First Results of the Low Background Chamber and the DAMIC-M Experiment

Jean-Philippe Zopounidis on behalf of the DAMIC-M collaboration
Sorbonne University, LPNHE

UCLA Dark Matter 2023
03/31/2023

DAMIC @ Modane

Location

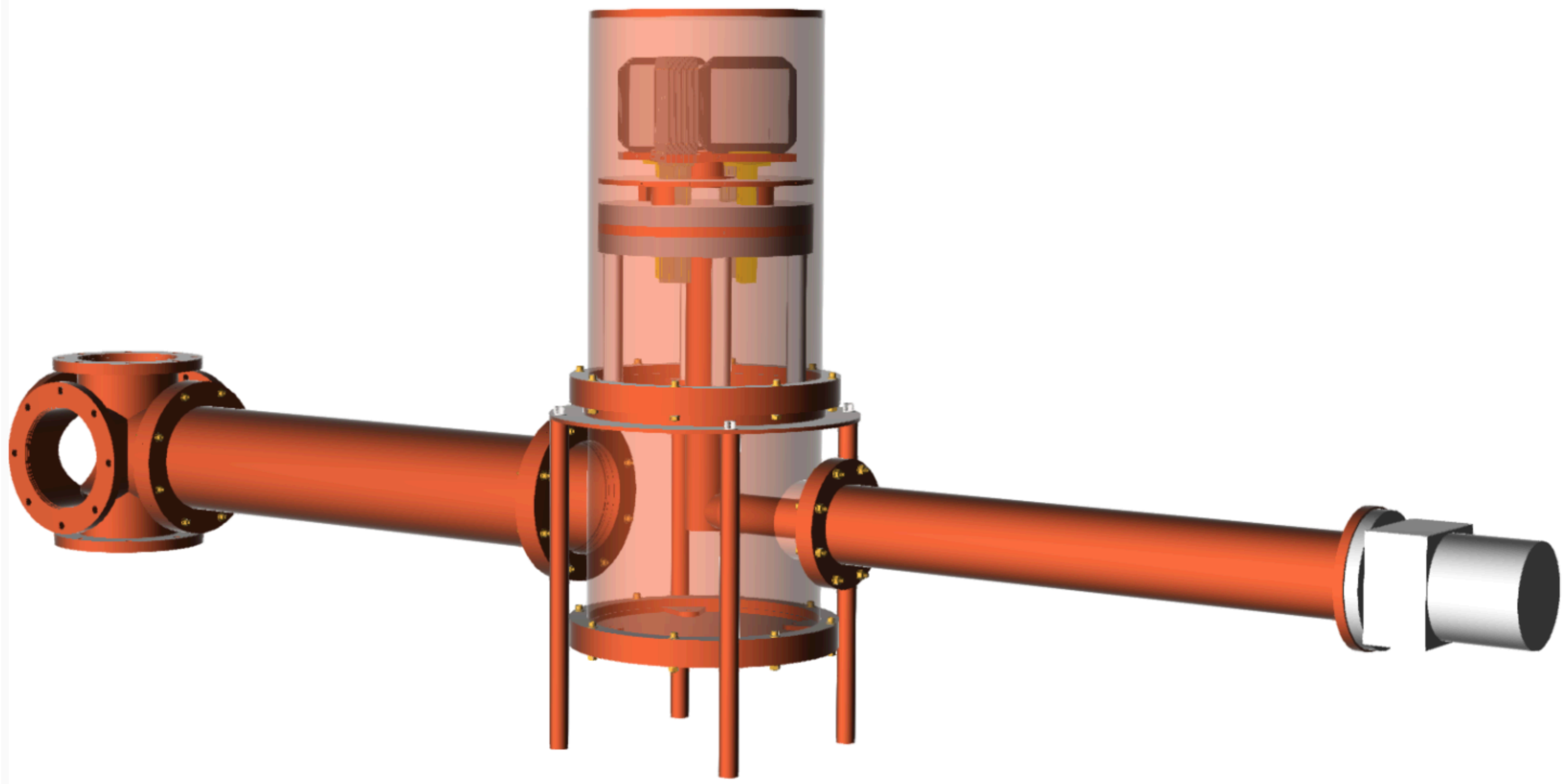
Modane Underground Laboratory (LSM), France

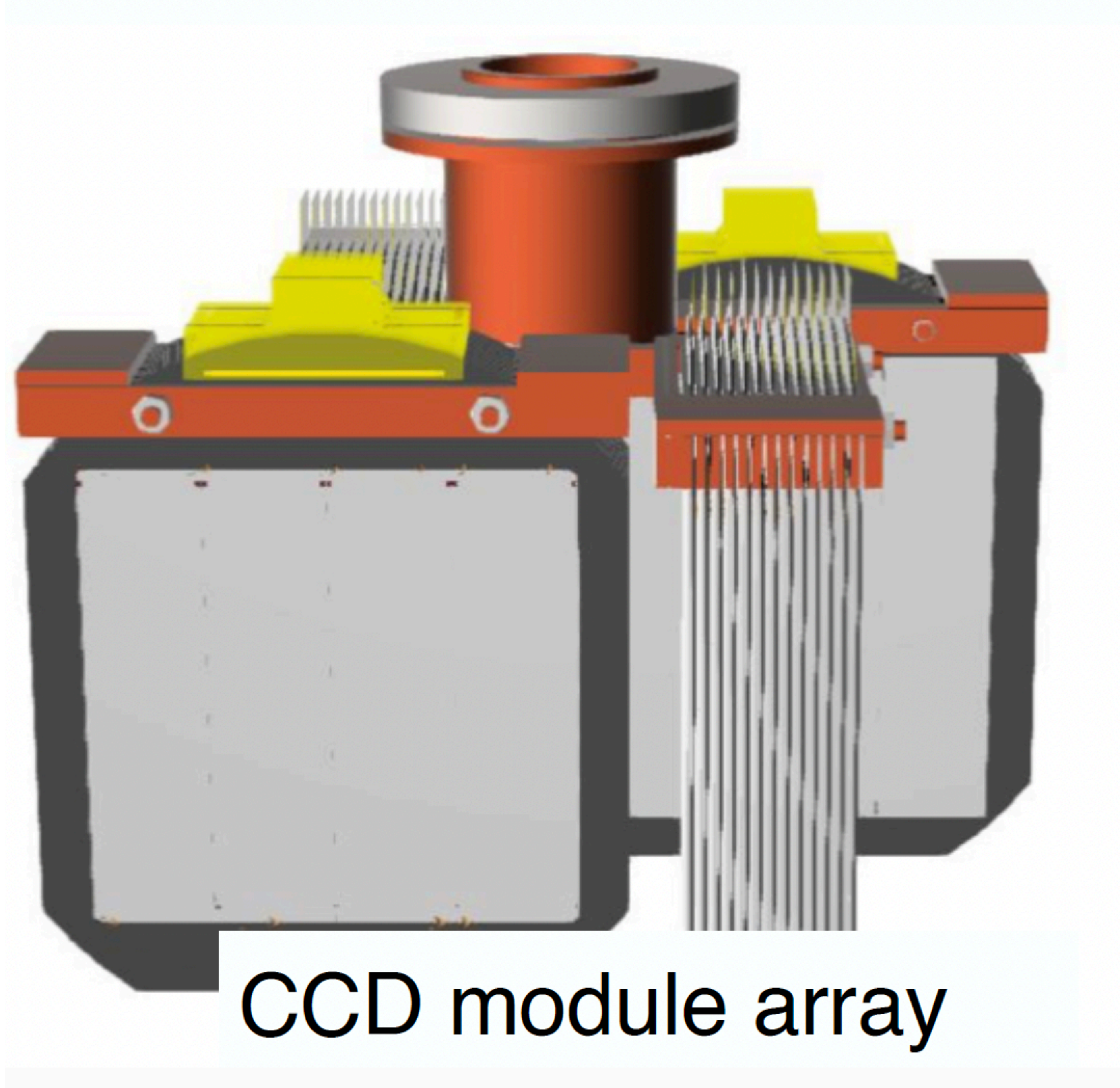
CCD technology

- Use of skipper-readout silicon CCDs with thickness of 675 um and 9 Mpixels
- 200 CCDs in order to achieve a 700 gr target mass
- Custom electronics for the transfer of charge and a low noise read-out

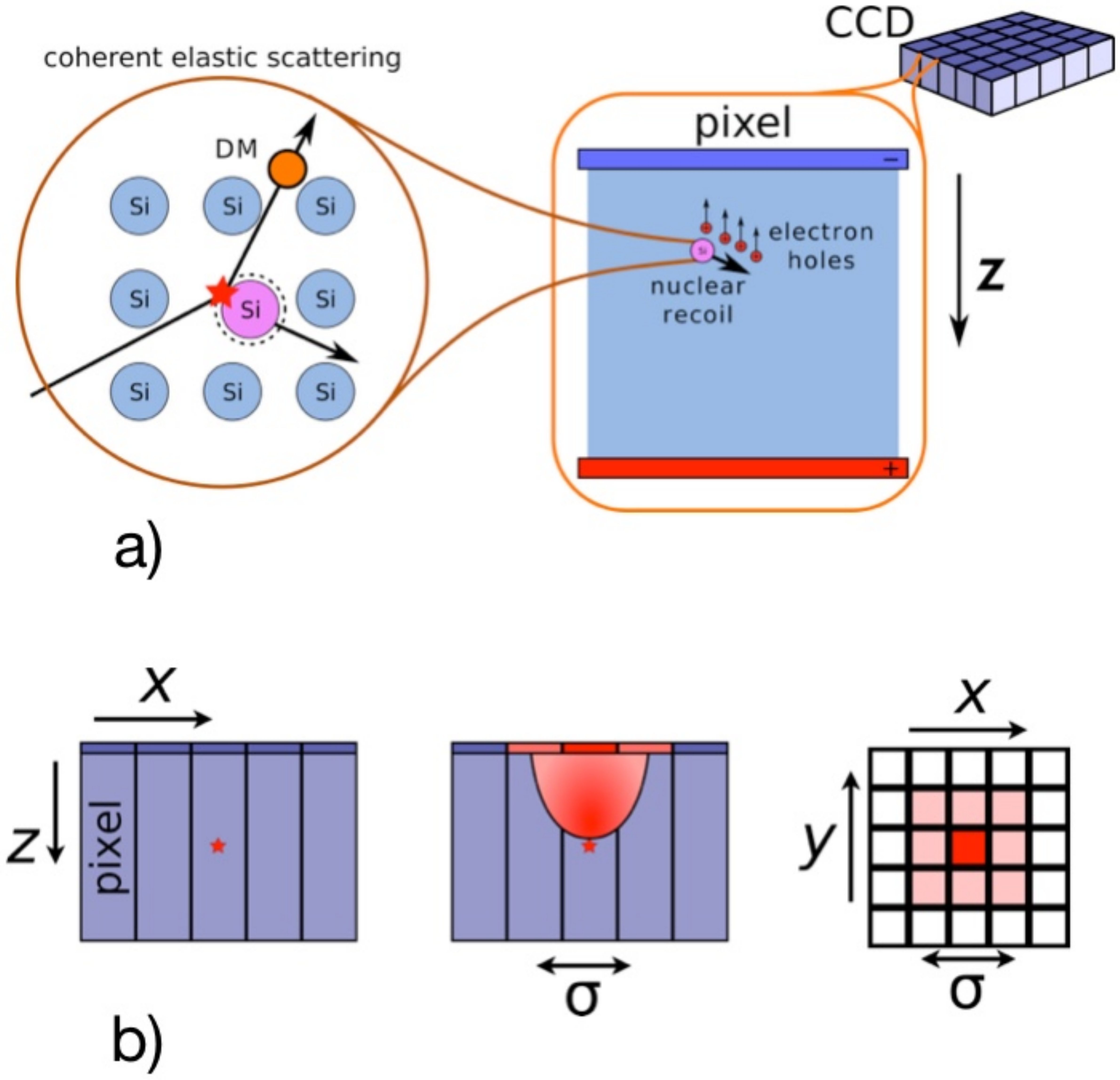
Main scientific objectives

- Sub-electron charge resolution together with low-noise readout electronics
- Operate ionization detector with energy threshold 5-10 eV
- Achieve a background rate of a fraction of dru
- Search for light-mass DM candidates of the hidden sector or light WIMPs





Detection principle

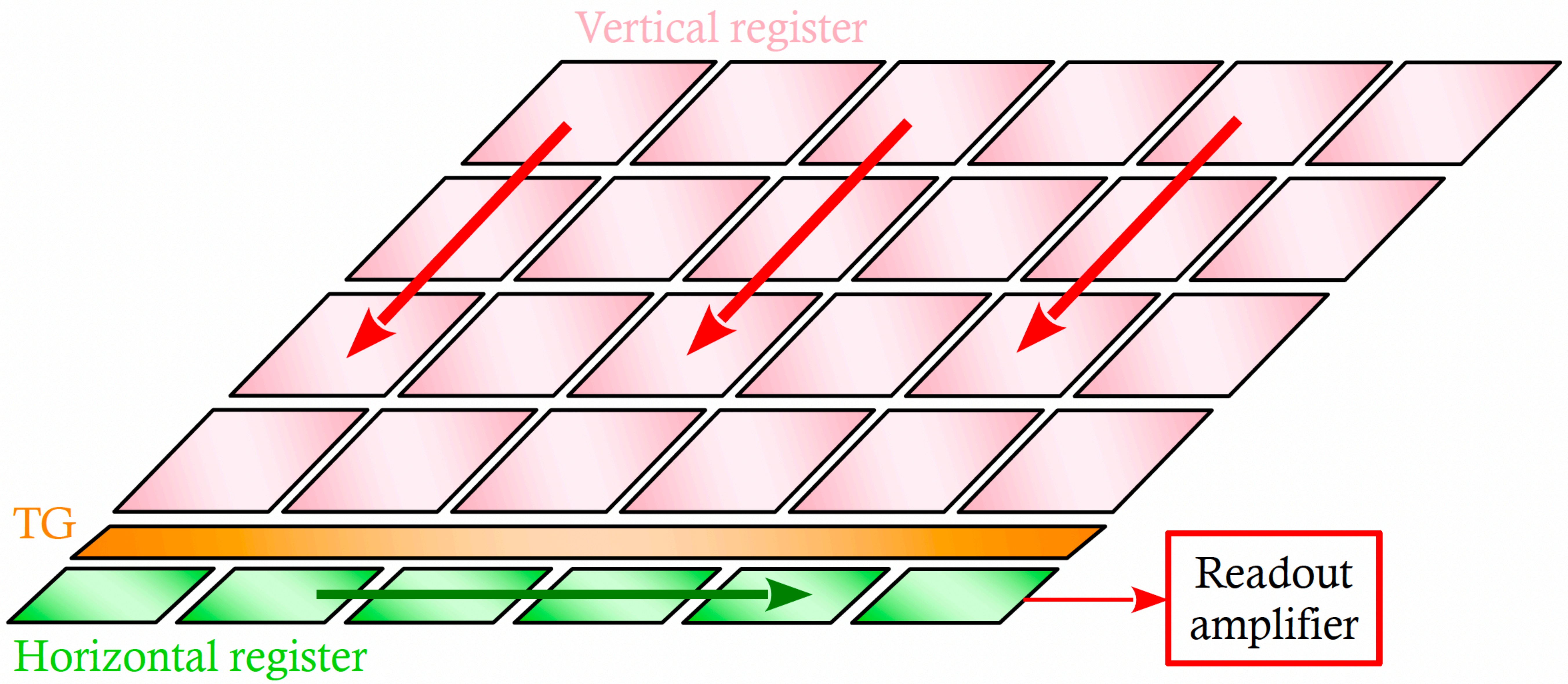


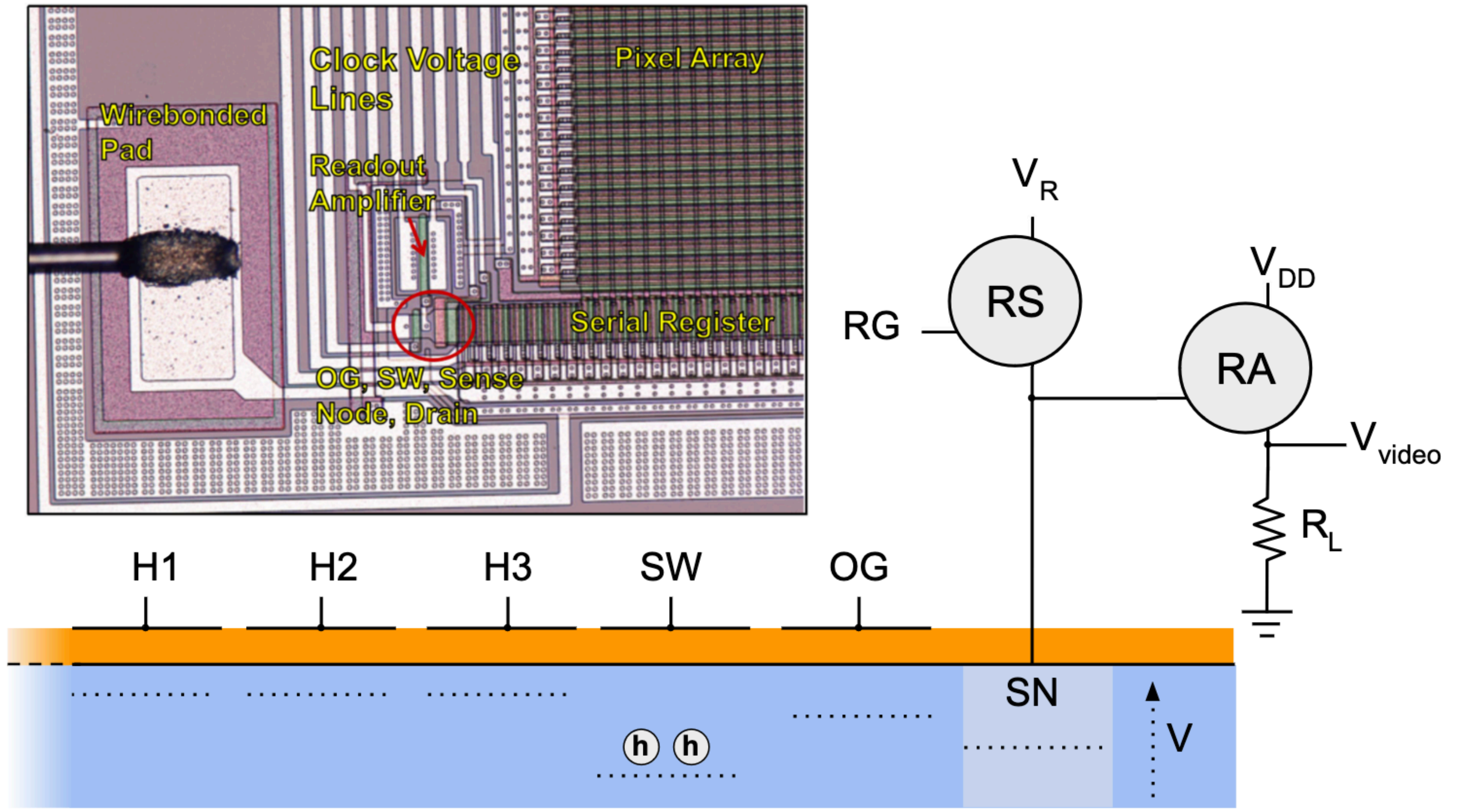
- A DM particle can scatter off a nucleus or a valence electron and create a point-like ionization event
- Charge will be drifted to the pixel array under a voltage bias
- Lateral spread of the charge cloud due to thermal diffusion
- The lateral spread is proportional to the drift time (depth of the interaction)

3D reconstruction of the interaction location	Identification of particle type via cluster pattern

Charge transfer and skipper readout

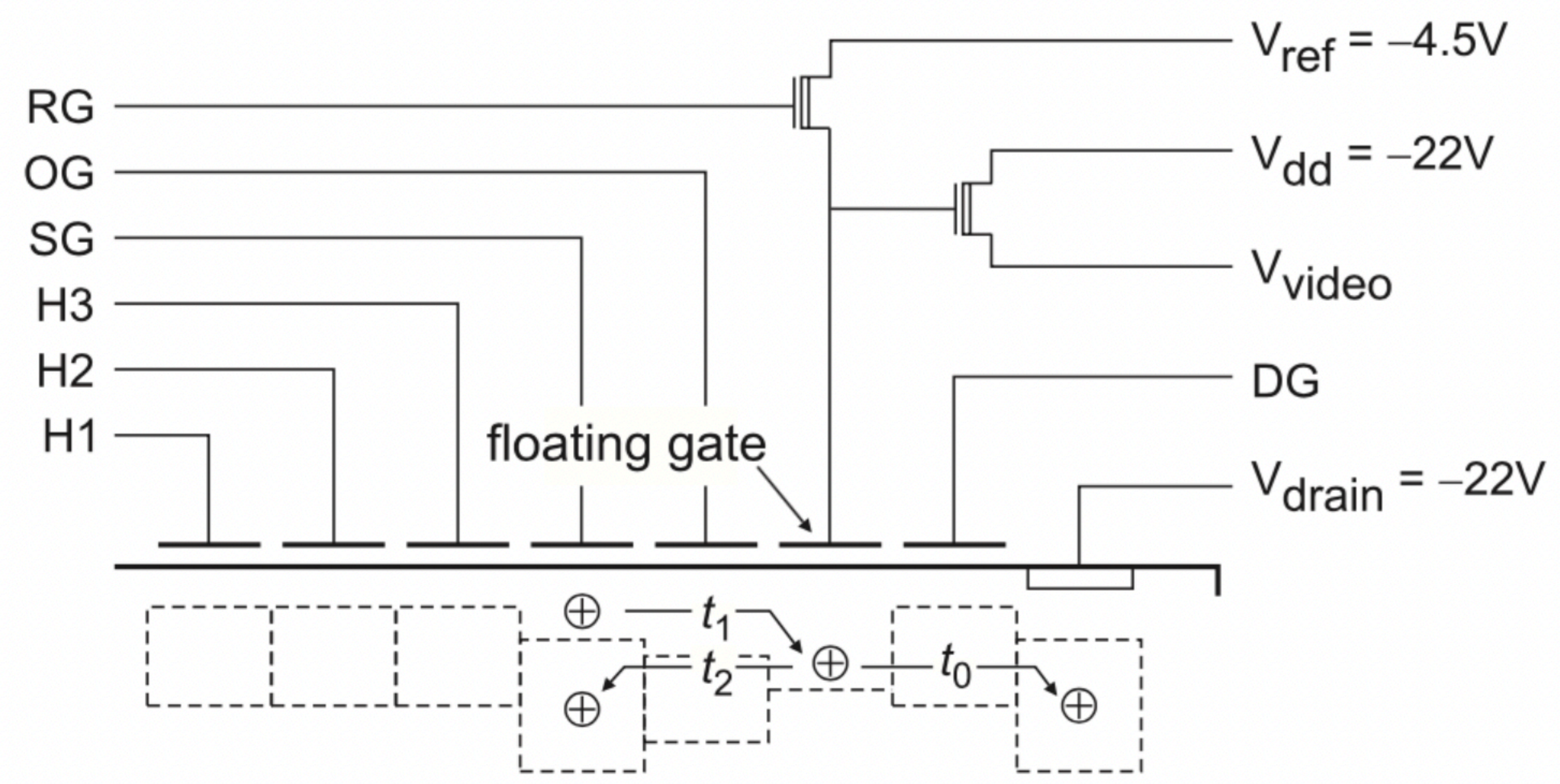
- After exposure of the active target and charge generations the readout take place
- A series of 3 voltage clocks create potential walls that are used to move the charges through the pixels
- In a vertical transfer one row of pixels is moved one row closer to the horizontal register
- The charge in the horizontal register is moved pixel-by-pixel to a readout amplifier
- The charge fall into the SW gate and then to the SN where it is measured

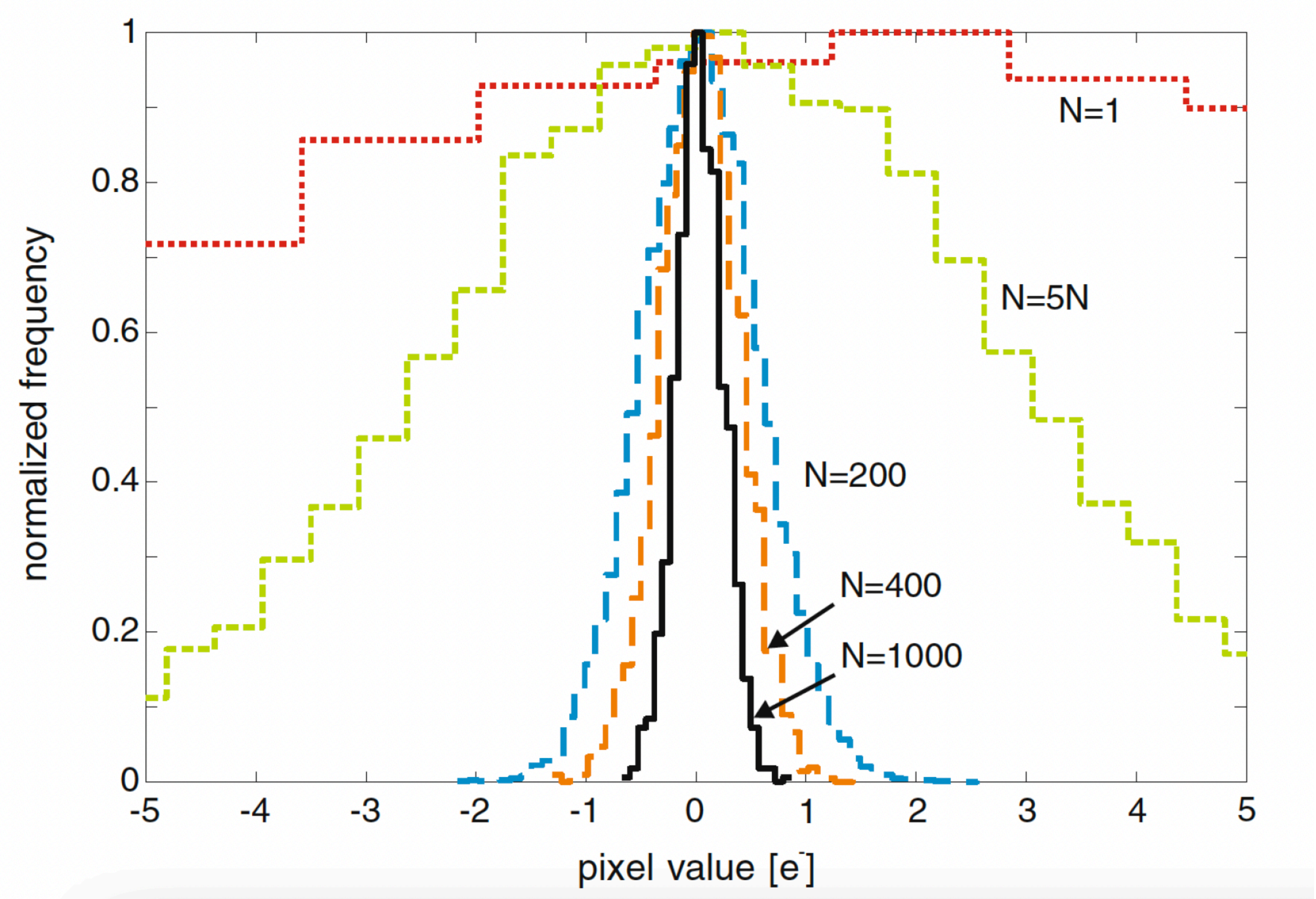




Charge transfer and skipper readout

- Using a floating gate as SN and replacing the bias VOG with a clock, permits a multiple non-destructive measurement of the charge packet
- The measurement error σ will decrease as $\sim 1/\sqrt{N_{skip}}$
- Thus the 1/f amplifier low frequency noise is now subdominant
- For a large number of N_{skip} the resolution reaches sub-electron values
- But $t_{readout} \sim N_{skip}$



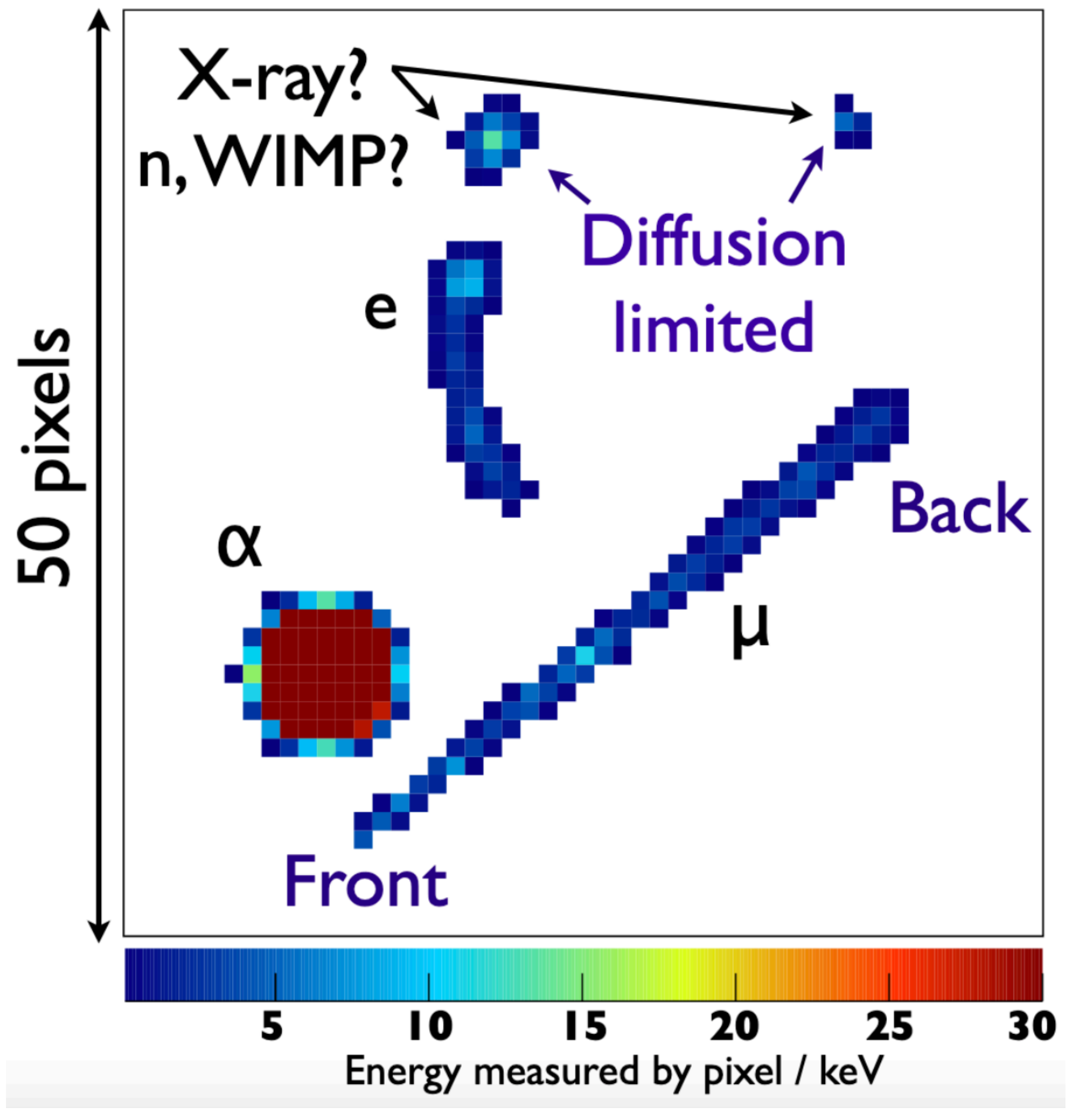


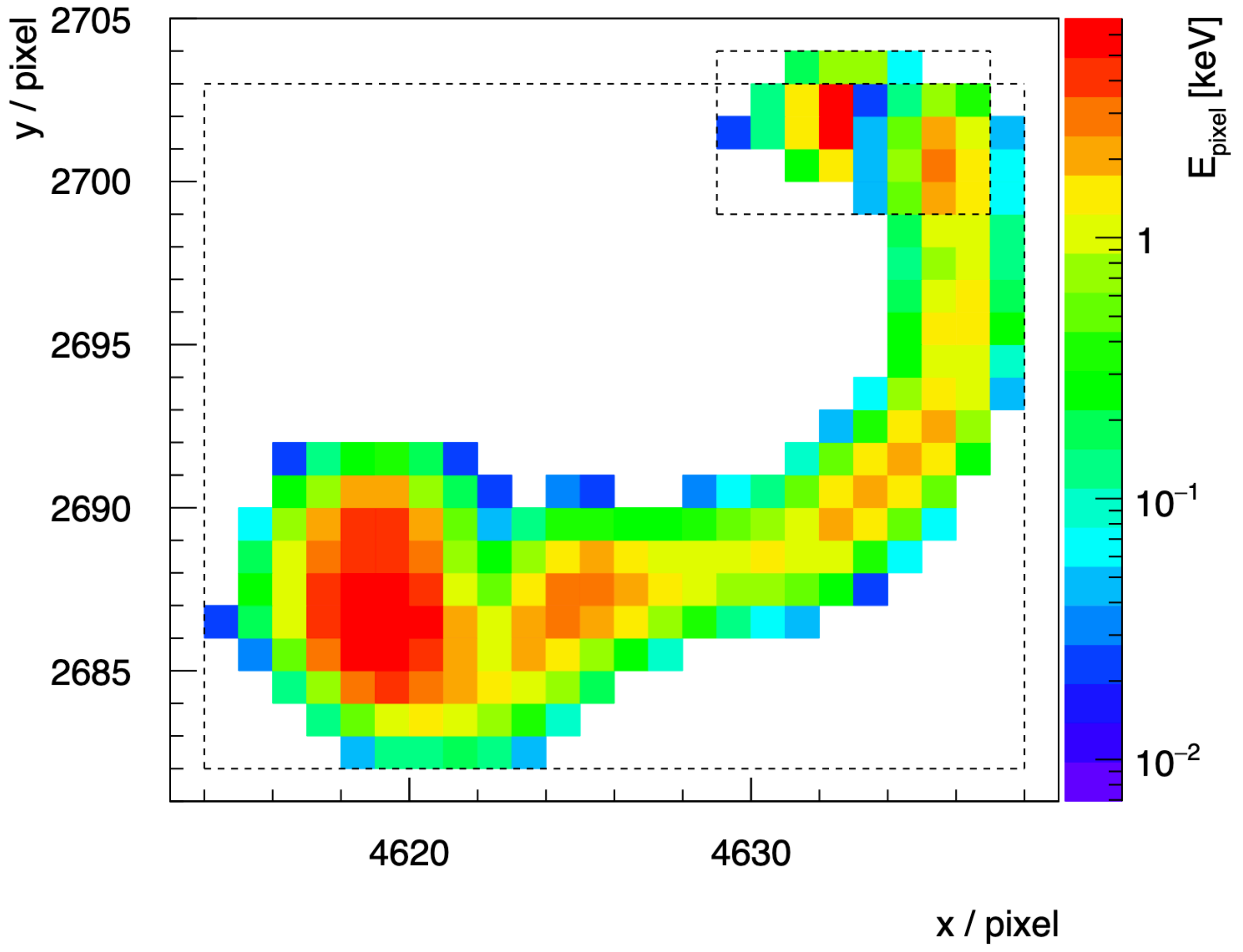
Exp Astron 34, 43–64 (2012)

Effort for Background mitigation

Radiogenic and cosmogenic background limit the sensitivity for WIMP search (nuclear recoils of $\sim$ keV$_{ee}$ energy deposits)

- Use of Si wafers with low cosmogenic activation and limited time above ground (fabrication, transport and storage)
- Careful material selection
- Oxygen-free copper box for CCDs and further reduction by multiple layers of Pb Shield
- Analysis techniques for efficient identification of particle type from cluster shape





JINST 16 (2021) P06019 DAMIC Collaboration

Low Background Chamber at LSM

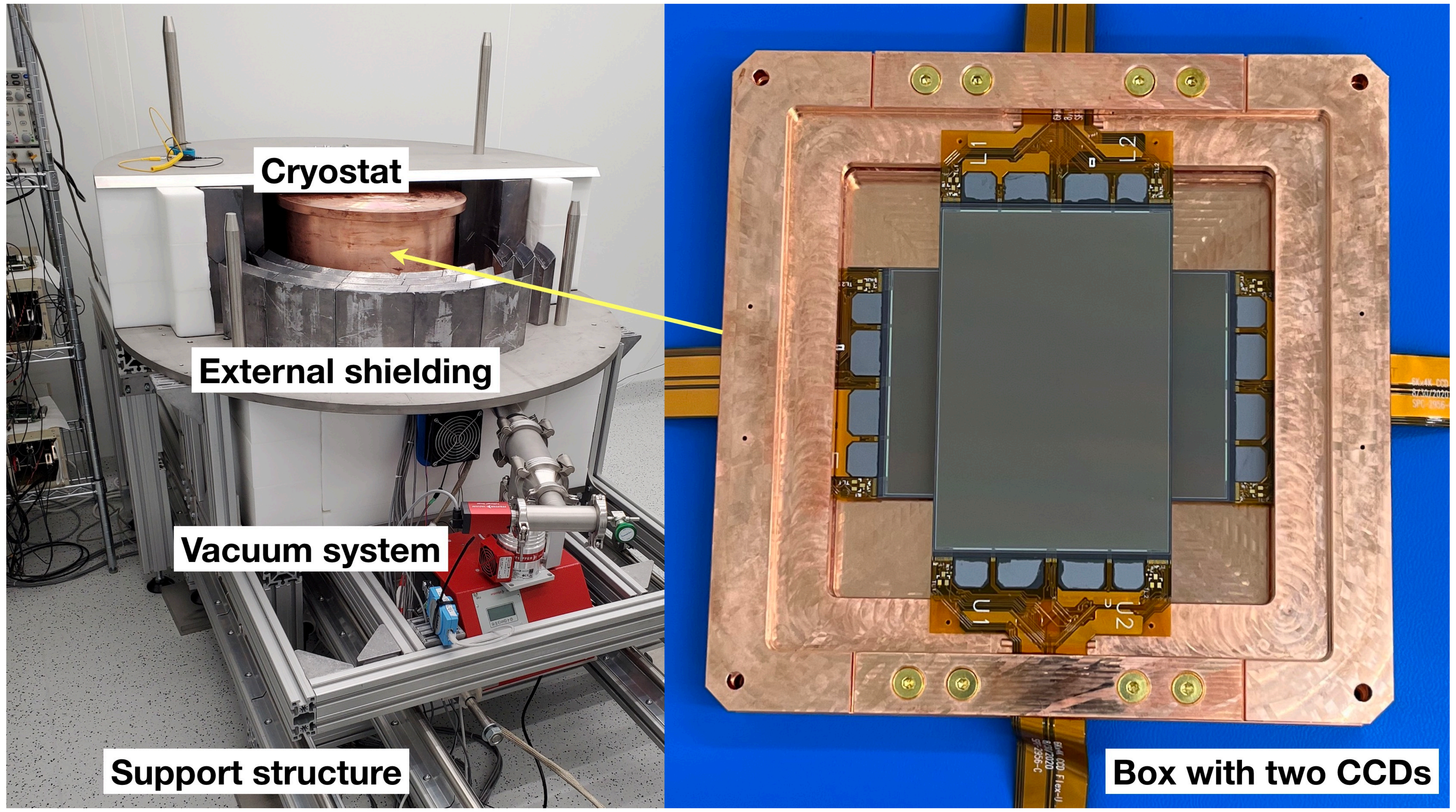
Low Background Chamber at LSM

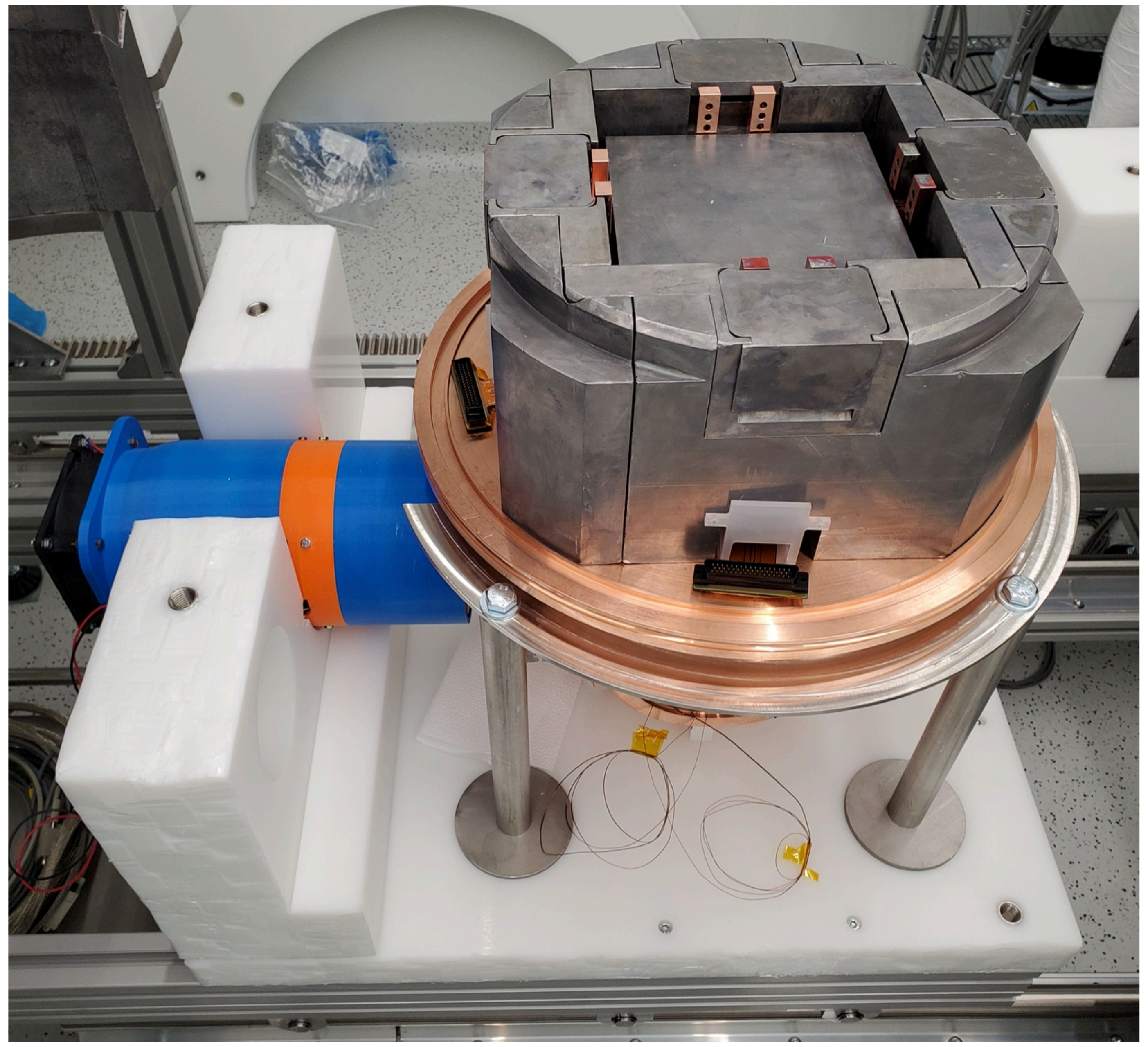
LBC experimental configuration

- $6k \times 4k$ pixel skipper CCDs ($\times$ 2)
- Total mass of active target $\sim$ 18gr
- Background reduction with layered polyethylene+lead shielding, innermost layer of ancient lead
- Readout is done with the commercially available Astronomical Research Cameras electronics

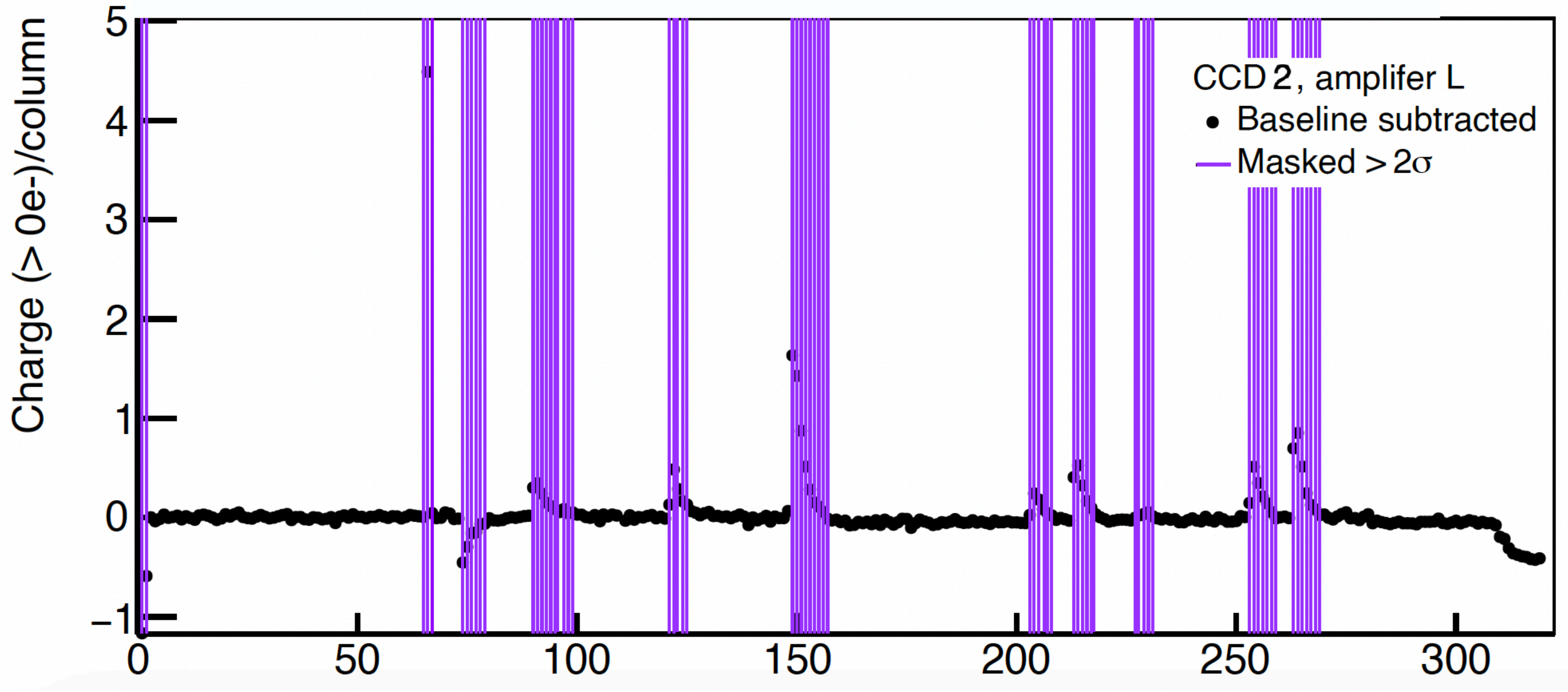
Advancements

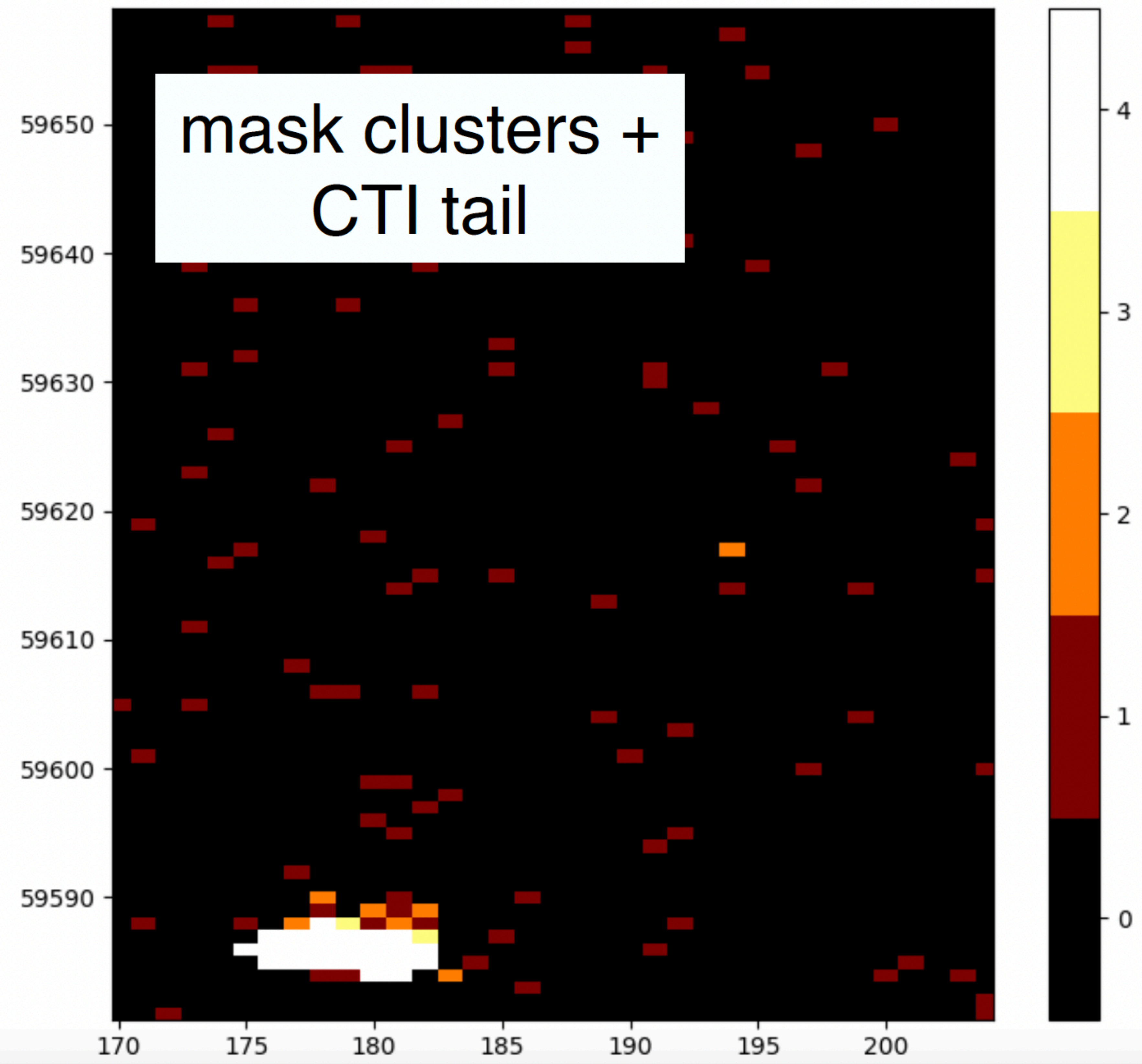
- Validation of detector components and subsystems (DAQ, slow control monitoring)
- Reduction of the high-energy background levels to few d.r.u
- Operation with 650 NDCM (resolution of 0.2e)
- The level of DC is 3×10^{-3}e/pix/day (x10 higher than the initial goal)
- First results for hidden sector candidates with an exposure of 85.2 gr-day





Data selection procedure





Identification and Rejection of high-energy events

clustering reconstruction algorithm, with threshold of $2\sigma_{avg}$ and seed of $2e^{-}$

Masking

Removal of pixel clusters and tails from CTI

Defect masking

Searching for "hot" columns with abnormally high charge

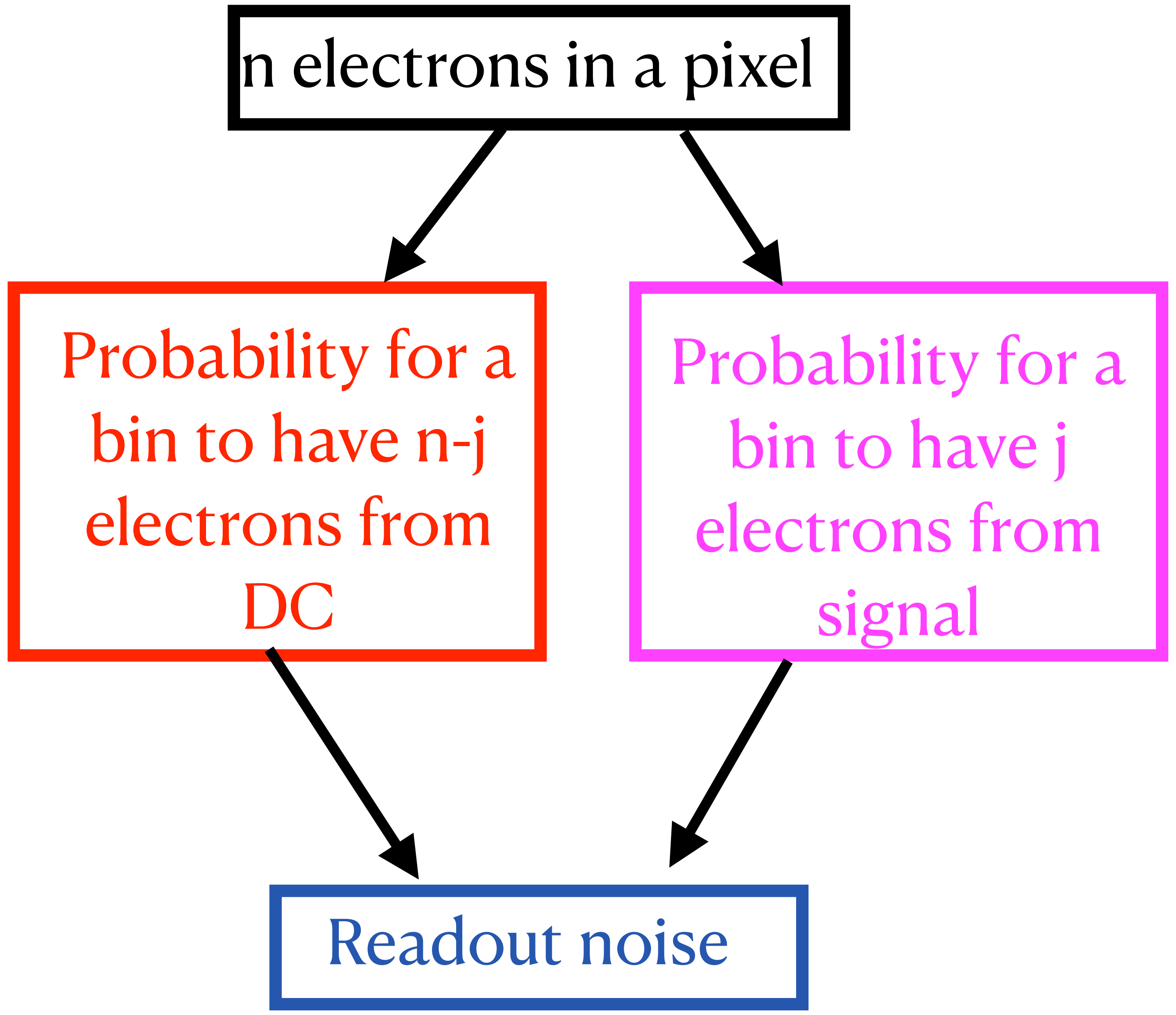
Artefacts in the serial register

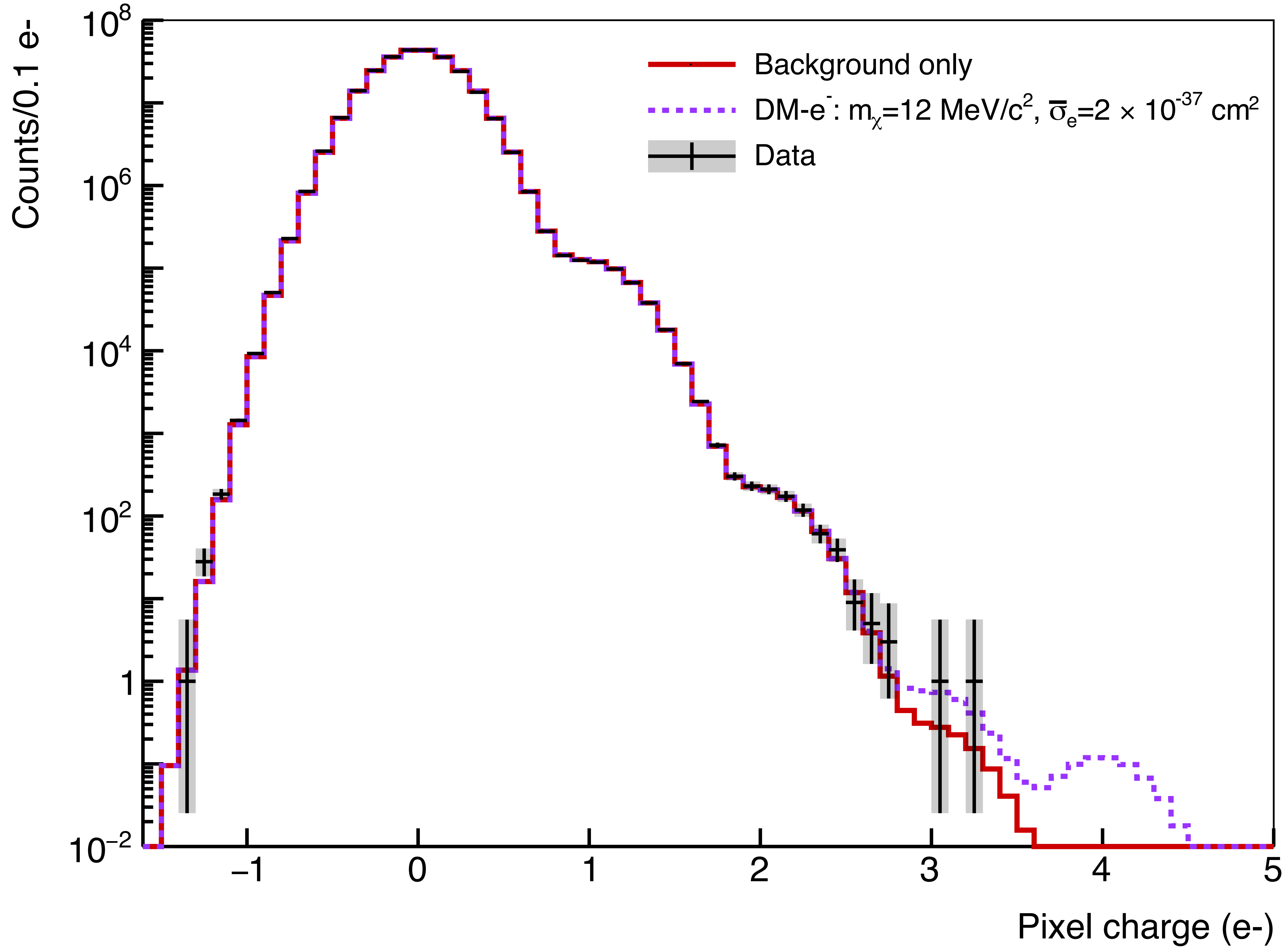
They can distort the pixel charge distribution

Final Signal and Background model

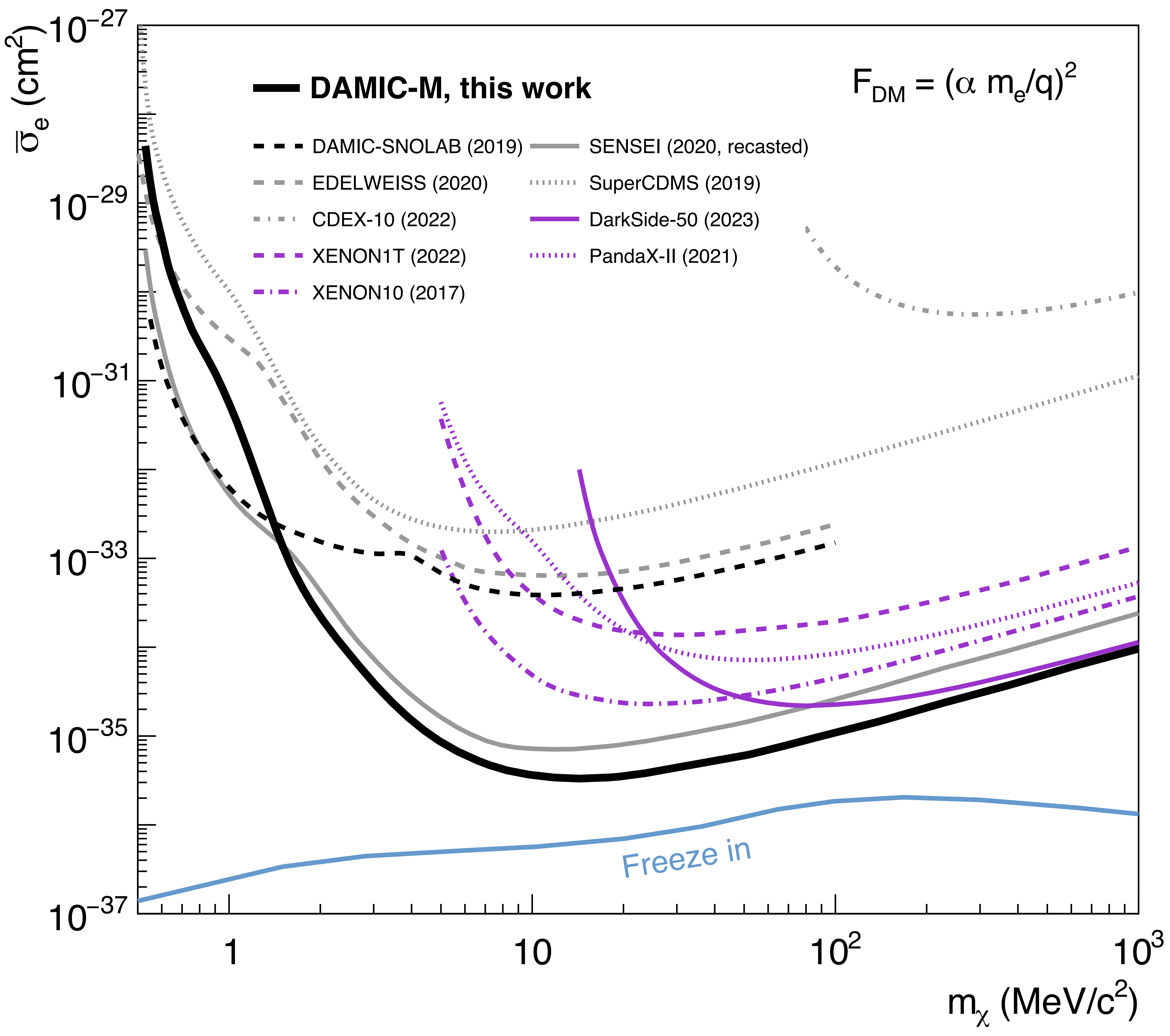
Then one can construct the pixel charge distribution
for any particular value for the dark current λ_{DC} and the cross section σ_e

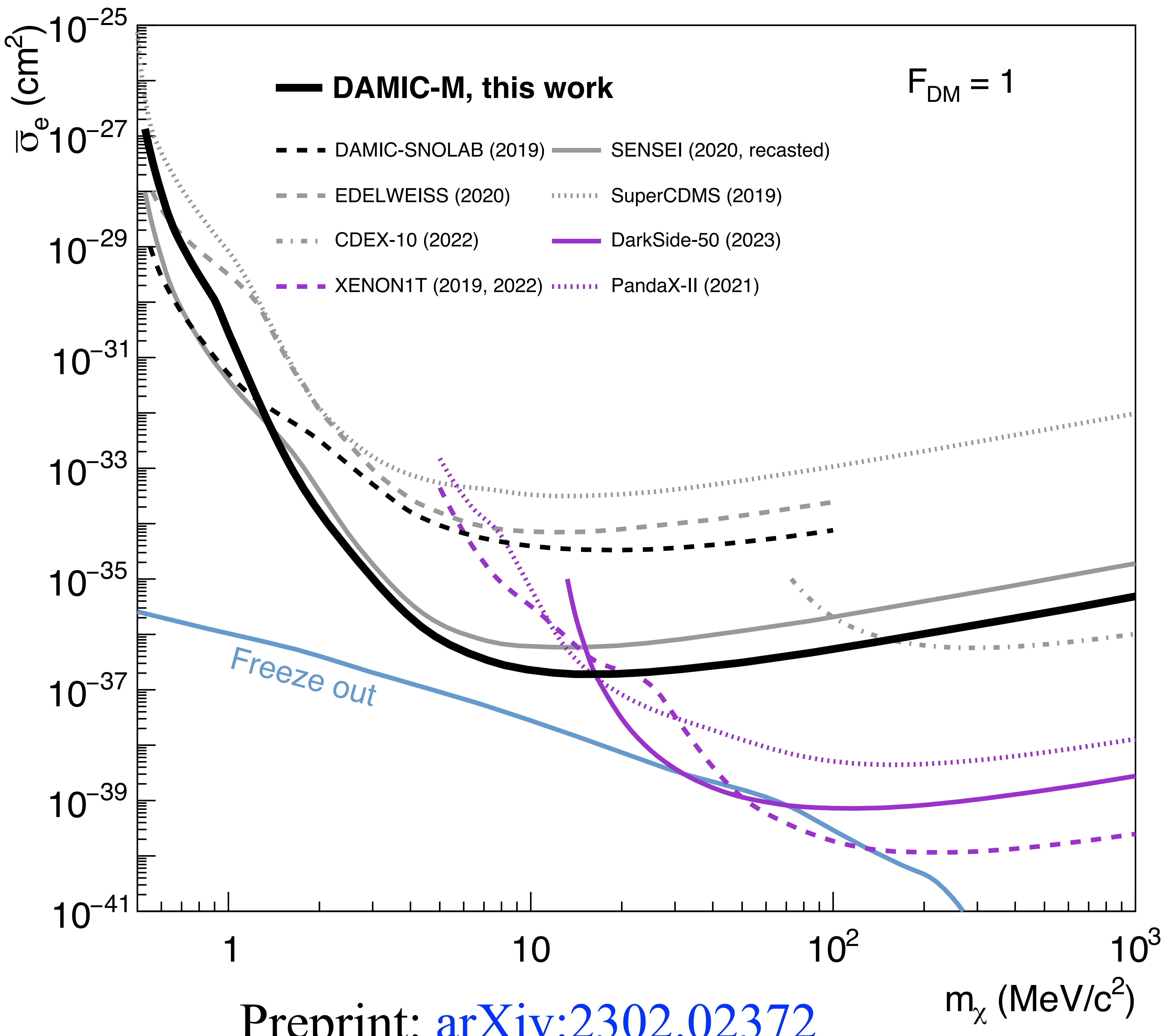
$$\Pi(p) = N_{pixels} \sum_{n=0}^{\infty} \left(\sum_{j=0}^{n} S(j \mid m_\chi, \sigma_e) \mathrm{Poisson}(n - j \mid \lambda_{DC}) \right) \mathrm{Normal}(p \mid n, \sigma_{avg})$$





90% CL upper limits results





Preprint: arXiv:2302.02372
accepted for publication in PRL

Conclusion

- Prototype LBC is already installed at the LSM

- LBC is taking data under stable conditions of low background and optimised readout noise

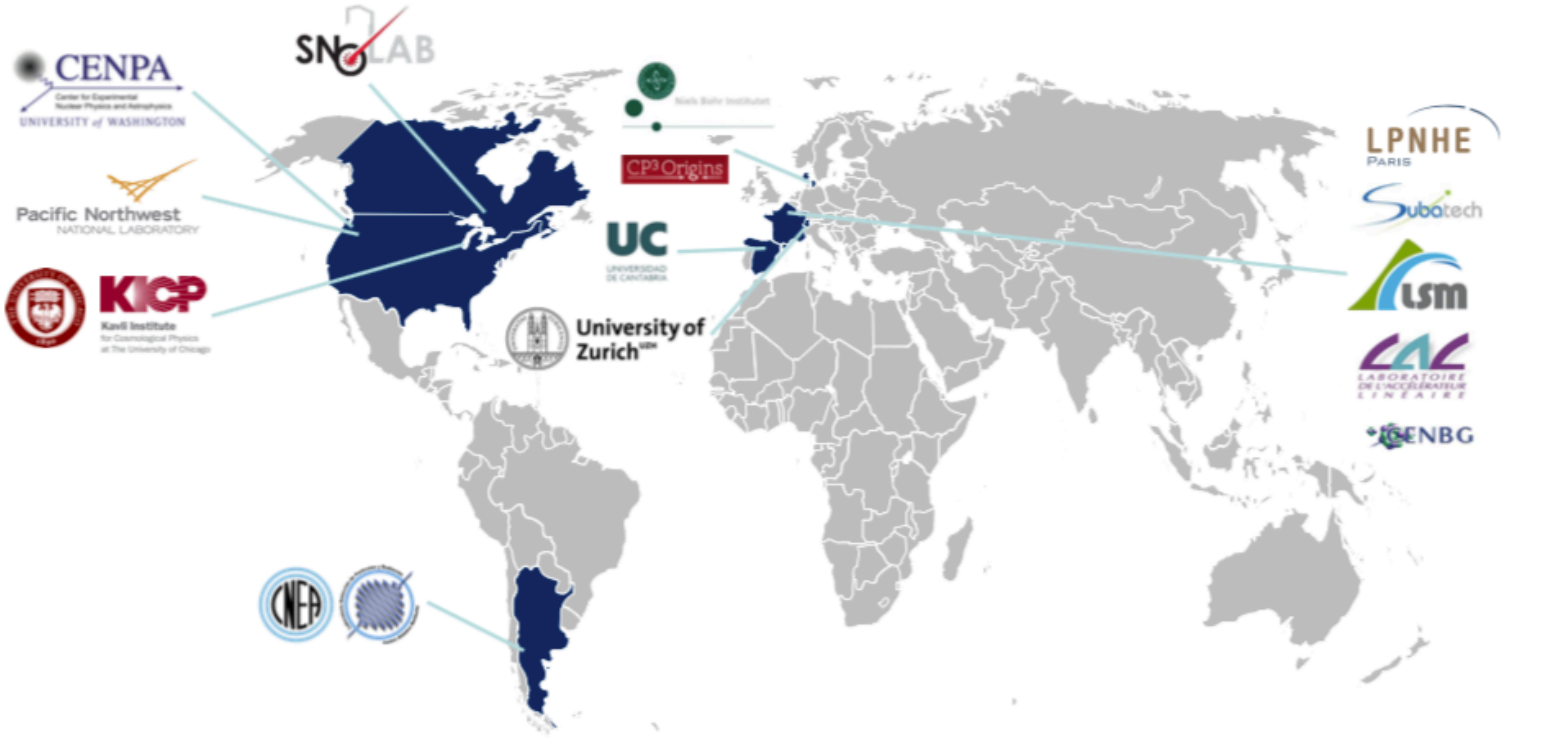
- First science results with 85.2 gr-day exposure. World leading limits for DM-e scattering candidates

- DAMIC-M aim to explore a vast region of the parametric space in light supersymmetric and hidden sector DM candidates

- The final DAMIC-M detector will reach a kg-year scale exposure using skipper silicon-CCD technology with a fraction of a dru as goal of the background rate

- The actual experiment construction will start in 2024

DAMIC-M Collaboration



European Research Council

The National Science Foundation

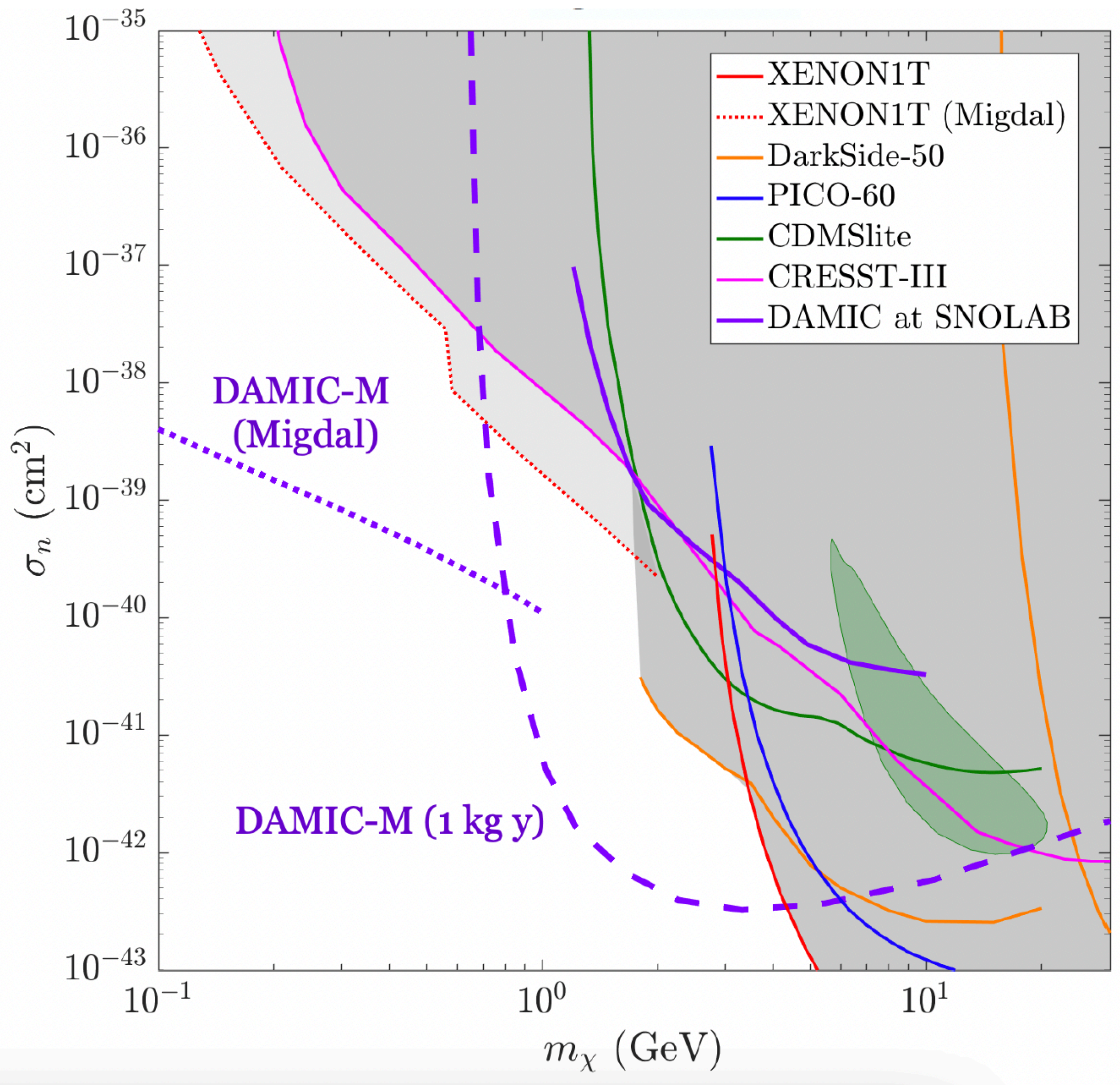
FNSNF
Fonds national suisse
Schweizerischer Nationalfonds
Fondo nazionale svizzero
Swiss National Science Foundation

Supplementary slides

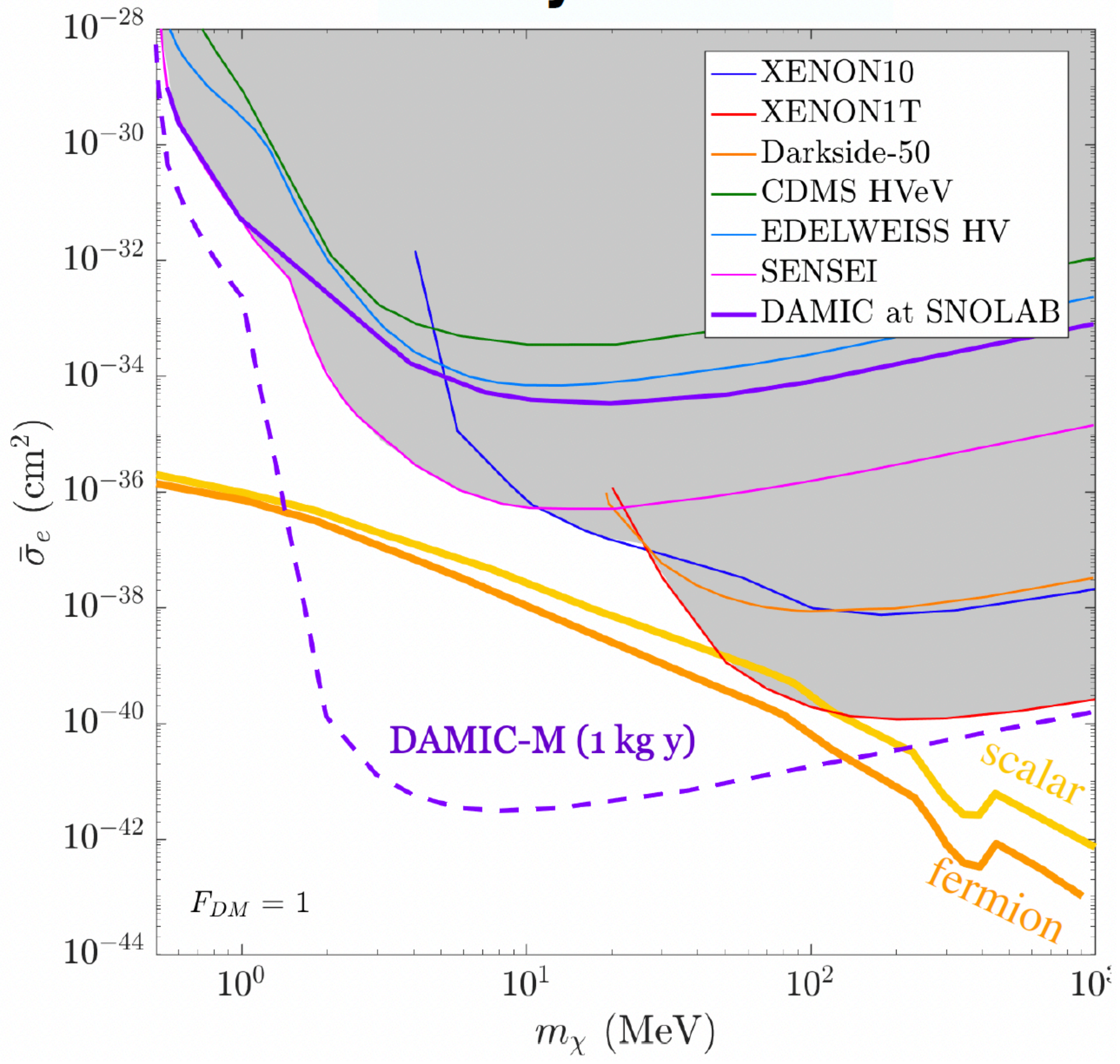
Science goals

- Spin independent WIMP-nucleon elastic scattering
- Hidden sector candidates (DM-e scattering, Bosonic DM)

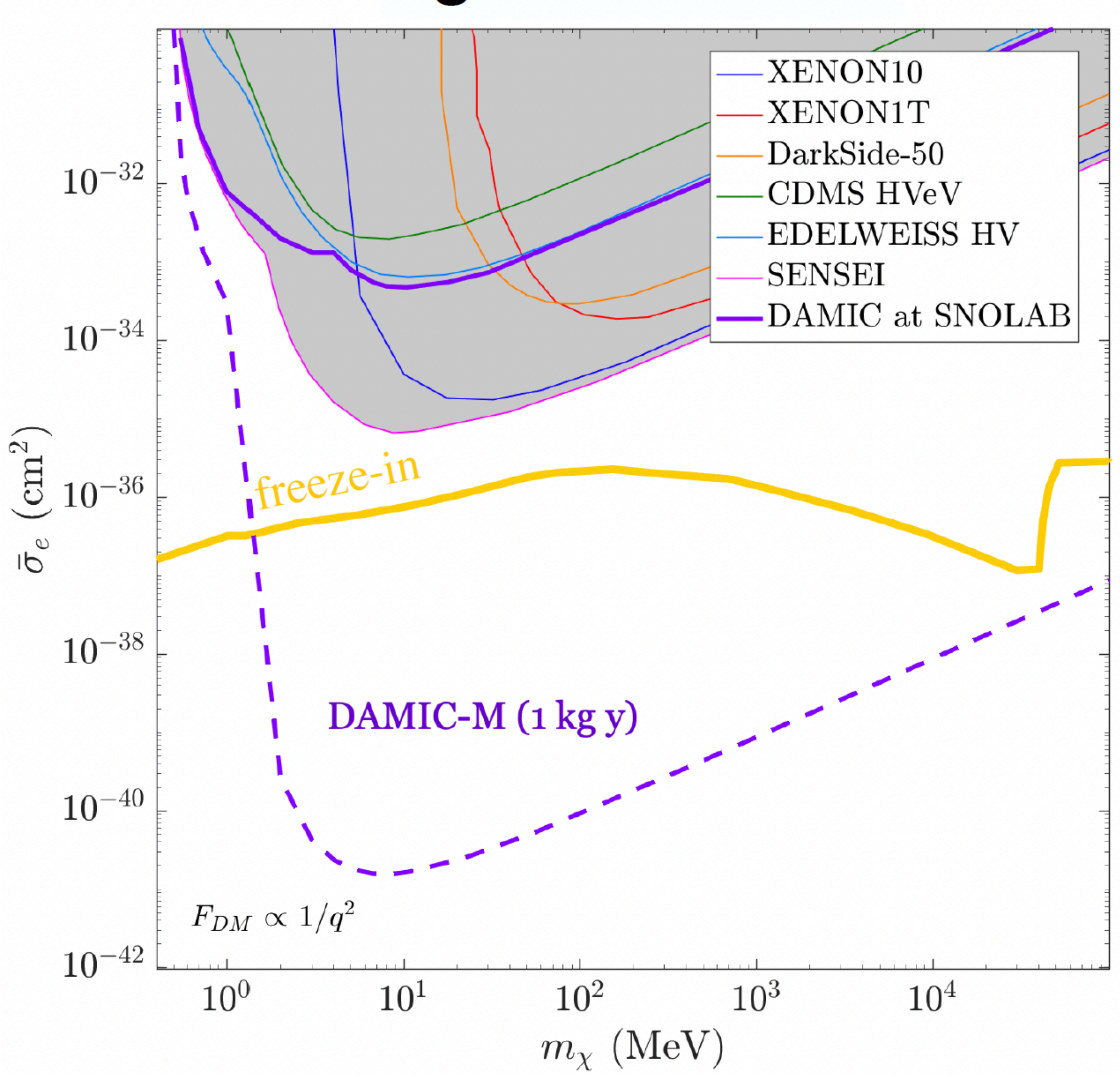
With an exposure of 1 kg-year and low background and Dark Current conditions is possible to explore a vast region of the available parametric space

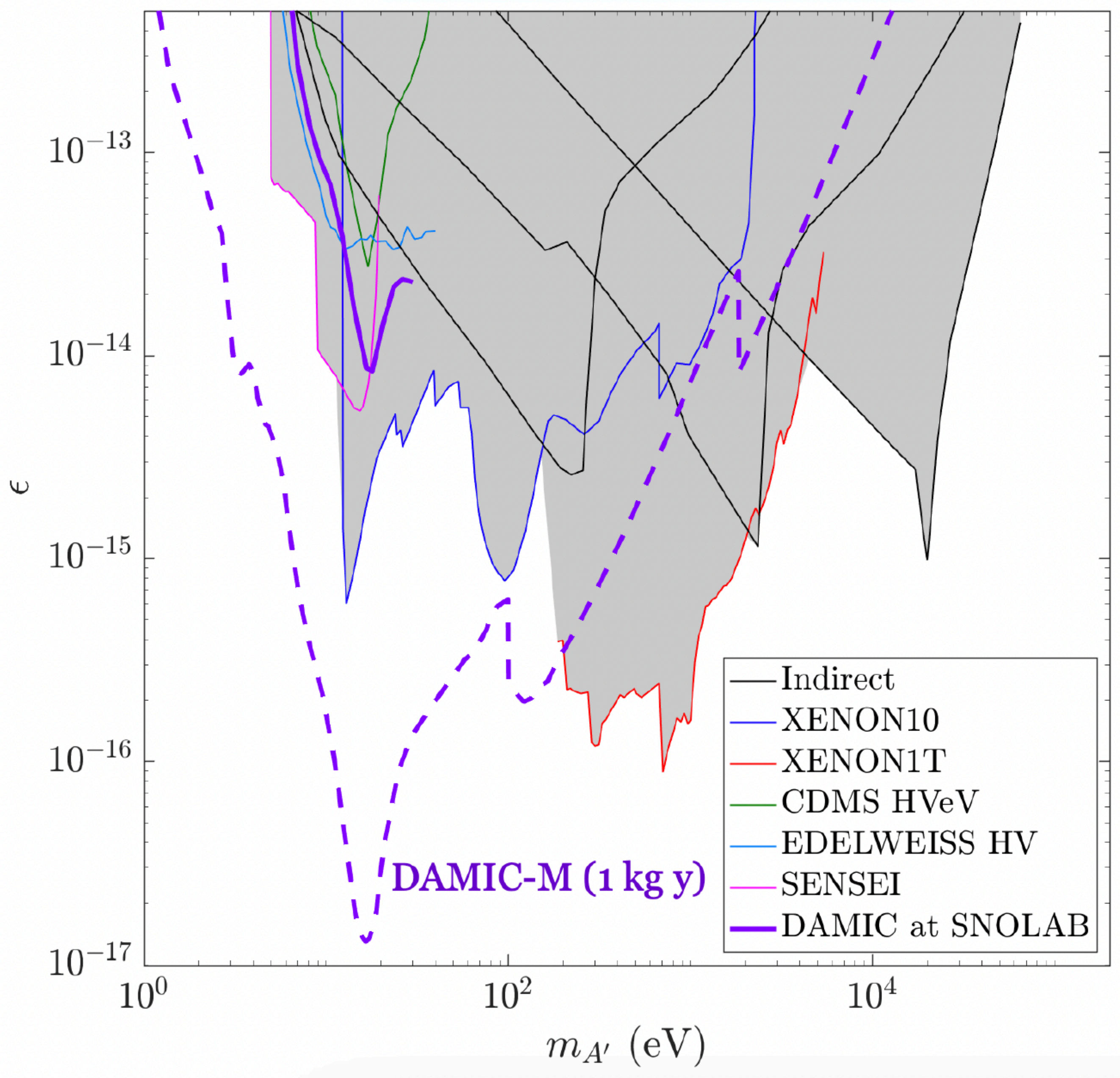


heavy mediator



light mediator





Searching for Hidden Sector candidates

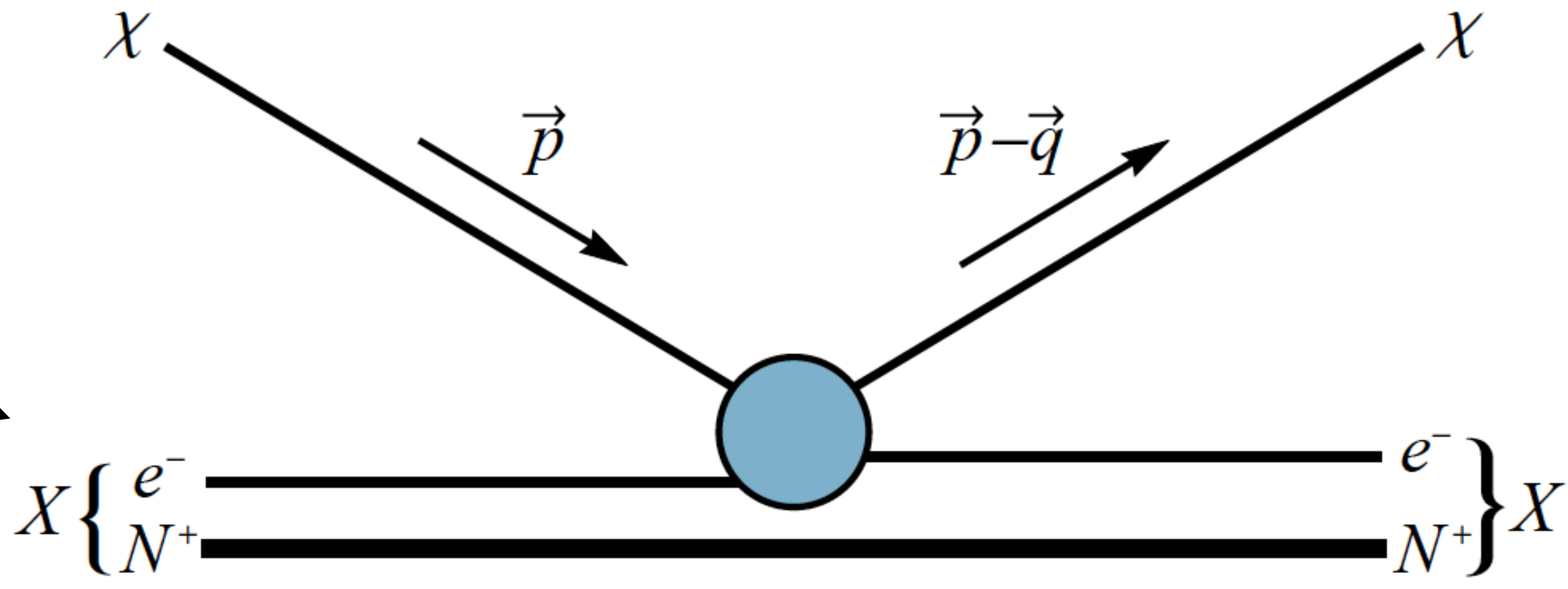
A hypothetical massive vector boson A' of a broken (dark) gauge group $U(1)_D$ that kinetically mix with the SM weak hypercharge. At low energies the mixing is between A' and a photon

Cosmic Time

Particle candidates for a light dark matter

$$\mathscr{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu}$$

The Dark Sector interacts with the SM via the gauge boson A'.
DM particles can scatter off bound electrons of the Xe atom via A' exchange.



J. High Energ. Phys. 2016, 46 (2016)

Two cases are of interest

- $F_{DM}(q) = 1$, heavy mediator, $(m_{A'} \gg \alpha m_e)$
- $F_{DM}(q) = (\alpha m_e/q)^2$, ultra-light vector mediator. $(m_{A'} \ll \alpha m_e)$

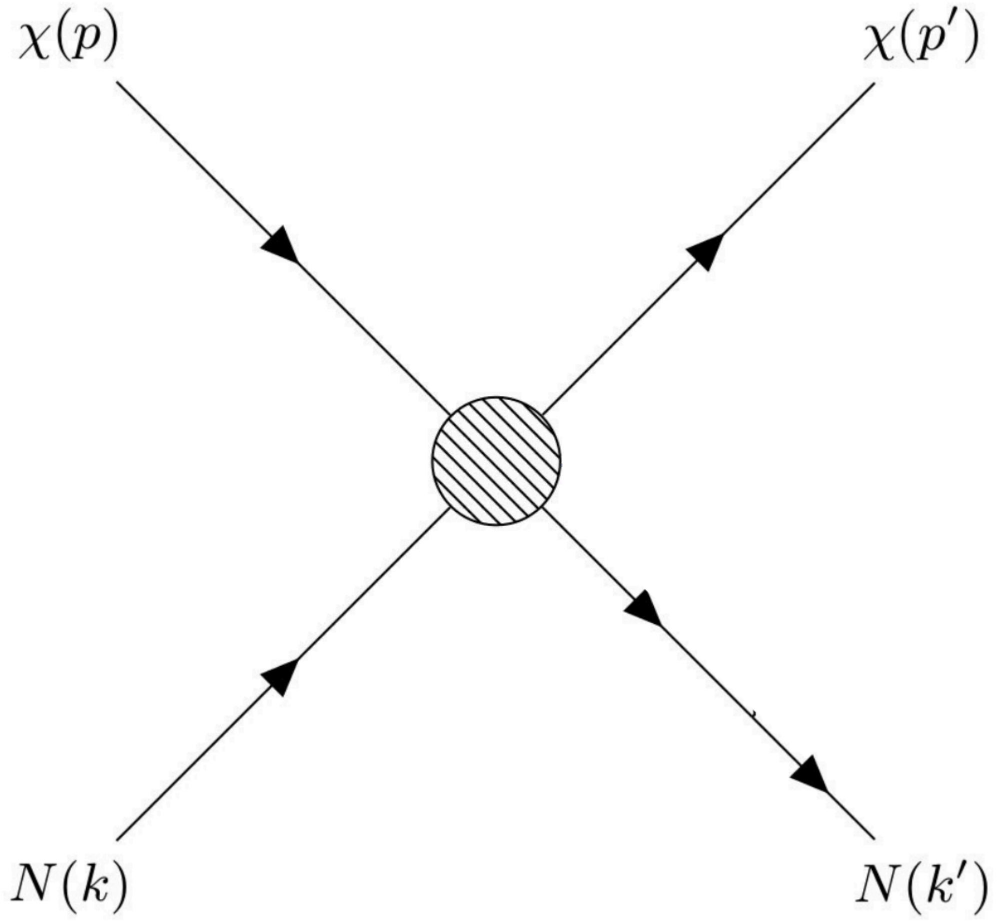
$$\frac{dR_{crystal}}{d\ln E_{er}} = \frac{\rho_\chi}{m_\chi} N_{cell}\bar{\sigma}_e \alpha \frac{m_e^2}{\mu^2_{\chi,e}} \int d\ln q \left(\frac{E_e}{q}\eta(u_{\min})\right) |f_{crystal}(q,E_e)|^2 |F_{DM}(q)|^2 dq$$

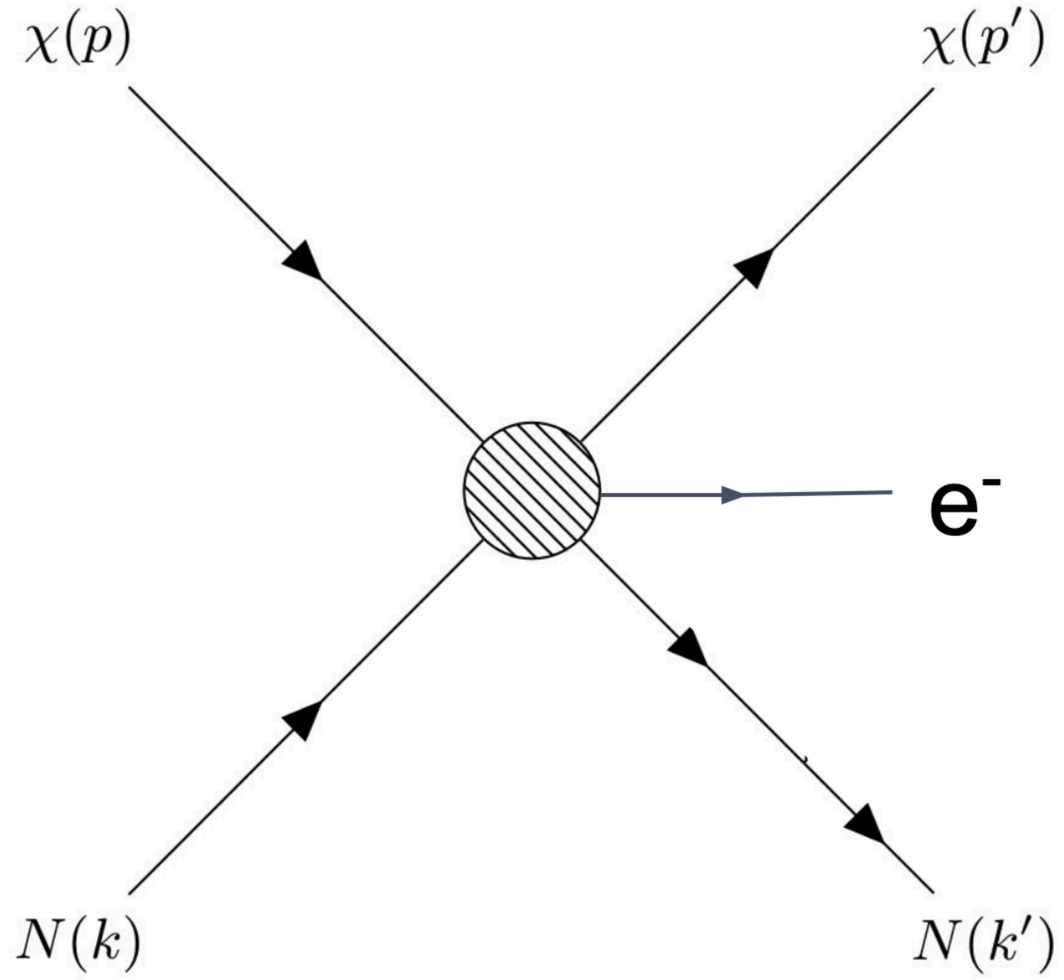
The rate depends on the initial and final state of the electron, the particular interaction and the Halo model

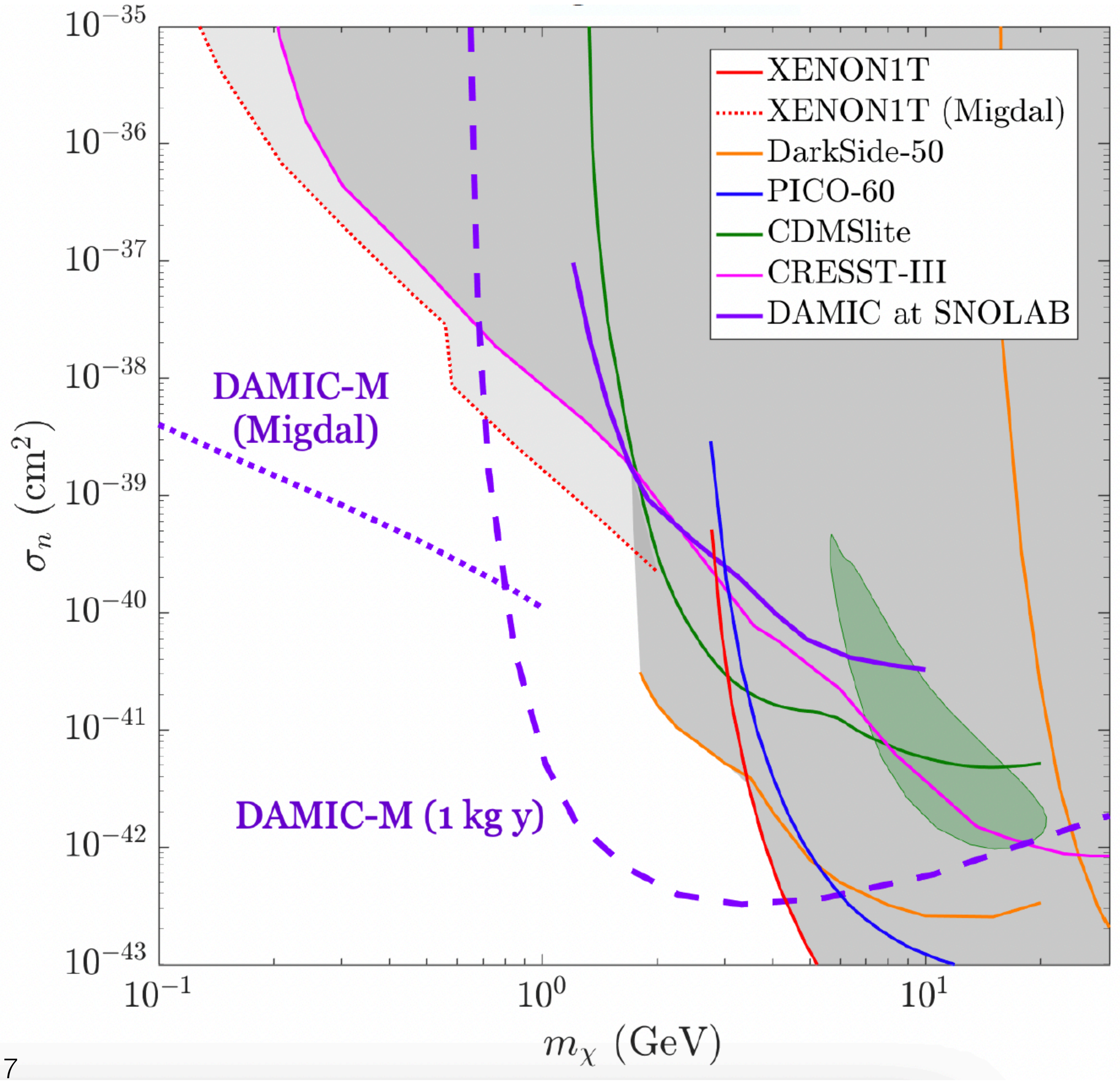
Science goals: Light WIMPs

Spin independent WIMP-nucleon elastic scattering

- Signal expects to be diffusion limited NR interaction
- Due to the small mass of Si atom the sensitivity is strong down to WIMPs with mass $\mathcal{O}$(1GeV)
- Possibility to explore a vast region of the available parametric space with kg-year scale exposure
- Possibility to extend to lower DM masses via the Migdal channel



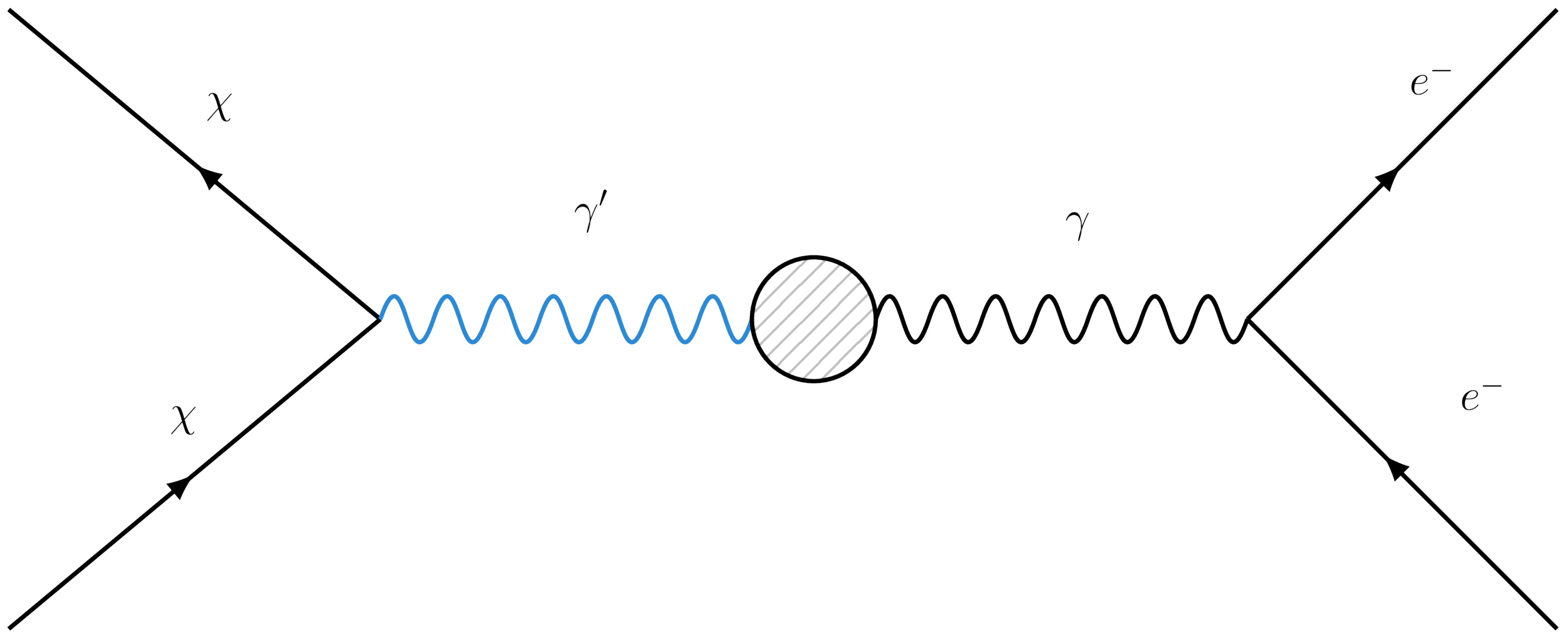




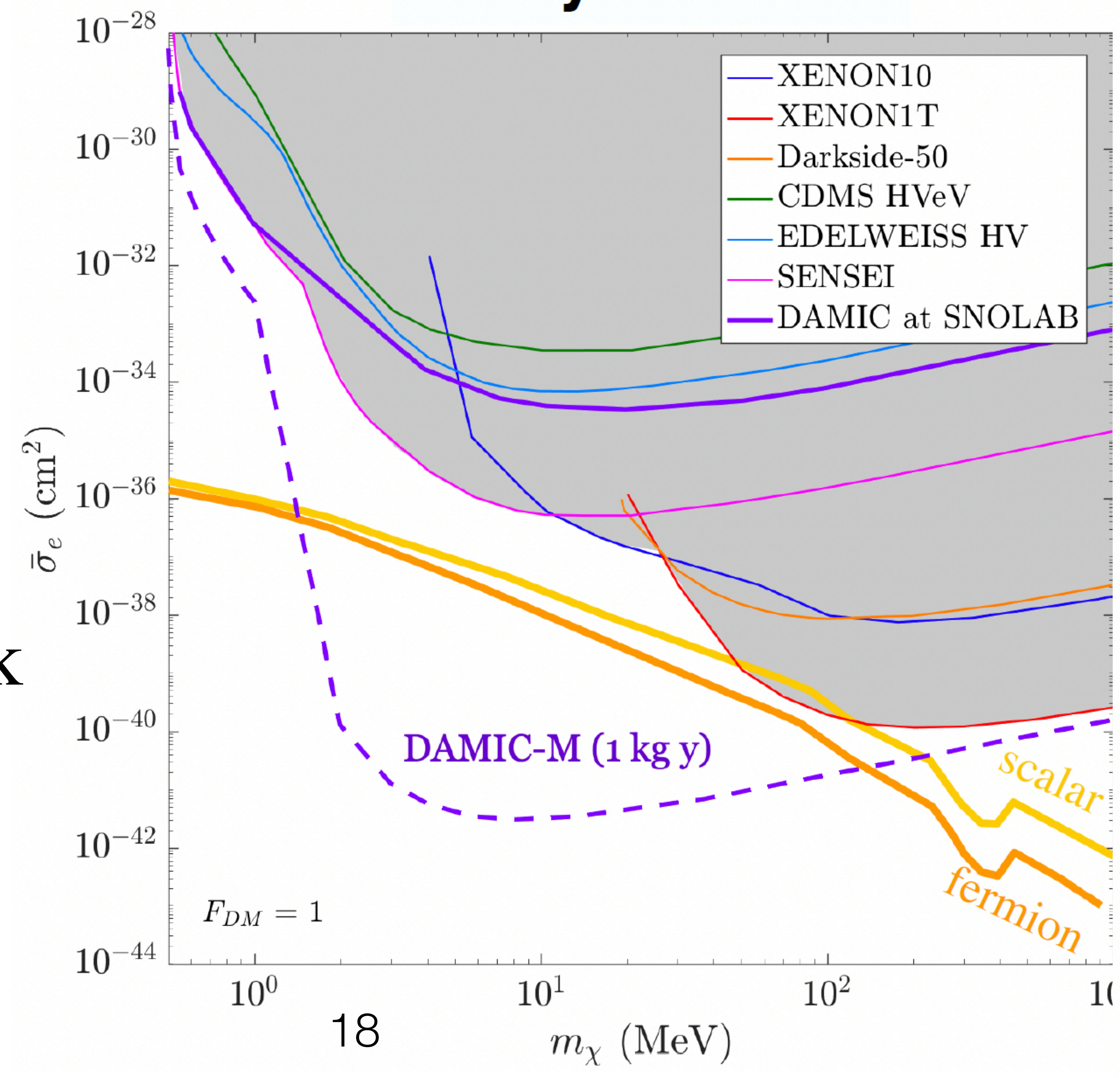
Science goals: Hidden Sector candidates

DM scattering off electrons

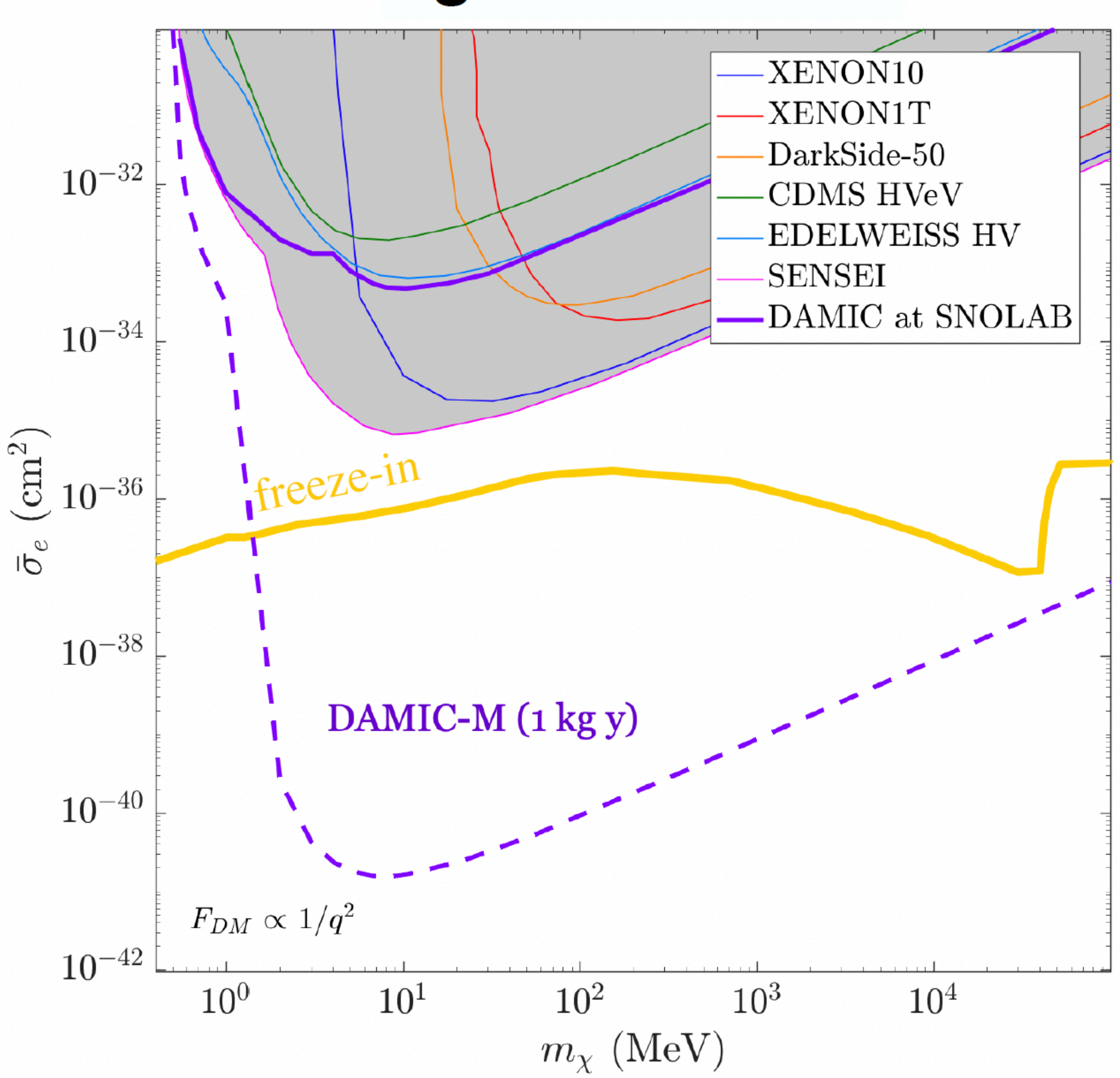
- Signal expects to be diffusion limited ER interaction
- Due to the very small dark current and the single electron resolution the sensitivity is strong down to DM masses of $\mathcal{O}(10^{-1}) MeV$
- Possibility to explore a vast region of the available parametric space with kg-day scale exposure
- Physics channels to be explored: DM-electron scattering via heavy or ultralight mediator, dark photon absorption



heavy mediator



light mediator



How DM interacts with the Si crystal?

It's necessary to account for the crystal lattice nature of the Si target.

Si crystal is a **multi-body system** with **delocalised valence electrons** occupying an energy **band-structure** with energy gap separating from the unoccupied conduction bands

QM Problem in a periodic potential can be reduced to the 1st Brillouin zone

$$\psi_{i,\mathbf{k}}(\mathbf{x}) = \frac{1}{V_{cryst}} \sum_{\mathbf{G}} u_i(\mathbf{k}+\mathbf{G}) \cdot \exp\Big(i(\mathbf{k}+\mathbf{G})\mathbf{x}\Big)$$

The wave function coefficients are obtained with **DFT approximations**. All the properties of the system are obtained from the ground state particle density. This is obtained by use of pseudo-potential approximation of independent electrons with the same ground state density

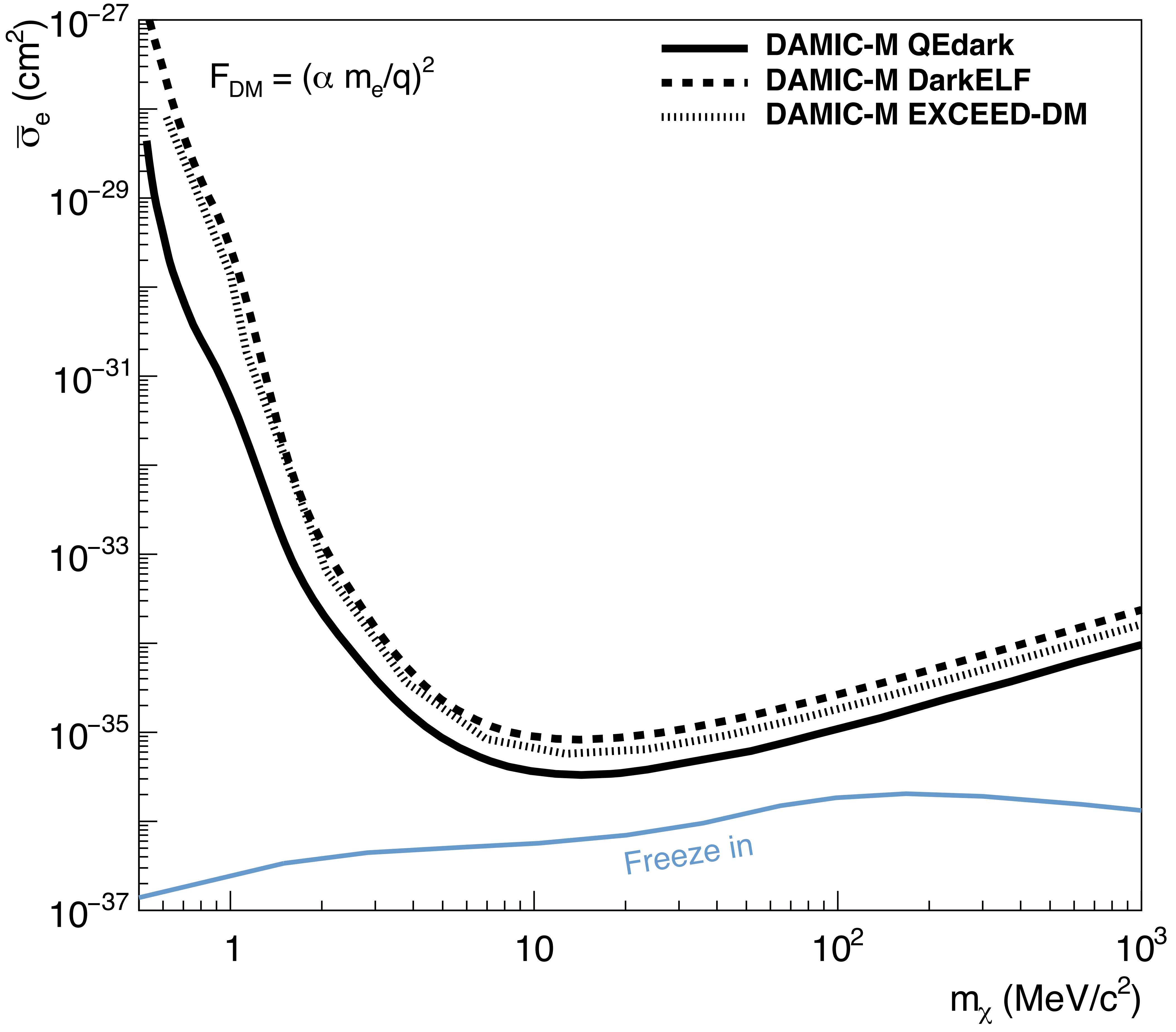
The form factor for the transition from occupied valence state to unoccupied conduction state is

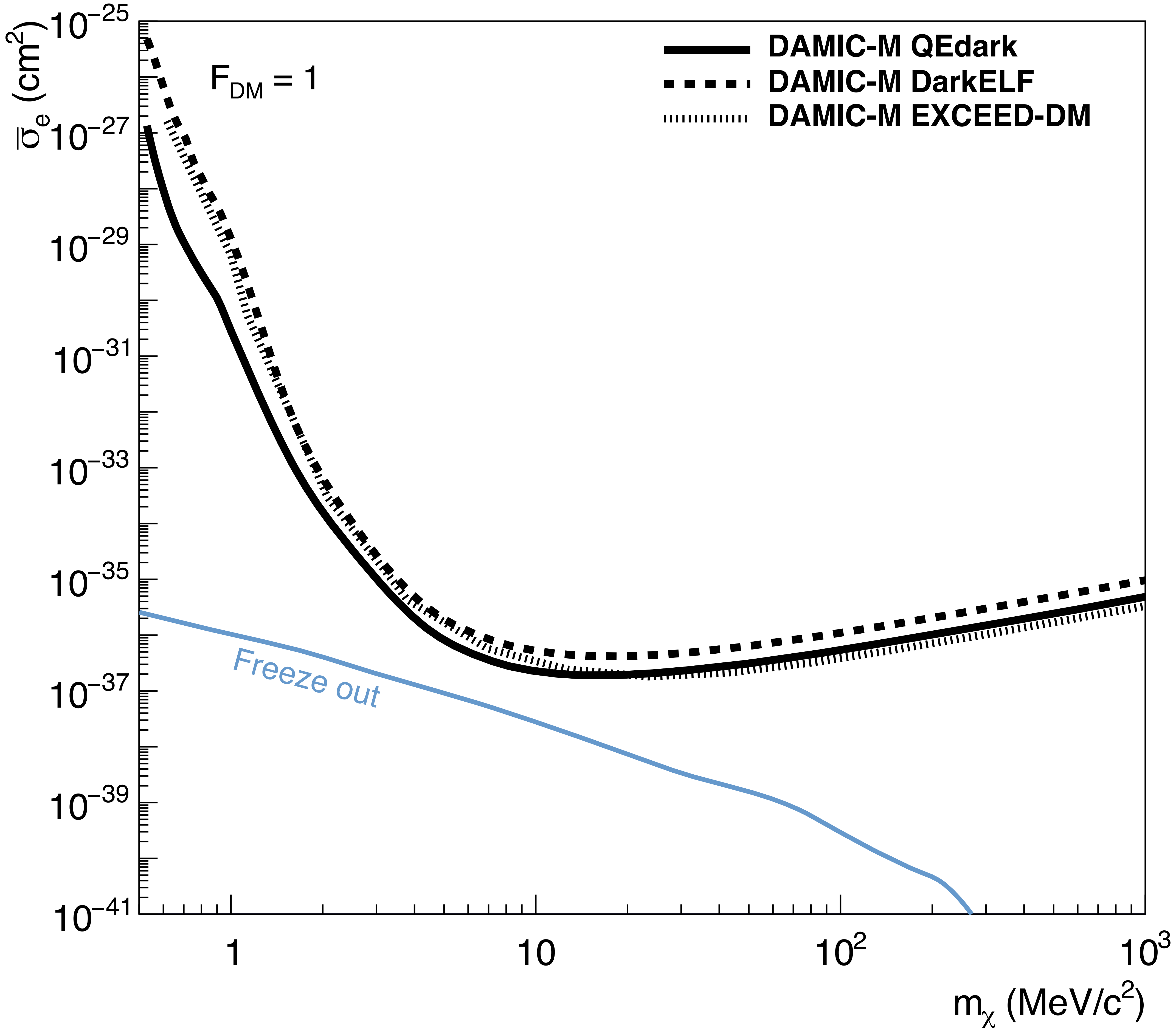
$$f_{i\mathbf{k},i'\mathbf{k}',\mathbf{G}'} = \sum_{\mathbf{G}} u^*_{i'}(\mathbf{k}'+\mathbf{G}'+\mathbf{G}) \cdot u_i(\mathbf{k}+\mathbf{G})$$

The form factor for the transition from occupied valence state to unoccupied conduction state is

$$|f_{crystal}(q,E_e)|^2 = \frac{2\pi^2(\alpha m_e^2 V_{cell})^{-1}}{E_e} \sum_{i,i'} \int_{BZ} \frac{V_{cell}d\mathbf{k}}{(2\pi)^3} \frac{V_{cell}d\mathbf{k}'}{(2\pi)^3} E_e \delta(E_e - E_{i'\mathbf{k}'} - E_{i\mathbf{k}}) \sum_{\mathbf{G}'} q\delta(q - |\mathbf{k}'-\mathbf{k}+\mathbf{G}'|)\,|f_{i\mathbf{k},i'\mathbf{k}',\mathbf{G}'}|^2$$

Evaluation of theoretical uncertainties



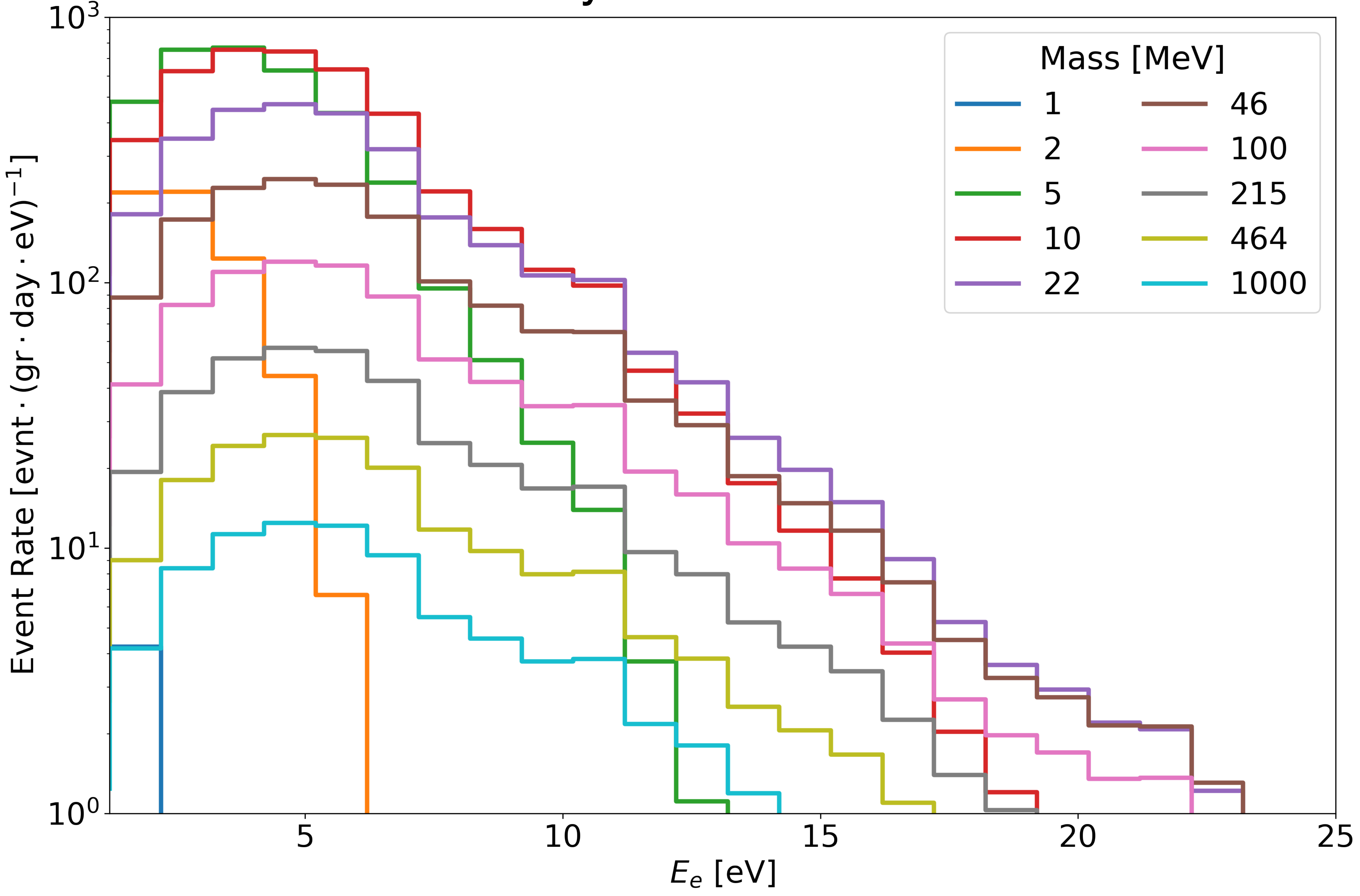


DAMIC-M 90% C.L. upper limits on DM-electron interactions through an ultra-light mediator (left) and heavy mediator (right) obtained with **QEdark**, **DarkELF** (dashed), and **EXCEED-DM** (dotted) theoretical models.

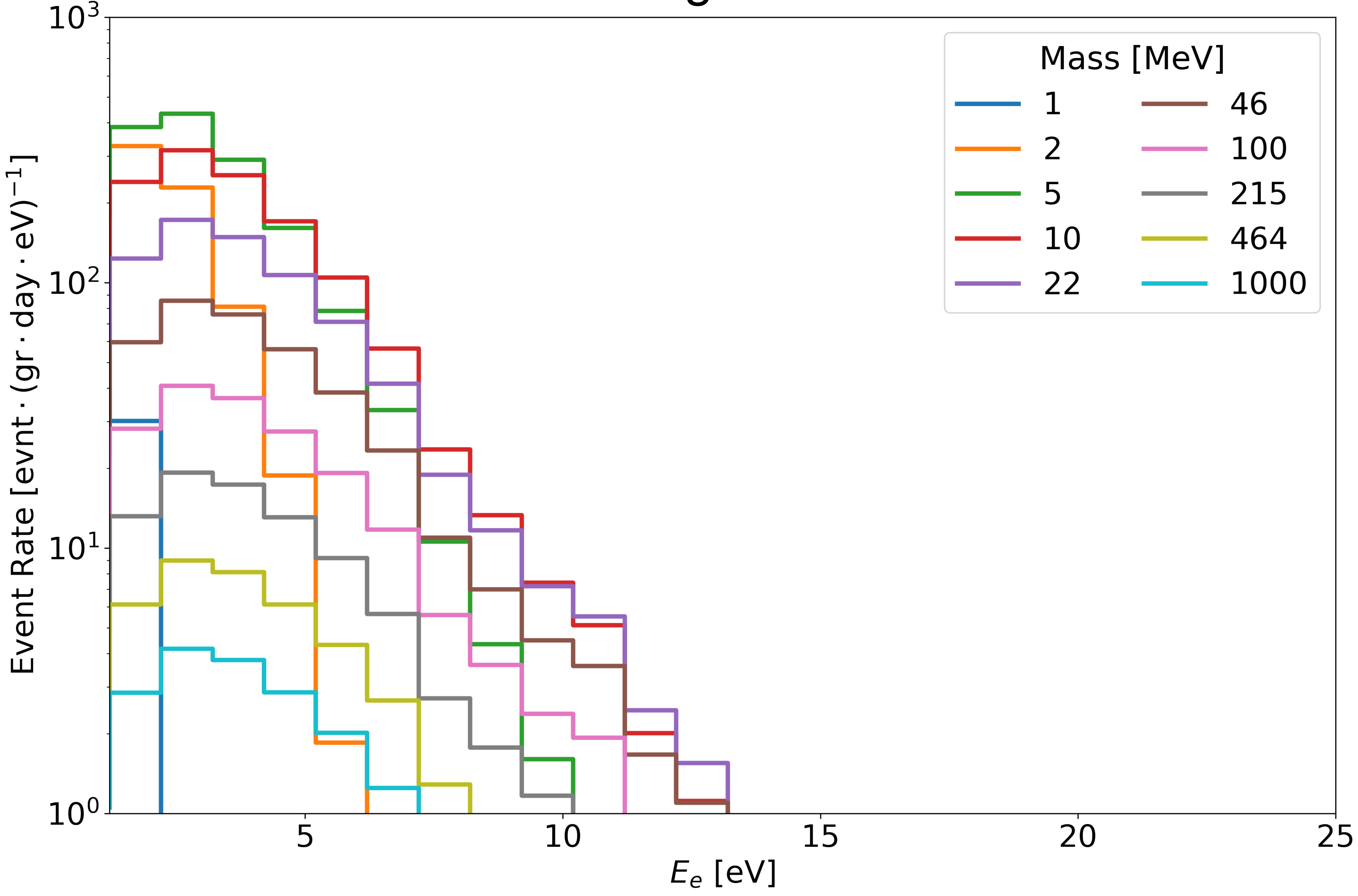
Computing the expected event rates

$$\frac{dR_{crystal}}{d\ln E_{er}} = \frac{\rho_\chi}{m_\chi} N_{cell}\bar{\sigma}_e \alpha \frac{m_e^2}{\mu_{\chi,e}^2} \int d\ln q \left(\frac{E_e}{q}\eta(u_{\min})\right) |f_{crystal}(q,E_e)|^2 |F_{DM}(q)|^2 dq$$

Heavy mediator



Ultralight mediator



- We are using the QEDark (JHEP05(2016)046) framework to obtain the computed $f_{cryst}(q, E_e)$
- We use the PhystatDM conventions about the halo model and the local DM density parameters

Detector response: Ionization

$$\frac{dR_{crystal}}{d\ln E_{er}} = \frac{\rho_\chi}{m_\chi} N_{cell} \bar{\sigma}_e \alpha \frac{m_e^2}{\mu_{\chi,e}^2} \int d\ln q \left(\frac{E_e}{q}\eta(u_{\rm min})\right) |f_{crystal}(q, E_e)|^2 |F_{DM}(q)|^2 dq$$

Necessity to convert the deposited energy in resulted ionization Q

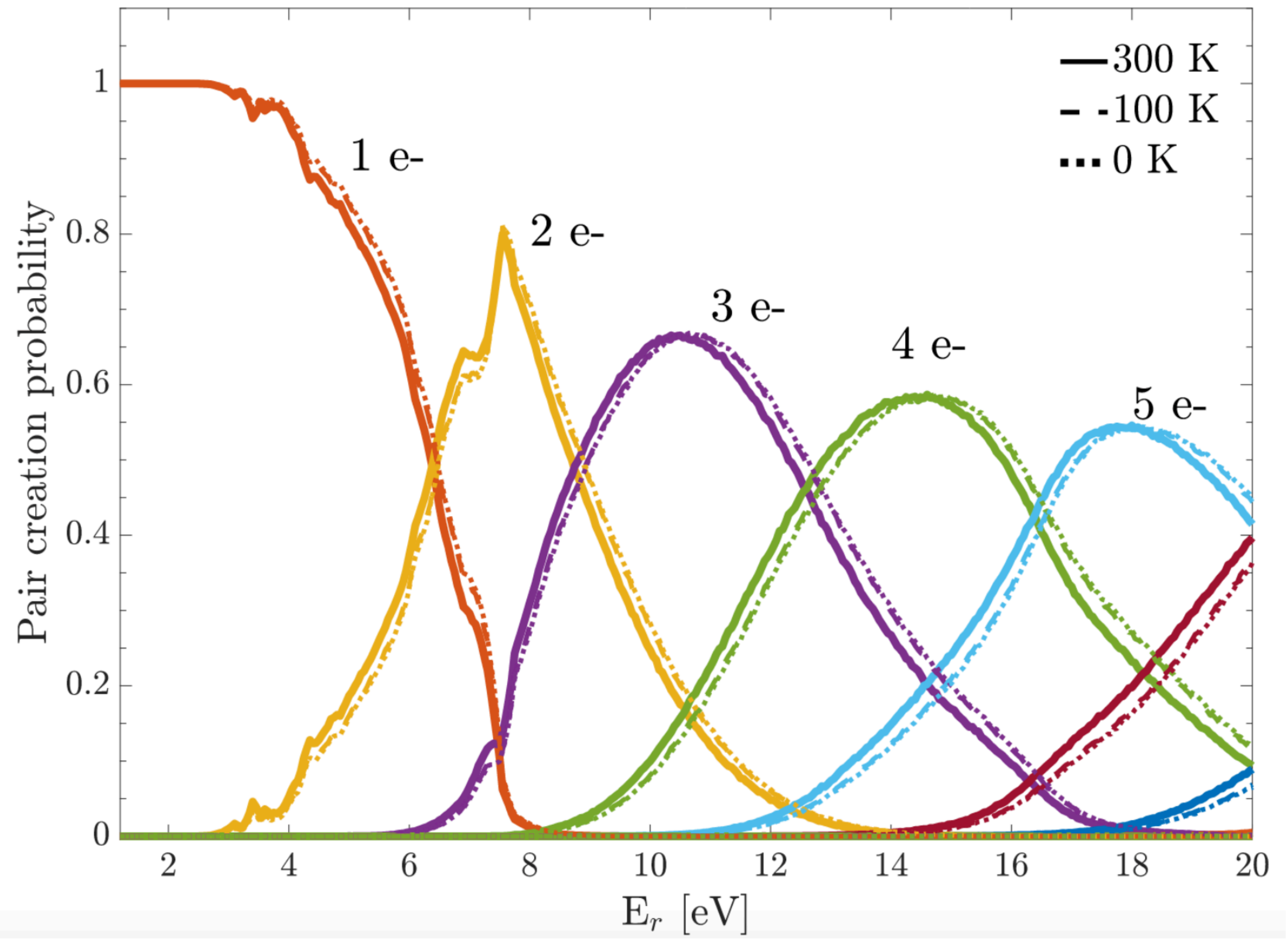
E_{er} and Q are related by a long chain of secondary scattering processes redistributing the deposited energy

Simple model: Extrapolation of the high energy understanding of ionization. If ε is the mean energy to create an electron hole pair then:

$Q(E_{er}) = 1 + [(E_{er} - E_{gap})/\epsilon]$

Previous relation brake-down when $E_{er} = \mathcal{O}(E_{gap})$.

We use a phenomenological model of impact ionization to explore the likely charge yield in this energy regime.

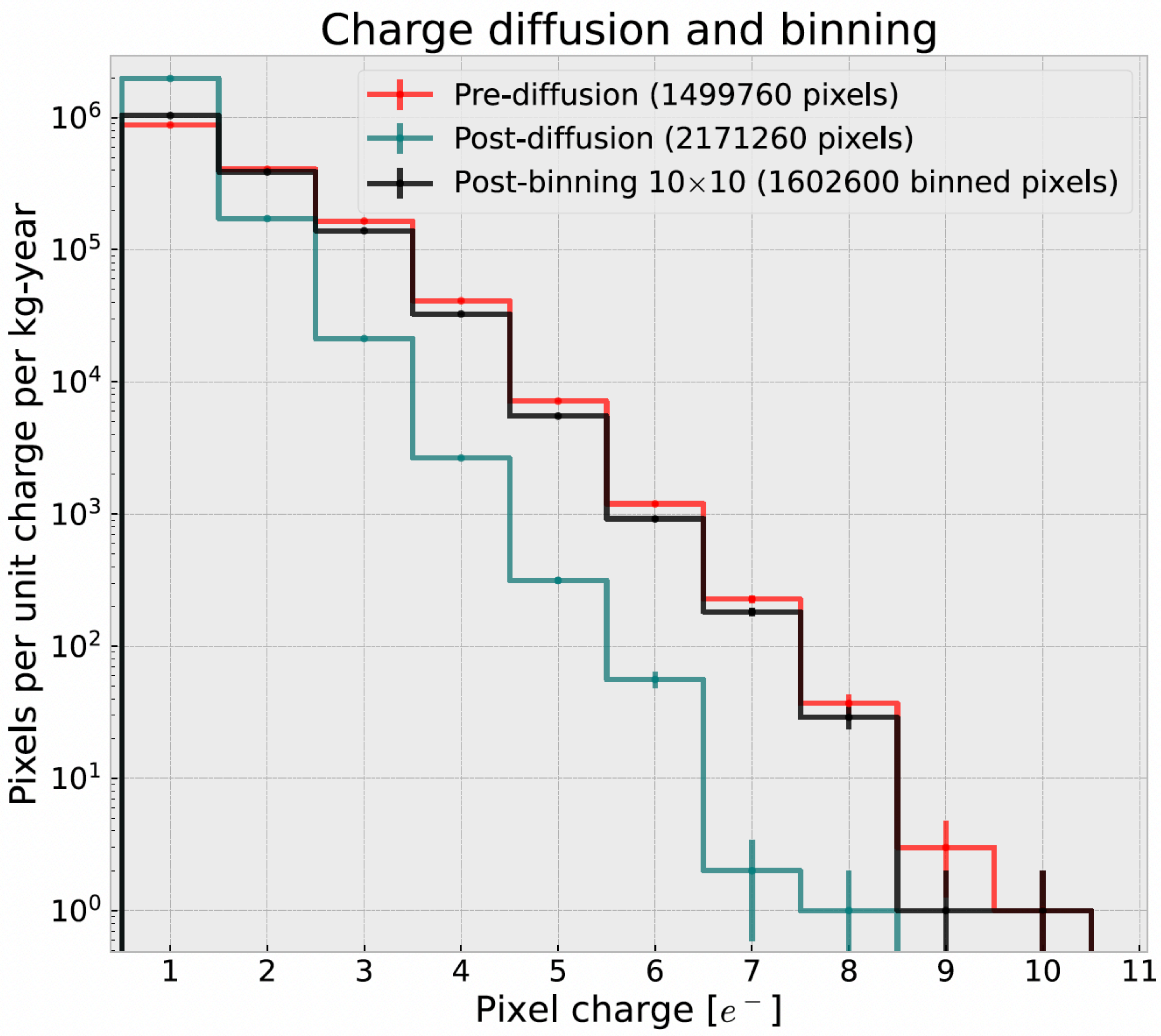


Phys. Rev. D 102, 063026 (2020)

Detector response

Computation of the signal probability per pixel

- We simulate CCD images with DM events for a given cross section
- We take into account the pair creation probability in the determination of the secondary ionization
- We account for the diffusion of the ionization charges during drift to the pixel array
- We account for the 10x10 binning readout mode



For a detailed description of the signal model calculation see:
[Michelangelo Traina Ph.D. thesis, Sorbonne University, 2022]

Inference process

The signal framework can give us the histogram of the signal or the DC-only $\Pi_i, i \in bins$. This can be compared to the data histogram $D_i, i \in bins$ by a binned likelihood

$$\log \mathscr{L} = -(\theta - \bar{\theta})^{\top} \Sigma^{-1} (\theta - \bar{\theta}) + \sum_{i \in bins} \Big(D_i \log(\Pi_i) - \Pi_i - \log(D_i!) \Big)$$

If one want to set an upper limit to a value s of the signal strength then one can define the **log likelihood ratio** (Cowan et al.)

$$t_s = -2 \log \frac{\mathscr{L}(s, \hat{\hat{\theta}})}{\mathscr{L}(\hat{s}, \hat{\theta})}$$

The asymptotic distribution of this test statistic can either be evaluate with toy MC either make use of Wilks' theorem

LBC commissioning and first science runs

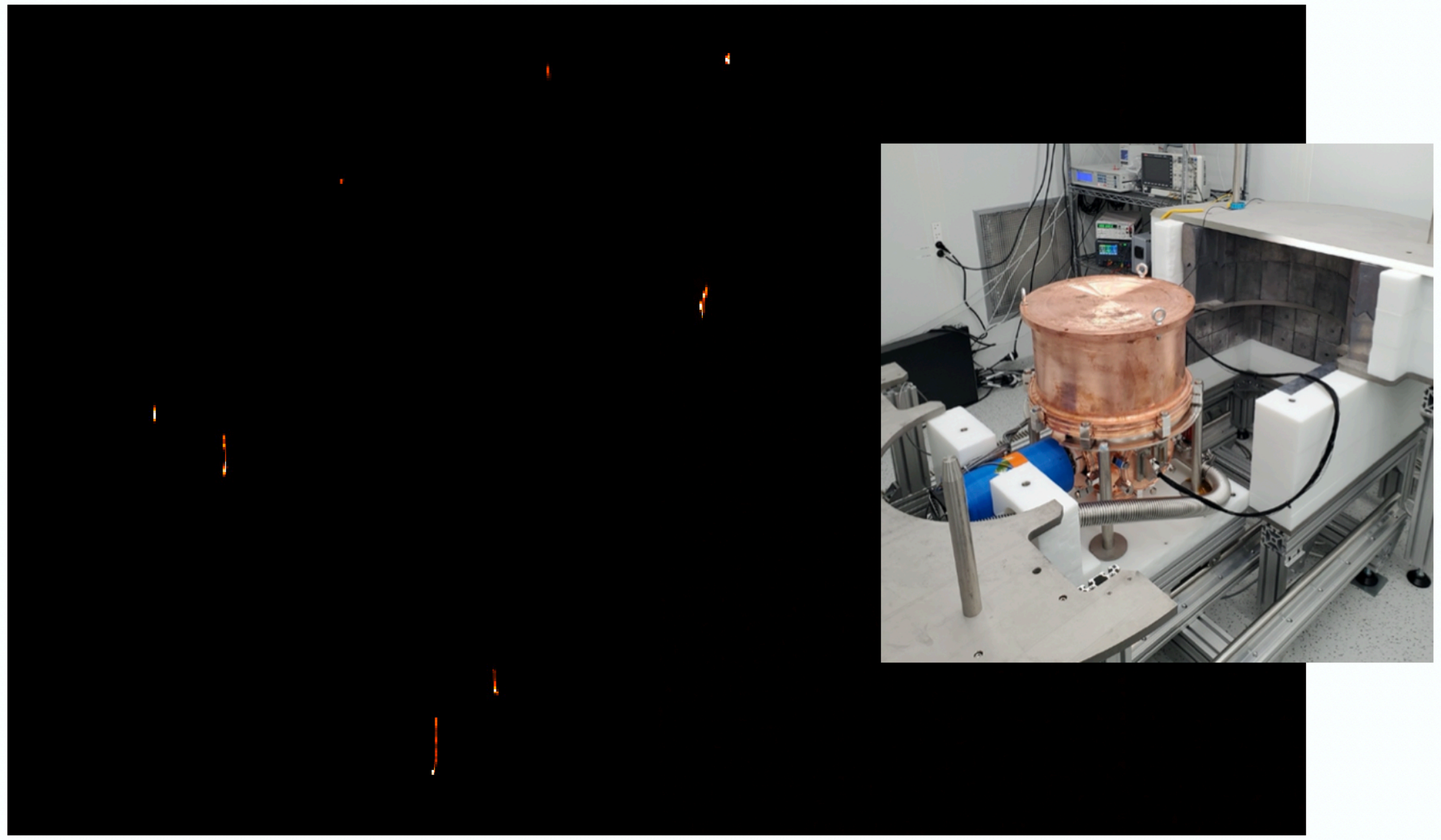
Feb 22 - May 22: Commissioning runs

- Systematic effort for DC reduction
- High-energy BG at 3000 dru with the internal lead shield
- Various calibrations and analysis tools development
- Optimisation of CCD readout scheme

May 22 - now: Science runs

- Further suppression of high-energy BG at 10 dru with external polyethylene+lead shielding
- Data taking with 650 skips and resolution of 0.2 e
- Accumulation of 115 gr-days of exposure with a binning readout scheme of 10x10
- First science results on DM-e scattering

Internal shield



Internal + external shield