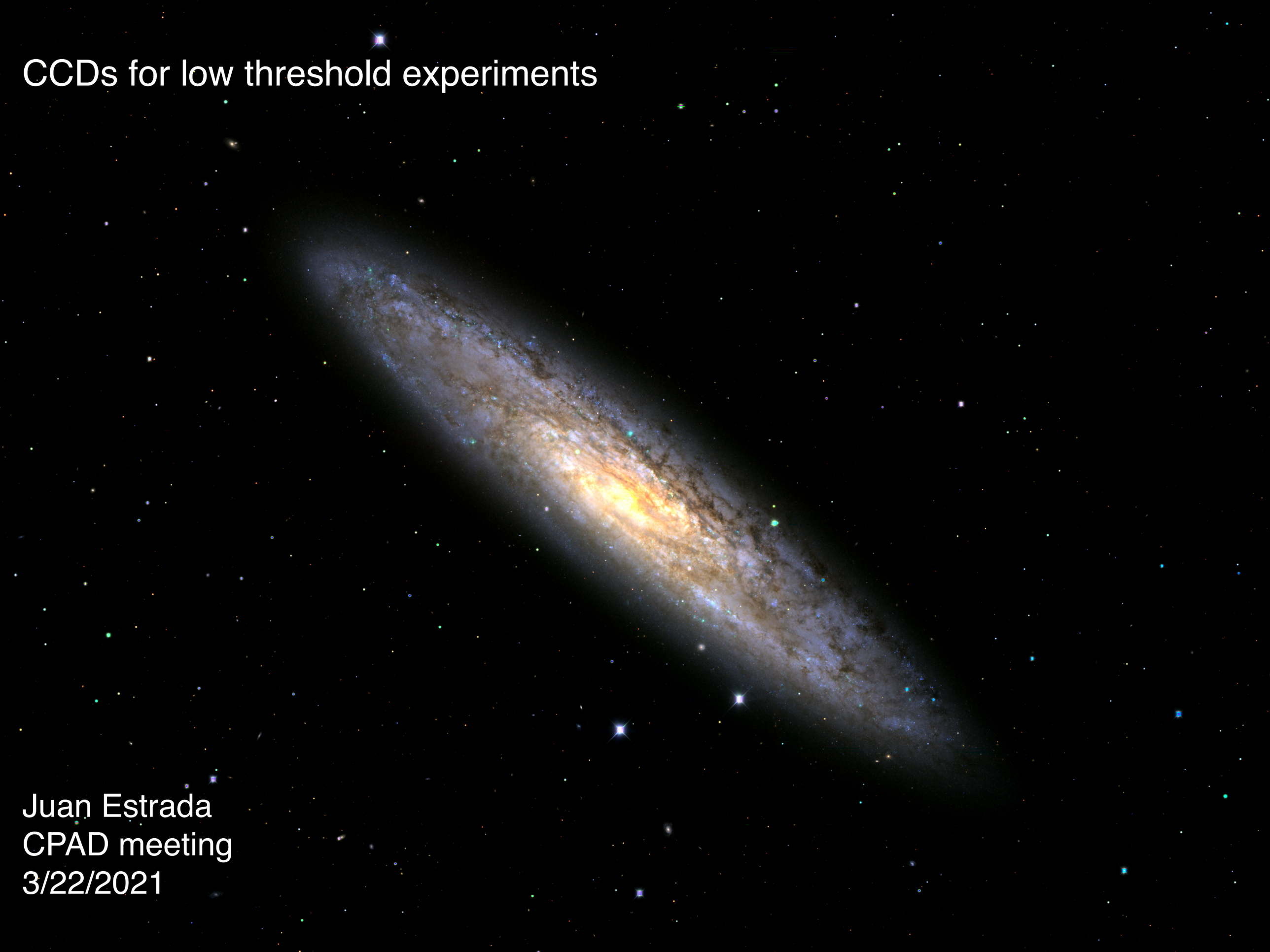
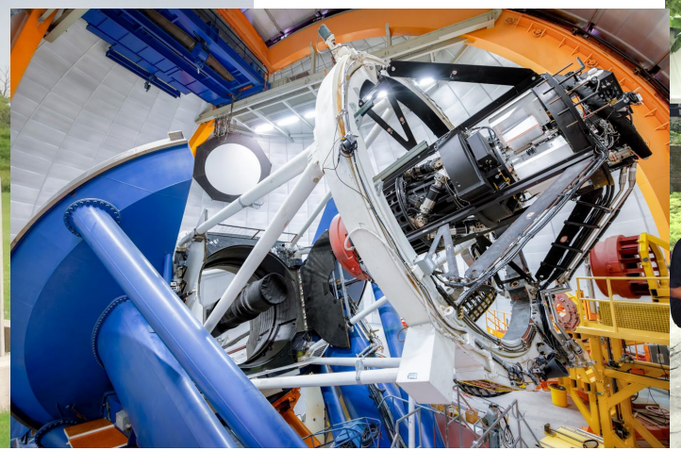
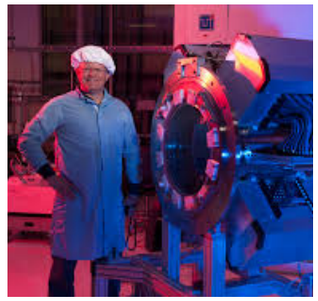
CCDs for low threshold experiments



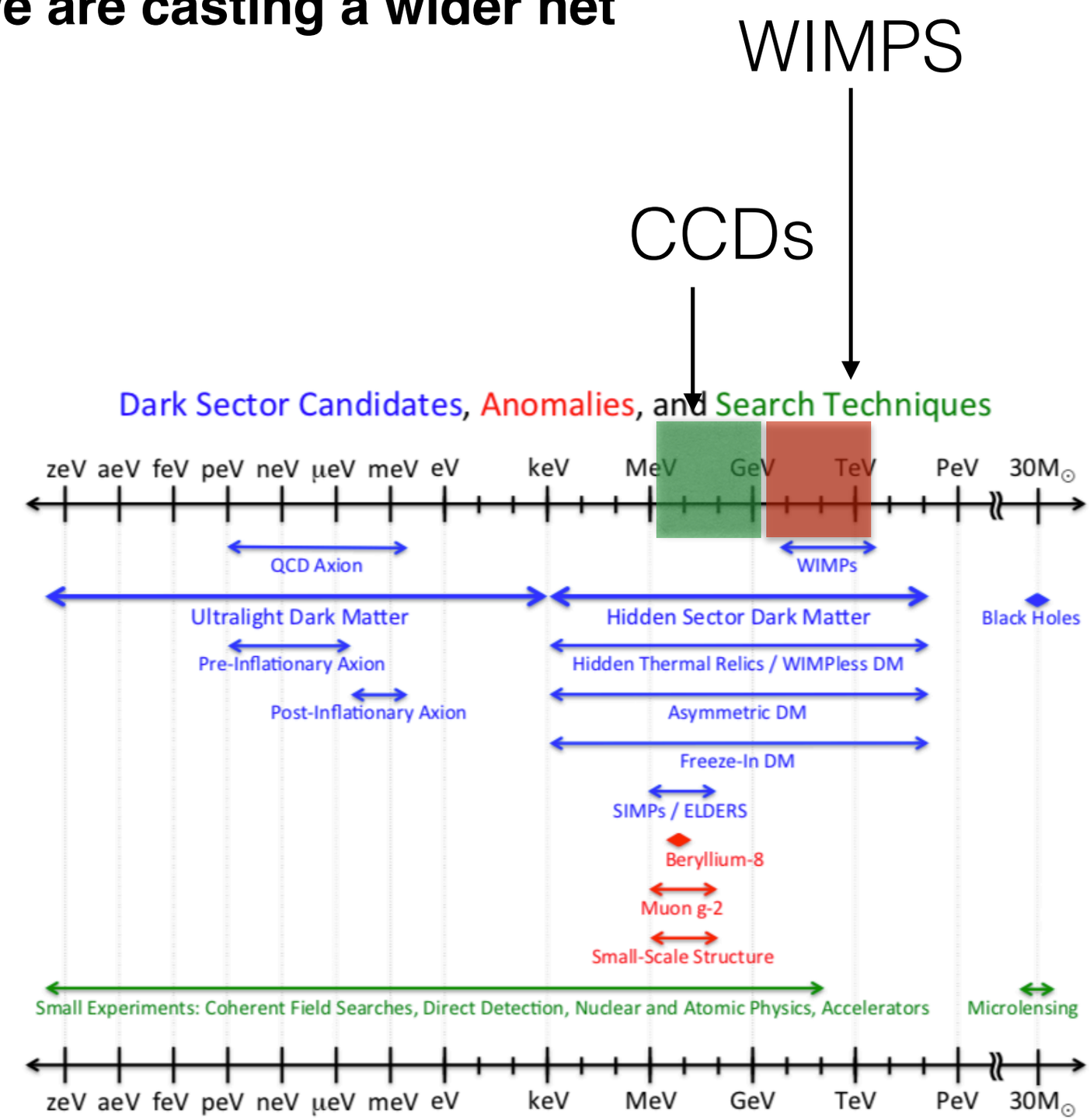
Juan Estrada
CPAD meeting
3/22/2021



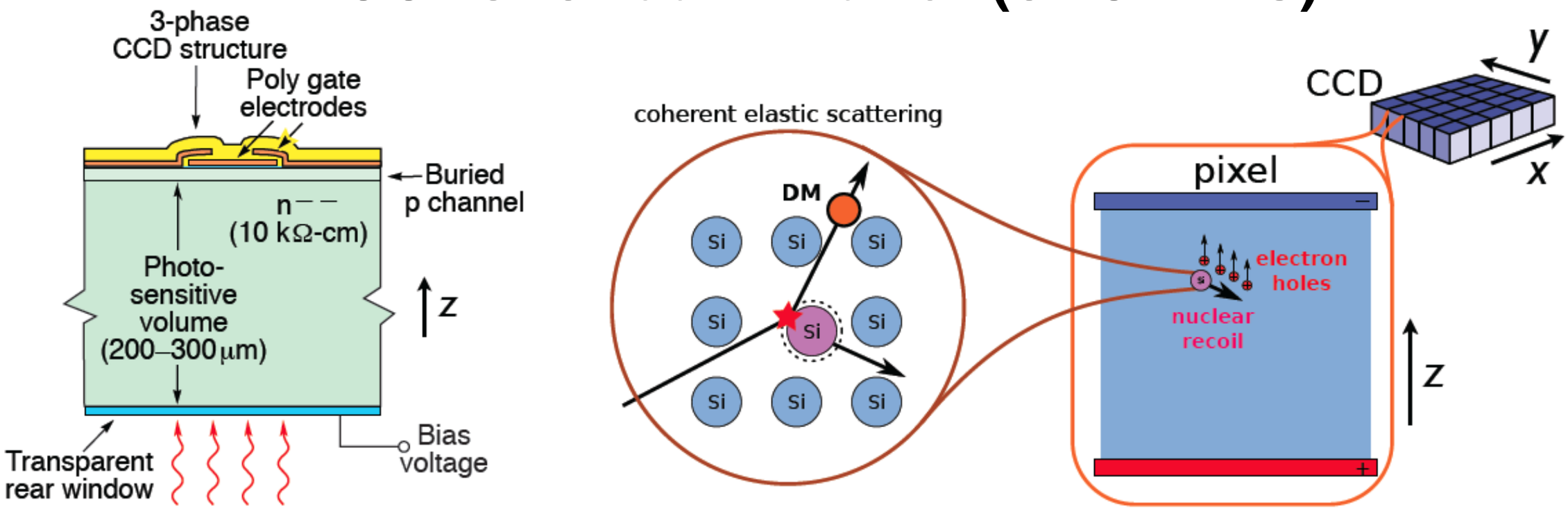


Thanks for the instrumentation award, I am happy to accept it on behalf of a lot o people that worked on all these CCD experiments over many years.

because we have not seen DM yet, we are casting a wider net

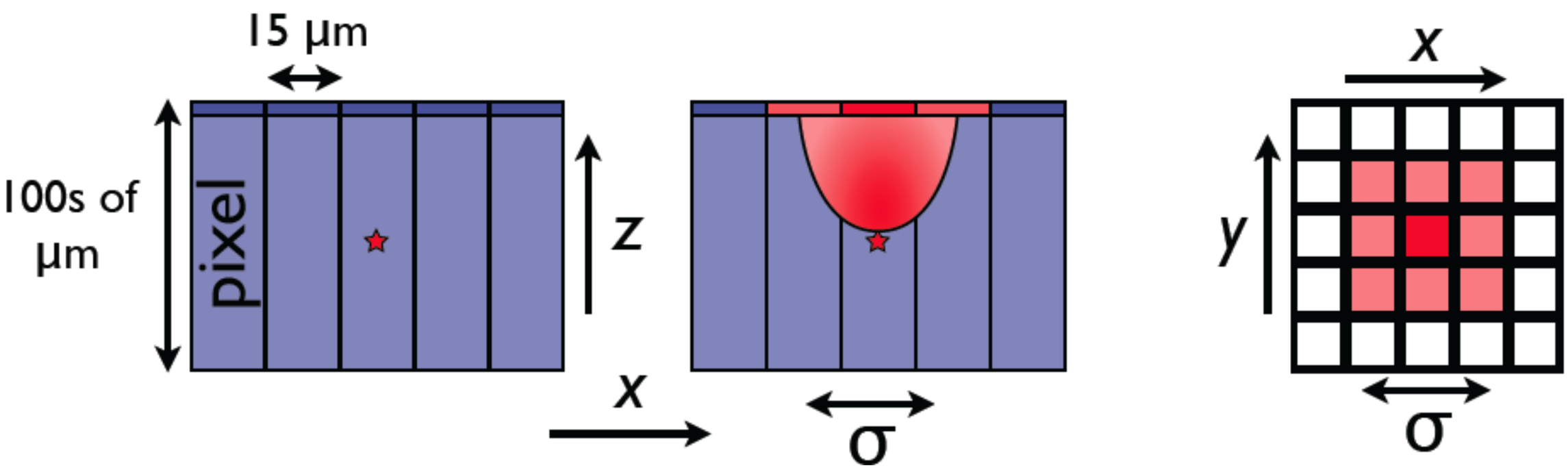


CCDs for dark matter (or CEvNS)



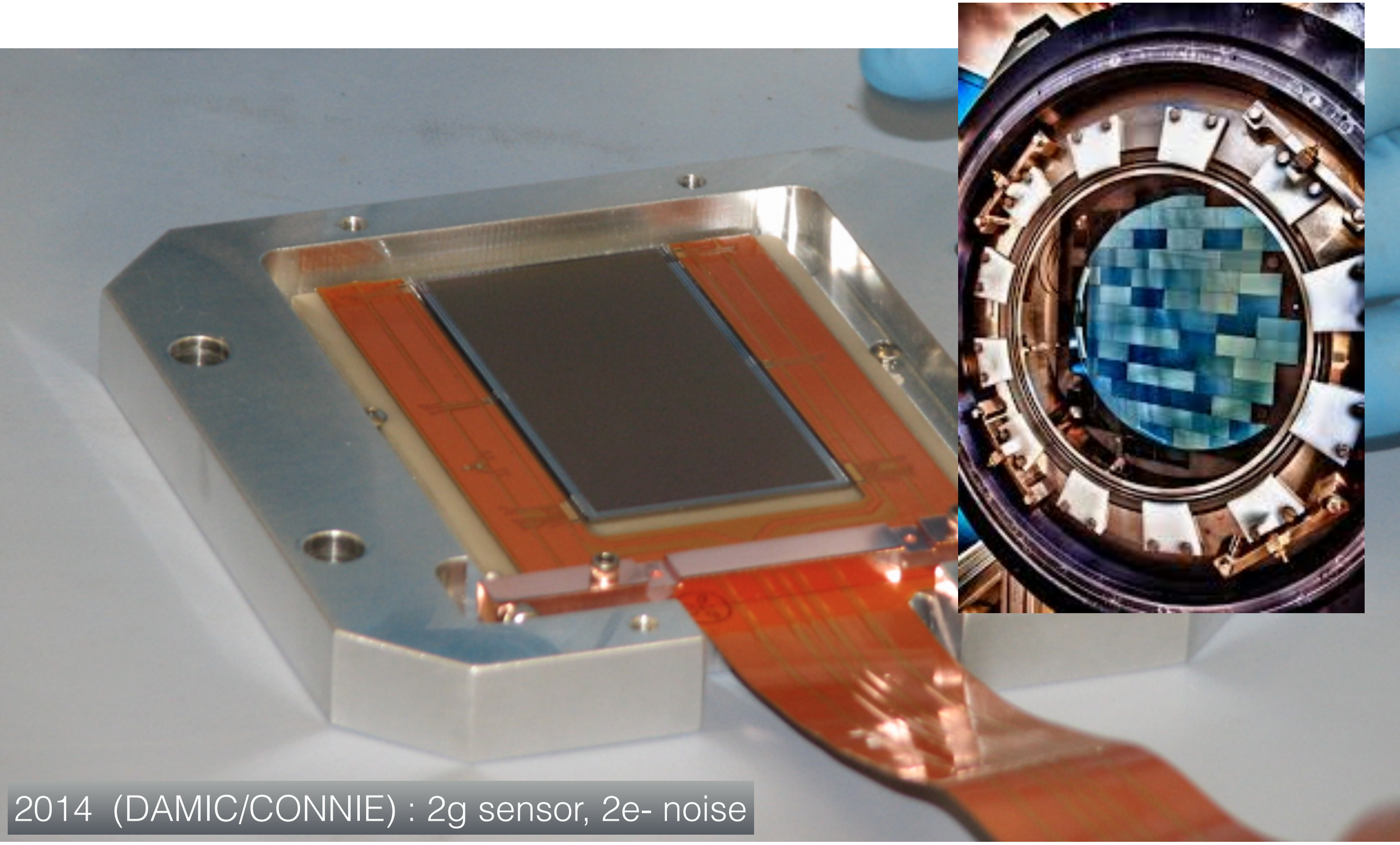
(a) A CCD pixel

(b) WIMP detection principle



"Recent" developments by the MSL group at LBNL has allowed the fabrication for thick CCDs. 675 um is now possible.

DECam

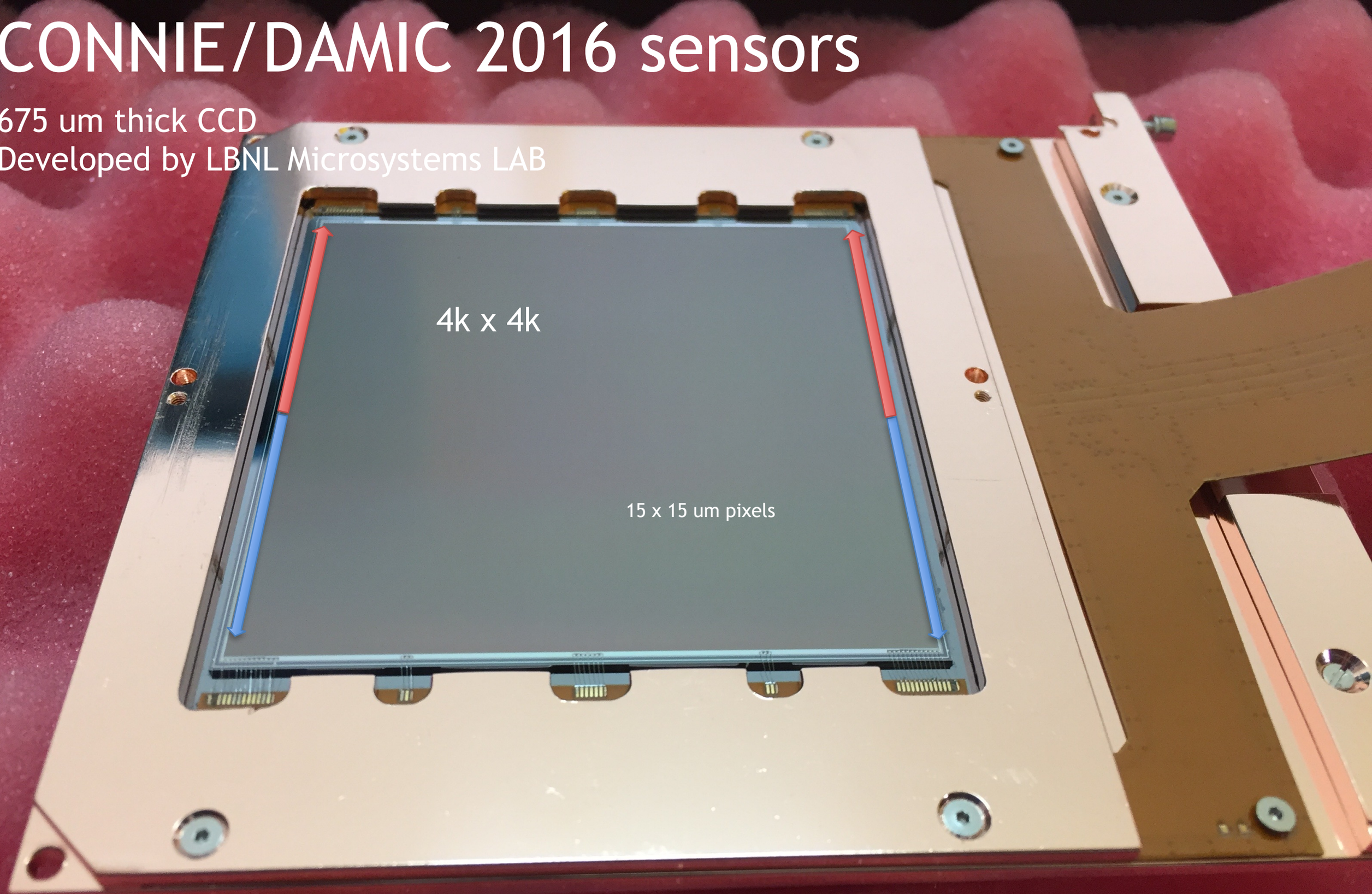


2014 (DAMIC/CONNIE) : 2g sensor, 2e- noise

essentially “borrowed” CCDs from Dark Energy Camera, and looked for dark matter

CONNIE/DAMIC 2016 sensors

675 um thick CCD
Developed by LBNL Microsystems LAB

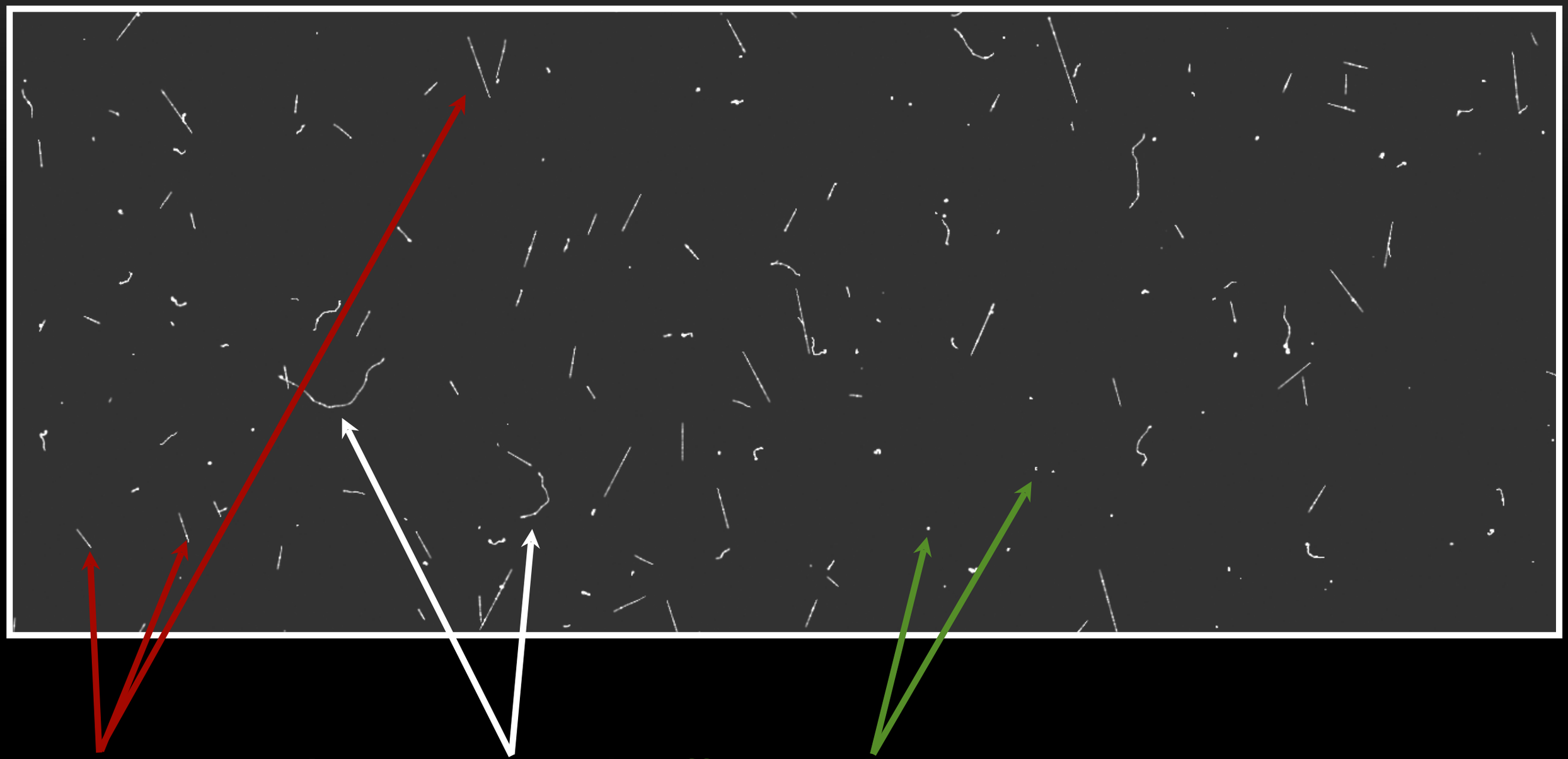


4 amplifiers
2e- noise
low background package

16 Mpix ~ 6g

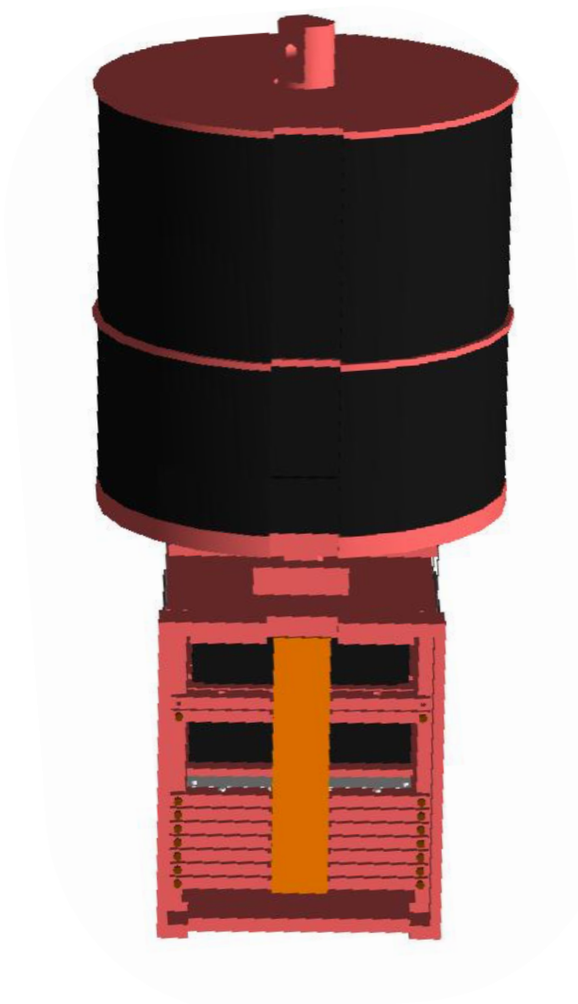
CCDs for fabricated for DM and neutrinos

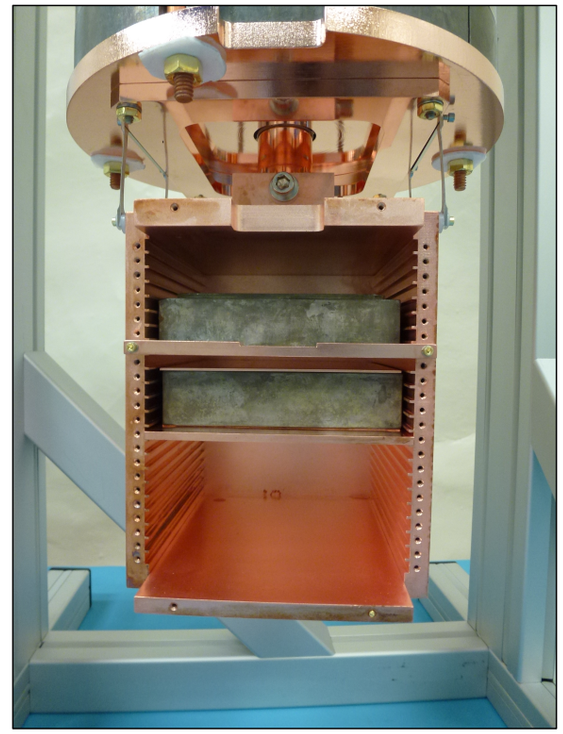
Particle identification in a CCD image

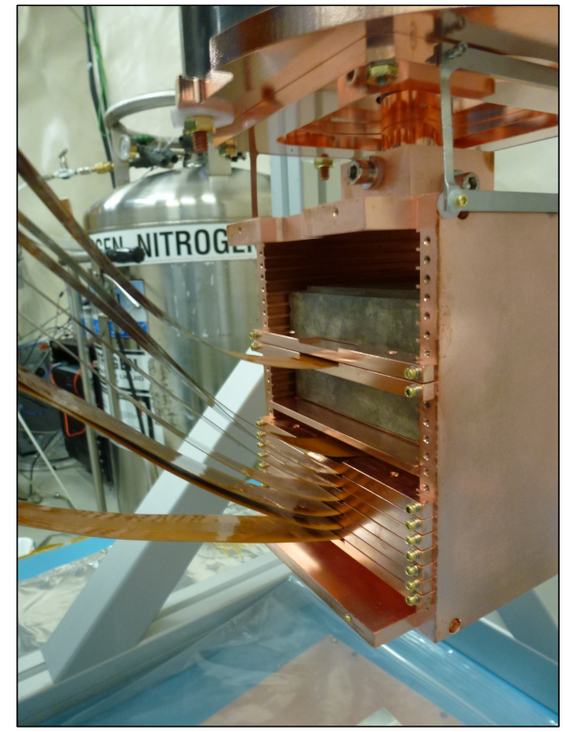


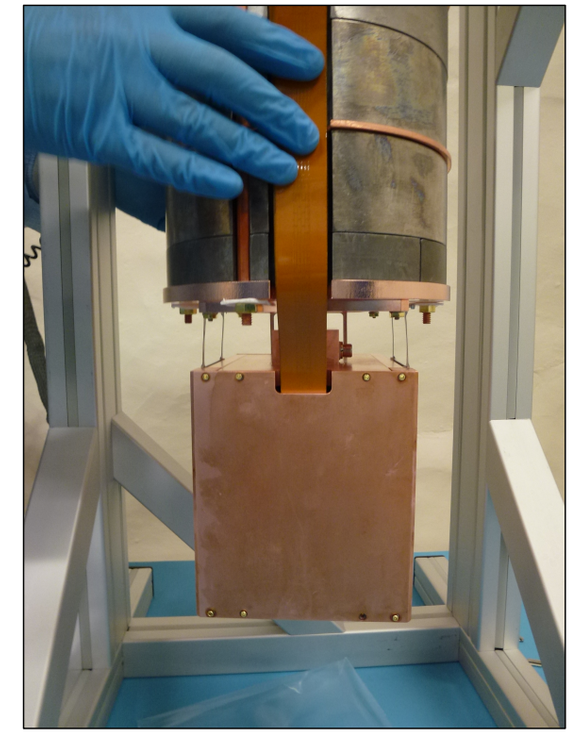
muons, electrons and diffusion limited hits.

DAMIC @ SNOLAB
started in 2014

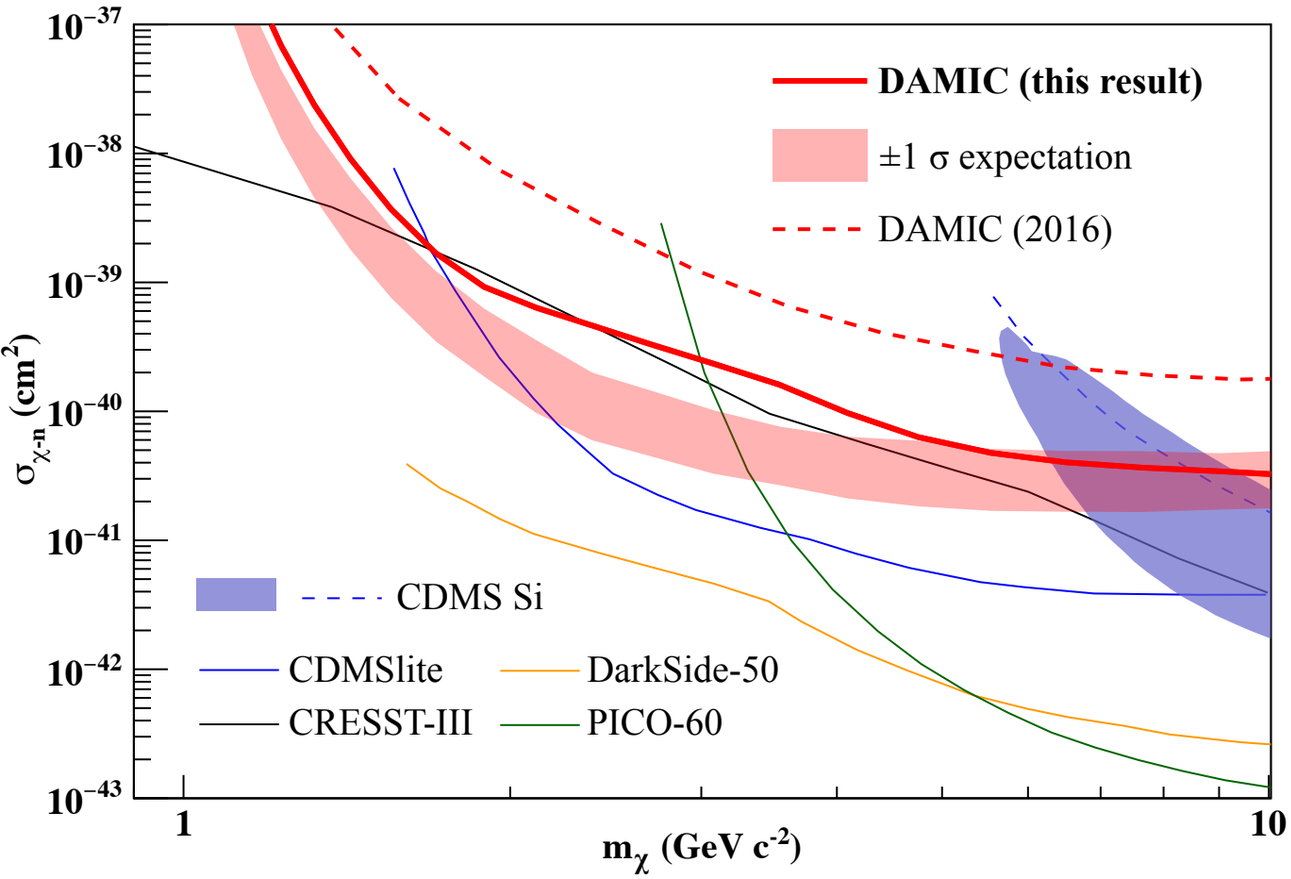




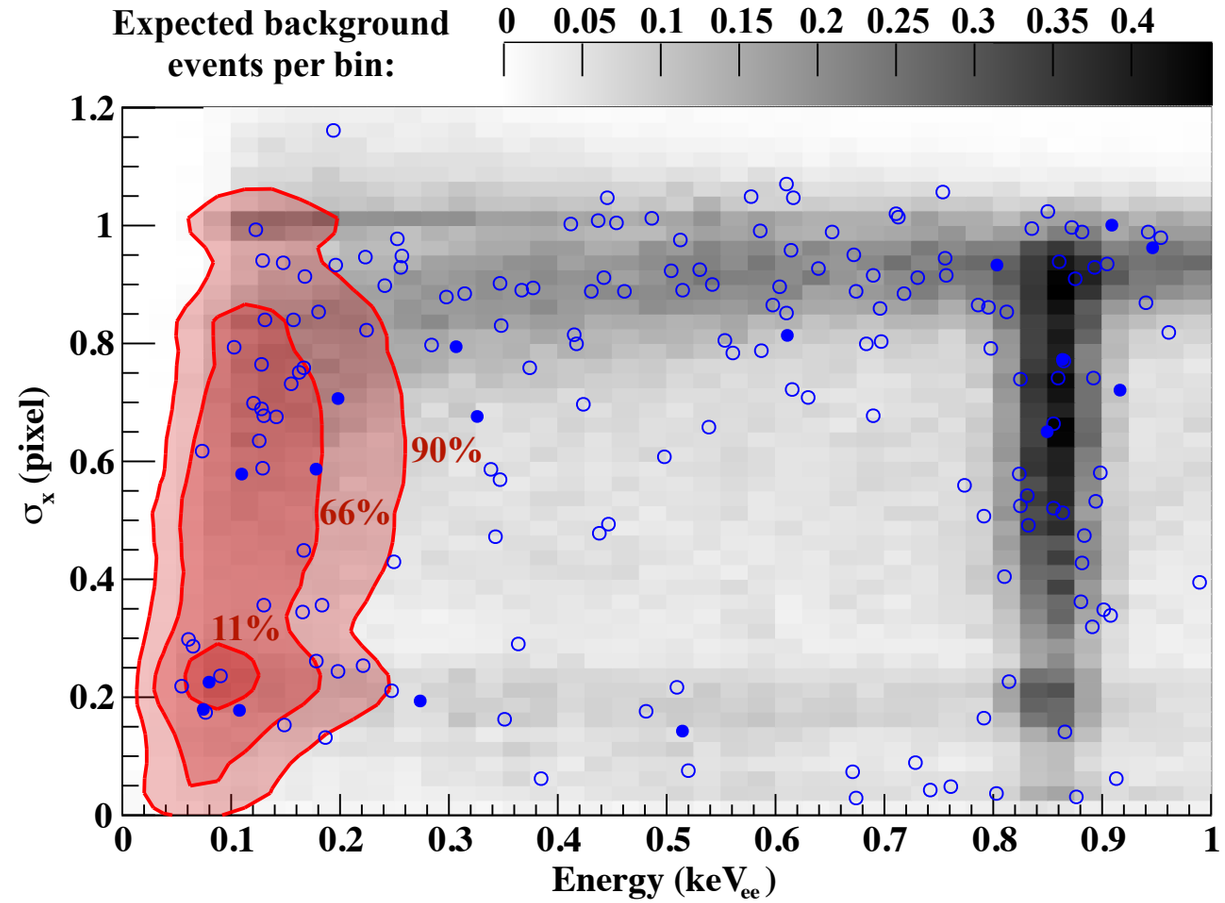




new WIMP result DAMIC: arXiv:2007.15622



Phys. Rev. Lett. 125, 241803 (2020)



We have pushed as far as we can we classic CCDs… now we need other tools.

FIG. 3. Best-fit to the final data sample in (E, σ_x) space. The blue data points are overlaid on the best-fit background model in gray. Open circles correspond to CCDs 2–7, while filled circles correspond to CCD 1. The red contours represent the best-fit exponential excess with ϵ=66 eV$_{ee}$. The Ne K de-excitation line (0.85 keV$_{ee}$) emitted following electron capture by ^{22}Na in the CCD bulk is visible.

skipper-CCD: not a new invention,

1

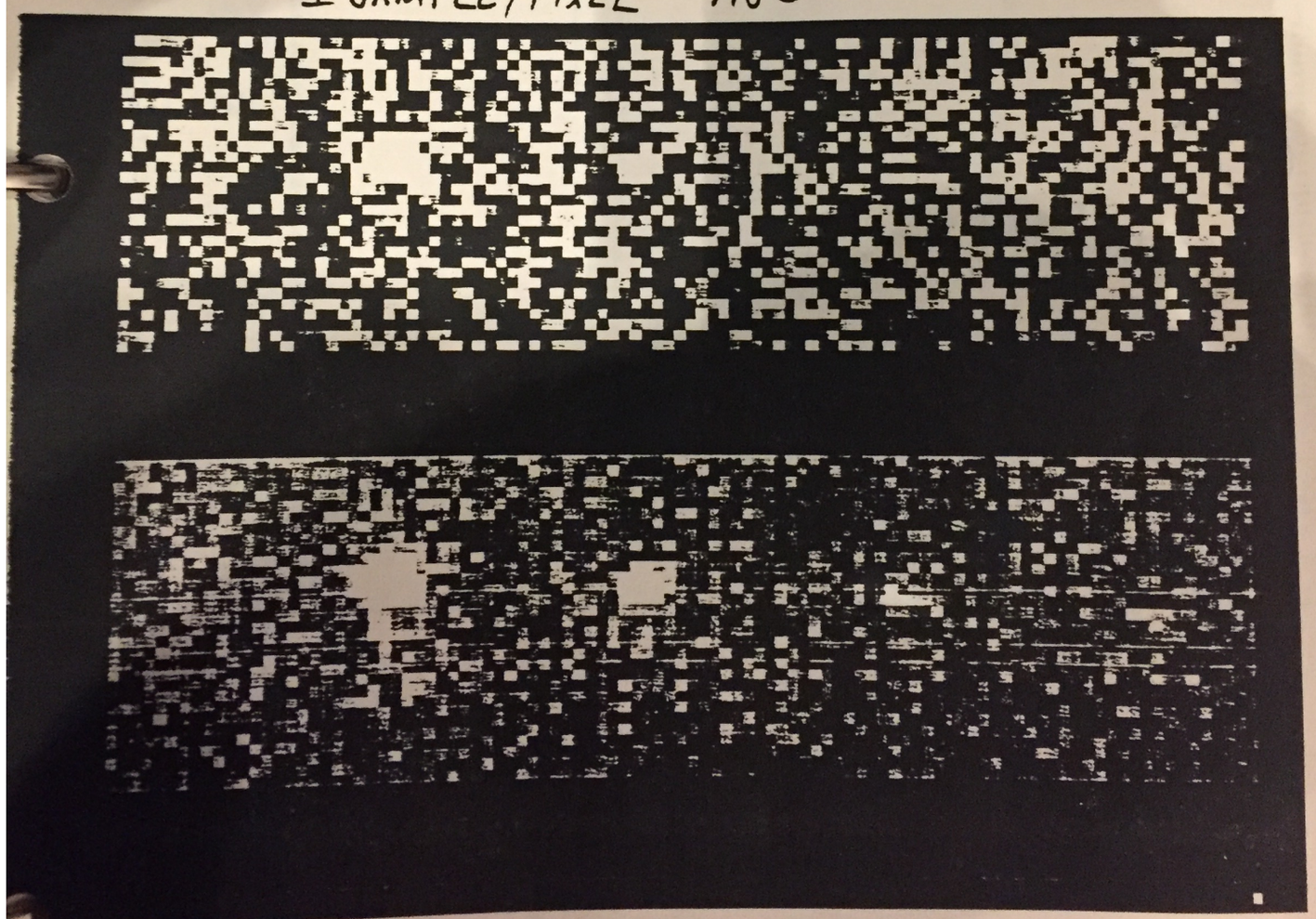
July 18, 1989

Amazing!

To: Distribution
From: J. Janesick, T. Elliott, A. Dingizian
Subject: SKIPPER IMAGING

The two images below demonstrate the power of the Skipper CCD in detecting ultra-low signals. The first image was generated by sampling each pixel once. A read noise of 7.8 electrons is achieved. The second image, which employs 64 samples/pixel, achieves a noise floor of slightly less than 1 electron rms. Four point images are seen, the smallest at the 3-4 electron level. In the top picture only the larger point image can be distinguished. However, in the Skipper image all four can be clearly discerned.

1 SAMPLE/PIXEL 7.8e⁻



SKIPPER – 64 SAMPLES/PIXEL 0.98e⁻

Scientific Charge-Coupled Devices — **J. Janesick 2000 CCD textbook**

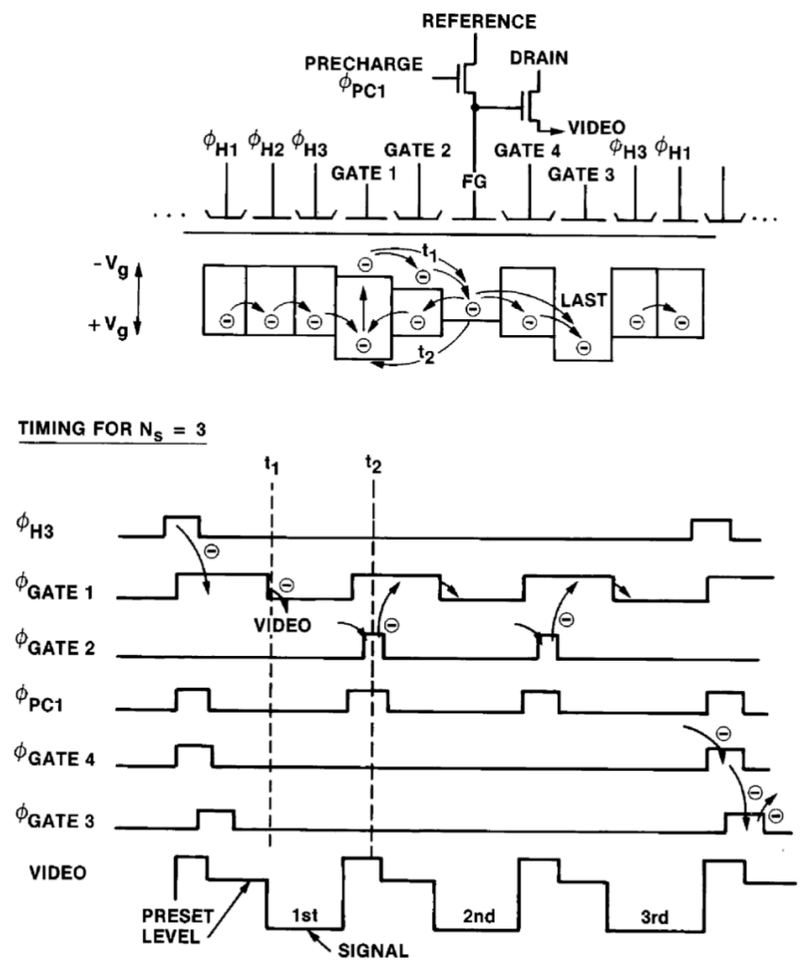


Figure 6.55 Timing diagram for Skipper operation.

The first Skipper CCD fabricated exhibited a high noise level (7.6 e^-), in part due to a non-LDD amplifier configuration. Improvements in amplifier sensitivity have reduced the noise to <3 e^-/sample, allowing subelectron performance in

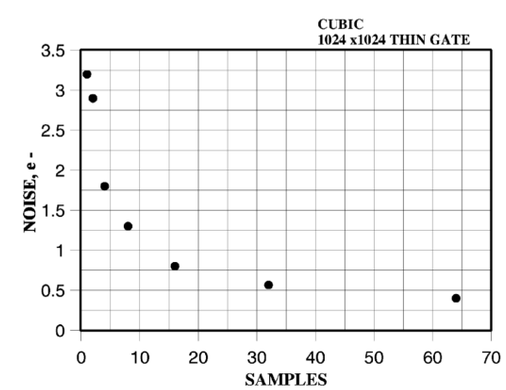
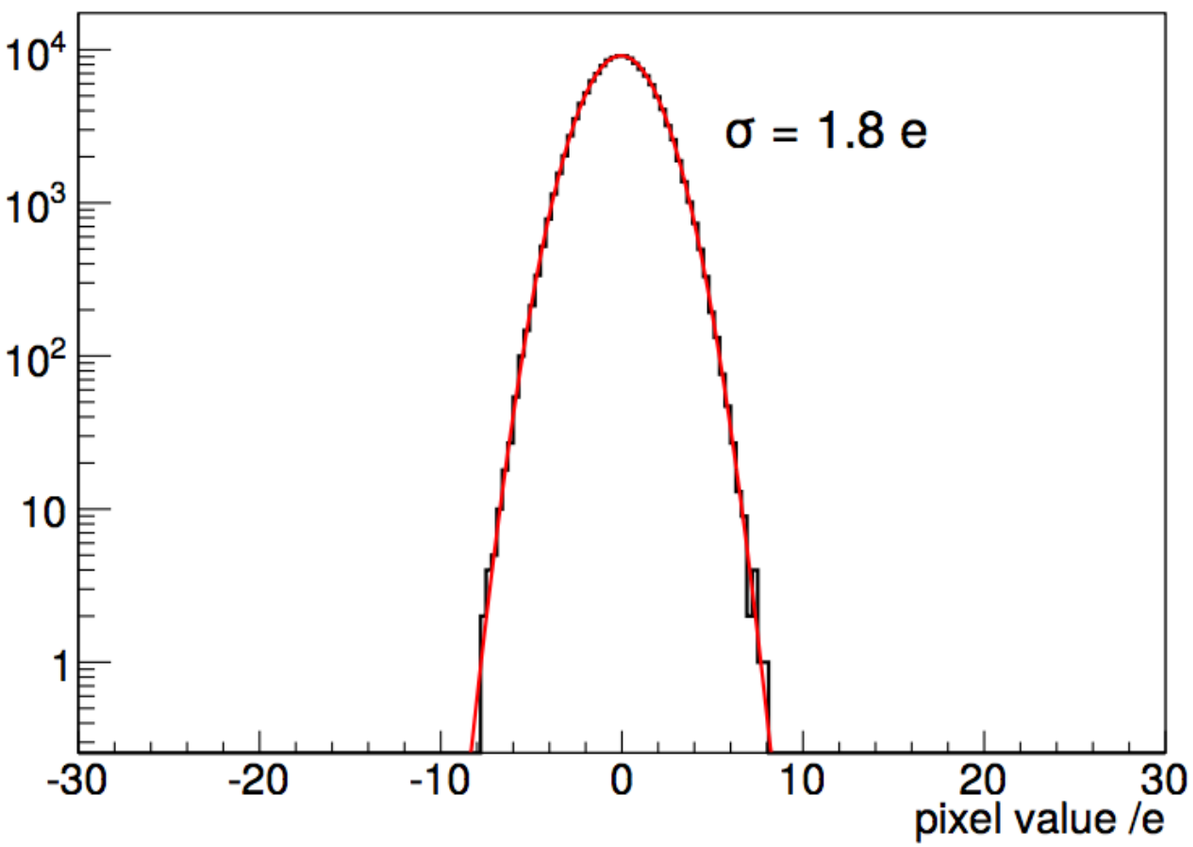


Figure 6.59 Read noise as a function of number of samples for a 1024 × 1024 Skipper CCD.

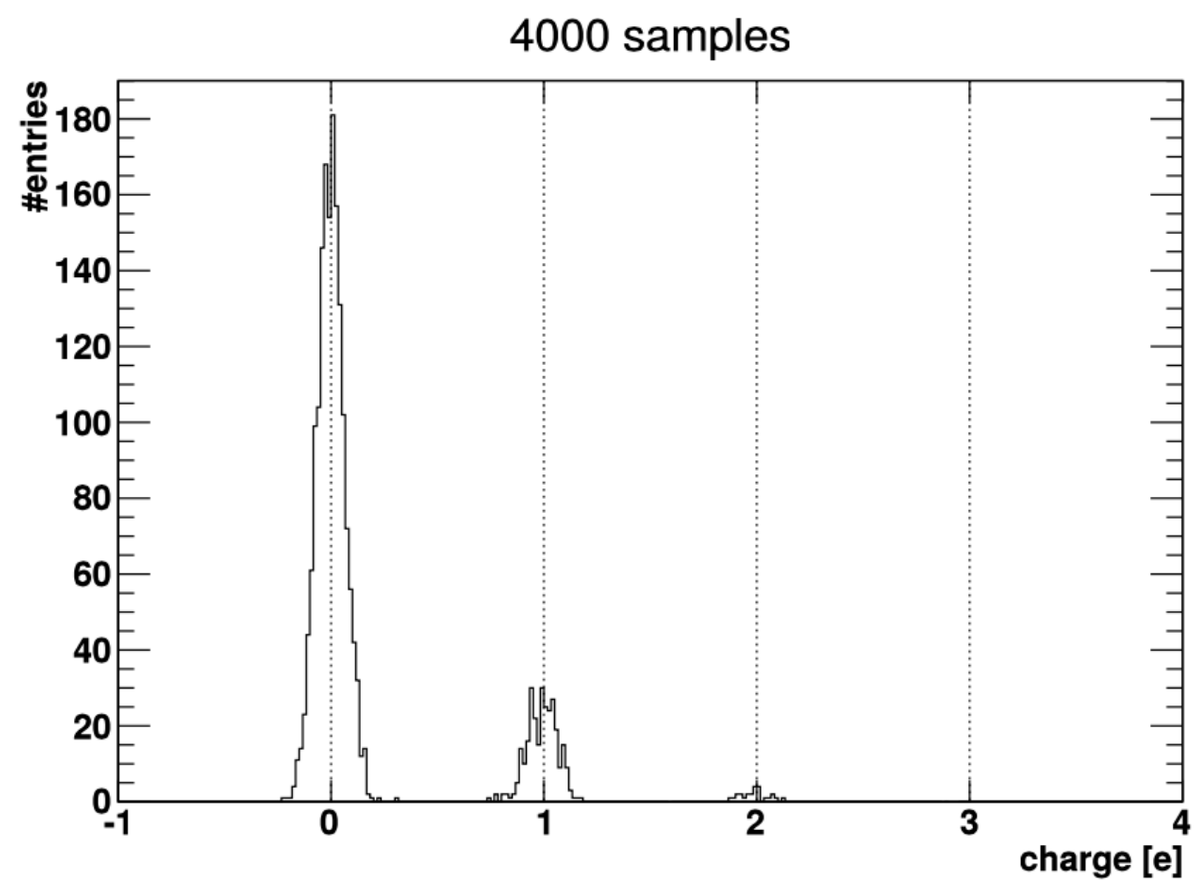
Single-electron and single-photon sensitivity with silicon Skipper-CCD (J. Tiffenberg et al)

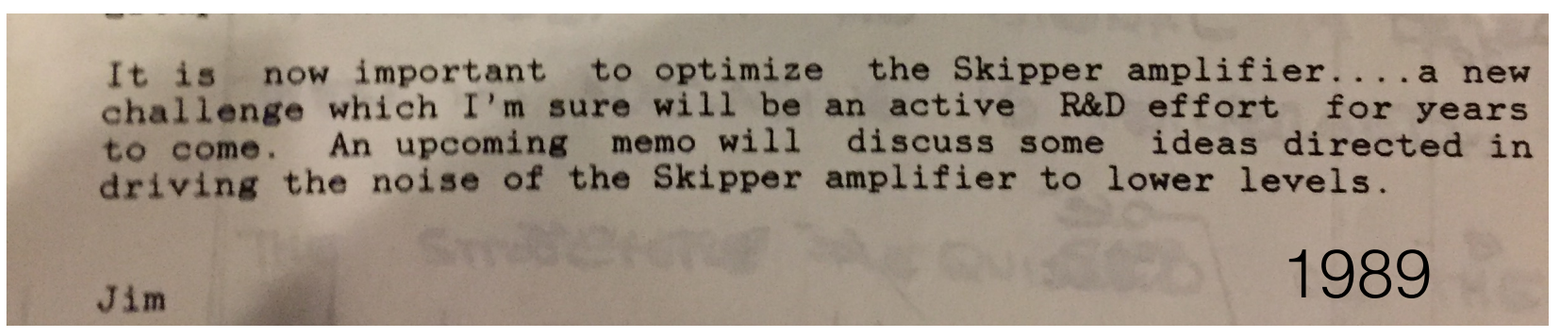
Physical Review Letters, Volume 119, Issue 13, (2017)

DAMIC “classic CCD”



skipper CCD





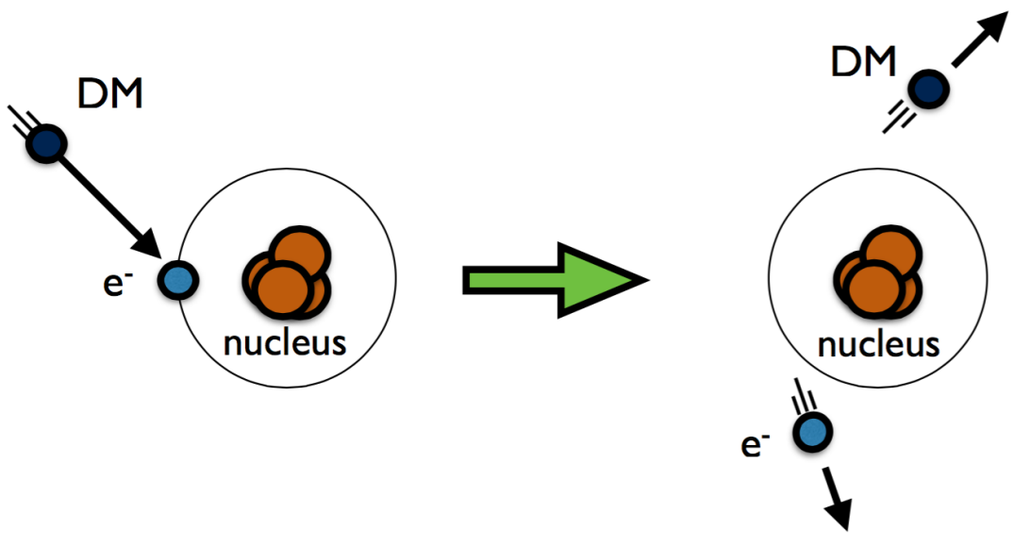
It is now important to optimize the Skipper amplifier....a new challenge which I'm sure will be an active R&D effort for years to come. An upcoming memo will discuss some ideas directed in driving the noise of the Skipper amplifier to lower levels.

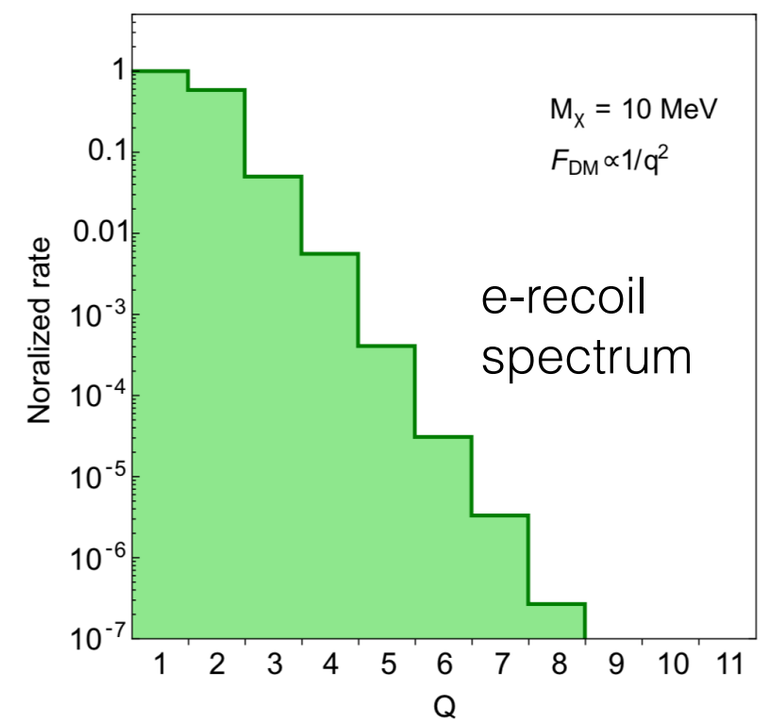
Jim

1989

… it was not a very active field, but it took ~30 years for the optimization

the "classic" search for wimps looks for nuclear recoils, but when looking at lower mass particles the e-recoil channel could be more competitive.





biding energy (~1 eV)

$$E_{\rm DM} \sim \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 > \Delta E$$

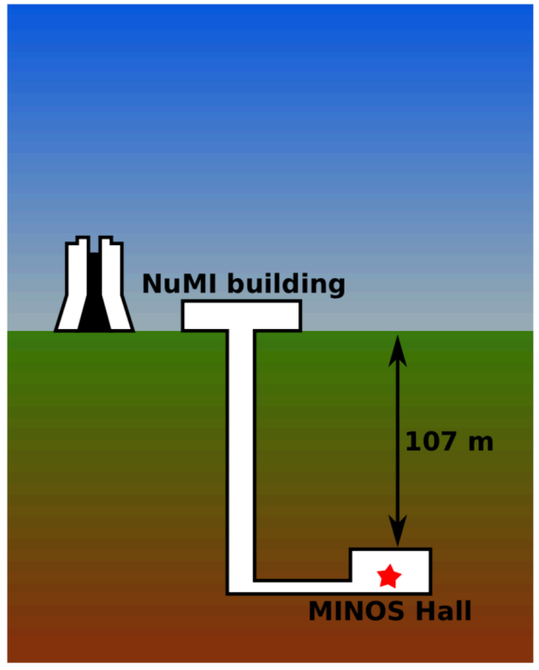
$$v_{\rm DM} \lesssim 800 \text{ km/s} \implies m_{\rm DM} \gtrsim 300 \text{ keV} \left(\frac{\Delta E}{1 \text{ eV}}\right)$$

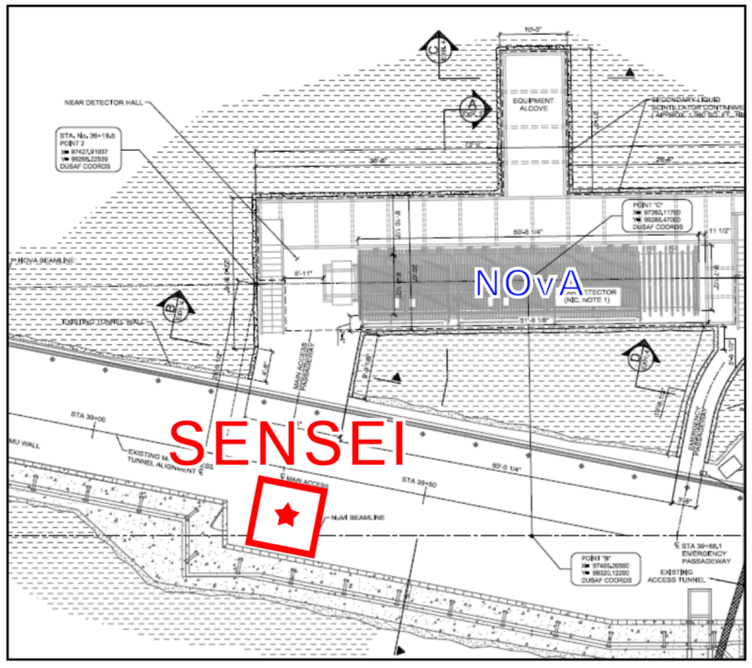
typical recoil energy: $\Delta E \sim 4$ eV

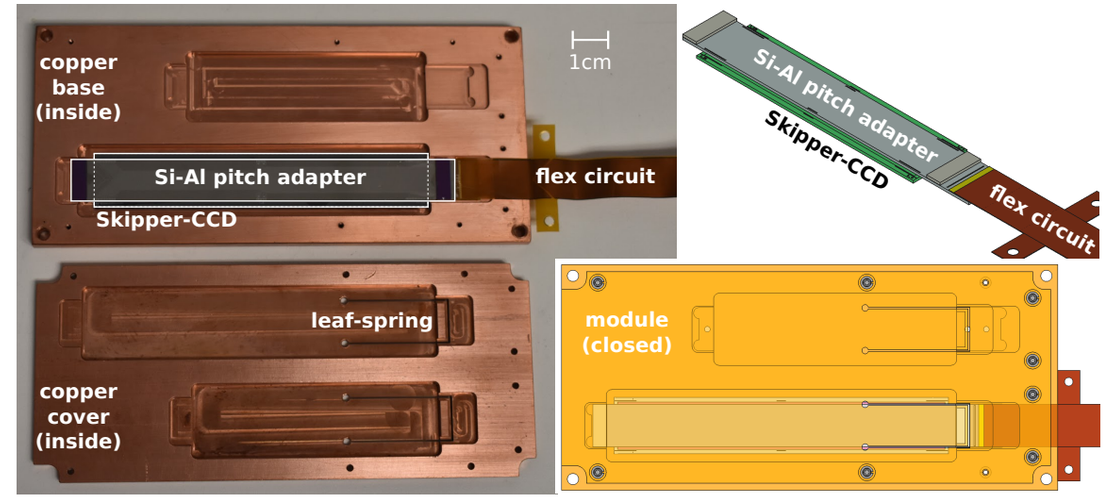
early sensei theory team

Essig, Volansky, Yu

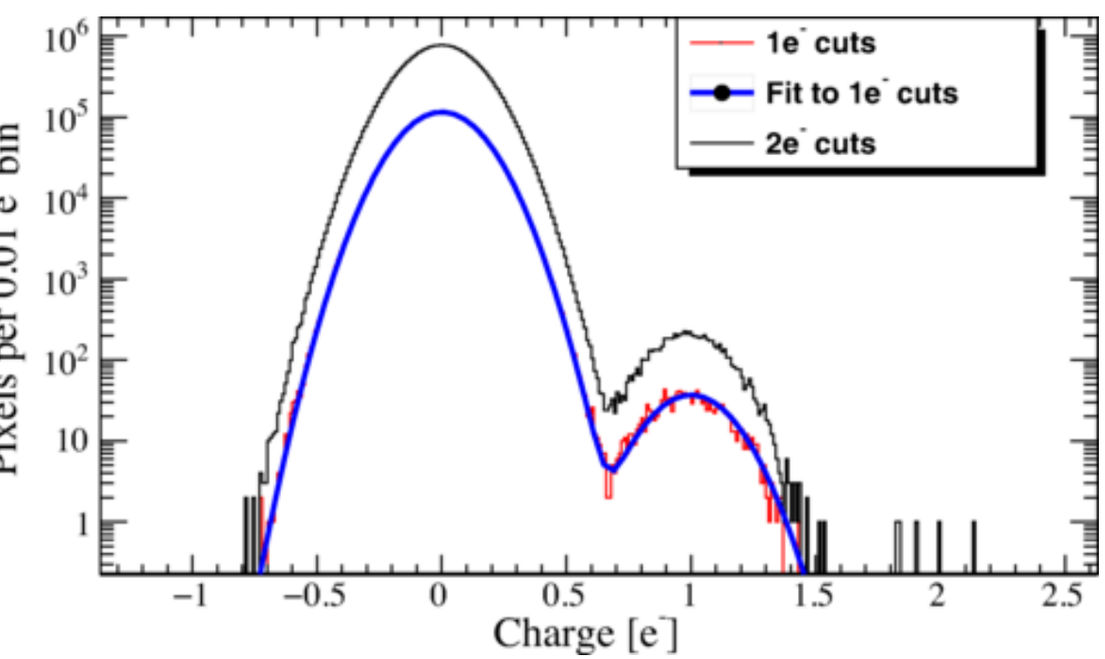
The first step was operation of a single detector ~2g at MINOS

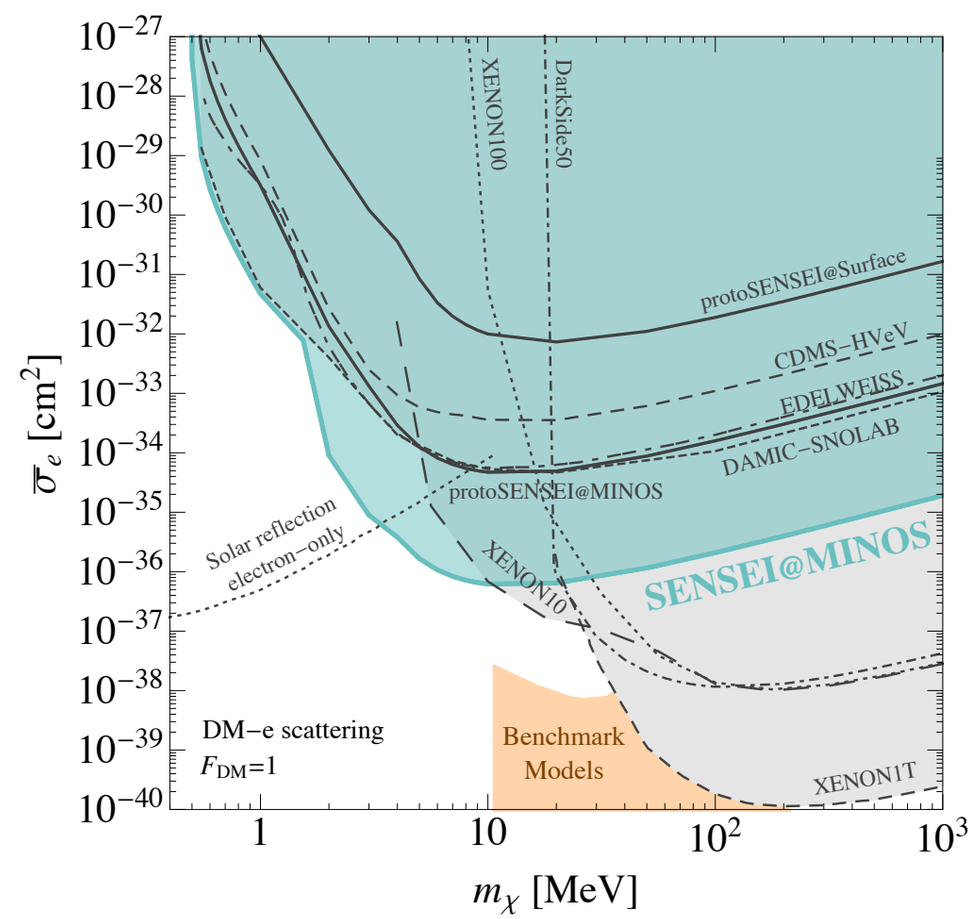






Phys. Rev. Lett. **125**, 171802 (2020)

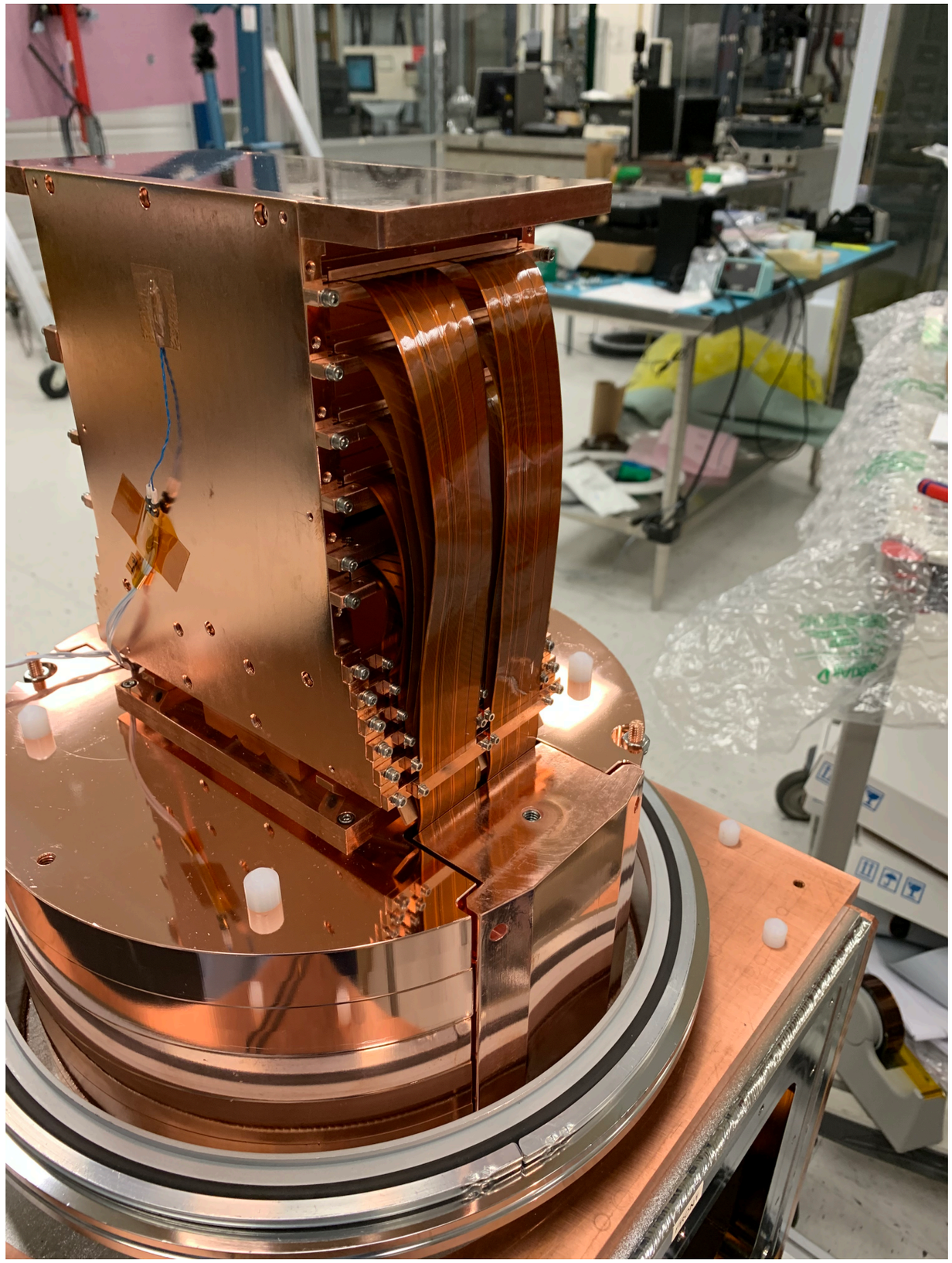


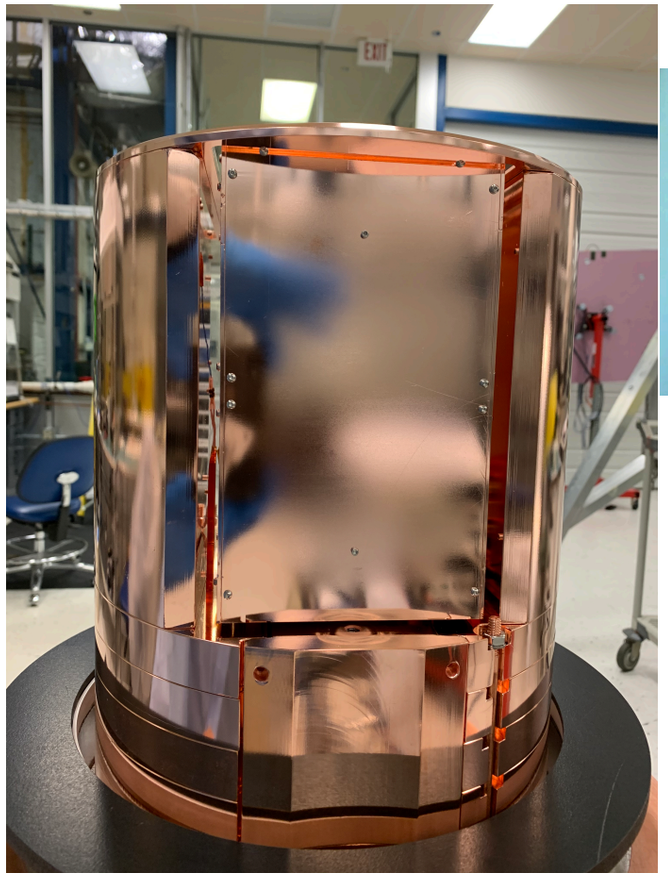


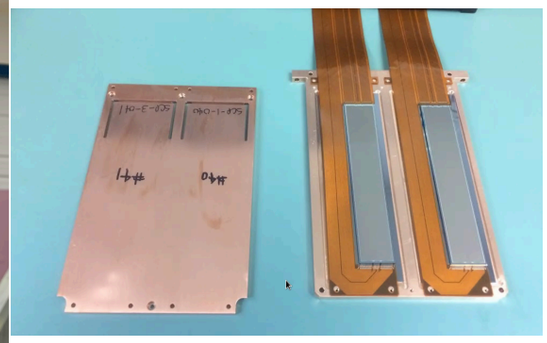
Rates:

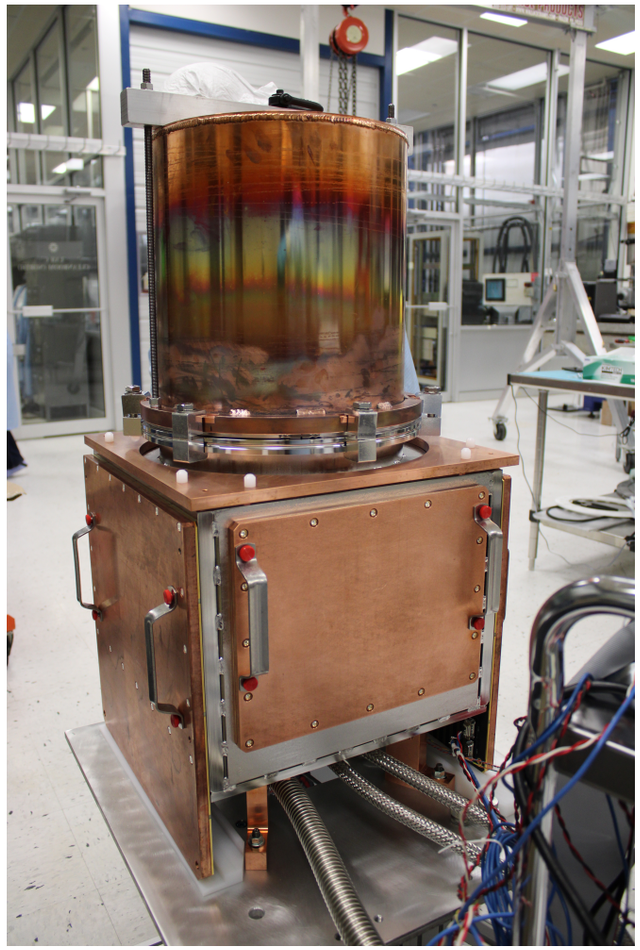
- 1e- = 450 ev/g-day (1.6 10^{-4} e/pix/day)
- 2e- = 2.4 ev./g-day

SENSEI 100g









Now underground @ SNOLAB. Starting installation in a couple of weeks.

Oscura : 10-kg skipper-CCD experiment

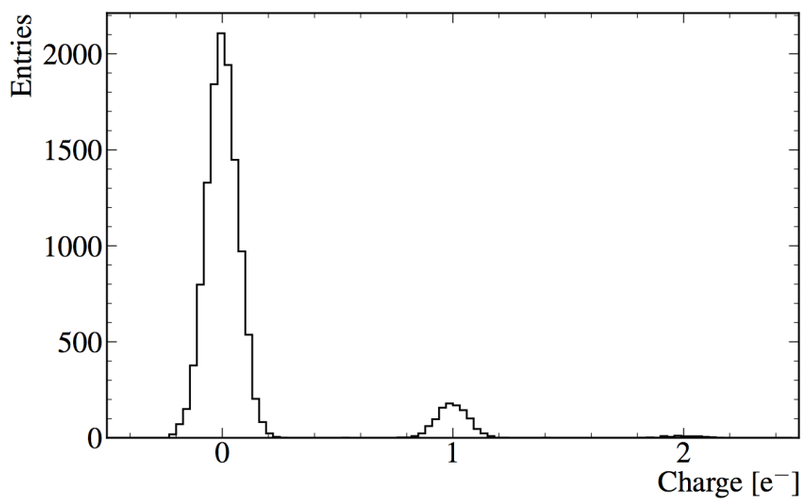
https://astro.fnal.gov/science/dark-matter/oscura/

- **Observatory of Skipper CCDs Using Recoiling Atoms**
- **Science goal : e-recoil low mass direct dark matter search (1 MeV → 1 GeV)**
- **Technology : skipper-CCD array (sub-electron noise) at underground lab (SNOLAB, SURF, other).**
- **R&D: scale the existing technology towards a 10kg experiment**
- **Schedule : small project execution plan completed in 2023**

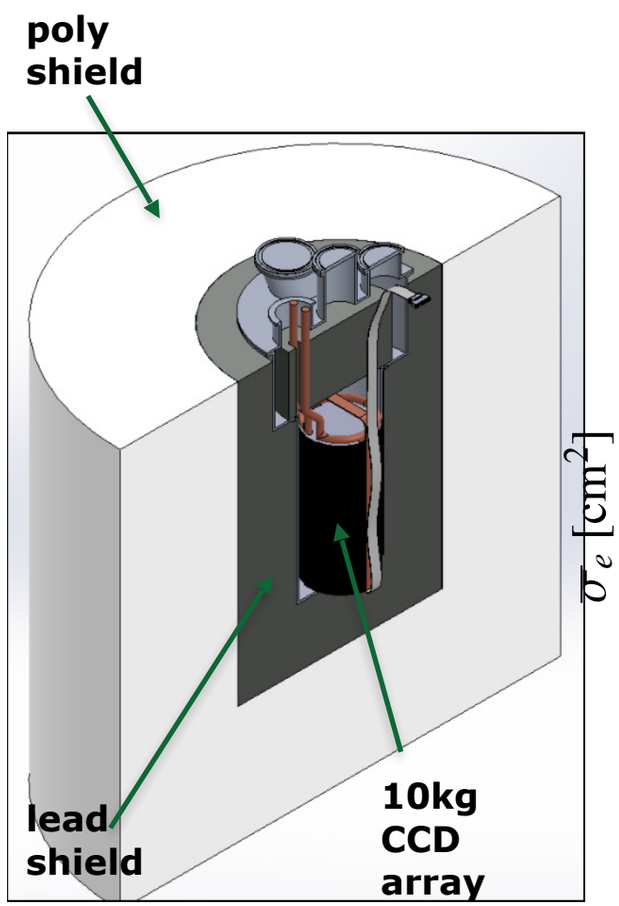
R&D: FY19,FY20,FY21

Design: FY22,FY23

Execution : FY24-27

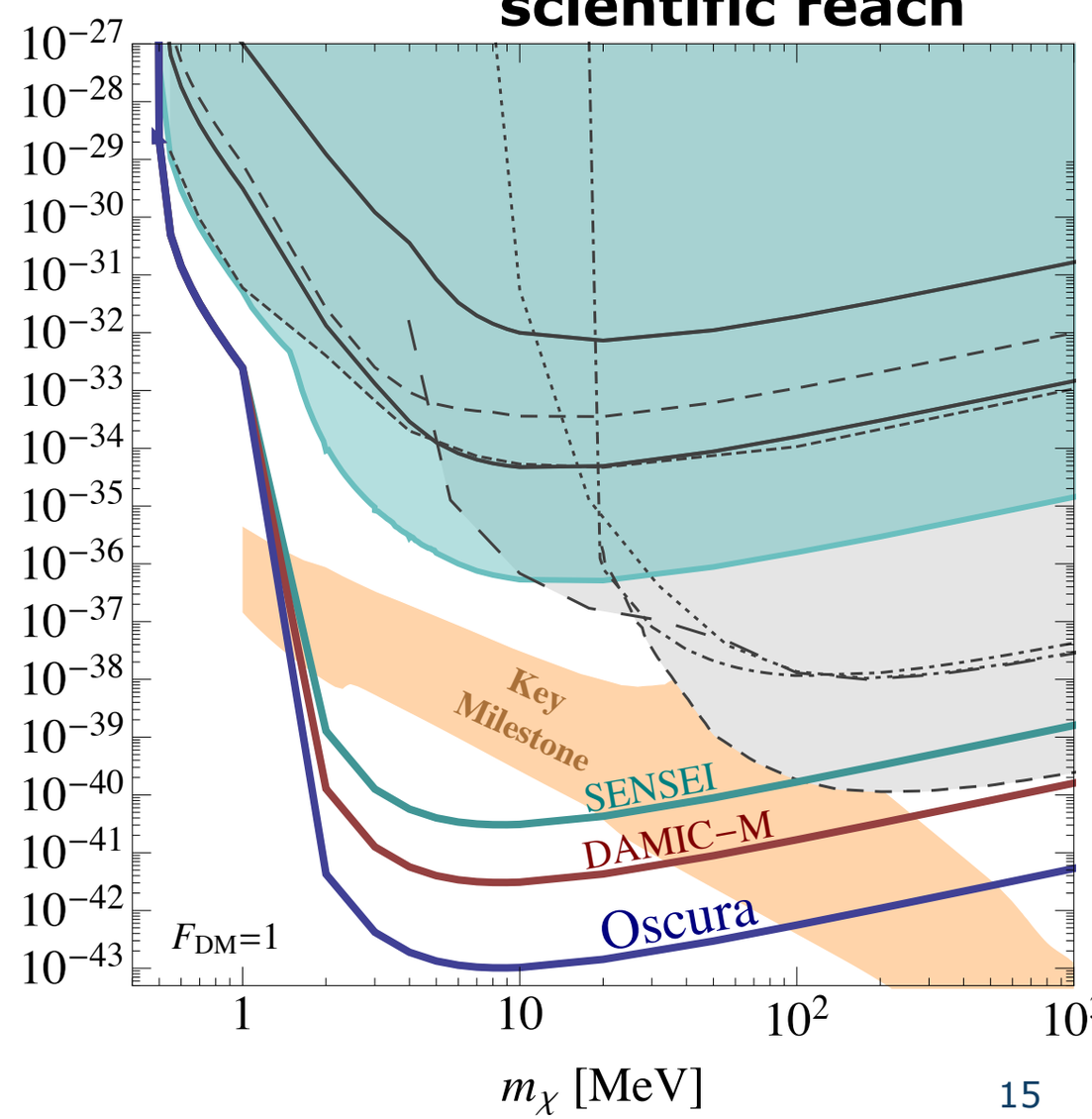


demonstrated performance of skipper-CCD



detector concept

scientific reach



Oscura R&D priorities

Sensors : transfer to new fab technology.

The foundry we have been using for our thick CCD (DM, dark energy, neutrinos) experiments is not going to continue with this technology. Need to find a new way of making the sensors. We also see this an as opportunity to take advantage of more modern technologies "CMOS-compatible"
This is where we starting to work with MIT-LL

Electronics: large channel number/cold electronics.

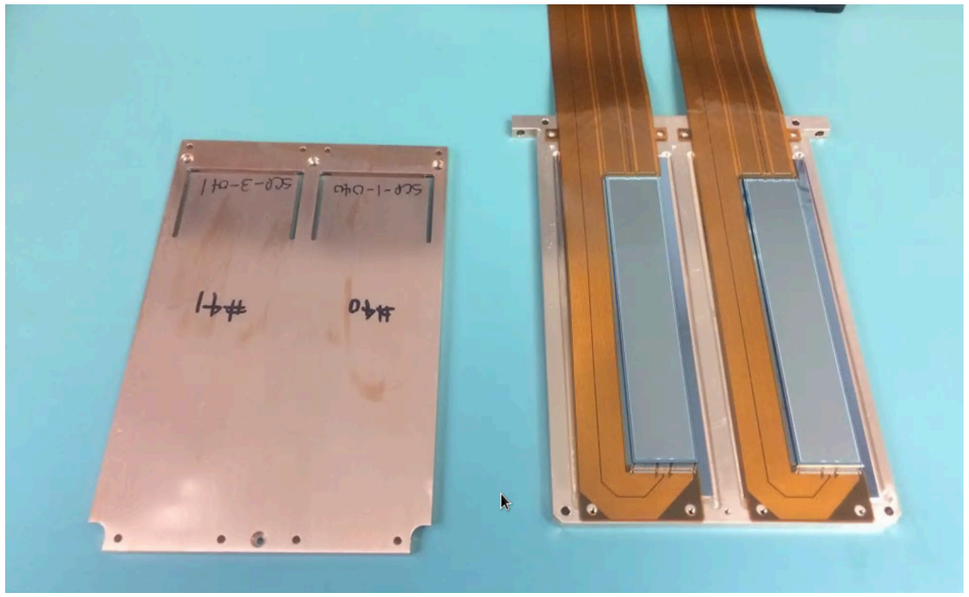
10 kg means a lot of CCD… and a lot of readout channels.

Background

The experiments need to have 0.01 events/kg/day/keV !

mechanical challenges

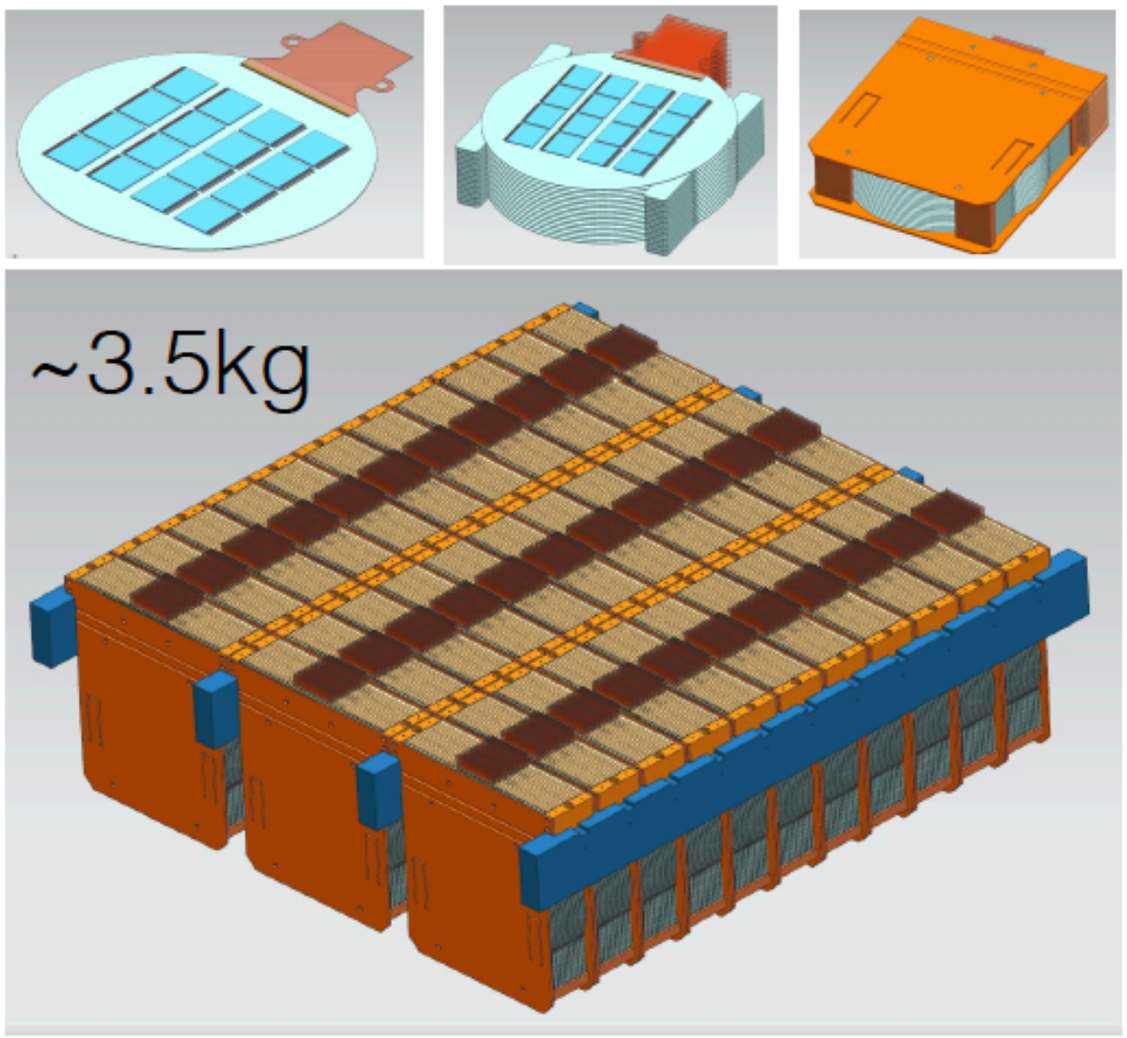
~4 gram CCD module (SENSEI)



We have developed experiments for ~100g of active mass with skipper-CCDs. We need to push for another factor of 100.

New ideas on packaging, cryogenics and electronics are needed.

Oscura is a a 28Gpix CCD array. The sensors have comic activation budget of 5 days. Electronics needs to be close to the package, but low background. New ideas on packaging, cryogenics and electronics are needed.



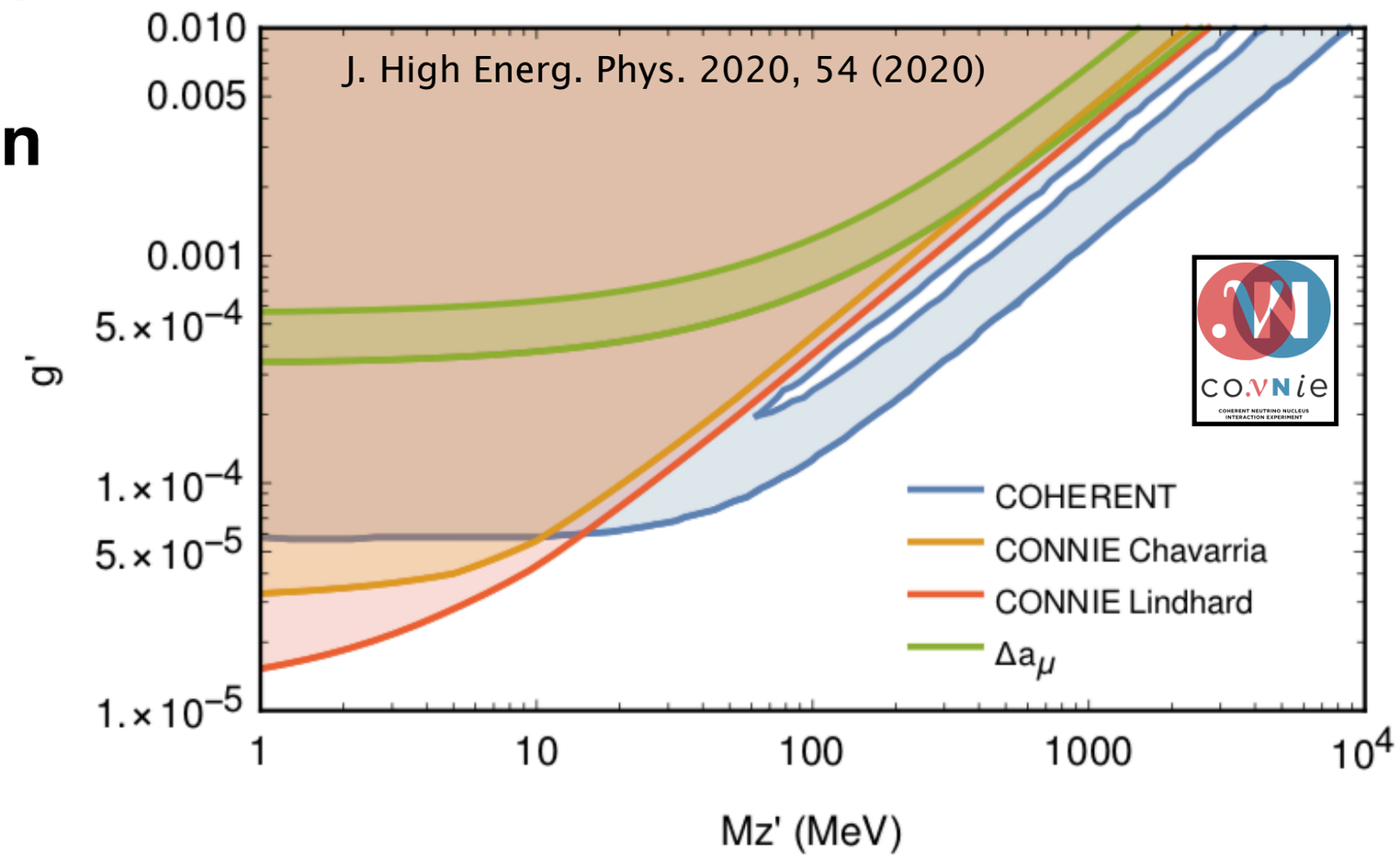
CEvNS

CCDs at nuclear reactor are exploring new physics in the low energy neutrino sector. CONNIE experiment.

As for the case of DM, skipper CCD extend the reach of these searches.

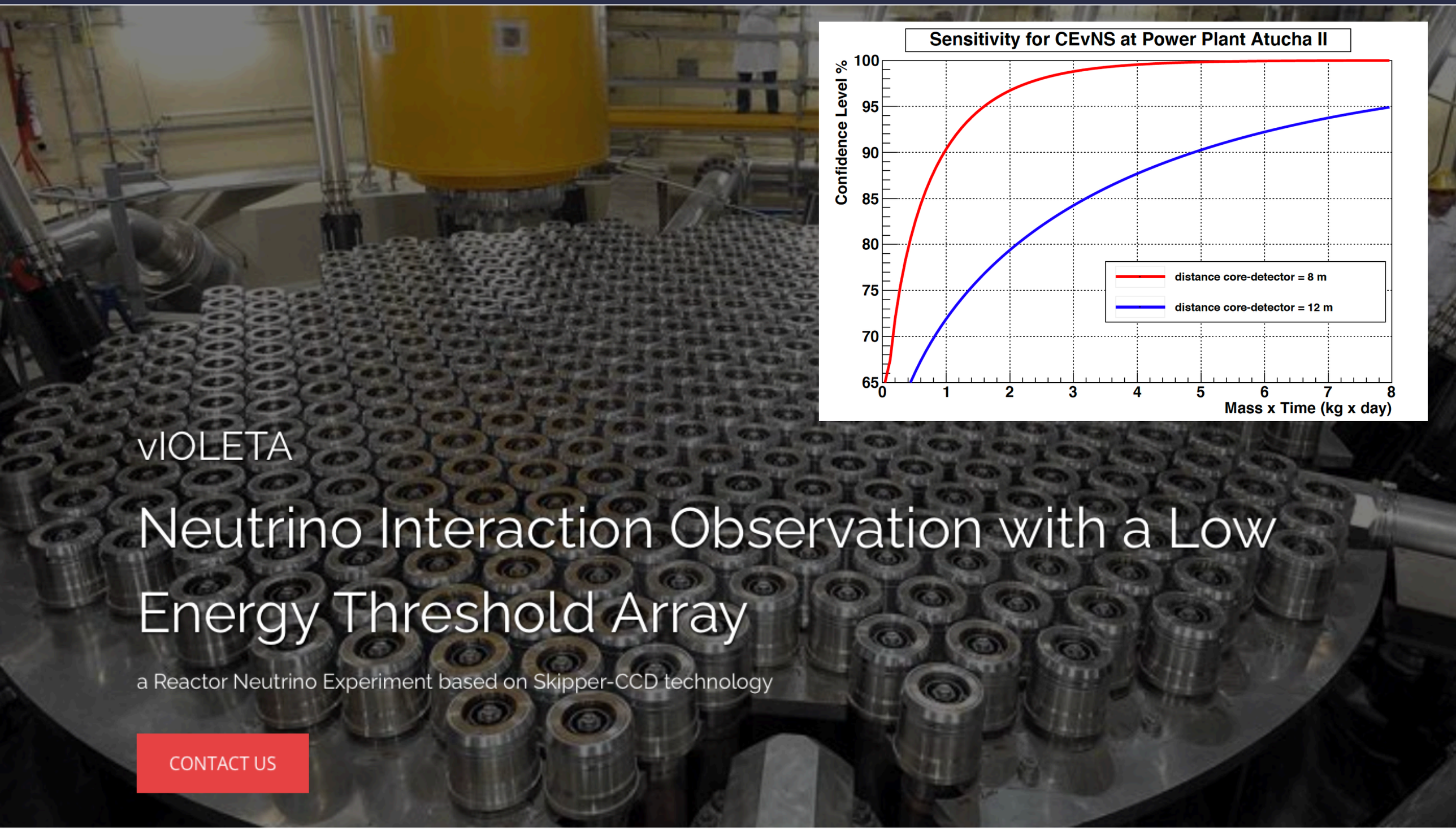
The Violeta collaboration is pushing for large skipper-CCD arrays at reactors.

search of for dark sector mediators



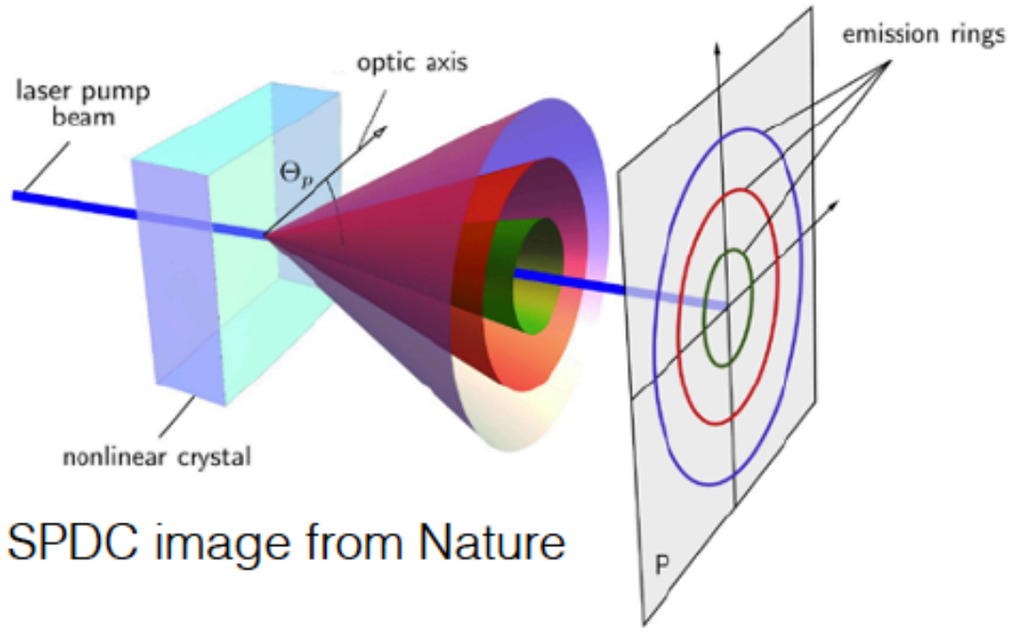
vIOLETA Experiment

HOME | PHYSICS GOALS | PROJECTED SENSITIVITIES | SKIPPER-CCD | ABOUT VIOLETA | COLLABORATION MEMBERS | JOIN US!



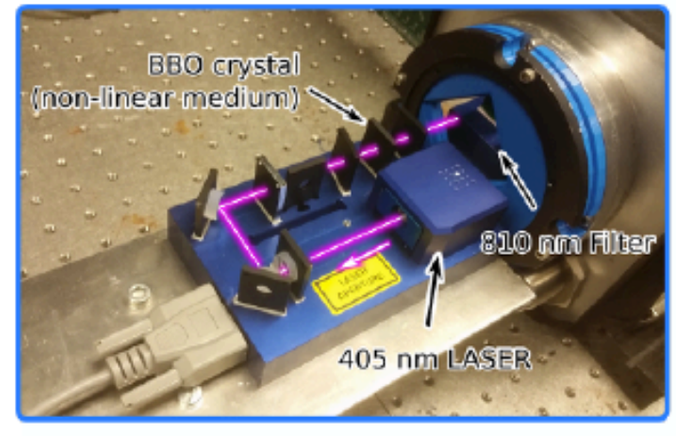
https://www.violetaexperiment.com

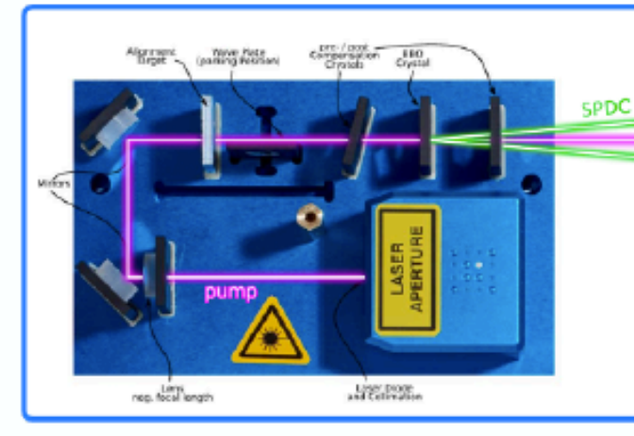
Quantum imaging with skipper-CCD



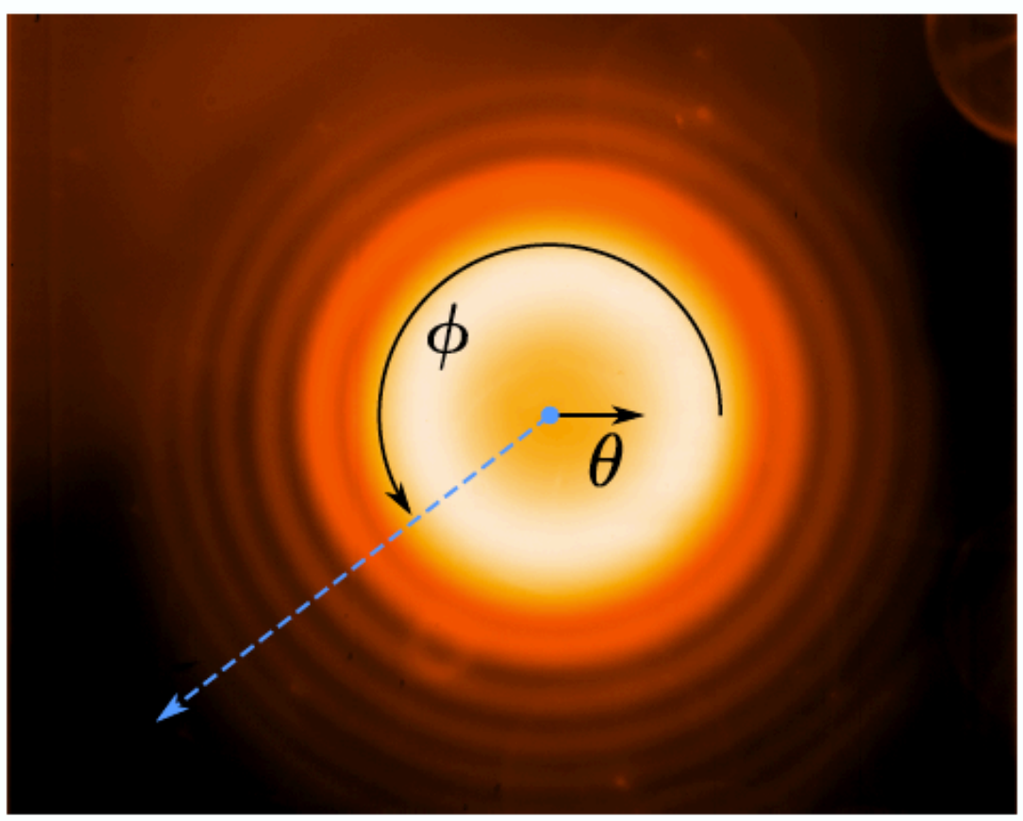
SPDC image from Nature

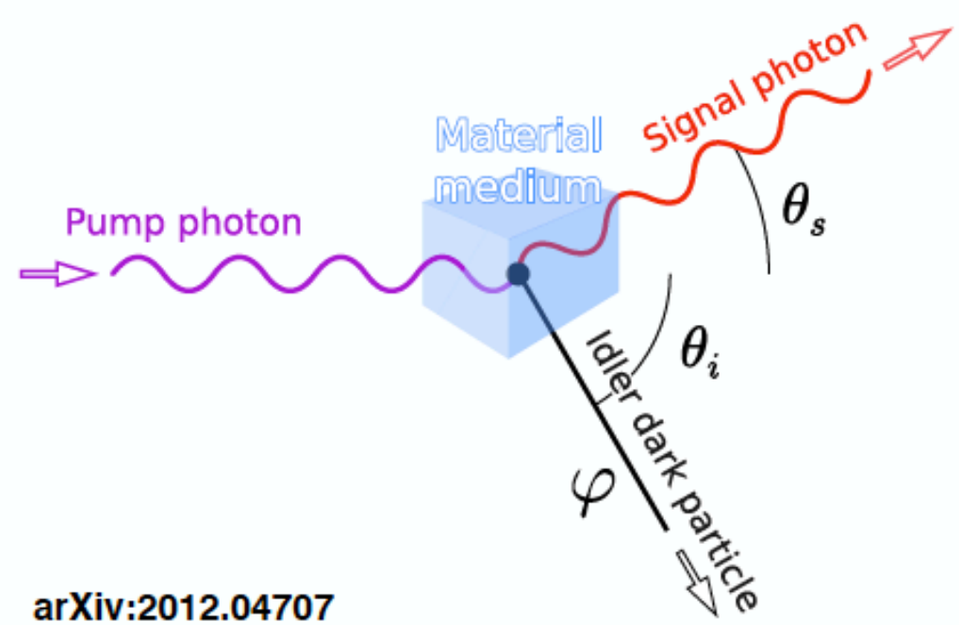
At FNAL





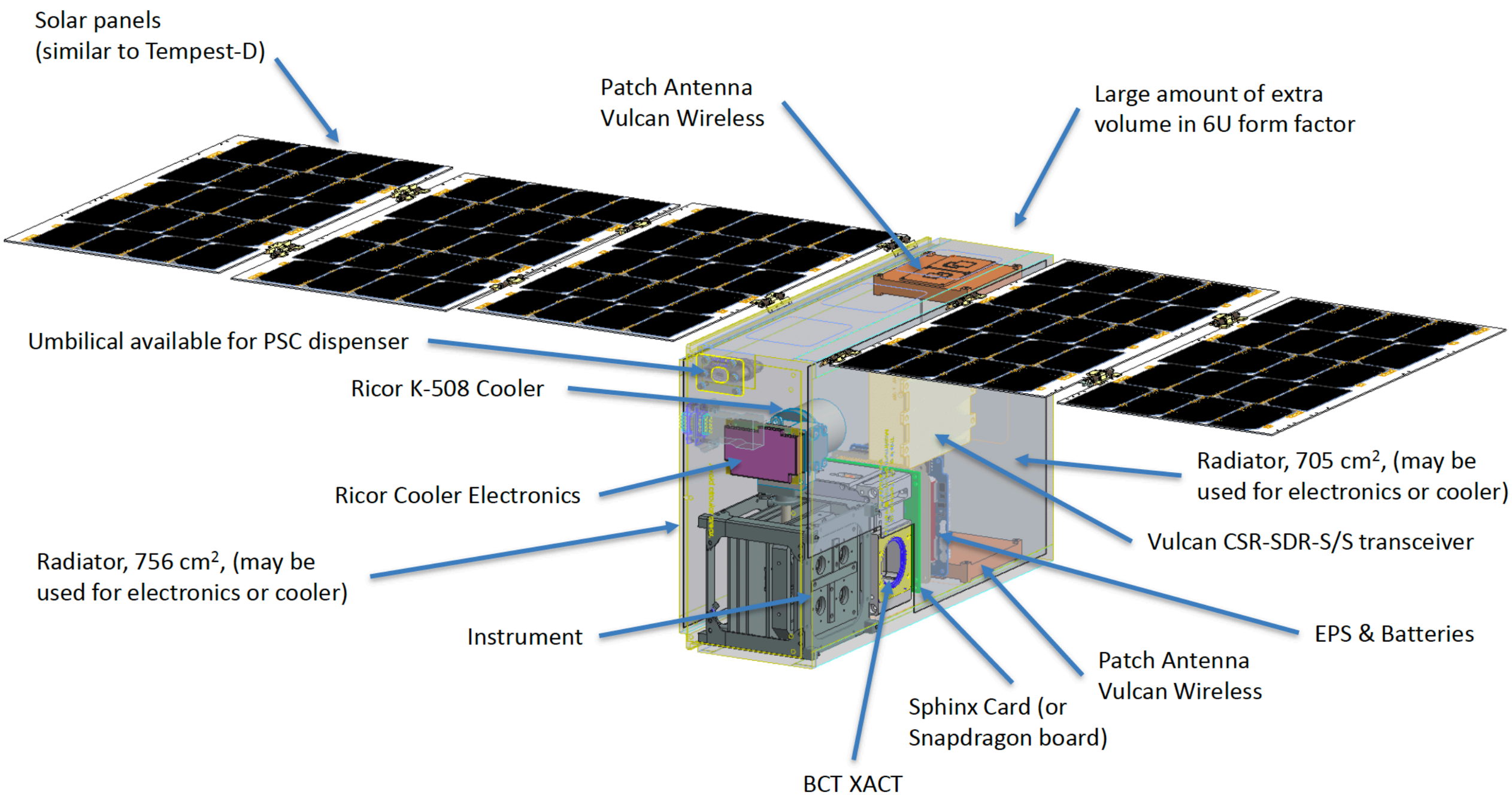
LASER → BBO → FILTERS → Skipper CCD





arXiv:2012.04707

Darkness satellite to mount CCDs in space for direct dark matter search (Team-X study 2019 JPL)



credits

Steve Holland (LBNL)	*CCD designer*
Fernando Chierchie (UNS)	*smart skipper readout*
Alex Drilica-Wagner (FNAL)	*astronomy applications*
Guillermo Fernandez (FNAL)	*Neutrinos and smart skipper*
Roni Harnik (FNAL)	*QIS applications*
Dario Rodrigues (UBA)	*QIS applications*
Matias Senger (UBA)	*QIS applications*
Miguel Sofo-Haro (CAB)	*sensors and readout*
Javier Tiffenberg (FNAL)	*first demo and dark matter*
DAMIC Collaboration	*WIMP search*
SENSEI Collaboration	*e-recoil dark matter*
CONNIE Collaboration	*CEvNS*
Oscura Collaboration	*future dark matter experiment*
Violeta Collaboration	*future reactor experiment*

We present constraints on the existence of weakly interacting massive particles (WIMPs) from an 11 kg d target exposure of the DAMIC experiment at the SNOLAB underground laboratory. The observed energy spectrum and spatial distribution of ionization events with electron-equivalent energies >200 eVee in the DAMIC CCDs are consistent with backgrounds from natural radioactivity.

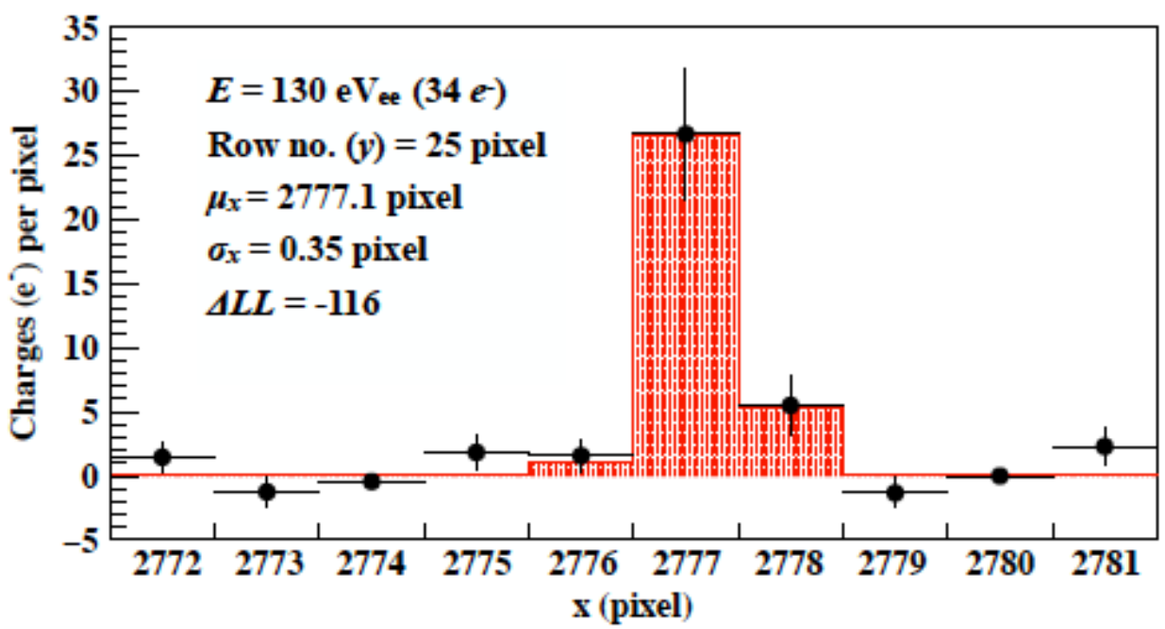


FIG. 1. Data cluster in the WIMP search energy region. The black markers show the pixel values along the row while the red histogram is the result of the best-fit Gaussian function. Cluster variables are given in the inset.

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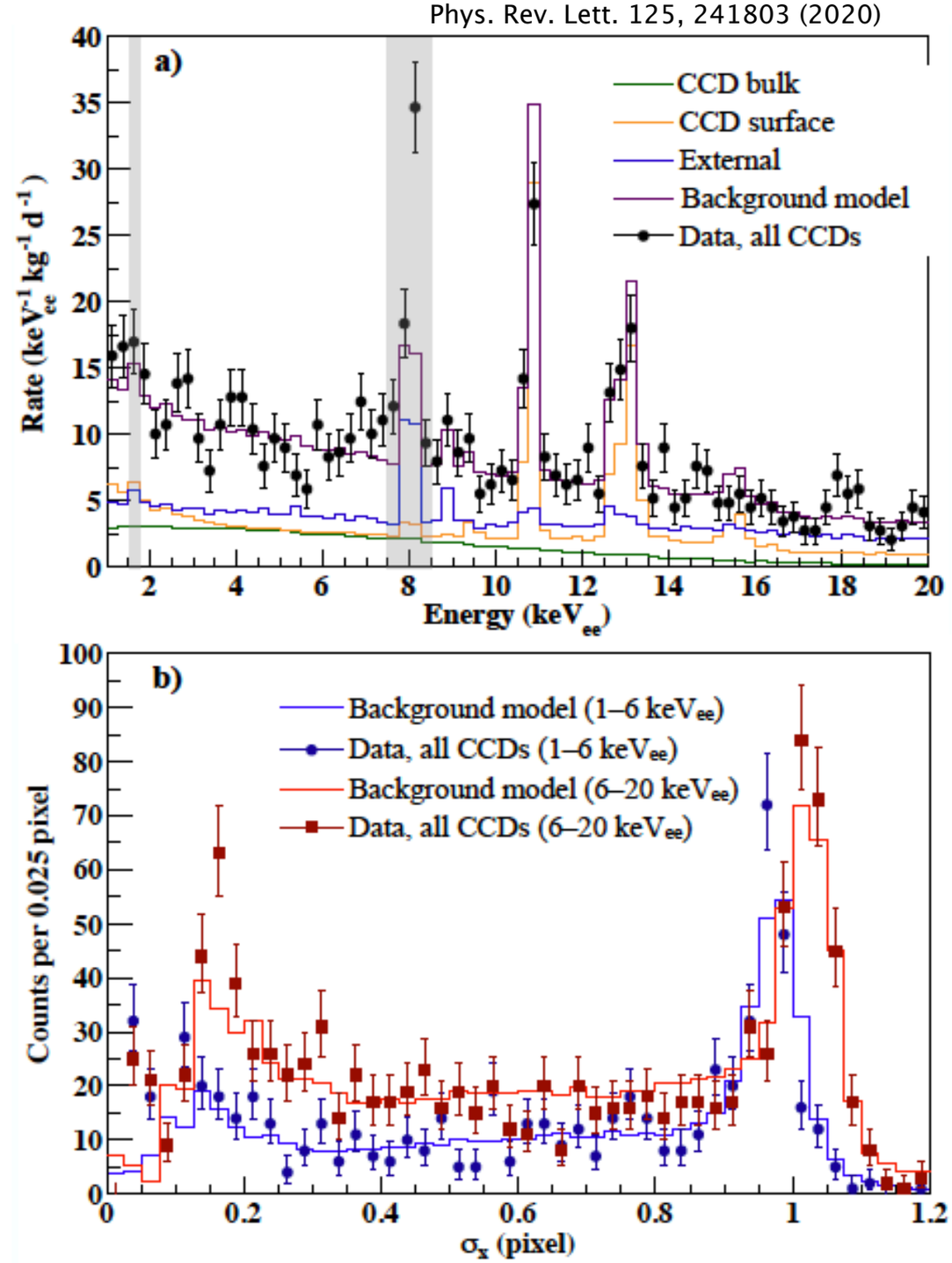

FIG. 2. Projections in E and σ_x of the best-fit background model (solid lines) compared to the fast clustered data (markers). a) The total background model spectrum is shown along with four separate contributions grouped by background origin. Shaded energy regions are excluded from the analysis. b) Comparison of σ_x distributions in the fit energy region (red) and at lower energies (blue). The peak at low (high) σ_x corresponds to events at the front (back) of the CCDs.