A short story about a dark matter sensor: the Skipper CCD

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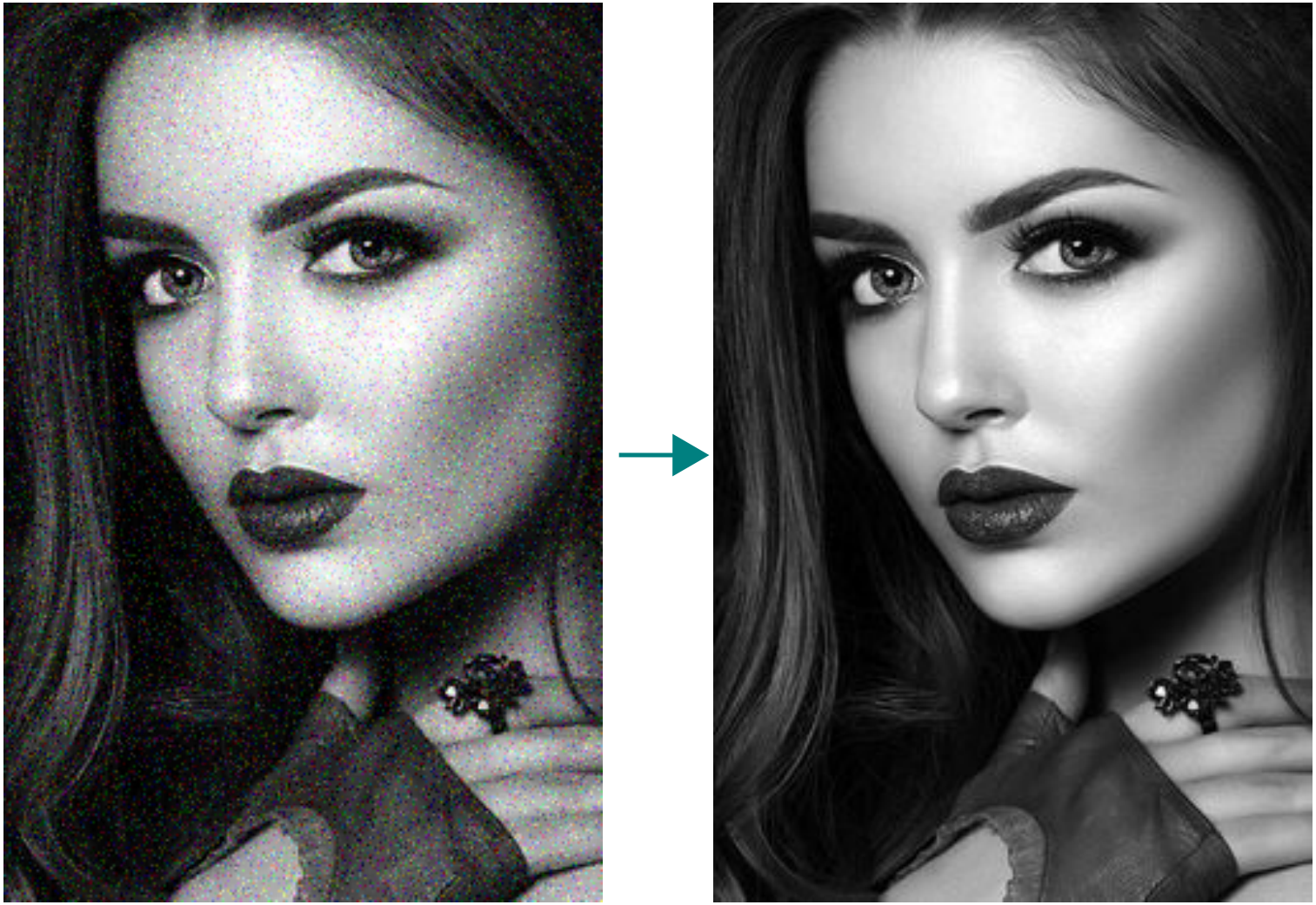
2010

Strong R&D program @ FNAL for the Skipper CCD

- Good synergy with FNAL-LBNL (J. Estrada - S. Holland).
- SENSEI LDRD Collaboration (2015, J. Tiffenberg).
- approx. 8 years on the R&D of the Skipper CCD
- Idea proposed in 1990 by Janesick et al. (doi:10.1117/12.19452)

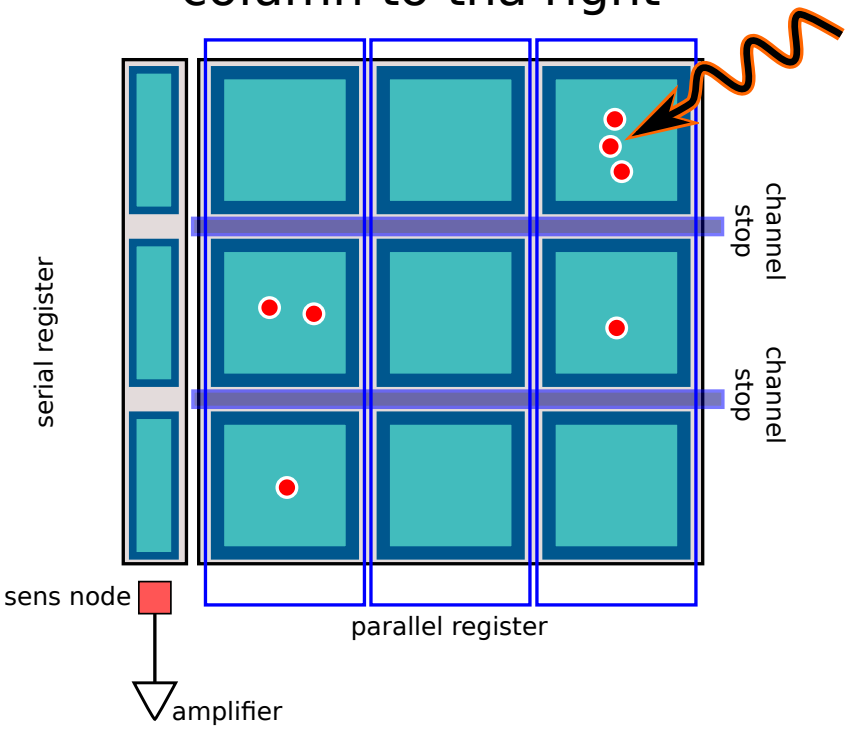
Cool stuff you can do with the Skipper CCD



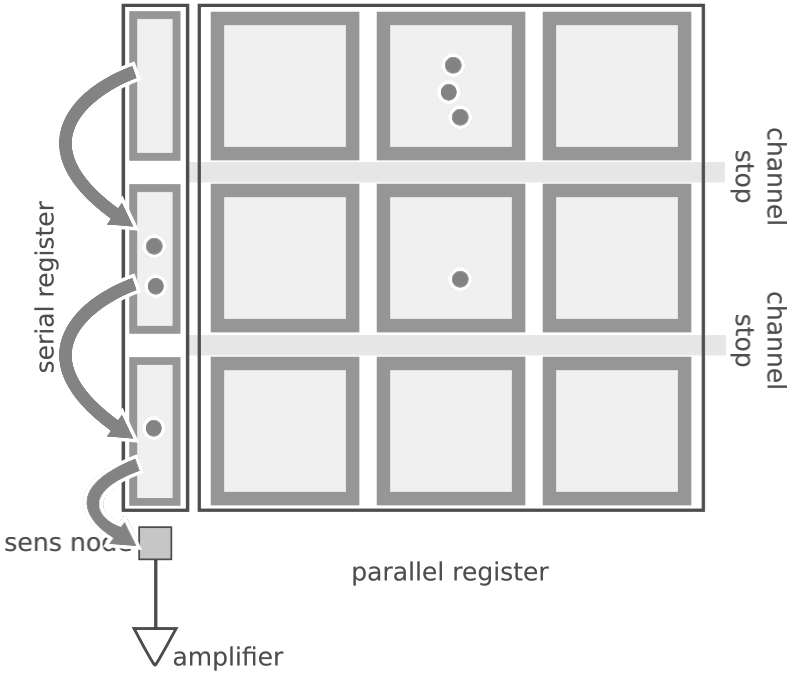
CCD: readout

3x3 pixels CCD

Shift charge one column to tha right



Shift charge in serial register one pixel down (3 times)



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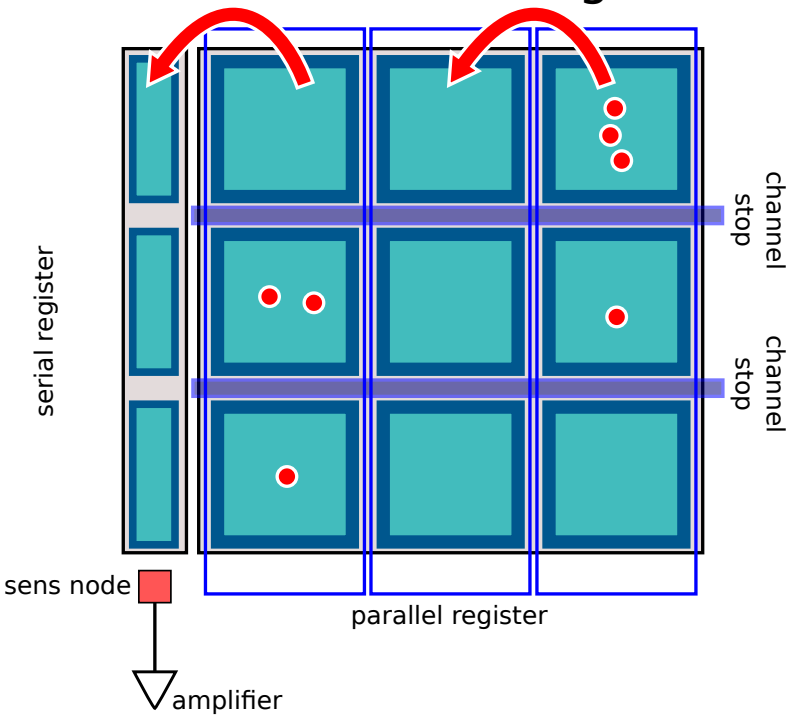

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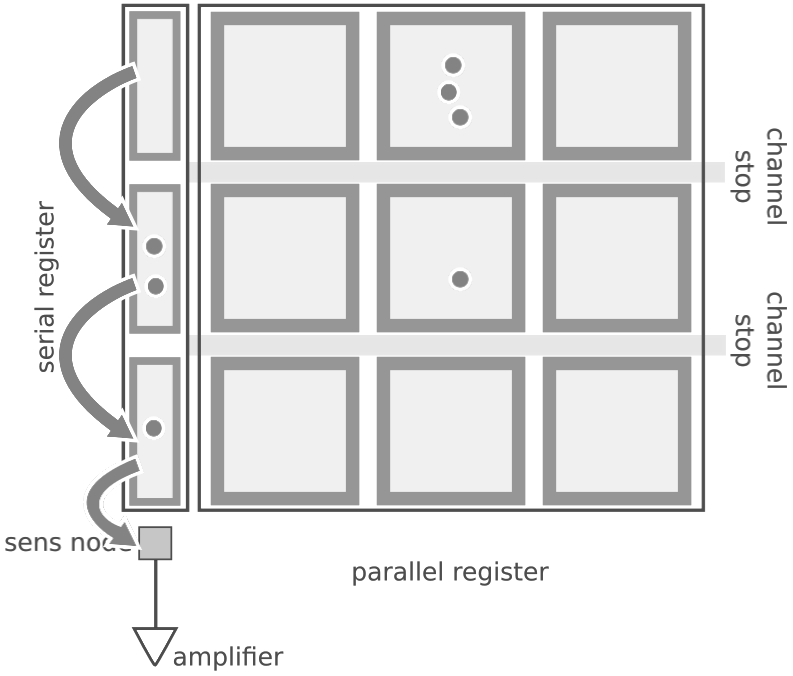

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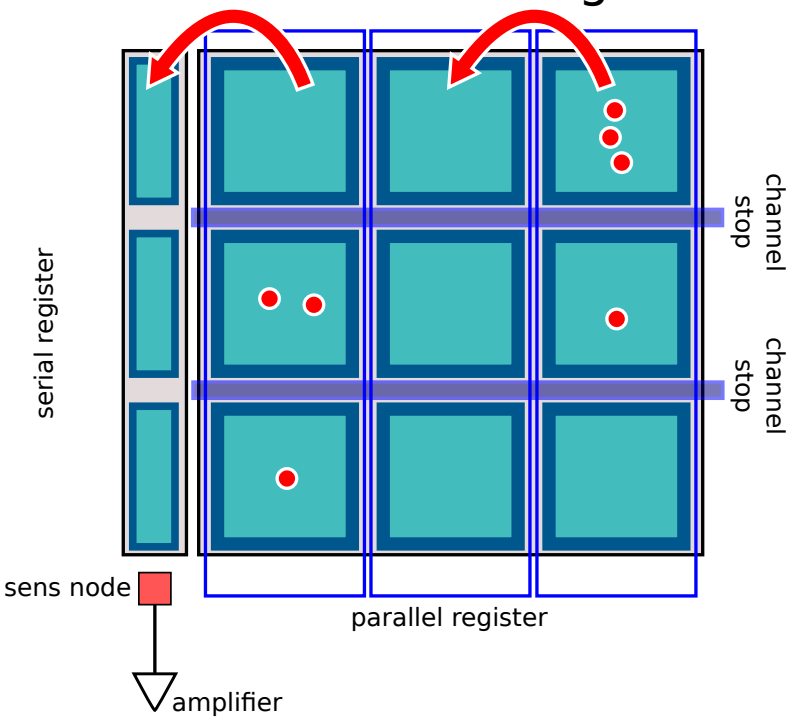

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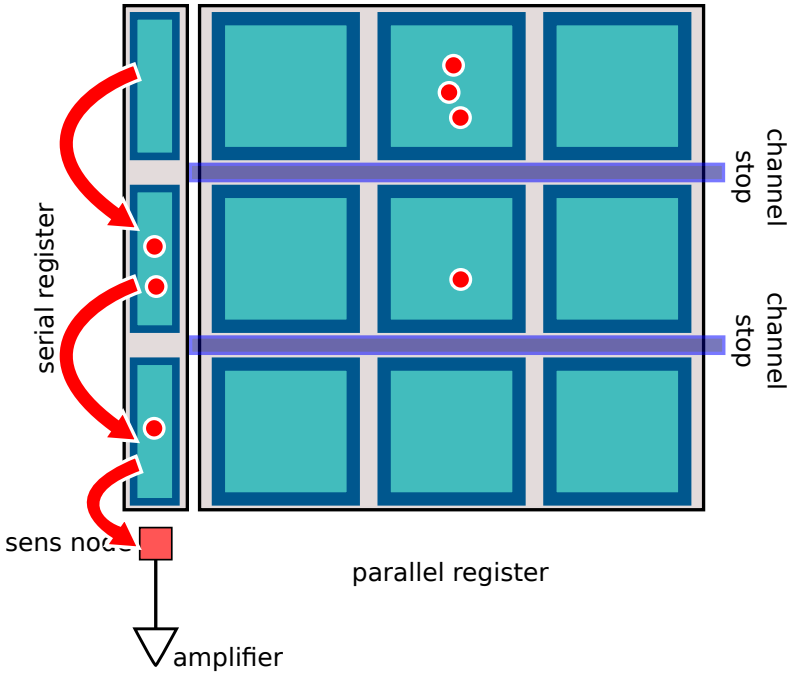
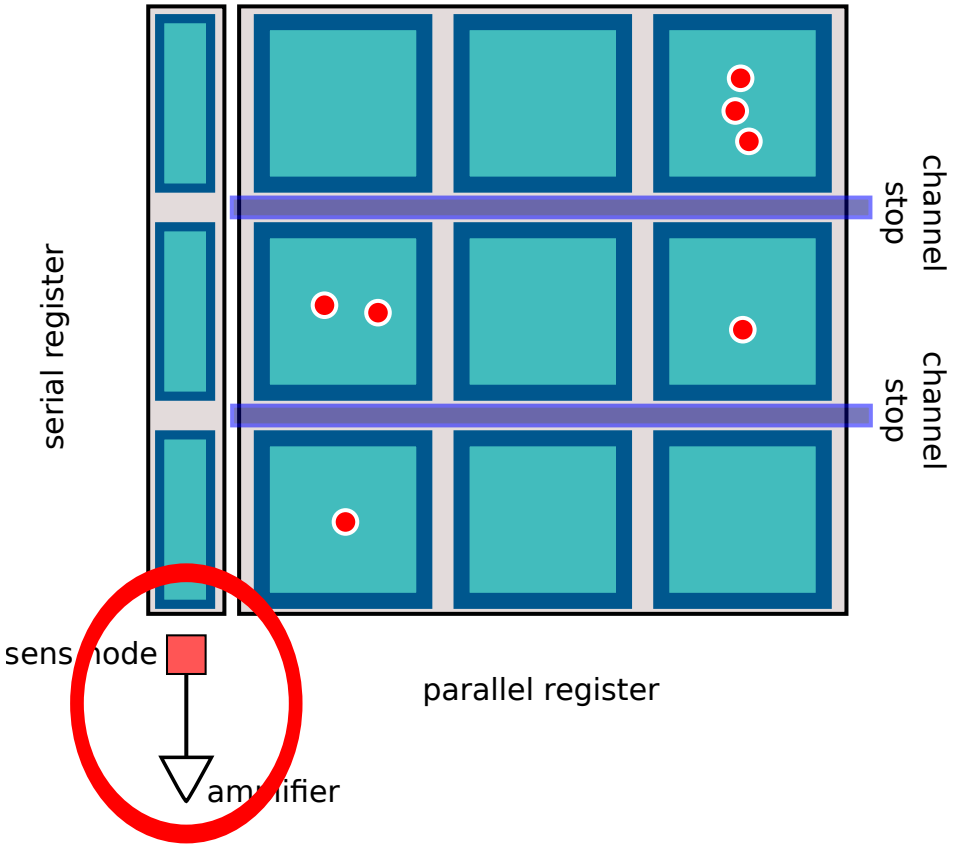


capacitance of the system is set by the SN: C=0.05pF$\rightarrow$ 3μV/e

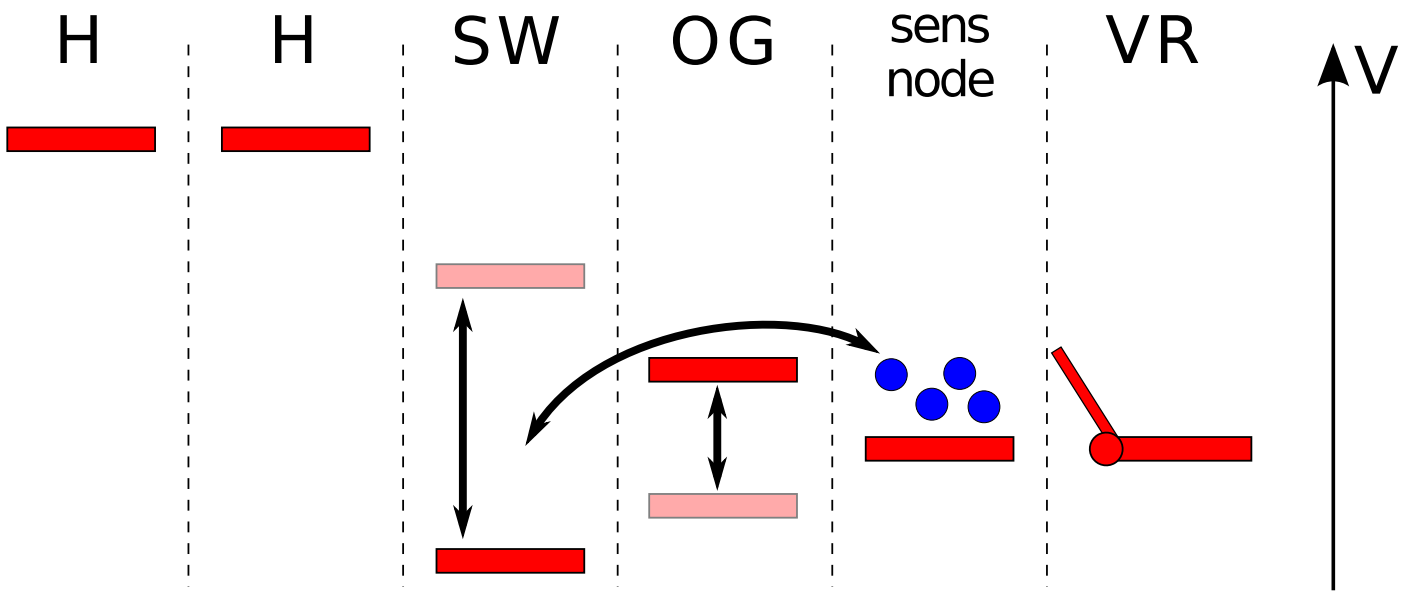
Lowering the noise: Skipper CCD



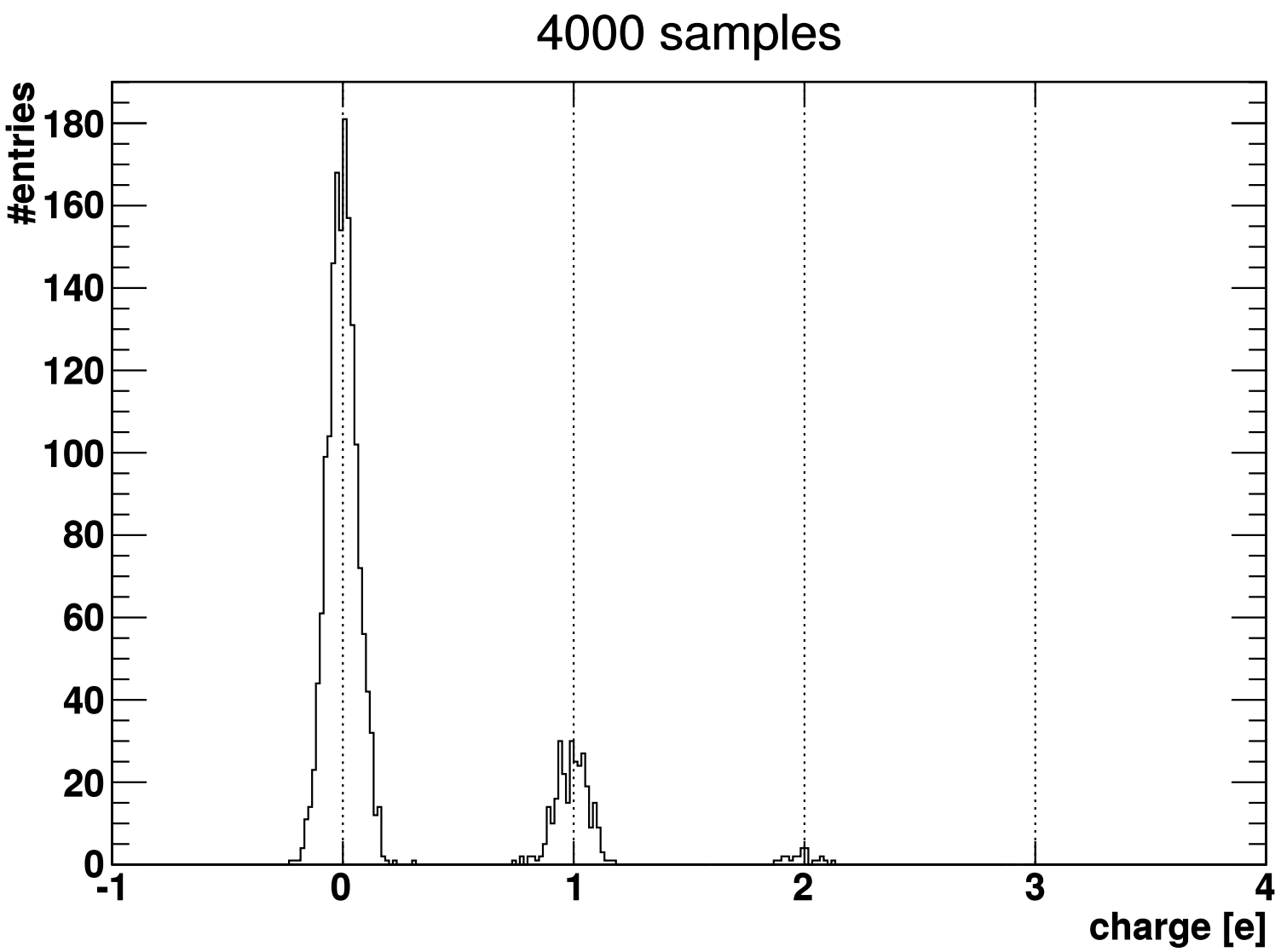
Only the readout stage is modified

Lowering the noise: Skipper CCD

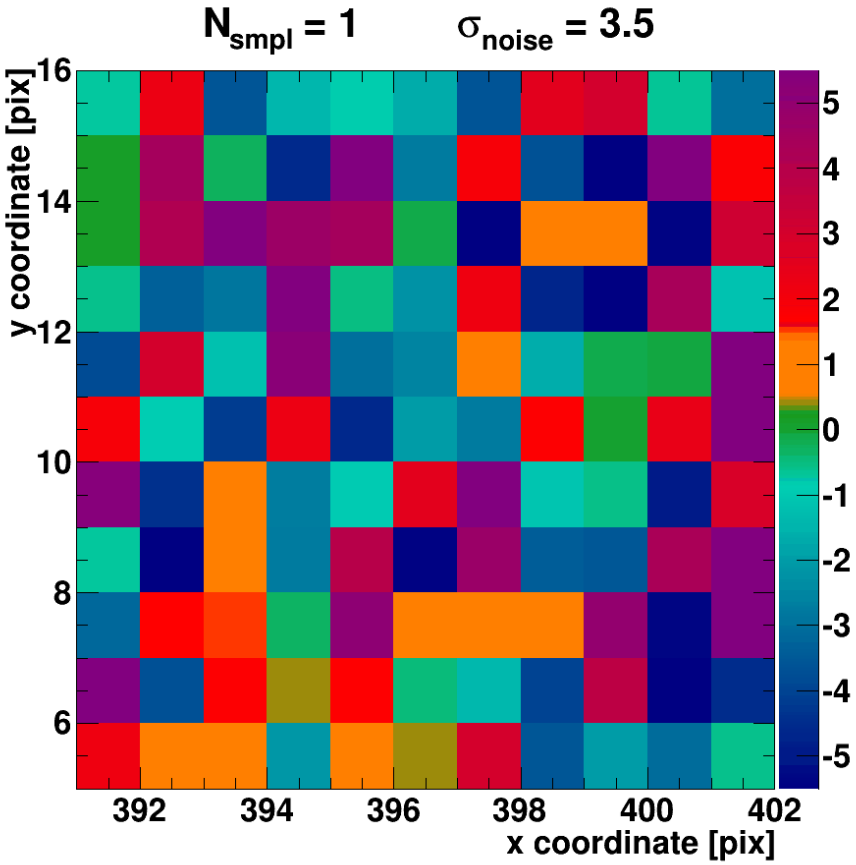
- **Main difference:** the Skipper CCD allows multiple sampling of the same pixel without corrupting the charge packet.
- The final pixel value is the average of the samples
  $\boldsymbol{Pixel\ value = \frac{1}{N}\Sigma_i^N\,(pixel\ sample)_i}$

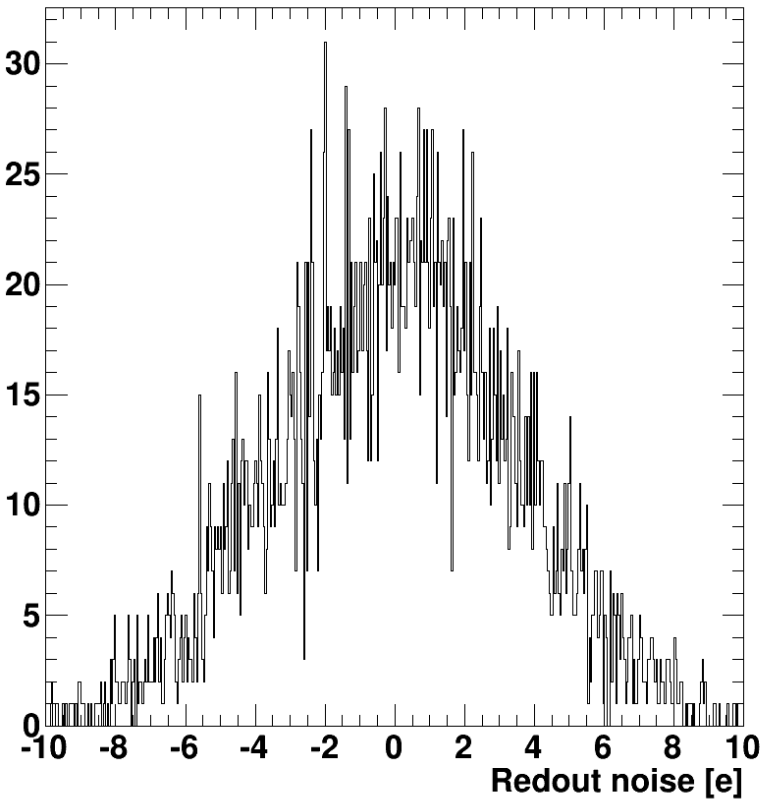


Charge in pixel distribution. Counting electrons: 0, 1, 2..



Counting electrons: 0, 1, 2.. n





Counting electrons: ..48, 49, 50..

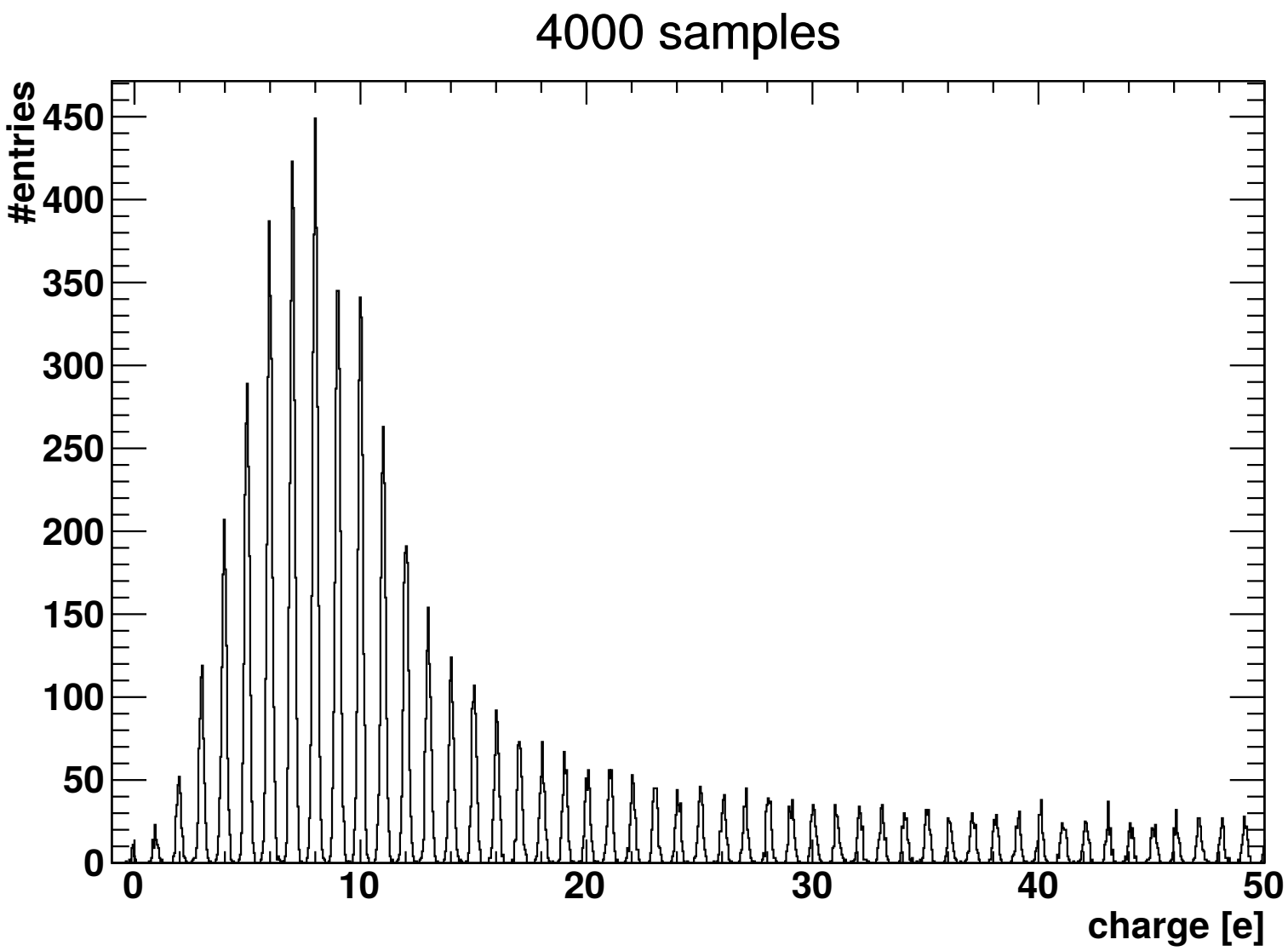
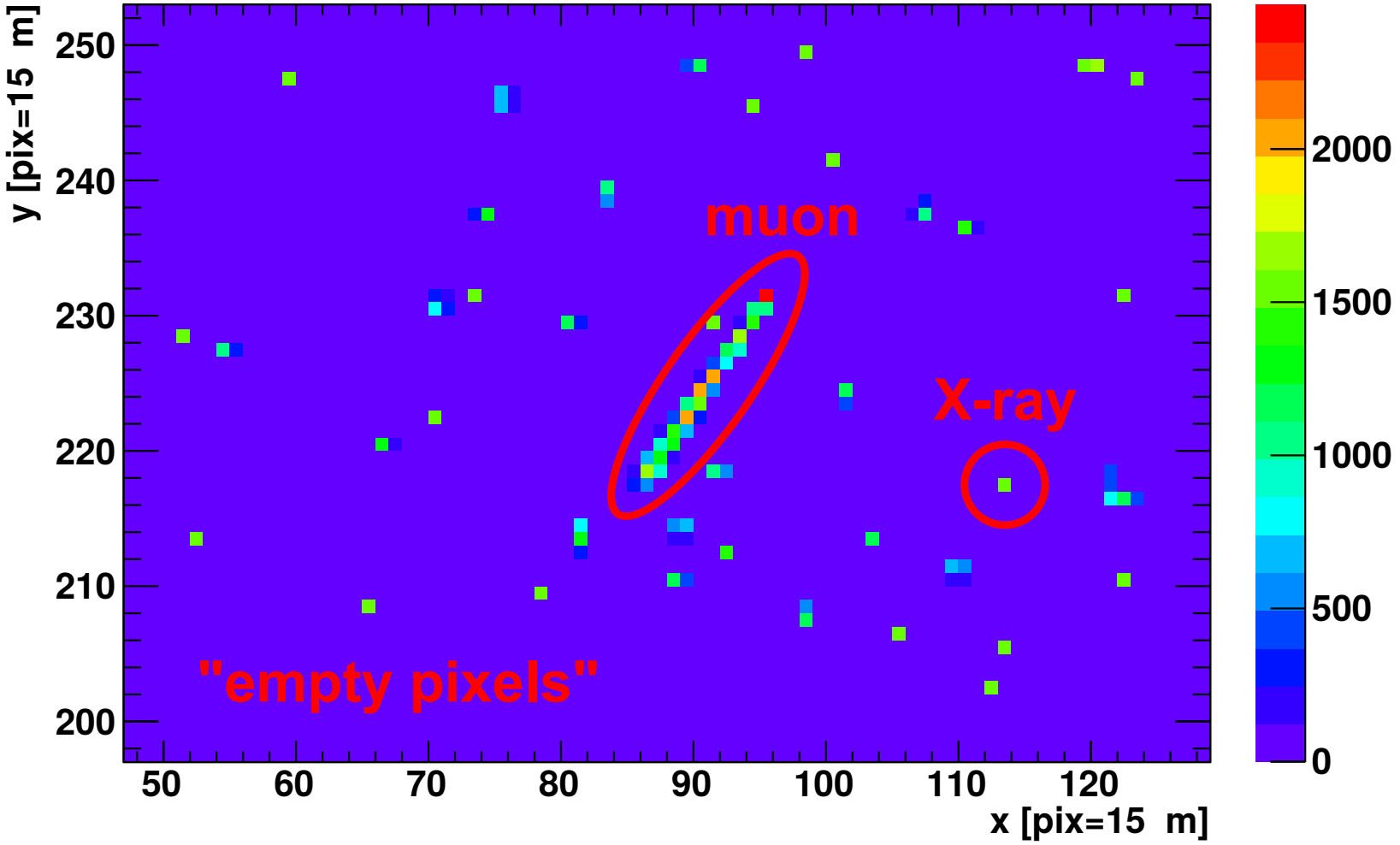


Image taken with SENSEI: 4000 samples per pixel (processed)



2017

We finally understood how to operate the sensor:

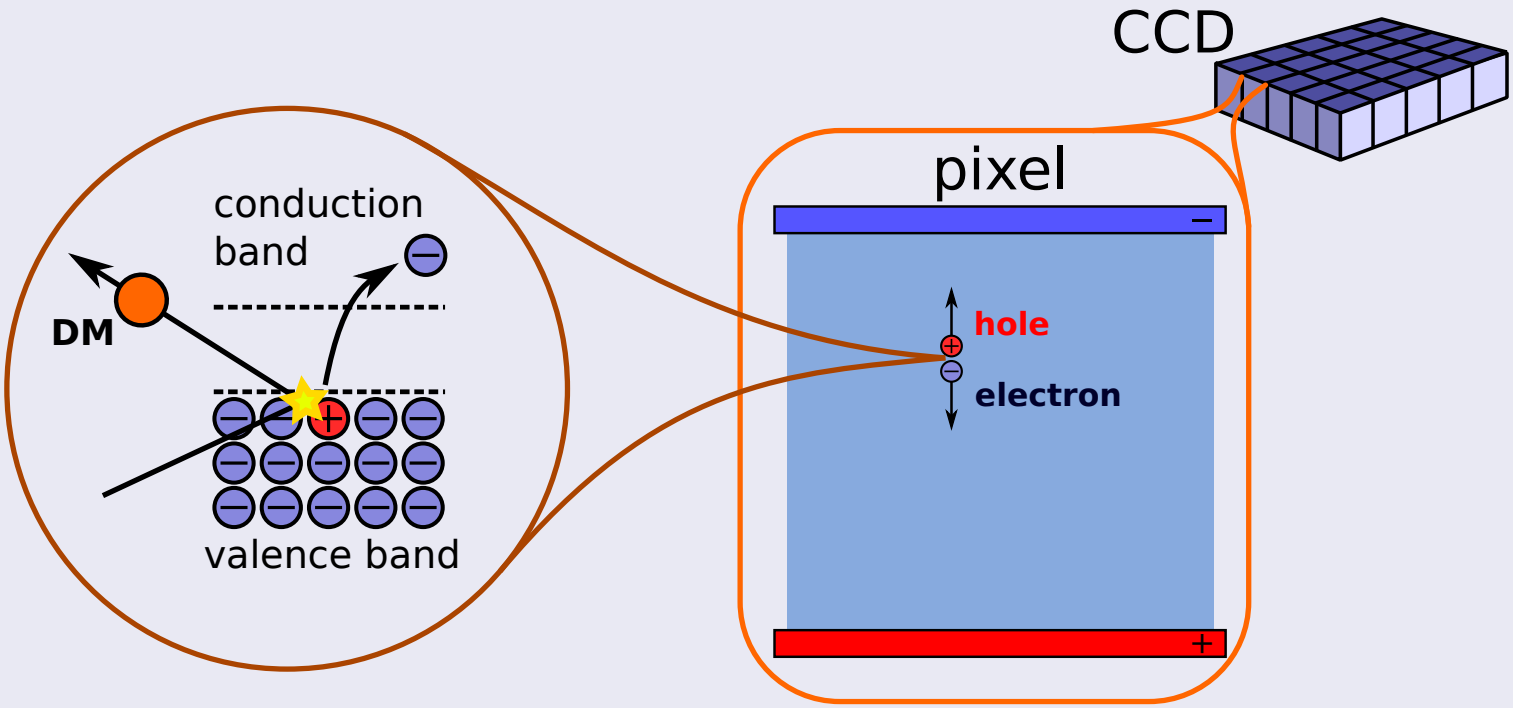
- 2011: Achieving sub-electron readout noise in Skipper CCDs (arXiv:1106.1839v2)
- 2017: Single-electron and single-photon sensitivity with a silicon Skipper CCD (arXiv:1706.00028)

SENSEI collaboration (old pict.)

SENSEI: lower the energy threshold to look for light DM candidates

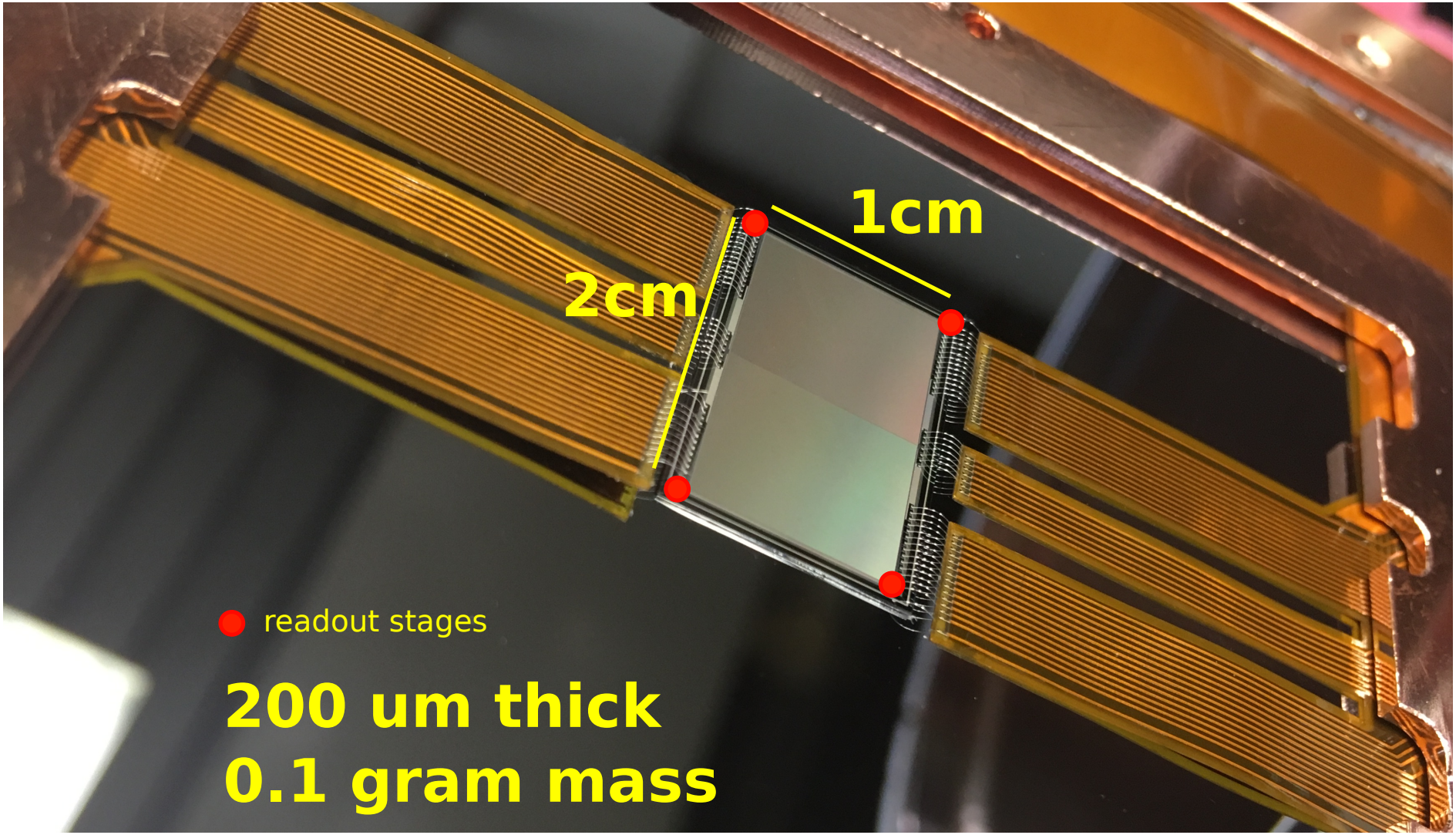
Detect DM-e interactions by measuring the ionization produced by the electron recoils. See arXiv:1509.01598

Idea: use electrons in the CCDs as target

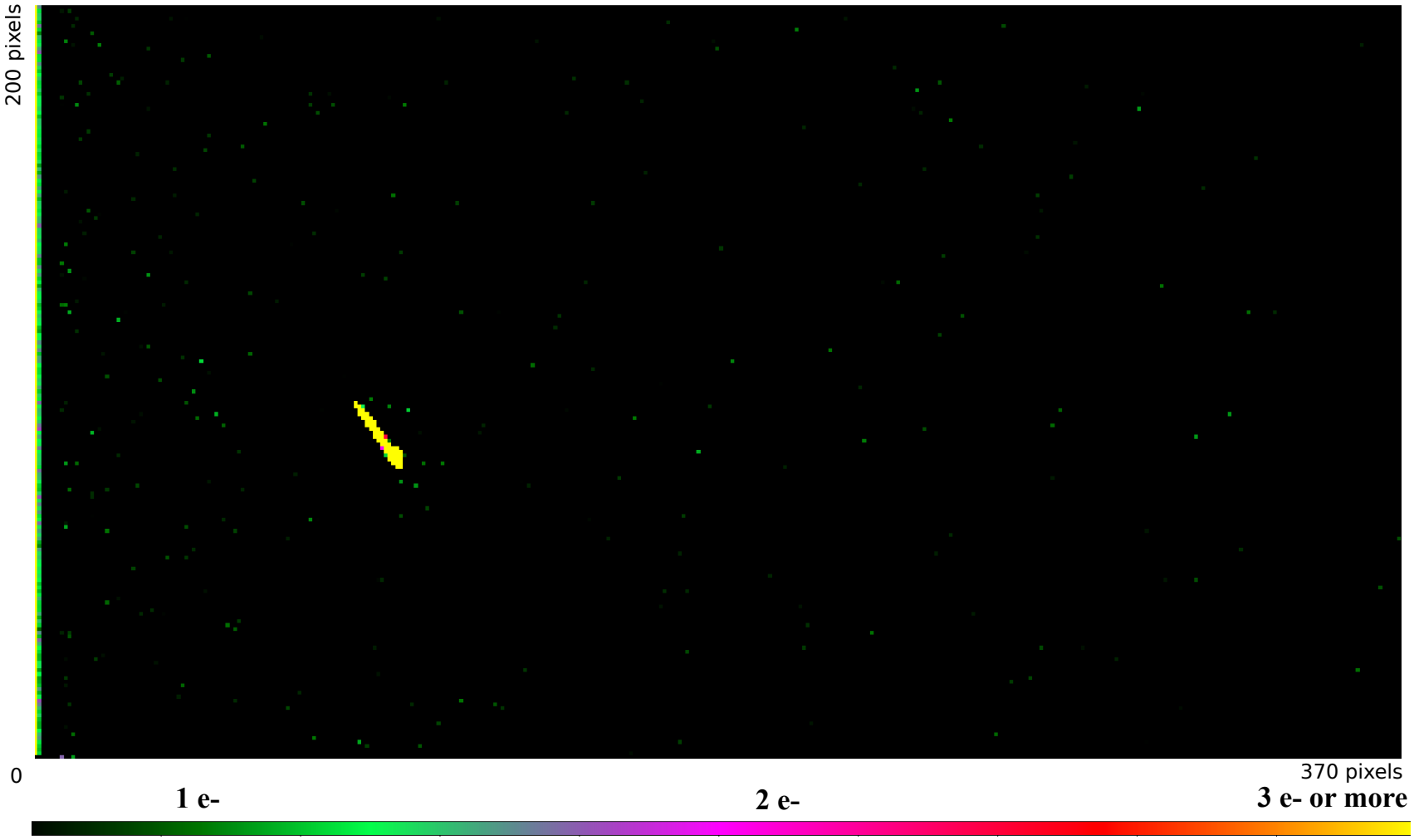


This requires very low noise!

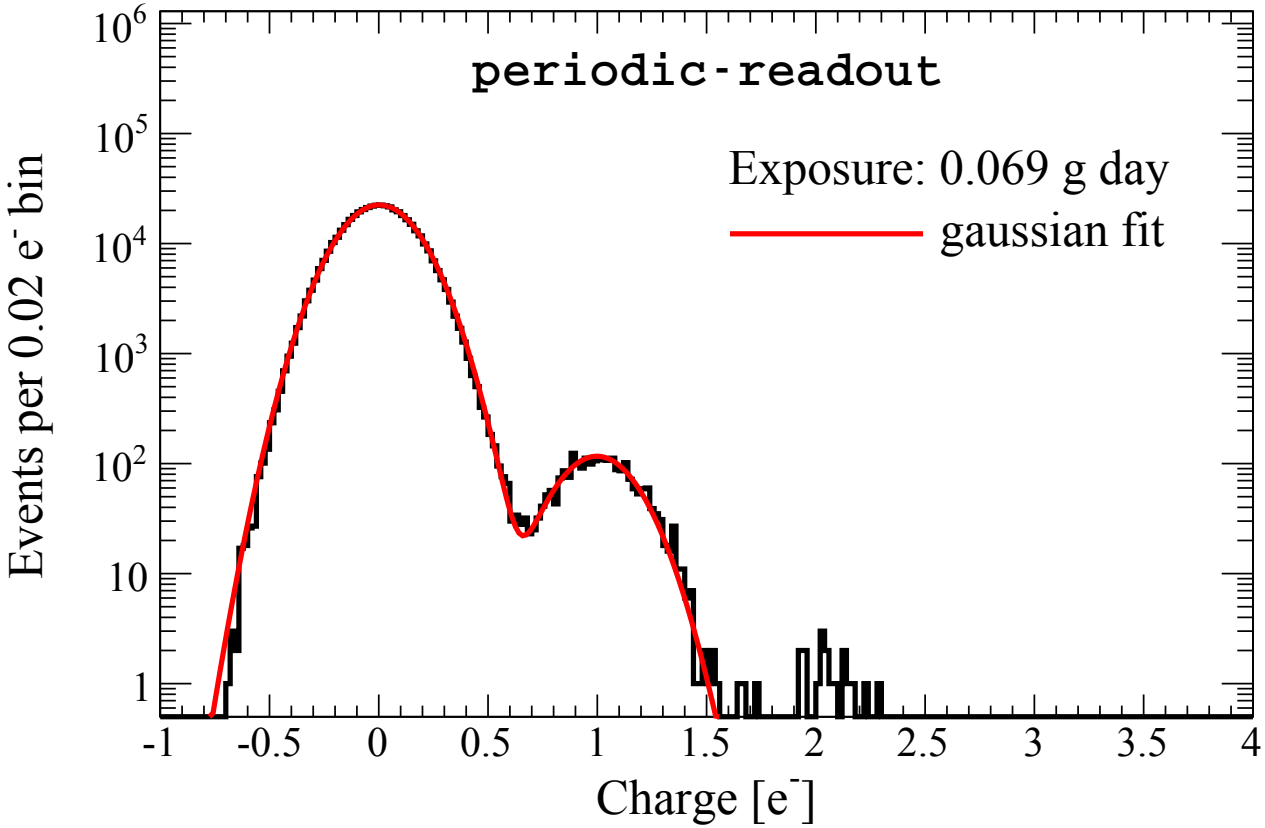
Skipper CCD sensor.



SENSEI output data. Dark matter detection.



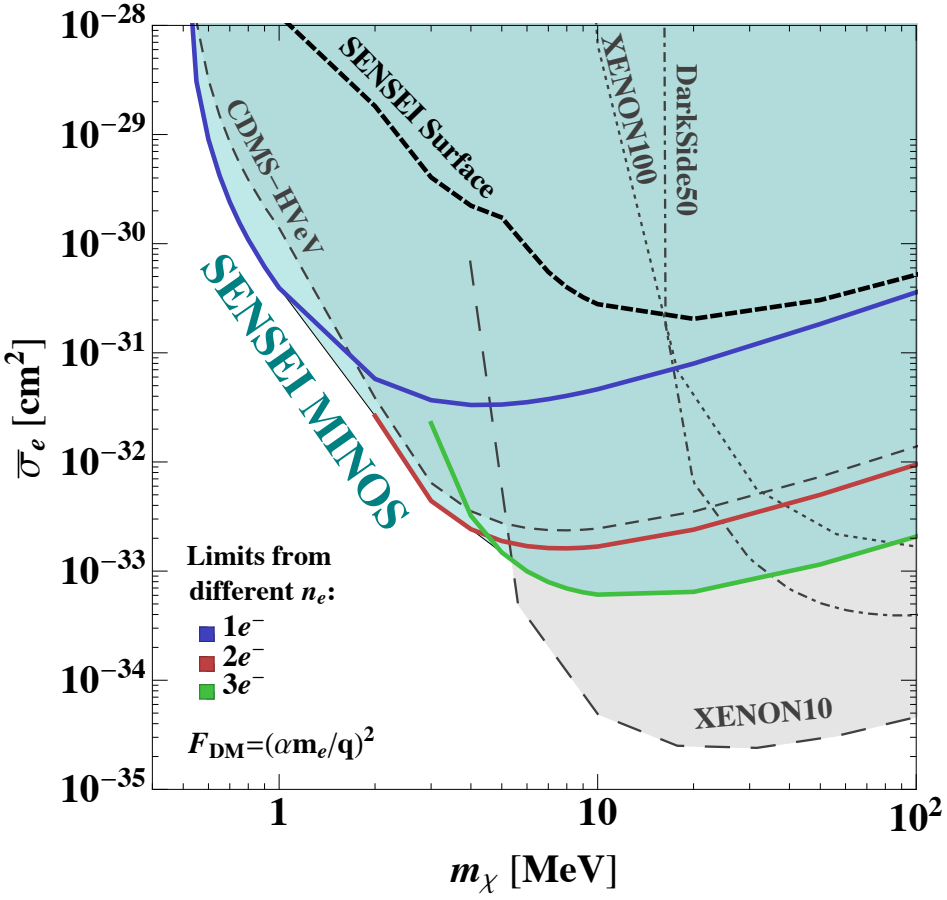
SENSEI: Event spectrum



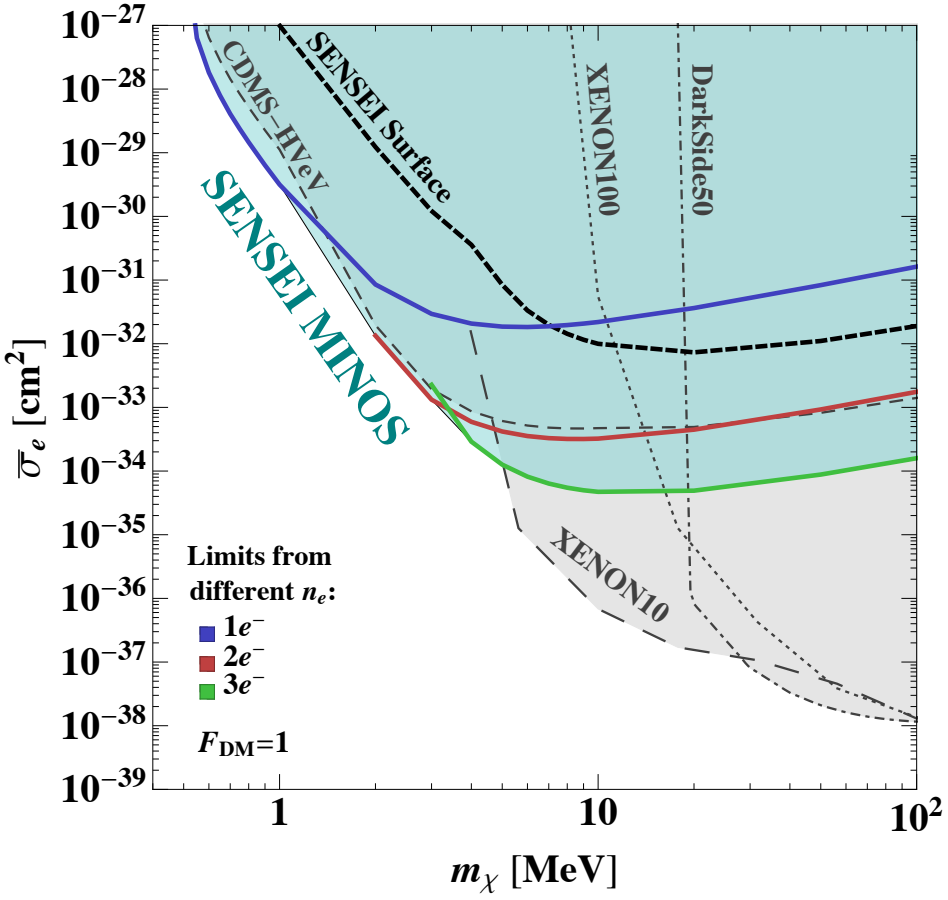
- **No events with $3e^-$ or more**
- **Keeping dark count rate low is the key.**

SENSEI: last results (2019) at shallow depth

Light Dark Photon



Heavy Dark Photon



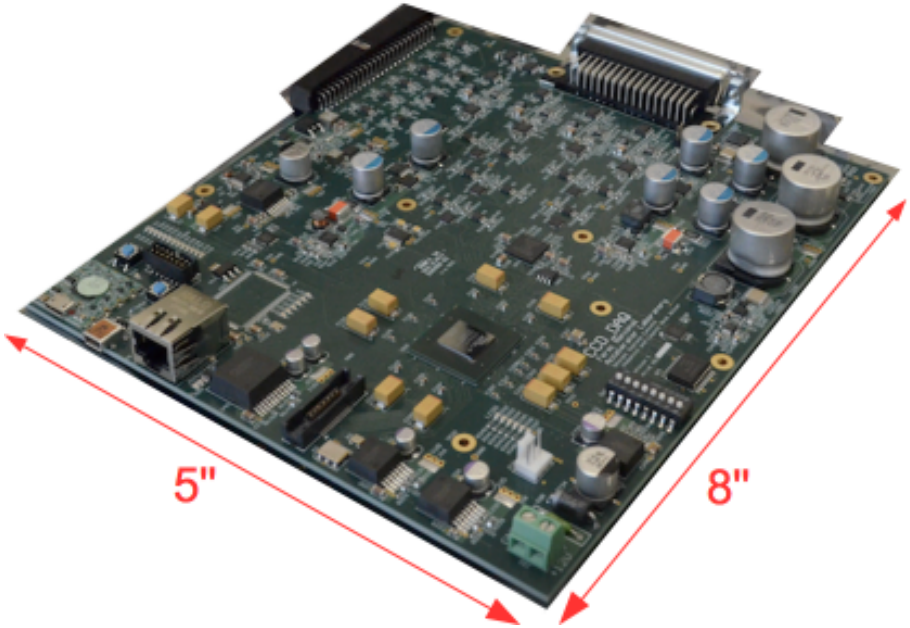
World best limit below 5 MeV!!

2018

- **Bottleneck: No readout system to scale up in mass.**
- No commercial solution.
- Strong requirement in noise and dark count production.
- **We couldn't wait for other 8 years to develop the controller. We needed bet... people.**

Bright people solving this issue

Low **T**hreshold **A**cquisition

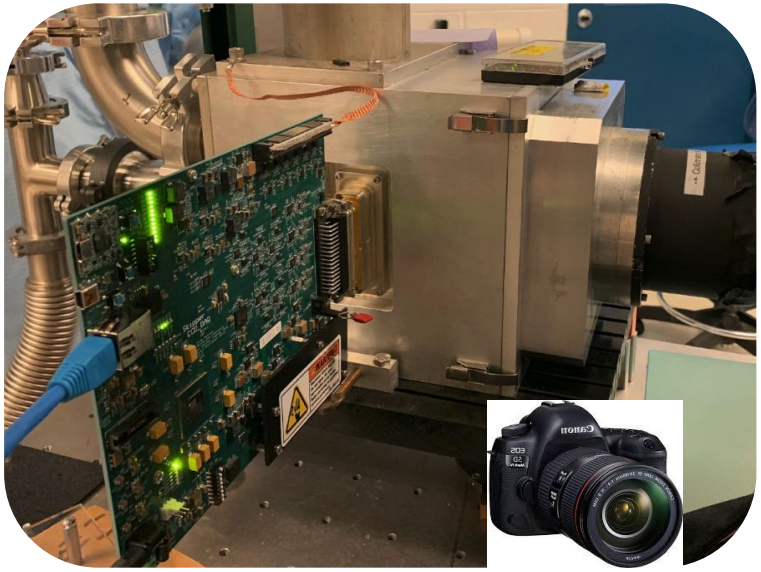


- First controller for Skipper CCD.
- Design for dark count and noise minimization.
- Now we use it for many projects: DM, QIS, ν, Q-UCN ...

With the right motivation

Bright people solving this issue

Low **T**hreshold **A**cquisition



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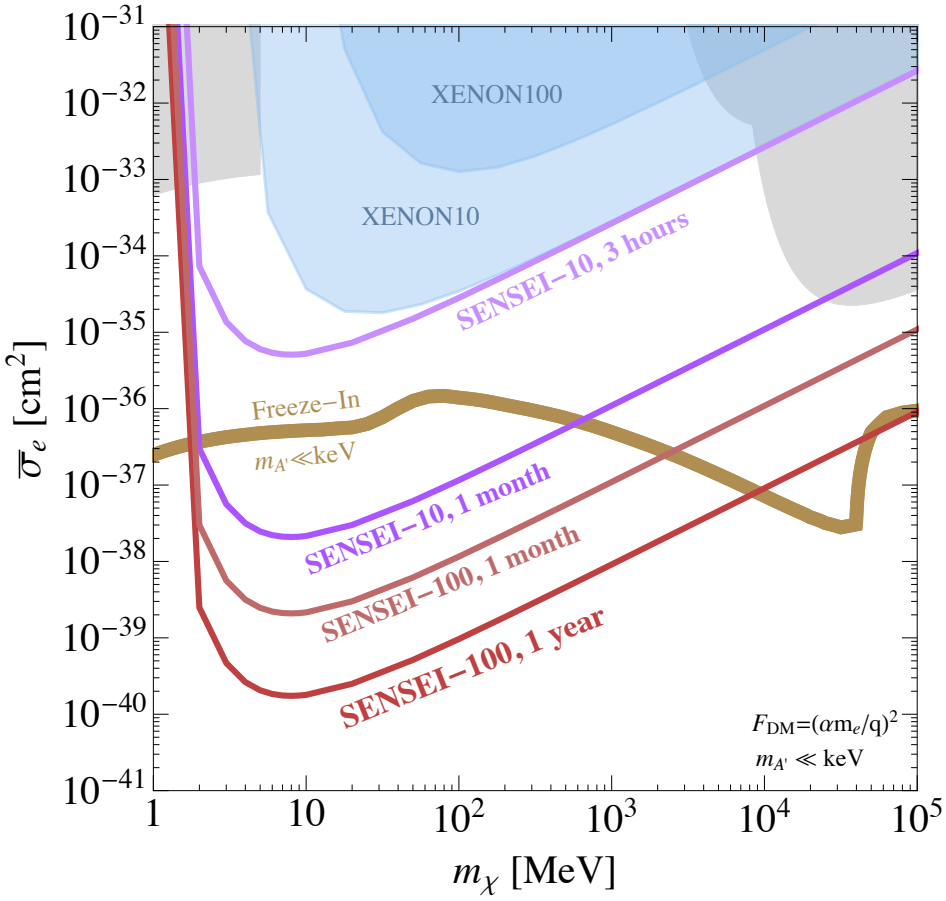
SENSEI: reach of a 100g (2019-2021)

Light Dark Photon



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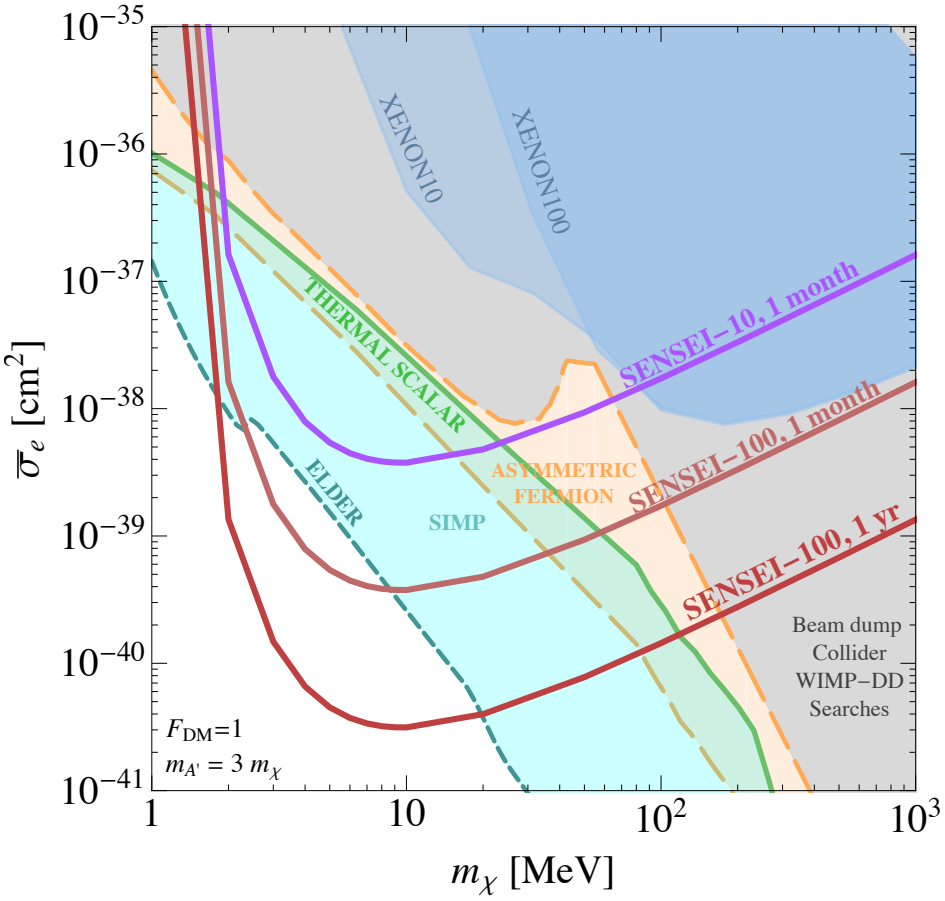
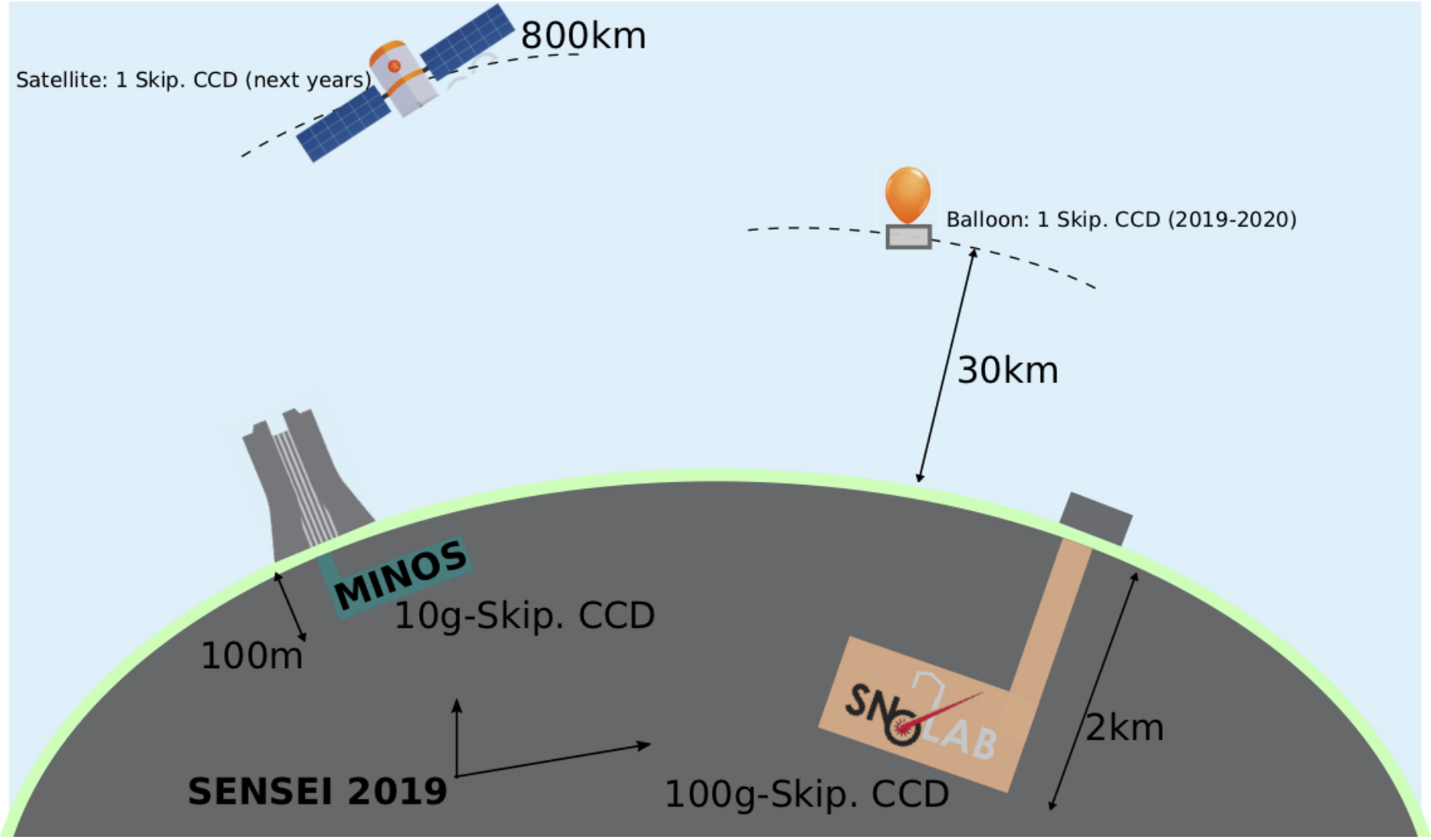


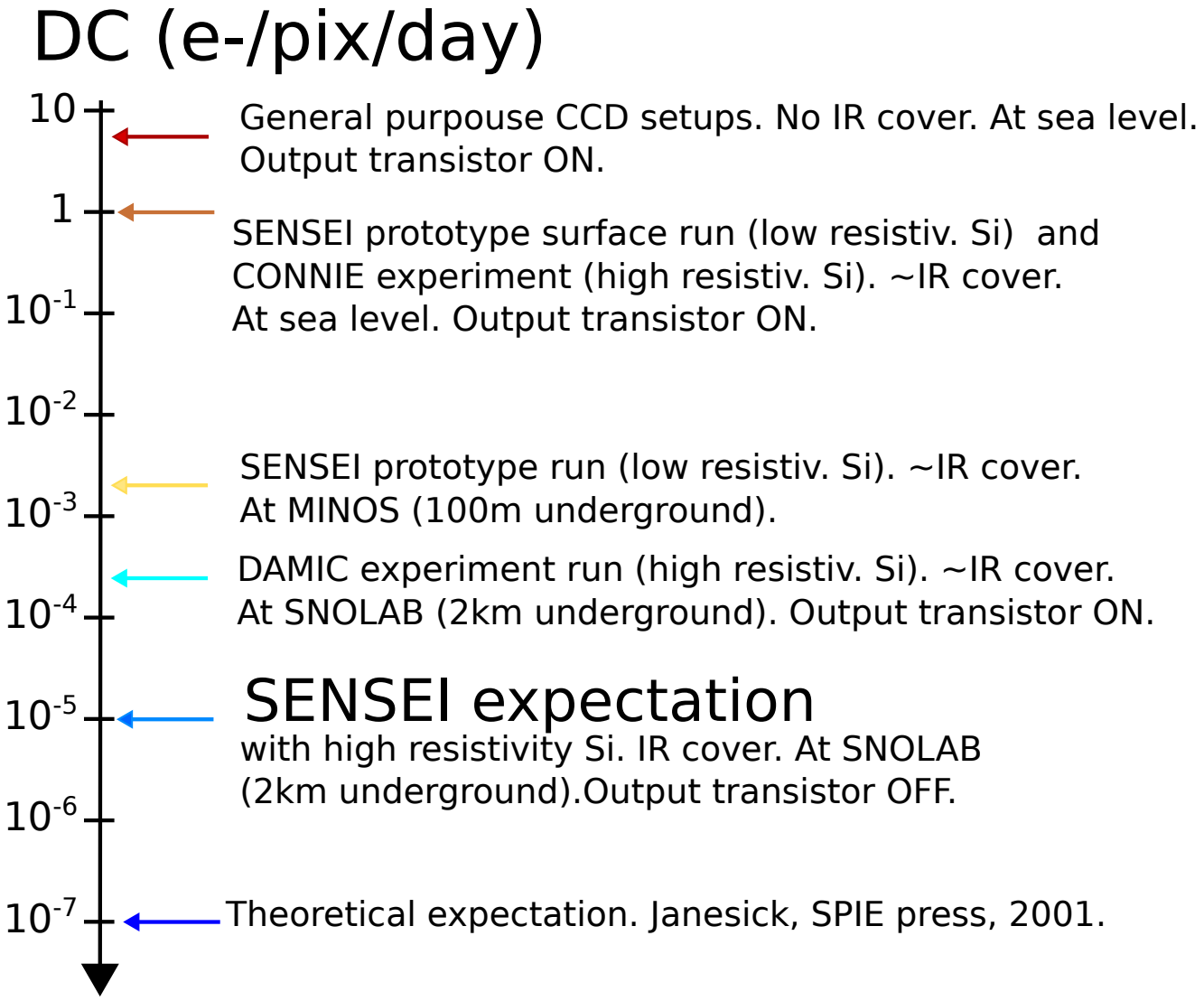
Future of the sensor for dark matter detection



Thanks!

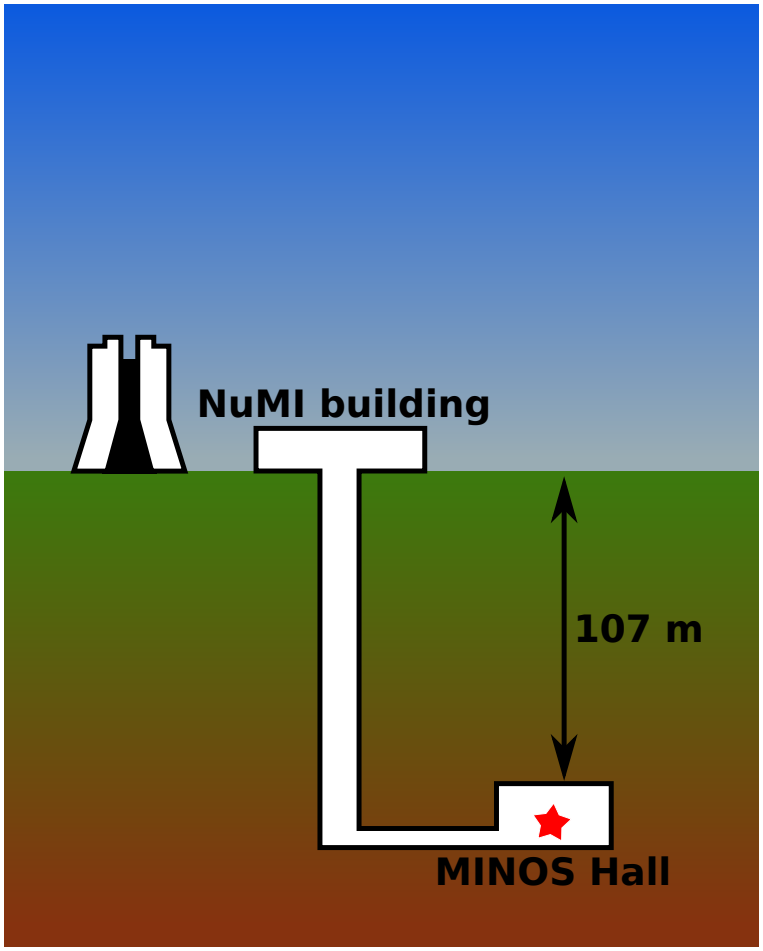
BACK UP SLIDES

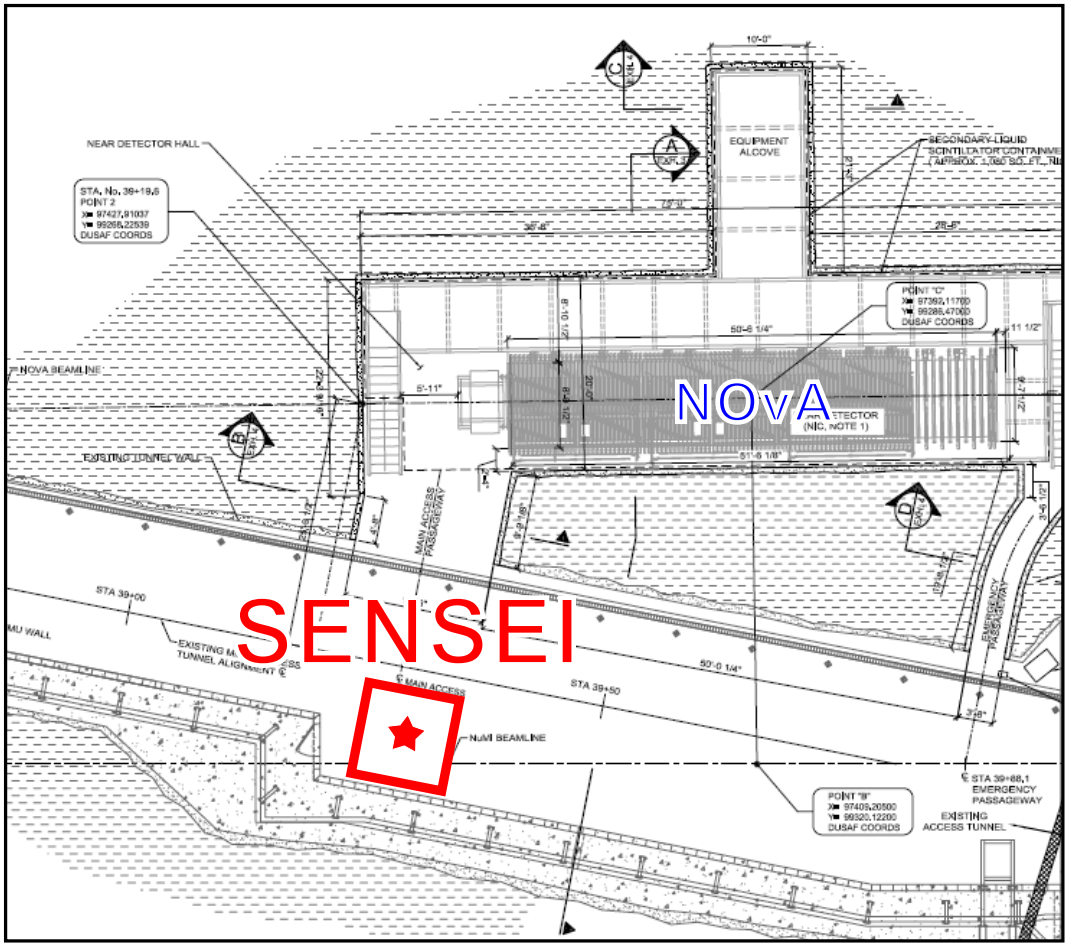
Dark current measurements and expectation



Current step: Prototype running @MINOS

Technology demonstration: installation at shallow underground site





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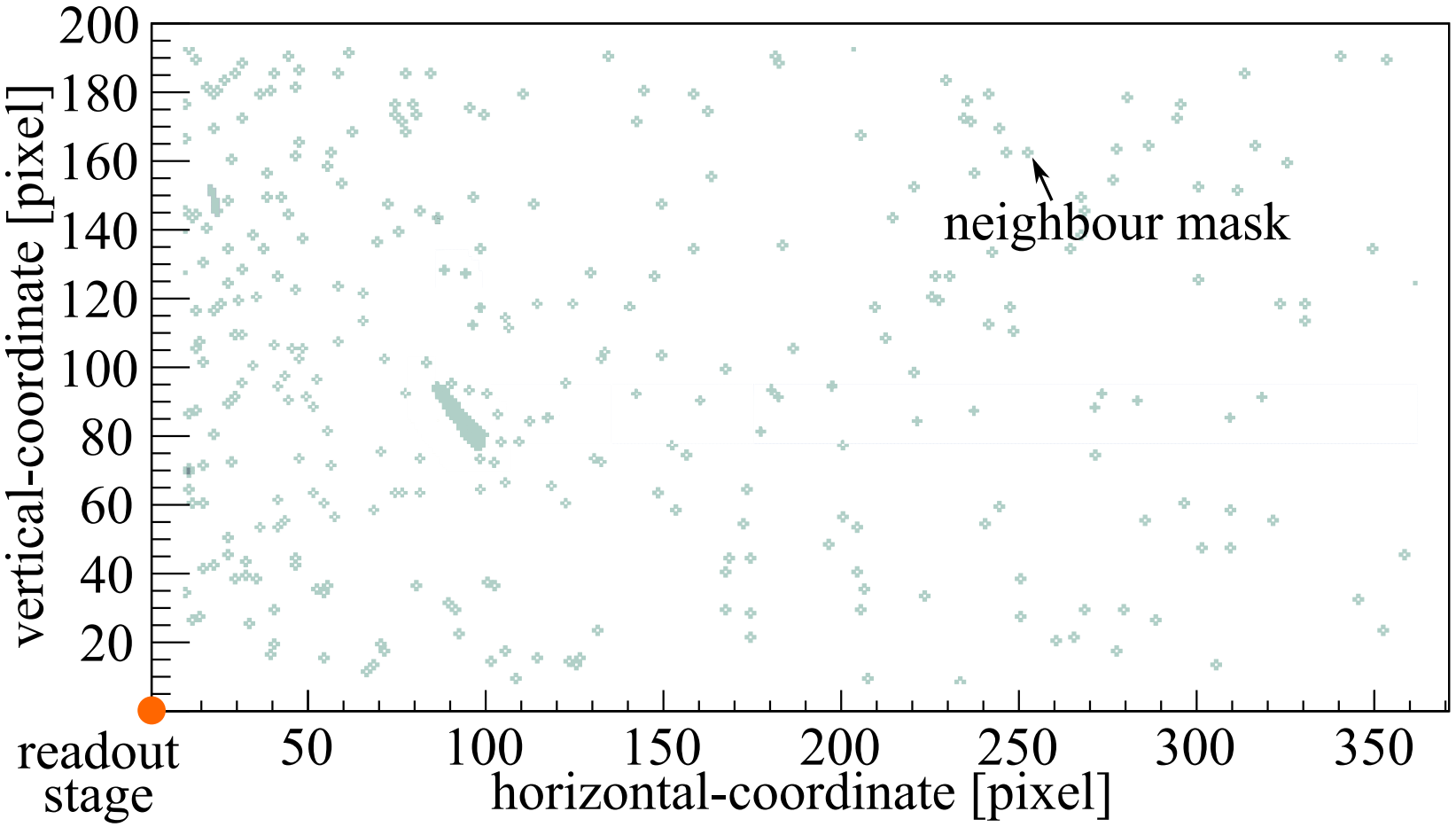
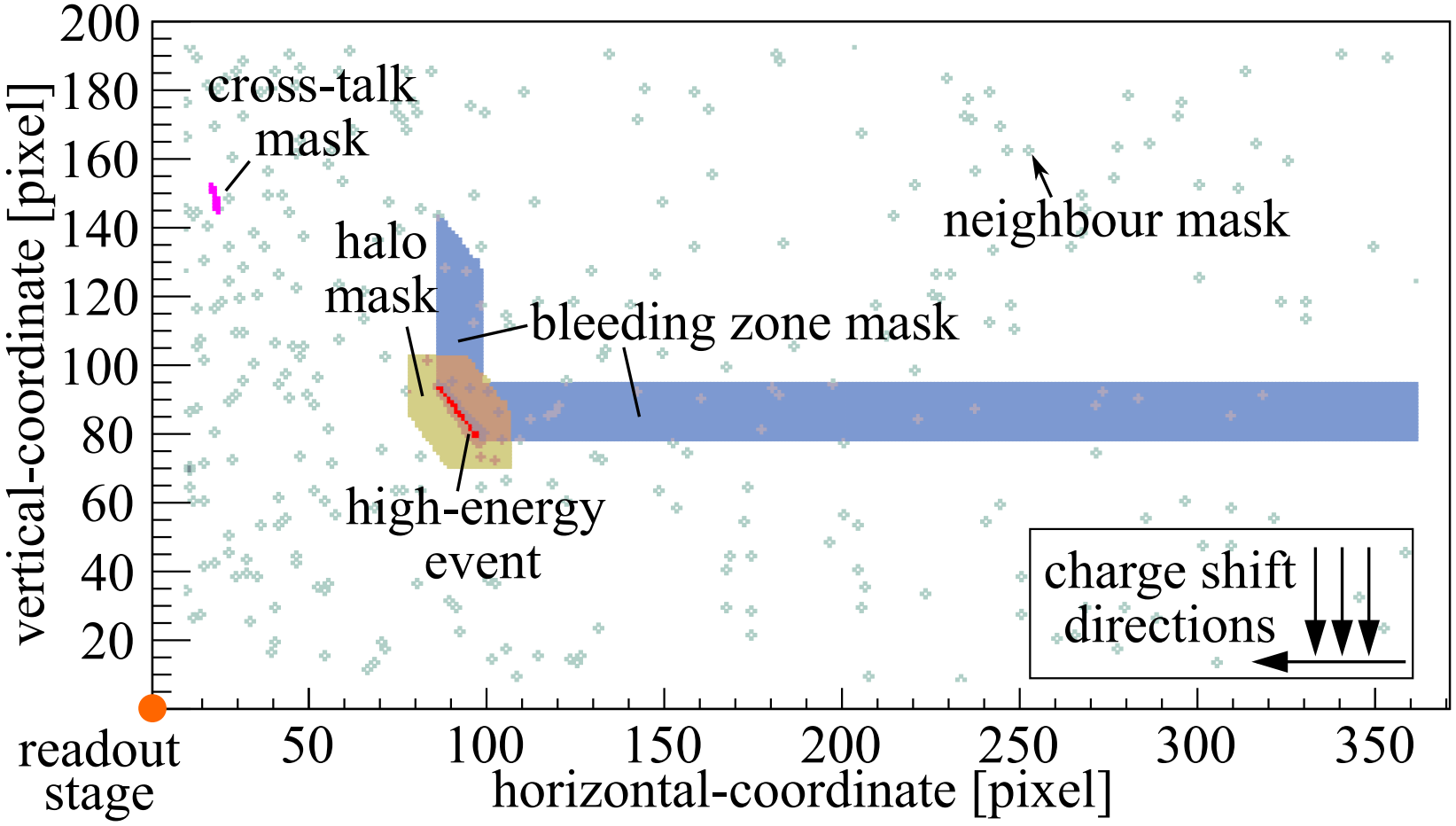
Event reconstruction



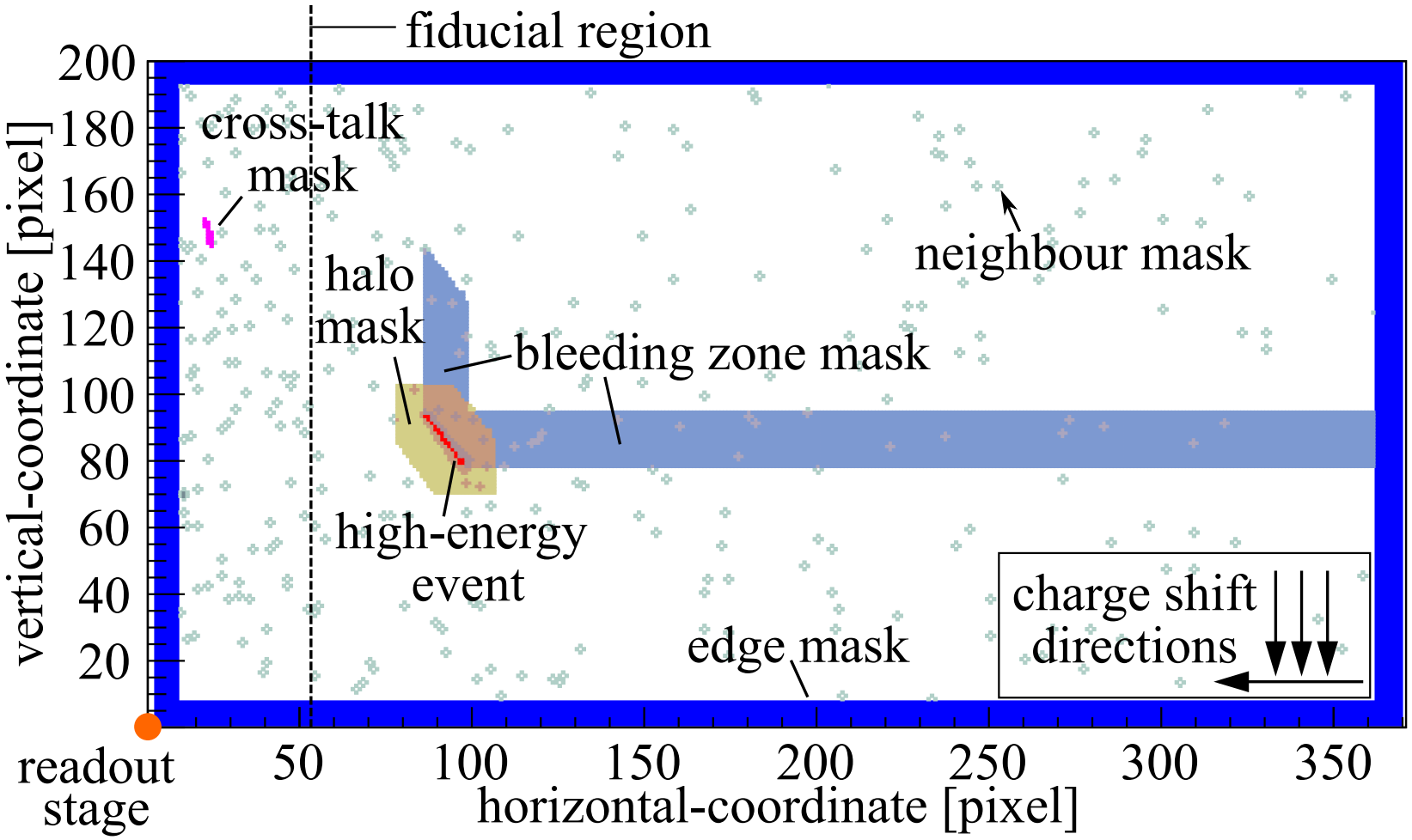
adjacent pixels with one or more electrons are grouped together

Selection cuts based on high energy events



Cross talk, Bleeding and Halo

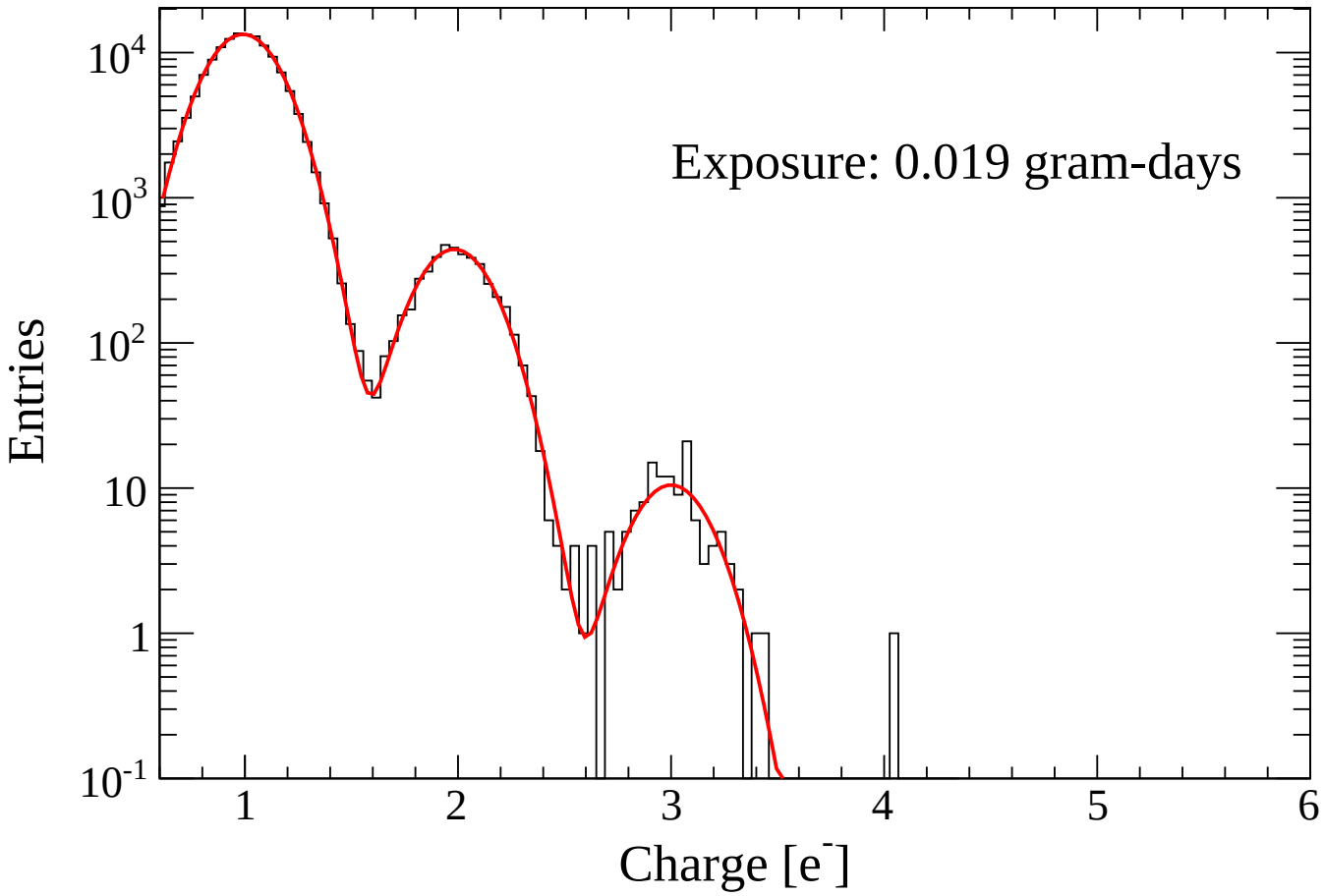
Geometric cuts



Edges and column dependence.

SENSEI commissioning run at surface: arXiv:1804.00088

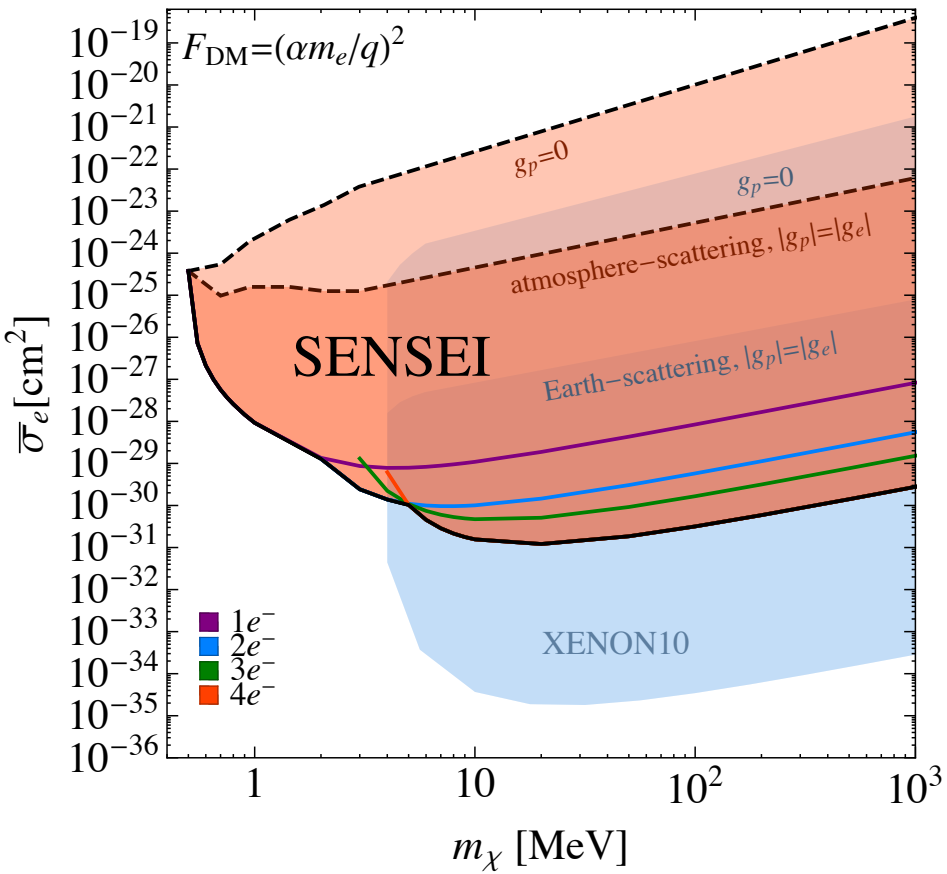
Observed spectrum using 800 samples per pixel



dark current: $\sim$1.1 e^- /pix/day; no events with 5-100 electrons

SENSEI commissioning run at surface: arXiv:1804.00088

First direct-detection constraints between ∼500 keV to 4 MeV!



Terrestrial effects: Timon Emken, RE, Kouvaris, Mukul Sholapurkar (to appear)

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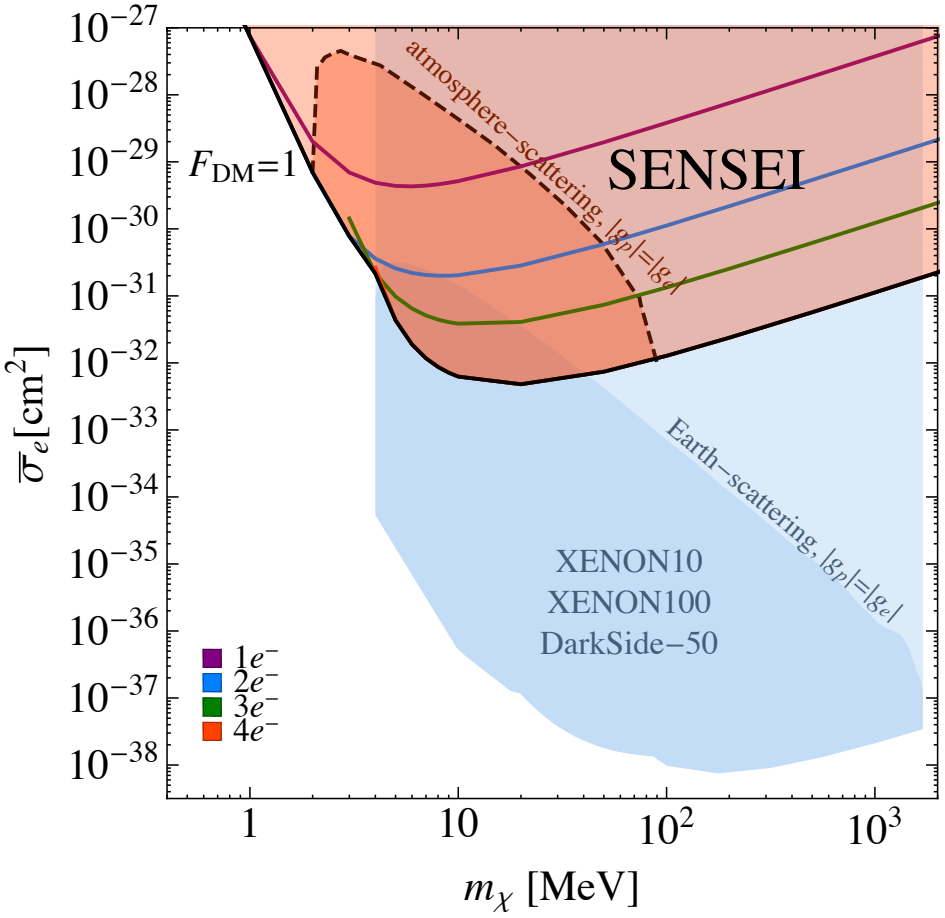

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