Direct Dark Matter Research : The Damic-M* experiment

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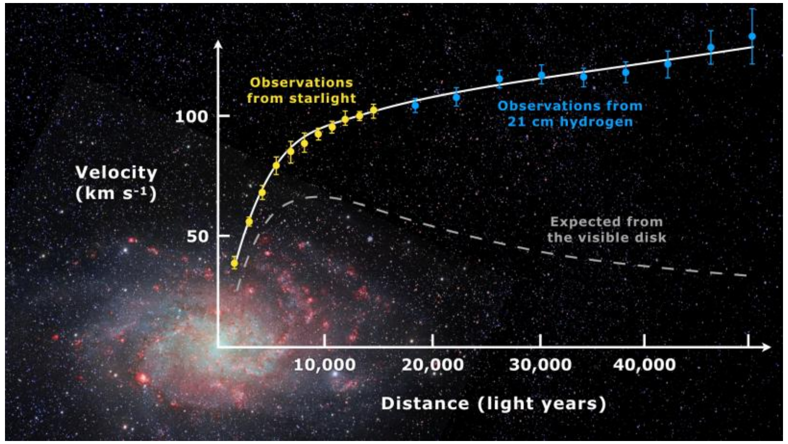
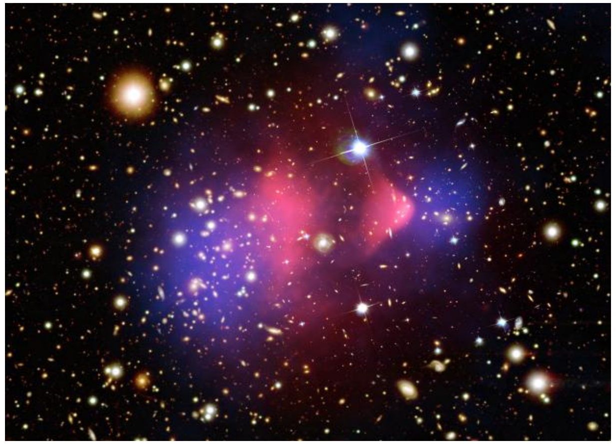
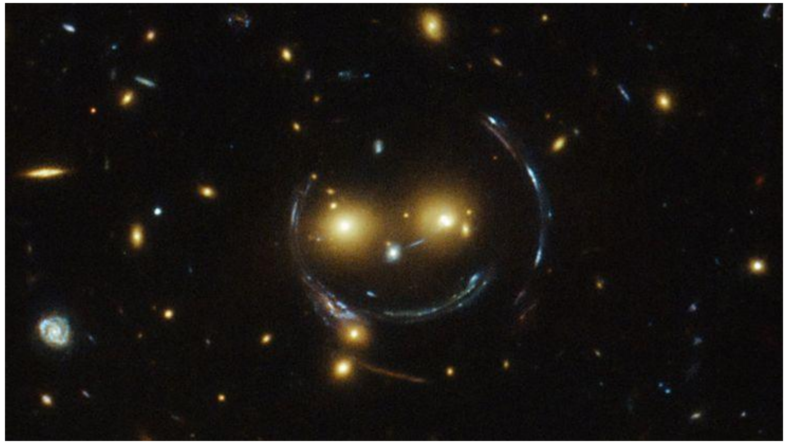
* **DA**rk **M**atter **I**n **C**CDs at **M**odane

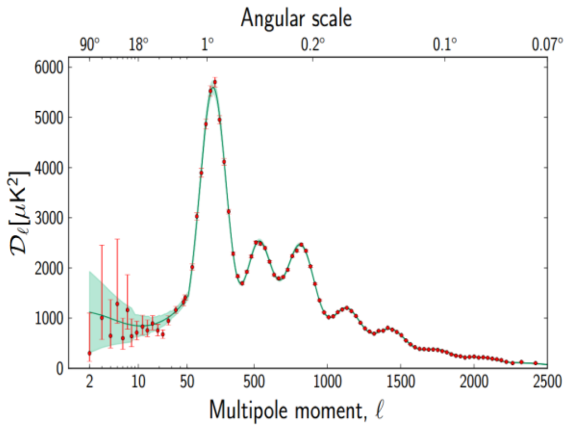
Evidence for Dark Matter in the Universe

- Galaxy Rotation Curves
- Lensing
- Cluster Virialization, Mergers
- CMB Anisotropies
- Etc.

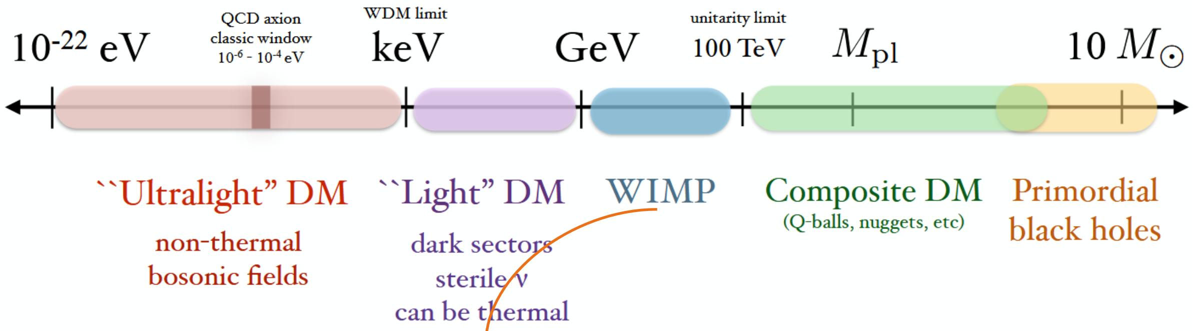






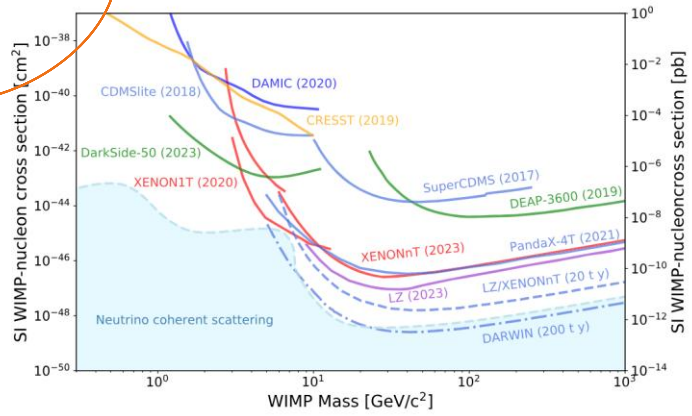


Mass scale of dark matter

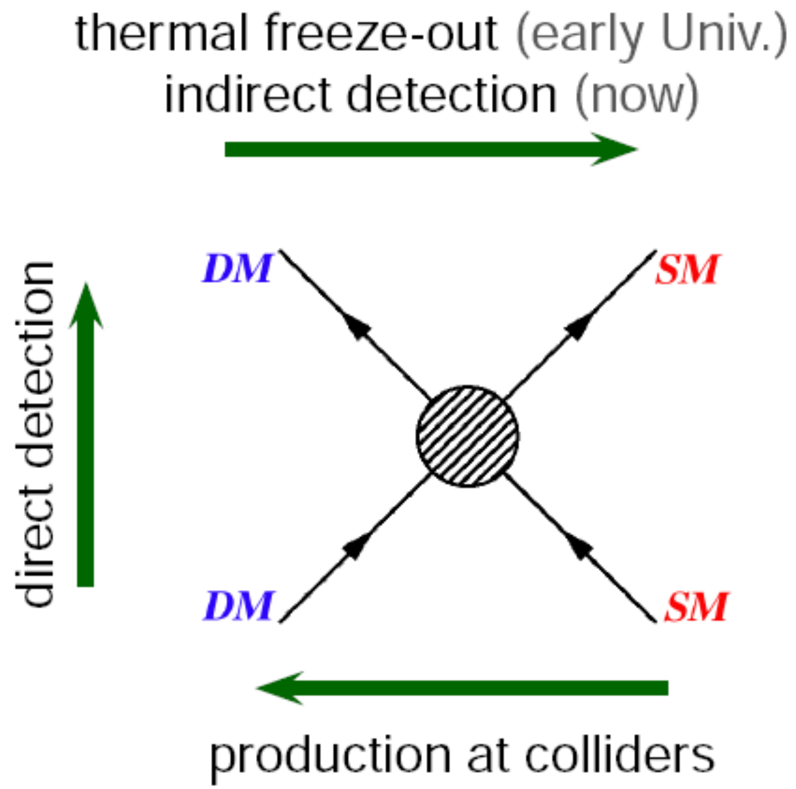


T. Lin, arxiv:1904.07915

WIMP Waning, Nearly Excluded



Detection of particles produced by the annihilation of SM particles



Search for missing transverse energy

Detection of electronic/nuclear recoils

An alternative to the Wimp paradigm : The Hidden Sector

- The SM is not complete (neutrino, dark matter, ...)
- New Interactions may exist !
- Simple natural extension of the Standard Model : new U(1) symmetry
  - Dark QED
  - Electroweak extension
- Leads to MeV-scale Dark Matter

New bosons expected to mediate new interactions

New spin-1 bosons $\leftrightarrow$

new gauge symmetries beyond $\boldsymbol{SU(3) \times SU(2) \times U(1)}$

Simplest possibility

$$\boldsymbol{SU(3) \times SU(2) \times U(1) \times \textbf{extra } U(1)}$$

new gauge coupling (g'') $\leftrightarrow$ intensity of new interaction $(\propto g''^2)$

Pierre FAYET, “The U BOSON as a generalized DARK PHOTON”

$$\mathcal{D}_\mu = \partial_\mu - \mathrm{i} g T_3 W_\mu^3 - \frac{\mathrm{i}}{2} g' Y B_\mu - \frac{\mathrm{i}}{2} g'' X C_\mu,$$

Symmetry breaking

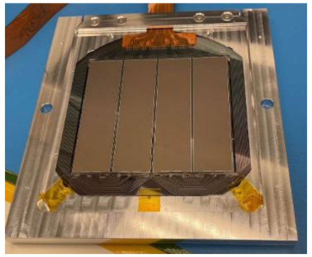
$$\begin{aligned} A_\mu &= \sin\theta_W\, W_\mu^3 + \cos\theta_W\, B_\mu, \\ \tilde{Z}_\mu &= \cos\xi \cos\theta_W\, W_\mu^3 - \cos\xi \sin\theta_W\, B_\mu - \sin\xi\, C_\mu, \\ A'_\mu &= \sin\xi \cos\theta_W\, W_\mu^3 - \sin\xi \sin\theta_W\, B_\mu + \cos\xi\, C_\mu. \end{aligned}$$

Modification of the Z boson's coupling constant and a new gauge boson in the electroweak theory

$$\begin{aligned} g_A(T_3, Y, X) &= eQ, \\ g_{\tilde{Z}}(T_3, Y, X) &= g \cos\theta_W \cos\xi\, T_3 + g' \sin\theta_W \cos\xi\, \frac{Y}{2} + g'' \sin\xi\, \frac{X}{2}, \\ g_{A'}(T_3, Y, X) &= g \cos\theta_W \sin\xi\, T_3 + g' \sin\theta_W \sin\xi\, \frac{Y}{2} + g'' \cos\xi\, \frac{X}{2}. \end{aligned}$$

Olivier Deligny, DAMIC-M internal note

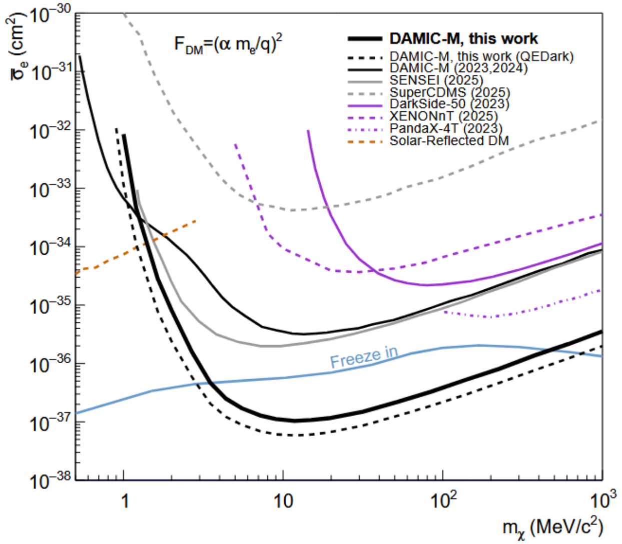
Damic-M in Dark Matter research

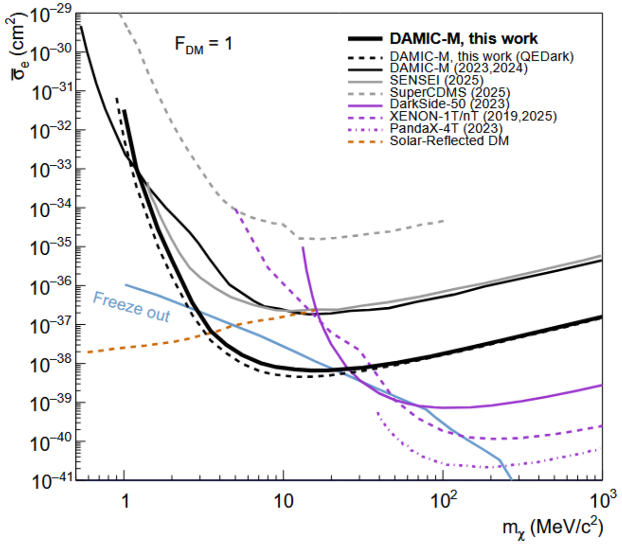


- Direct Dark Matter experiment
- Skipper-CCD detectors
- Single electron detection capability
  - For low-mass dark matter :

$$E_{Target} < 4\frac{M_{DM}}{M_{Target}}E_{DM}$$

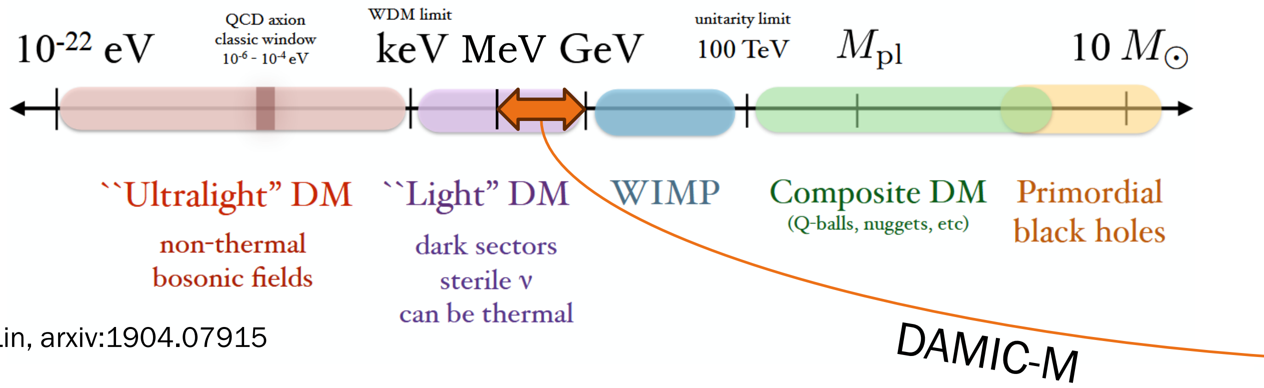
- Sub-electron readout noise
- World-leading limits on hidden sector Dark Matter



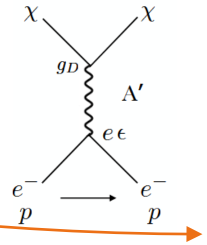


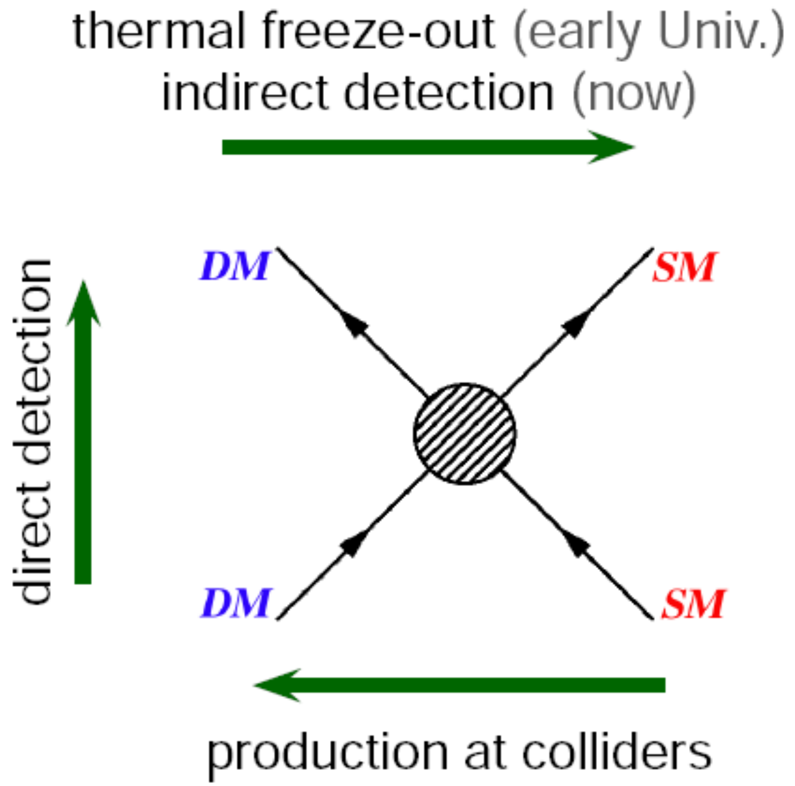
Mass scale of dark matter

(not to scale)

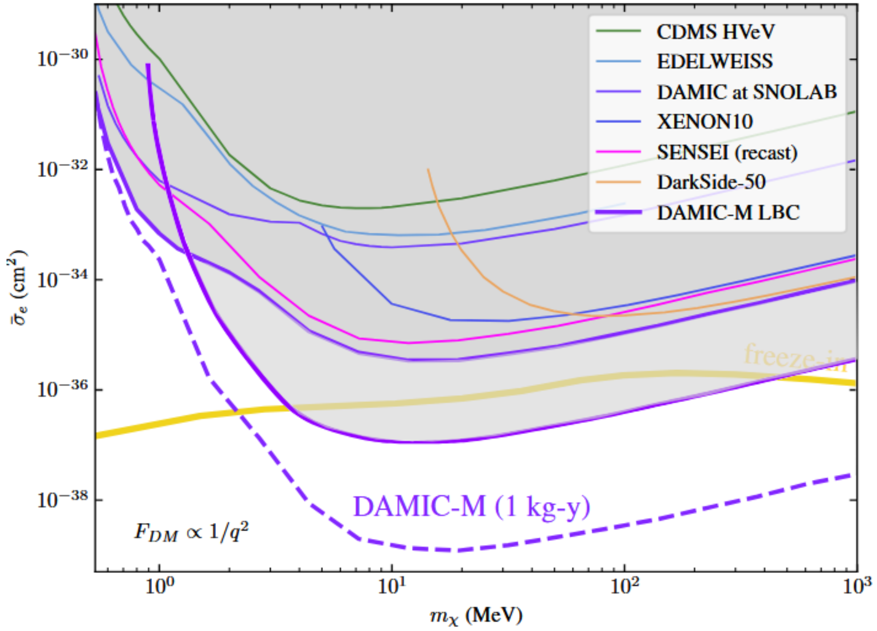


T. Lin, arxiv:1904.07915



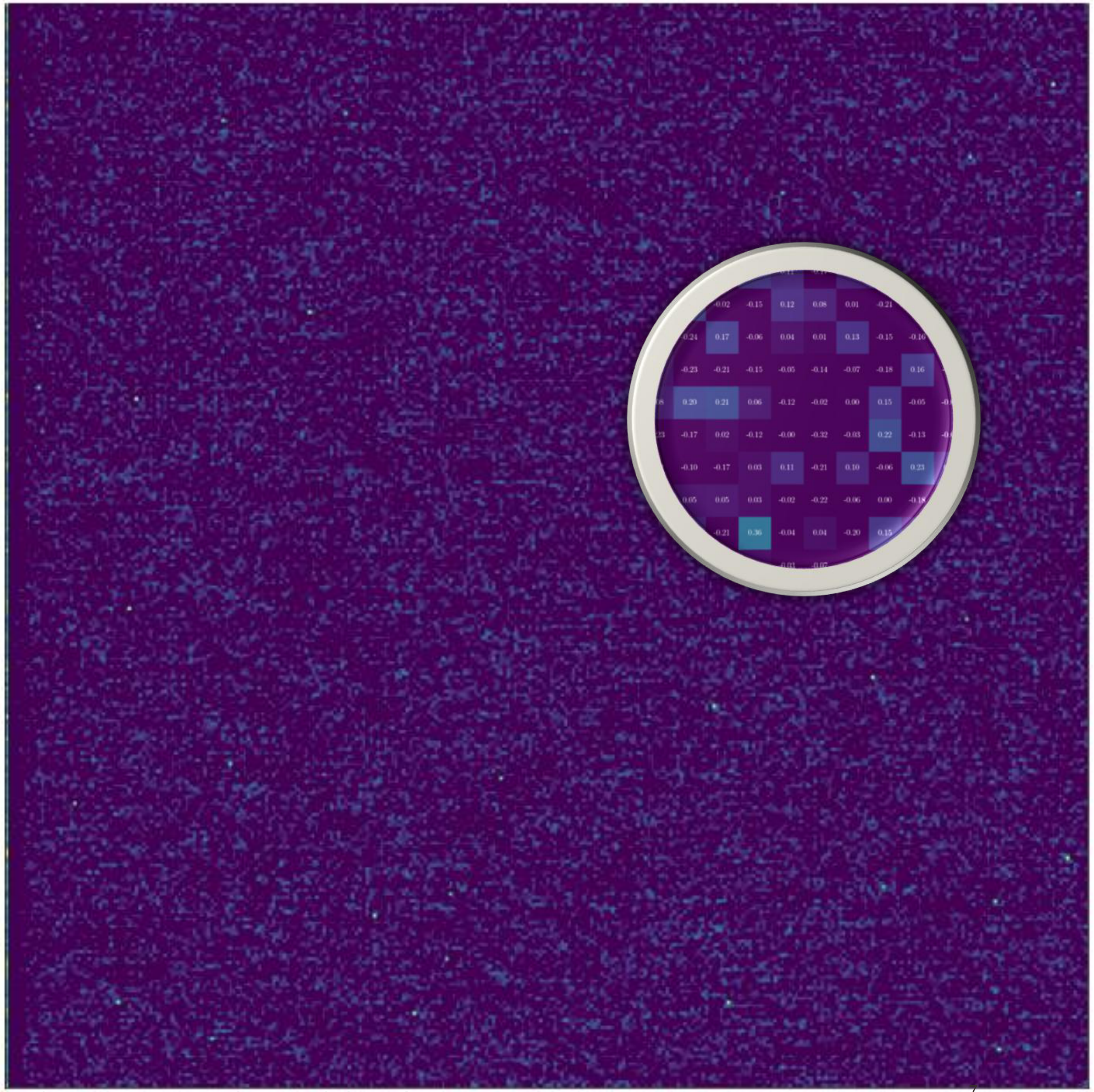


Max Planck Institute for Nuclear Physics



The data

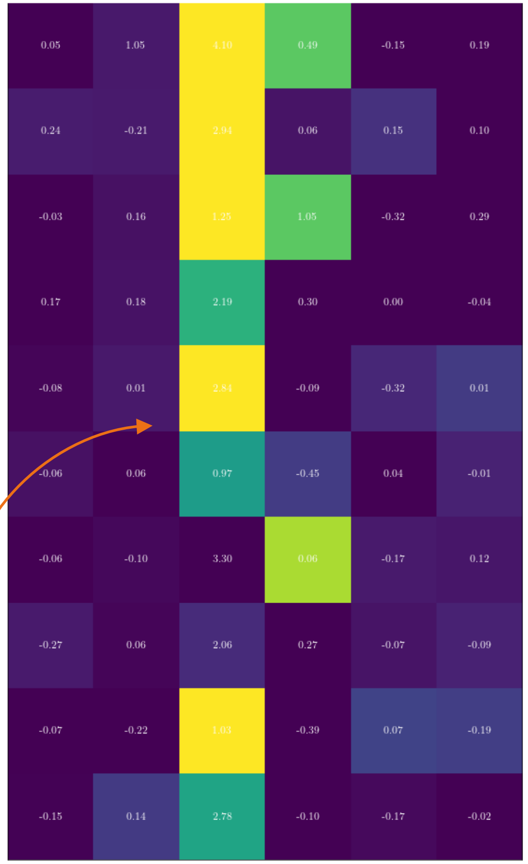
- ~8 days of DAMIC-M LBC data
- 4 CCDs → 4 images of 6560 × 6148 pixels
- $\sim 2.9 \;\; 10^{-4}$ kg.year exposure
- 500 skips for $\sigma \sim 0.17 e^{-}$

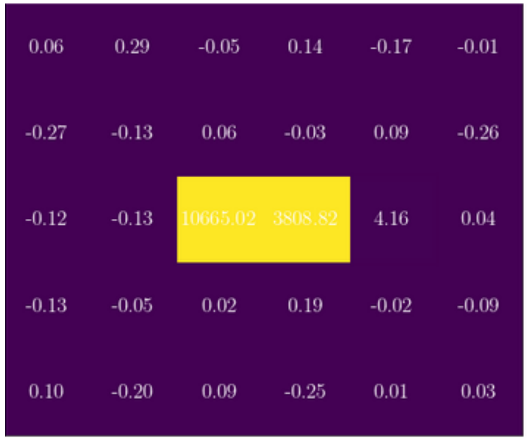


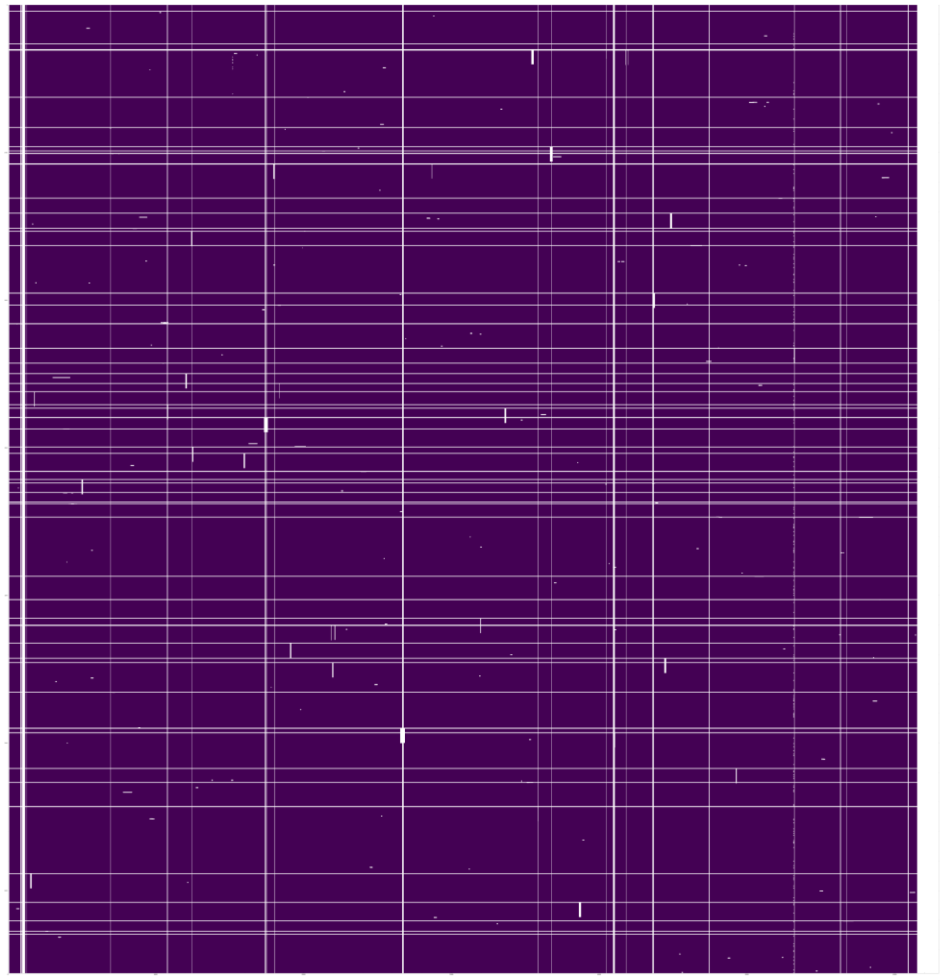
Portion of the image from CCD 1

Image masking

- Hot region (large 1e- rate)
- Defects generating charges continuously
- Clusters of high-charge pixels (>5 e-)
- Cross-talk between CCDs
- 79.75% of data are kept

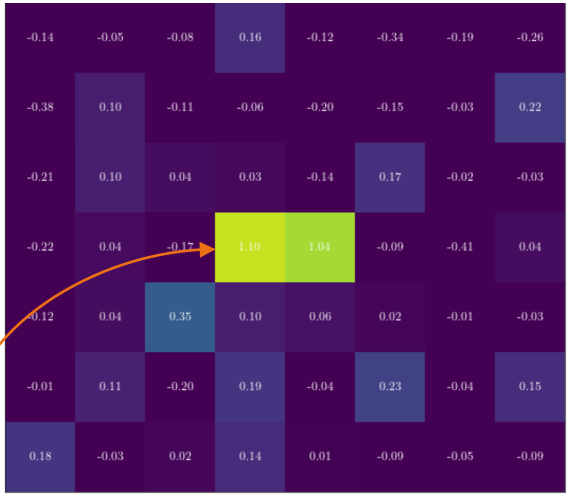






Pattern analysis and exclusion limits

- Searching for {11}, {111} or {12}/{21} events
- ~2.9 10^{-4} kg.year exposure
- ~13.5 expected events / 14 observed
- Comparison with observed events
  - Background is compatible with observations
  - No evidence for Dark Matter
- Dark matter could be hidden in our events, even if they are compatible with the background
- Feldman-Cousins table provides confidence interval limits for Poisson distributions

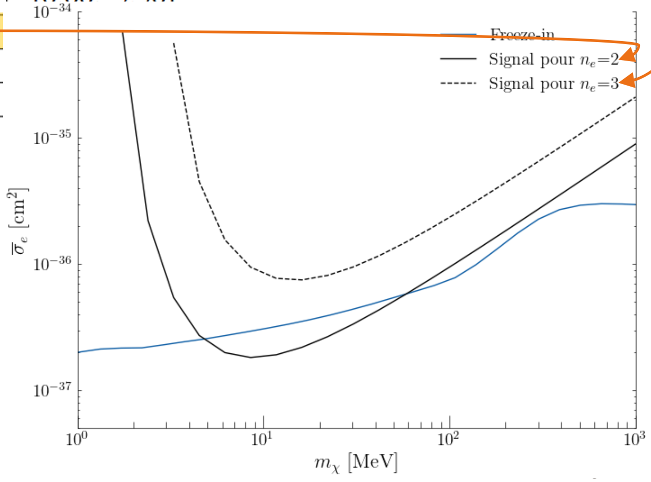


Attendu	CCD 1	CCD 2	CCD 3	CCD 4
{11}	3.2	2.6	4.9	2.8
{111}	$1 . 10^{-3}$	$7 . 10^{-4}$	$2 . 10^{-3}$	$8 . 10^{-4}$
{21}, {12}	$5 . 10^{-4}$	$4 . 10^{-4}$	$9 . 10^{-4}$	$4 . 10^{-4}$

Observations are compatible with the prediction based on the DC

Observé	CCD 1	CCD 2	CCD 3	CCD 4
{11}	3	3	8	0
{111}	0	0	0	0
{21}, {12}	0	0	0	0

$n_0 \setminus b$	0	13	14	15
0	[0.00, 2.44]	[0.00, 0.92]	[0.00, 0.92]	[0.00, 0.92]
2	[0.53, 5.91]	[0.00, 1.05]	[0.00, 1.06]	[0.00, 1.07]
4	[1.47, 8.60]	[0.00, 1.36]	[0.00, 1.39]	[0.00, 1.42]
6	[2.21, 11.47]	[0.00, 1.52]	[0.00, 1.55]	[0.00, 1.59]
8	[3.96, 13.99]	[0.00, 2.06]	[0.00, 2.11]	[0.00, 2.16]
10	[5.50, 16.50]	[0.00, 3.20]	[0.00, 3.27]	[0.00, 3.35]
12	[7.01, 19.00]	[0.00, 5.09]	[0.00, 5.19]	[0.00, 5.30]
14	[8.50, 21.50]	[0.00, 7.41]	[0.00, 7.50]	
16	[9.99, 23.99]	[0.00, 9.90]	[0.00, 9.99]	
18	[11.47, 26.16]	[0.00, 12.07]	[0.00, 12.16]	



Annexe

Dark Matter production scenarios

- Multiple production scenarios :
  - Freeze-in/out
  - Gravitational
  - Etc.
- Freeze-out assumption : thermal equilibrium in early universe
- Freeze-in assumption : production from thermal bath species over time
  - Y^2 *is neglected*

$$ds^2 = dt^2 - a^2(t)(dx^2 + dy^2 + dz^2)$$

Boltzman equation : $\boldsymbol{L}[f] = \boldsymbol{C}[f]$

$$\boldsymbol{L}[f] = E\frac{\partial f}{\partial t} - \| \boldsymbol{p}^2 \| \frac{\dot{a}}{a}\frac{\partial f}{\partial E}$$

$$\frac{g}{(2\pi^3)}\int d^3p \frac{\boldsymbol{L}[f]}{E} = \frac{dn}{dt} + 3Hn$$

$$n = \frac{g}{(2\pi^3)}\int d^3p\, f(p,T)$$

$$\|$$

$$\frac{g_1}{(2\pi)^3}\int d^3p_1 \frac{\mathrm{C}[f_1]}{E_1} = \int d\pi_1 d\pi_2 d\pi_3 d\pi_4 (2\pi)^4 \delta_D^{(4)}(\sum_{i=1}^{4} \boldsymbol{p}_i)\times$$
$$[f_1 f_2 (1 \pm f_3)(1 \pm f_4)|M_{12\to 34}|^2 - f_3 f_4 (1 \pm f_1)(1 \pm f_2)|M_{34\to 12}|^2]$$

$$\frac{dY}{dx} = \frac{<\sigma v>}{Hx} s(Y^2 - Y_{Eq}^2)(1 + \frac{1}{3}\frac{T}{h}\frac{dh}{dT})$$

$$<\sigma v> = \frac{\int \sigma v\, dn_\chi^{Eq} dn_{\bar{\chi}}^{Eq}}{n_\chi^{Eq} n_{\bar{\chi}}^{Eq}}$$

$$Y = \frac{n}{s}, \qquad x = \frac{m_\chi}{T}$$

$$s = \frac{2\pi^2}{45} g_{*s}(T) T^3, \qquad h = g_{eff}(T)\frac{\pi^2}{30}T^4$$

Freeze-in setup

$$\frac{dY}{dx} = -\frac{<\sigma v>}{Hx} sY_{Eq}^2(1 + \frac{1}{3}\frac{T}{h}\frac{dh}{dT}) \simeq -\frac{<\sigma v>}{Hx} sY_{Eq}^2$$

$$\frac{dY}{dT} = -\frac{M_P}{(2\pi)^2 T^6}\left(\frac{45}{\pi}\right)^{\frac{3}{2}} \frac{1}{g_{*s}\sqrt{g_{\mathrm{eff}}}}\times$$
$$\left(\sum_i \left(\bar{n}_i^2 \langle\sigma v\rangle_{ii\to\chi\bar{\chi}}\right) + \sum_j \left(\bar{n}_j^2 \Gamma_{j\to\chi\bar{\chi}}\right)\right)$$

Freeze-In Production in a Dark QED Sector

$$\mathcal{D}_\mu = \partial_\mu - igT_3W^3_\mu - \frac{i}{2}\mathcal{Y}g'B_\mu - \frac{i}{2}Q_X g''C_\mu$$

$$\mathcal{L}_{\text{mix}} = -\frac{\epsilon}{2}B_{\mu\nu}C^{\mu\nu}$$

$$\mathcal{L} = -\frac{1}{4}W^3_{\mu\nu}W^{3\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}C_{\mu\nu}C^{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}C^{\mu\nu}$$

$$= -\frac{1}{4}\hat{W}^3_{\mu\nu}\hat{W}^{3\mu\nu} - \frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{C}_{\mu\nu}\hat{C}^{\mu\nu}$$

Modification of the Z boson's coupling constant and a new gauge boson in the electroweak theory

$$\begin{pmatrix}\hat{W}^3_\mu\\ \hat{B}_\mu\\ \hat{C}_\mu\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & 1 & \epsilon\\ 0 & 0 & \frac{1}{\sqrt{1-\epsilon^2}}\end{pmatrix}\begin{pmatrix}W^3_\mu\\ B_\mu\\ C_\mu\end{pmatrix}$$

$$g_A = eQ$$

$$g_{\tilde{Z}} \simeq g\cos\theta_W T_3 - g'\sin\theta_W\frac{\mathcal{Y}}{2} - g''\epsilon\sin\theta_W\frac{Q_X}{2}$$

$$g_{A'} \simeq \epsilon e\cos\theta_W T_3 - g'\epsilon(1+\cos^2\theta_W)\frac{\mathcal{Y}}{2} + g''\frac{Q_X}{2}$$

Computation of the matrix element

$$\int d\Omega^*\overline{|\mathcal{M}|}^2 = \frac{16\pi N_c}{3}\frac{(Qe)^2 g^2_{A'}s^2}{(s-m^2_{A'})^2}\left(1+\frac{2m_i^2}{s}\right)\left(1+\frac{2m_\chi^2}{s}\right)$$

$$\Omega_\chi h^2 = \frac{m_\chi s_{today}Y_{today}}{\rho_c/h^2}$$

+

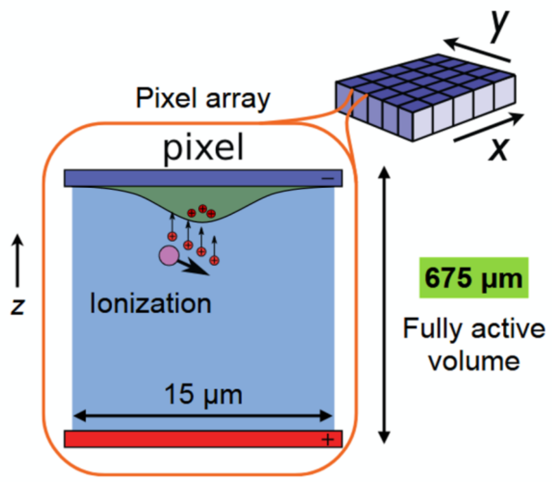
$$\frac{dY}{dT} = -\frac{M_P}{(2\pi)^2T^6}\left(\frac{45}{\pi}\right)^{\frac{3}{2}}\frac{1}{g_{*s}\sqrt{g_{\text{eff}}}}\times$$

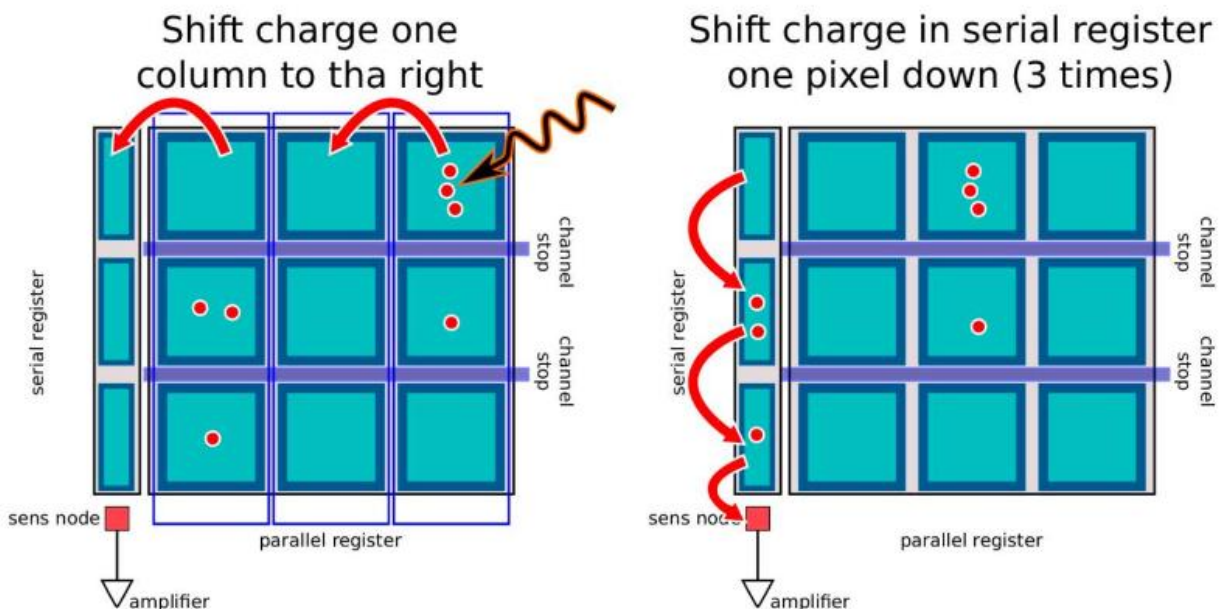
$$\left(\sum_i\left(\bar{n}_i^2\langle\sigma v\rangle_{ii\to\chi\bar{\chi}}\right) + \sum_j\left(\bar{n}_j^2\Gamma_{j\to\chi\bar{\chi}}\right)\right)$$

$$g^2_{A'} = \frac{\Omega_\chi\rho_c}{s_0 m_\chi}\left[\int\frac{2M_P\left(\frac{45}{\pi^3}\right)^{3/2}}{(2\pi)^2T^5g_{*s}(T)\sqrt{g_{\text{eff}}(T)}}\int ds\frac{N_c\alpha_{\text{QED}}Q^2}{24\pi^4}\times\left(\frac{(s-4m_\chi^2)(s-4m_i^2)}{s}\right)^{1/2}K_1\left(\frac{\sqrt{s}}{T}\right)\left(1+\frac{2m_i^2}{s}\right)\left(1+\frac{2m_\chi^2}{s}\right)\right]$$

Classical CCDs

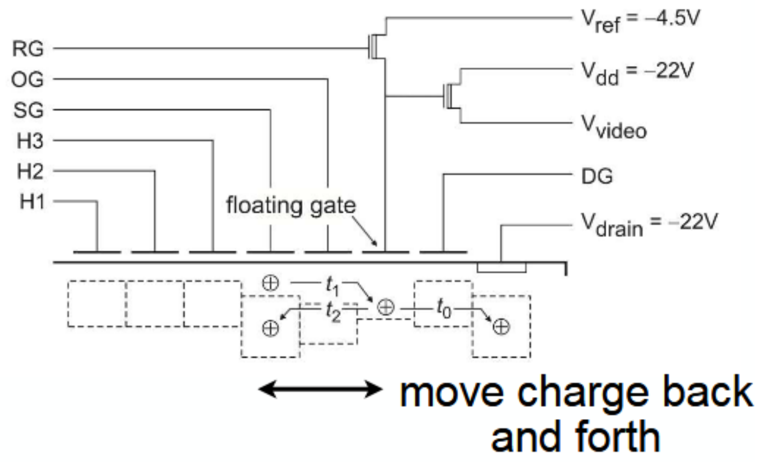
- interaction ionizes the medium and generates charges
- Charges are trapped in potential wells
- Then, the charges are moved line by line, pixel by pixel, toward the serial register
- Measurment of the charge on each pixel in the sens node

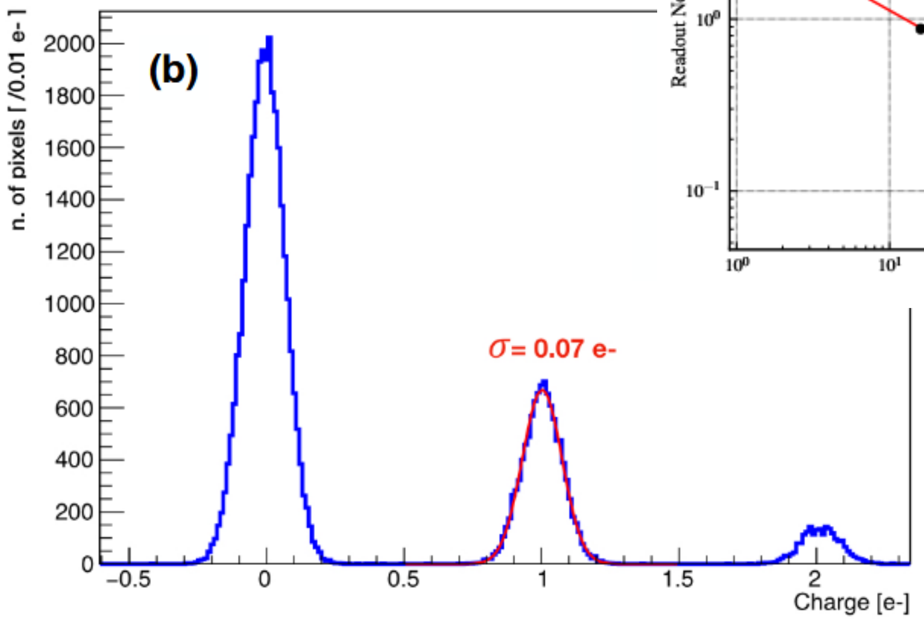


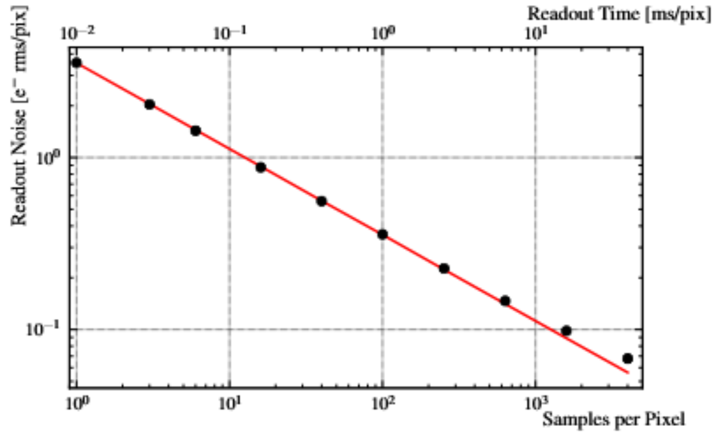


Skipper-CCD

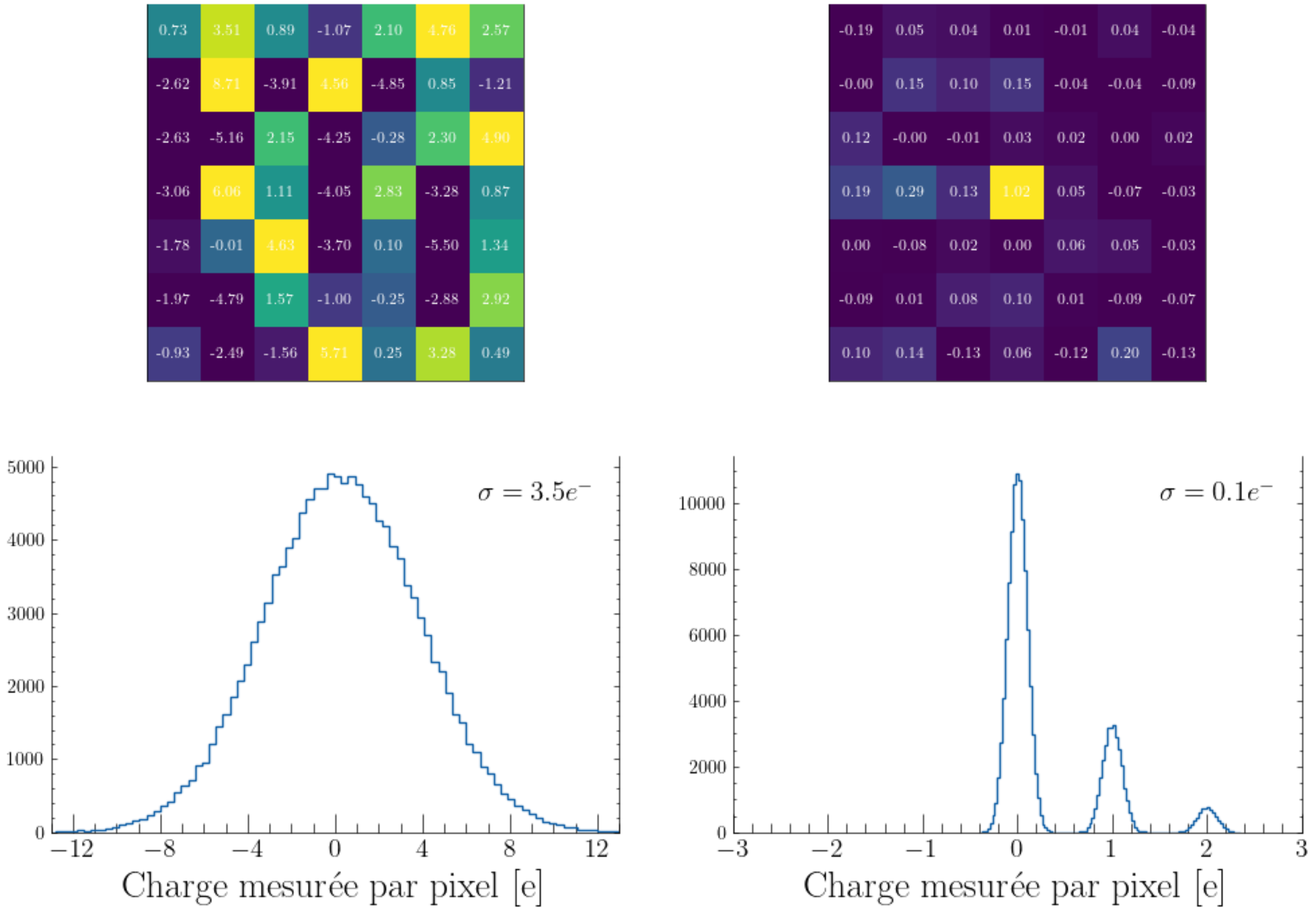
- Multiple non-destructive charge measurments
- Readout noise divided by $\sqrt{N_S}$
  - Sub-electron reading noise
- Allows us to explore small energy deposits







arxiv:1706.00028


0.73 3.51 0.89 -1.07 2.10 4.76 2.57
-2.62 8.71 -3.91 4.56 -4.85 0.85 -1.21
-2.63 -5.16 2.15 -4.25 -0.28 2.30 4.90
-3.06 6.06 1.11 -4.05 2.83 -3.28 0.87
-1.78 -0.01 4.63 -3.70 0.10 -5.50 1.34
-1.97 -4.79 1.57 -1.00 -0.25 -2.88 2.92
-0.93 -2.49 -1.56 5.71 0.25 3.28 0.49
-0.19 0.05 0.04 0.01 -0.01 0.04 -0.04
-0.00 0.15 0.10 0.15 -0.04 -0.04 -0.09
0.12 -0.00 -0.01 0.03 0.02 0.00 0.02
0.19 0.29 0.13 1.02 0.05 -0.07 -0.03
0.00 -0.08 0.02 0.00 0.06 0.05 -0.03
-0.09 0.01 0.08 0.10 0.01 -0.09 -0.07
0.10 0.14 -0.13 0.06 -0.12 0.20 -0.13
$\sigma = 3.5e^-$
Charge mesurée par pixel [e]
$\sigma = 0.1e^-$
Charge mesurée par pixel [e]

Clustering and high charge pixels

- Clustering
  - We mask two pixels before and after the cluster, and one pixel above and below
- High charge pixels
  - We mask two pixels before and after the cluster, and one pixel above and below it