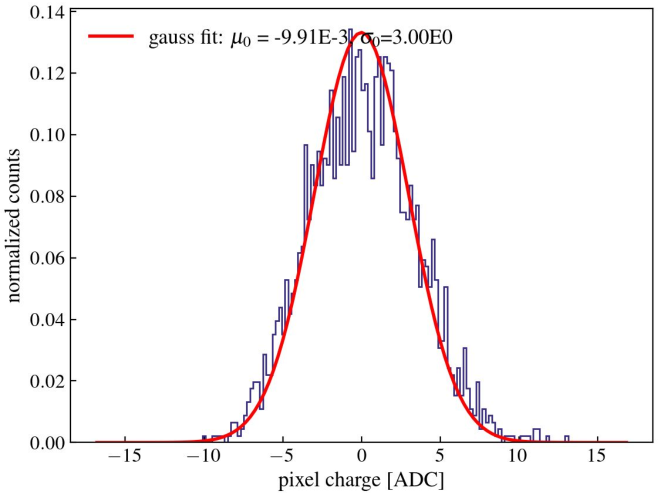


Expected normalized low-energy spectrum from Compton scattering of 122 keV γ rays in silicon

Source	γ Energy
Co57	14.1 keV **122.1 keV** **136.5 keV**
Am241	26.3 keV **59.5 keV**

Compton Analysis chain





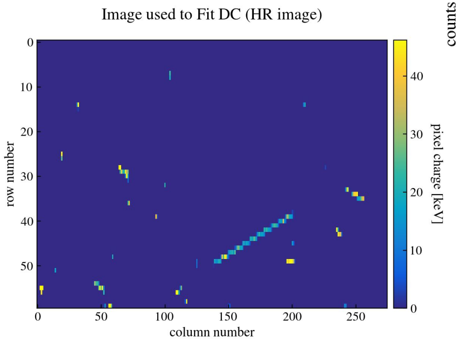
1 Image = mean all skipper images

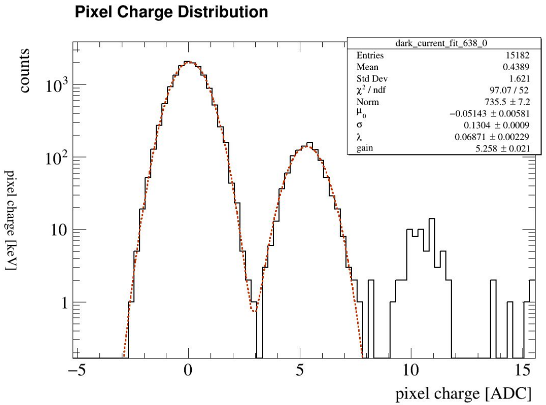
skips = Non-Destructive Charge Measurements

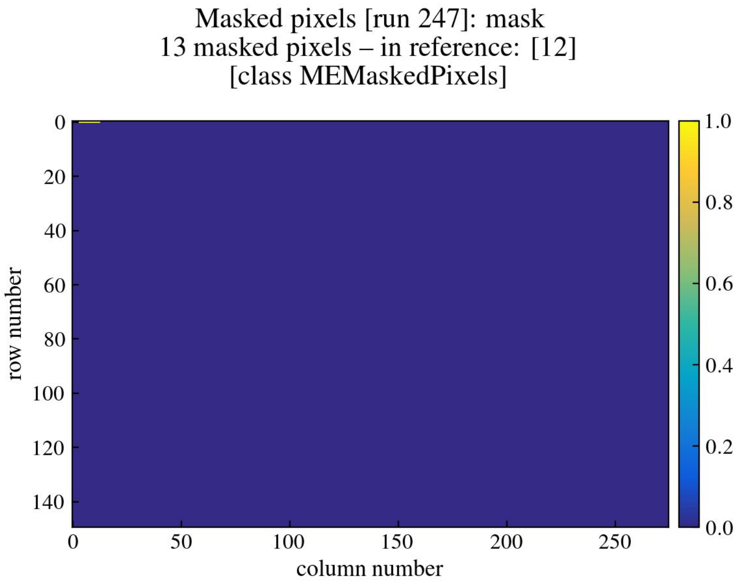
2 Pedestal subtraction:

- gaussian fit row by row overscan: μ_{row} σ_{row}
- subtraction μ_{row} in active area
- readout noise σ = median[σ_{row}]

Compton Analysis chain







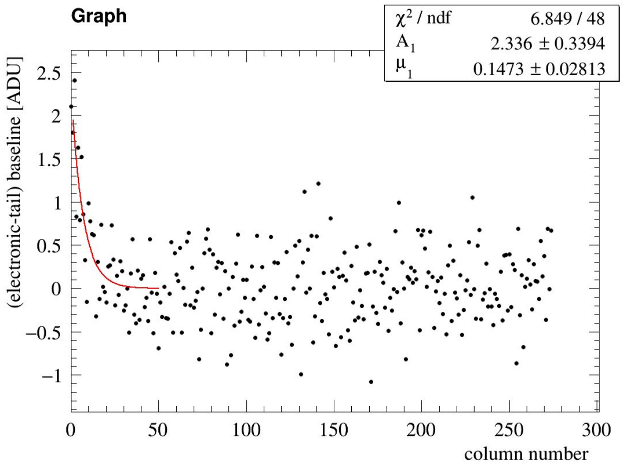
3 Fit Dark Current + Calibration (using image with 2000 skips):

- Fit active area convolution Poisson(λ [e-/pix]) and Gaussian(μ [ADU], σ [e-])
- gain [ADC/e-]= conversion ADC in e-

4 Mask hot pixels and columns/rows:

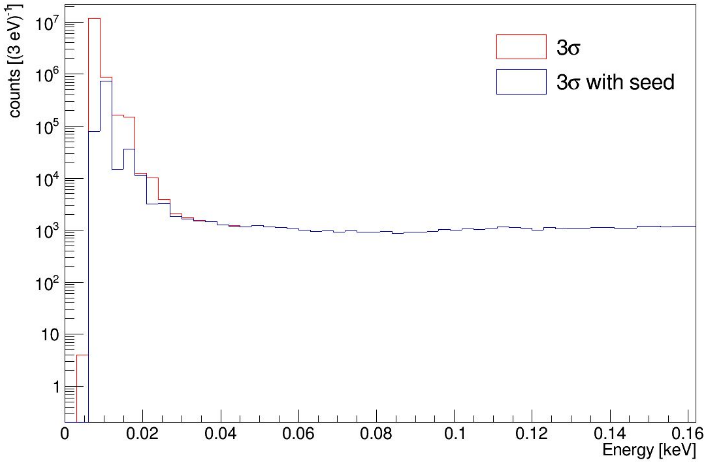
- hot pixels: if in 50% images of a run the pixel charge > median(μrows) + 3MAD
- hot column/row: 30% of pixels are hot

Compton Analysis chain



5 Correction Column transient effect:

- calculate median of charge in a given column: median[col]
- calculate median MED of median[col] from col50 to col260
- subtract MED to median[col1] to median[col49]: median[col1] - MED, ..., med[col49]-MED
- fit with an exponential y(col) = [0]*exp(- [1]* col)
- subtract fit result y to col 1 to col 49



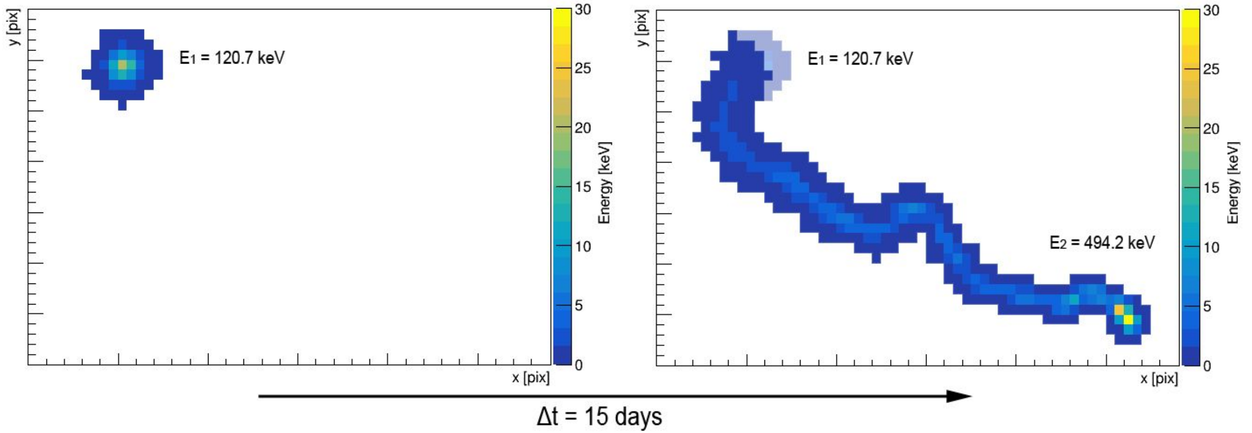
6 Clusters = all contiguous pixels with:

- all pixels with charge above 3σ (readout noise from pedestal subtraction)
- at least 1 pixel above 4σ (SEED)

Analysis Spatial correlated events in simulations

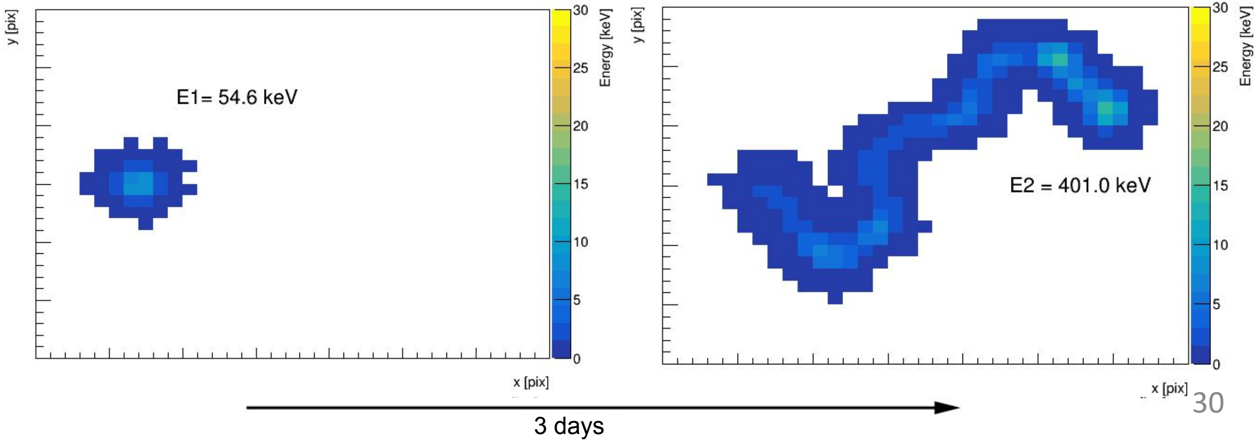
Si32 decay chain in CCD bulk

Si32 → P32 + e-
with t1/2=150y, Q-value = 227 keV
P32 → S32 + e-
with t1/2= 14d, Q-value = 1.71 MeV



Pb210 decay chain in CCD bulk

Pb210 → Bi210 + e- + IC (80%)/ γ(4%)
with t1/2= 22y, Q-value = 63.5 keV
Bi210 → Po210 + e- with t1/2= 5d,
Q-value = 1.16 MeV



Outlook spatially correlated events

- Add readout noise and dark current in simulations

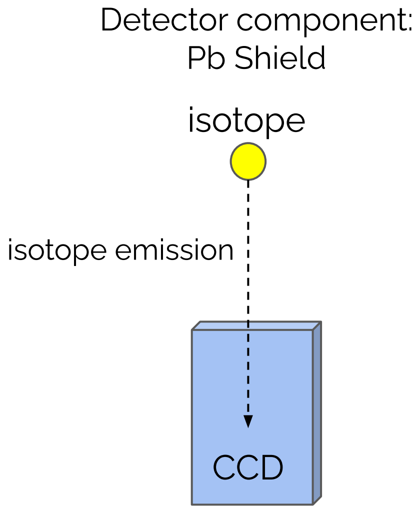
- Adapt and compare with data to get Si32 and Pb210 activities:

$$\text{Activity} = n / (M\ t\ \varepsilon)$$

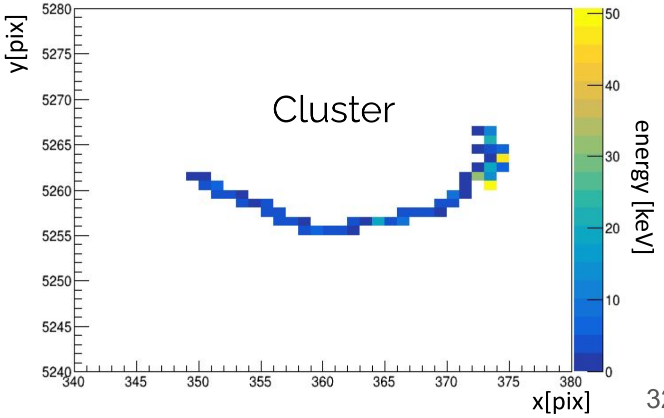
n = number observed sequence
M t= mass exposure
ε = efficiency from simulations

Simulation chain

1. Geant4:
   - simulate passage of particles through matter
   - geometry implementation
   - simulation isotopes in detector components
   - energy deposits of isotopes emission in CCD



2. Python code:
   - reproduce CCD response
   - cluster information: a cluster is a set of contiguous pixels with charges



Simulation chain

3. Personal script:

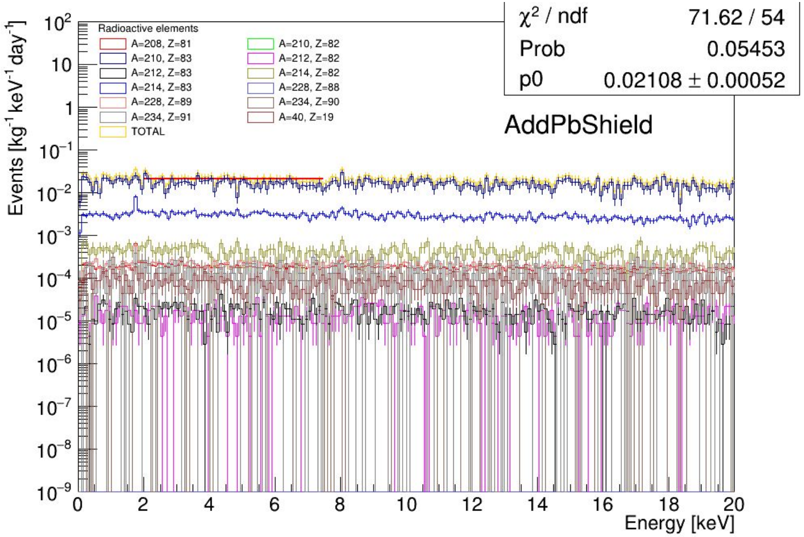
   - each isotope cluster energy spectrum scaled by:

     Activity x component mass / (detector mass x number simulated evts)

   - sum all isotopes contributions

     background rate = linear fit between 2 and 7.5 keV

Clusters Energy Spectrum



Simulation details

- Livermore physics list + neutron processes and radioactive decays.

  The Livermore low-energy electromagnetic models are used to describe the interactions with matter of electrons and photons between 20 eV and 100 GeV.

- The DAMIC-M detector design and the relative materials are implemented through a GDML
- Production cuts for $e^{\pm}$, γ and protons
  - 0.0001 mm nearest component to the CCD Stack
  - 0.001 mm farther components

Simulated Isotopes and activities

from DAMIC

material suppliers

assumption: measured/10

calculated: Texp = 3m, Tcool=6m, Trun= 1y

U238 & Th232

cosmogenic isotopes

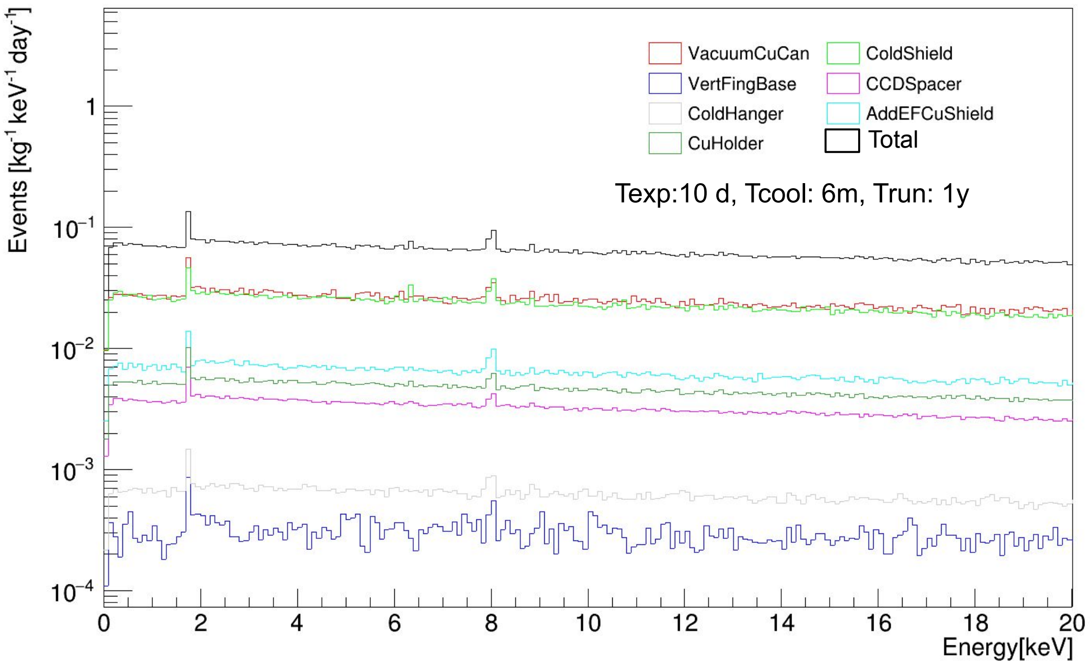
in Epoxy

in Epoxy & Cu

		Activities [decays/kg/day]					
A	Z	Copper	Luvata Cu (from LBC assays)	EF Copper	Ancient Lead	Dirty Lead	Kapton 2 layers
208	81	<1.26	<0.4355	<0.000792	0.072	<0.144	15.3
210	82	2350	2453	<45.8	2850	1560000	1182
210	83	2350	2453	<45.8	2850	1560000	1182
212	82	<3.5	<1.2096	<0.0022	0.2	<0.4	42.5
212	83	<2.24	<0.774	<0.0014	0.128	<0.256	27.2
214	82	<11.2	<38.53	<0.018	<2.0	<17.6	1182
214	83	<11.2	<38.53	<0.018	<2.0	<17.6	1182
228	88	<3.5	<1.2096	<0.0022	0.2	<0.4	42.5
228	89	<3.5	<1.2096	<0.0022	0.2	<0.4	42.5
234	90	<10.7	1.4688	<0.018	<2	<1.1	1182
234	91	<10.7	1.4688	<0.018	<2	<1.1	1182
40	19	<2.7	<17.28	<2.7	<0.5	<19	2480
87	37	7.4	7.4	7.4			7.4
54	25	1.55	1.55	**NB cosmo iso in EFCu always treated <u>separately,</u> not in bkg rate of the individual components!**			
56	27	0.64	0.64				
57	27	13.12	13.12				
58	27	3.9	3.9				
59	26	0.31	0.31				
60	27	5.08	5.08				
46	21	0.17	0.17				

Cosmogenic Isotopes - All EFCu components

Tot rate cosmo iso in EFCu = 0.071 d.r.u



Cold Shield, VacuumCuCan are the major contributors

Activity cosmogenic isotopes:

$$A = \text{Saturation} \times (1 - \exp(-\lambda T_{exp})) \times \exp(-\lambda T_{cool}) \times (1 - \exp(-\lambda T_{run}))/(\lambda T_{run})$$

	t1/2 [days]	S (uBq/kg)
Co56	77.236	230
Co57	271	1800
Co58	70.83	1650
Co60	1923	2100
Mn54	312.13	215
Fe59	44.495	455
Sc46	83.788	53

Dark matter mass scale

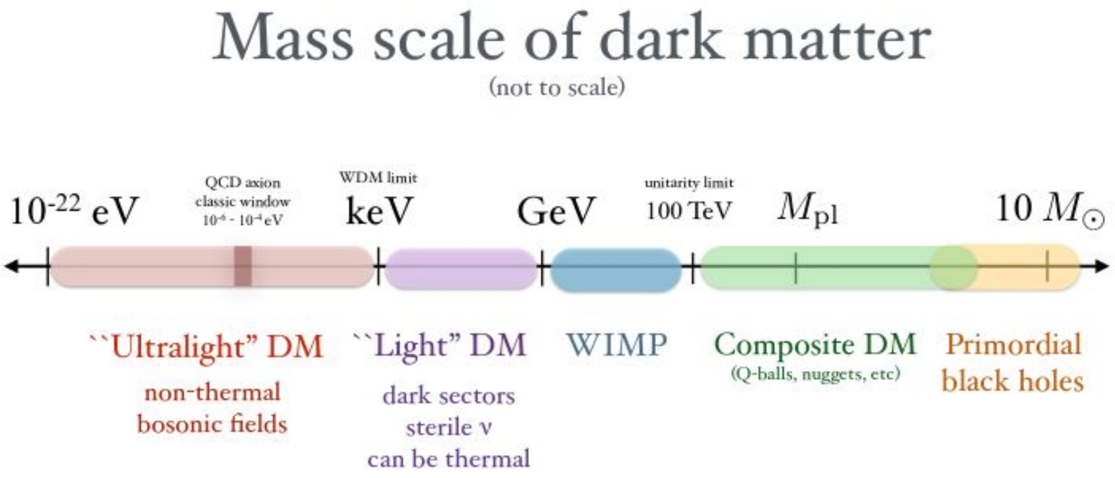


FIG. 3. The mass range of allowed DM candidates, comprising both particle candidates and primordial black holes. Mass ranges are only approximate (in order of magnitude), and meant to indicate general considerations.

T. Lin, TASI lectures on DM models and direct detection, arXiv:1904.07915

Physics reach direct DM experiment

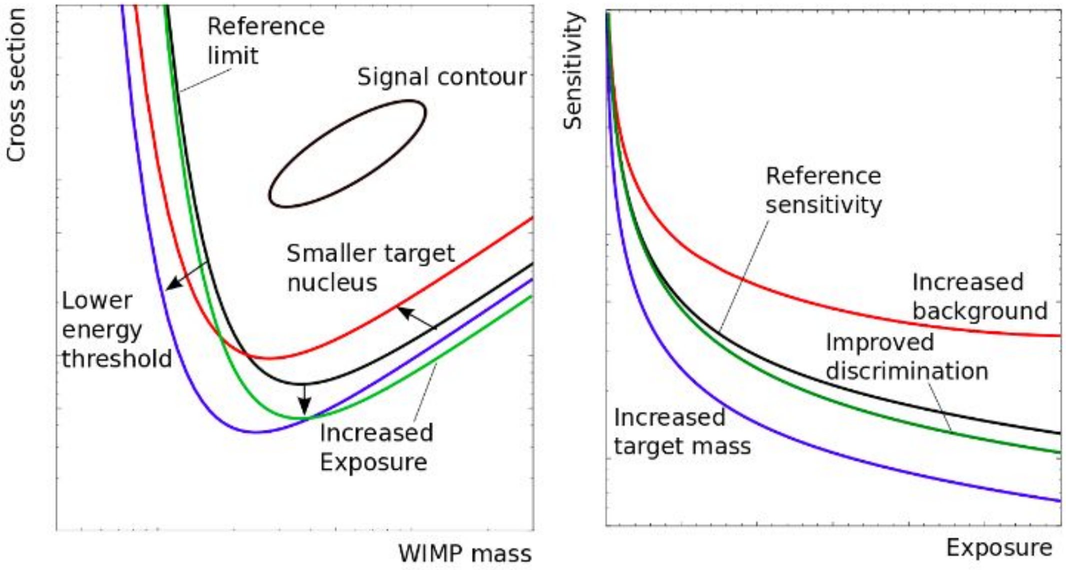


Figure 6. Left: Illustration of a result from a direct dark-matter detector derived as a cross-section with matter as function of the WIMP mass. The black line shows a limit and signal for reference, while the coloured limits illustrate the variation of an upper limit due to changes in the detector design or properties. Right: Evolution of the sensitivity versus the exposure. For more information see text.

differential recoil spectrum DM-nuclei interaction:

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

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

T. M. Undagoitia, L. Rauch, Dark matter direct-detection experiments, arXiv:1509.08767

Differential rate

electronic recoil

$$\frac{dR^{ER}}{dE_e} = \overline{\sigma}_e \frac{\rho_\chi}{M_\chi} \frac{1}{8\mu_{e\chi}^2} \int q dq |F_{DM}(q)|^2 |f_{n,l}^{ion}(q, E_e)|^2 \eta(v_{min})$$

Integral over momentum transfer

Dependence on DM velocity

Rate scales linearly with DM-electron cross section

Properties of the DM

DM Form Factor
- Choice of DM interaction mediator

$$|f_{n,l}^{ion}(q, E_e)|^2 = \frac{k'^3}{4\pi^3} \sum_{n,l} |\langle \psi_{E_e} | e^{-i \sum_\alpha \mathbf{q} \cdot \mathbf{x}^\alpha} | \psi_{n,l} \rangle|^2$$

ionization form factor

nuclear recoil

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

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

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v) \, d^3v$$

Deposited energy as a function of DM mass

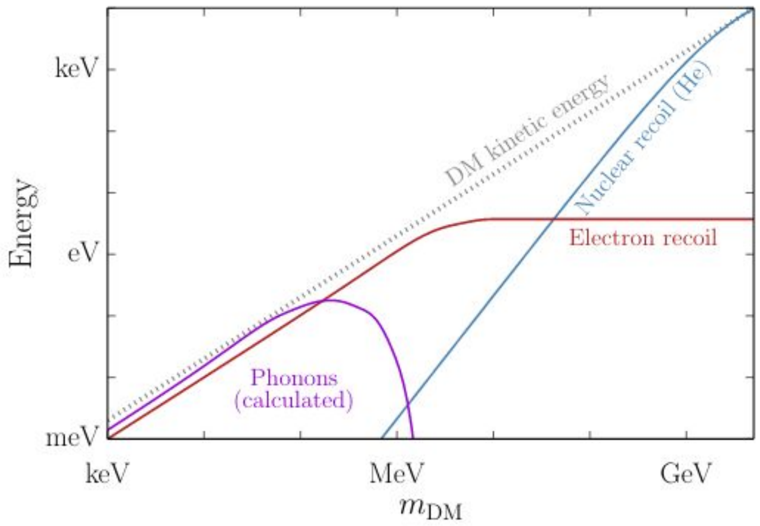


FIG. 19. A schematic comparison of the total DM kinetic energy (dotted, gray) with the energy deposited in a regular nuclear recoil (blue, taking a helium target), the typical energy deposited in an electron recoil (red), and the typical energy in phonon excitations (purple). Note that the phonon excitation case cuts off above DM masses above an MeV only because the current theoretical calculations focus on sub-MeV DM; see Section V B for more details.

T. Lin, TASI lectures on DM models and direct detection, arXiv:1904.07915