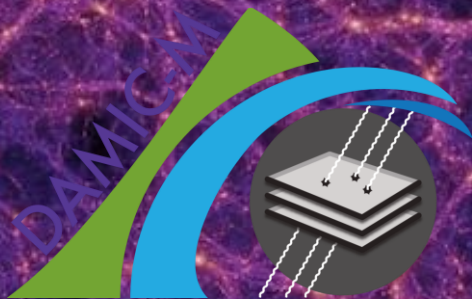


université  
PARIS-SACLAY



# Direct Dark Matter Research : The Damic-M\* experiment

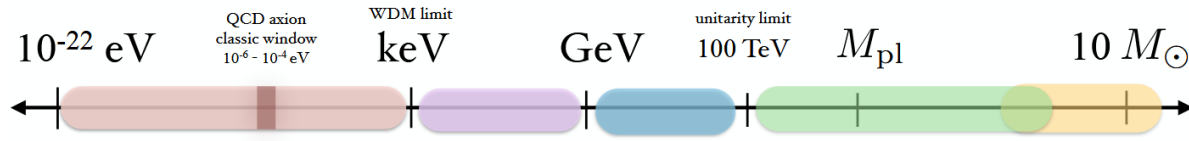
---

MELLOUKI ISSAM-EDDINE

\* **D**ark **M**atter **I**n **C**CDs at **M**odane

# Mass scale of dark matter

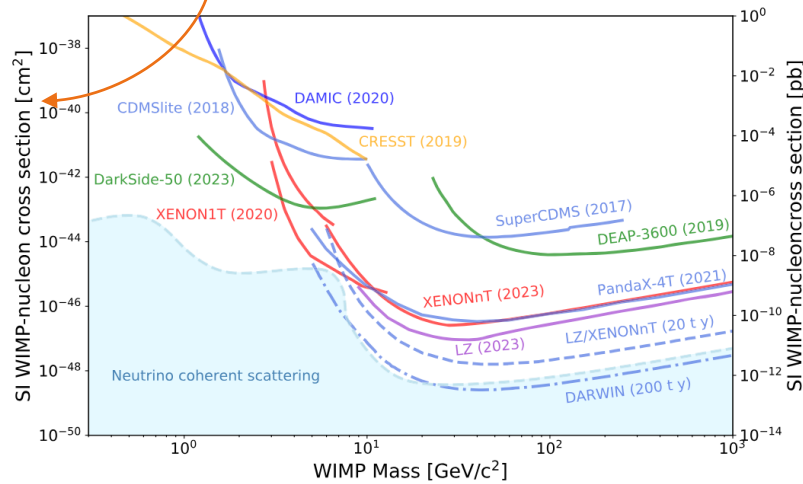
(not to scale)



`Ultralight` DM `Light` DM WIMP Composite DM Primordial black holes  
non-thermal bosonic fields dark sectors sterile  $\nu$  can be thermal (Q-balls, nuggets, etc)

T. Lin, arxiv:1904.07915

WIMP Waning, Nearly Excluded

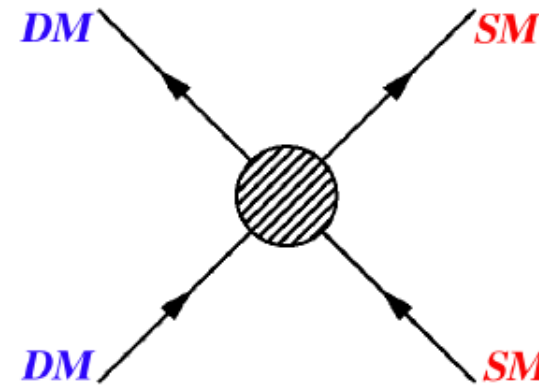


Detection of electronic/nuclear recoils

Detection of particles produced by the annihilation of SM particles

thermal freeze-out (early Univ.)  
indirect detection (now)

direct detection



production at colliders

Search for missing transverse energy

# Dark Matter production scenarios

## ❖ Production scenarios :

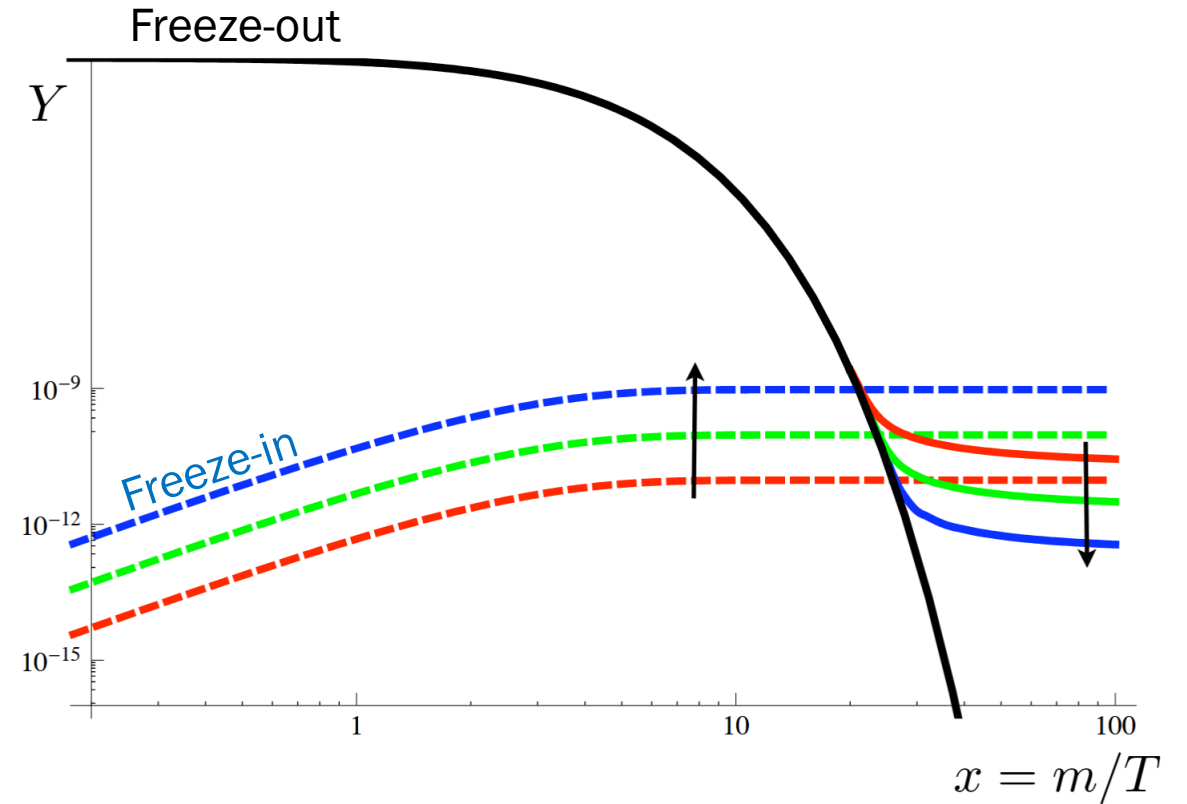
- ❖ Freeze-in/out
- ❖ Gravitational
- ❖ Etc.

## ❖ Freeze-out :

- ❖ Dark Matter in thermal equilibrium in early universe

## ❖ Freeze-in assumption :

- ❖ No Dark Matter in the primordial plasma
- ❖ Production from thermal bath species over time



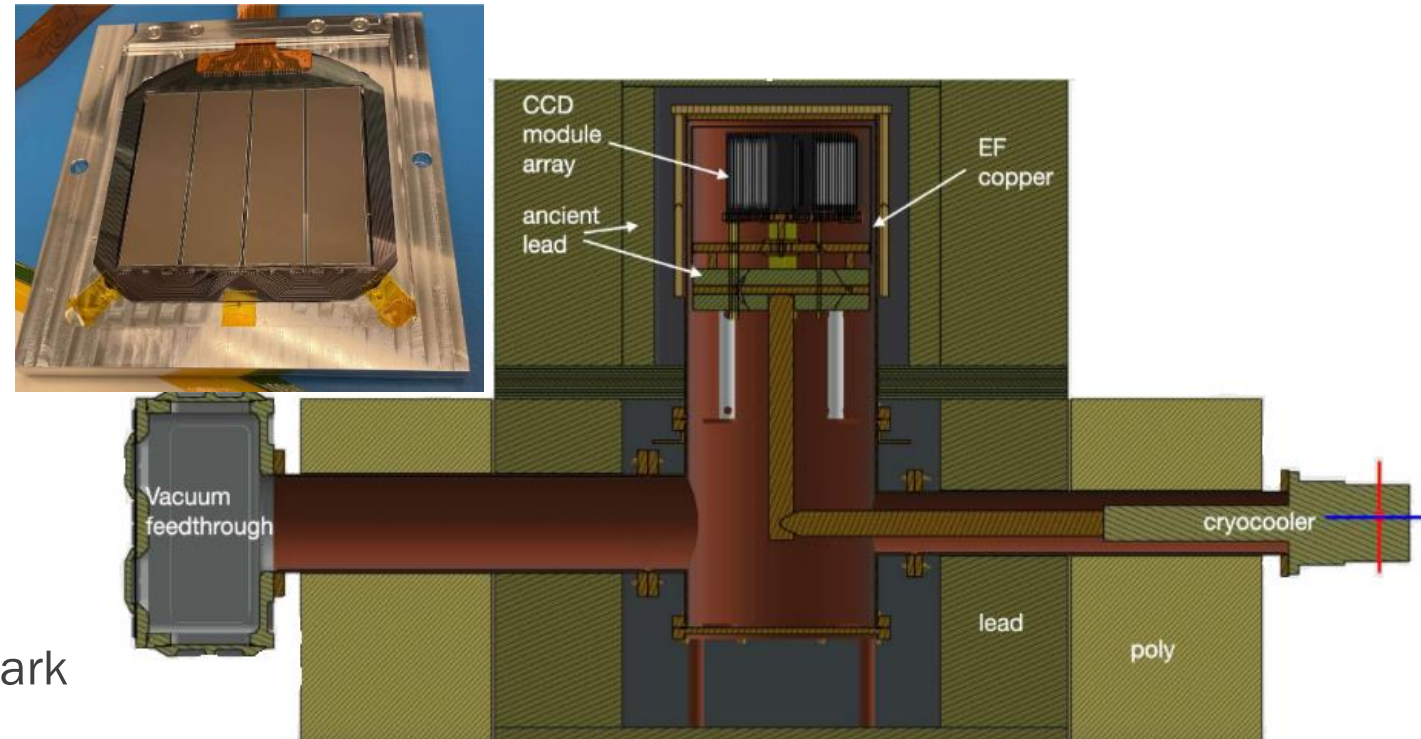


# Damic-M in Dark Matter research

- ❖ 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



# Dark Sector Theory

- ❖ The SM is not complete (neutrino, dark matter, ...)
- ❖ New Interactions may exist !
- ❖ Simple natural extension of the Standard Model : new U(1) symmetry
- ❖ New gauge boson which can be :
  - ❖ Analogous to the photon
  - ❖ Analogous to the Z boson with V-A structure
- ❖ Leads to MeV-scale Dark Matter

*New bosons expected to mediate new interactions*

**New spin-1 bosons**  $\leftrightarrow$

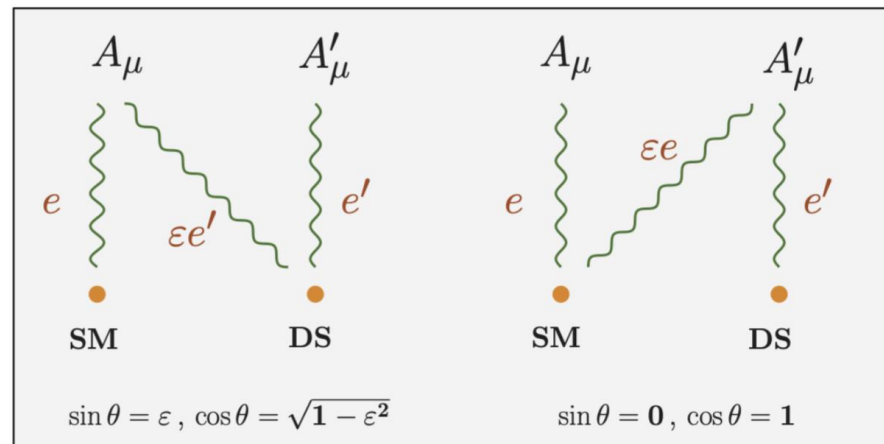
*new gauge symmetries beyond*  $SU(3) \times SU(2) \times U(1)$

*Simplest possibility*

**$SU(3) \times SU(2) \times U(1) \times \text{extra } U(1)$**

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

Pierre FAYET, "The U BOSON as a generalized DARK PHOTON"

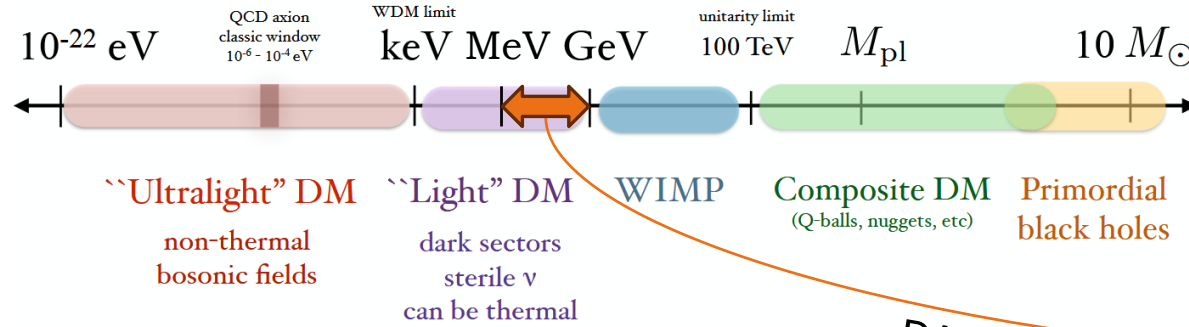


arXiv:2005.01515

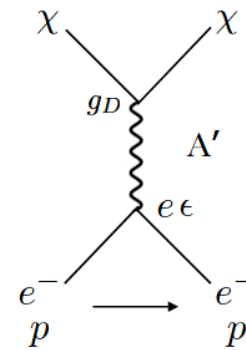
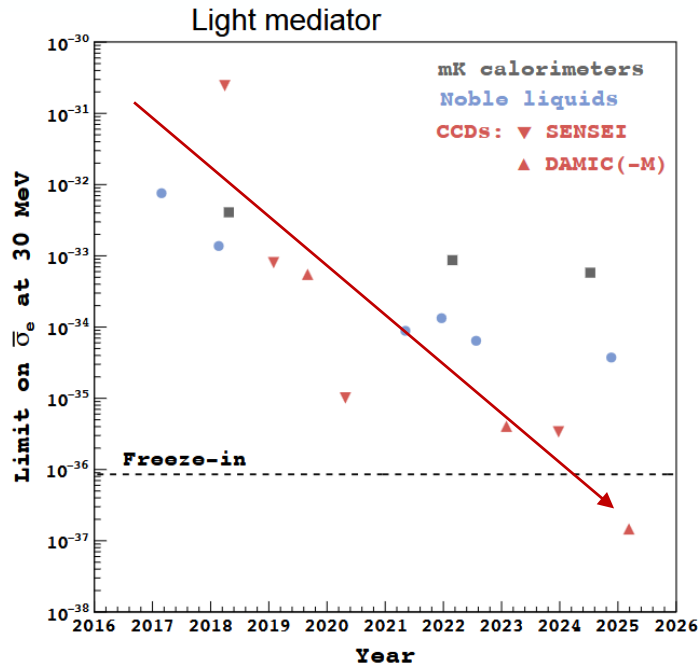
# Mass scale of dark matter

(not to scale)

T. Lin, arxiv:1904.07915

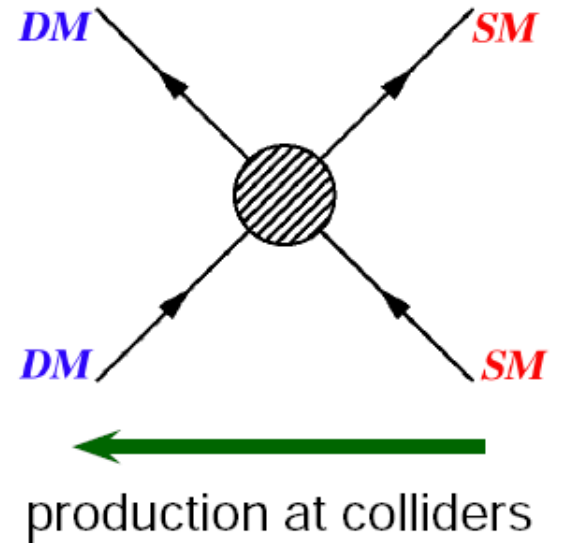


DAMIC-M



direct detection

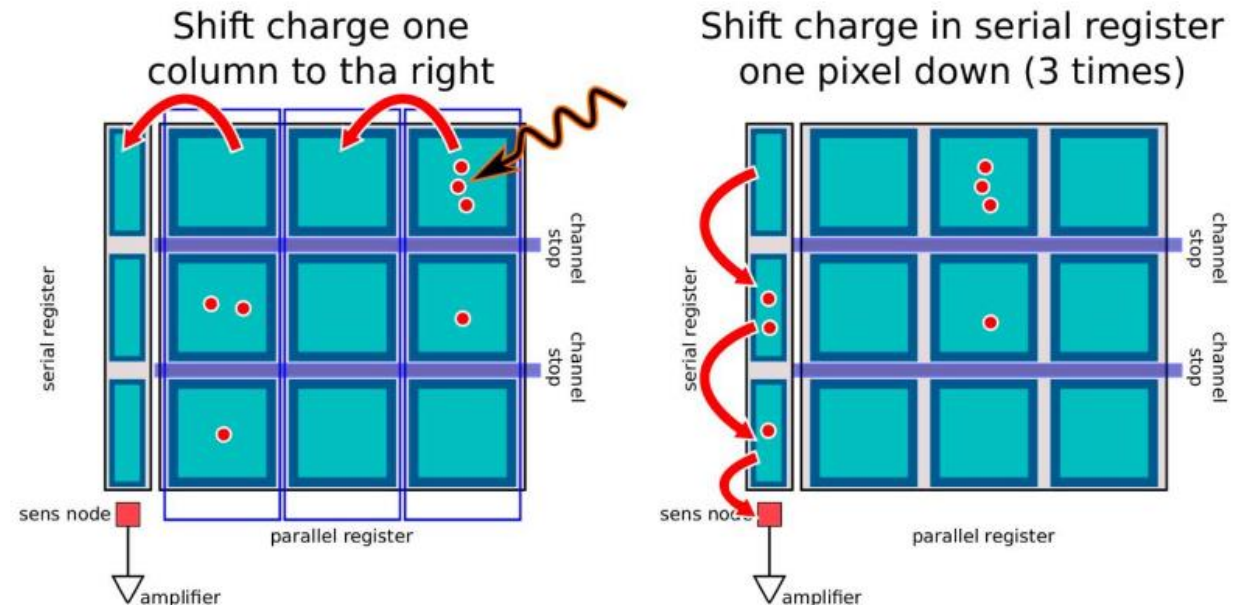
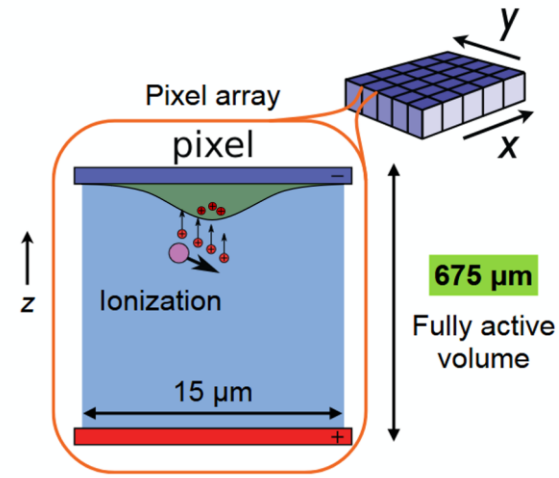
thermal freeze-out (early Univ.)  
indirect detection (now)



Max Planck Institute for Nuclear Physics

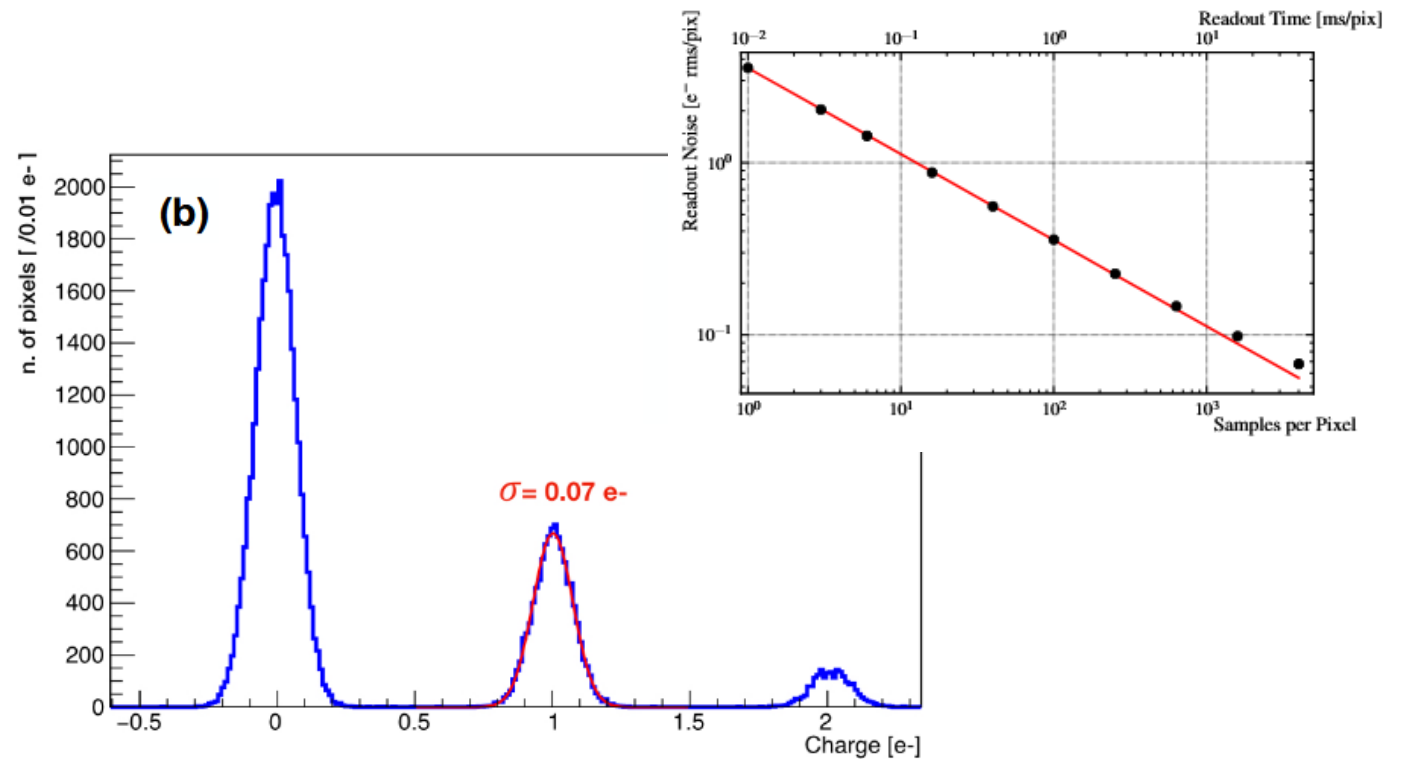
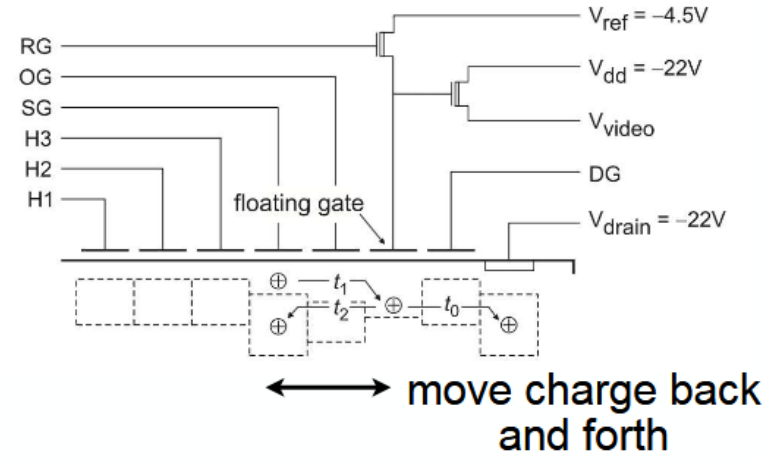
# Classical CCDs

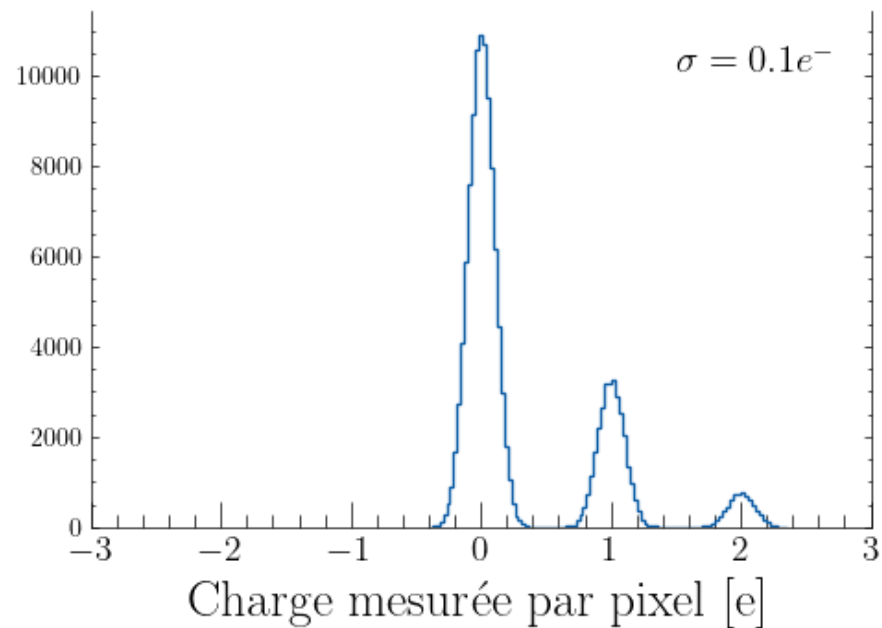
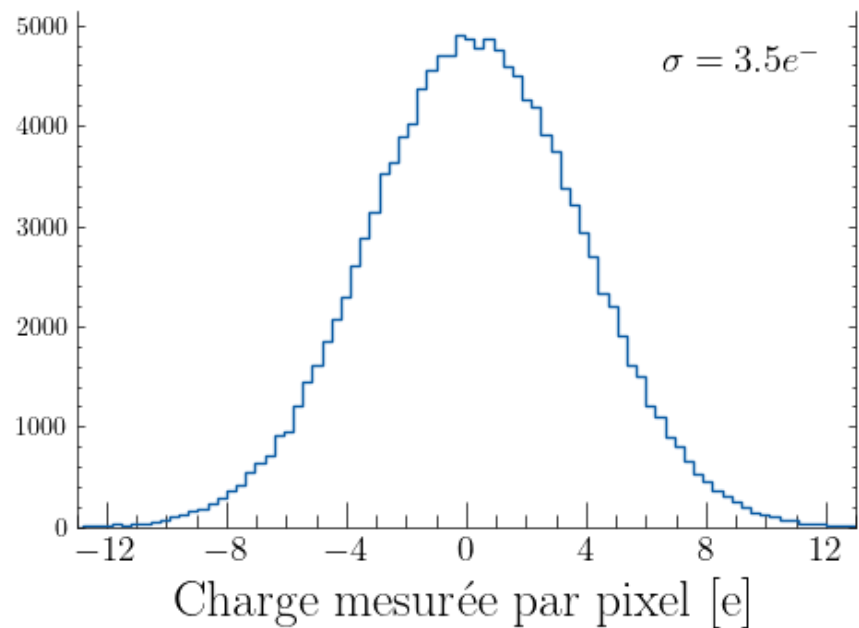
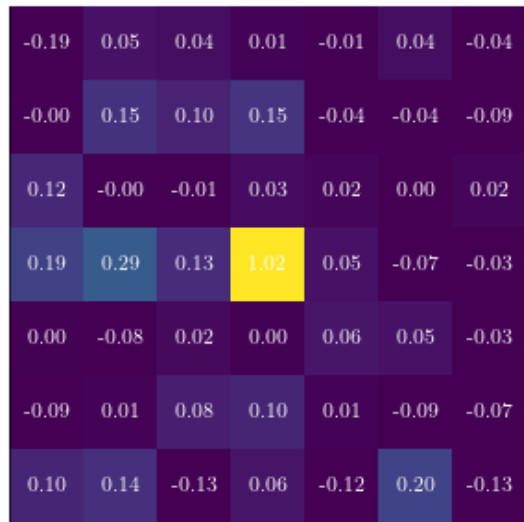
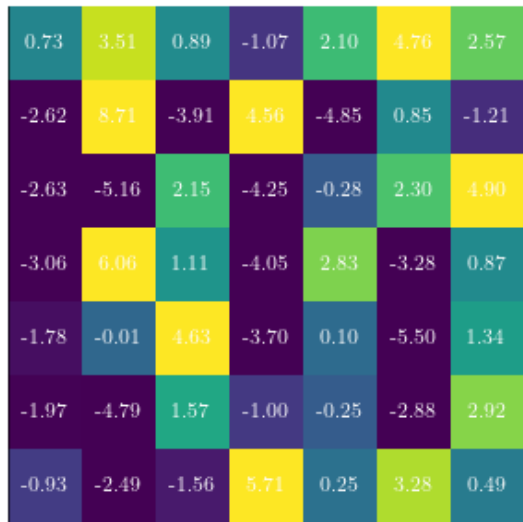
- ❖ interaction ionizes the medium and generates charges
- ❖ Charges are trapped in potential wells
- ❖ Then, the charges are moved line by line, pixel by pixel, toward the serial register
- ❖ Measurement of the charge on each pixel in the sens node



# Skipper-CCD

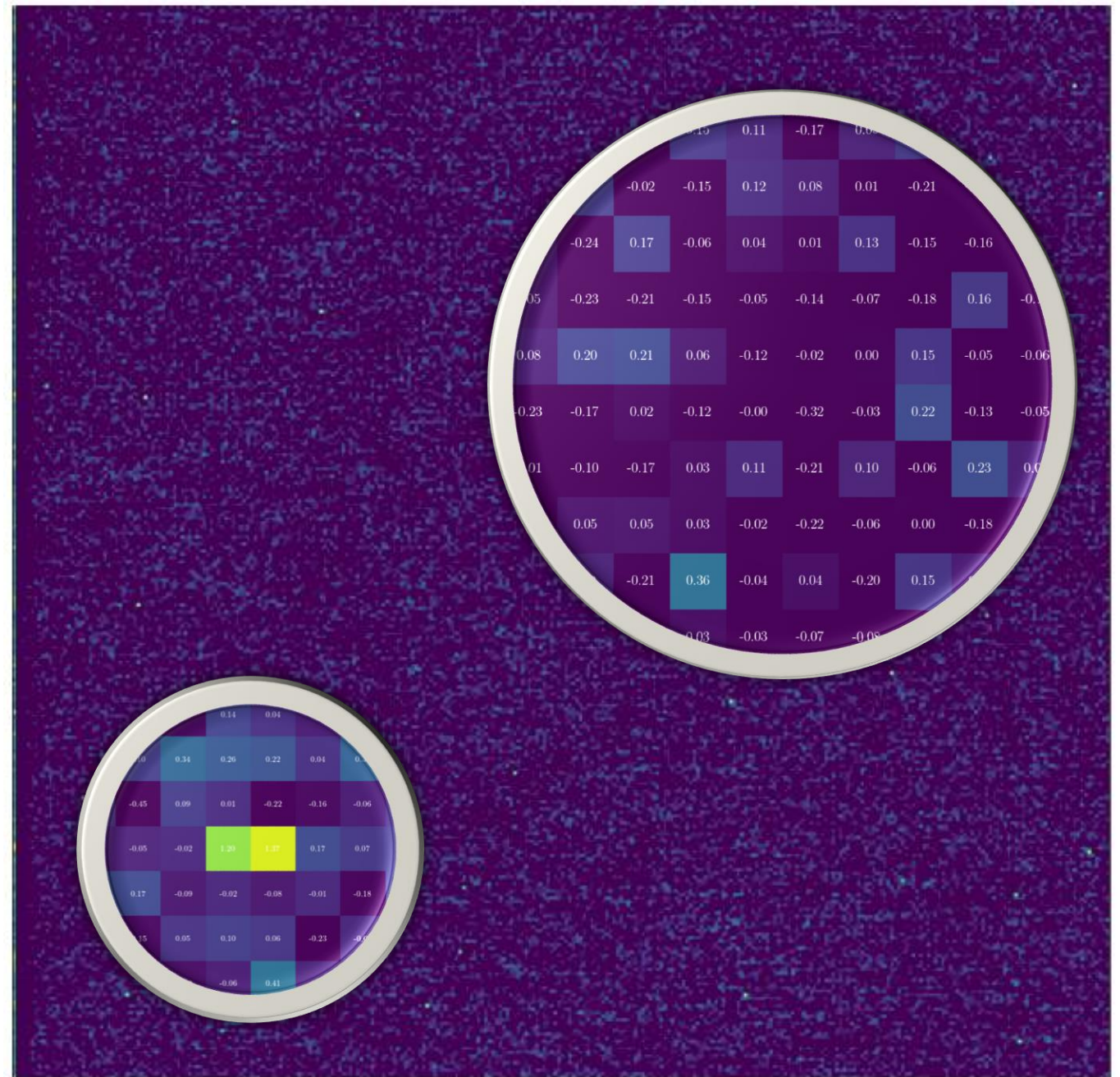
- ❖ Multiple non-destructive charge measurements
  - ❖ Sub-electron reading noise
- ❖ Readout noise divided by  $\sqrt{N_S}$
- ❖ Allows us to explore small energy deposits





# Some informations

- ❖ CCD mass : ~4g
- ❖ Images of 6300×1600 pixels taken every 1668 seconds
- ❖ Pixel size :
  - ❖ 15  $\mu\text{m}$  ×15  $\mu\text{m}$
  - ❖ 675  $\mu\text{m}$  thick
- ❖ DAMIC-M readout noise :  $\sigma \sim 0.17e^-$
- ❖ In comparison :
  - ❖ Euclid space telescope :  $\sigma \leq 4.5e^-$
  - ❖ 3.2-Gigapixel LSST :  $\sigma \leq 6e^-$
- ❖ DAMIC-M LBC (2025):
  - ❖ 4 CCDs for ~1.3 kg-day exposure
- ❖ DAMIC-M (2026-202X)
  - ❖ ~80 CCDs with better bkg/noise



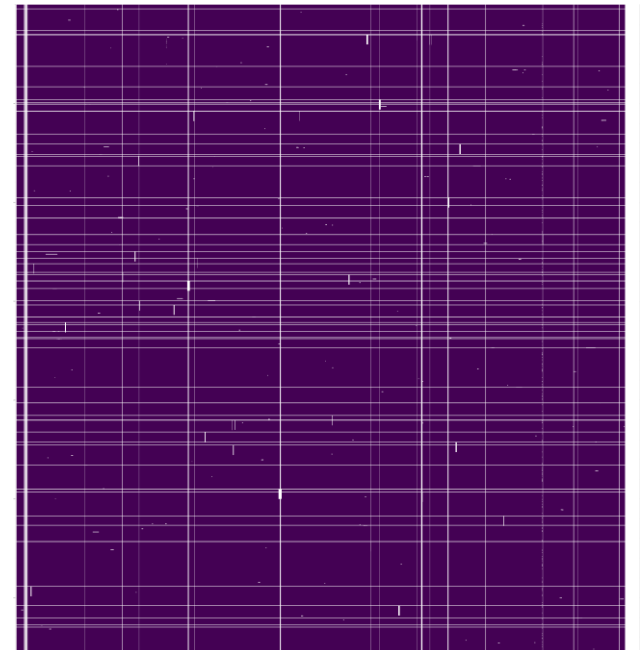
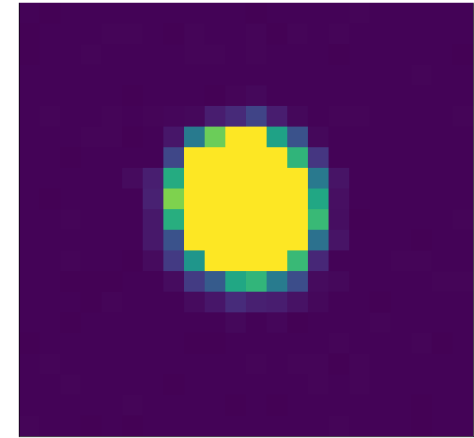
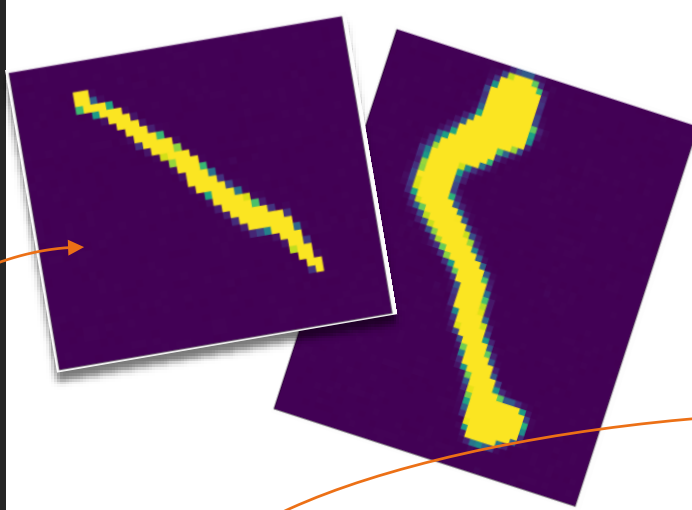
# Data Analysis

## ❖ Contamination sources :

- ❖ Astroparticles
- ❖ Radioactivity
- ❖ Defects generating charges continuously
- ❖ Charge transfer inefficiency (CTI)
- ❖ Infrared light
- ❖ Etc.

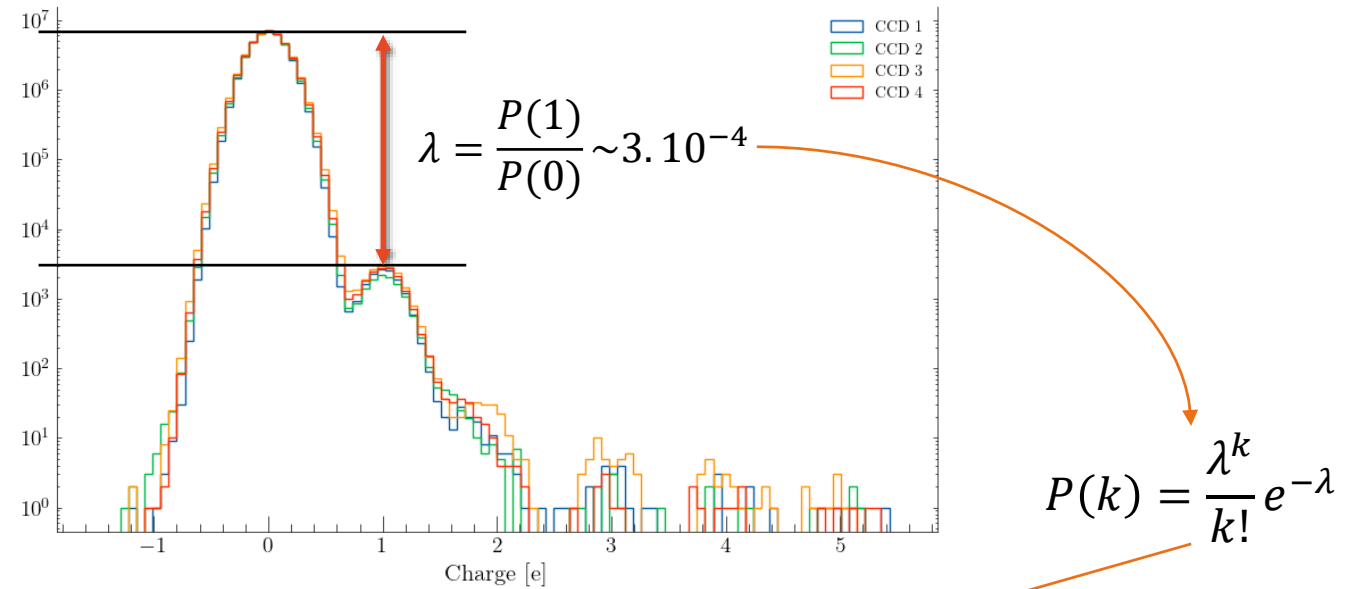
## ❖ Pixel selection :

- ❖ Hot region (large  $1e^-$  rate)
- ❖ Clusters of high-charge pixels ( $> 5e^-$ )
- ❖ Line/column multiplicity
- ❖ Etc.
- ❖ ~90% of data are kept



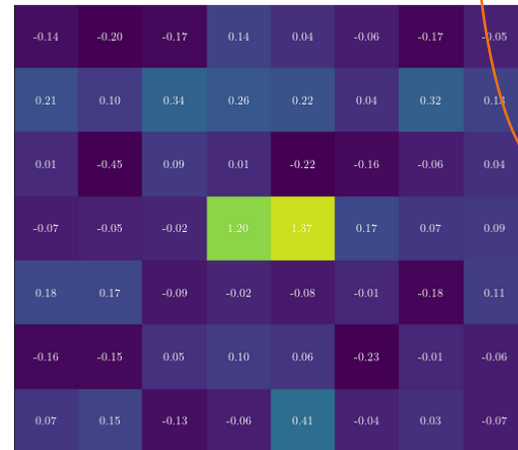
# Pattern Event Research: Predictions vs Observations for DAMIC-M LBC

- ❖ The Dark Current (DC) is poissonian
- ❖ Need to find the  $\lambda$  for the Dark Current to calculate the expected number of events ( $B_p^{rc}$ ,  $B_p^{rad}$ )
- ❖ Comparison with observed events ( $D_p$ ):
  - ❖ Background is compatible with observations
  - ❖ No evidence for Dark Matter

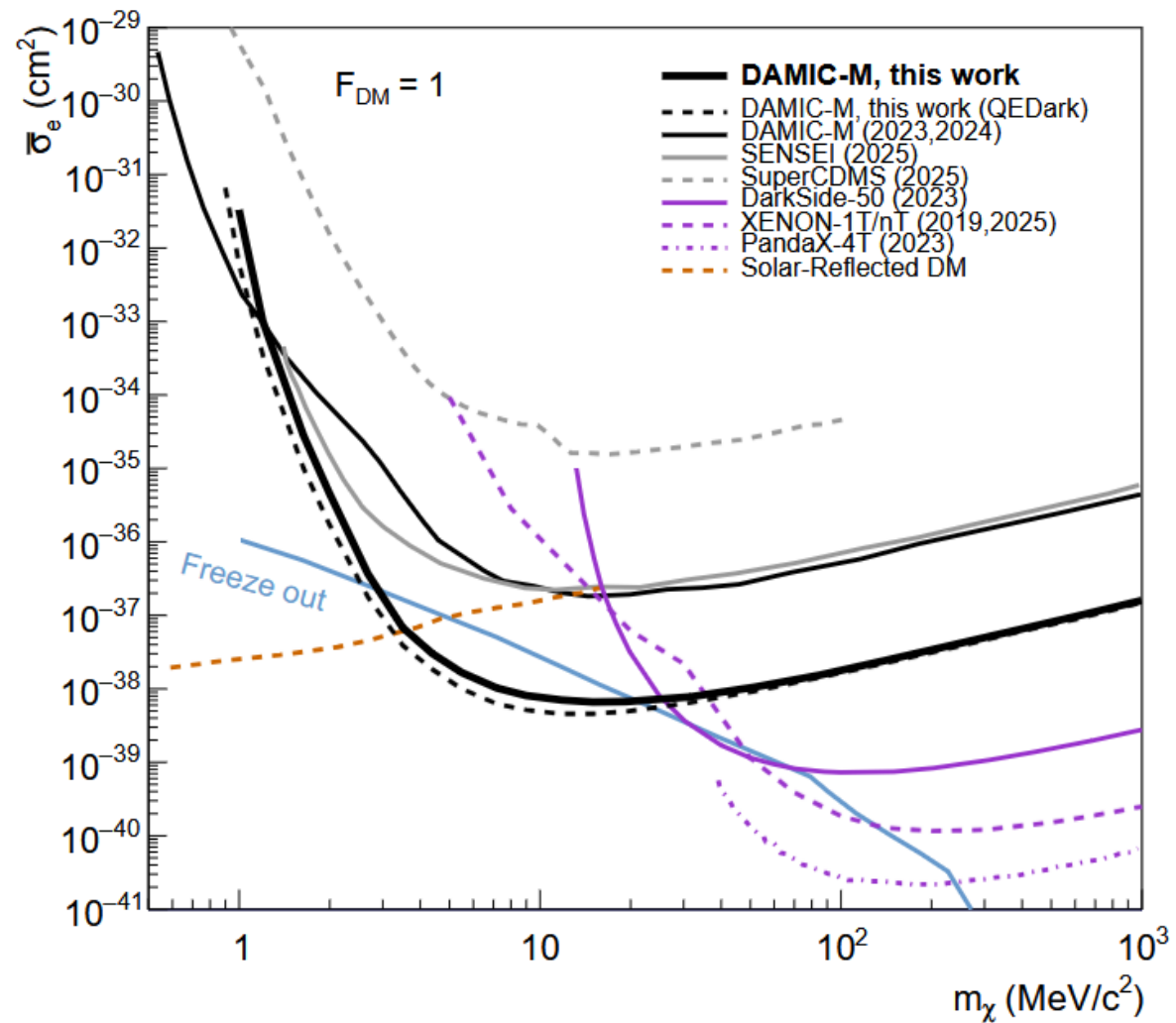
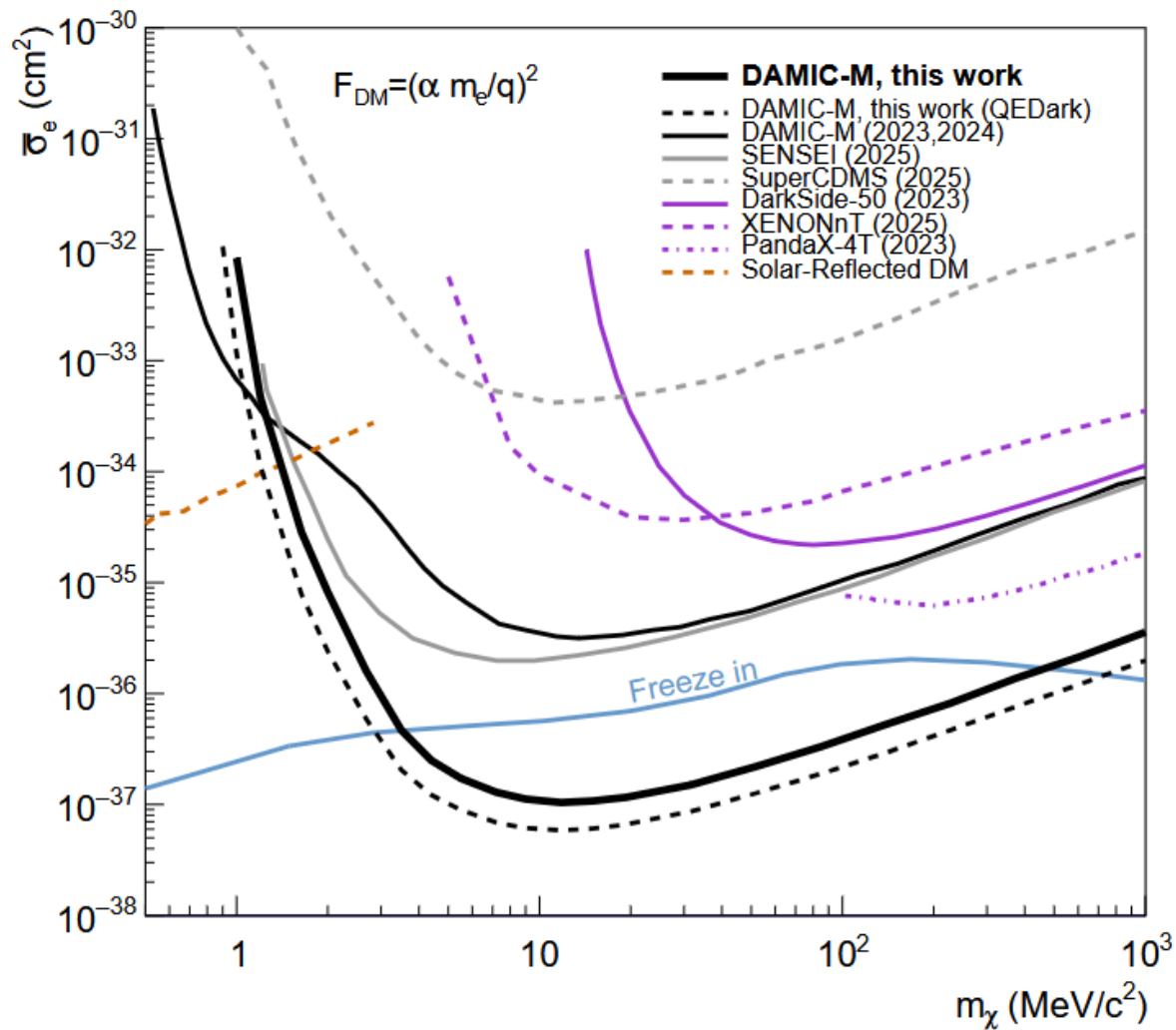


$$P(k) = \frac{\lambda^k}{k!} e^{-\lambda}$$

$$B_p^{rc}(\{11\}) = N_{pixel,tot} \times P(1)^2$$



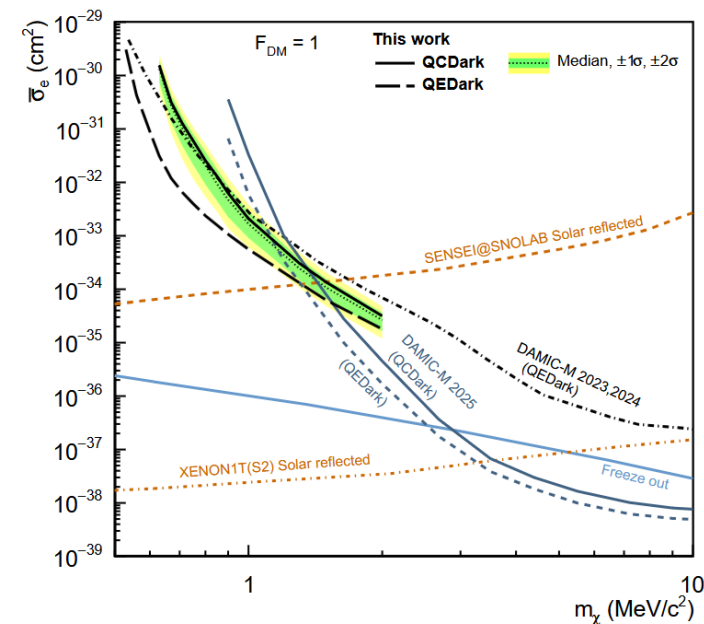
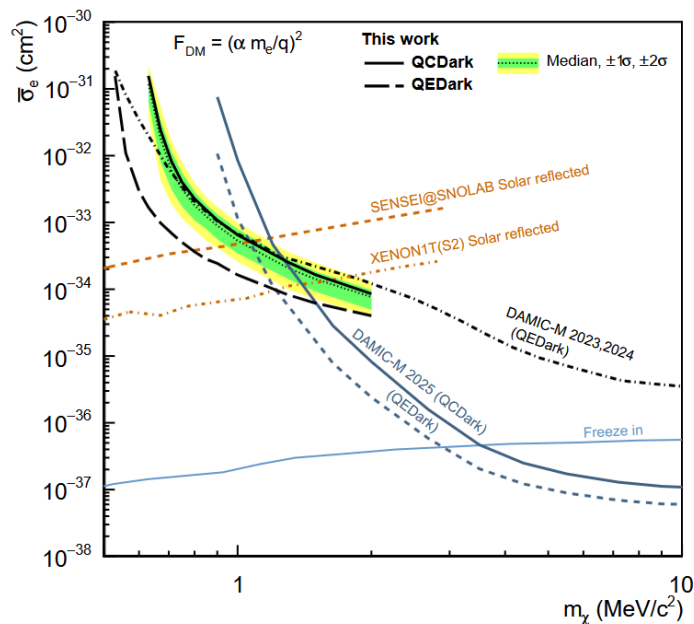
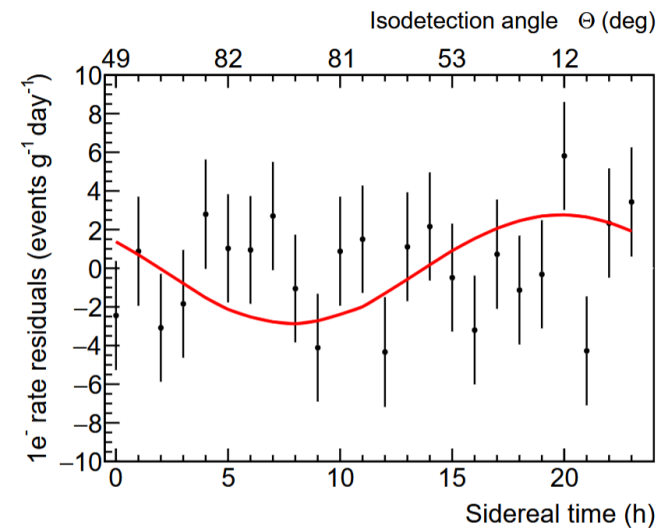
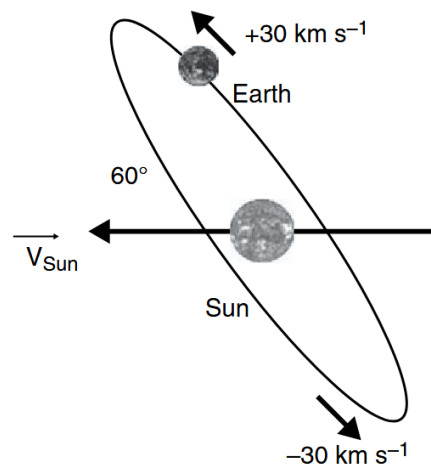
	Pattern $p$		
	{11}	{21}	{111}
$D_p$	144	0	0
$B_p^{rc}$	141.4	0.111	0.042
$B_p^{rad}$	0.039	0.039	0.016
	{31}	{22}	{211}
$D_p$	1	0	0
$B_p^{rc}$	0.019	$2.5 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$
$B_p^{rad}$	0.052	0.011	0.035



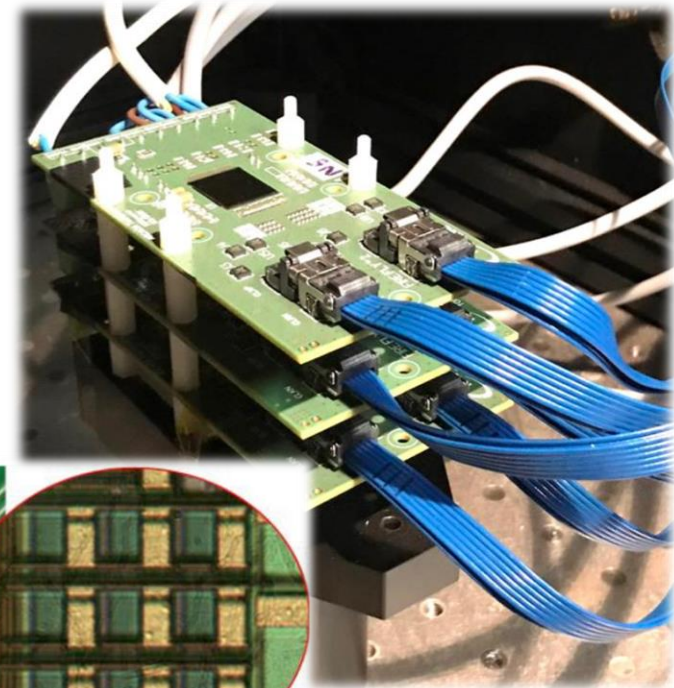
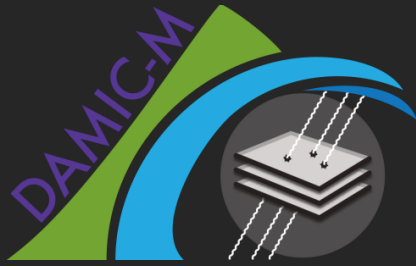
arXiv:2503.14617 : Probing Benchmark Models of Hidden-Sector Dark Matter with DAMIC-M (2025)

# Daily Modulation

- ❖ Attenuation of the event rate while crossing the Earth
- ❖ Signal modulated by Earth's rotation
- ❖ Can be used to improve the constraints

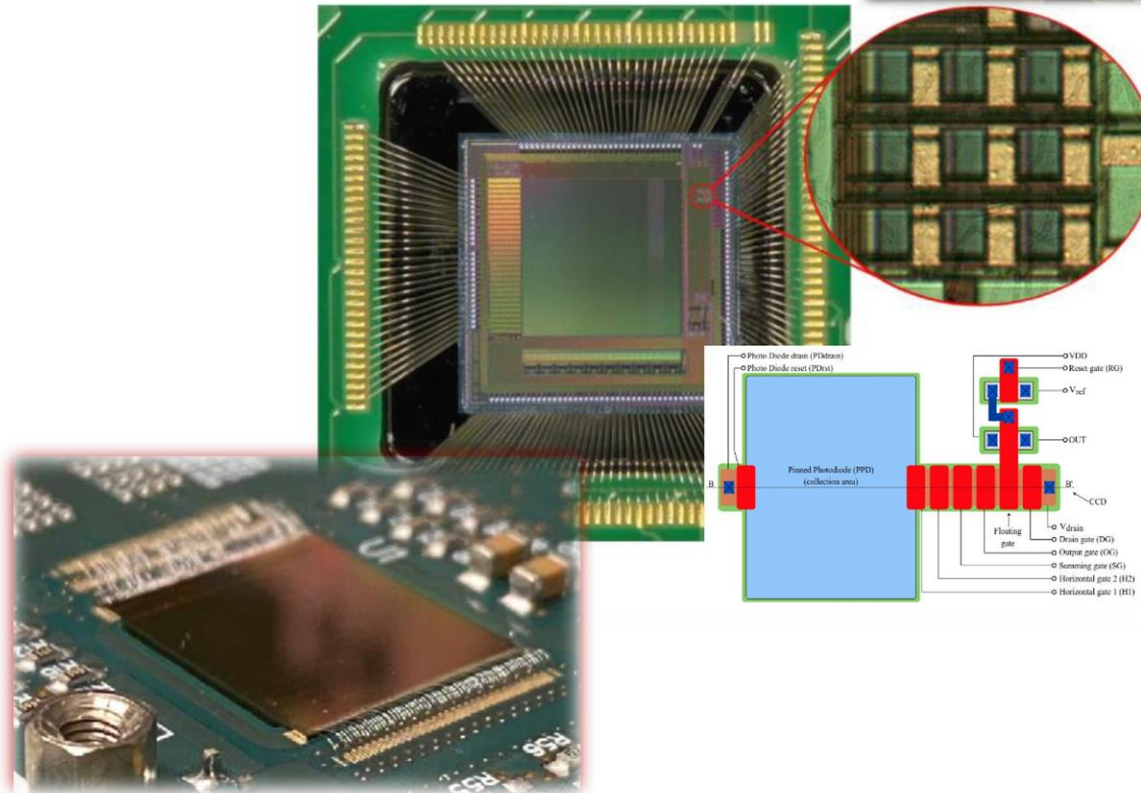


arXiv:2511.13962



# Skipper-CMOS

- ❖ Taking images with Skipper-CCD can be long
- ❖ Skipper-CMOS are  $10^9$  times faster !
- ❖ In developpement here at IJCLab !



# Conclusion

---

- ❖ The DAMIC-M experiment allows us, for the first time, to probe MeV-scale Dark Matter with remarkable sensitivity
- ❖ Skipper technology is a powerful tool and may have other interesting applications in physics
- ❖ Charge-coupled devices are currently among the best detectors for MeV-scale direct Dark Matter searches
- ❖ Current DAMIC-M LBC limits challenge hidden-sector benchmark models
- ❖ The upcoming full-scale experiment may achieve the first detection of Dark Matter

# Annex

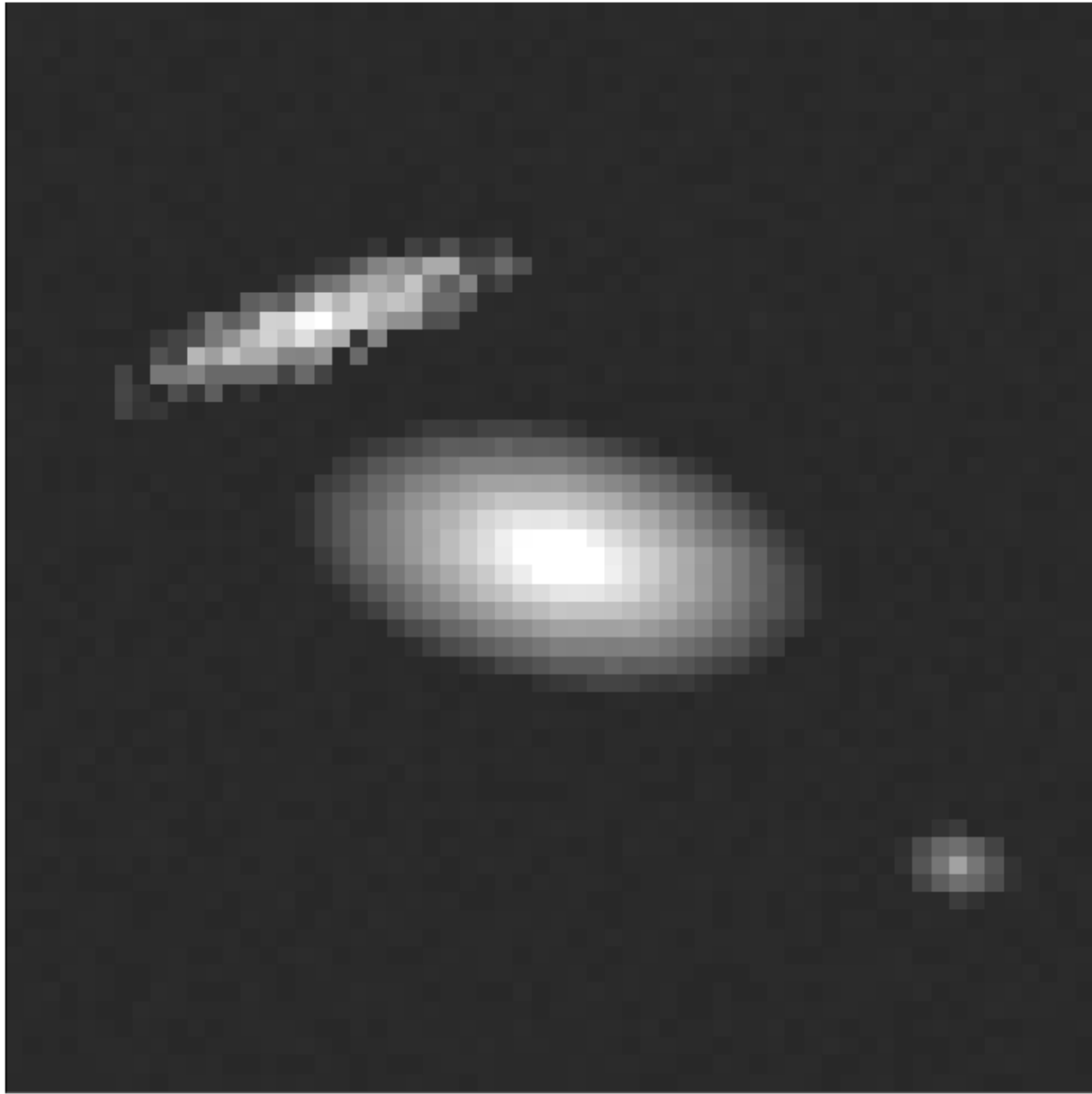
---

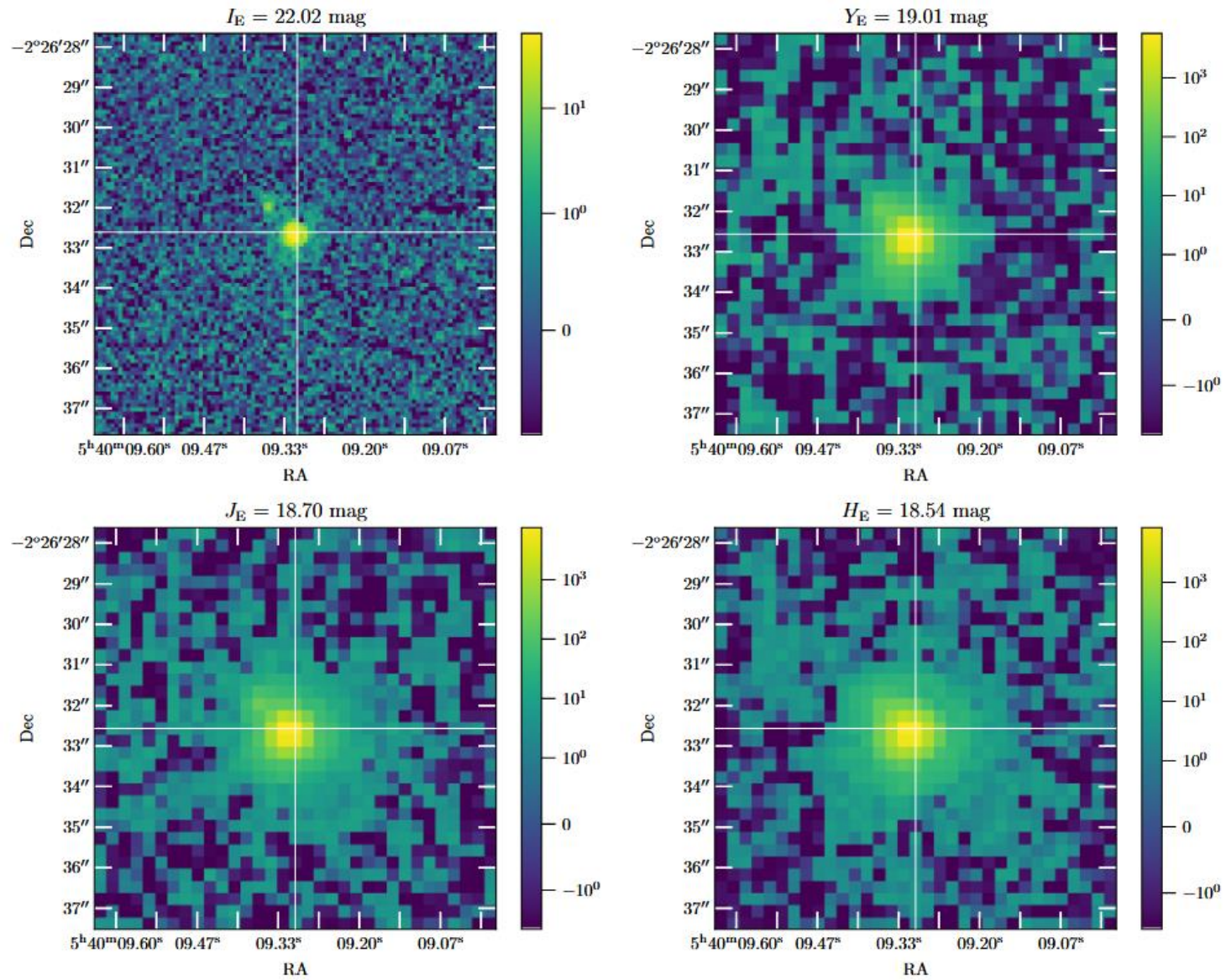
# Skipper technology for other fields

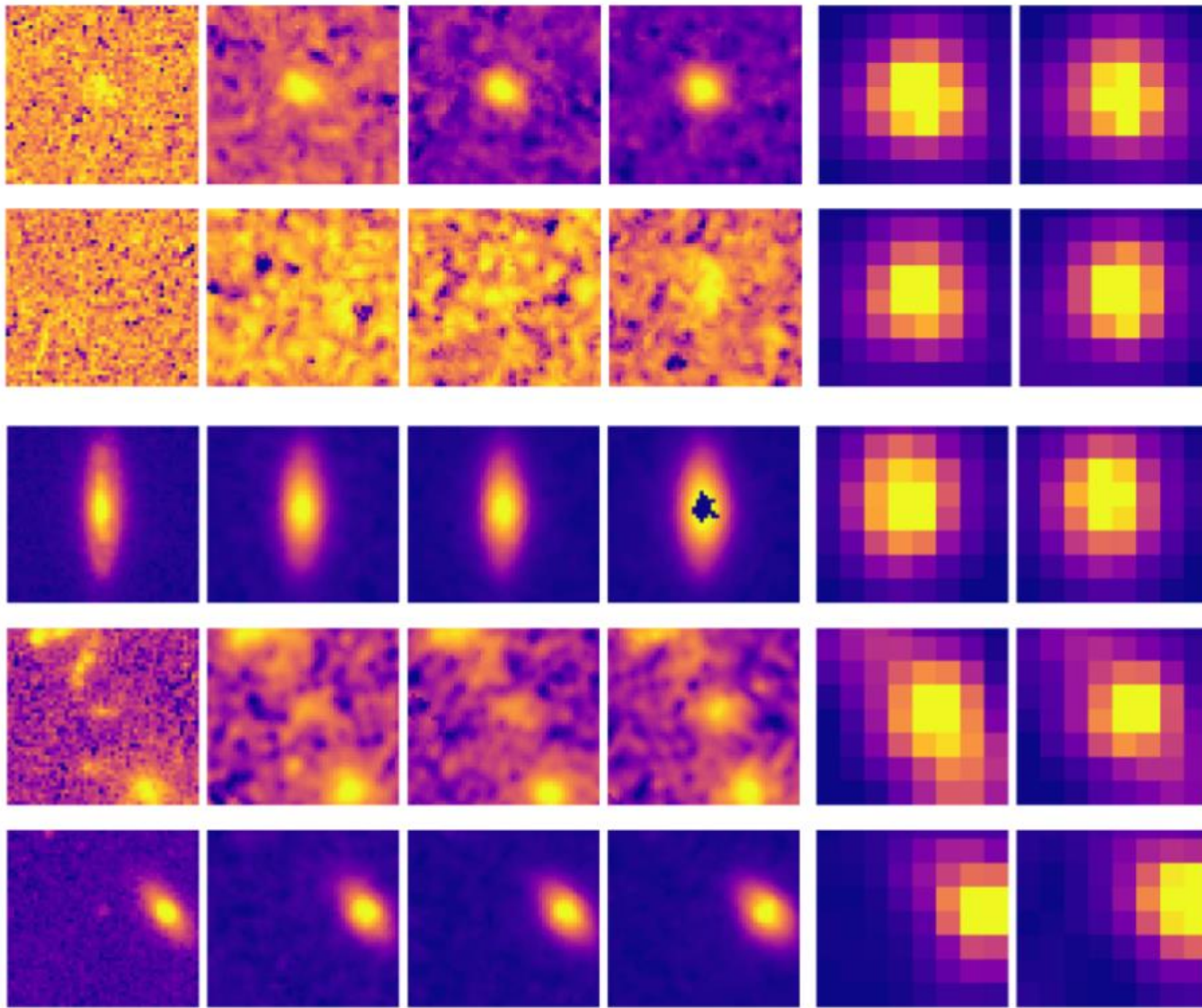
---

A COSMOLOGICAL EXAMPLES

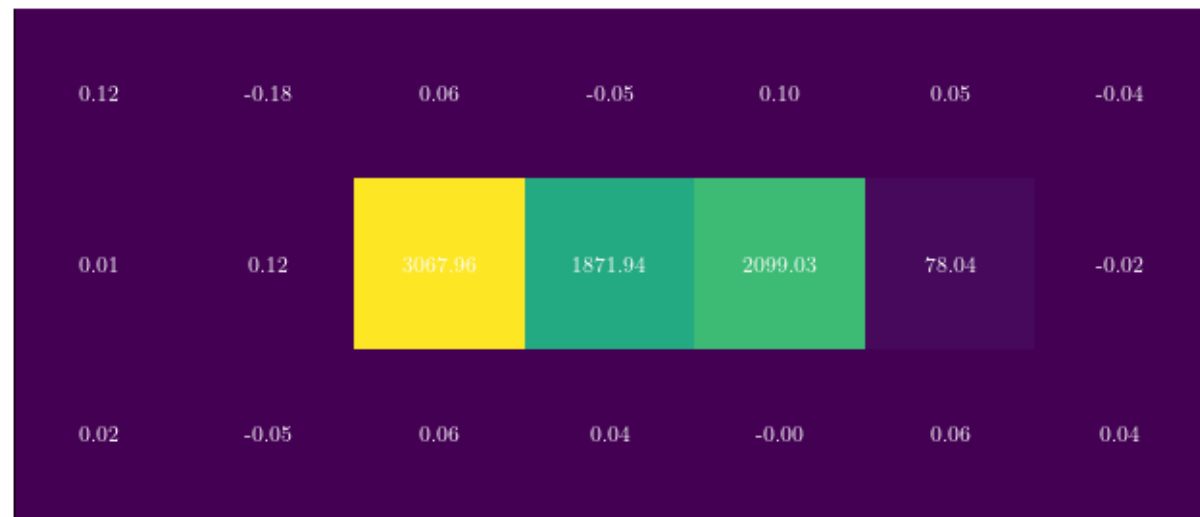
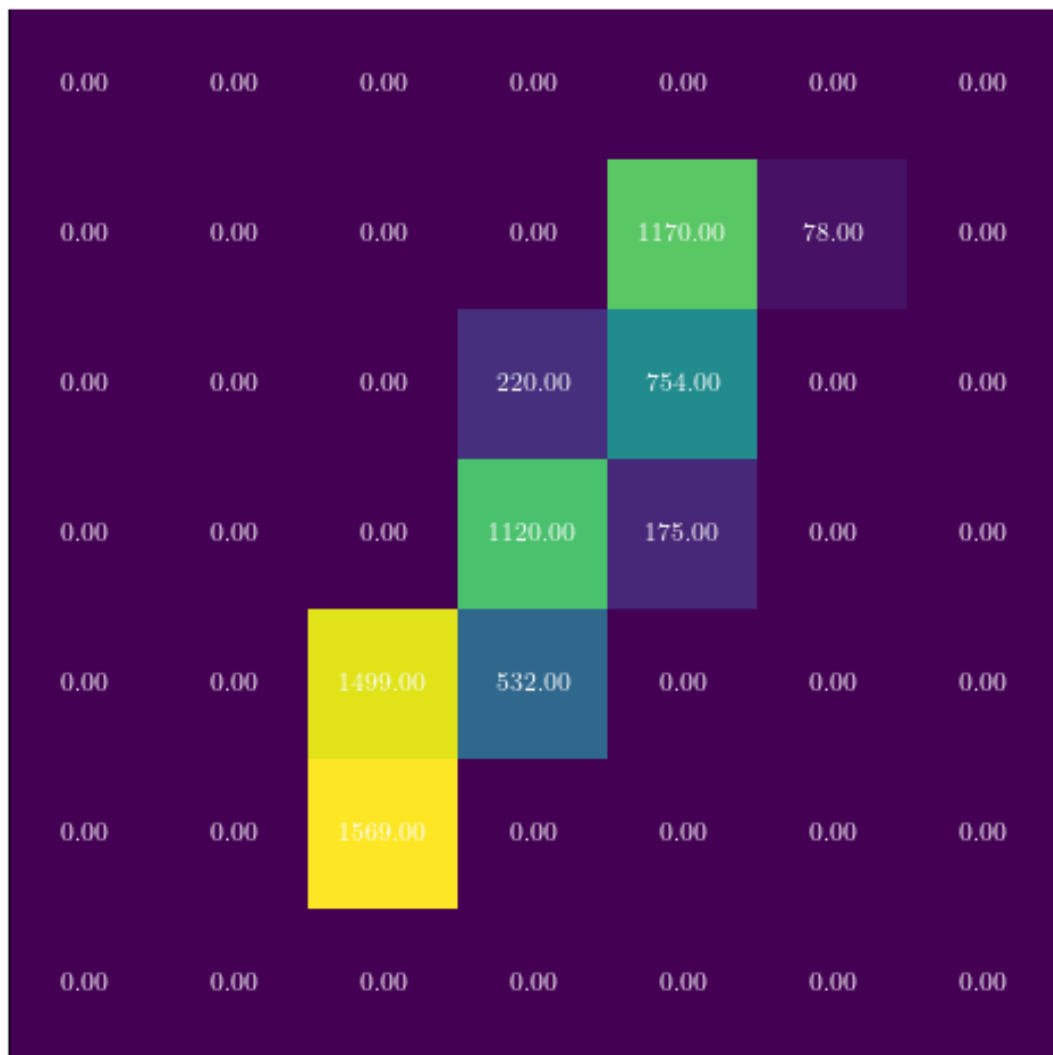


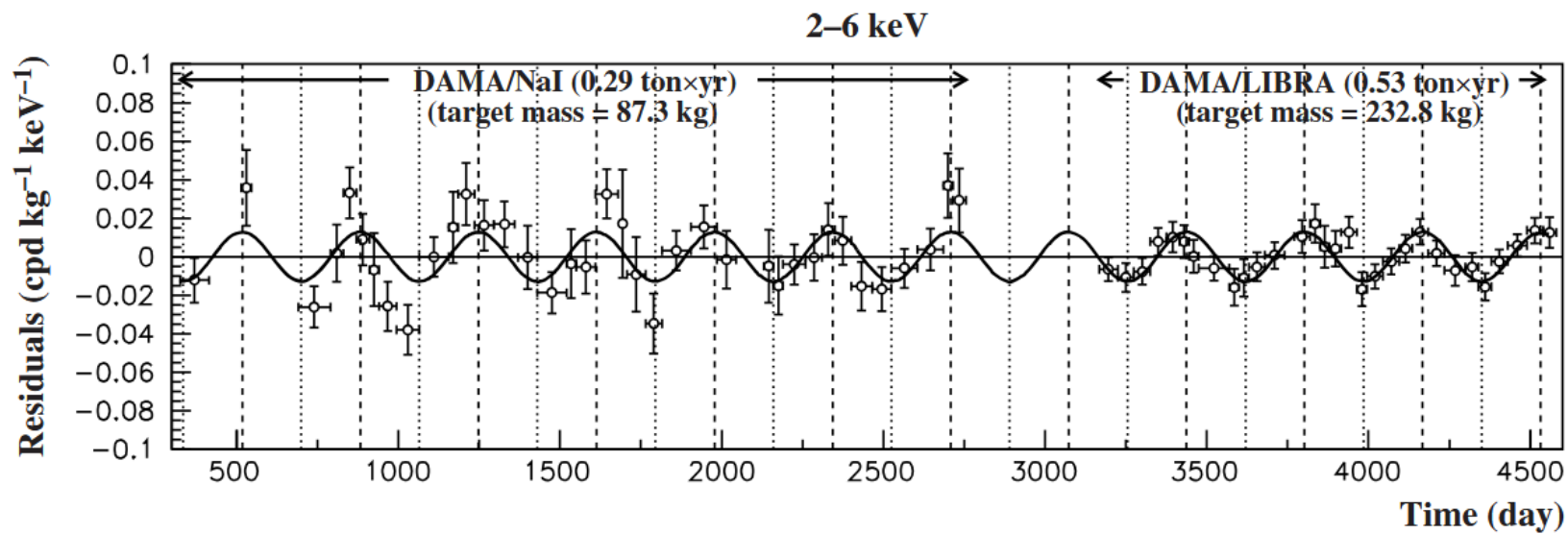
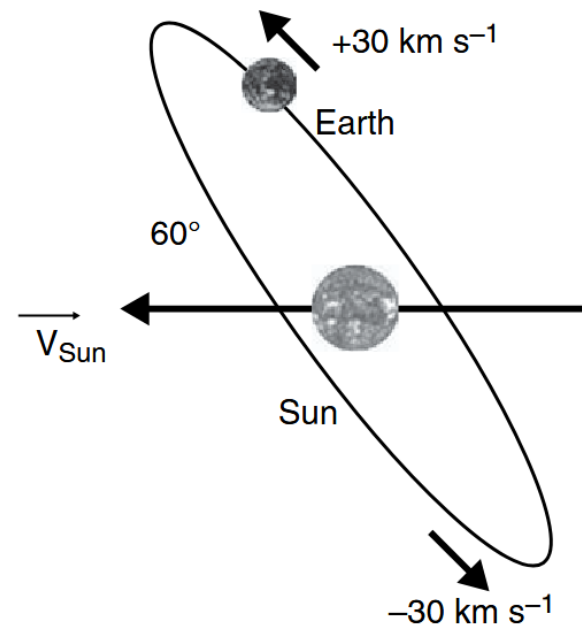
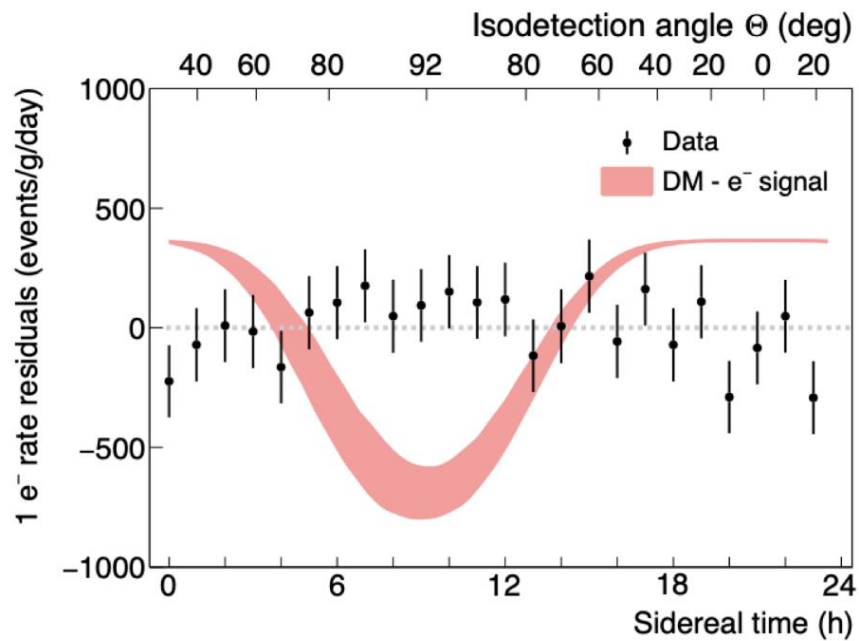






From left to right: IE, YE, JE, HE, IRAC1, and IRAC2.





$$\frac{dR}{dE_e} \propto \bar{\sigma}_e \int \frac{dq}{q^2} \left[ \int \frac{f(\mathbf{v})}{v} d^3v \right] |F_{DM}(q)|^2 |F_c(q, E_e)|^2$$

Differential event rate

Dark matter–electron cross section

Crystal form factor calculated in QEDark

Dark matter velocity distribution

Dark matter form factor :  $F_{DM}(q) = \left( \frac{\alpha_{QED} m_e}{q} \right)^n$