Direct Detection of Dark Matter and Exclusion Limits

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XXV Giambiagi Winter School

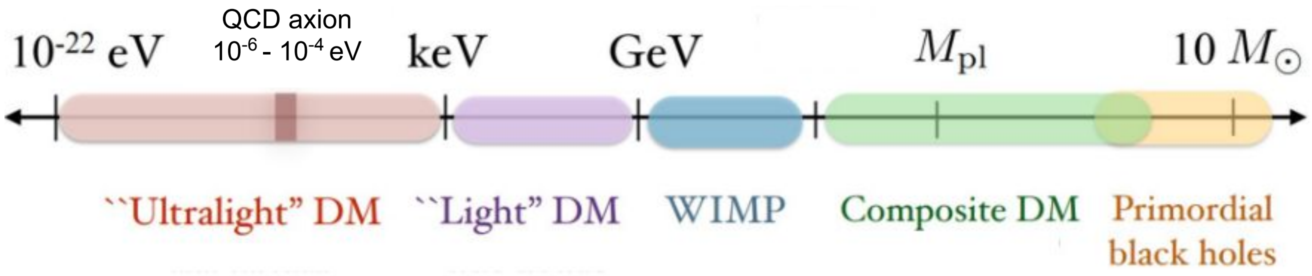
The question for most particle physicists is not whether dark matter exists but rather what type of particle- or particles-make up dark matter

The New Dark Matter Landscape, Budnik & Essig (2023)

Is Dark Matter part of a Dark Sector?

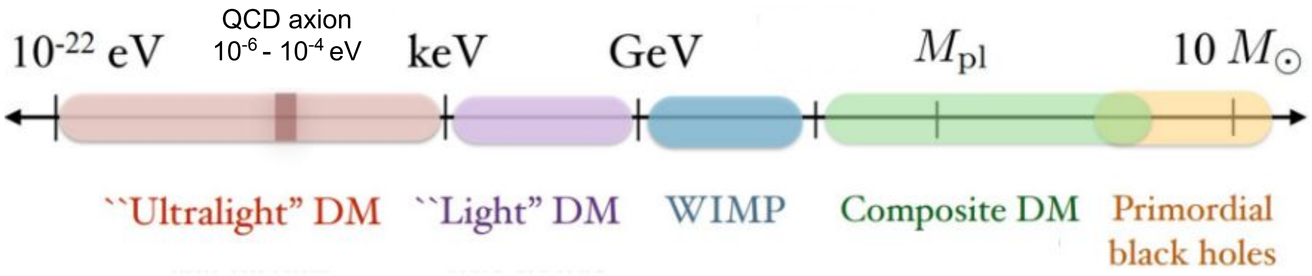
A wide range of masses to explore

spans 90 order of magnitude in mass



T. Lin (2019)

A wide range of masses to explore



T. Lin (2019)

220 km/second

$$\lambda_{dB} \sim \frac{h}{p} \sim \frac{h}{m_{DM}\ v_{DM,0}} \sim 34\ \mu\text{m} \left(\frac{50\ \text{eV}}{m_{DM}}\right)$$

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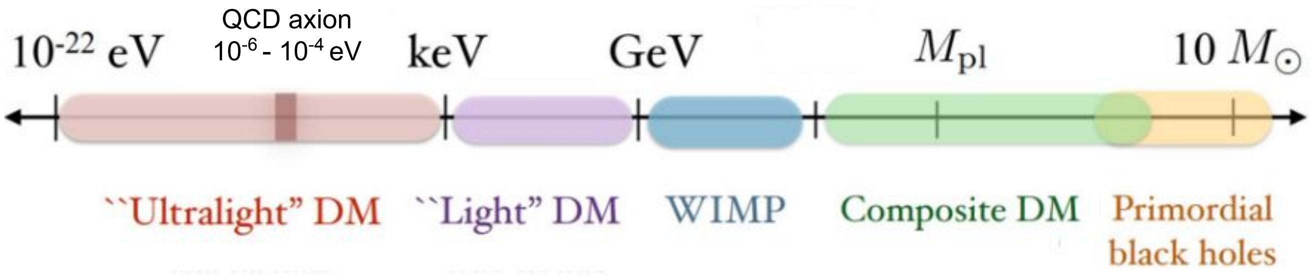

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220 km/second

$\rho_{DM,0} \sim 0.4\ \text{GeV/cm}^3$

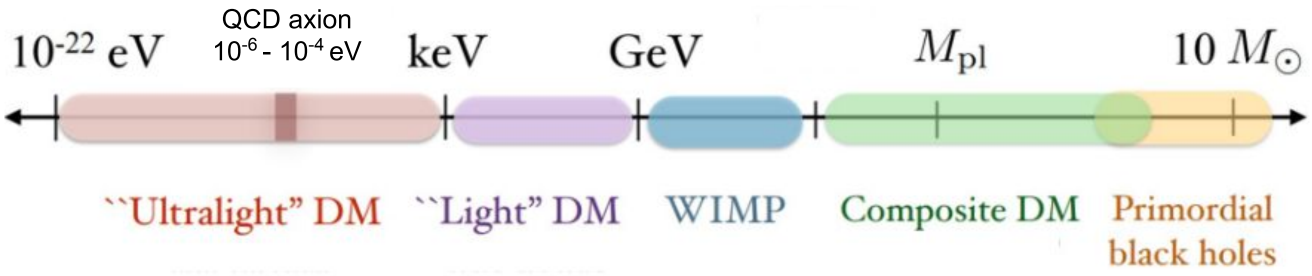
$n_{DM,0} \sim \frac{8\ \text{billion}}{\text{liter}} (1\ \text{eV}/m_{DM})$

$$\lambda_{dB} \sim \frac{h}{p} \sim \frac{h}{m_{DM}\ v_{DM,0}} \sim 34\ \mu\text{m} \left(\frac{50\ \text{eV}}{m_{DM}}\right)$$

$$d \sim \left(\frac{3}{4\pi n_0}\right)^{1/3} \sim 30\ \mu\text{m} \left(\frac{50\ \text{eV}}{m_{DM}}\right)^{1/3}$$

The New Dark Matter Landscape, Budnik & Essig (2023)

A wide range of masses to explore



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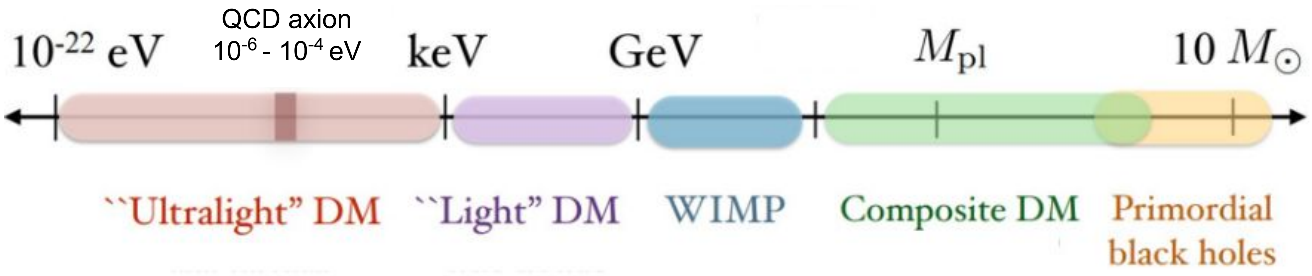
$$\frac{\lambda_{\mathrm{dB}}}{d} \sim 1.1\left(\frac{50\ \mathrm{eV}}{m_{\mathrm{DM}}}\right)^{4/3}$$

The New Dark Matter Landscape, Budnik & Essig (2023)

A wide range of masses to explore



T. Lin (2019)

- **Ultralight DM** must be a boson, since fermion would not be able to form observed dwarf galaxies due to Pauli exclusion principle.

- The 10^{-22} eV limits corresponds to the de Broglie wavelength comparable to the size of observed dwarf galaxies.

- QCD axion: It would also solve the strong CP problem in QCD.

$$\lambda_{\rm dB} \sim \frac{h}{p} \sim \frac{h}{m_{\rm DM}\; v_{\rm DM,0}} \sim 34\ \mu{\rm m} \left(\frac{50\ {\rm eV}}{m_{\rm DM}}\right)$$

The New Dark Matter Landscape, Budnik & Essig (2023)

Terrestrial Probes

Production of DM

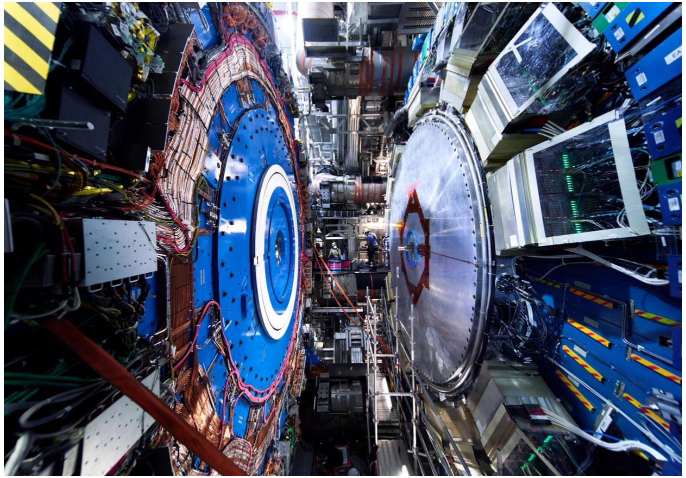
Accelerators could be able to produce DM in collisions of SM particles, and then look for missing energy.

Precision measurements

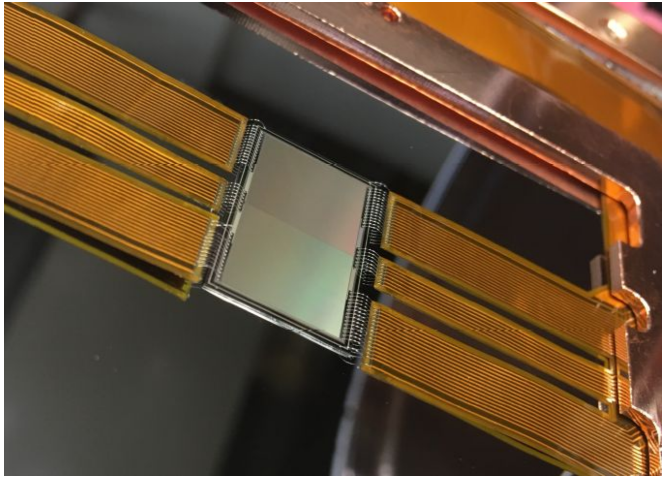
Reducing the uncertainty in SM cross section determination helps to constraint DM cross section interaction.

Direct detection

Search for the small signals created when a DM particle in our halo scatters off a target material.

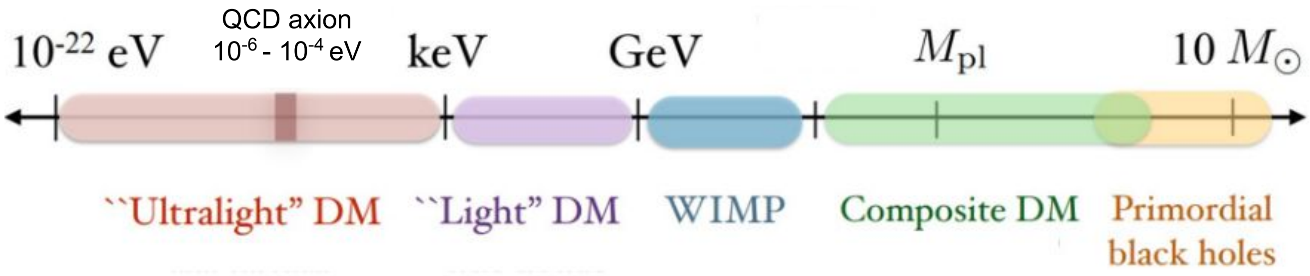


Credit: Maximilien Brice/Julien Marius Ordan/ CERN.



Silicon sensor used to look for Dark Matter

Ultralight Dark Matter searching



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Axion Dark Matter eXperiment (ADMX) uses strong magnetic field in a cavity to convert DM axions to microwave photons.

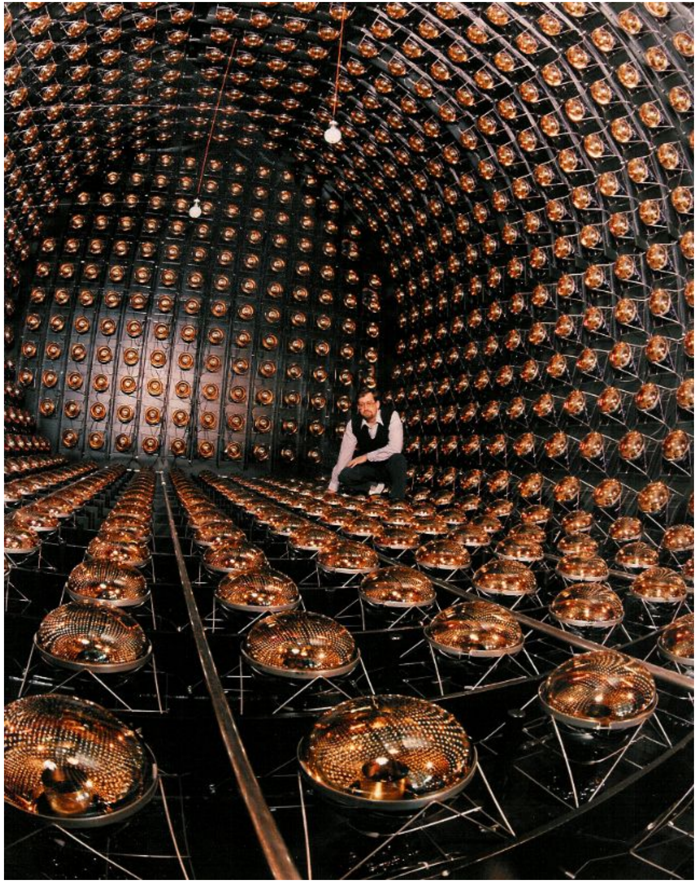
- ➢ ADMX-HF
- ➢ NASDUCK
- ➢ HAYSTAC
- ➢ CASPEr
- ➢ ABRACADABRA
- ➢ DM-Radio

The New Dark Matter Landscape, Budnik & Essig (2023)

Accelerator-based probes of Light Dark Matter

Particle-like dark matter with masses below proton have historically been scarcely explored

- **FASER**, in the far-forward region of the LHC to catch elusive dark-sector particles.
- **MiniBooNE**, a neutrino experiment able to search for DM produced in a proton beam dump.
- **LDMX**, electron beam incident on a fixed target and search for missing momentum of the electron after it passes through the target, which could be caused by the radiation of dark matter particles.



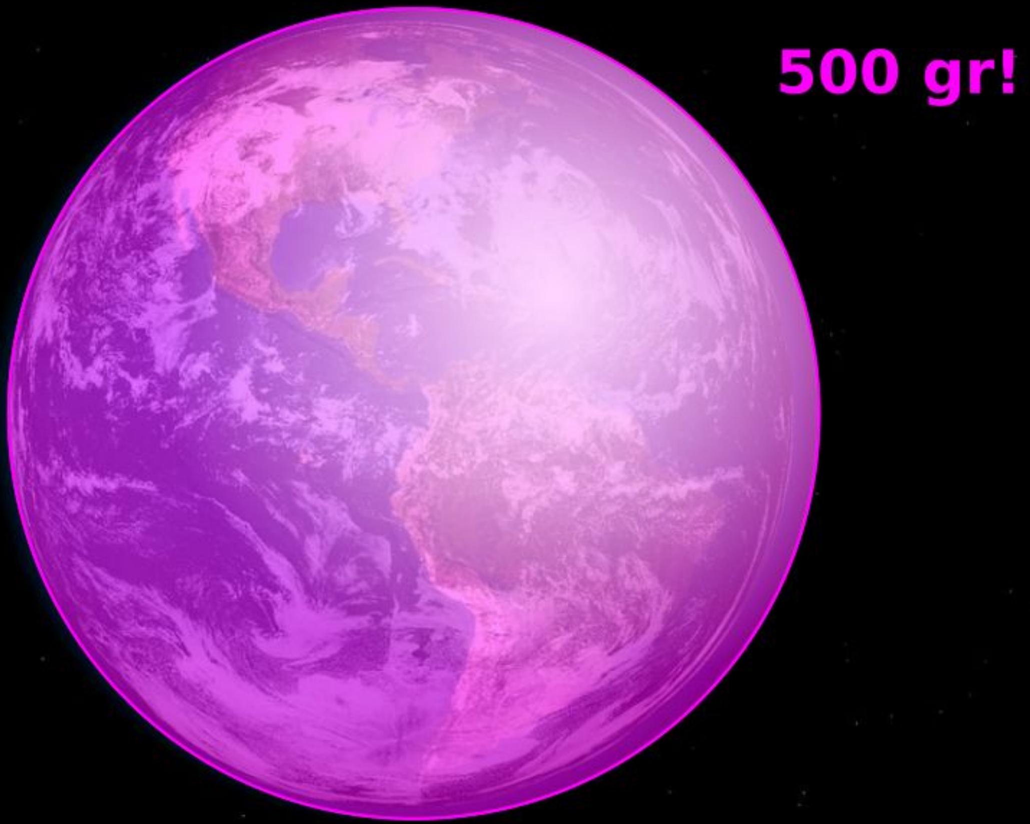
MiniBoone Cherenkov Detectors

The New Dark Matter Landscape, Budnik & Essig (2023)

Terrestrial Probes: Direct Detection of Dark Matter

Density ~ 0.4 GeV/cm^3

Terrestrial Probes: Direct Detection of Dark Matter



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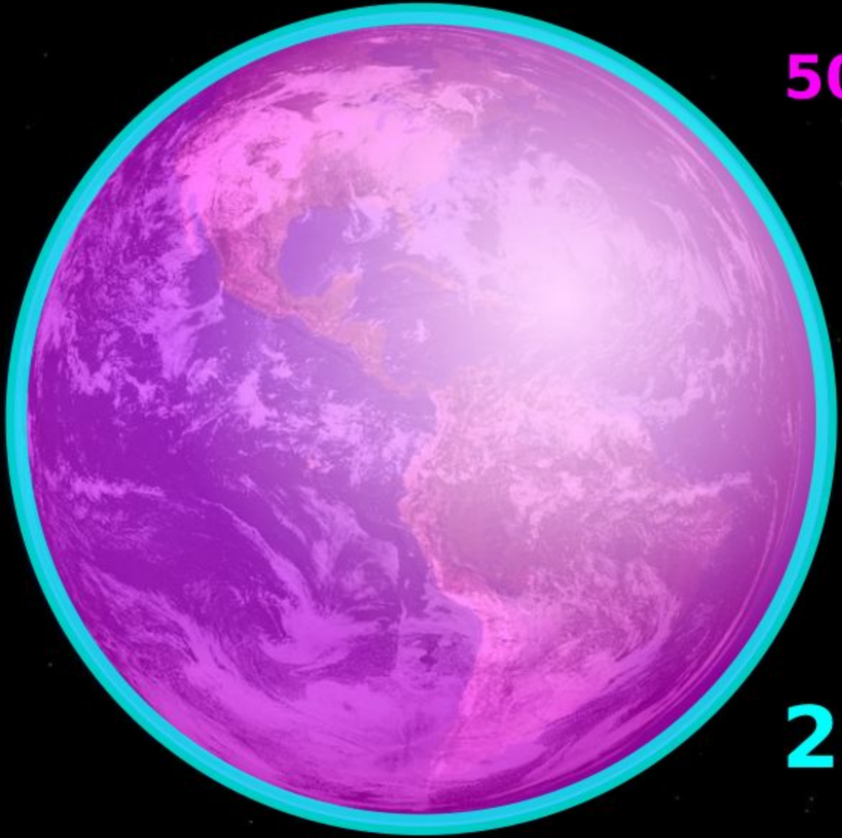
Terrestrial Probes: Direct Detection of Dark Matter



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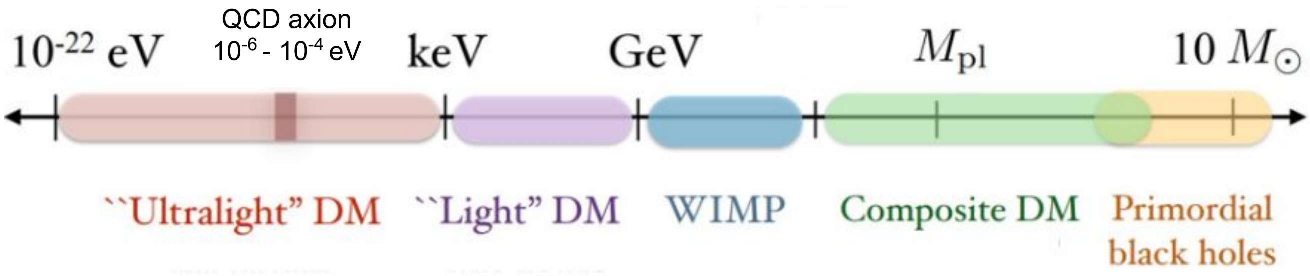
Direct Detection of Particle-like Dark Matter



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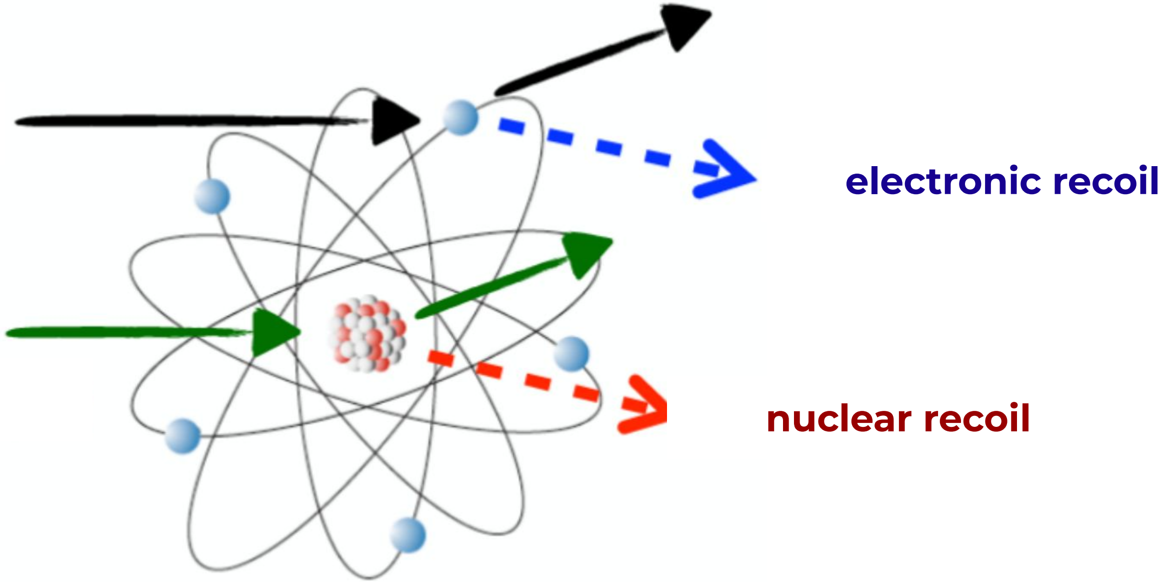


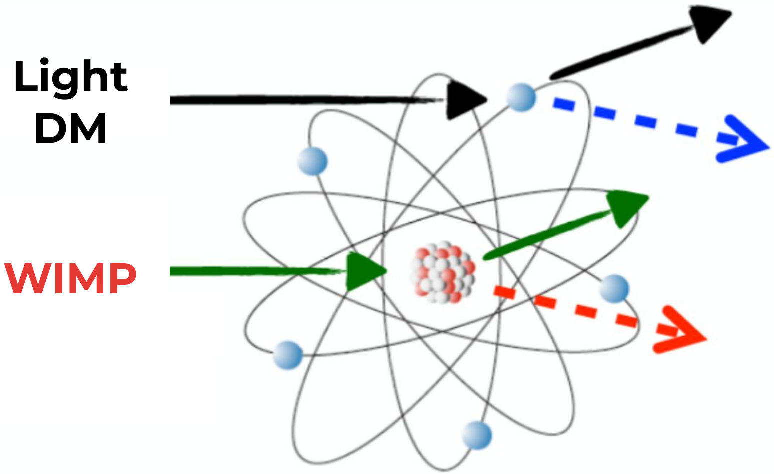
Direct Detection of Particle-like Dark Matter

➢ Elastic interaction of DM with a nucleus

$$E_{\rm NR} \sim 1\ {\rm eV} \left(\frac{m_{\rm DM}}{100\ {\rm MeV}}\right)^2 \left(\frac{28\ {\rm GeV}}{m_{\rm N}}\right)$$

➢ Inelastic interaction:
- DM-electron scattering
- Migdal effect
- DM scattering off collective excitations

$$E_{\rm kin} \sim 100\ {\rm eV} \left(\frac{m_{\rm DM}}{100\ {\rm MeV}}\right)$$



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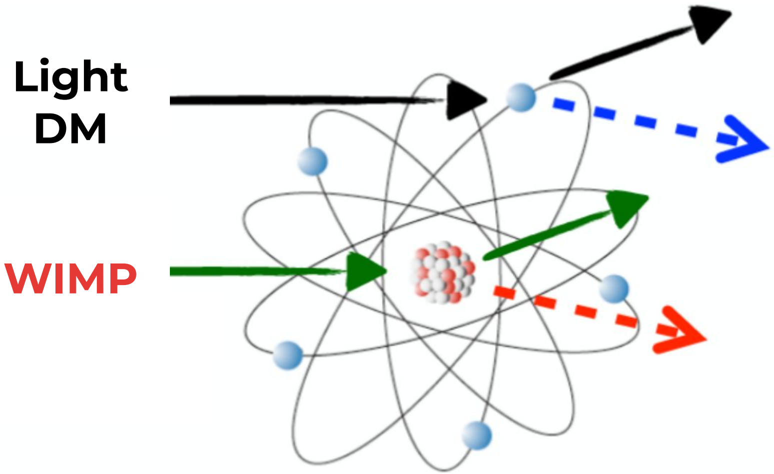
CEvNS produced an irreducible background



Quenching factor

The New Dark Matter Landscape, Budnik & Essig (2023)

Direct Detection of WIMPs

The XENONnT being installed in the LNGS laboratory in Italy

➢ **WIMPs**, with a mass 1 to 10 000 GeV, would be produced in the early Universe shortly after the Big Bang with a calculable abundance that roughly matches the one observed.

➢ Experiments: Multi-ton scale detectors with noble-liquid targets (xenon and argon) led by:

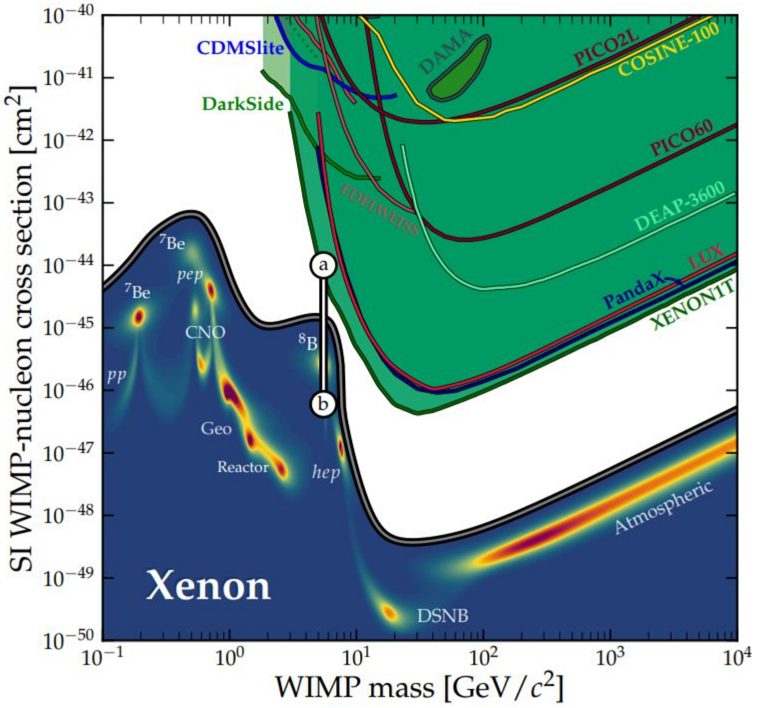
- XENONnT
- LZ
- PandaX-4T
- DarkSide-20k.

100 events per tonne per year
100 events per people per second on Earth's surface.

The New Dark Matter Landscape, Budnik & Essig (2023)

Direct Detection of WIMPs

Neutrino floor (fog?)



https://arxiv.org/pdf/2109.03116v2.pdf

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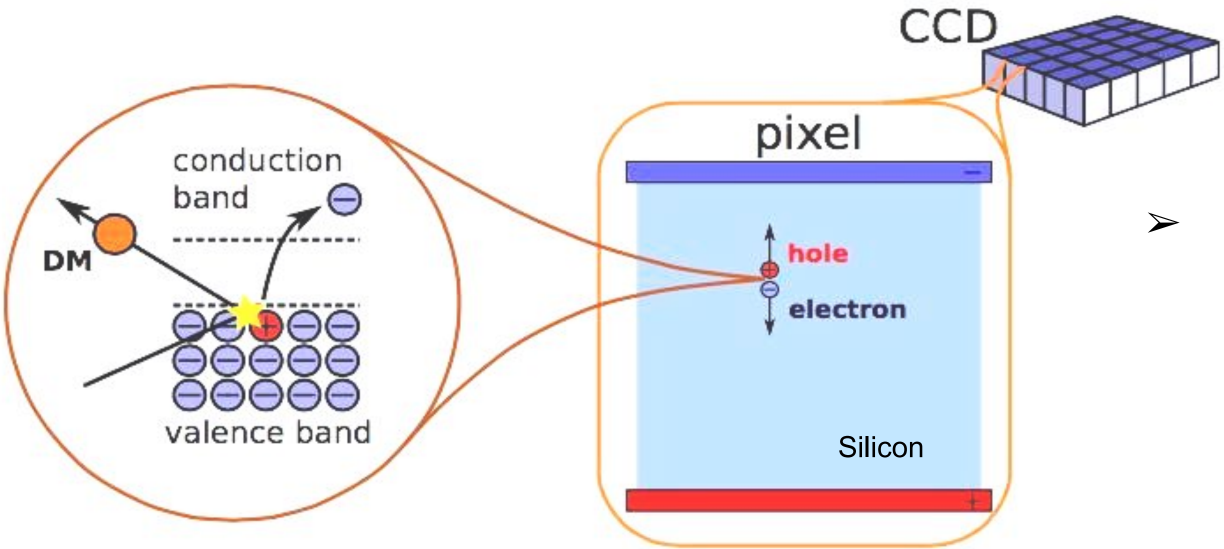
Direct Detection of Light Dark Matter



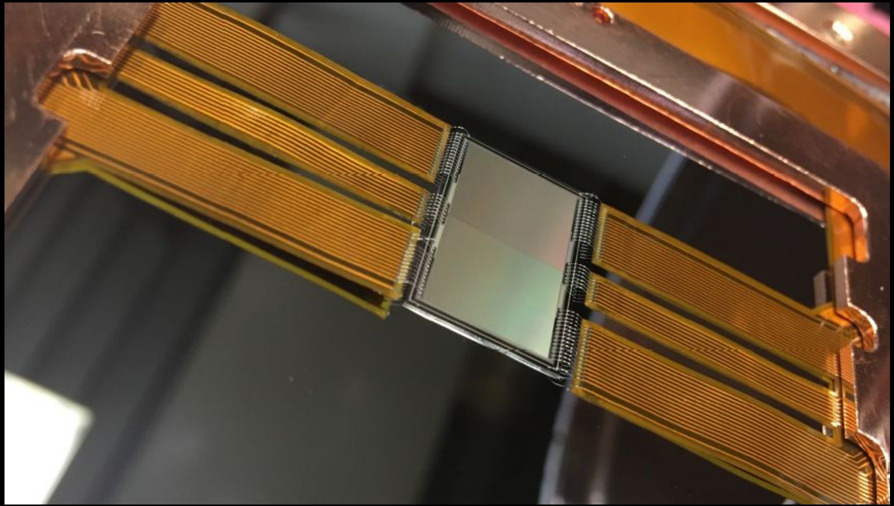
➢ Experiments:
  - DAMIC
  - SENSEI
  - DAMIC-M
  - OSCURA

Particle-like dark matter with masses below proton have historically been scarcely explored

Charge Coupled Device

Selfie by Boyle and Smith in 1969

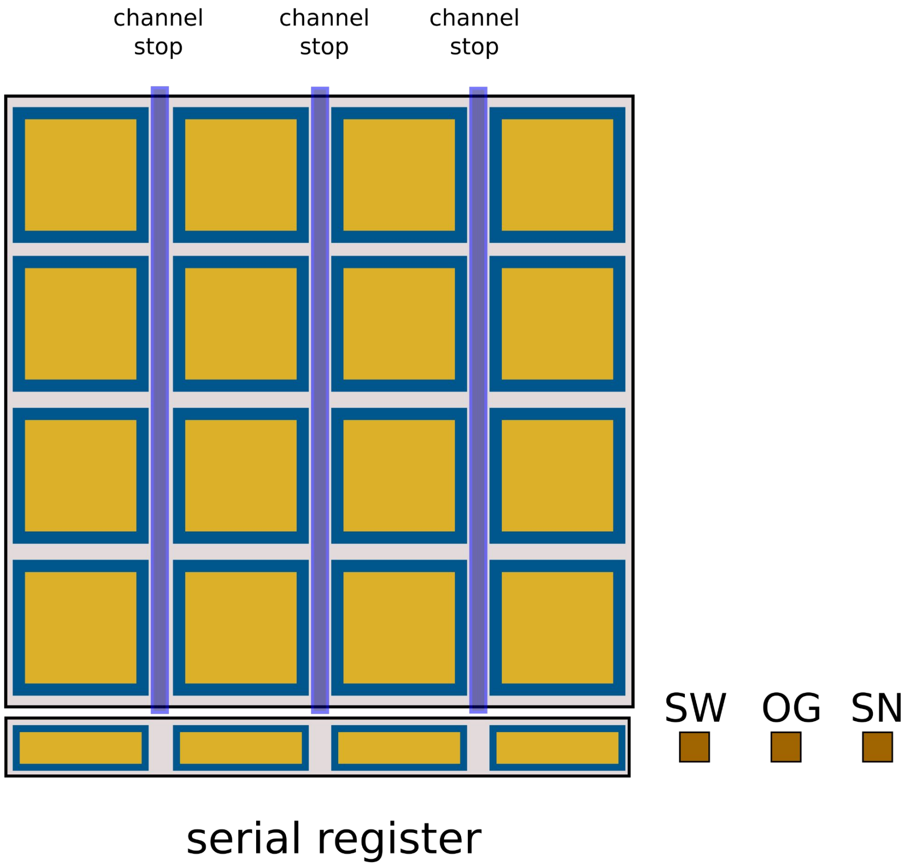
Nobel Prize in 2009



Skipper-CCD

Used by SENSEI to look for Dark Matter

CCD technology



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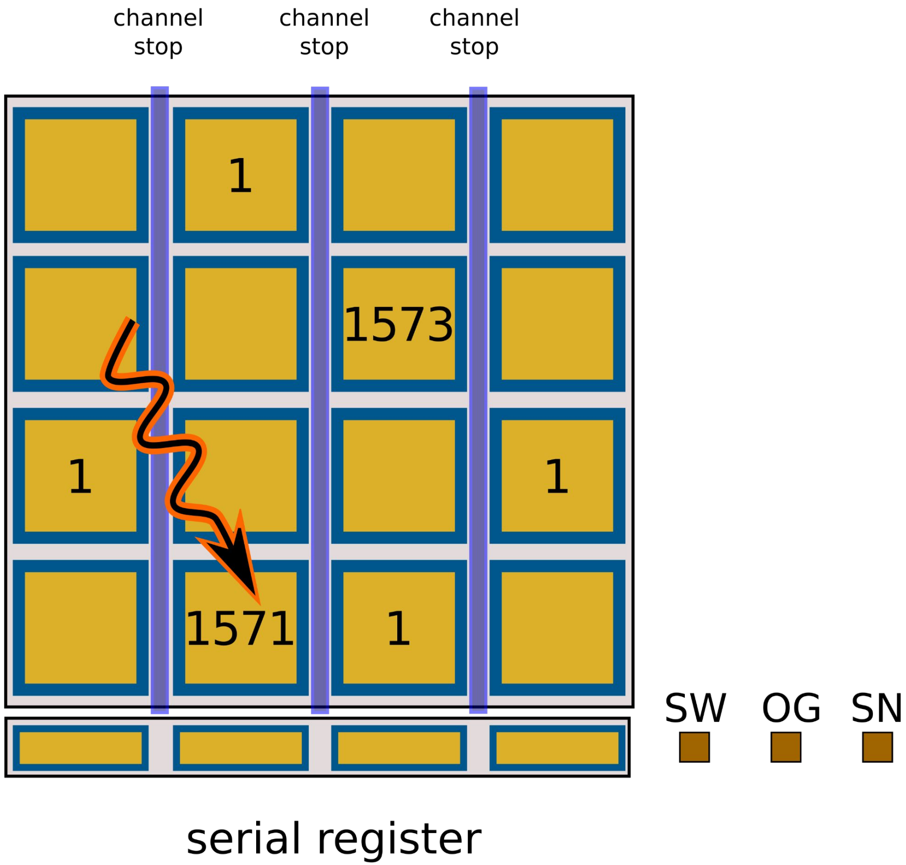

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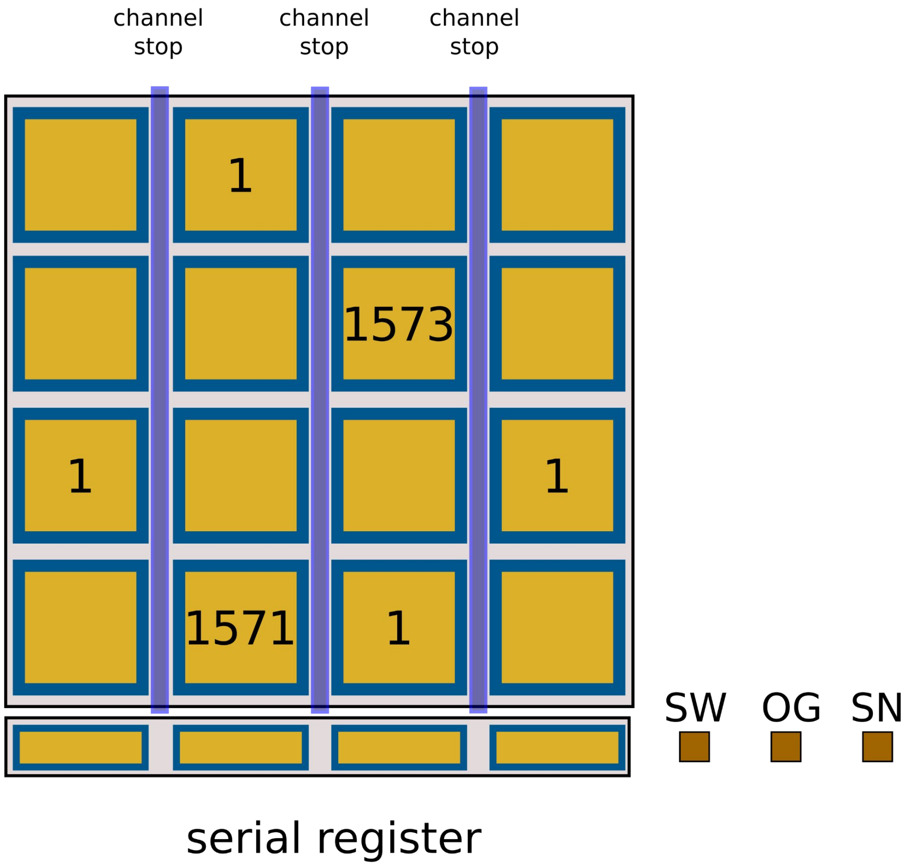

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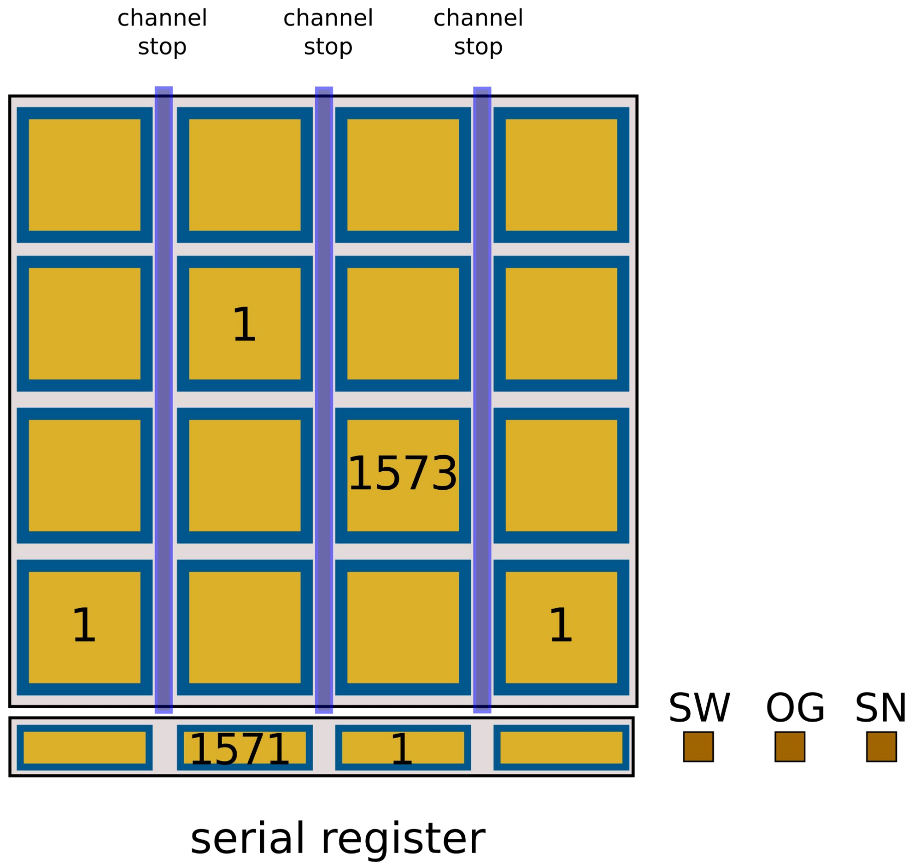

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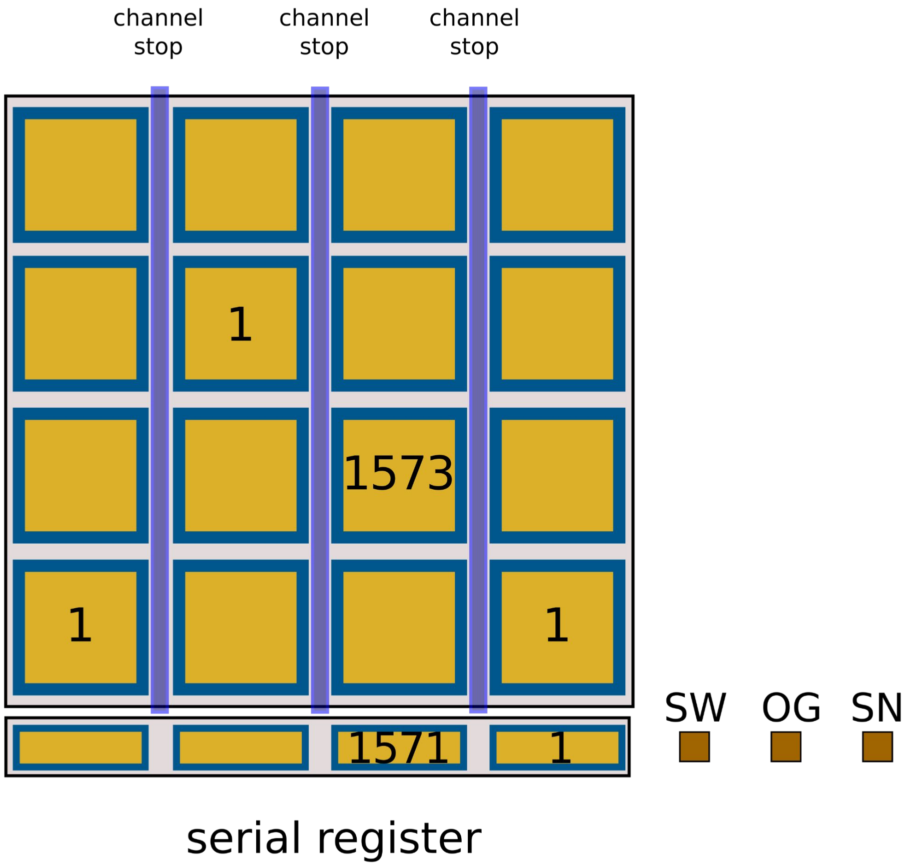

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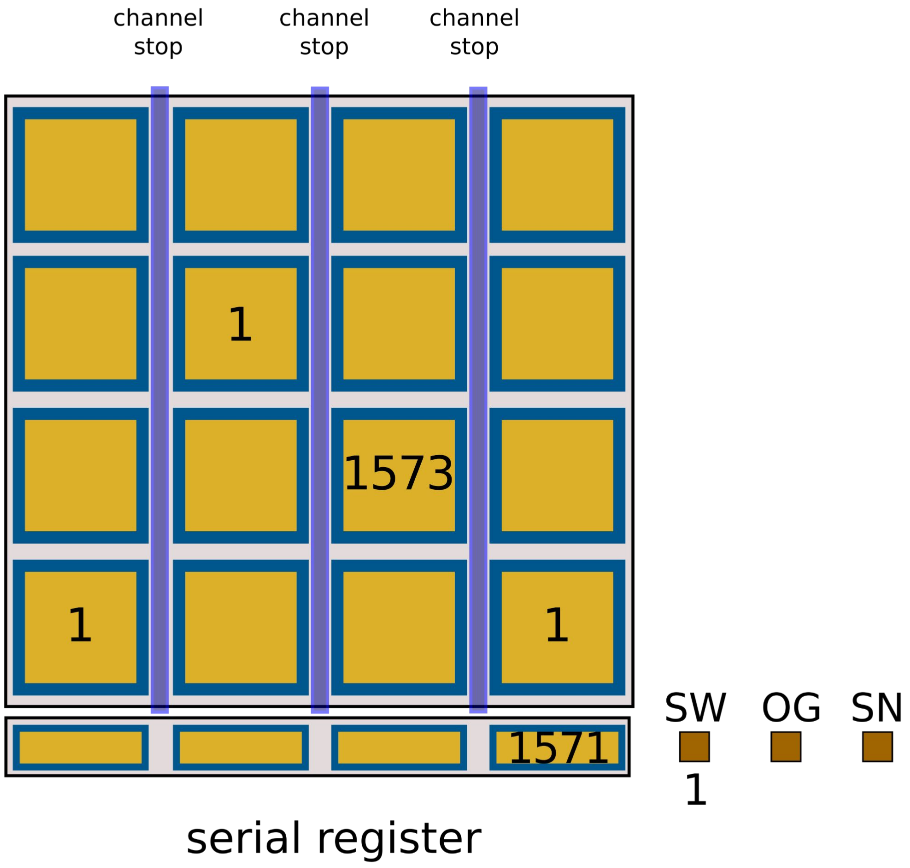

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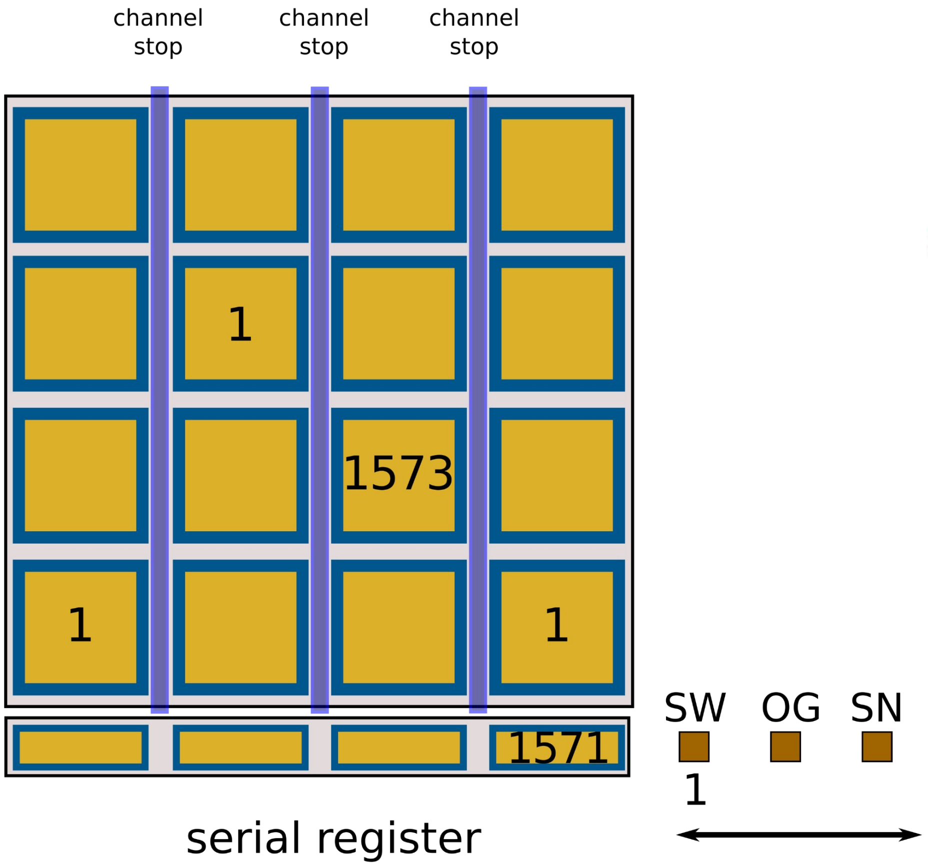

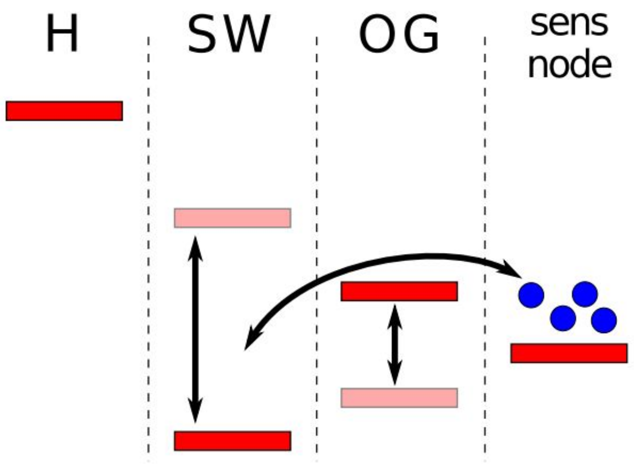

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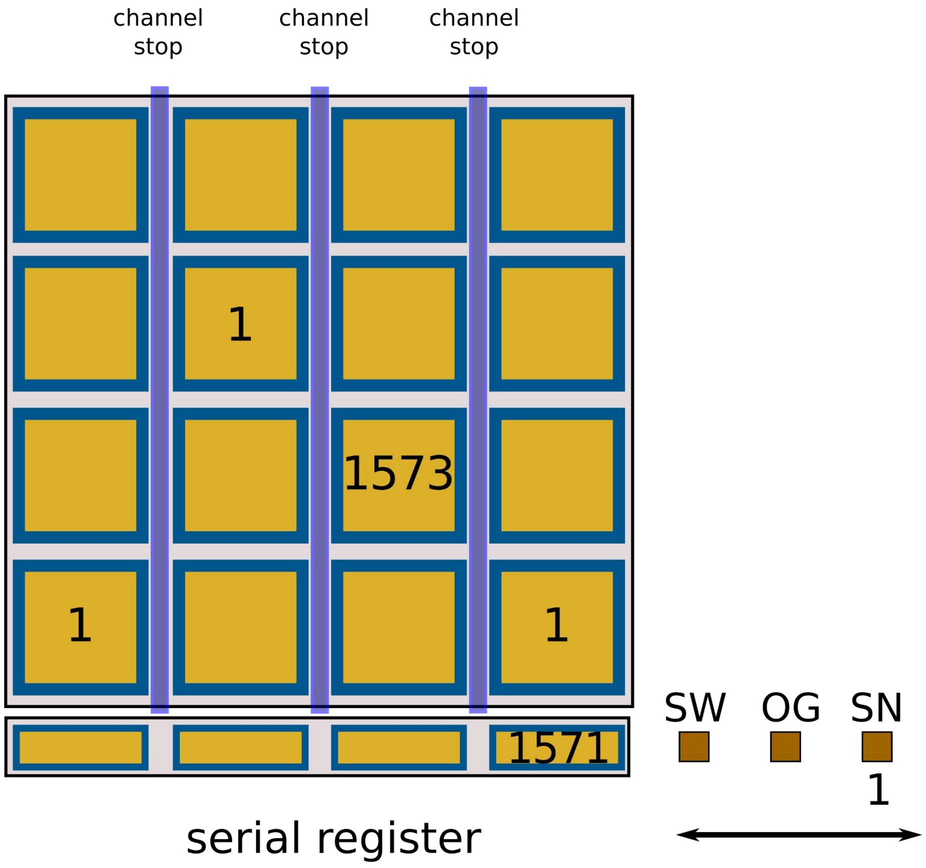

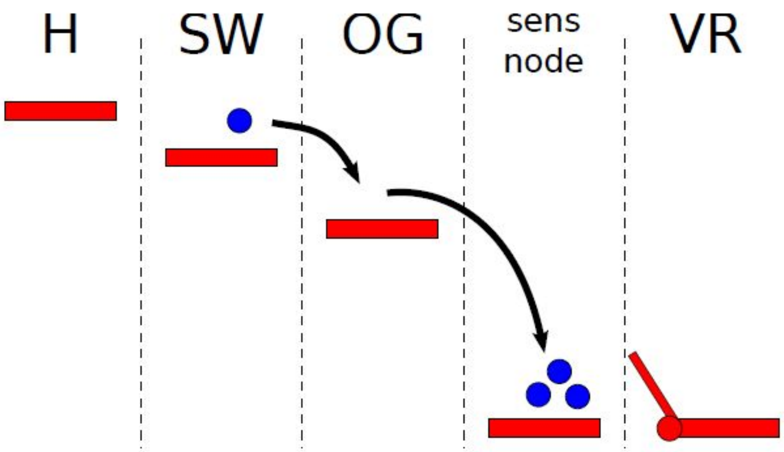

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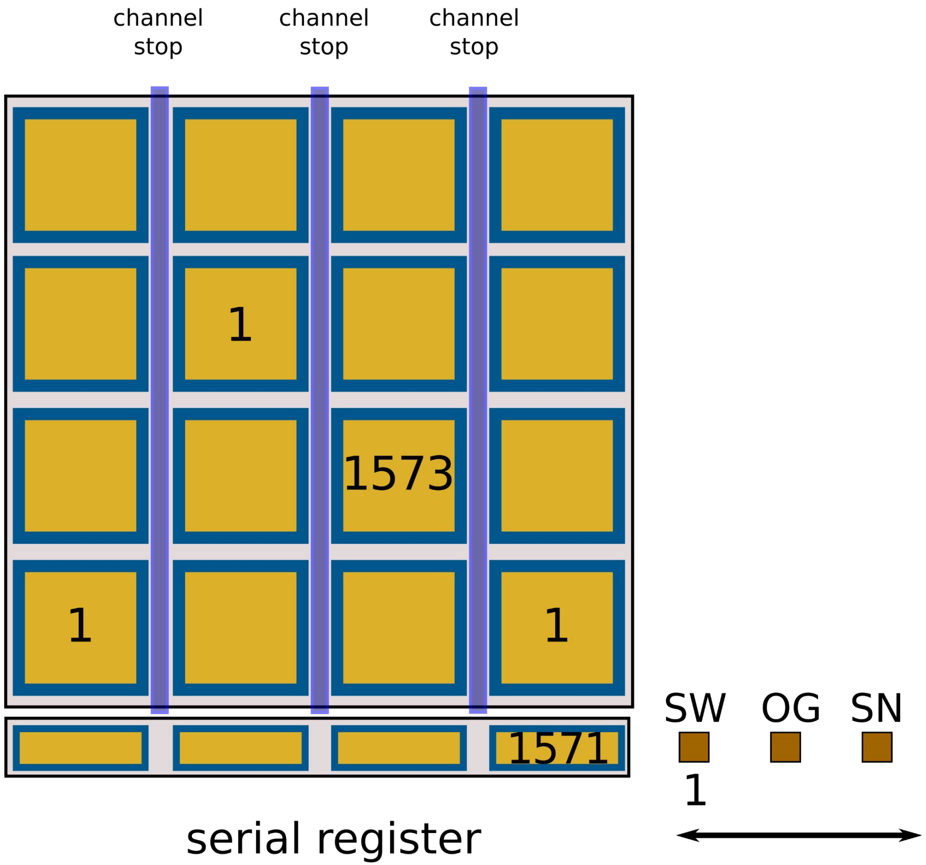

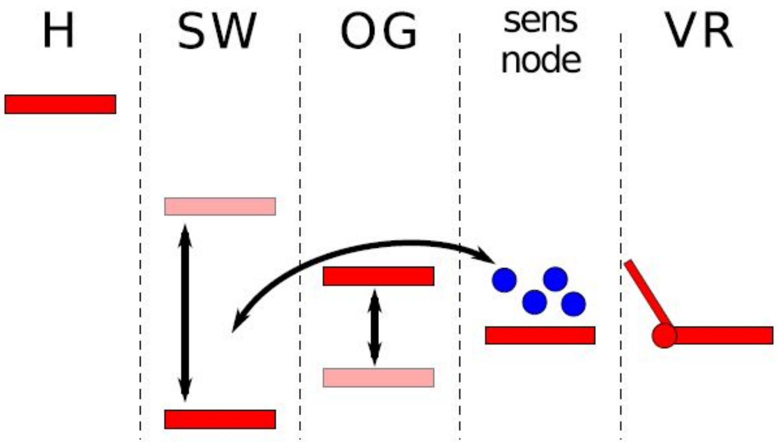

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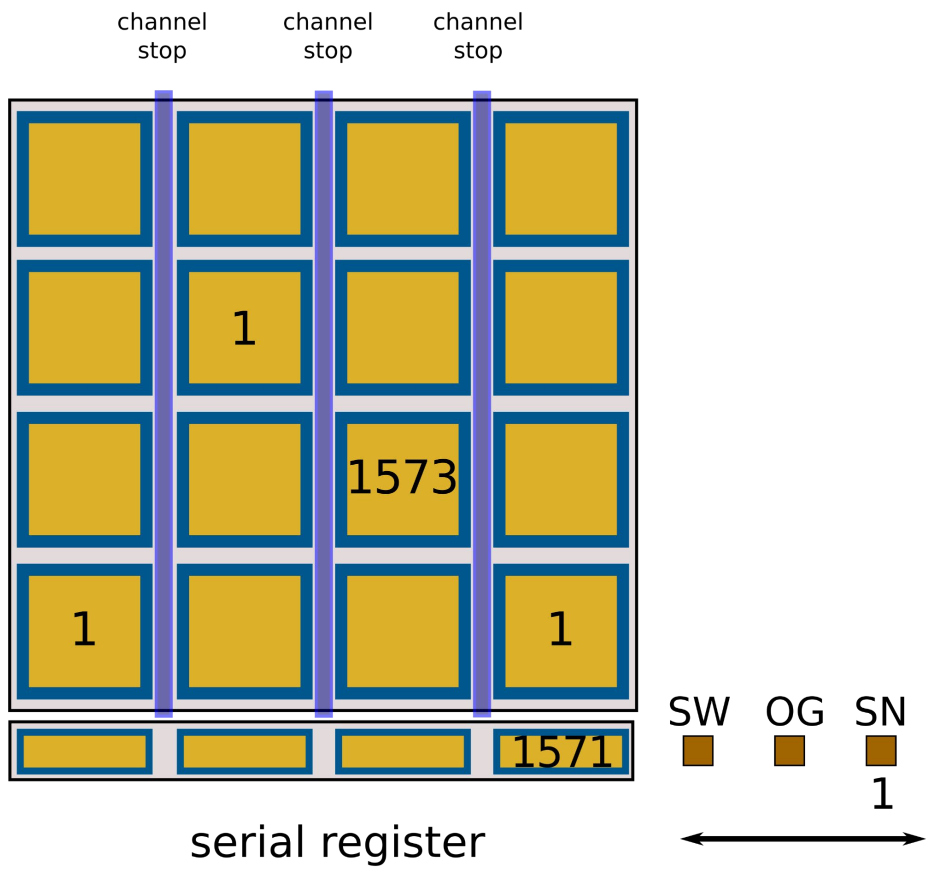

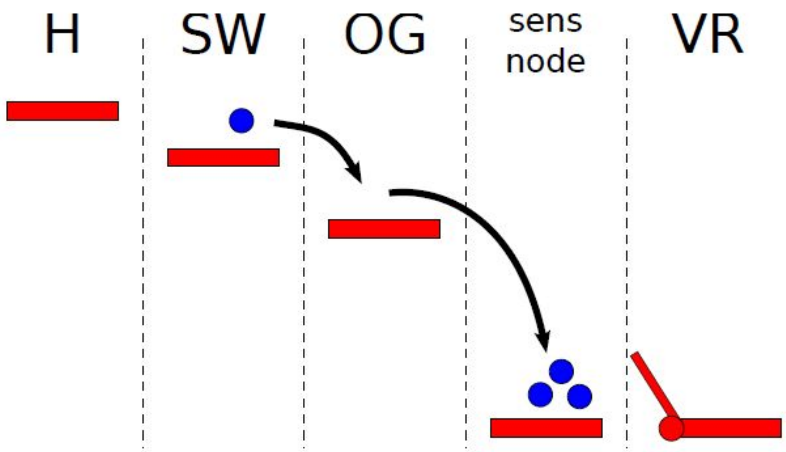

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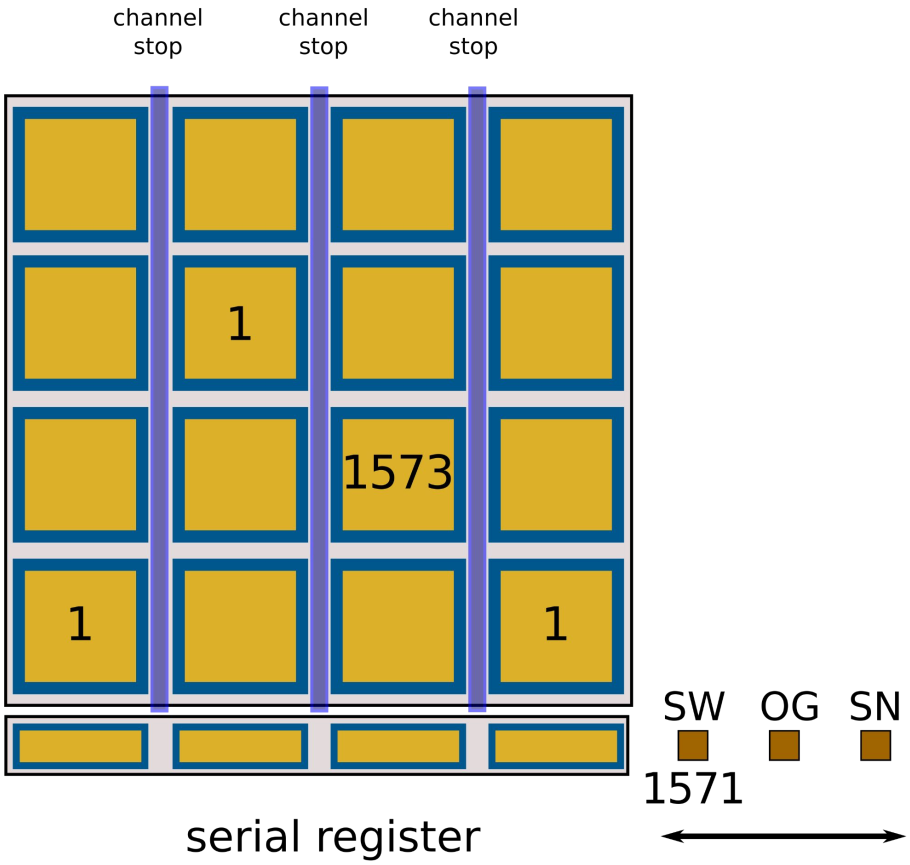

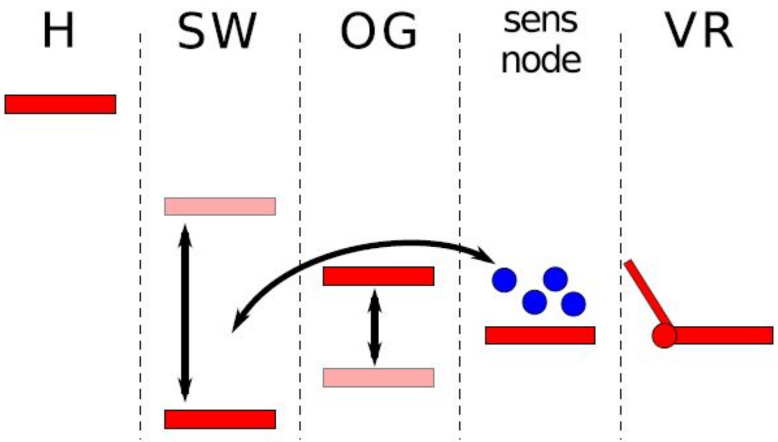

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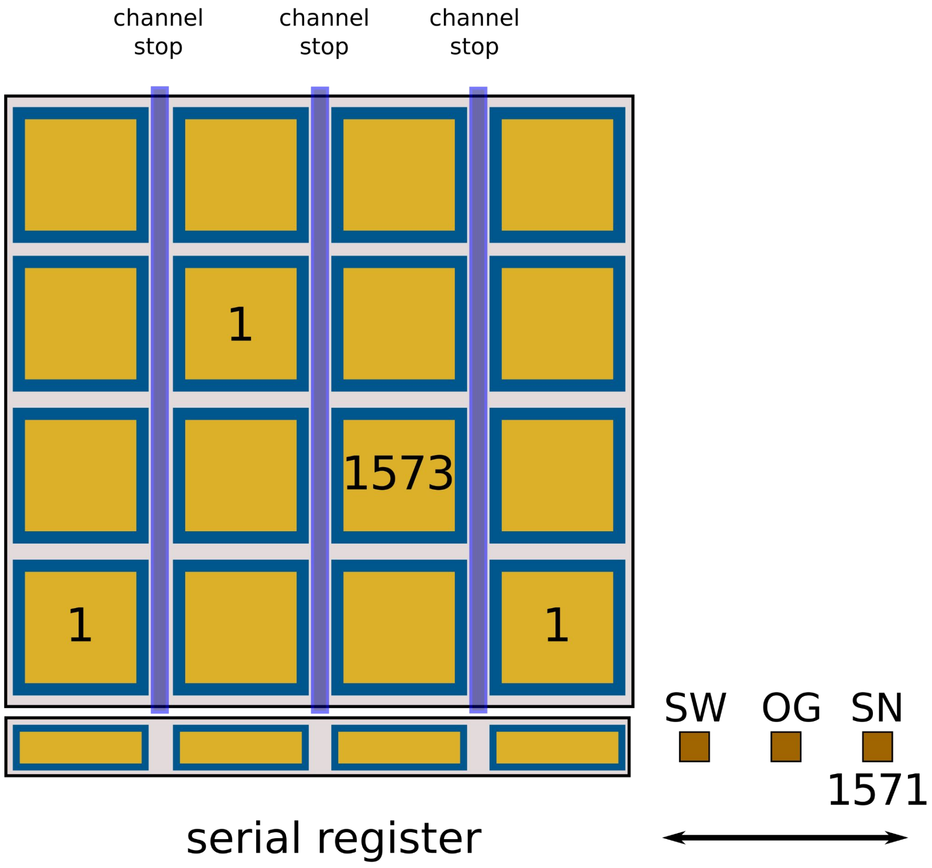

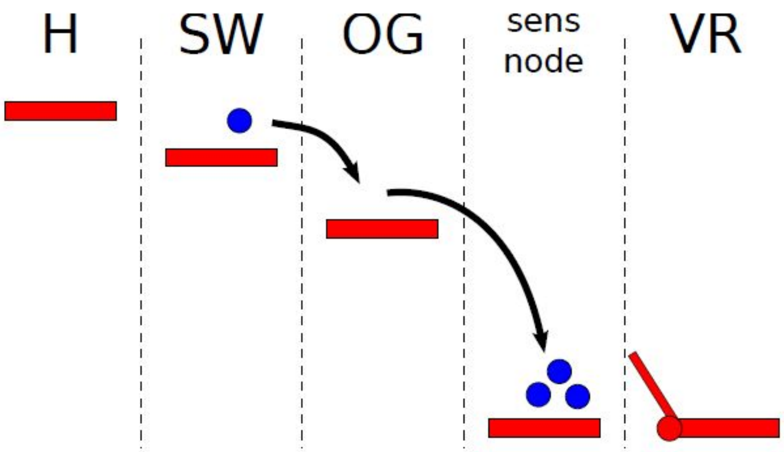

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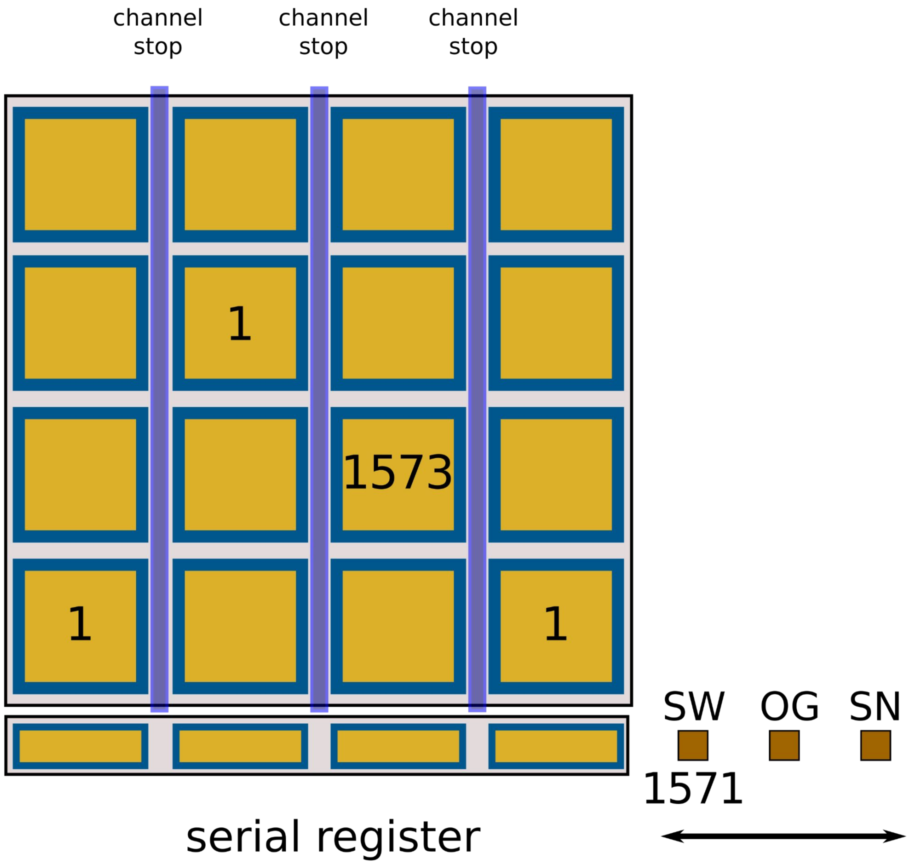

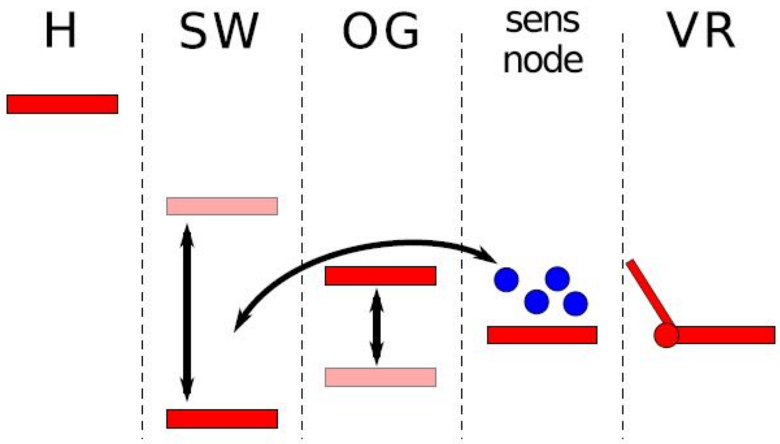

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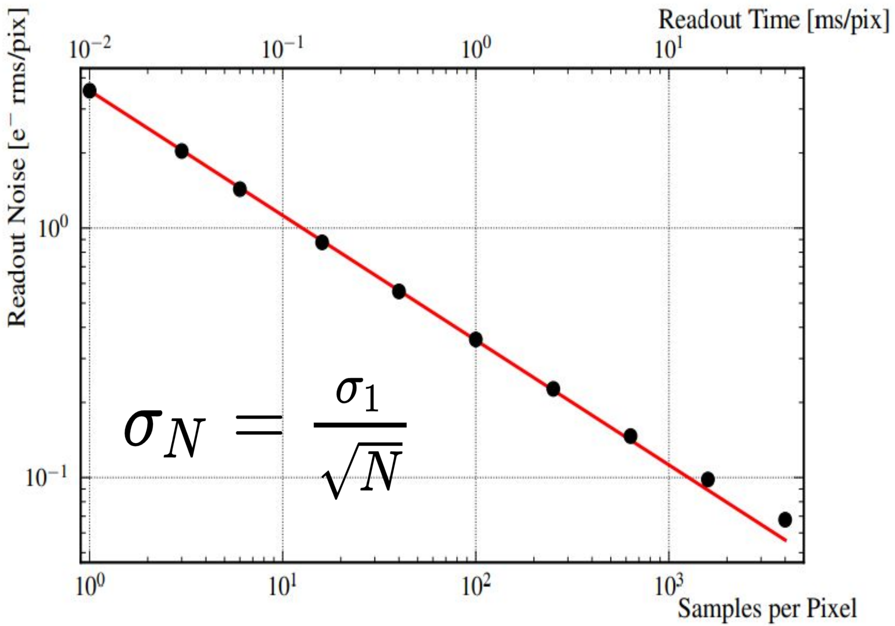
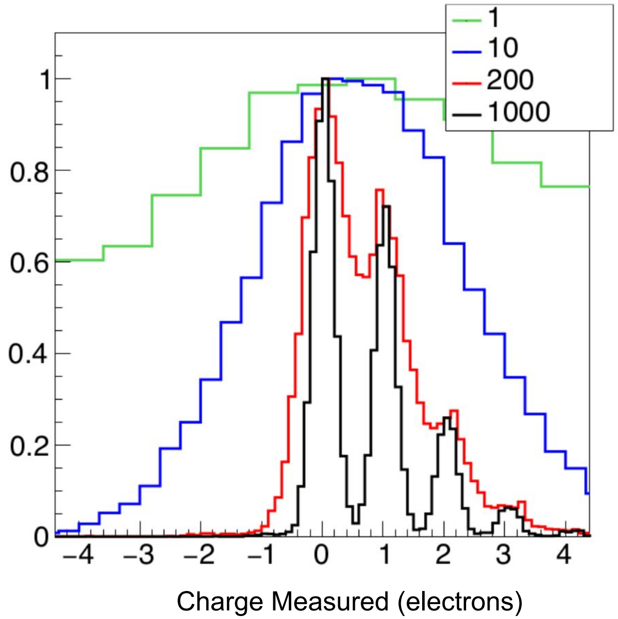
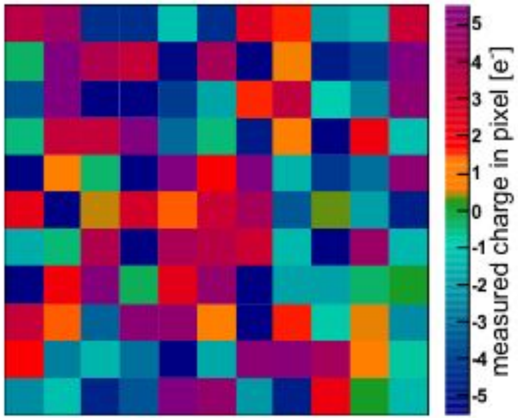


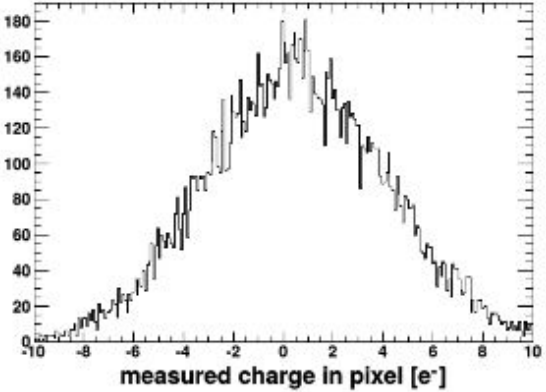


Skipper-CCD technology

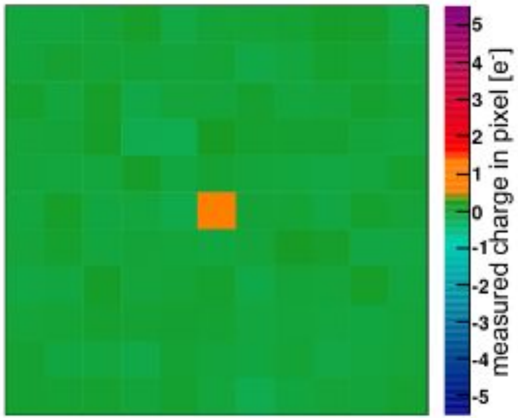
Standard CCD mode: charge in each pixel is measured once



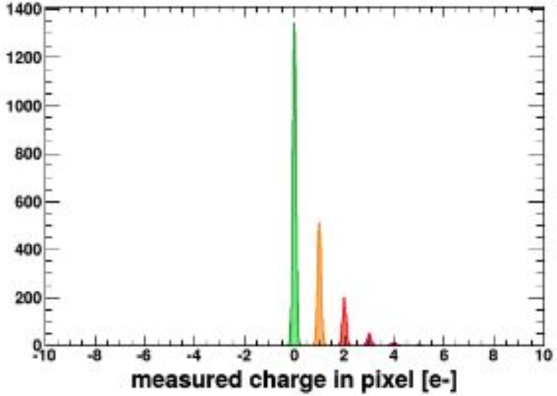
Readout-noise: 3.5 e RMS



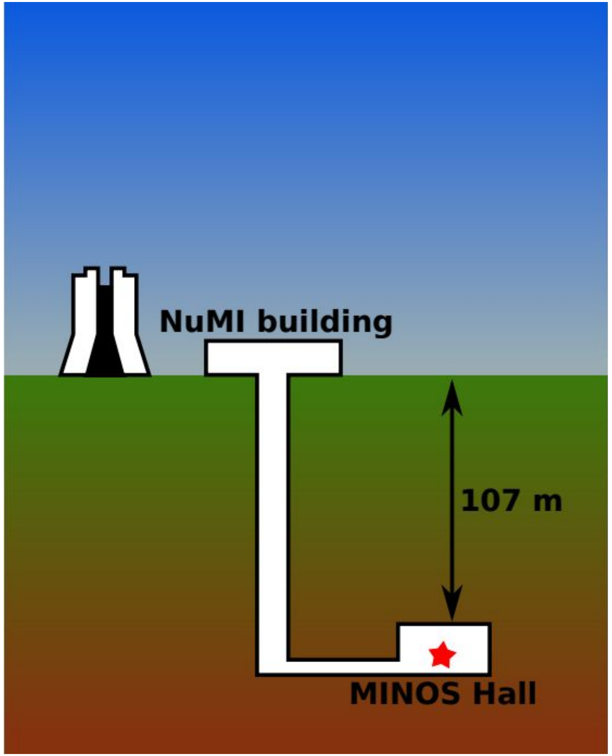
New Skipper CCD: charge in each pixel is measured multiple times



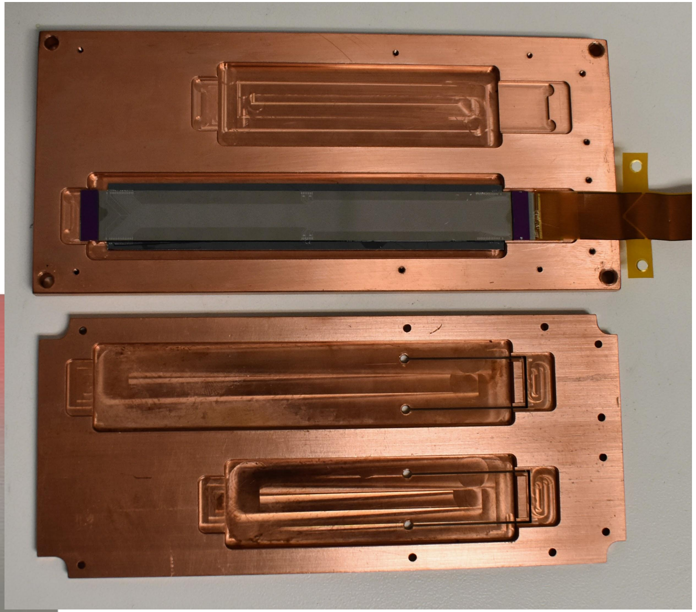
Readout-noise: 0.06 e RMS



SENSEI @ MINOS

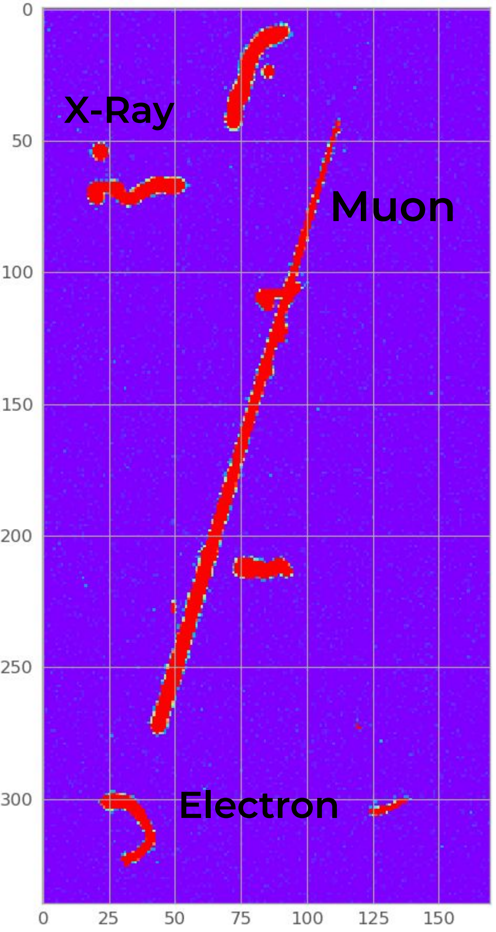


@ Fermilab



Copper +
2-3” lead +
107 m of rock

Event selection criteria



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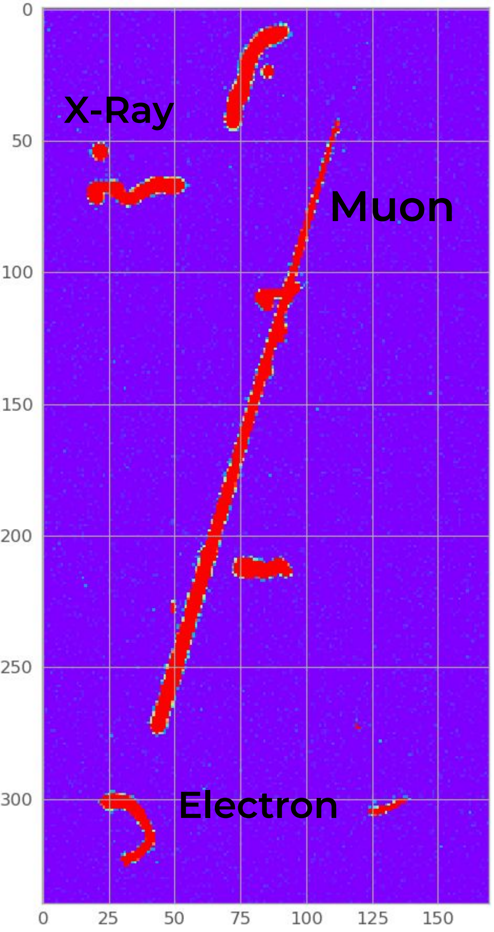

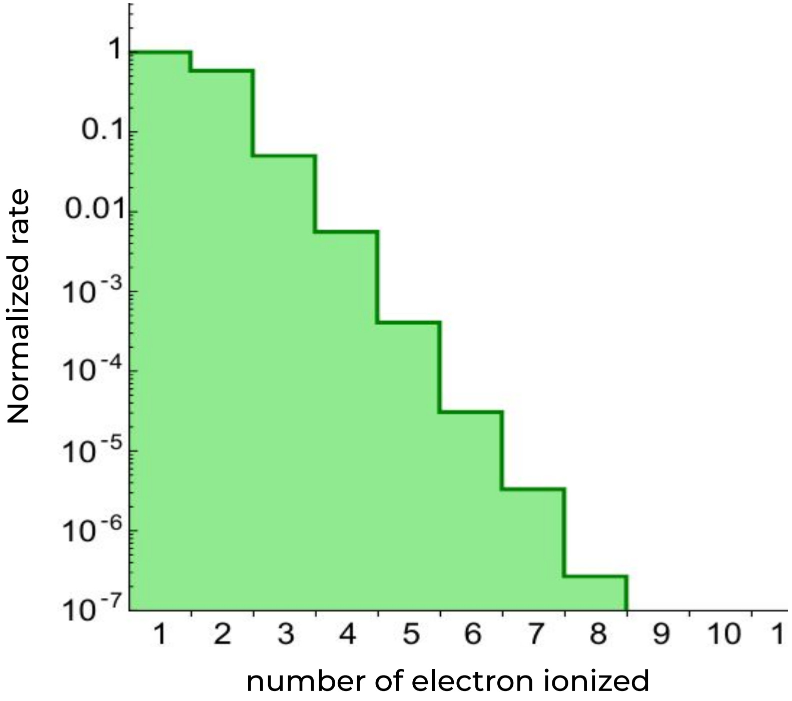

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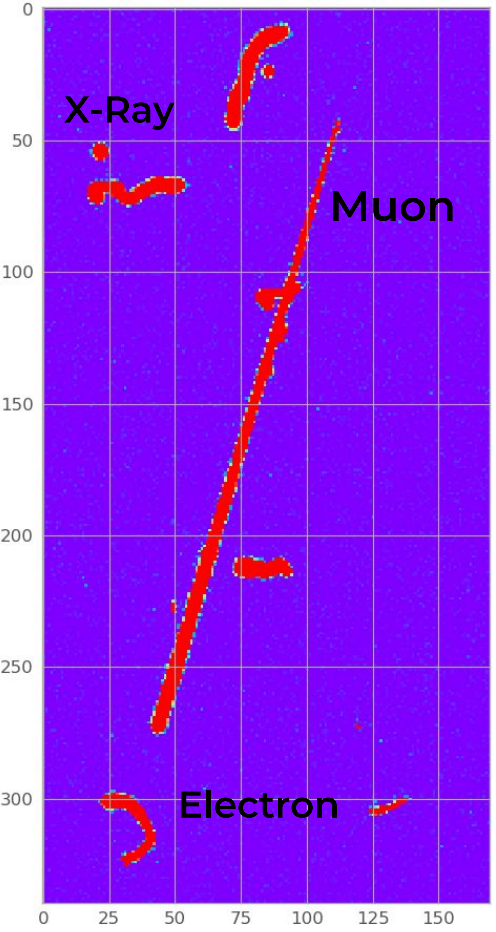
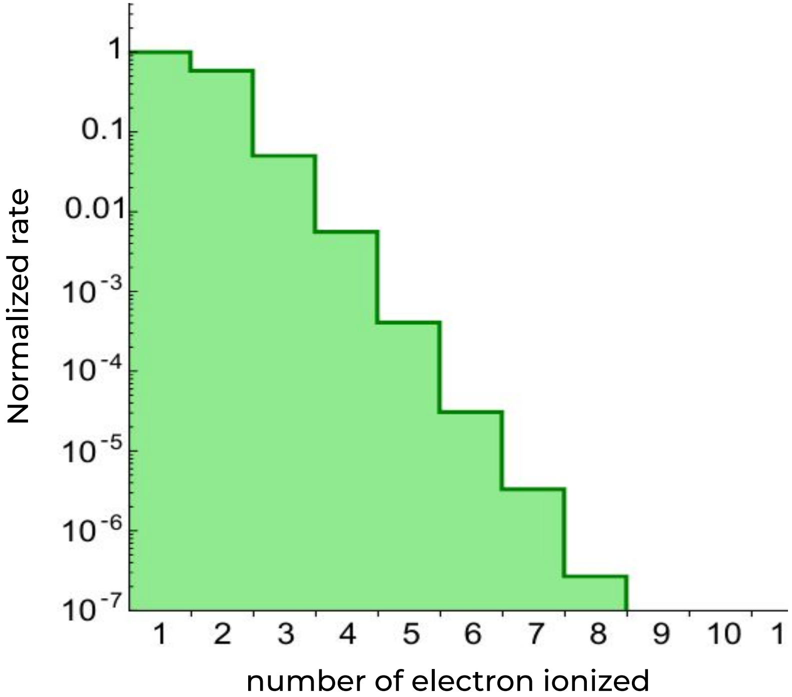
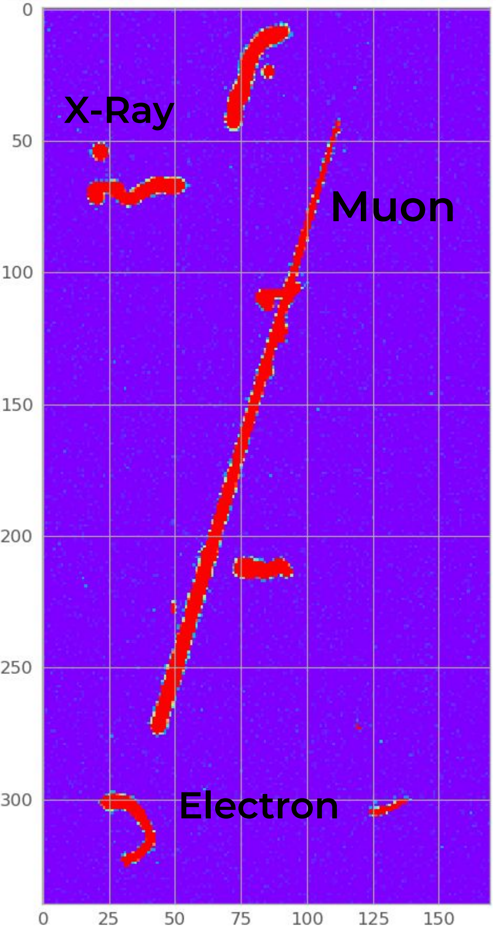
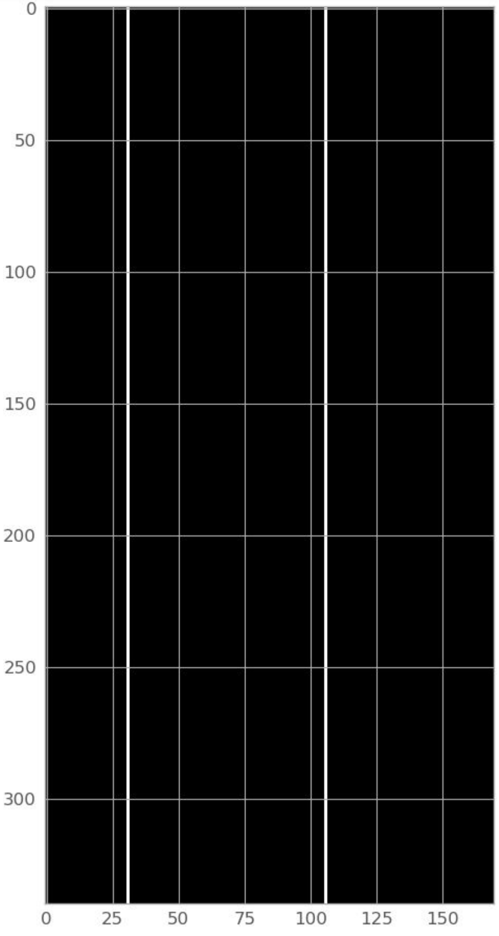




Mariano Cababie

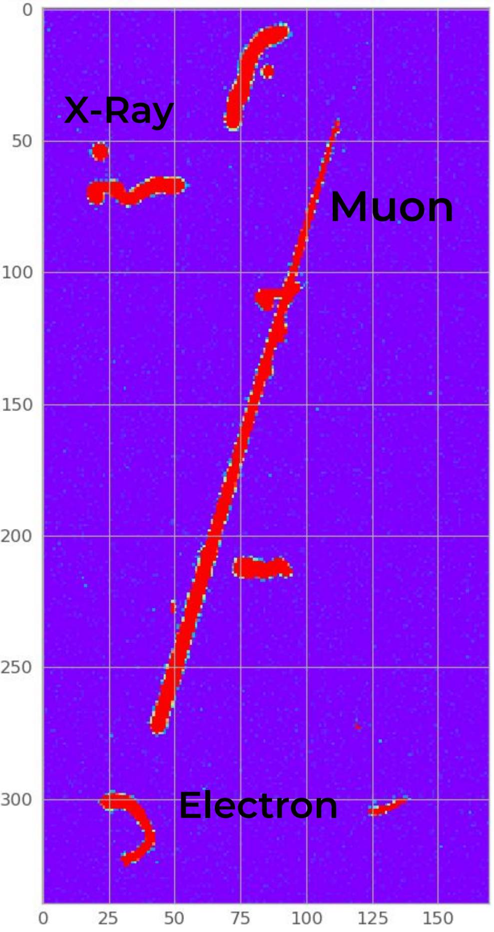
Event selection criteria

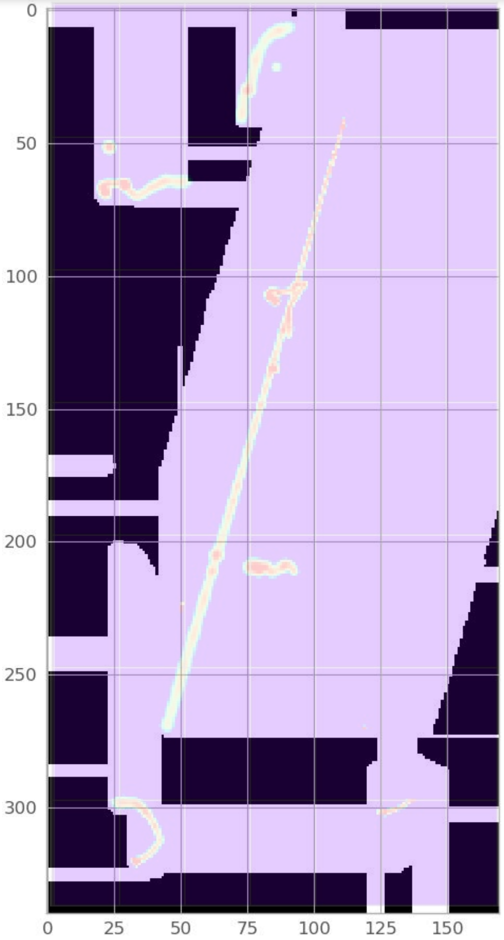




Hot pixels and hot columns

Event selection criteria

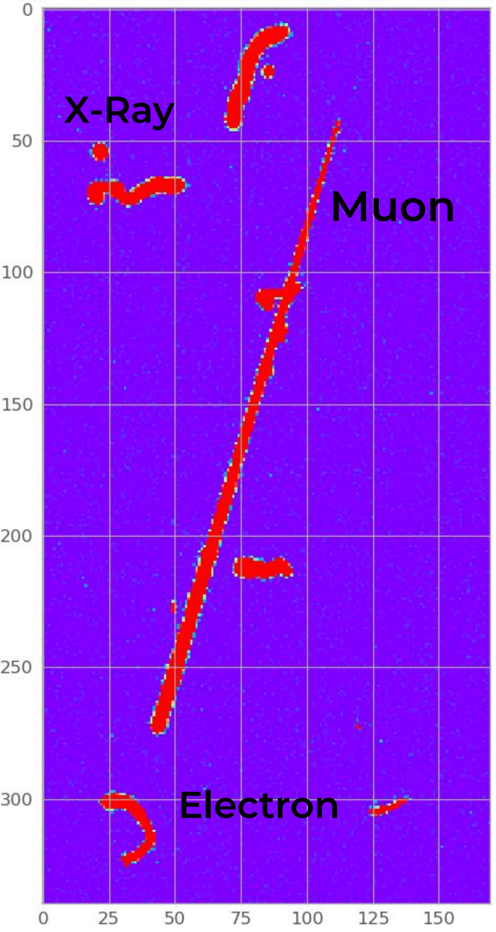


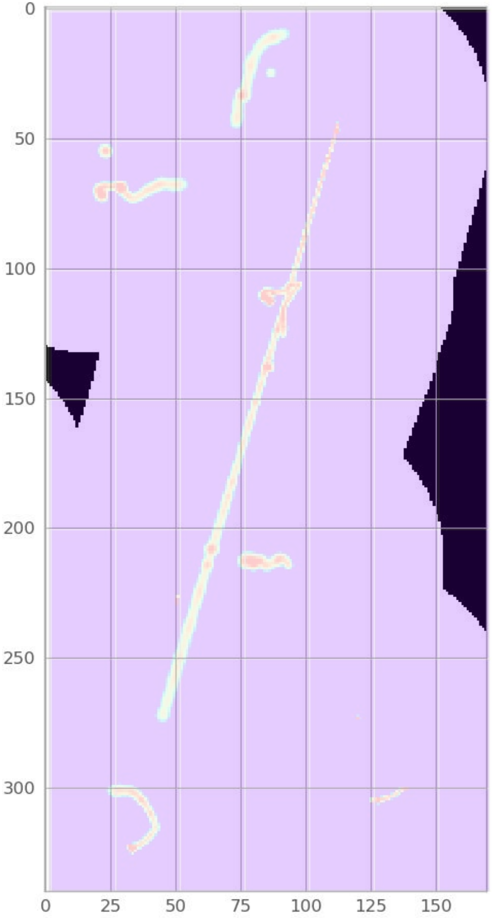


Hot pixels and hot columns

Bleeding

Event selection criteria



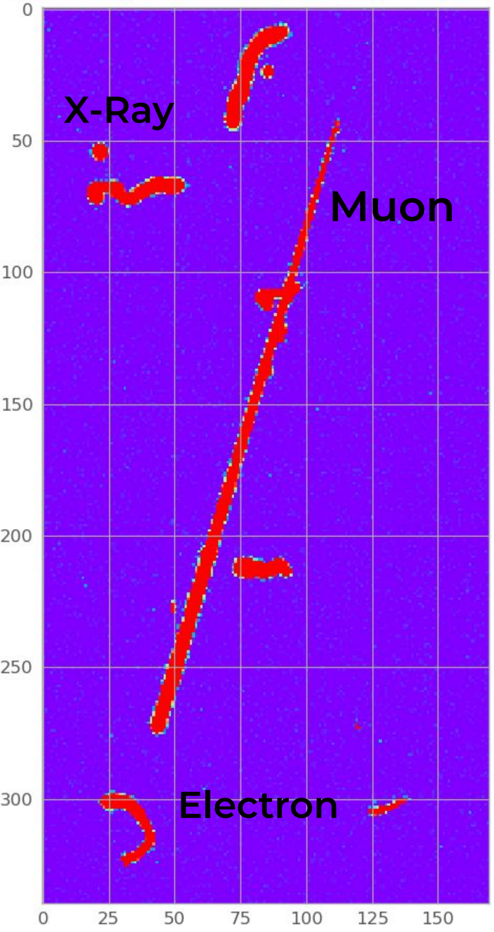


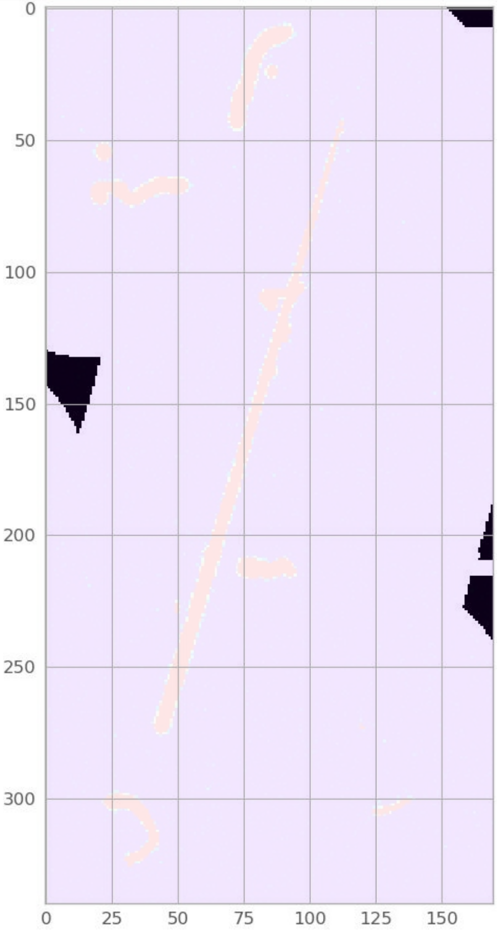
Hot pixels and hot columns

Bleeding

High energy halo

Event selection criteria





Hot pixels and hot columns

Bleeding

High energy halo

All criteria applied

Results

1312 events of 1e in 1.38 g-day

5 events of 2e in 2.09 g-day

0 events of 3e in 9.03 g-day

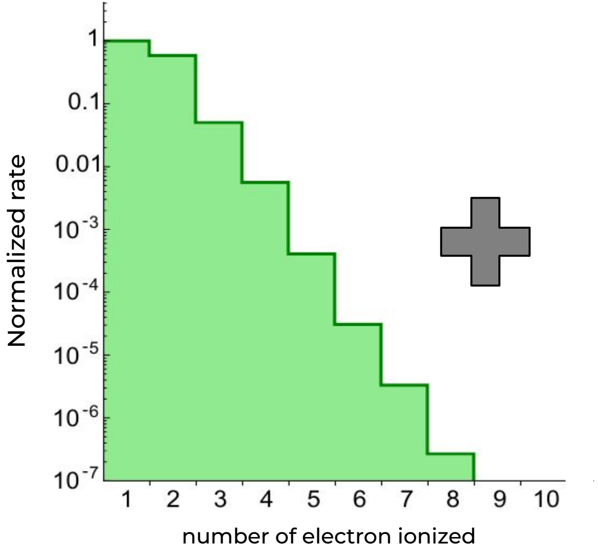
0 events of 4e in 9.10 g-day

Physical Review Letters 125, 171802 (2020)

Exclusion limits

Dark Matter exclusion limits

Expected theoretical rate



Journal of High Energy Physics 2016, 46 (2016).

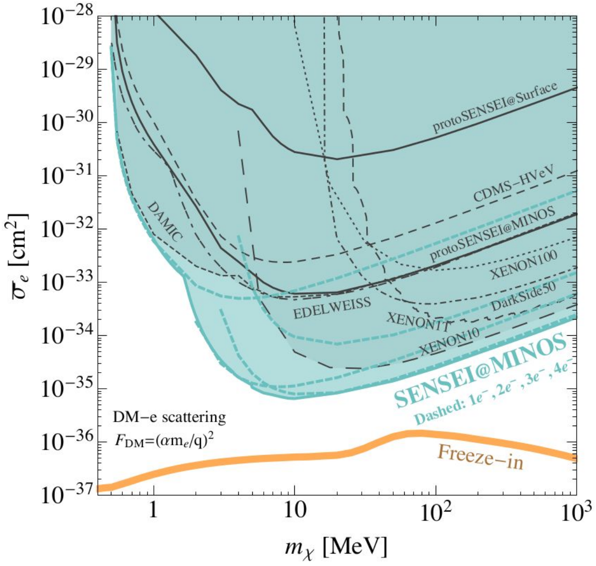
Experimental results

5 events of 2e in 2.09 g-day

0 events of 3e in 9.03 g-day

0 events of 4e in 9.10 g-day

Exclusion limits



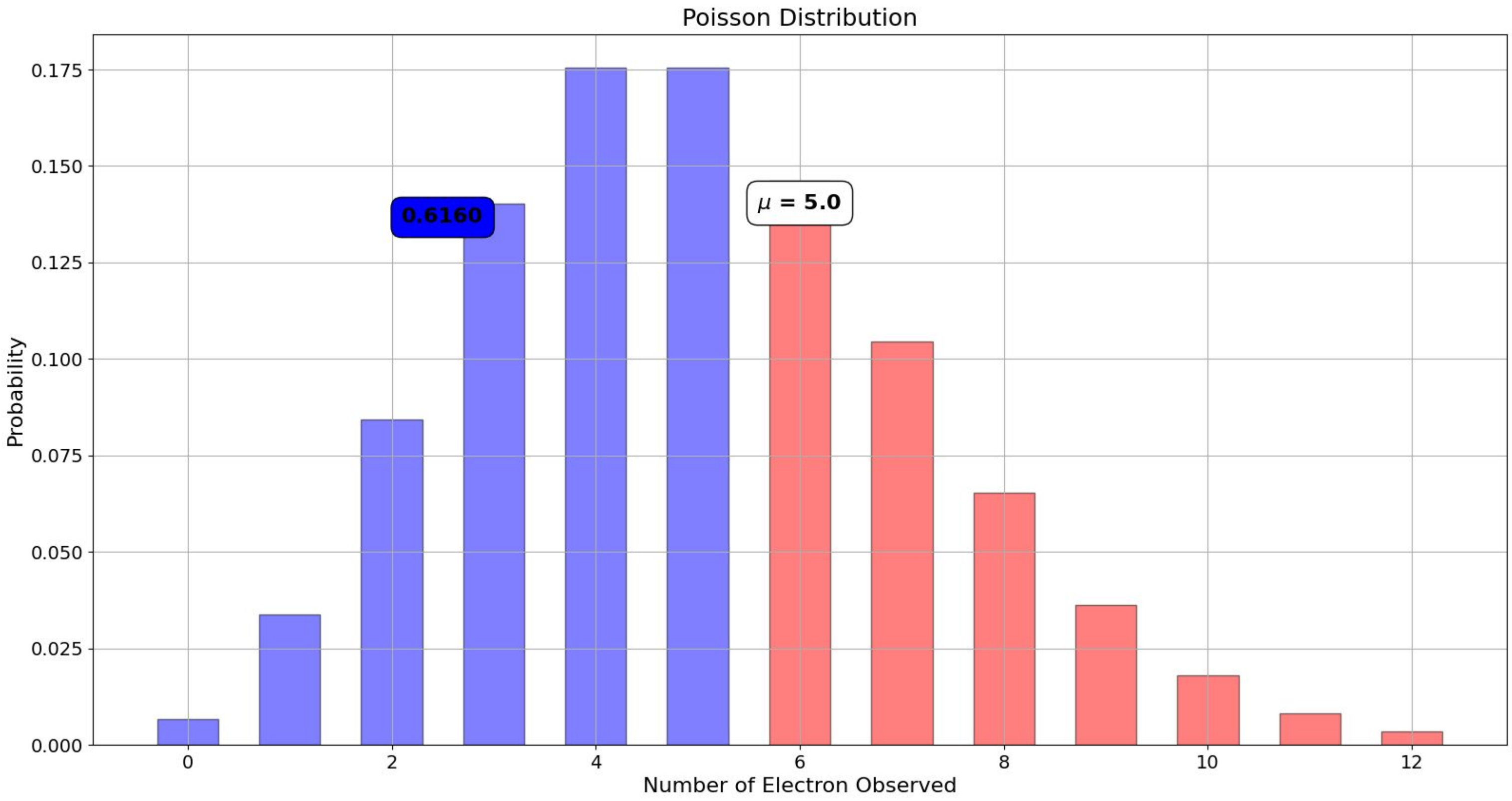
Physical Review Letters 125, 171802 (2020).

Exclusion limits

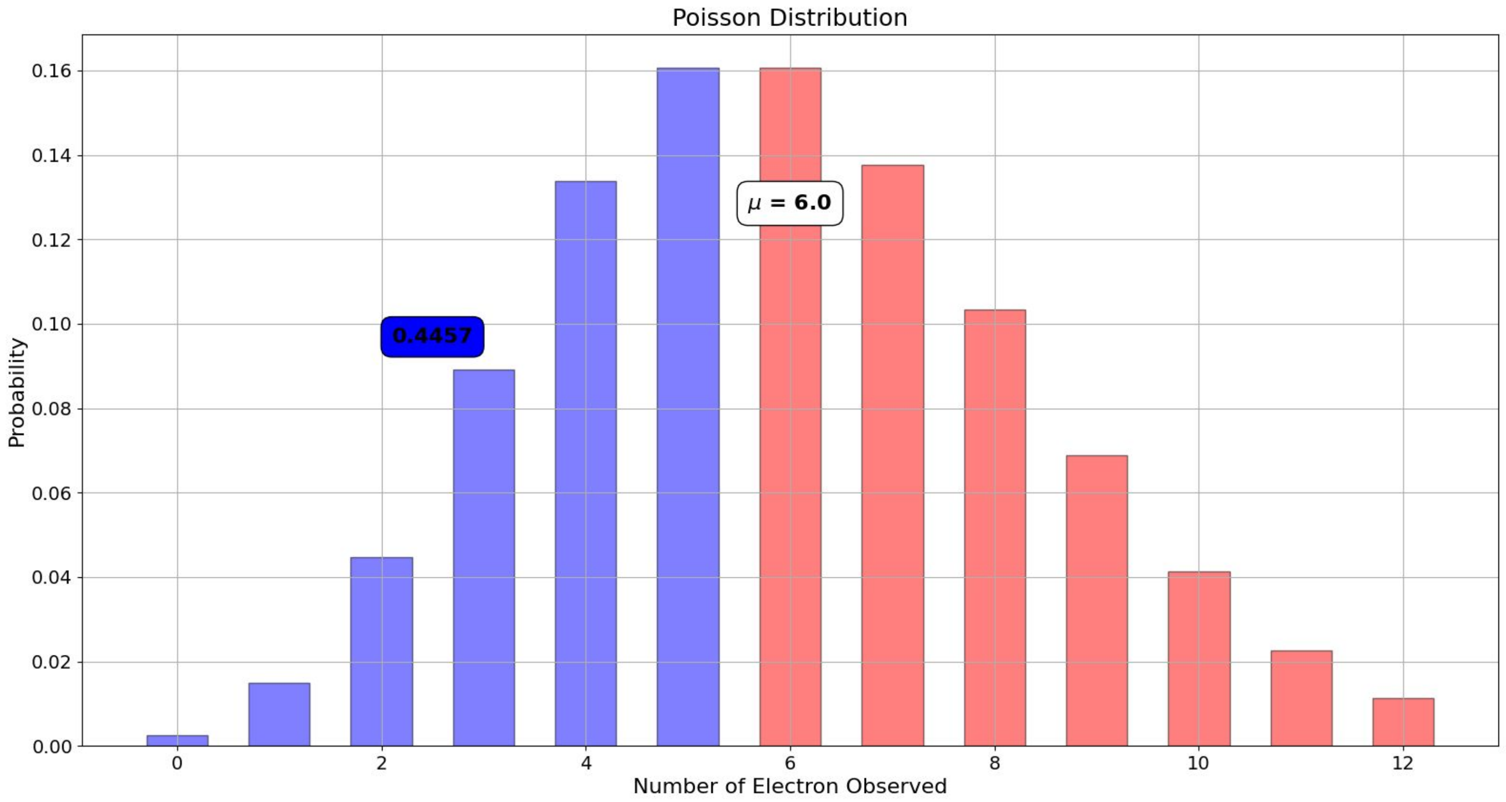
First, we use the frequentist prescription to establish the 90% confidence level upper limit for the number of observed events in each channel

	2e	**3e**	**4e**
Observed events	5	0	0
90 % C.L. Upper limit			
Effective exposure [g-day]	2.09	9.03	9.10
90 % C.L. [g-day]$^{-1}$			

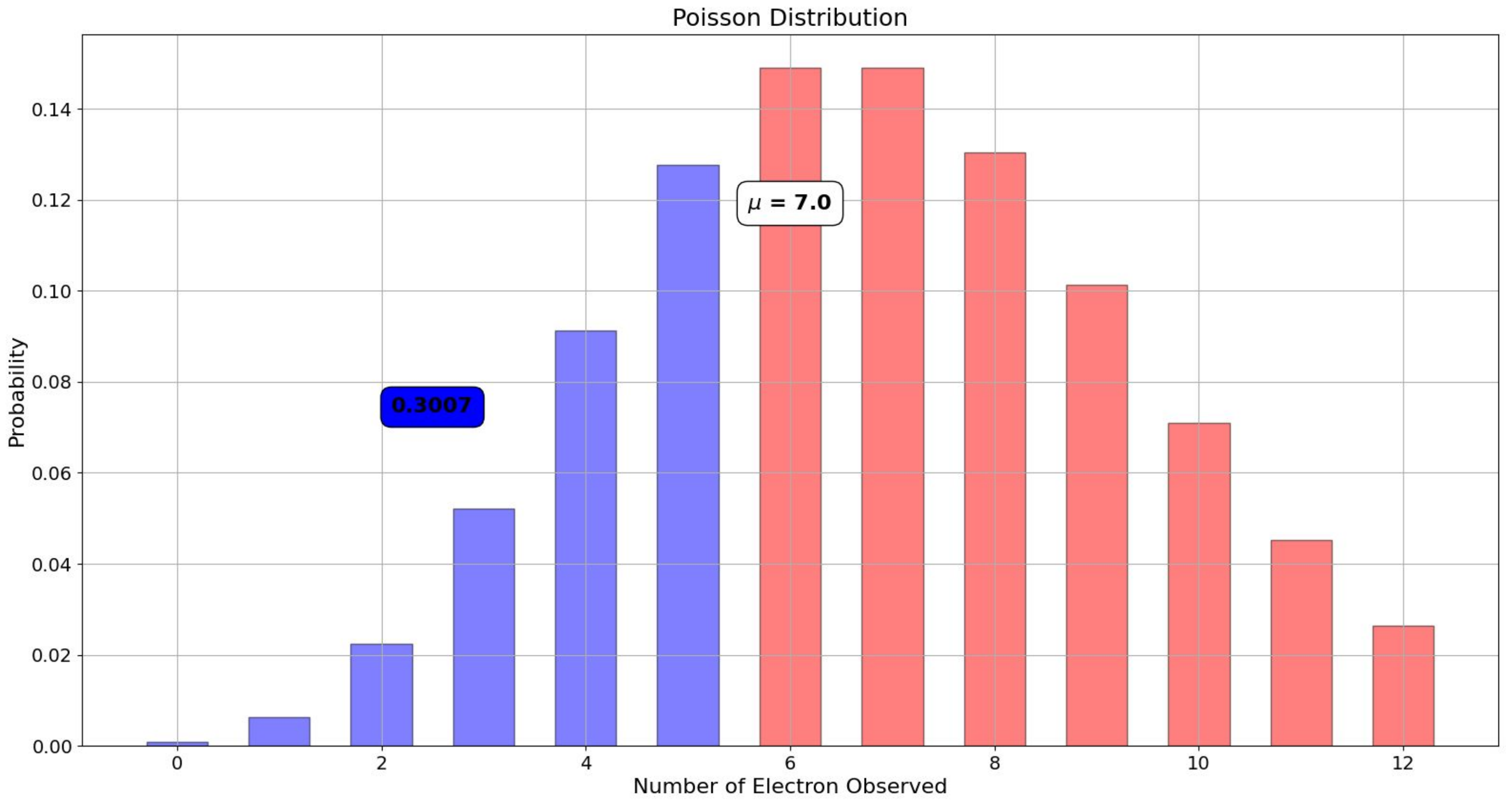
Exclusion limits



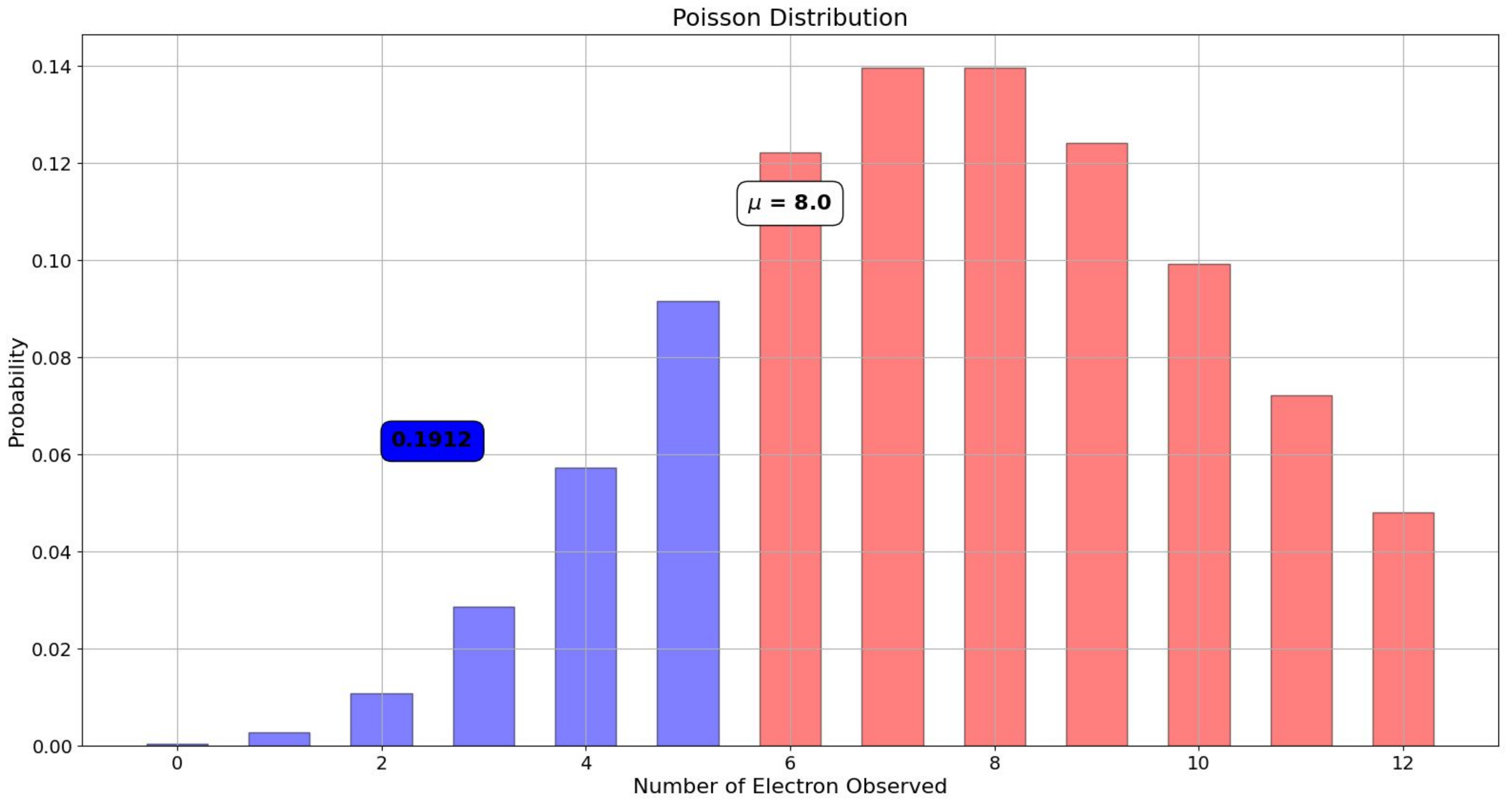
Exclusion limits



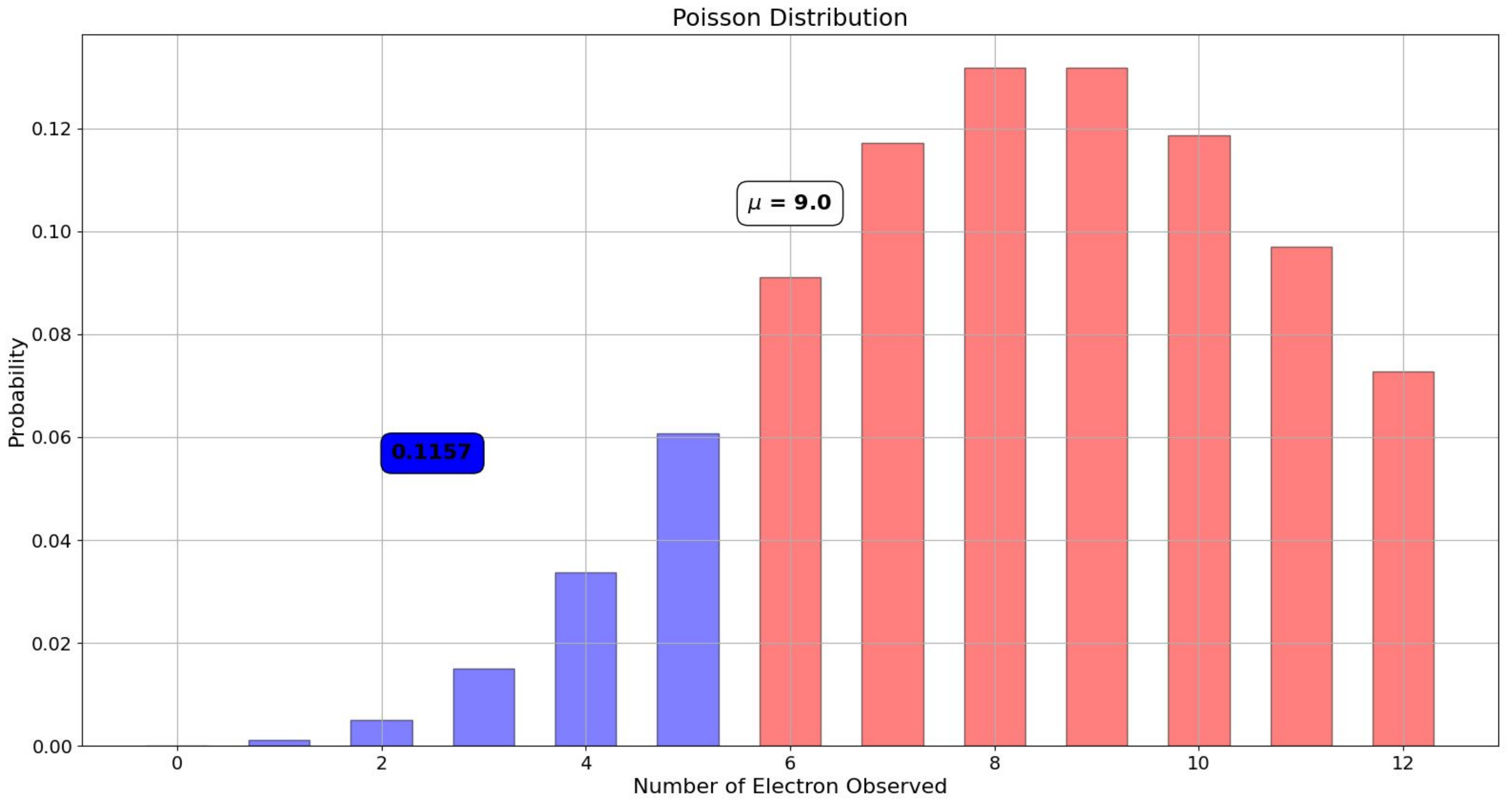
Exclusion limits



Exclusion limits



Exclusion limits



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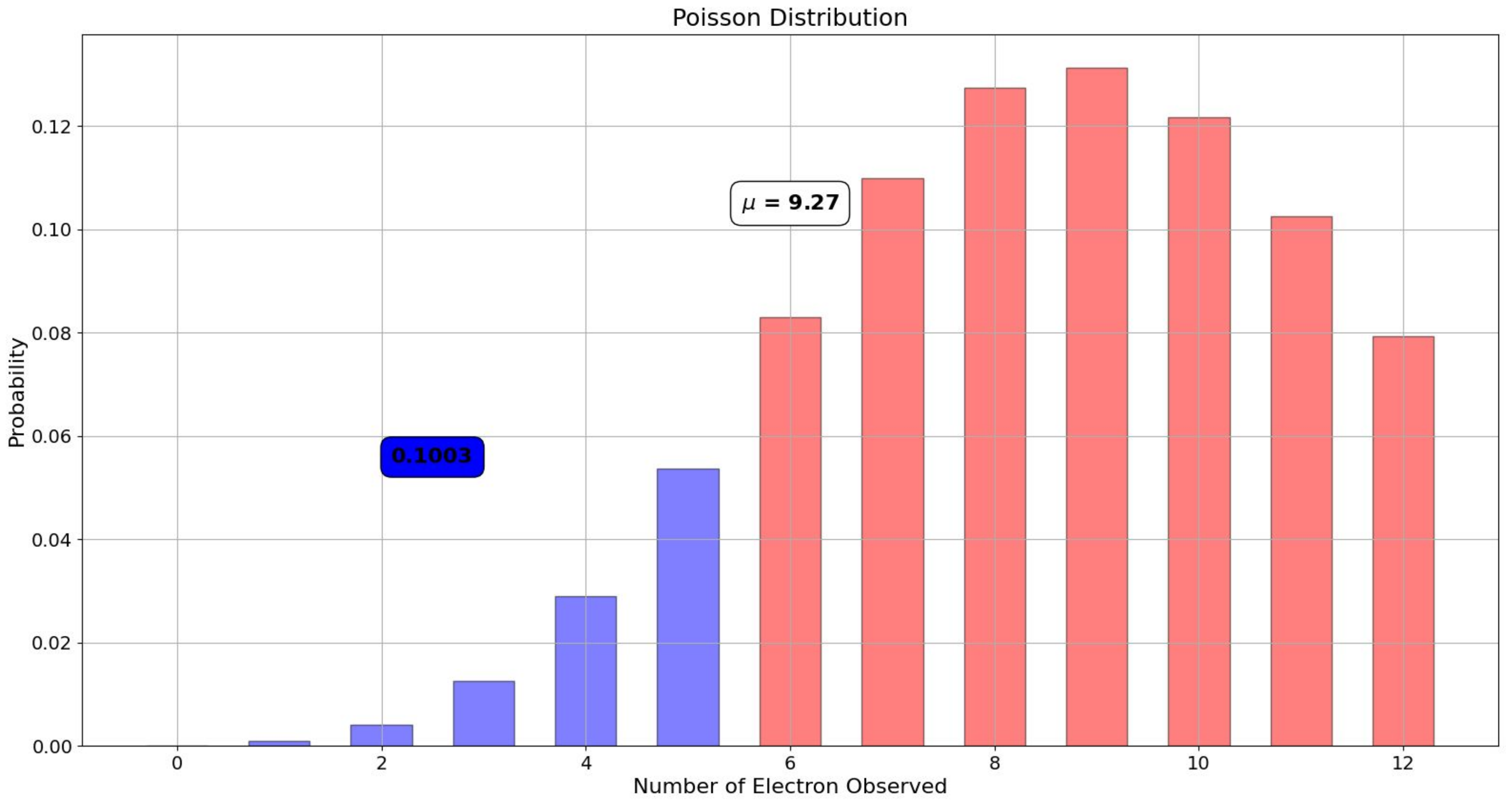
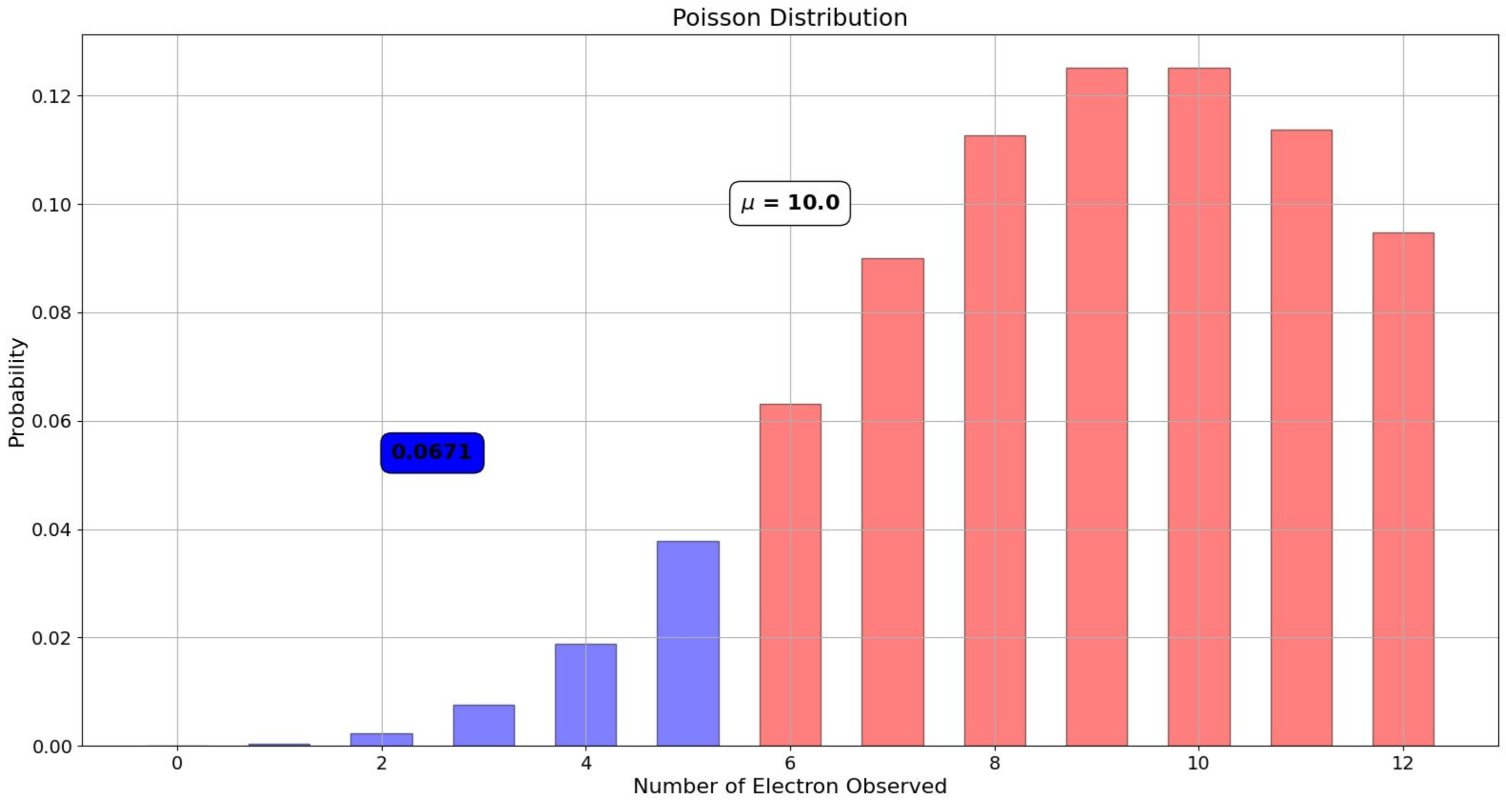
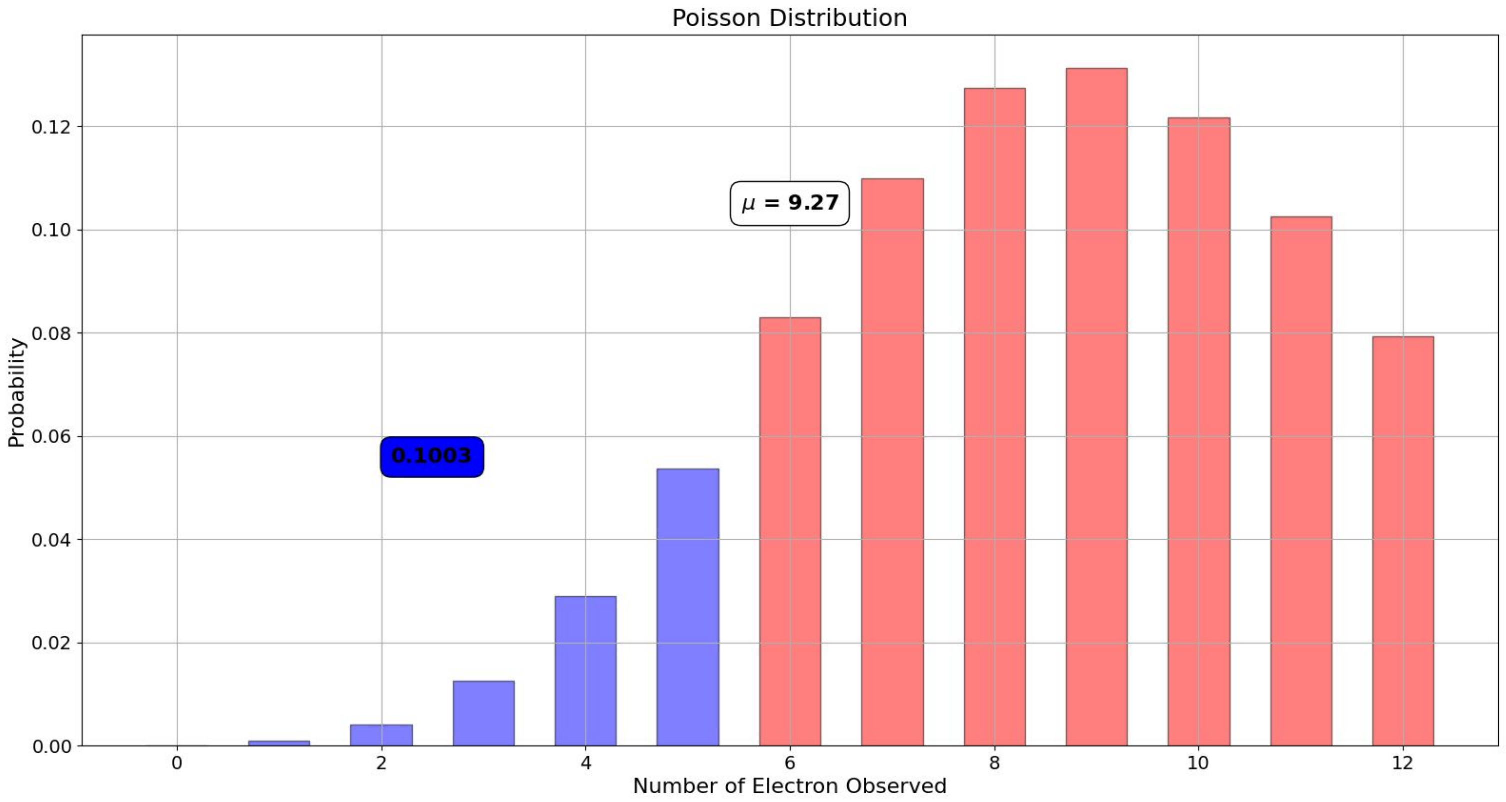


Exclusion limits



Exclusion limits

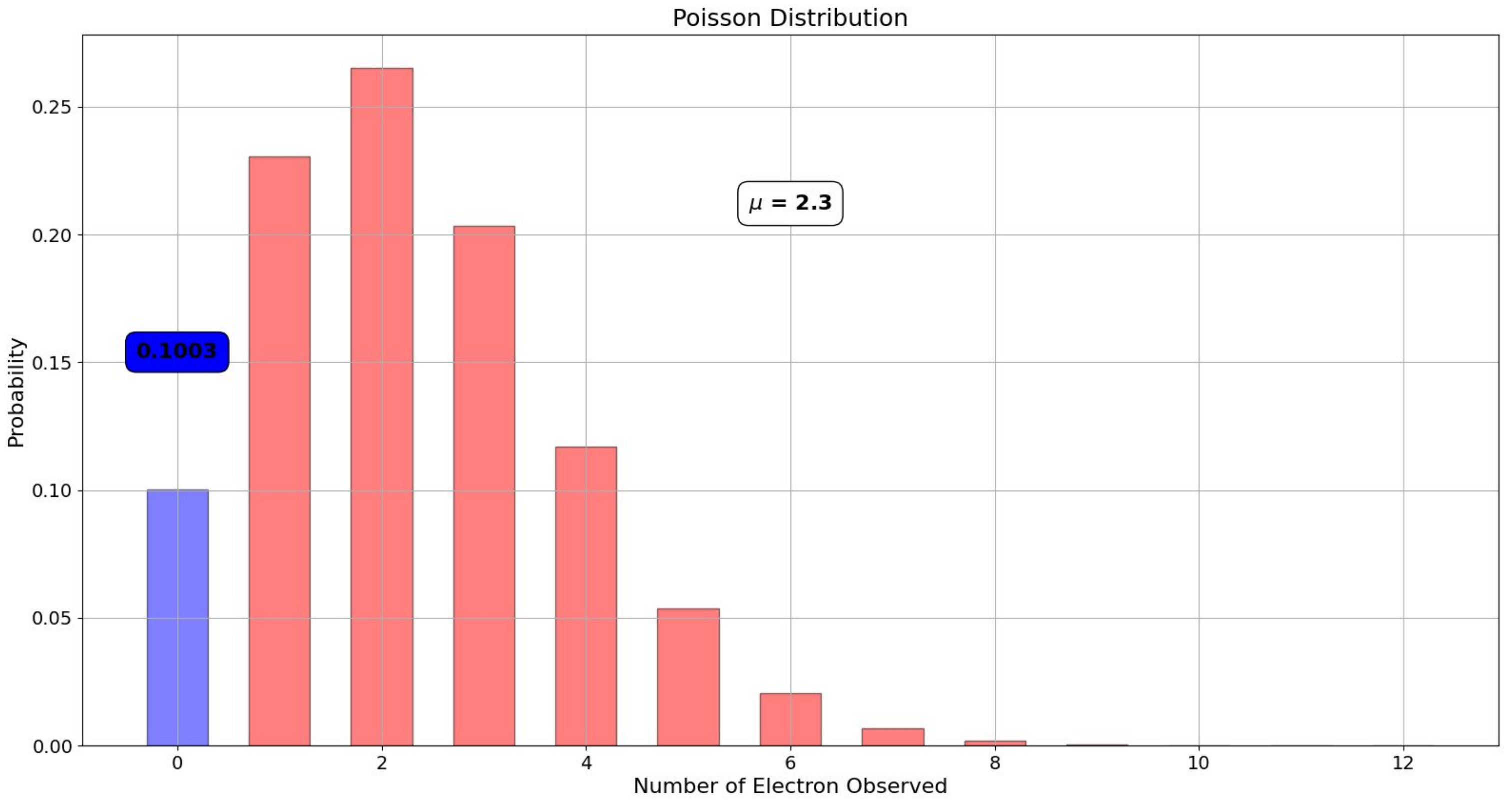


Exclusion limits

First, we use the frequentist prescription to establish the 90% upper limit for the number of observed events in each channel

	2e	**3e**	**4e**
Observed events	5	0	0
90 % C.L. Upper limit	**9.27**		
Effective exposure [g-day]	2.09	9.03	9.10
90 % C.L. [g-day]$^{-1}$	**4.449**		

Exclusion limits



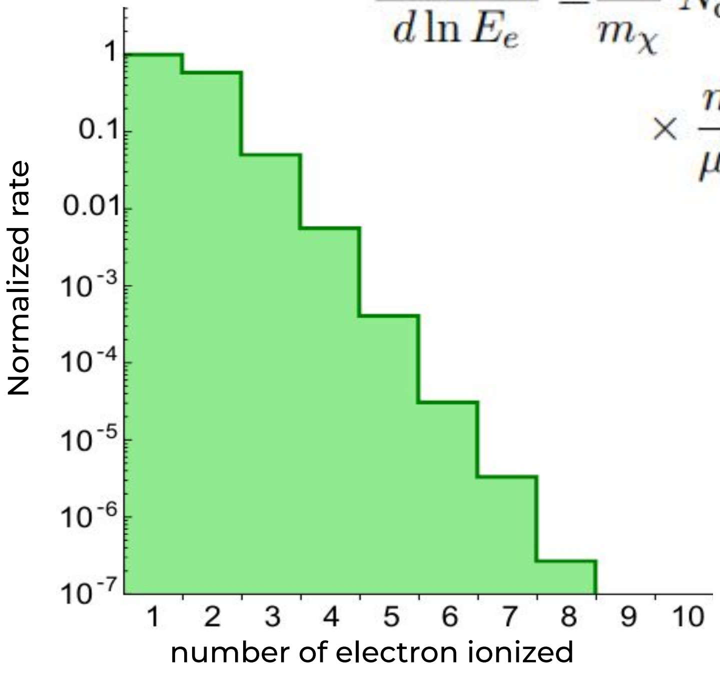
Exclusion limits

First, we use the frequentist prescription to establish the 90% upper limit for the number of observed events in each channel

	2e	**3e**	**4e**
Observed events	5	0	0
90 % C.L. Upper limit	**9.27**	**2.30**	**2.30**
Effective exposure [g-day]	2.09	9.03	9.10
90 % C.L. [g-day]$^{-1}$	**4.449**	**0.255**	**0.253**

Exclusion limits

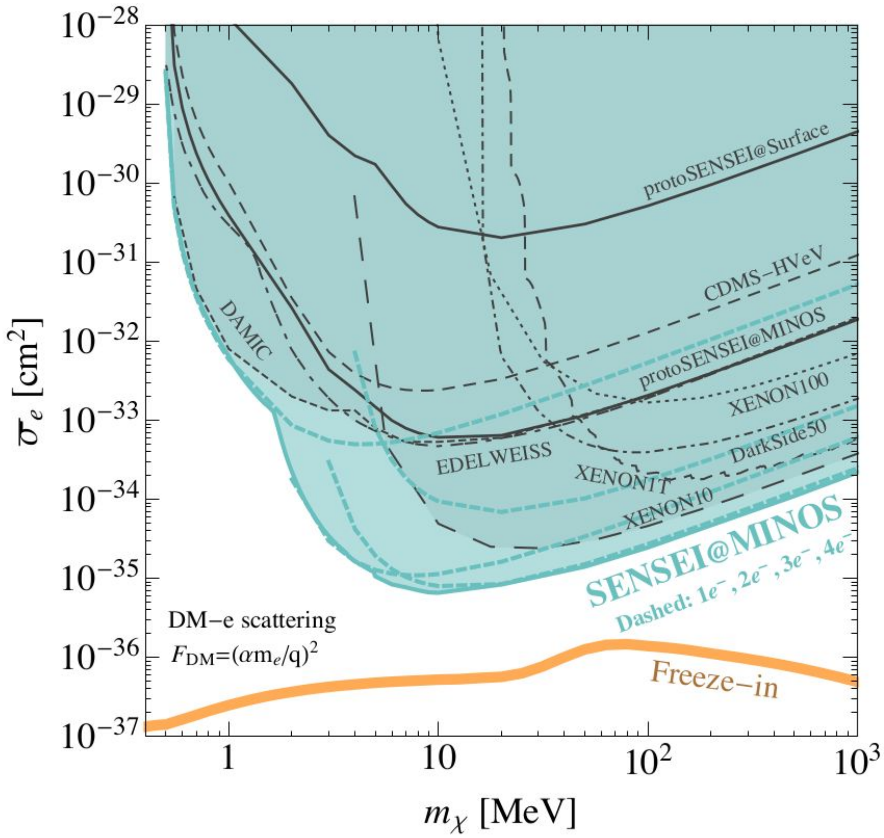
$$\frac{dR_{\text{crystal}}}{d\ln E_e} = \frac{\rho_\chi}{m_\chi} N_{\text{cell}}\, \overline{\sigma}_e\, \alpha \times \frac{m_e^2}{\mu_{\chi e}^2} \int d\ln q \left(\frac{E_e}{q} \eta(v_{\text{min}}(q, E_e)) \right) F_{\text{DM}}(q)^2 \left| f_{\text{crystal}}(q, E_e) \right|^2$$



Journal of High Energy Physics 2016, 46 (2016).

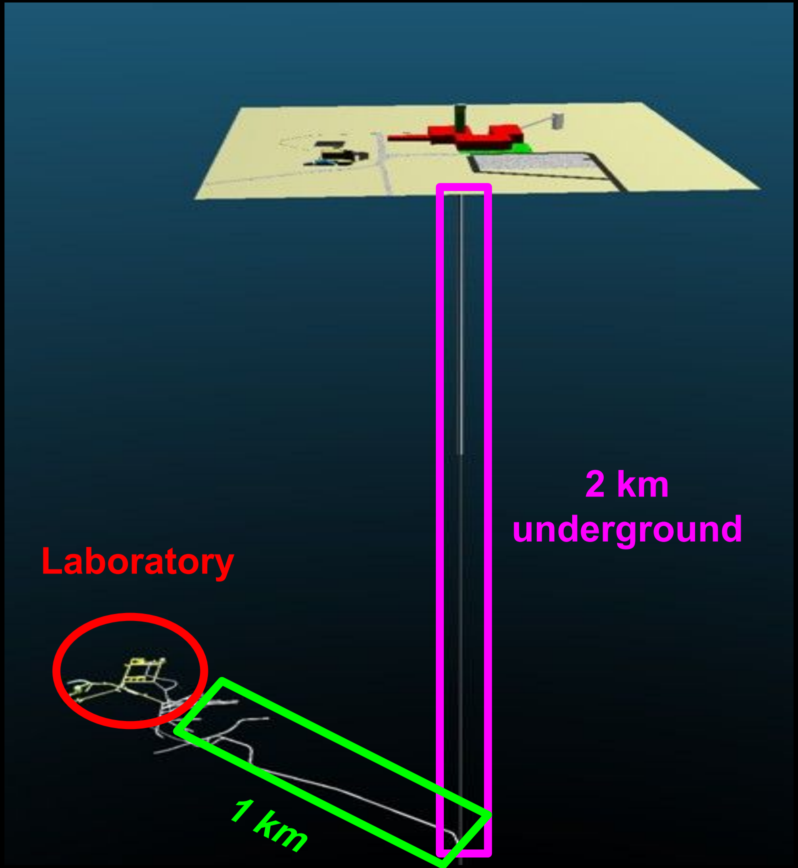
- For a given DM mass, we make the conservative assumption that all of the events observed are signal.
- Then, we calculate the cross-section, σ_e such that $N_{obs,90\%CL} = N_{signal}$.
- We repeat the procedure for each DM mass.

Dark Matter Exclusion limits

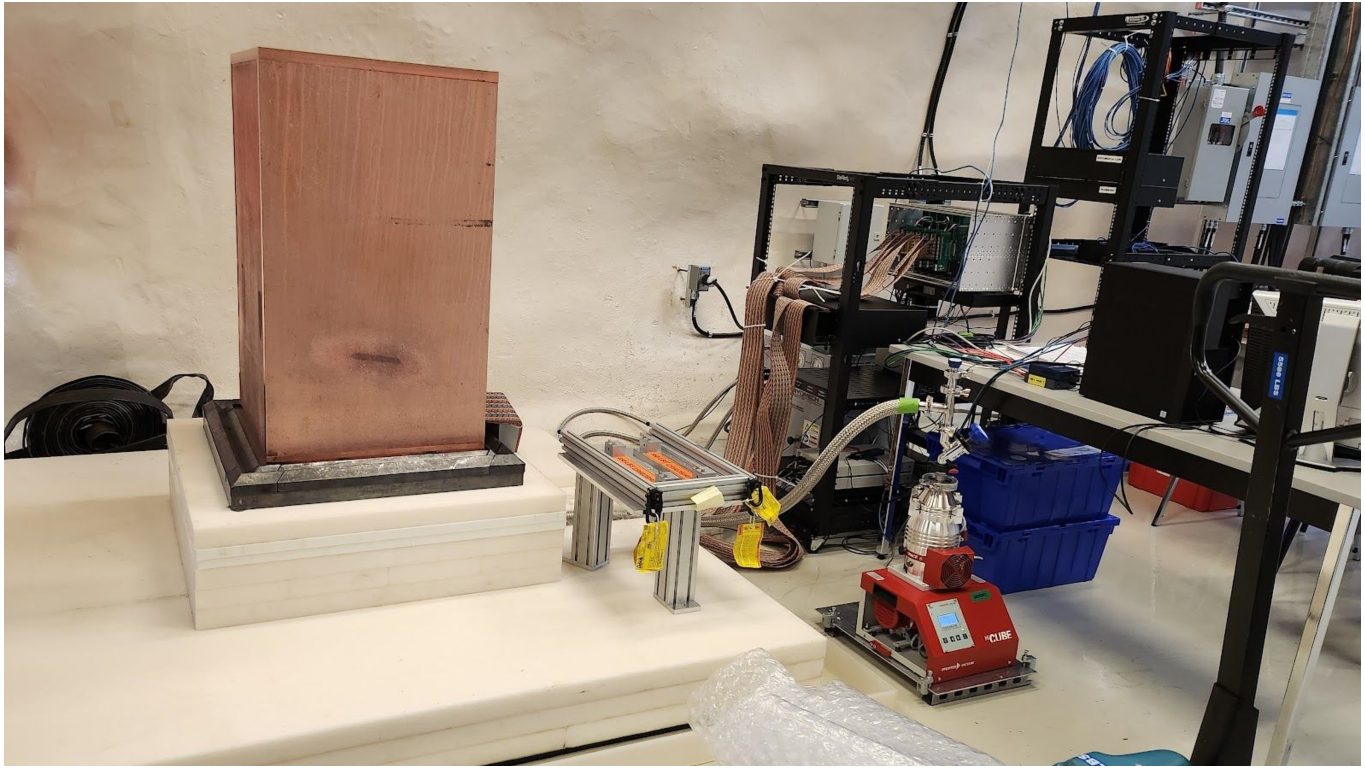


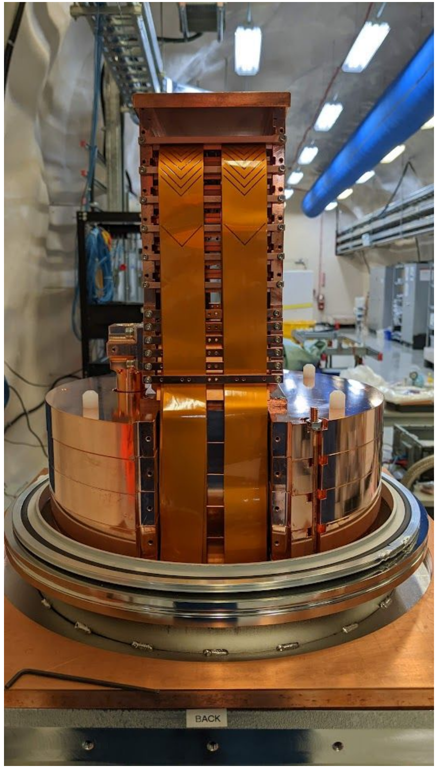
Physical Review Letters 125, 171802 (2020)

SENSEI @ SNOLAB



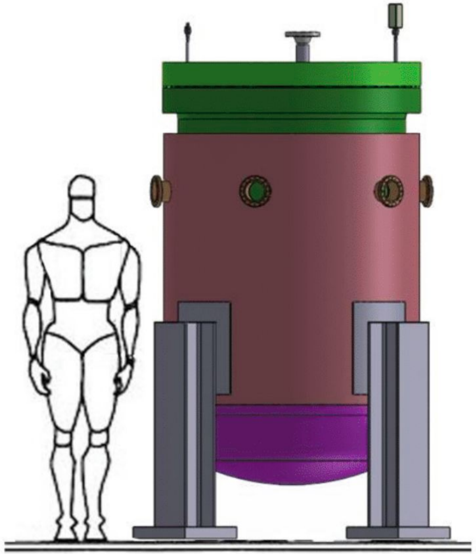
SENSEI @ SNOLAB



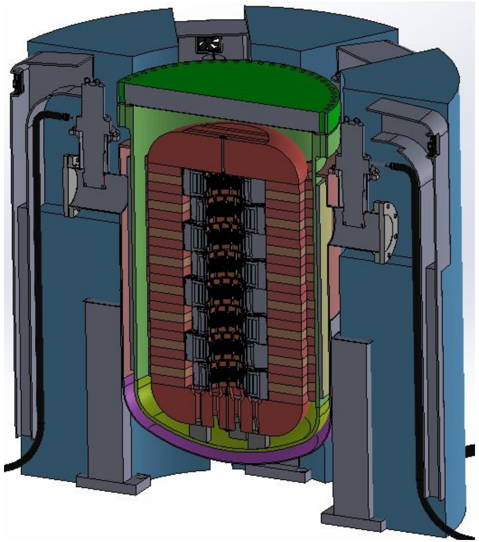


SENSEI already has 65 gr (26 detectors) 2000 mts underground

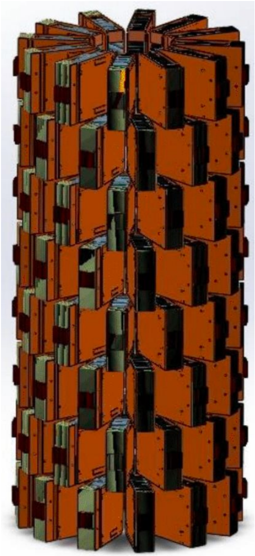
Oscura: 10 kg Skipper-CCD experiment



10 kg vessel



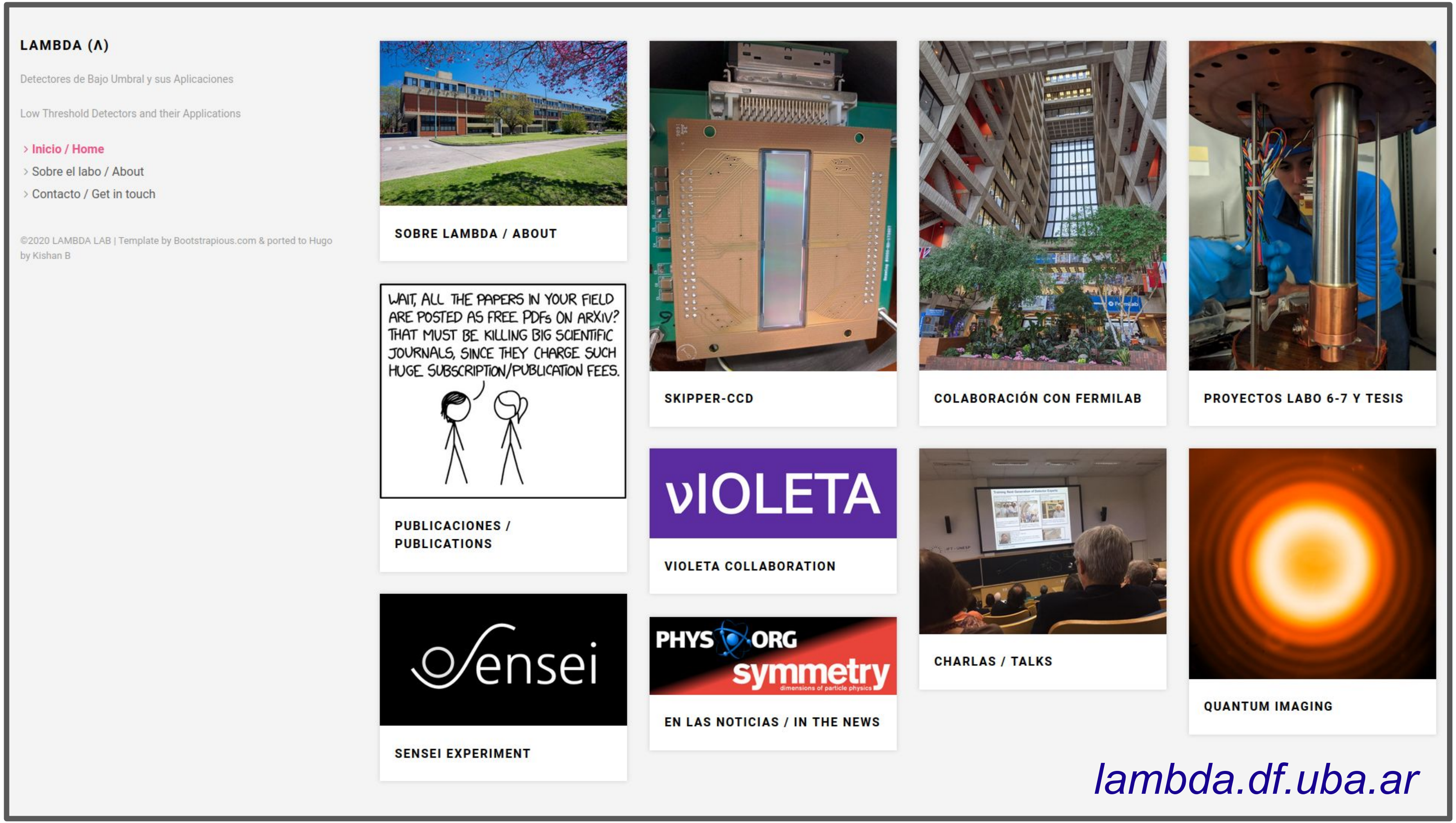
10 kg vessel



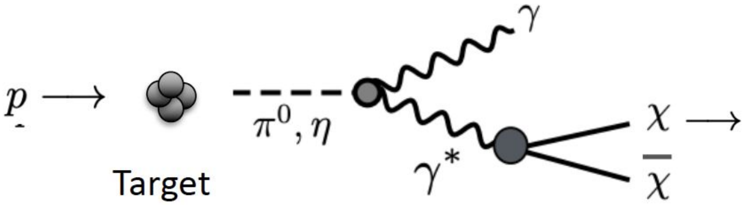
Detector payload

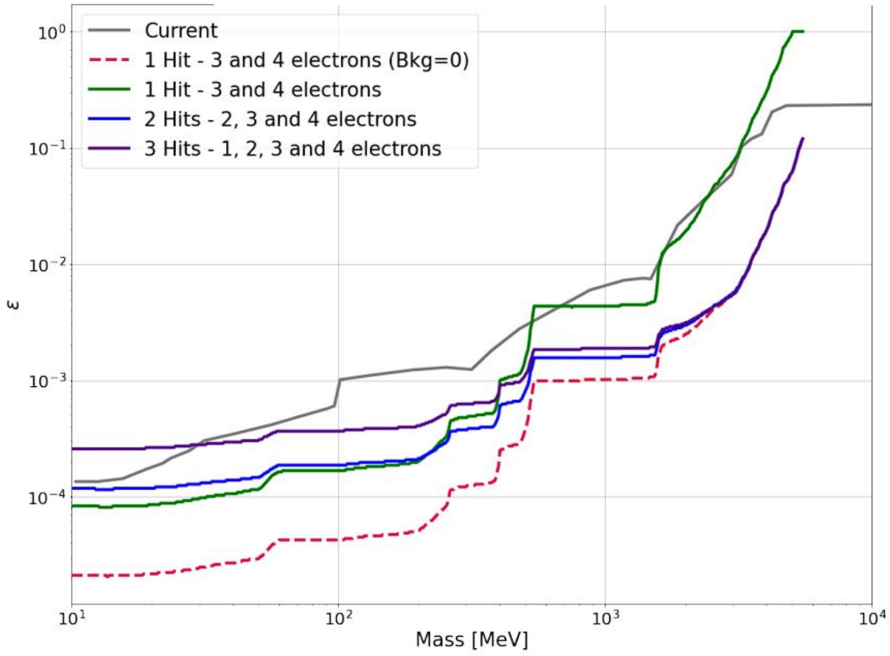
Oscura review paper: arXiv:2202.10518

Laboratorio Argentino de Mediciones de Bajo umbral de Detección y sus Aplicaciones



Oscura: Early Science: milliCharged particles search

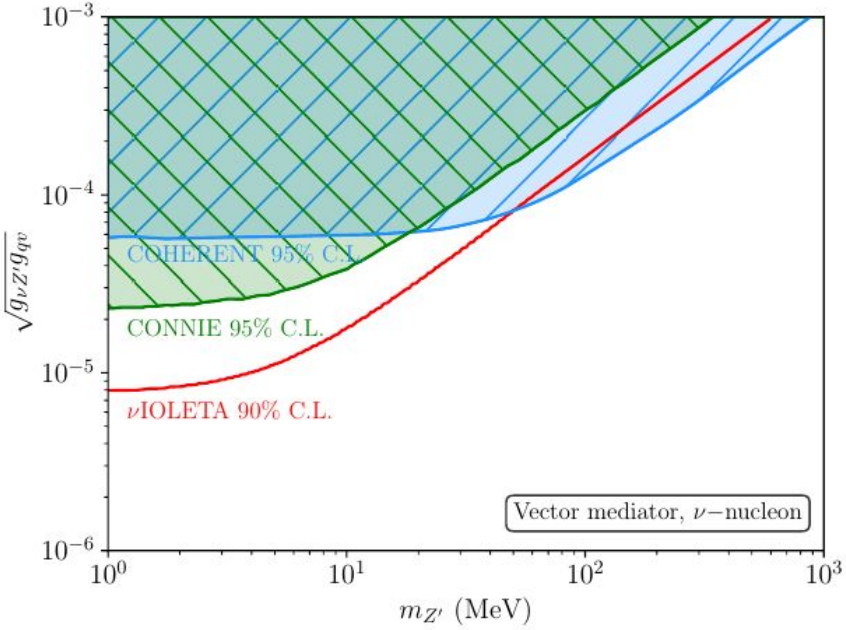




Santiago Perez

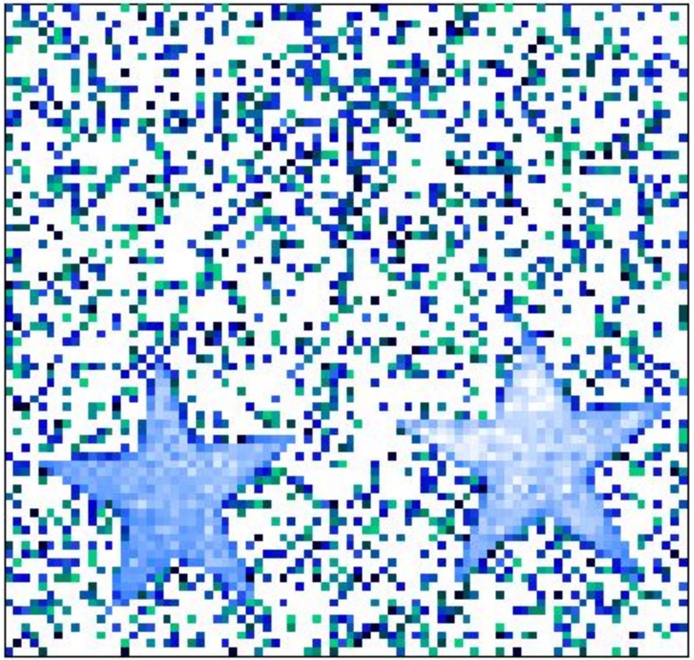
arXiv:2304.08625

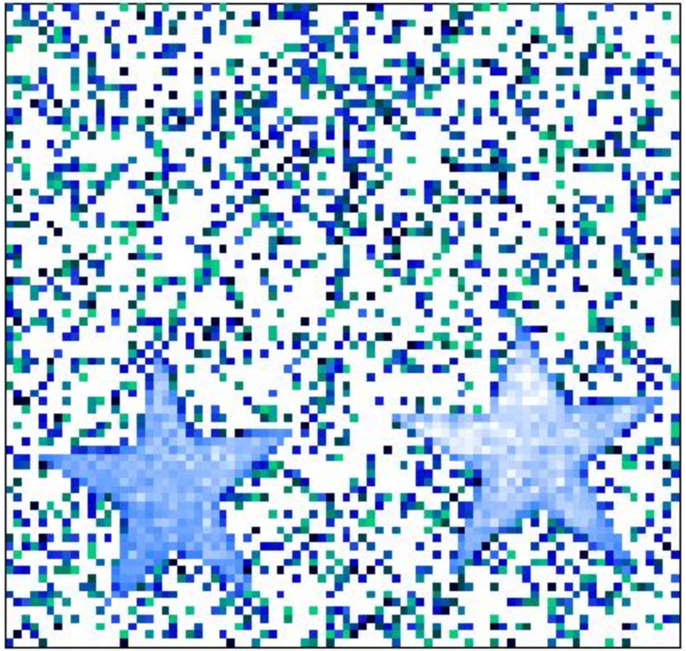
BSM physics at a nuclear reactor in Argentina with Skipper-CCD



Journal of High Energy Physics. 2022, 127 (2022).

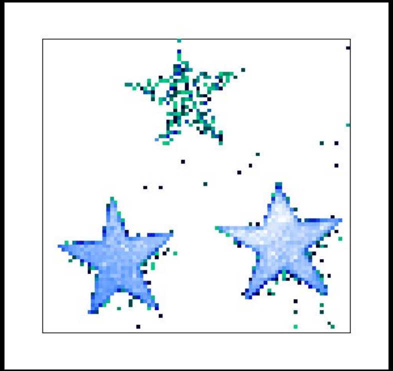
Single photon infrared images taken @ LAMBDA, UBA





Phys. Rev. Applied **19**, 064044 – Published 14 June 2023

We've already got the third little star ...



Now, we go for
the Dark Matter …