Quantum Sensors for HEP and HEP technology for Quantum Science.

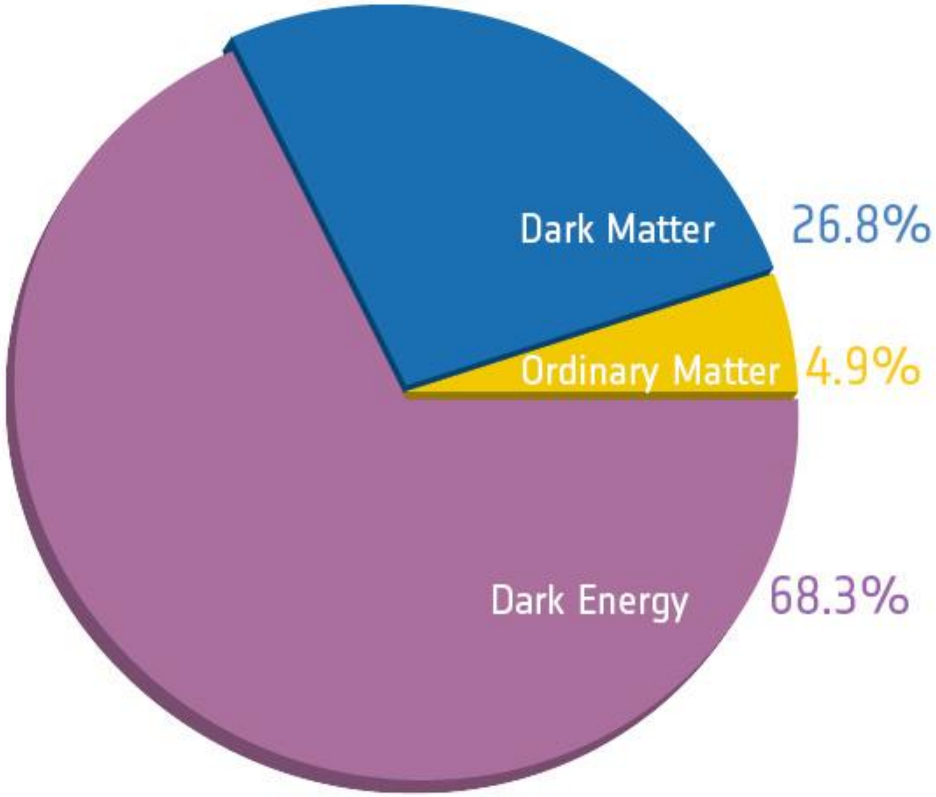
Juan Estrada
February 2019
Vienna

Fermilab

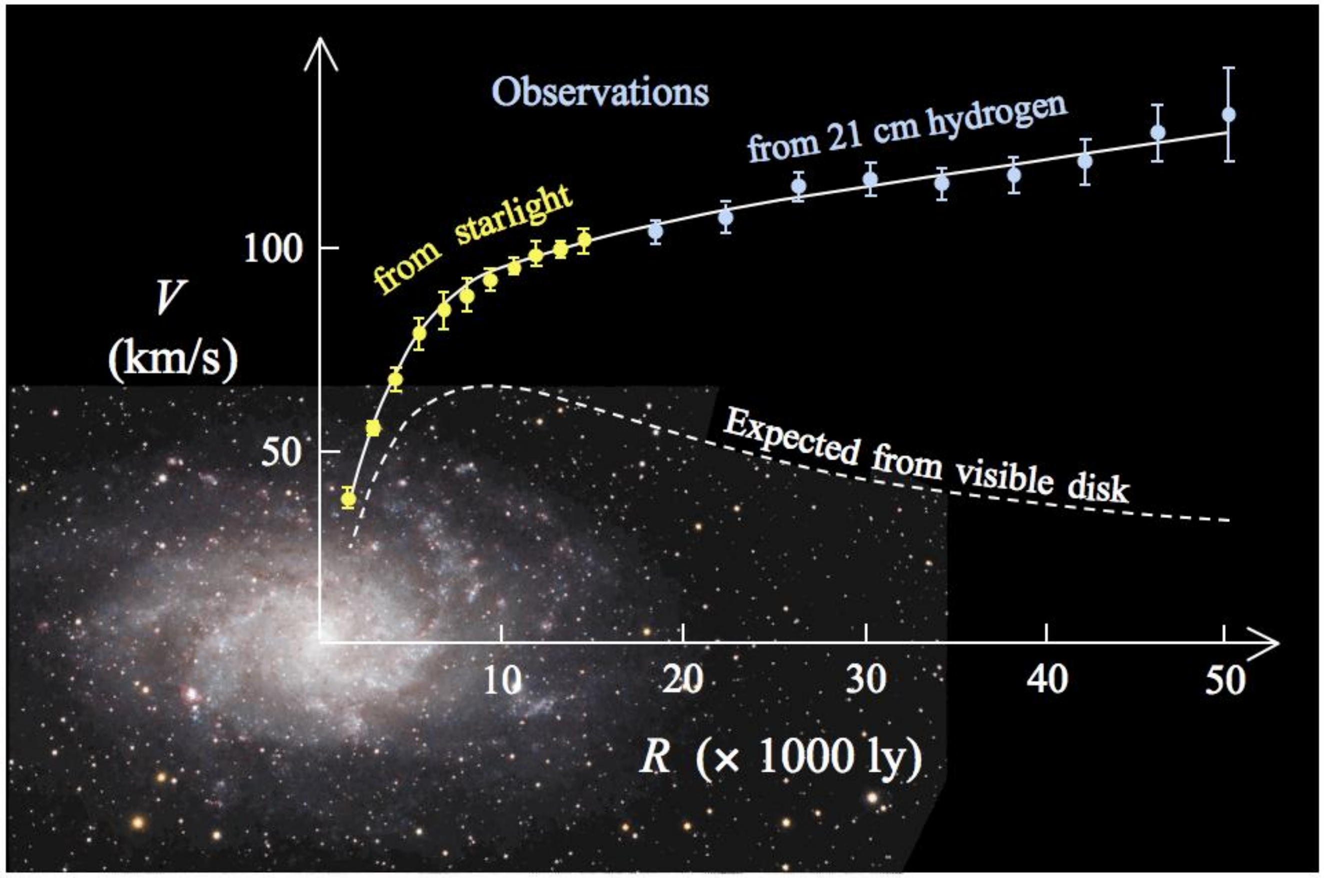
select a couple of examples of what is going on, to give you general idea of the excitement in this multidisciplinary field.

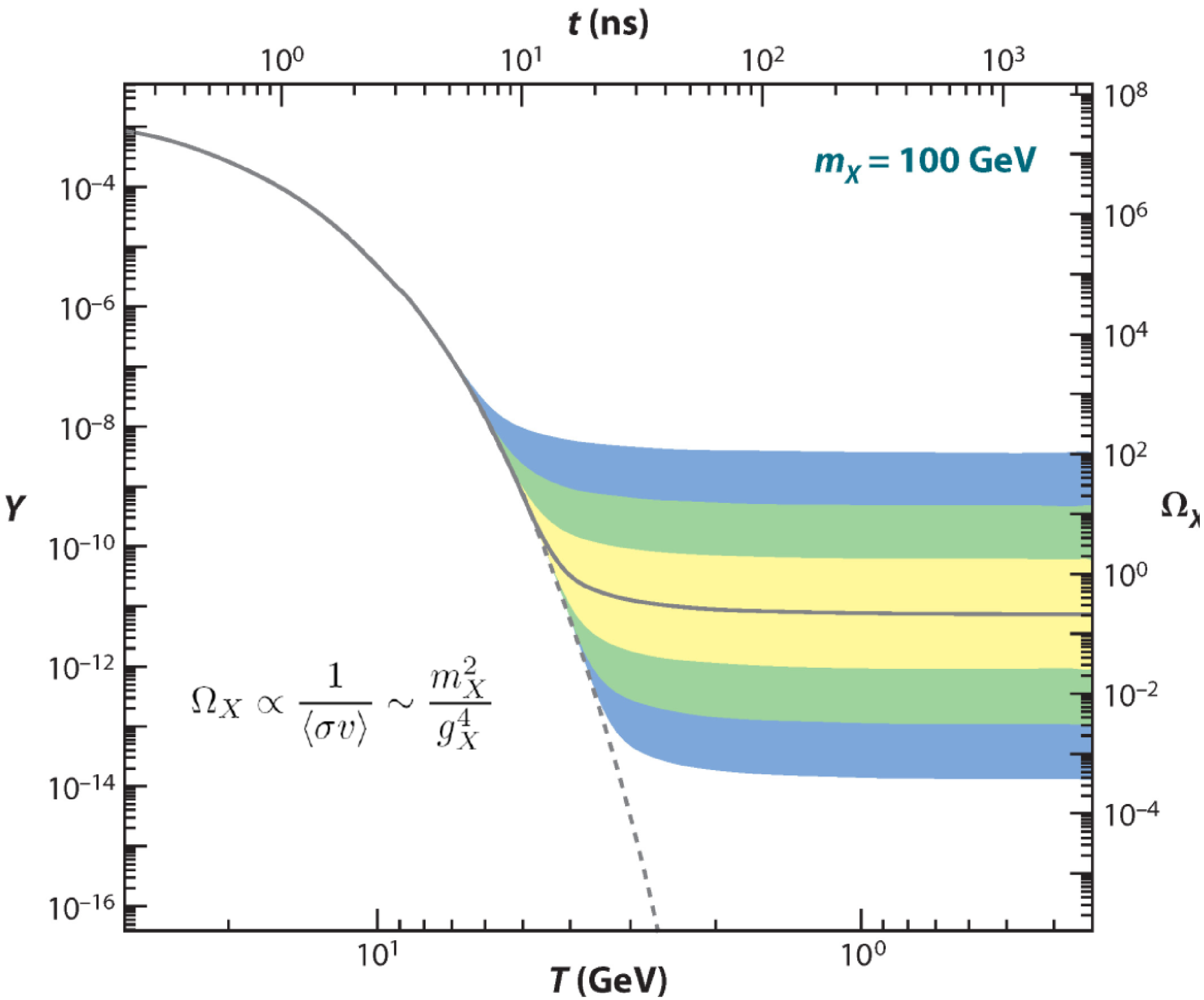
- Quantum sensors for Axion-like particle searches
- SRF cavities for quantum computing
- skipper-CCD for quantum science

Evidence for Dark Matter :Rotation curves of galaxies, gravitational lensing, large scale structure of the universe and CMB.



Thanks Vera Rubin (1928-2016) !



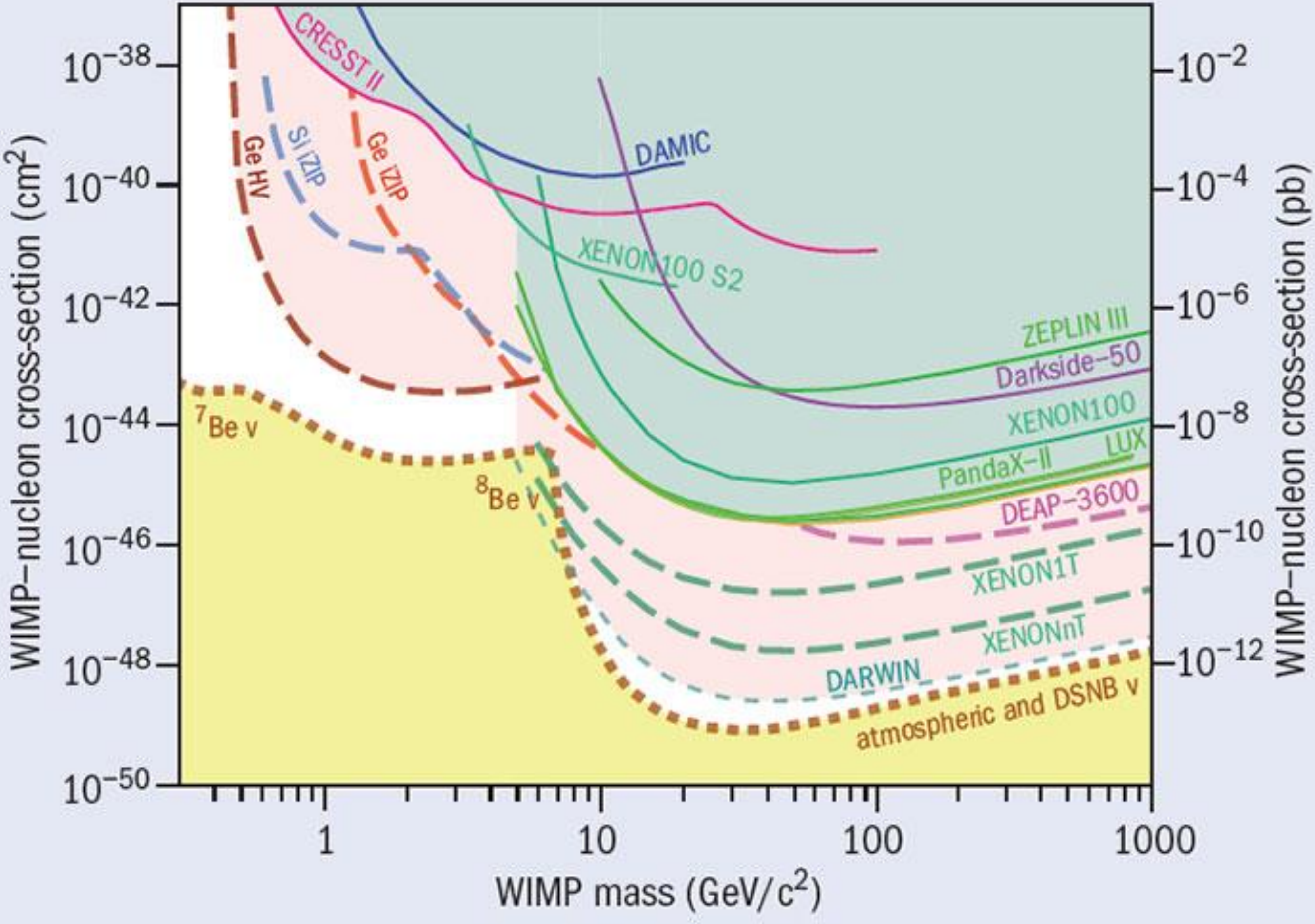


WIMP miracle:
Assuming that DM will freeze-out as the universe cools down.

This gives a good motivation for WIMPs, with a mass scale of ~100 GeV.

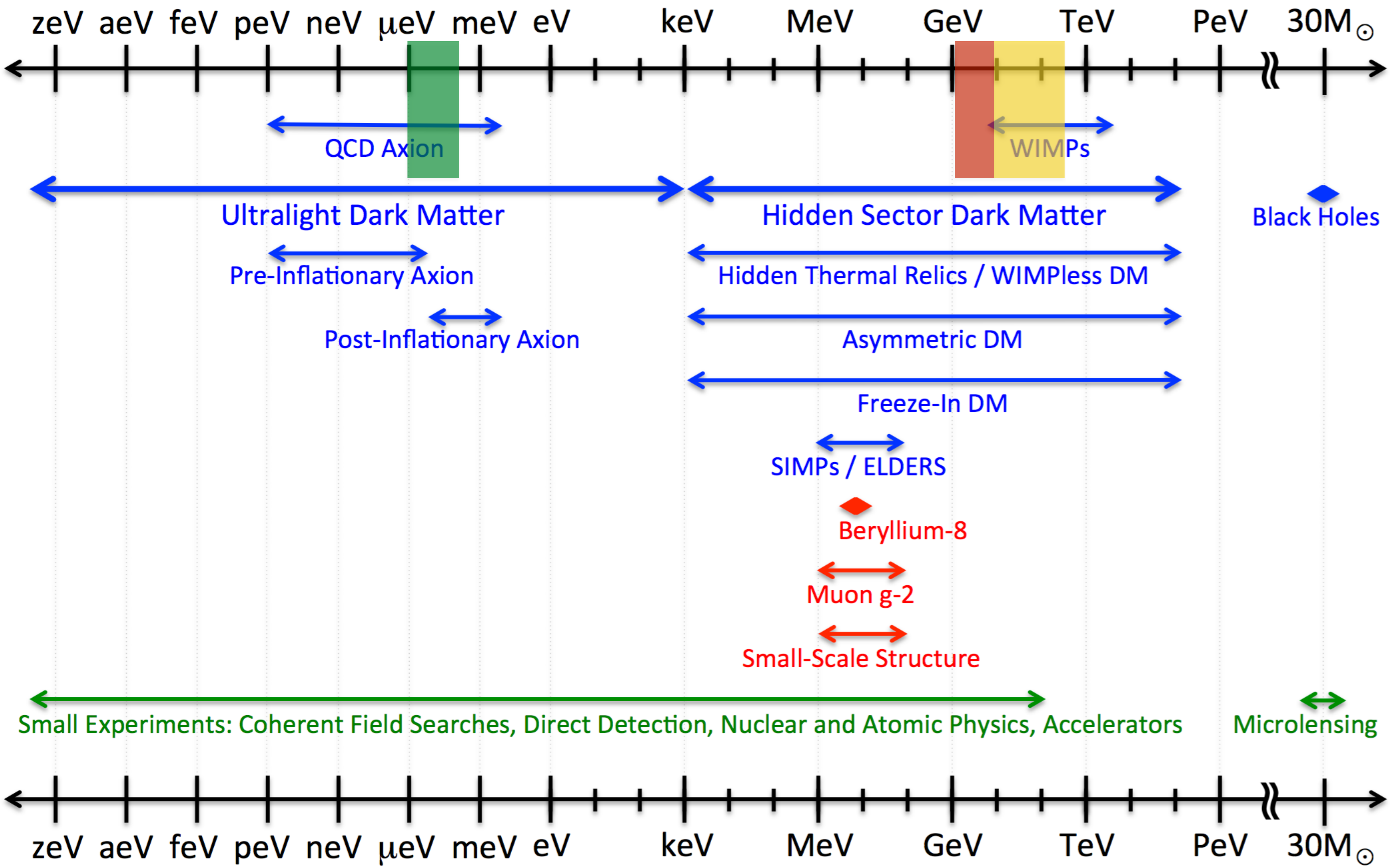
$$< \sigma v >_{ann} \approx 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{sec}^{-1}$$

this drove the field for many years, and is still the highest priority…
but now we are starting to look elsewhere, and we need new tools



https://cerncourier.com/testing-wimps-to-the-limit/ (2017)

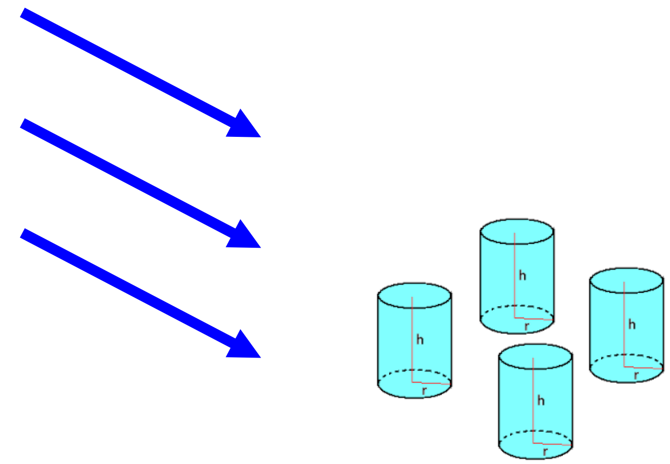
beyond wimps



for low mass (axions)

$$\Delta x = 1/\Delta p = 1/m_a \Delta v \approx 100 \text{ m}$$

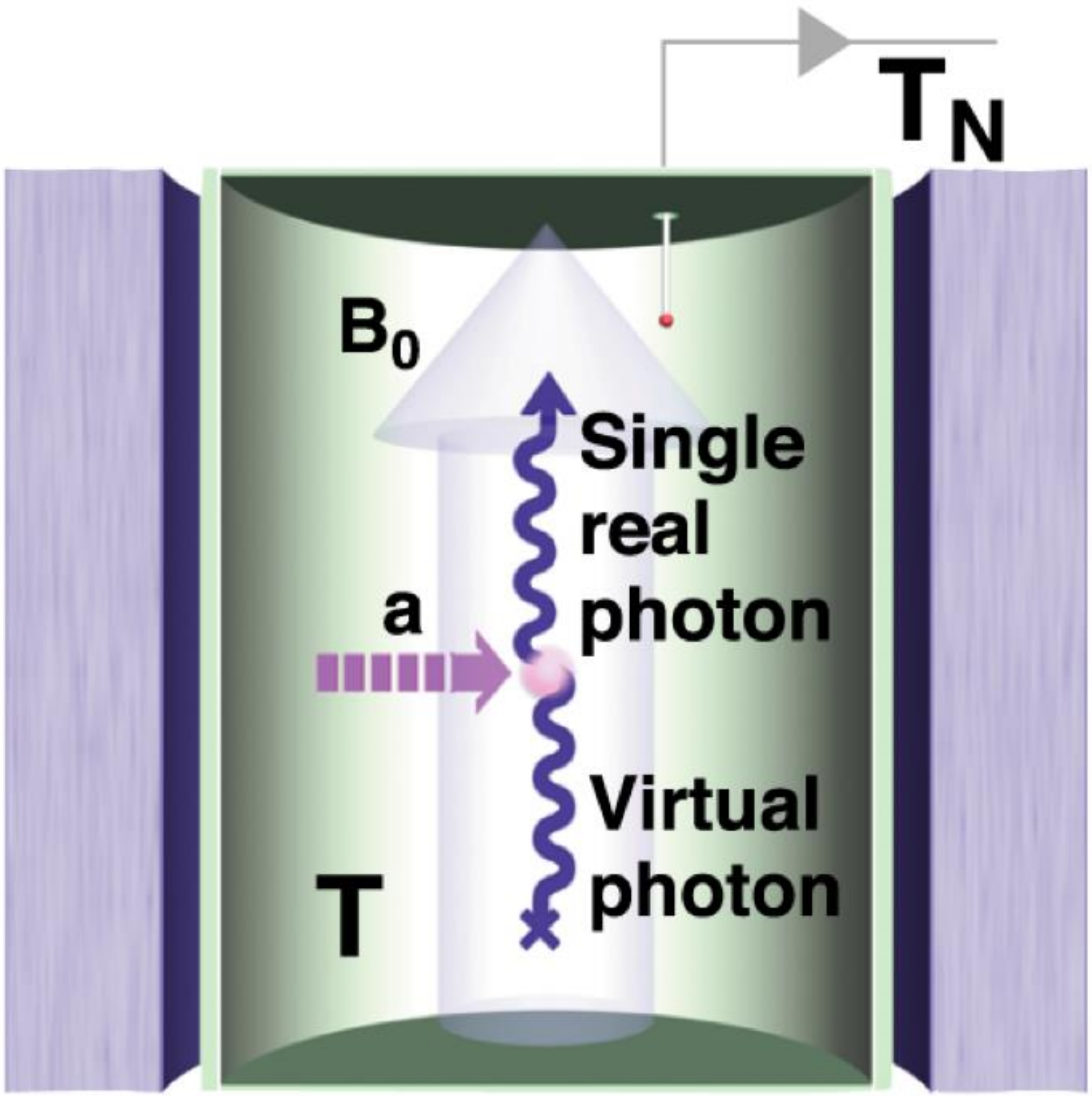
$v \approx \Delta v \approx 300$ km/s (galactic escape velocity)

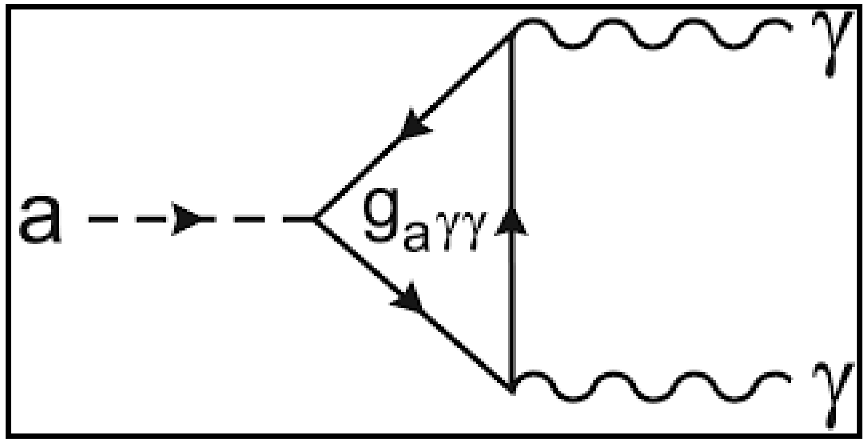


stadium-sized regions of coherently oscillating classical waves slowly drifting through detectors.

coupling that allows detection

Haloscope technique (Sikivie -1983) axion wave drives RF cavity mode





oscillation axion in magnetic field produces a current

$$\vec{J}_a(t) = -g\theta\vec{B}_0 m_a e^{i m_a t}$$

… this then becomes a source term in Faraday's law

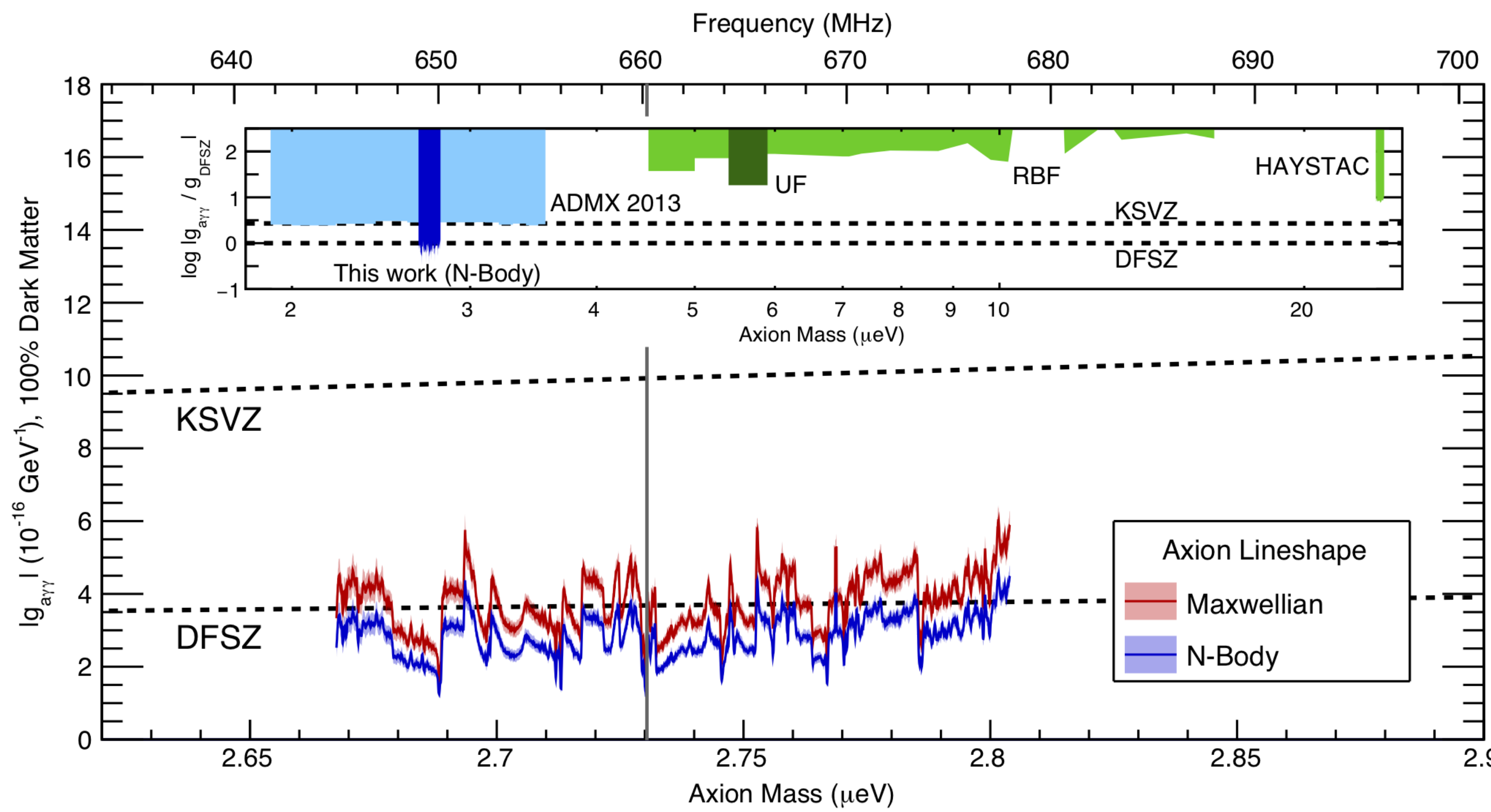
$$\vec{\nabla}\times\vec{H}_r - \frac{d\vec{D}_r}{dt} = \vec{J}_a$$

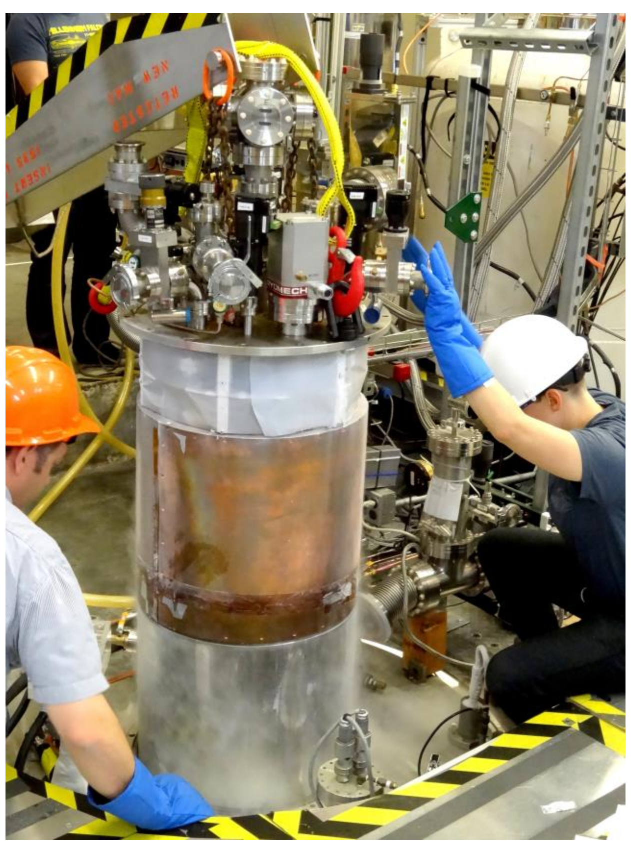
If the cavity is tuned to the right frequency, it will be excited this current in a measurable way

set up a low noise cavity, and scan the frequency until you find the axion

ADMX experiment

PRL 120, 151301 (2018)





Look for "spontaneous" emission from local axion dark matter into the empty cavity mode.

Signal power level = 10^{-23} W

Need 15 minutes integration per frequency bin to beat thermal noise power at 500 mK.

Operate an ultrasensitive radio in a cold, RF-shielded box to tune in to the axion broadcast.

PRL 120, 151301 (2018)

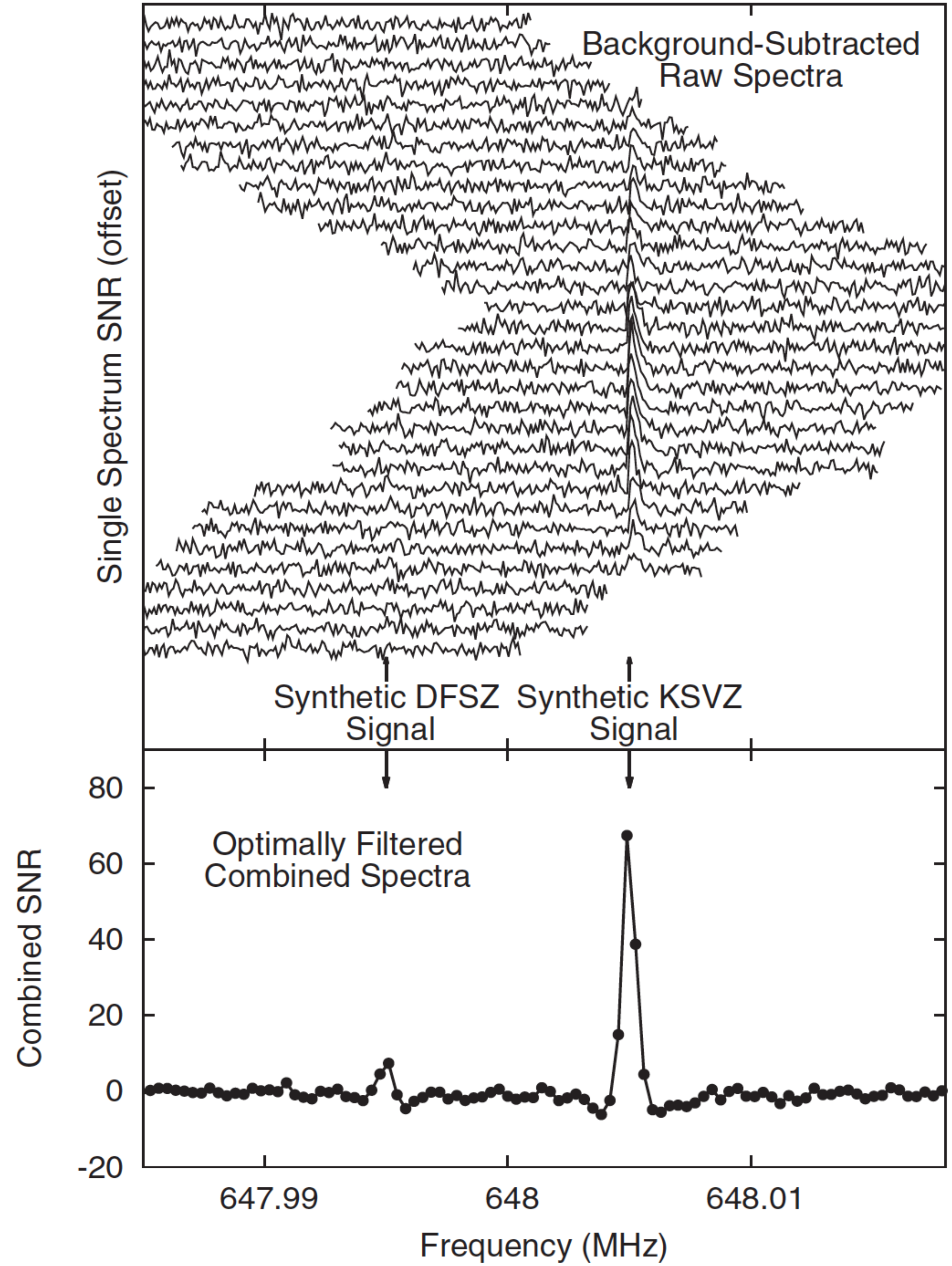
Dig out the signal buried beneath the noise

Each tuning ~ 100 s.
Obtain 10^4 spectra of 100 Hz resolution spanning the 20 kHz cavity bandwidth.

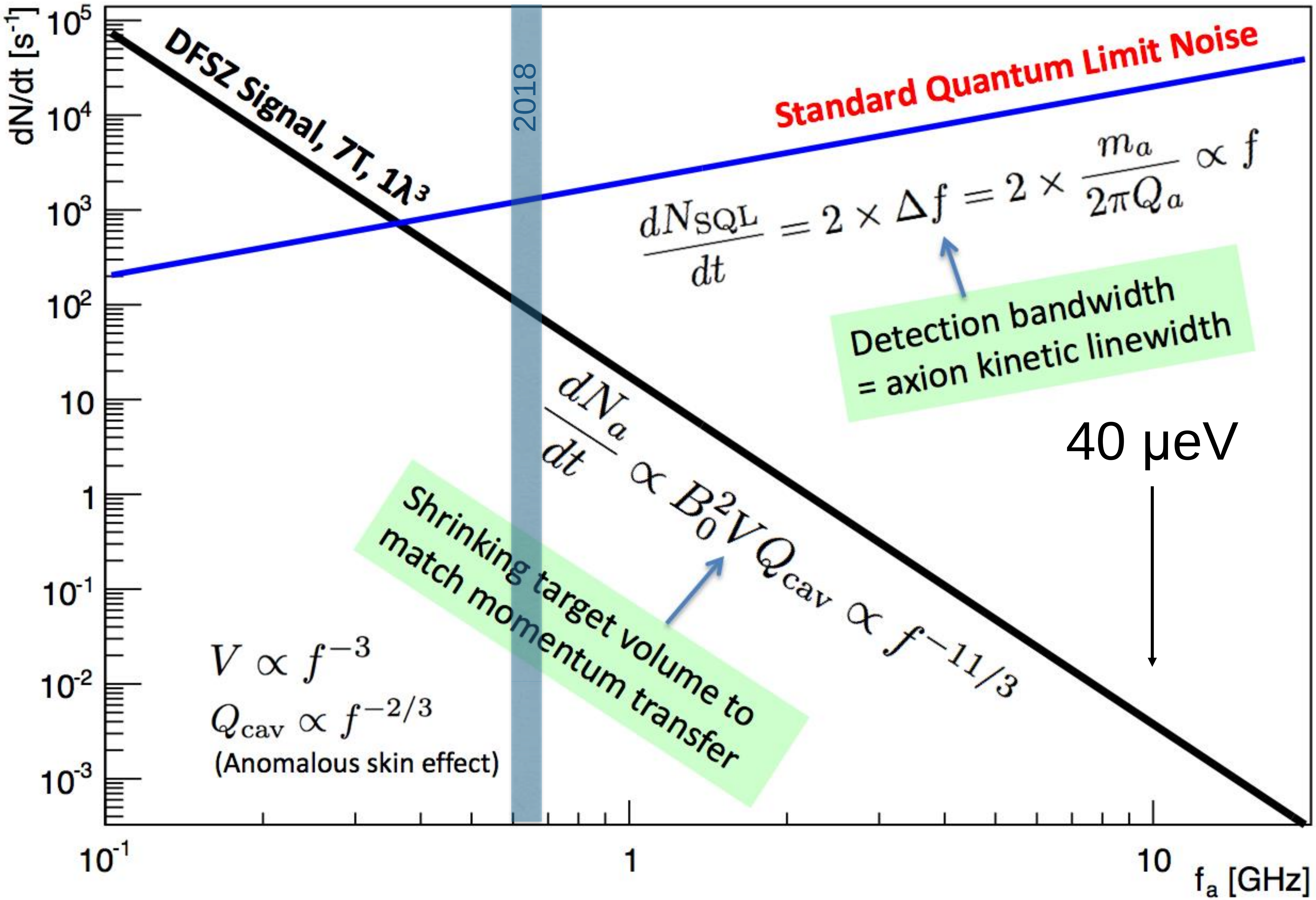
Tune cavity frequency slightly and repeat.

Average over all spectra to reduce noise.

$$SNR = \underbrace{\frac{P_{\rm signal}}{\sqrt{2}kT\Delta f}}_{10^{-3}} \underbrace{\sqrt{2\Delta f t}}_{\text{Require } 10^6 \text{ averages}}$$



it is hard now, but it will get a lot worse as get move towards higher mass



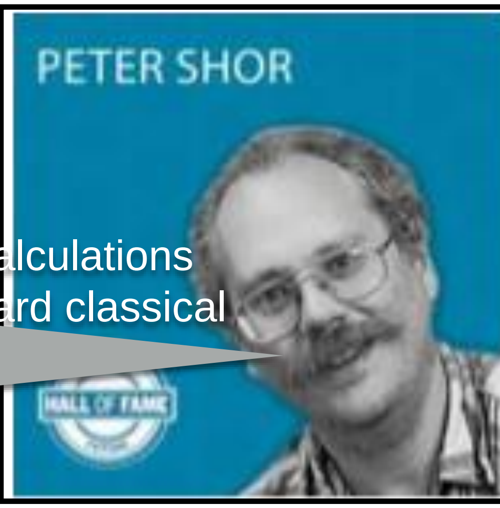
credit: A. Chou - Fermilab

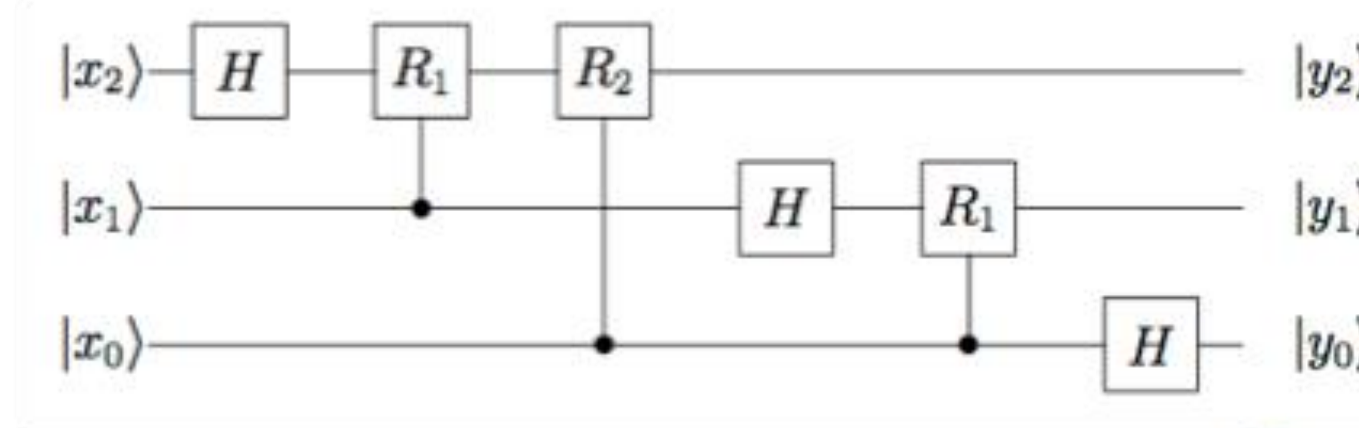
What does the axion have to do with quantum information?

neighbors with the right tools can help each other.

quantum supremacy is possible

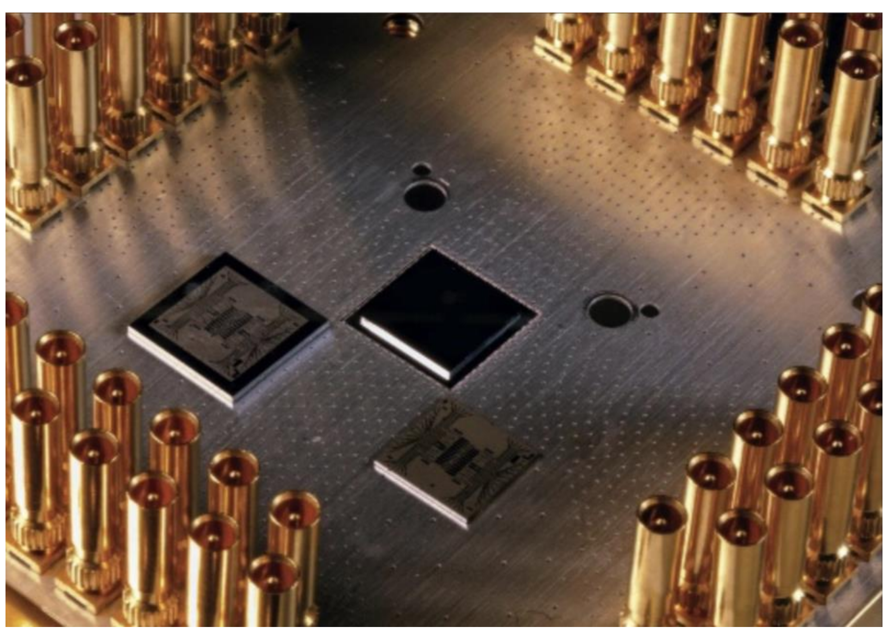
quantum computer can do some calculations that would be impossible for standard classical computers





Factorization into prime numbers using quantum Fourier Transformation algorithm (think cryptography) — n^2 vs $n2^n$

quantum computers are growing fast, but they are still in their infancy

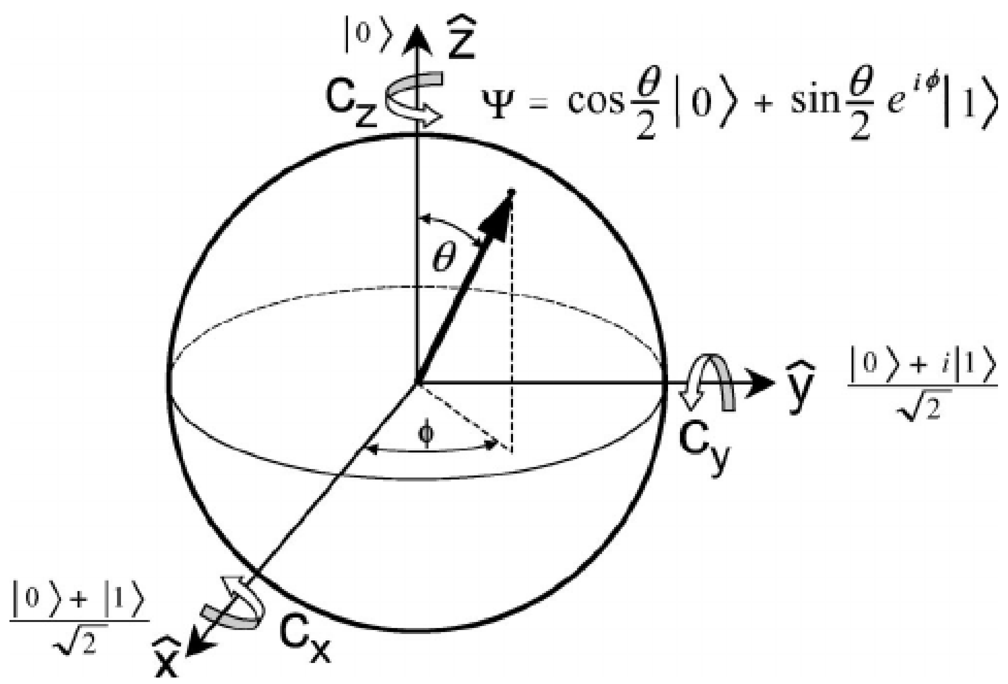


Google: 22 qubit (2017)

Google: 72 qubit (2018)

a bit can take two values “0” and “1”

qubit: represented by the surface of the sphere with all possible combinations of state “0” and “1”.

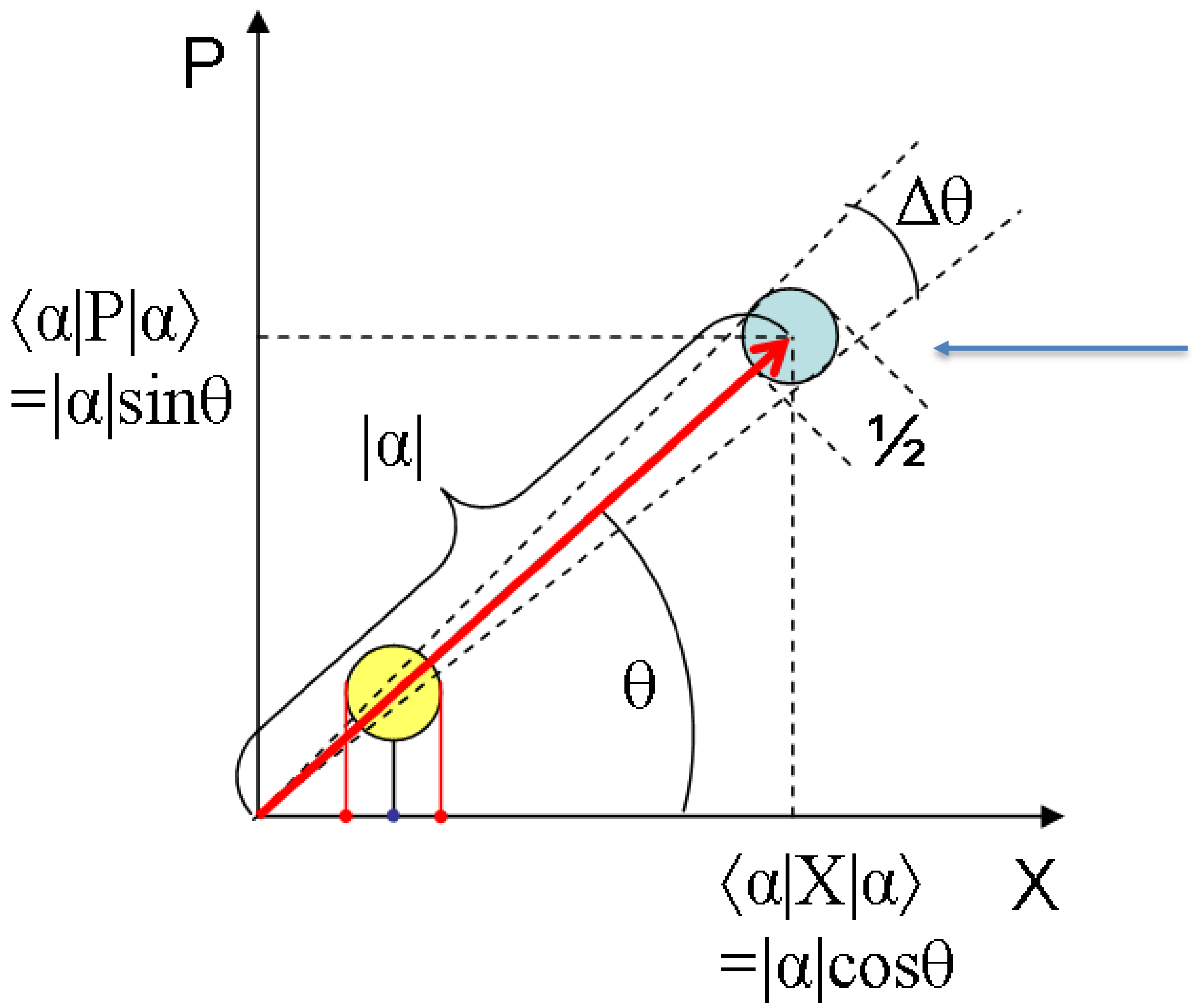


What do we need for digital quantum computers (DeVincenzo Criteria):

1. Qubits: fabrication of registers with several (many) qubits.
2. Initialization to a known state.
3. Universal gate operations (high fidelity).
4. Readout: the state of the qubit register must be possible to read out, typically as readout of individual qubits.
5. Long coherence times: a large number of single and 2-qubit gate operations must be performed within the coherence time of the qubit register.
6. Quantum interfaces for qubit interconversion.
7. Quantum interfaces to flying qubits for optical communication

directly relevant for DM

Quantum-limited amplifiers suffer from the Standard Quantum Limit (SQL)



½ ħ= quantum of phase space area.
Simultaneous measurement of wave amplitude and phase gives irreducible zero-point noise in measurement.
(Caves, 1982)

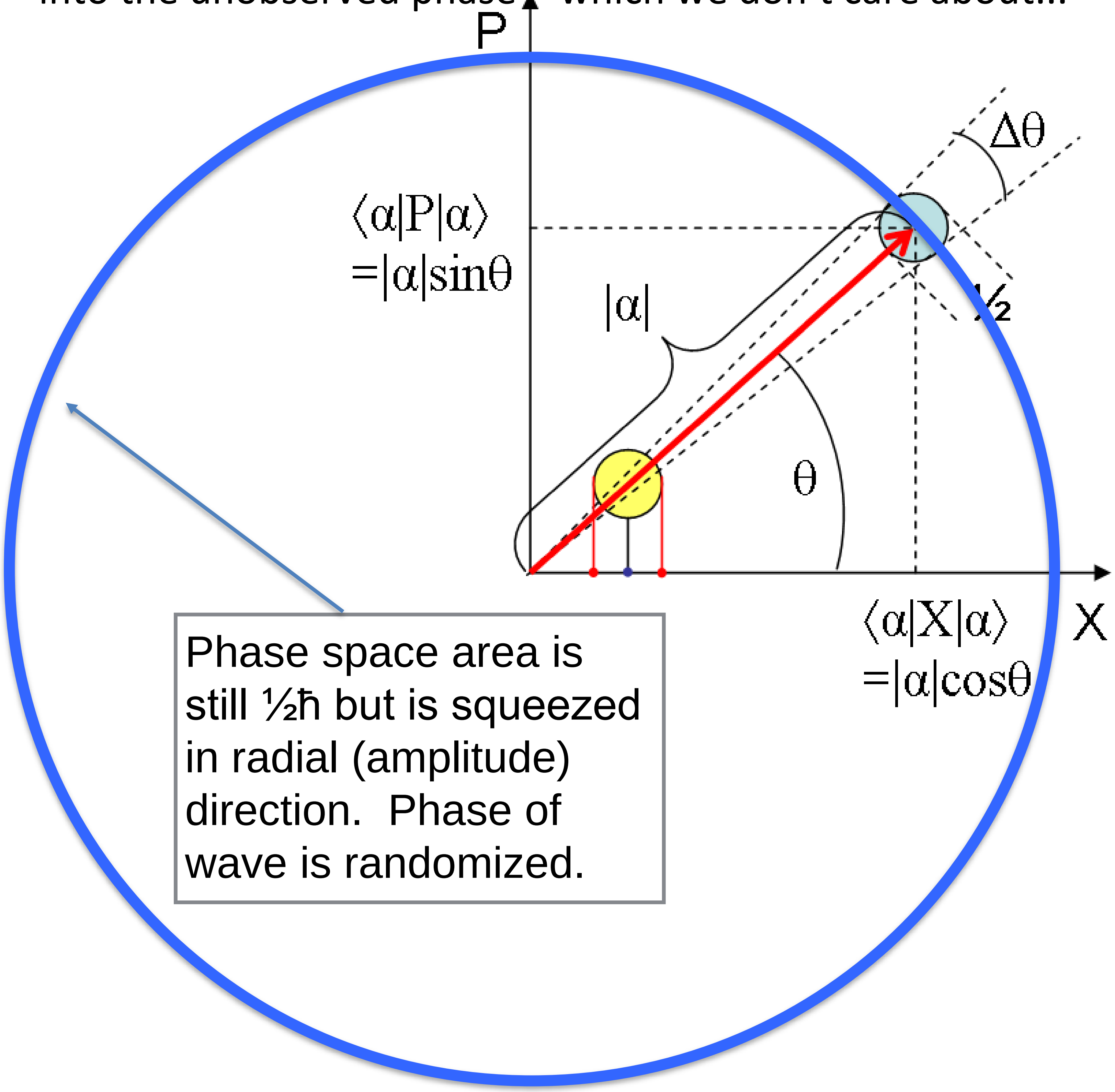
Thermal noise = kT of energy per resolved mode
à **Quantum noise = 1 photon per resolved mode in the T=0 limit.**

Noise photon rate exceeds signal rate in high frequency dark matter axion searches.
Need new sensor technology….

credit: A. Chou - Fermilab

Quantum non-demolition (QND) can do much better than SQL amplifiers to measure photon number

Number operator commutes with the Hamiltonian→ all backreaction is put into the unobserved phase – which we don't care about...



Phase space area is still ½ħ but is squeezed in radial (amplitude) direction. Phase of wave is randomized.

Demonstrated with Rydberg atoms, (Serge Haroche Nobel Prize 2012)

Implemented using solid state artificial atom qubits, D.Schuster et.al, 2007

Proposed for axion search: Lamoreaux, Lehnert, et.al, 2013, Zheng, Lehnert, et.al, 2016

CAVITY QUANTUM ELECTRODYNAMICS

1989

A new generation of experiments shows that spontaneous radiation from excited atoms can be greatly suppressed or enhanced by placing the atoms between mirrors or in cavities.

Serge Haroche and Daniel Kleppner

1999

review article

Quantum non-demolition measurements in optics

Philippe Grangier, Juan Ariel Levenson & Jean-Philippe Poizat

Quantum non-demolition measurements are designed to circumvent the limitations imposed by Heisenberg's uncertainty principle when performing repeated measurements of quantum states. Recent progress in quantum optics has enabled the experimental realization of quantum non-demolition measurements of the photon flux of a light beam. This achievement bears on fundamental issues about the ultimate sensitivity of measurements, and may open the way for applications such as noise-free information tapping in optical telecommunications.

nature physics

LETTERS

PUBLISHED ONLINE: 20 JUNE 2010 | DOI: 10.1038/NPHYS1710

2010

Quantum non-demolition detection of single microwave photons in a circuit

B. R. Johnson[1], M. D. Reed[1], A. A. Houck[2], D. I. Schuster[1], Lev S. Bishop[1], E. Ginossar[1], J. M. Gambetta[3], L. DiCarlo[1], L. Frunzio[1], S. M. Girvin[1] and R. J. Schoelkopf[1]*

Quantum Non-demolition Measurements on Qubits

2004

T.C.Ralph[1,2], S.D.Bartlett[2], J.L.O'Brien[1,2], G.J.Pryde[1,2] and H.M.Wiseman[3]
[1]*Centre for Quantum Computer Technology,*
[2]*Department of Physics, University of Queensland, Brisbane, QLD 4072, Australia*
[3]*Centre for Quantum Computer Technology, School of Science, Griffith University, Brisbane 4111 Australia*
email: ralph@physics.uq.edu.au

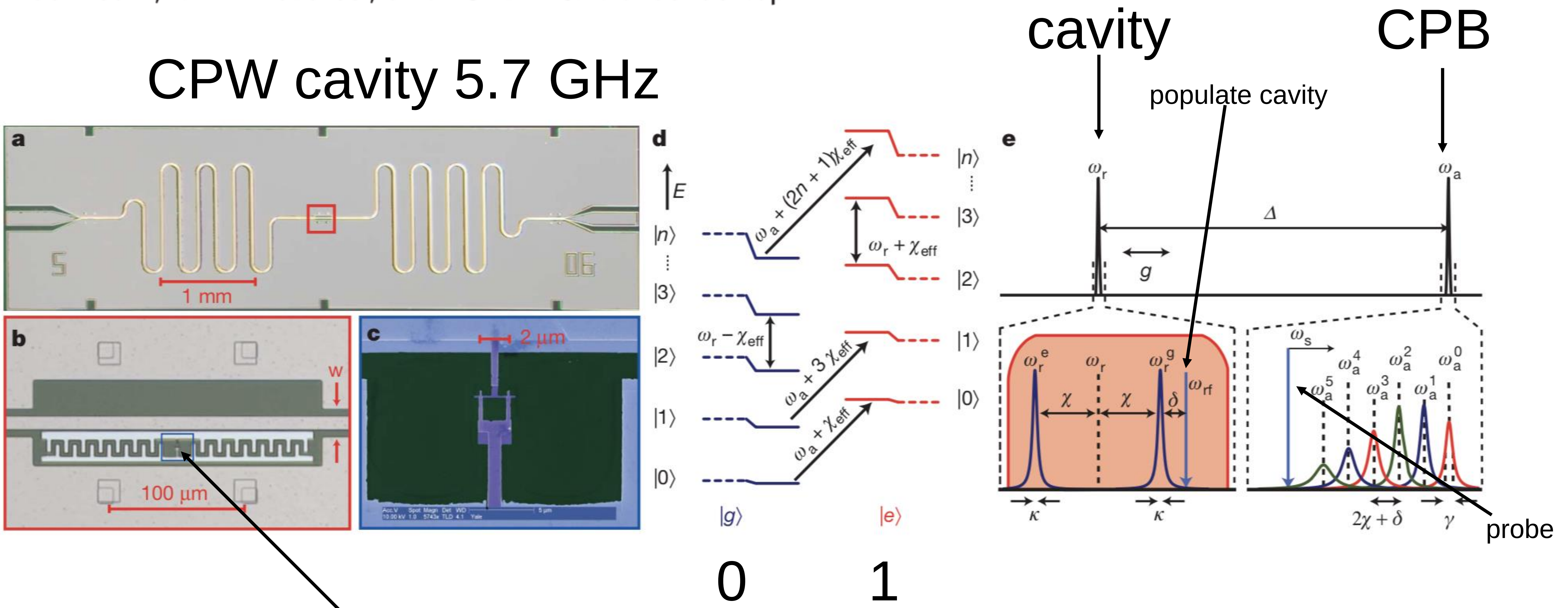
We discuss the characterization and properties of quantum non-demolition (QND) measurements on qubit systems. We introduce figures of merit which can be applied to systems of any Hilbert space dimension thus providing universal criteria for characterizing QND measurements. We discuss the controlled-NOT gate and an optical implementation as examples of QND devices for qubits. We also discuss the QND measurement of weak values.

which QND measurements can be demonstrated. Indeed QND measurements are critical to many key quantum information protocols, such as error correction [8], and enable new computation models [9]. However, in this new

Vol 445|1 February 2007|nature 05461

Resolving photon number states in a superconducting circuit

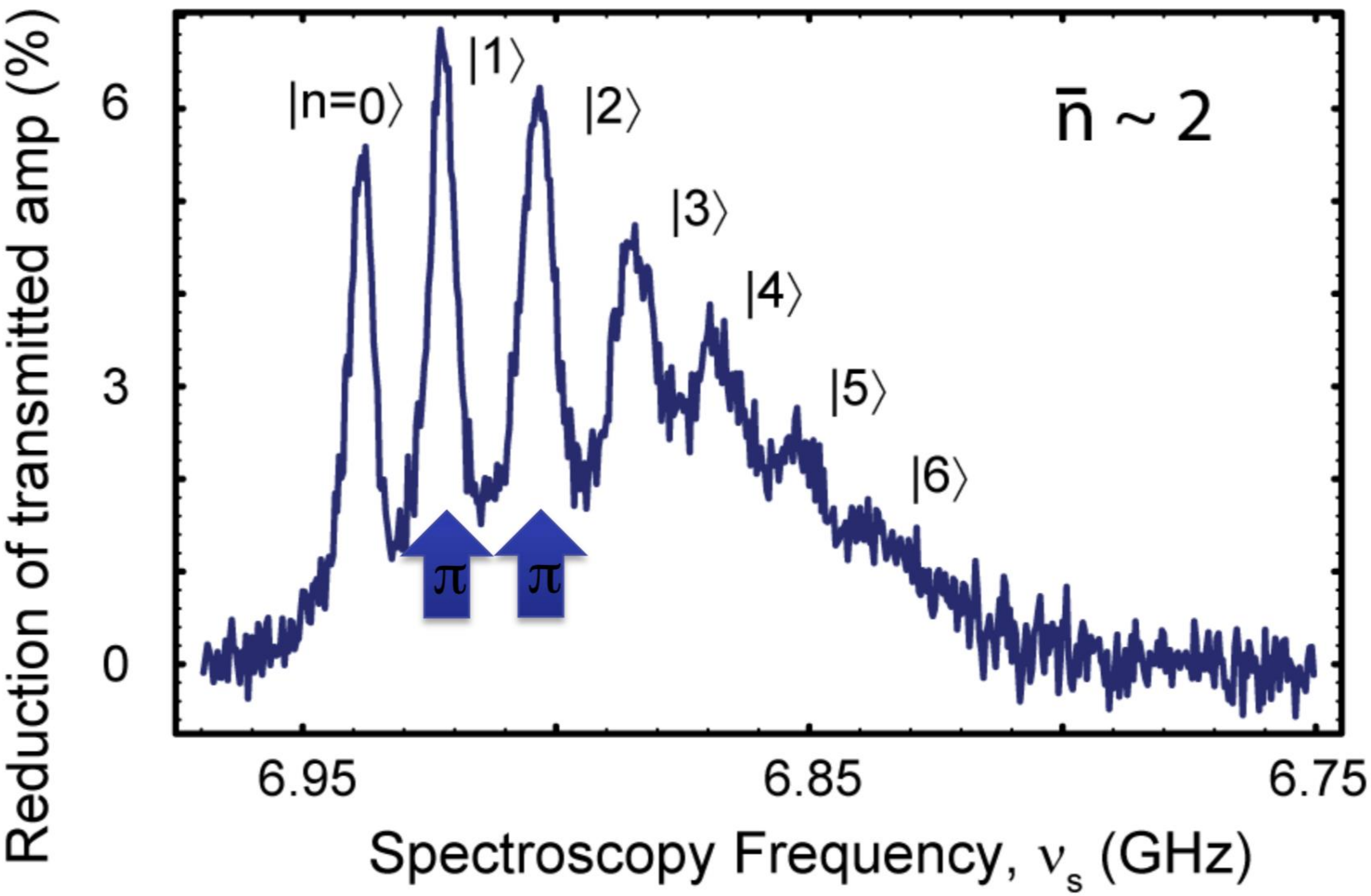
D. I. Schuster[1]*, A. A. Houck[1]*, J. A. Schreier[1], A. Wallraff[1]†, J. M. Gambetta[1], A. Blais[1]†, L. Frunzio[1], J. Majer[1], B. Johnson[1], M. H. Devoret[1], S. M. Girvin[1] & R. J. Schoelkopf[1]



Cooper Pair Box qubit
"cavity QED"

Vol 445|1 February 2007|nature 05461

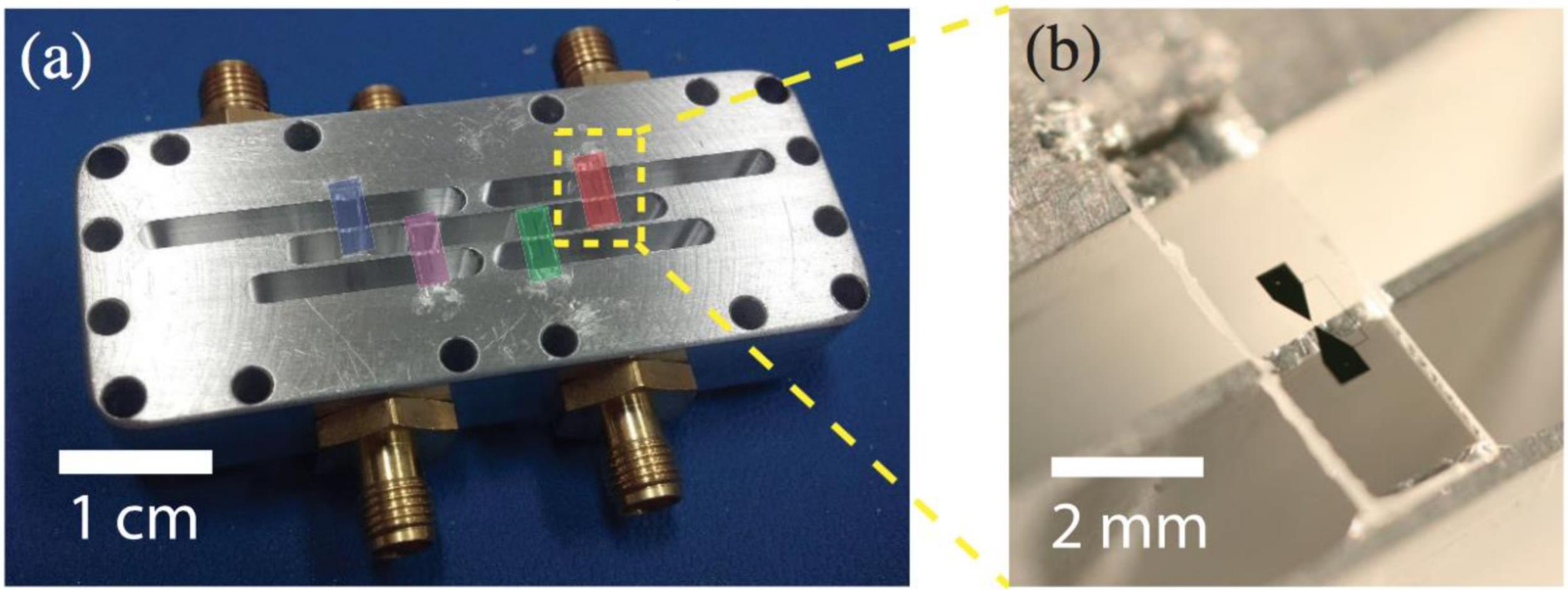
$$H \approx \hbar\omega_r a^\dagger a + \frac{\hbar}{2}(\omega_a' + 2\chi a^\dagger a)\sigma_z$$



get the cavity excited by the axion field, and the count single photons with QND

Also needed -> Long coherence times: a large number of single and 2-qubit gate operations must be performed within the coherence time of the qubit register.

Machined Aluminum host cavity

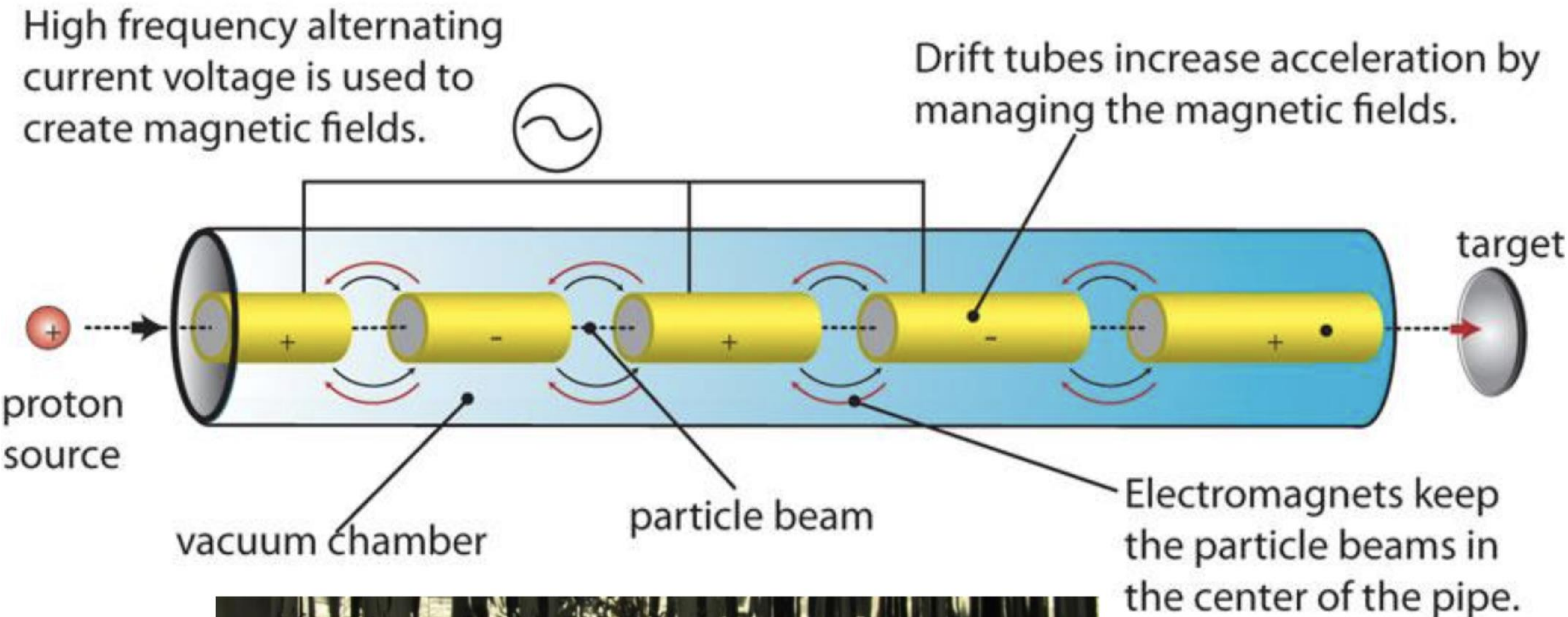


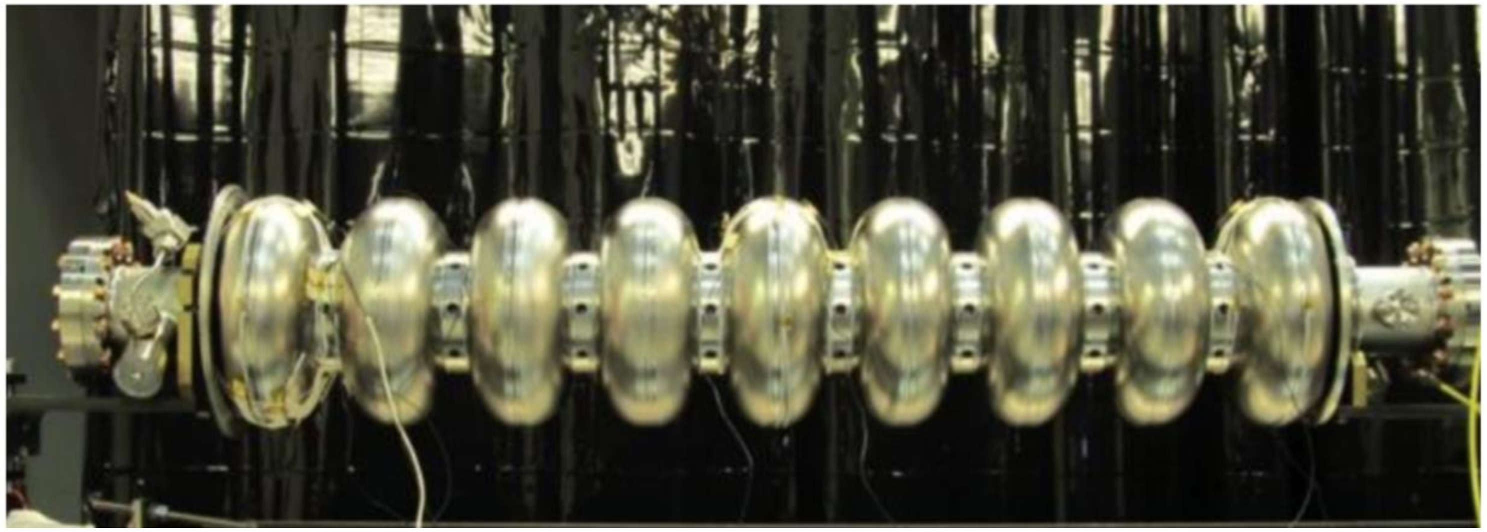
H. Paik et al, Phys. Rev. Lett. 117, 251502 (2016)

state-of-the-art in QC: Quality factor ~ 10^8

credit: A. Romanenko - Fermilab

Superconducting RF cavities for accelerators

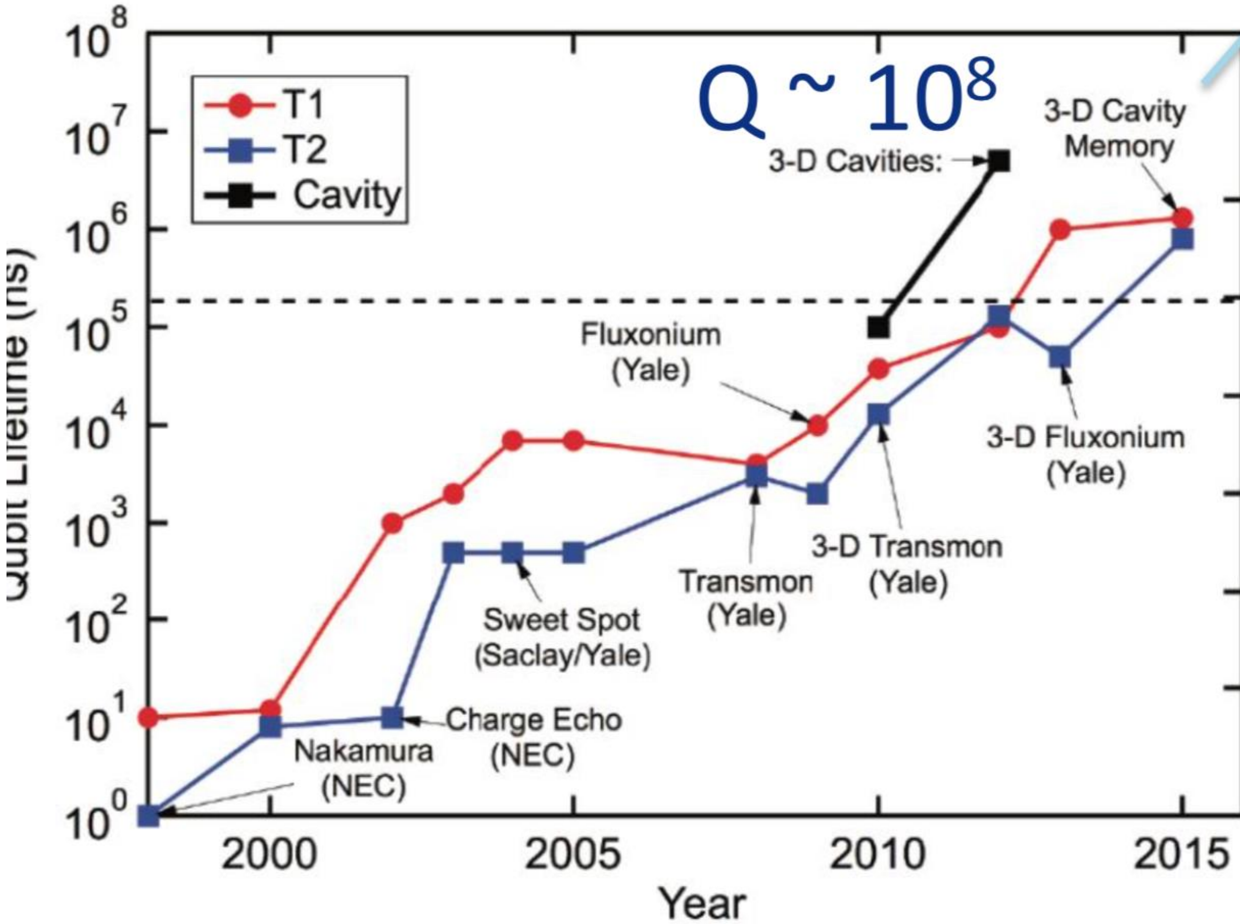




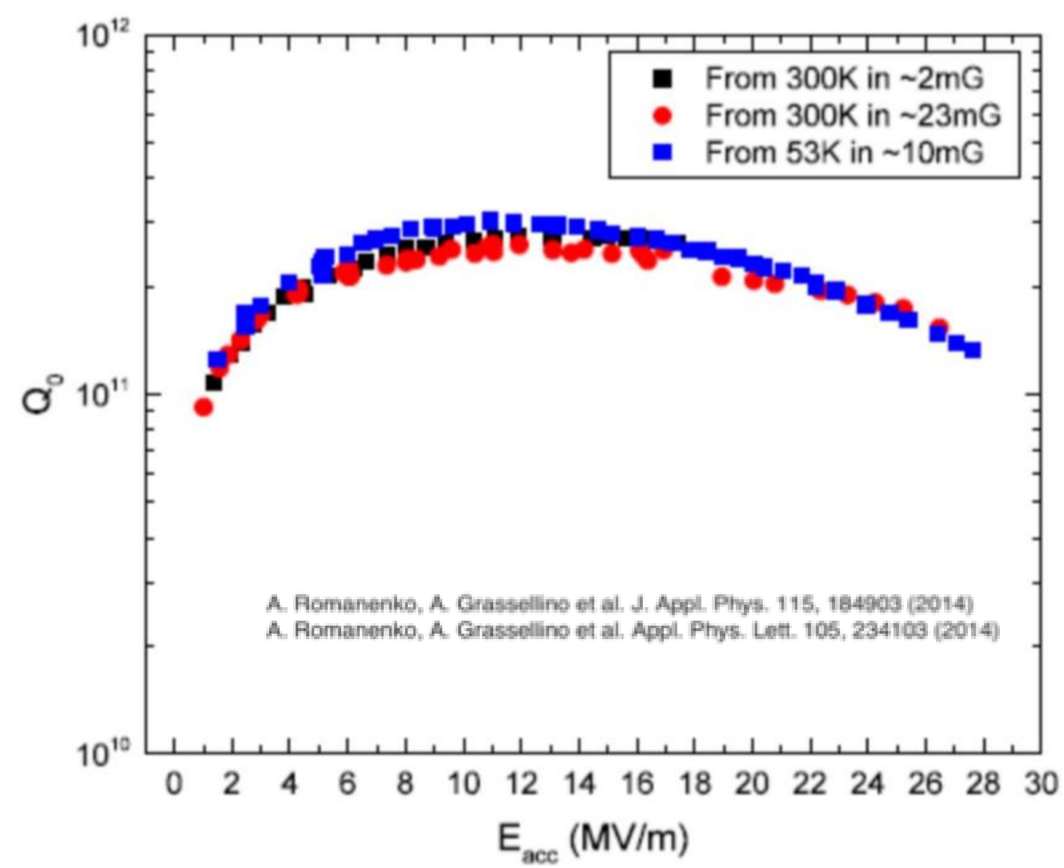
credit: A. Romanenko - Fermilab

$Q > 10^{11}$

Potential of up to ~10 seconds of coherence

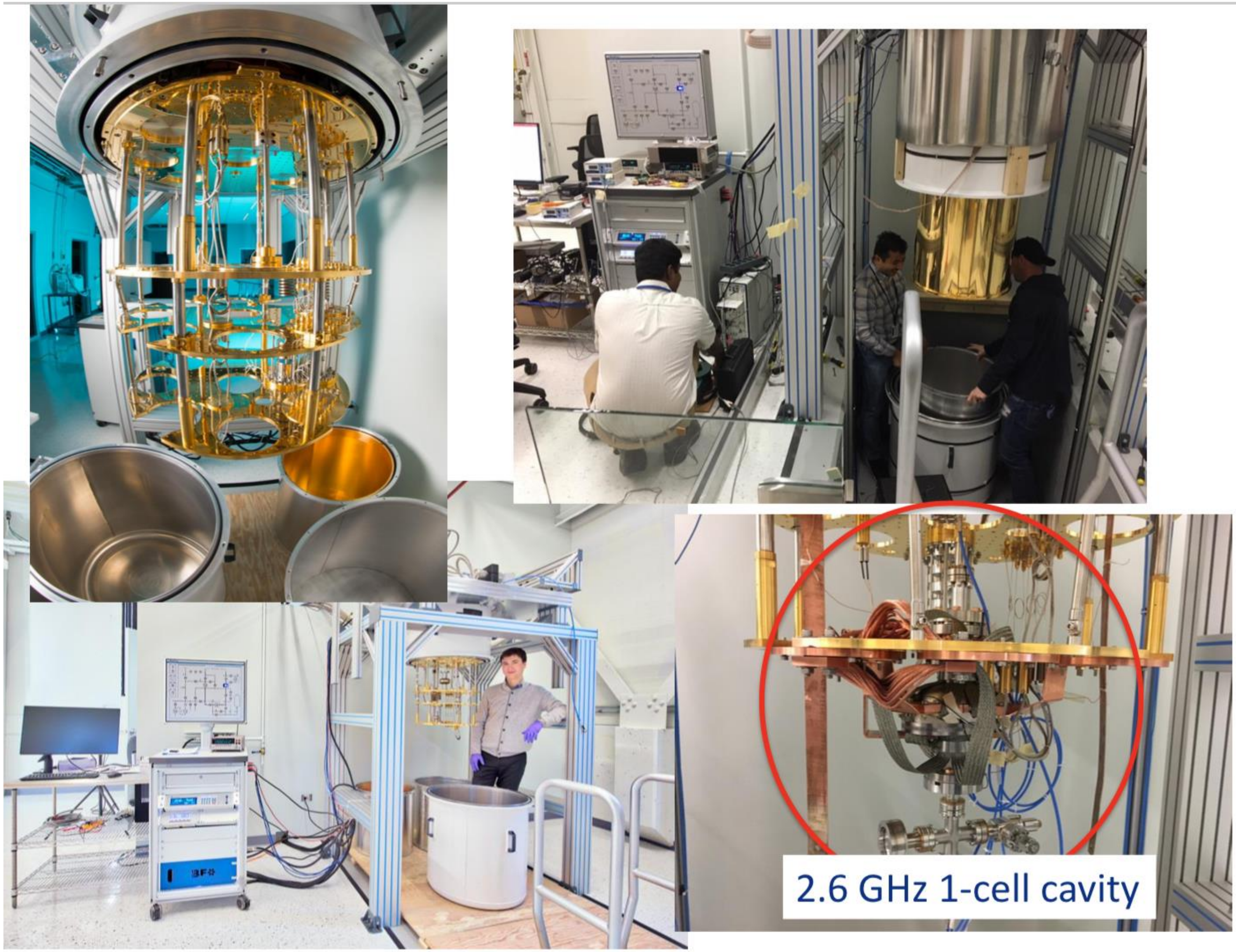


M. H. Devoret and R. J. Schoelkopf, *Science* 339, 1169–1174 (2013)



credit: A. Romanenko - Fermilab

here the technology developed for HEP will enable quantum science



at the same time these cavities can also be used for dark photon searches..

credit: A. Romanenko - Fermilab

IBM Raises the Bar with a 50-Qubit Quantum Computer

Intel's New Chip Aims For Quantum Supremacy

The troubled chipmaking giant is one of the first to build a quantum computing chip that can outrun a modern classical supercomputer.

NEWS IN BRIEF QUANTUM PHYSICS

Google moves toward quantum supremacy with 72-qubit computer

Intelligent Machines

Serious quantum computers are finally here. What are we going to do with them?

Hello, quantum world.

Knight February 21, 2018

The New York Times

The Next Tech Talent Shortage: Quantum Computing Researchers

Christopher Savoie, founder and chief executive of the start-up Zapata, said he had offered jobs to three foreign scientists who specialize in quantum computing. He's still waiting for their visas to be approved. Tony Luong for The New York Times

US Senate passes National Quantum Initiative Act

Next stop, the President's desk

December 17, 2018 By: Sebastian Moss

The US Senate has passed the National Quantum Initiative Act by unanimous consent.

The bill, which went through the House this September, aims to add $1.2 billion in quantum research funding over 10 years across the Department of Energy, the National Institute of Standards and Technology, NASA and the National Science Foundation.

Quantum Sensing for High Energy Physics

Report of the first workshop to identify approaches and techniques in the domain of quantum sensing that can be utilized by future High Energy Physics applications to further the scientific goals of High Energy Physics.

Organized by the Coordinating Panel for Advanced Detectors of the Division of Particles and Fields of the American Physical Society

March 27, 2018

big push for quantum, and interesting opportunities to work with HEP now let’s look at another regime…

Charge-coupled devices: CCDs

photon detector

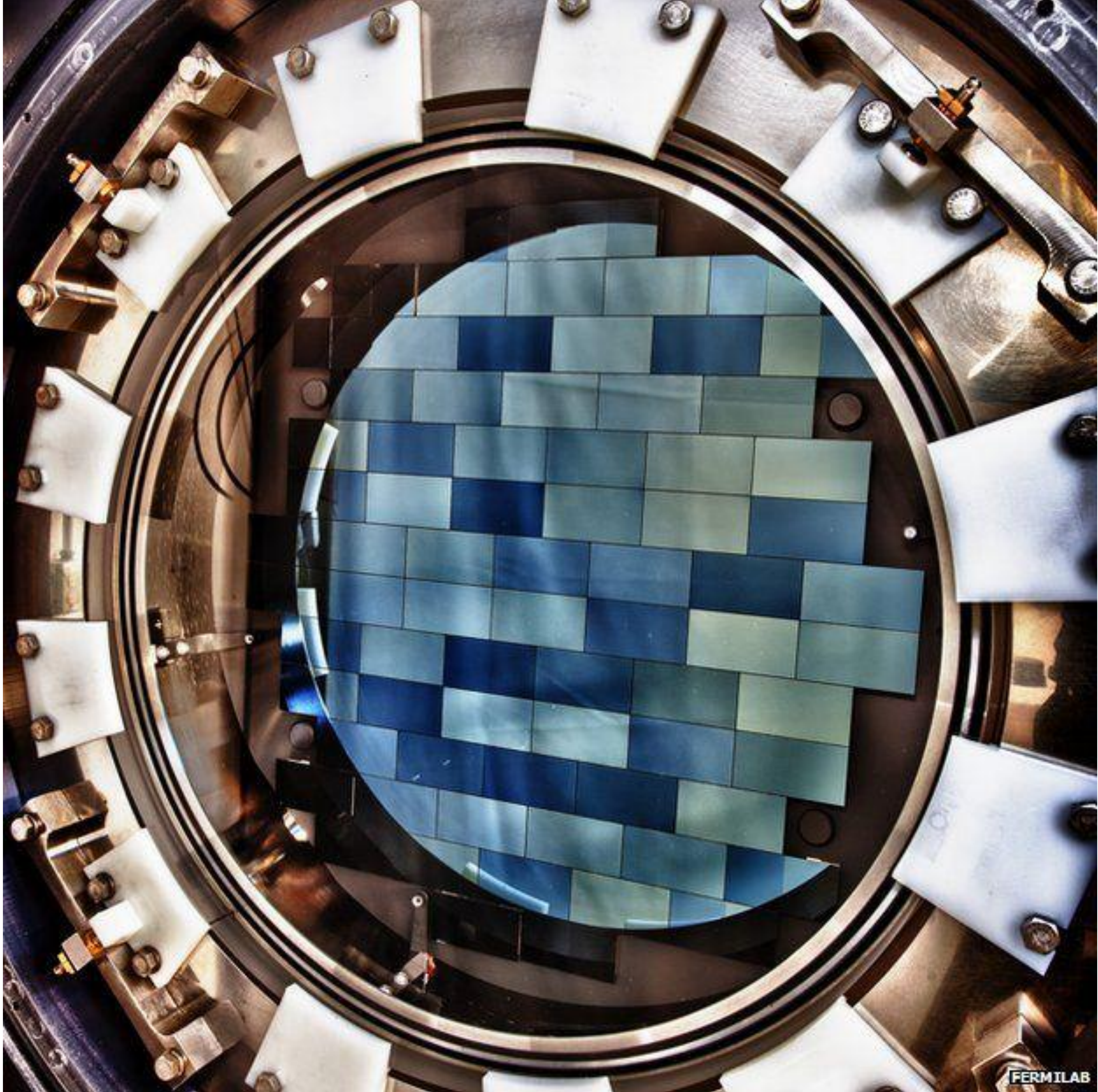
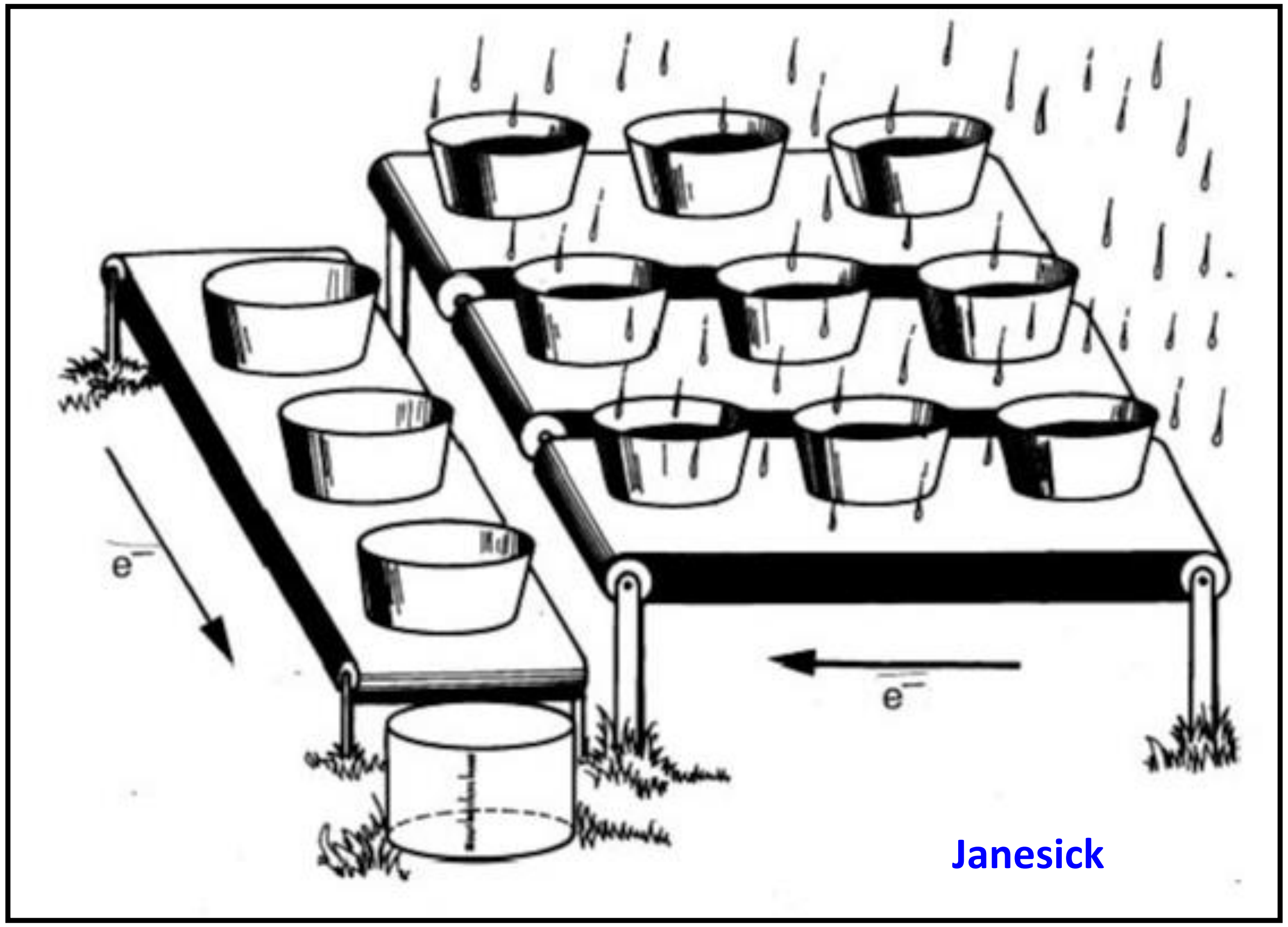
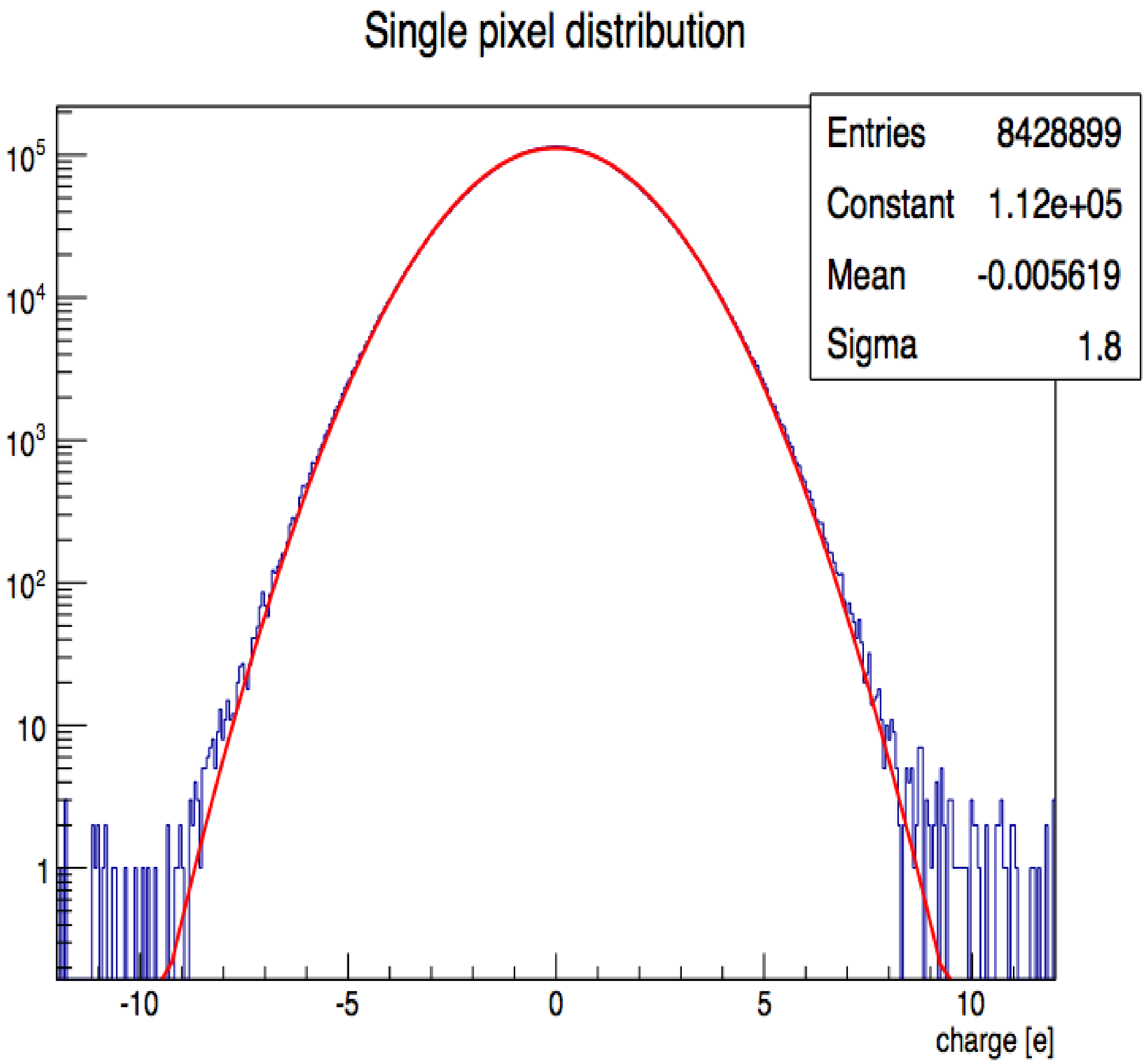


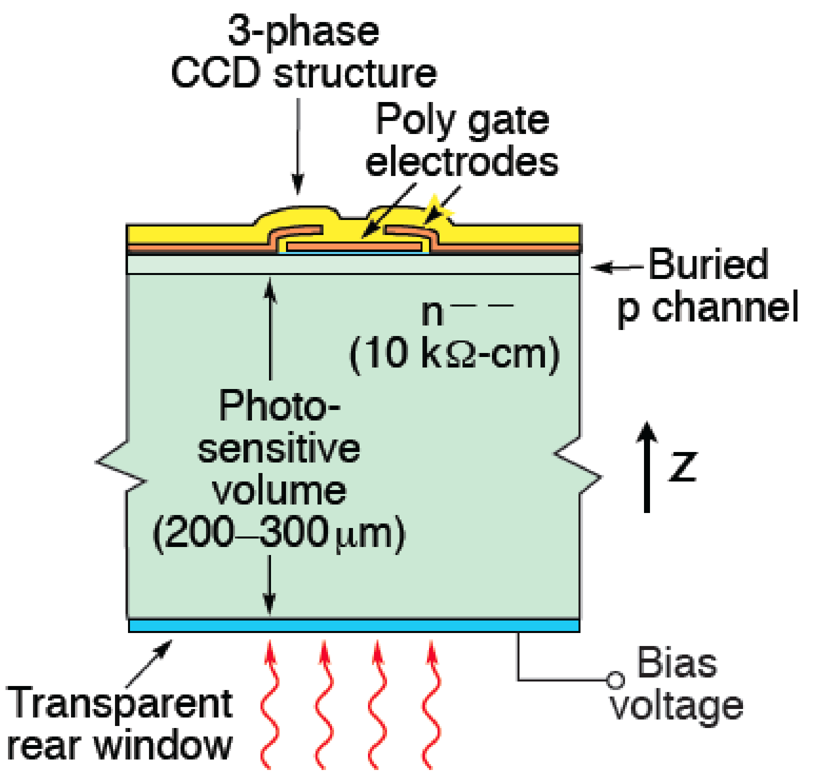
image from Dark Energy Camera

Charge-Coupled Device (CCD)

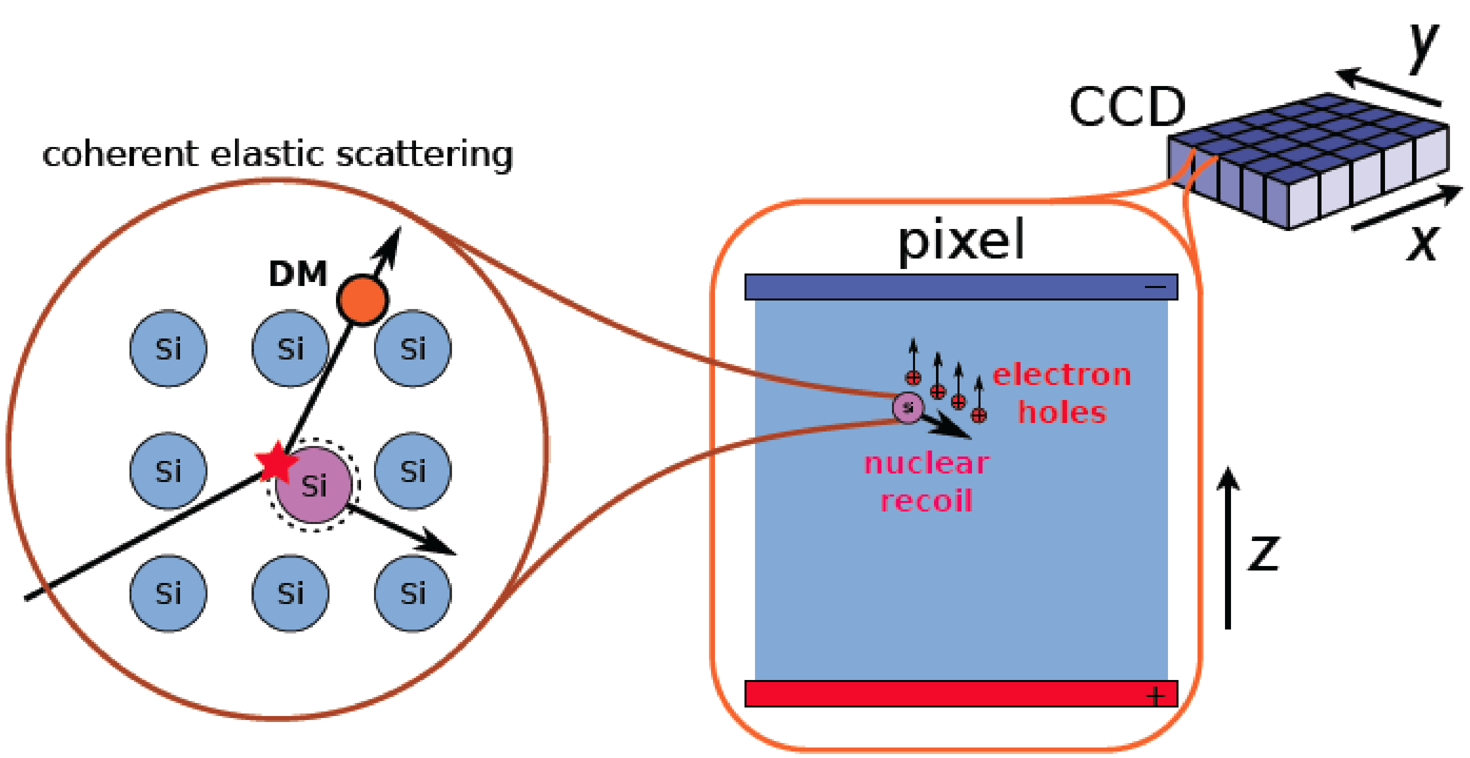




Charge coupling makes the detectors ideal for low noise measurements, typical noise for scientific CCDs is 2e- RMS (7.2eV). Very recent work pushing this to “0” noise.

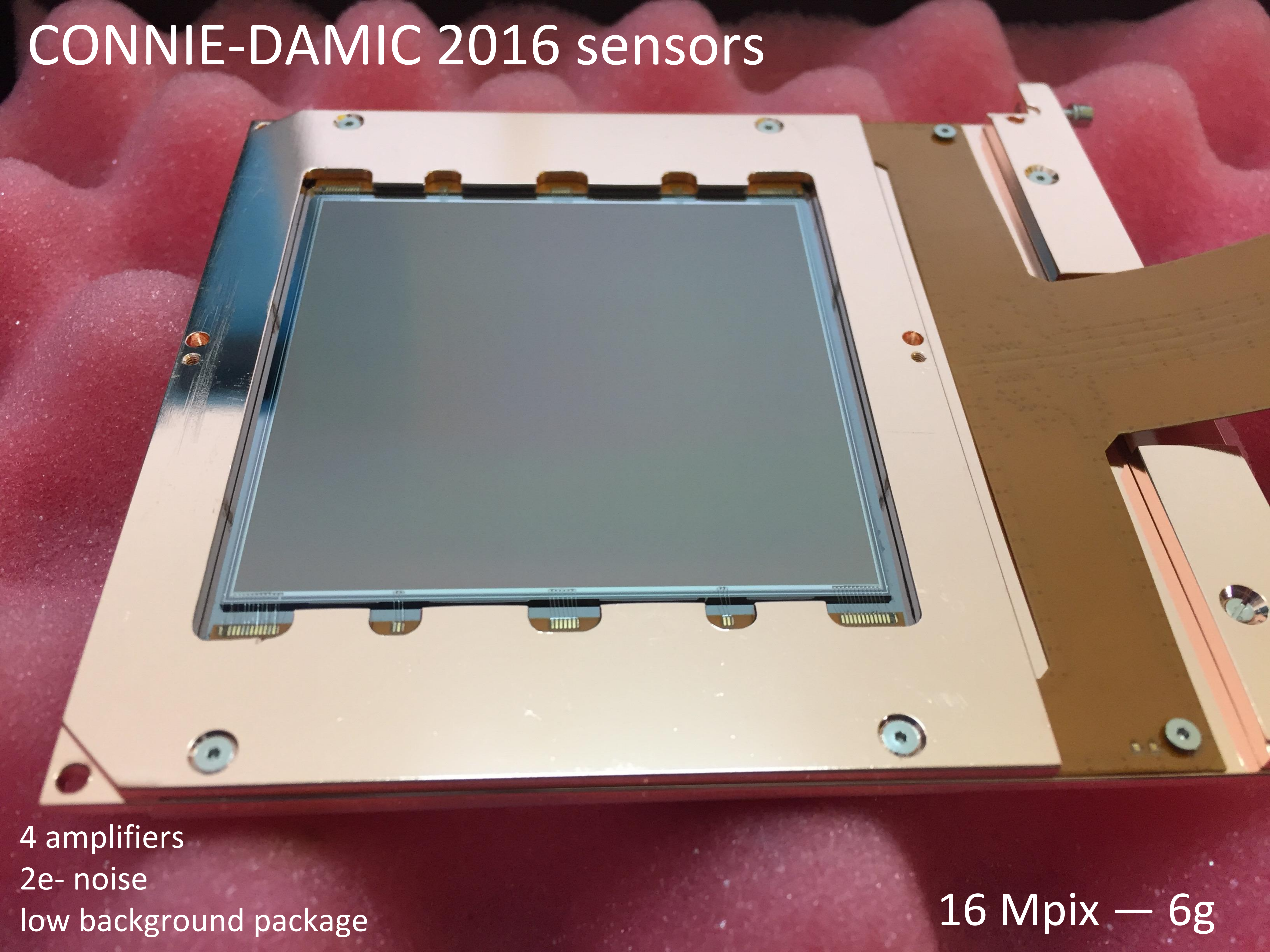


(a) A CCD pixel

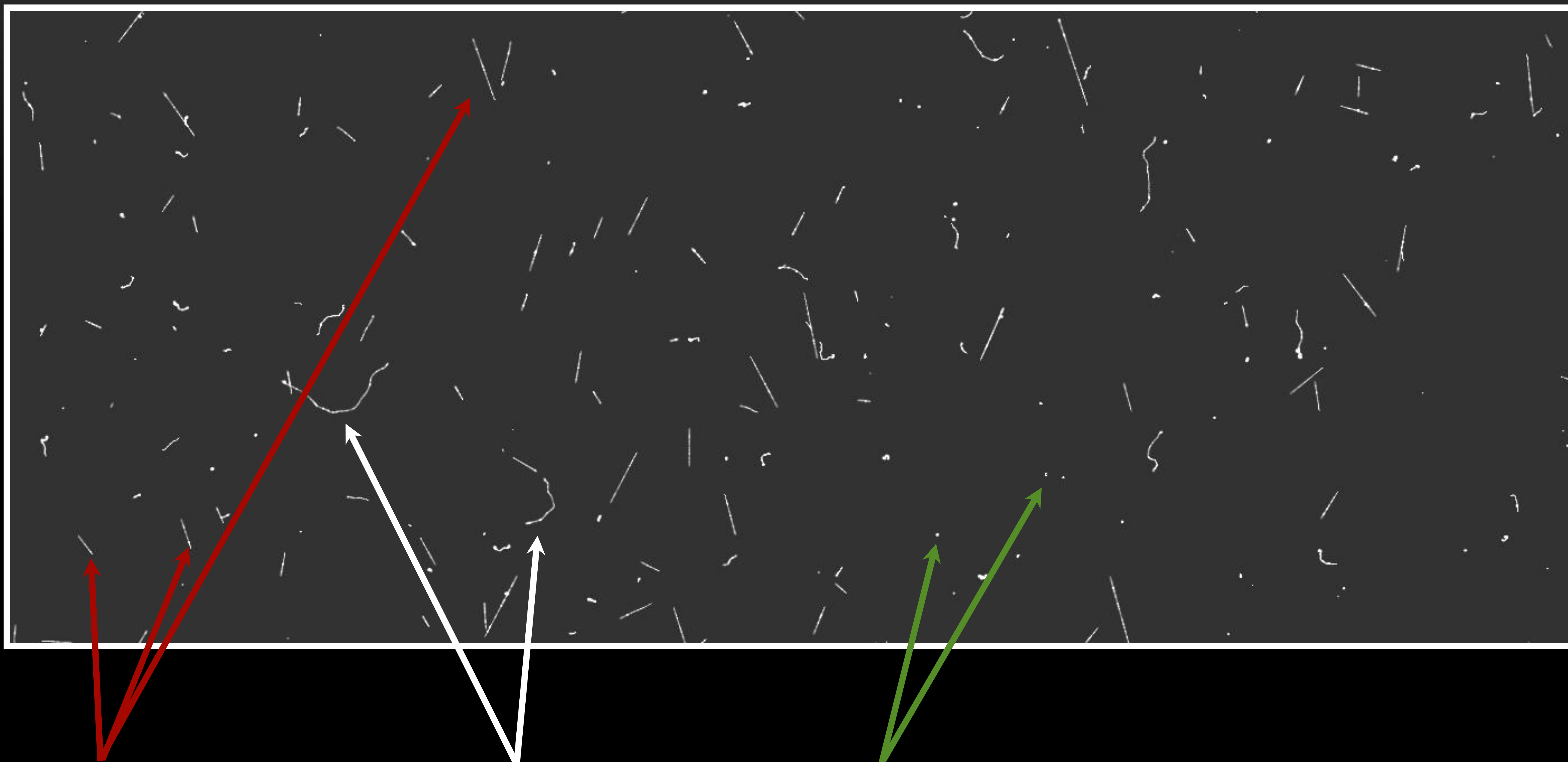


(b) WIMP detection principle

Recent developments by the MSL group at LBNL has allowed the fabrication for “massive” CCDs (675 um thick is now possible). Simple devices with a recent twist…

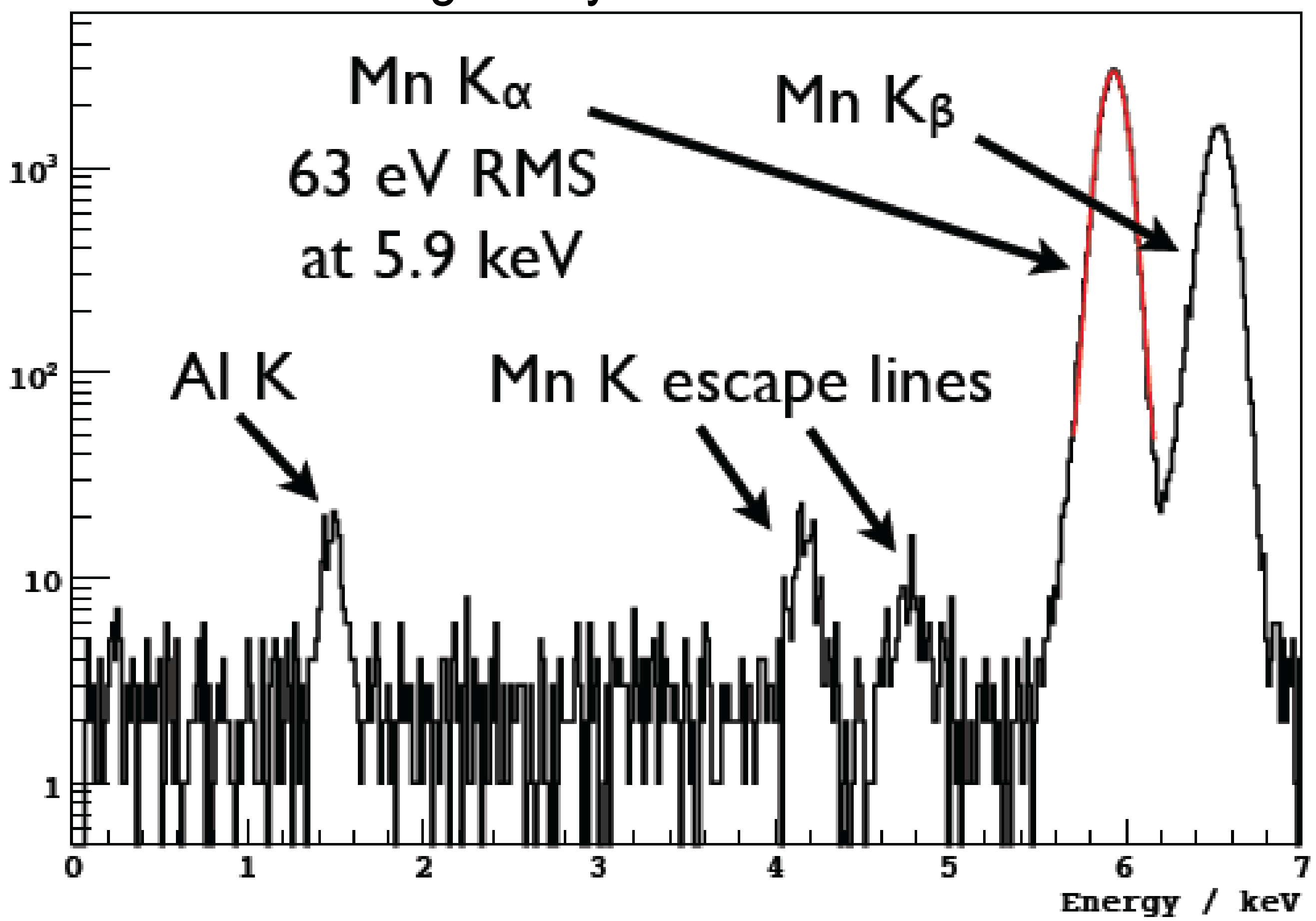

CONNIE-DAMIC 2016 sensors
4 amplifiers
2e- noise
low background package
16 Mpix — 6g

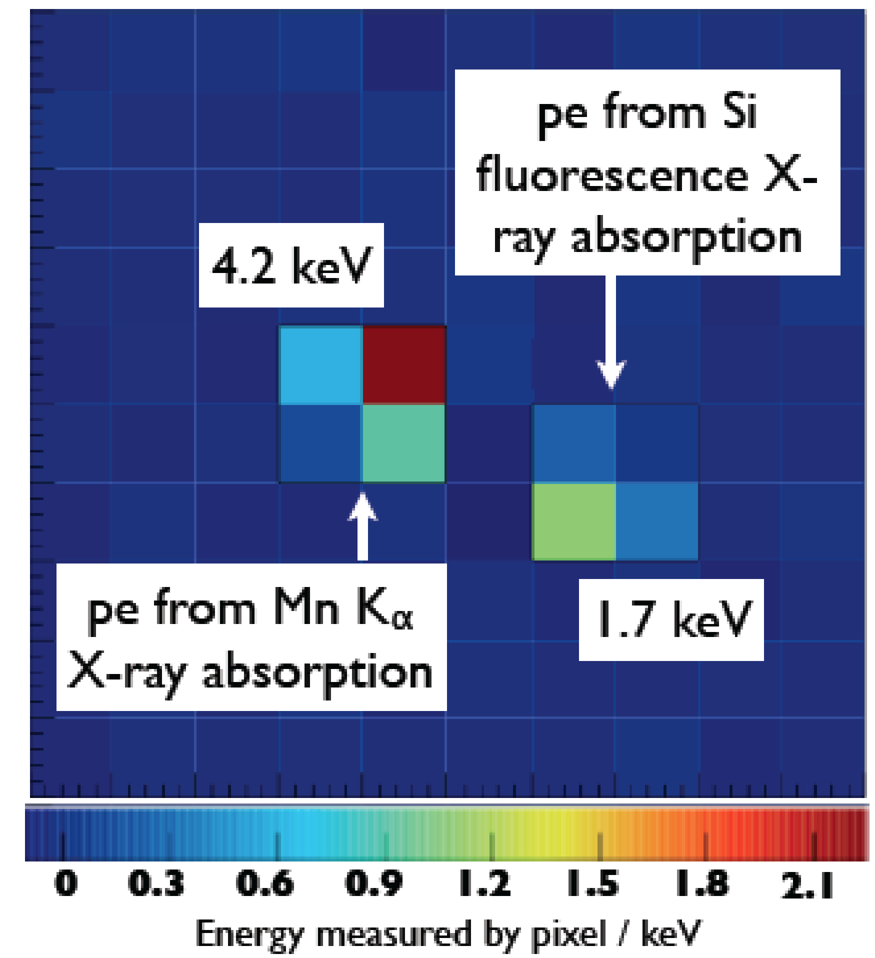
Particle identification in a CCD image

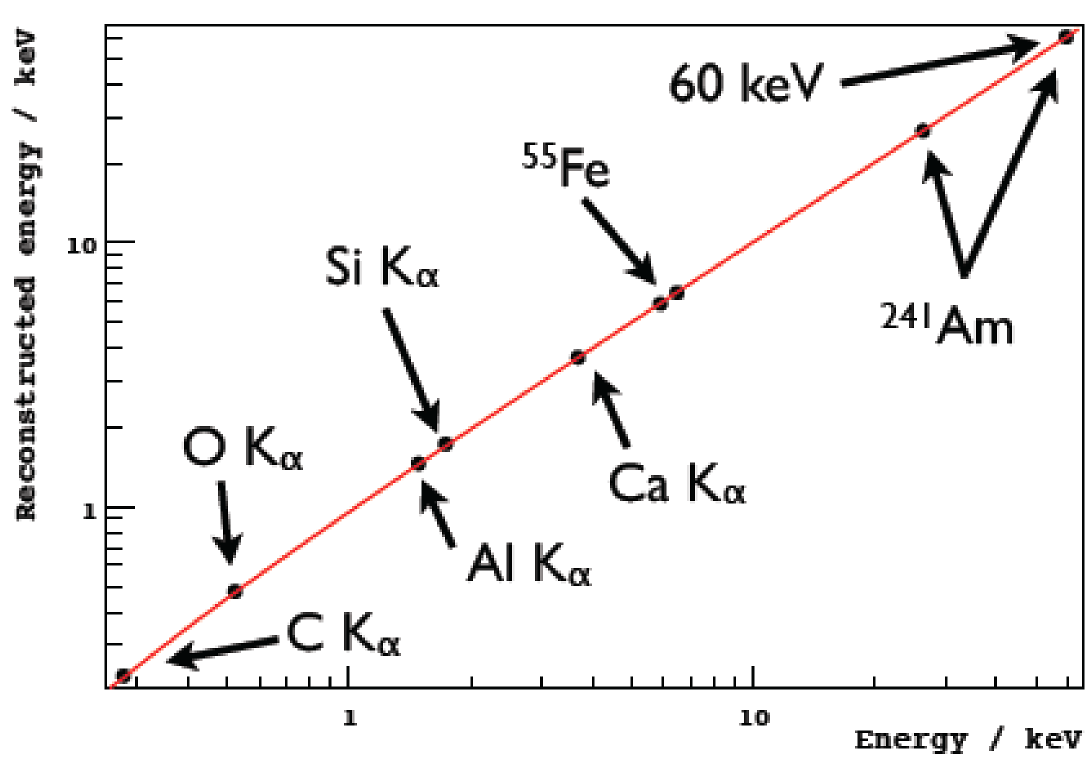


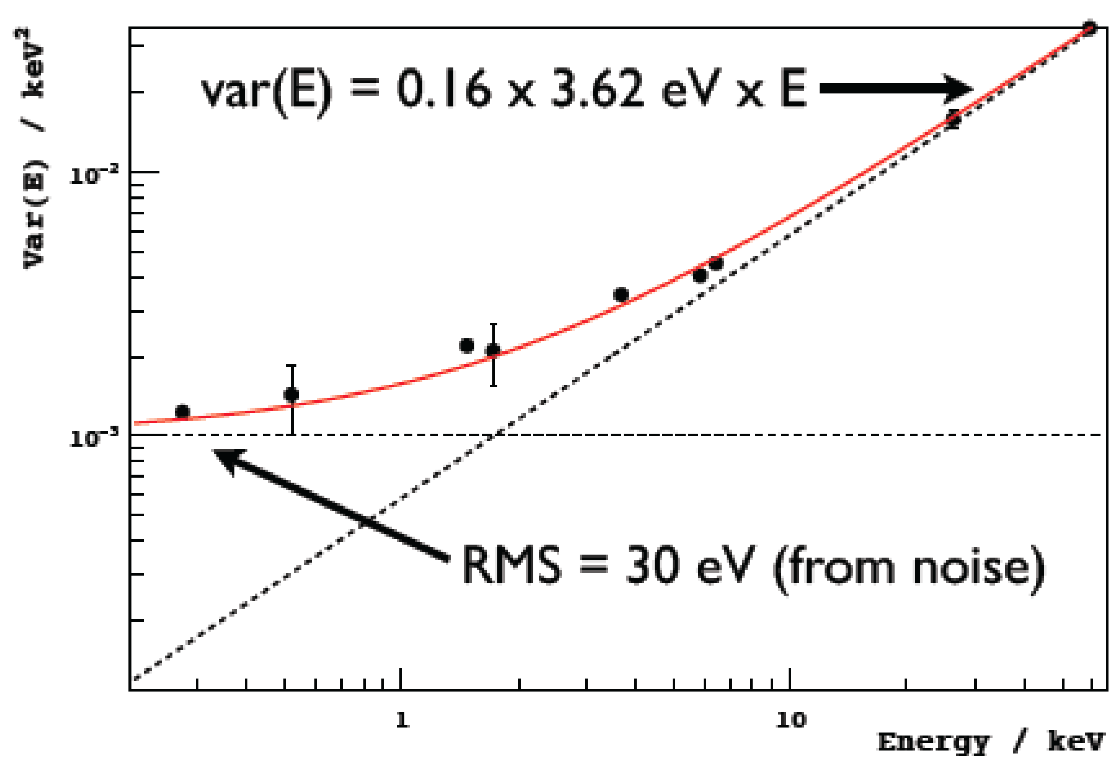
muons, electrons and diffusion limited hits.

Calibration using X-rays









CCD for Dark Matter search and neutrino nucleus elastic coherent scattering

2014

Measurement of radioactive contamination in the high-resistivity silicon CCDs of the DAMIC experiment

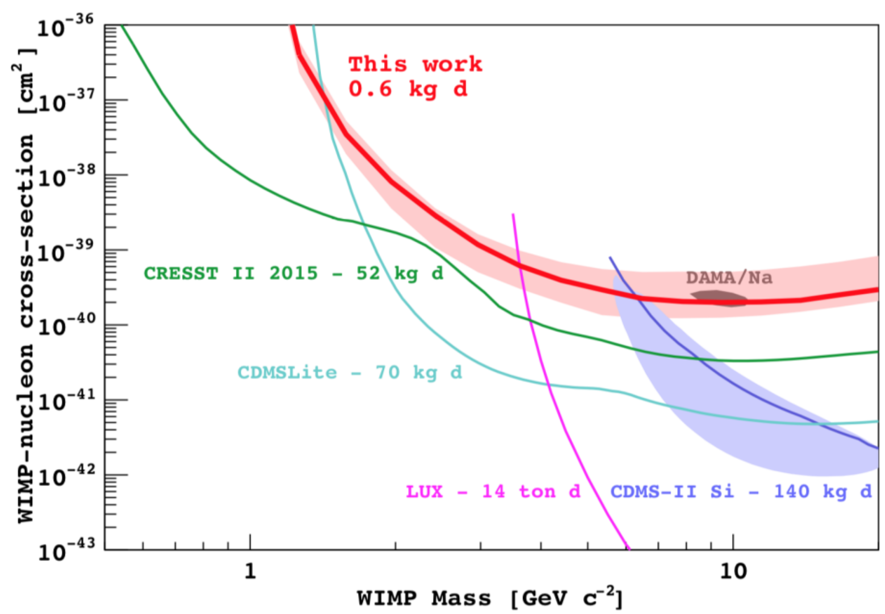
A. Aguilar-Arevalo[a], D. Amidei[b], X. Bertou[c], D. Bole[b], M. Butner[d,j], G. Cancelo[d], A. Castañeda Vázquez[a], A.E. Chavarria[e*], J.R.T. de Mello Neto[f], S. Dixon[e], J.C. D'Olivo[a], J. Estrada[d], G. Fernandez Moroni[d], K.P. Hernández Torres[a], F. Izraelevitch[d], A. Kavner[b], B. Kilminster[g], I. Lawson[h], J. Liao[g], M. López[i], J. Molina[i], G. Moreno-Granados[a], J. Pena[e], P. Privitera[e], Y. Sarkis[a], V. Scarpine[d], T. Schwarz[b], M. Sofo Haro[c], J. Tiffenberg[d], D. Torres Machado[f], F. Trillaud[a], X. You[f] and J. Zhou[e]

[a] Universidad Nacional Autónoma de México, México D.F., México
[b] University of Michigan, Department of Physics, Ann Arbor, MI, United States
[c] Centro Atómico Bariloche - Instituto Balseiro, CNEA/CONICET, Argentina
[d] Fermi National Accelerator Laboratory, Batavia, IL, United States
[e] Kavli Institute for Cosmological Physics and The Enrico Fermi Institute, The University of Chicago, Chicago, IL, United States
[f] Universidade Federal do Rio de Janeiro, Instituto de Física, Rio de Janeiro, RJ, Brazil
[g] Universität Zürich Physik Institut, Zurich, Switzerland
[h] SNOLAB, Lively, ON, Canada
[i] Facultad de Ingeniería - Universidad Nacional de Asunción, Paraguay

2016

Search for low-mass WIMPs in a 0.6 kg day exposure of the DAMIC experiment at SNOLAB

A. Aguilar-Arevalo,[1] D. Amidei,[2] X. Bertou,[3] M. Butner,[4,5] G. Cancelo,[4] A. Castañeda Vázquez,[1] B.A. Cervantes Vergara,[1] A.E. Chavarria,[6] C.R. Chavez,[7] J.R.T. de Mello Neto,[8] J.C. D'Olivo,[1] J. Estrada,[4] G. Fernandez Moroni,[4,9] R. Gaïor,[10] Y. Guardincerri,[4] K.P. Hernández Torres,[1] F. Izraelevitch,[4] A. Kavner,[2] B. Kilminster,[11] I. Lawson,[12] A. Letessier-Selvon,[10] J. Liao,[11] V.B.B. Mello,[8] J. Molina,[7] J.R. Peña,[6] P. Privitera,[6] K. Ramanathan,[6] Y. Sarkis,[1] T. Schwarz,[2] C. Sengul,[6] M. Settimo,[10] M. Sofo Haro,[3] R. Thomas,[6] J. Tiffenberg,[4] E. Tiouchichine,[3] D. Torres Machado,[8] F. Trillaud,[1] X. You,[8] and J. Zhou[6]
(DAMIC Collaboration)



2017

First Direct-Detection Constraints on eV-Scale Hidden-Photon Dark Matter with DAMIC at SNOLAB

A. Aguilar-Arevalo,[1] D. Amidei,[2] X. Bertou,[3] M. Butner,[4,5] G. Cancelo,[4] A. Castañeda Vázquez,[1] B.A. Cervantes Vergara,[1] A.E. Chavarria,[6] C.R. Chavez,[7] J.R.T. de Mello Neto,[8] J.C. D'Olivo,[1] J. Estrada,[4] G. Fernandez Moroni,[4,9] R. Gaïor,[10] Y. Guardincerri,[4] K.P. Hernández Torres,[1] F. Izraelevitch,[4] A. Kavner,[2] B. Kilminster,[11] I. Lawson,[12] A. Letessier-Selvon,[10] J. Liao,[11] A. Matalon,[6] V.B.B. Mello,[8] J. Molina,[7] P. Privitera,[6] K. Ramanathan,[6] Y. Sarkis,[1] T. Schwarz,[2] M. Settimo,[10] M. Sofo Haro,[3] R. Thomas,[6] J. Tiffenberg,[4] E. Tiouchichine,[3] D. Torres Machado,[8] F. Trillaud,[1] X. You,[8] and J. Zhou[6]
(DAMIC Collaboration)

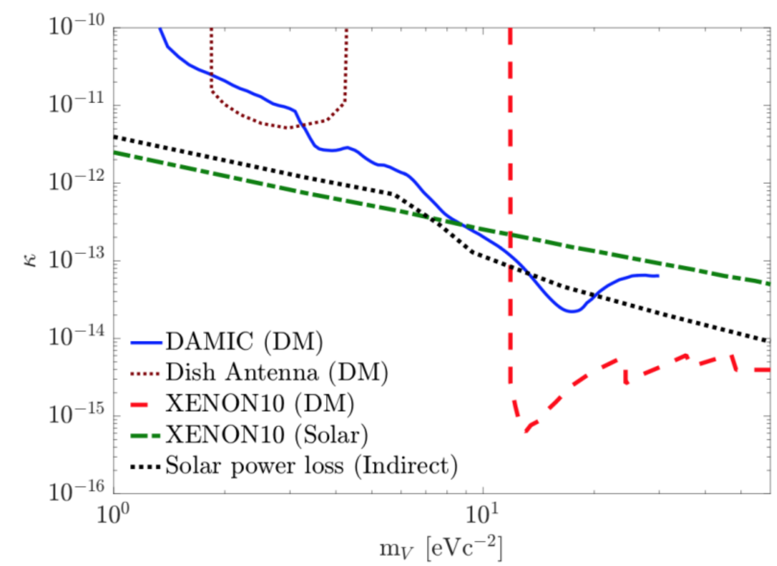
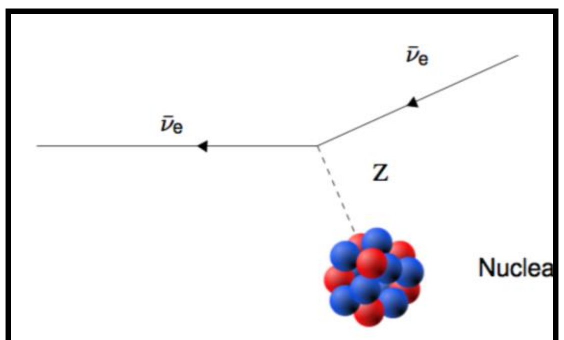


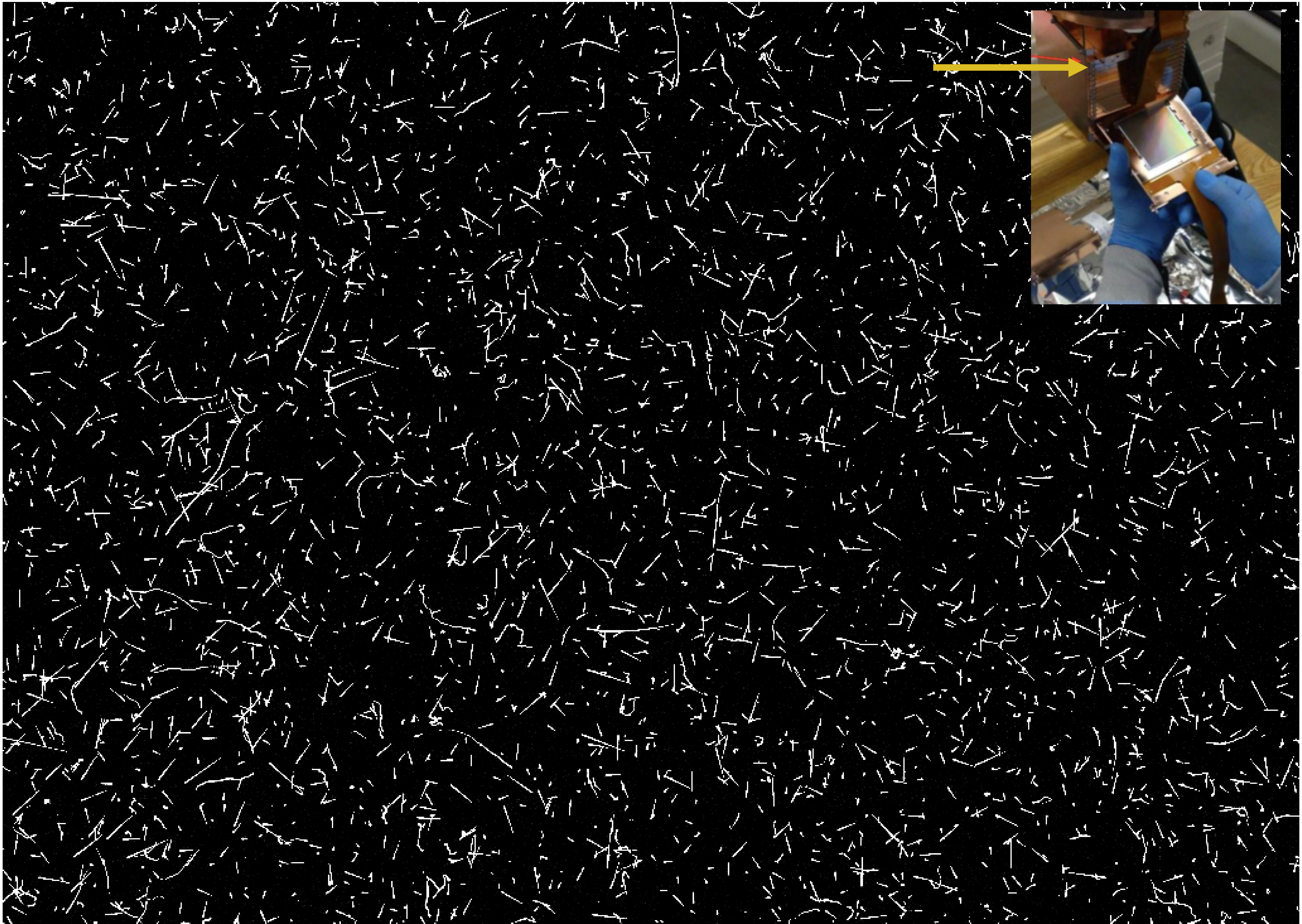
FIG. 5. Exclusion plot (90% C.L.) for the hidden-photon kinetic mixing κ as a function of hidden photon mass m_V from the dark matter search presented in this Letter (solid line). The exclusion limits from other direct searches for hidden-photon dark matter in the galactic halo with a dish antenna (thin dotted line) [13] and with the XENON10 experiment (dashed line) [5] are shown for comparison. A limit from a direct search with the XENON10 experiment for hidden photons radiated by the Sun (dot-dashed line) [5] and an indirect constraint from the upper limit of the power lost by the Sun into invisible radiation (thick dotted line) [14] are also presented.

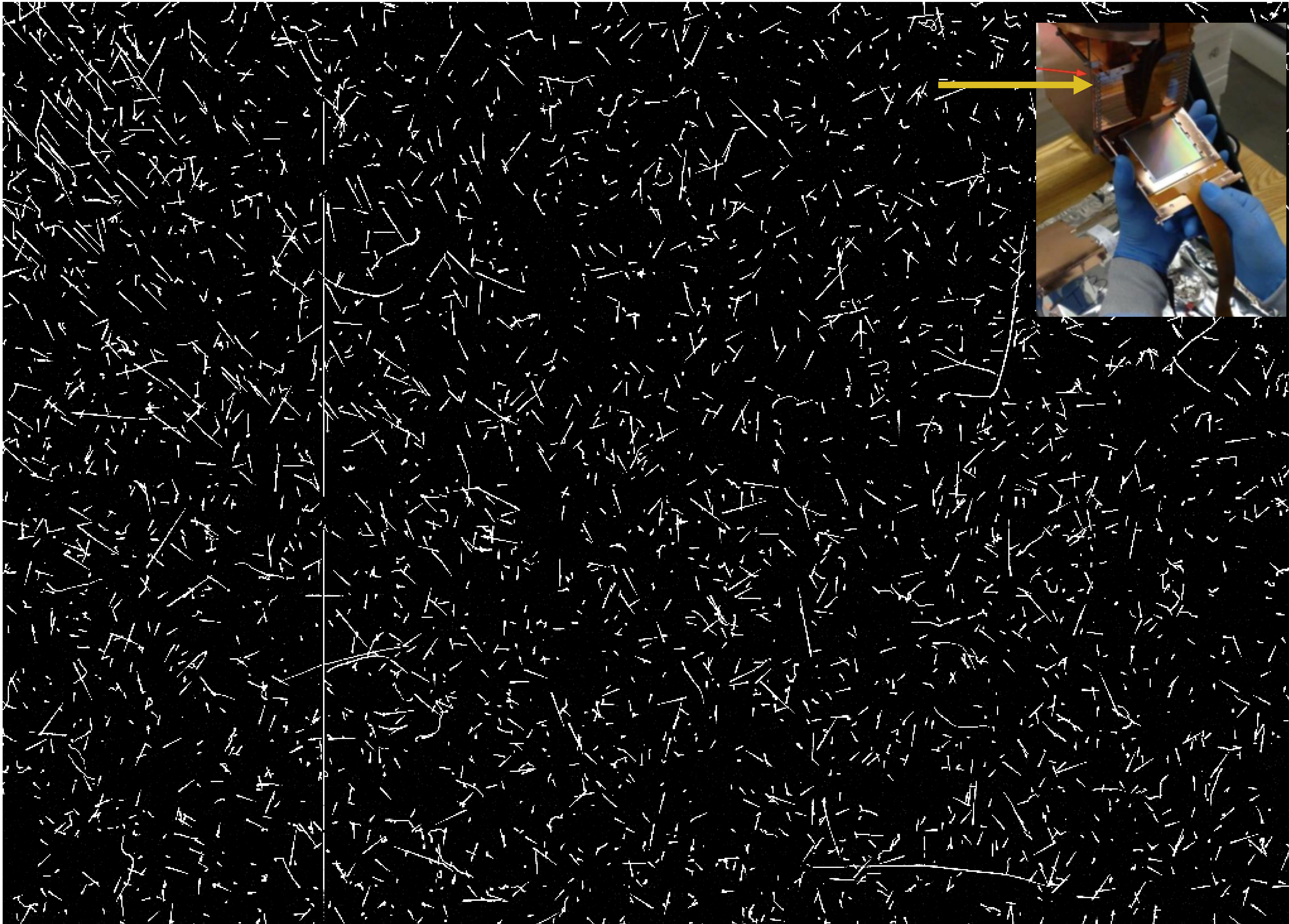
2016

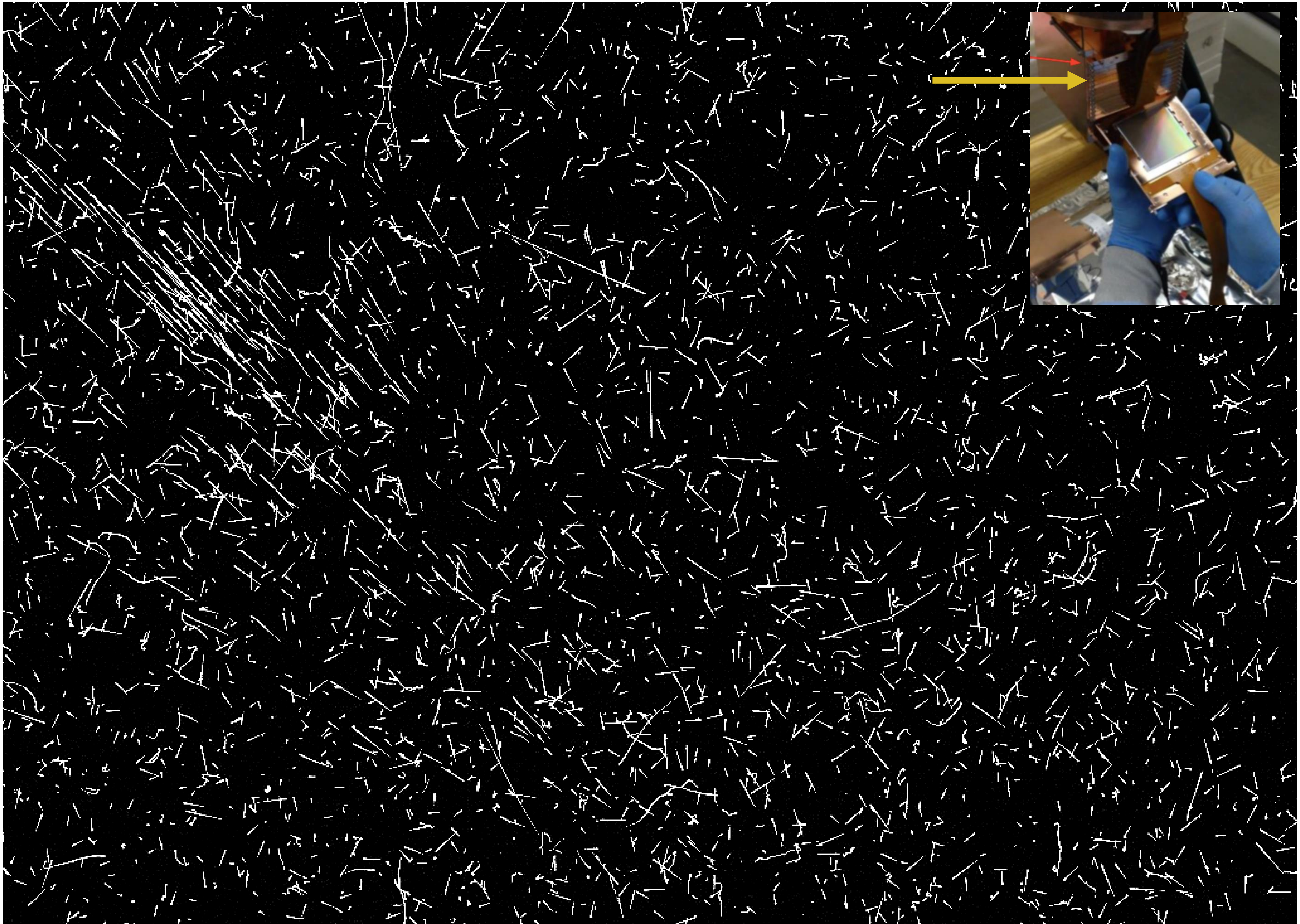
Results of the engineering run of the Coherent Neutrino Nucleus Interaction Experiment (CONNIE)

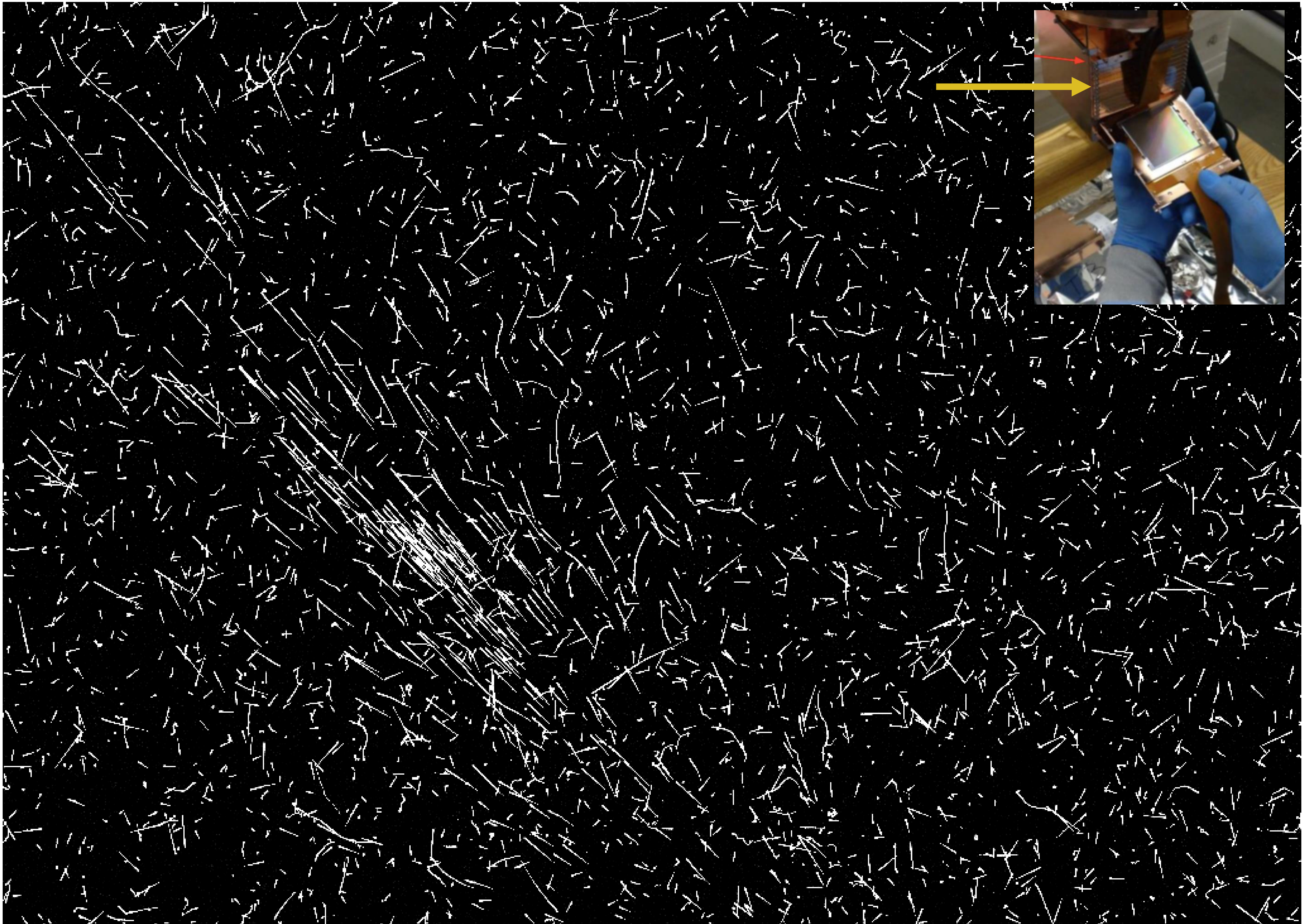
A. Aguilar-Arevalo,[1] X. Bertou,[2] C. Bonifazi,[3] M. Butner,[4] G. Cancelo,[4] A. Castañeda Vázquez,[1] C.R. Chavez,[5] H. Da Motta,[6] J.C. D'Olivo,[1] J. Dos Anjos,[6] J. Estrada,[4] G. Fernandez Moroni,[7,8] R. Ford,[4] A. Foguel,[3,6] K.P. Hernández Torres,[1] F. Izraelevitch,[4] H.P. Lima Jr.,[6] B. Kilminster,[9] K. Kuk,[4] M. Makler,[6] J. Molina,[5] G. Moreno-Granados,[1] J.M. Moro,[10] E.E. Paolini,[7,11] M. Sofo Haro,[2] J. Tiffenberg,[4] F. Trillaud,[1] and S. Wagner[6,12]

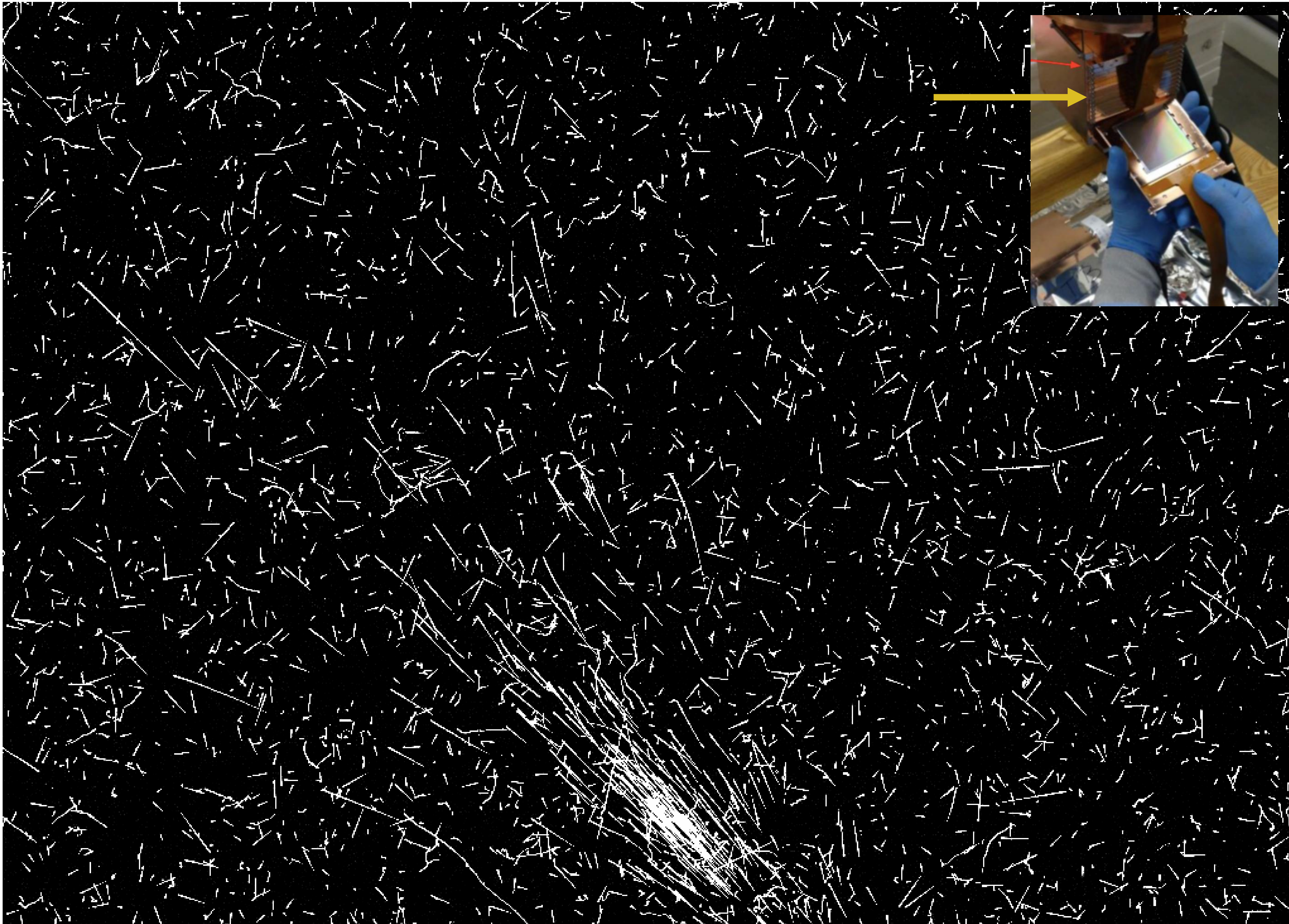








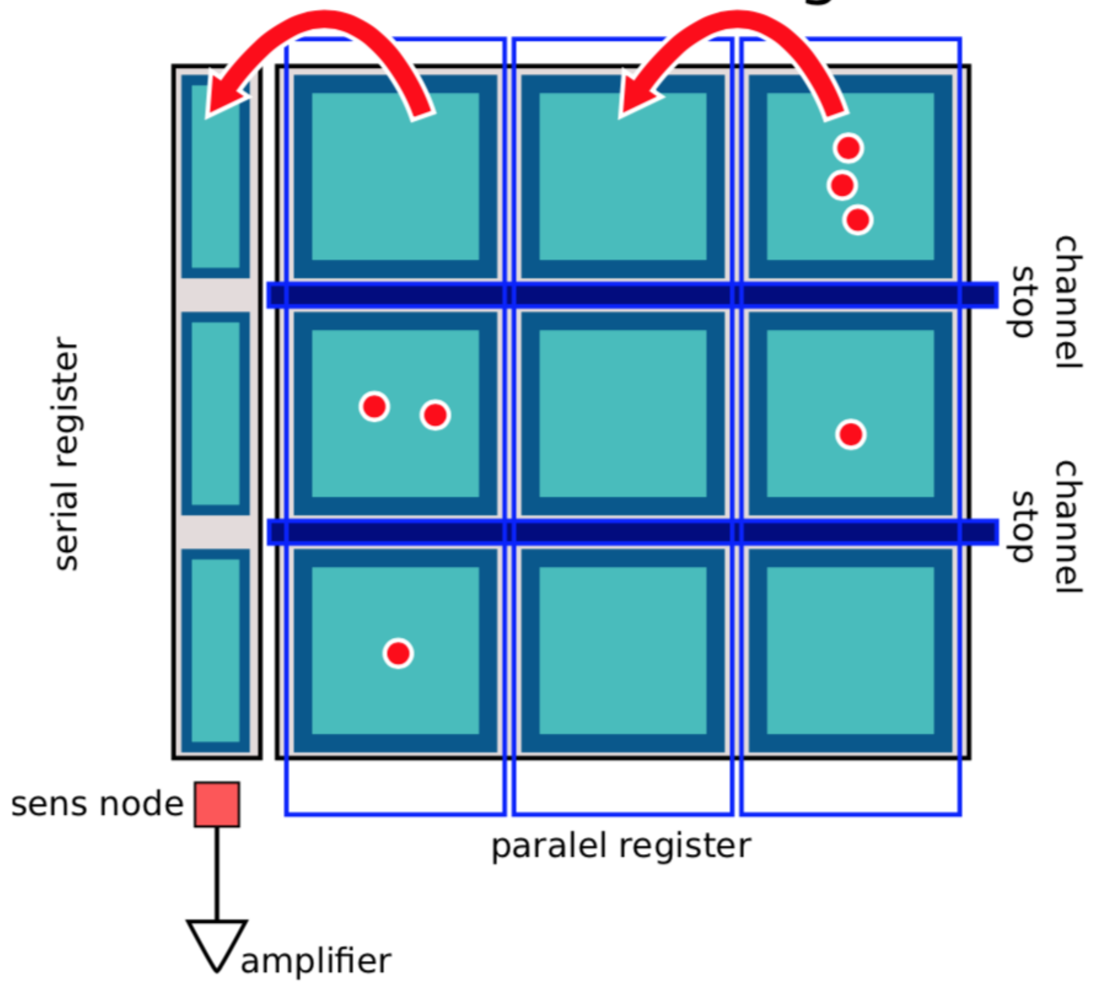




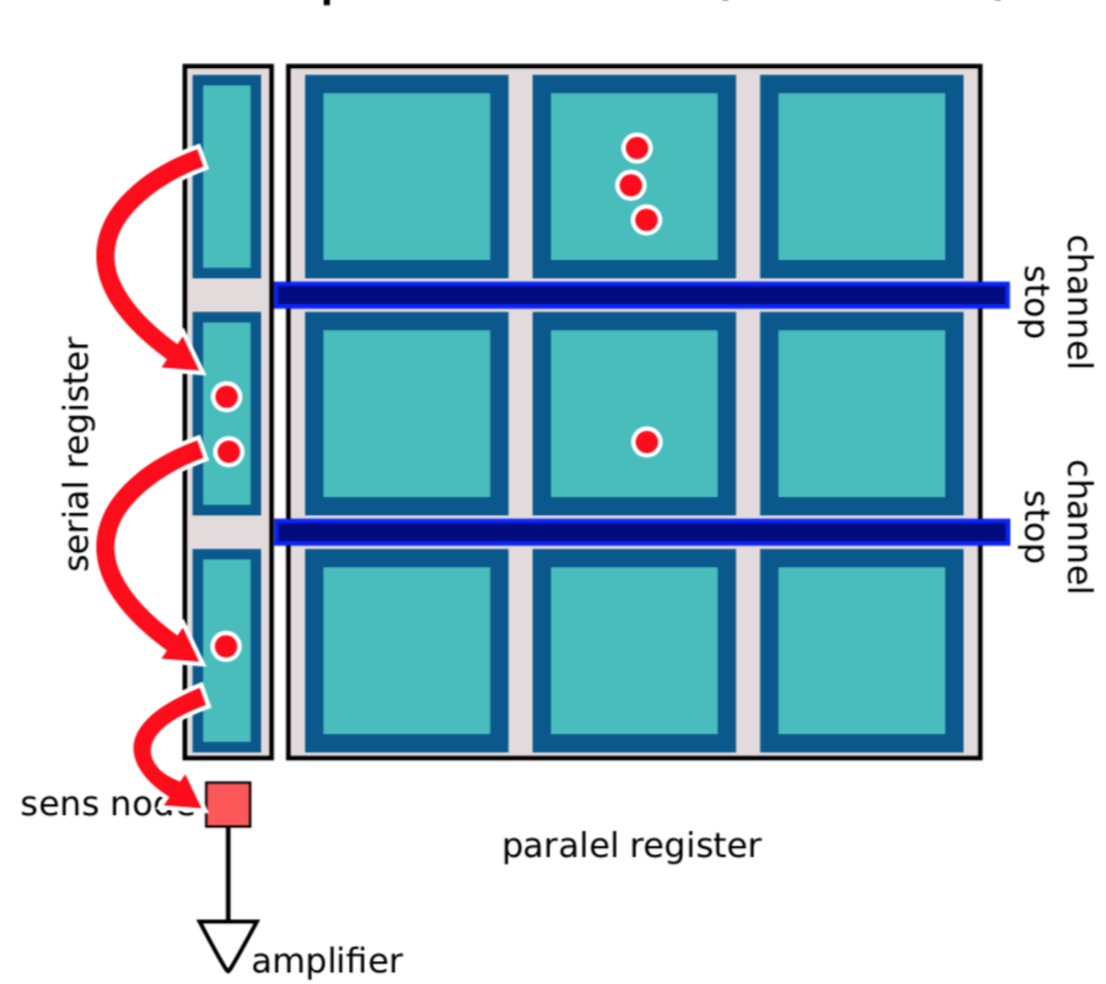
skipper-CCD

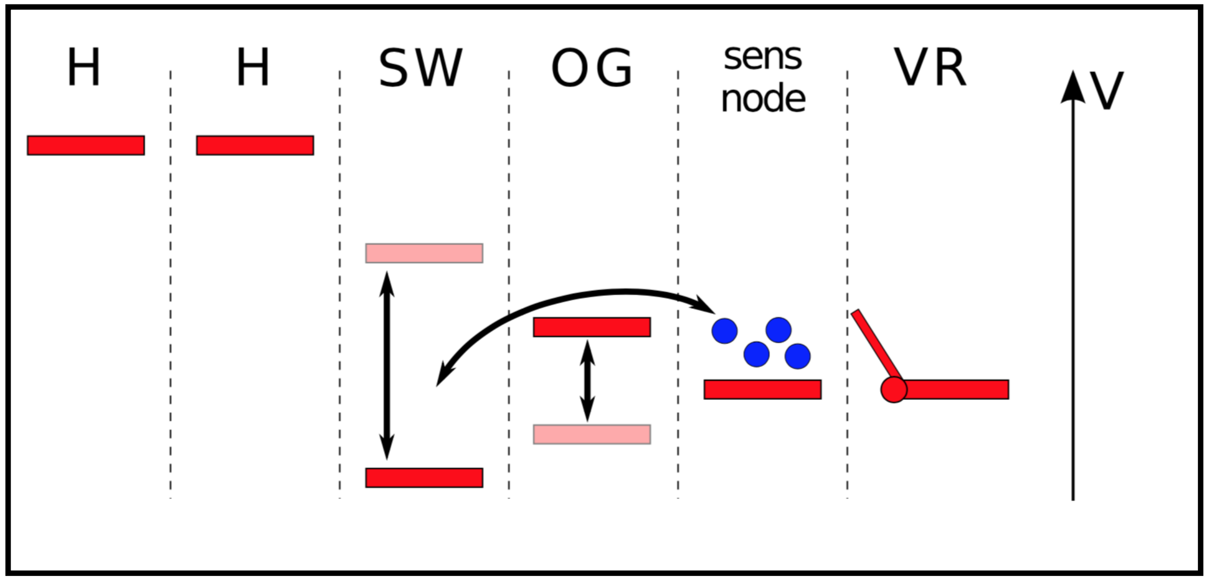
The skipper-CCD is a modification of the output stage of a CCD (Janesik et al - 1990). It allows for multiple non-destructive readout of the charge in a pixel.

Shift charge one column to tha right

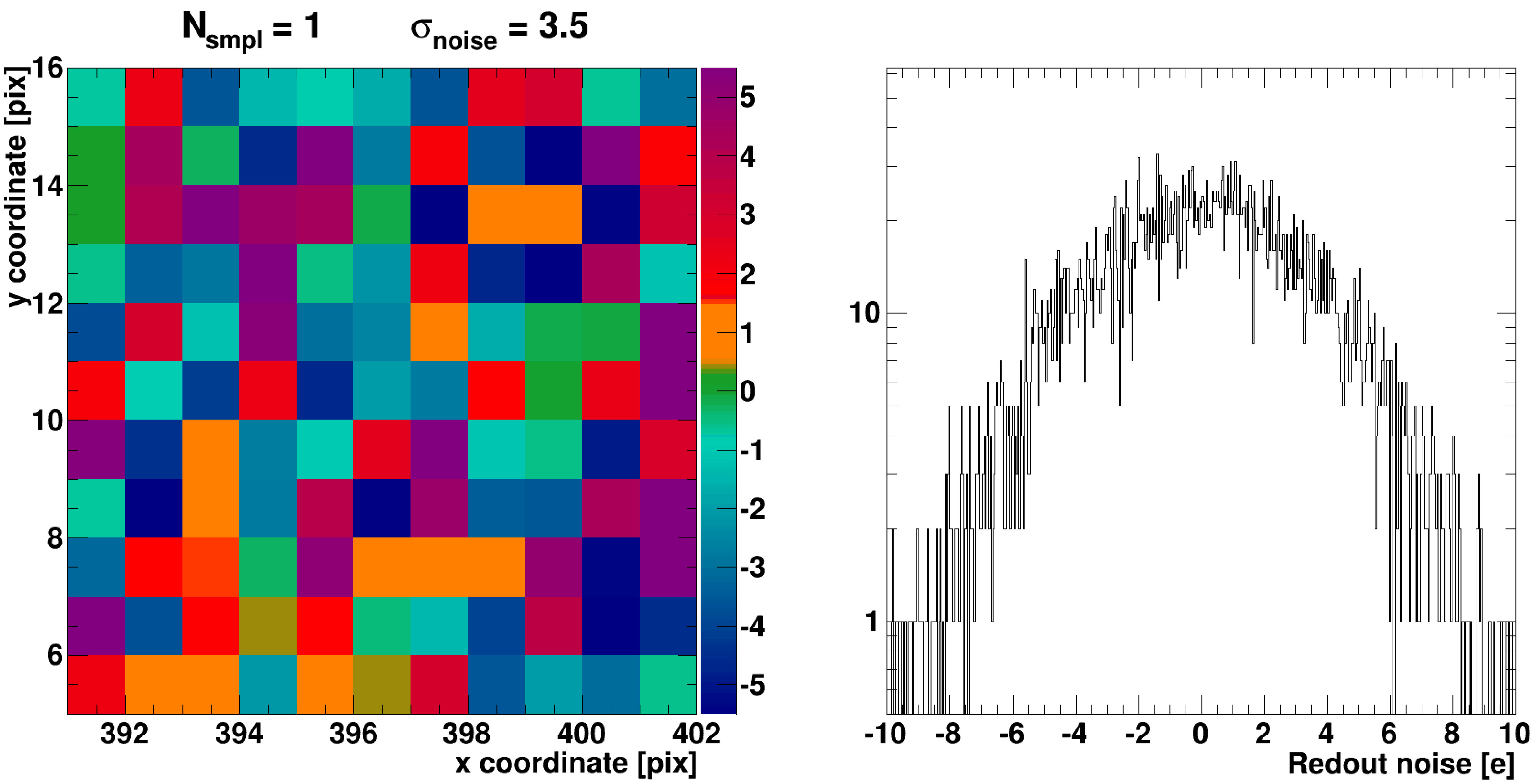


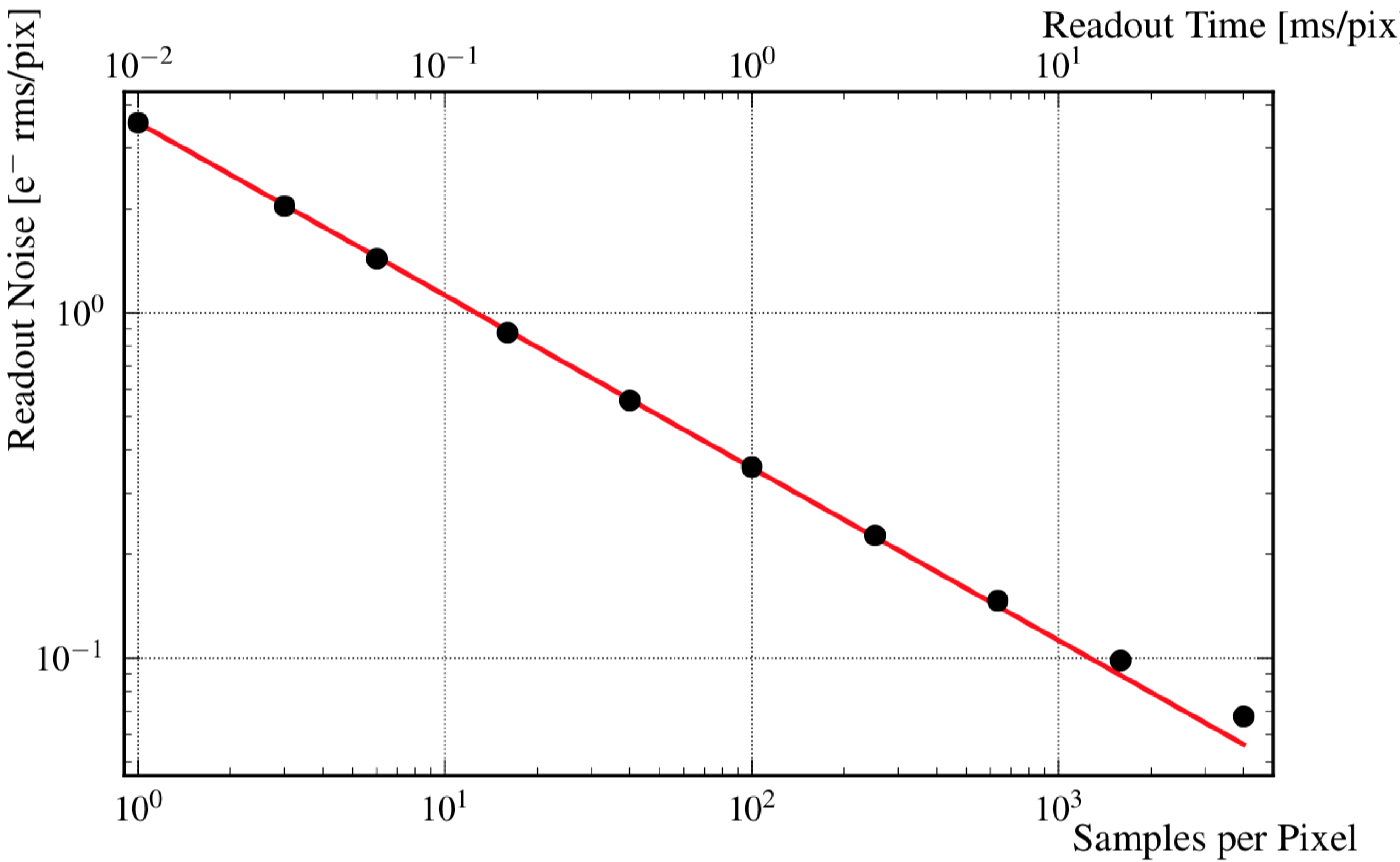
Shift charge in serial register one pixel down (3 times)





the new skippers



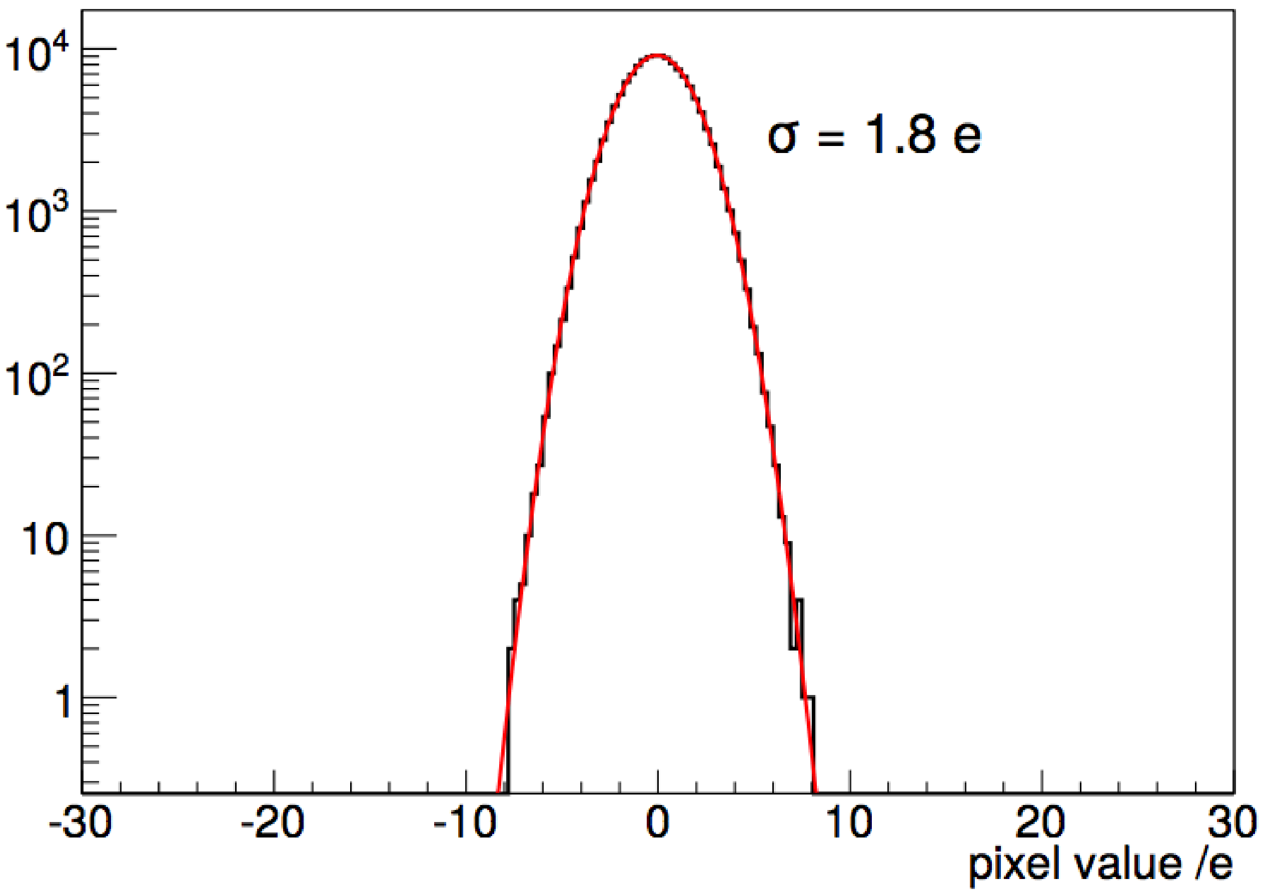


Readout Time [ms/pix]
10^{-2}
10^{-1}
10^{0}
10^{1}
Readout Noise [e^- rms/pix]
10^{0}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Samples per Pixel

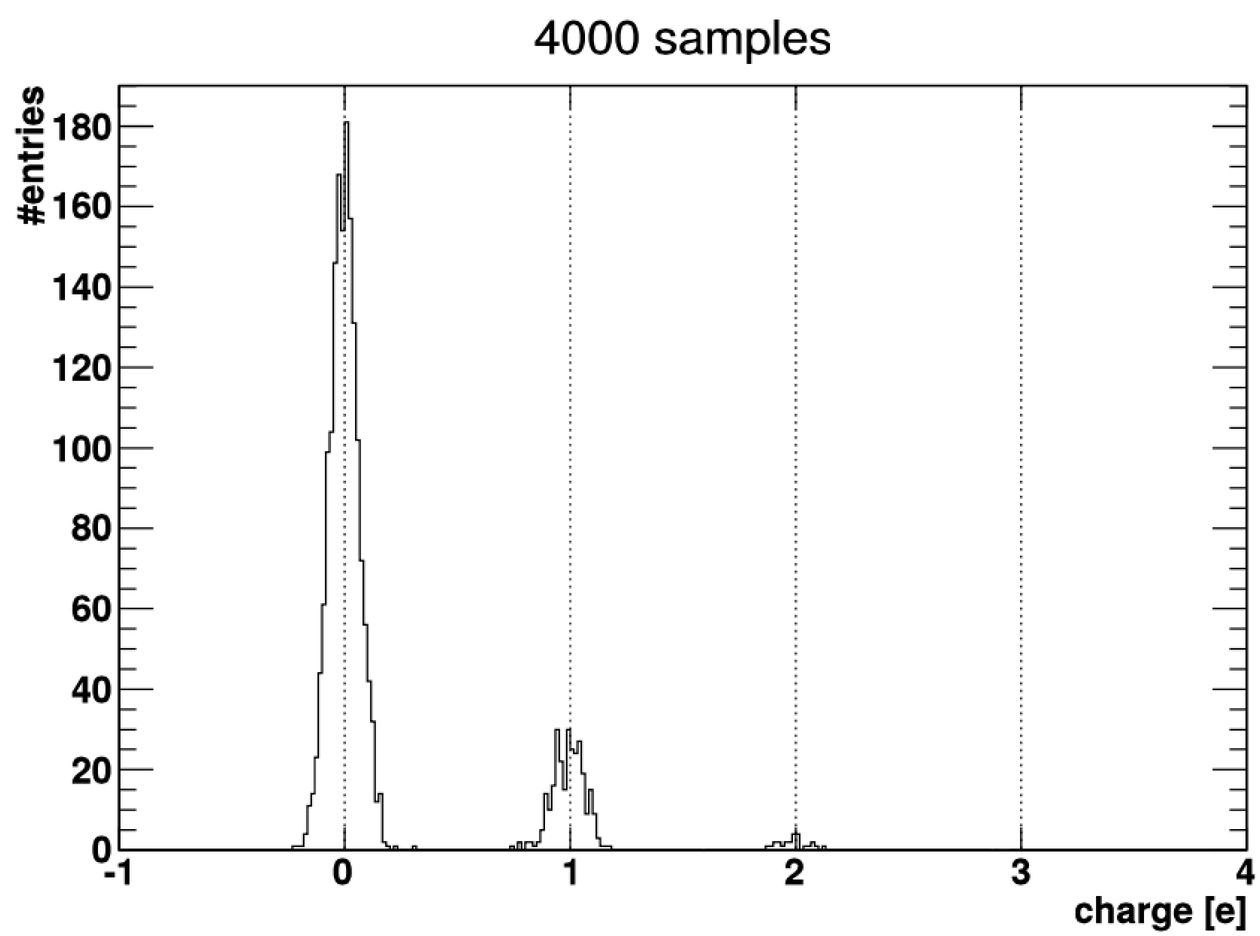
Single-electron and single-photon sensitivity with a silicon Skipper CCD

Javier Tiffenberg,[1,*] Miguel Sofo-Haro,[2,1] Alex Drlica-Wagner,[1] Rouven Essig,[3]
Yann Guardincerri,[1,†] Steve Holland,[4] Tomer Volansky,[5] and Tien-Tien Yu[6]

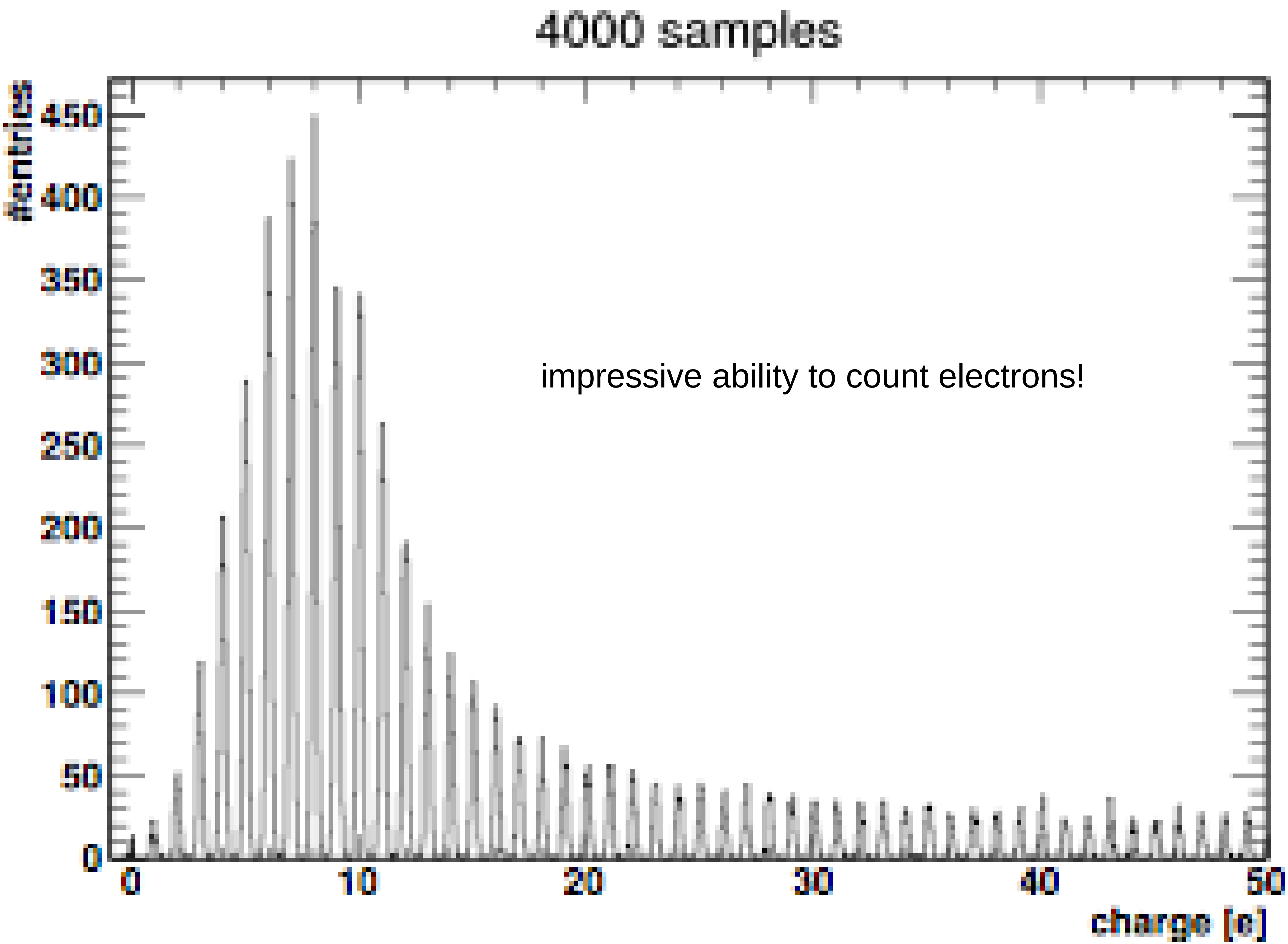
scientific CCDs now



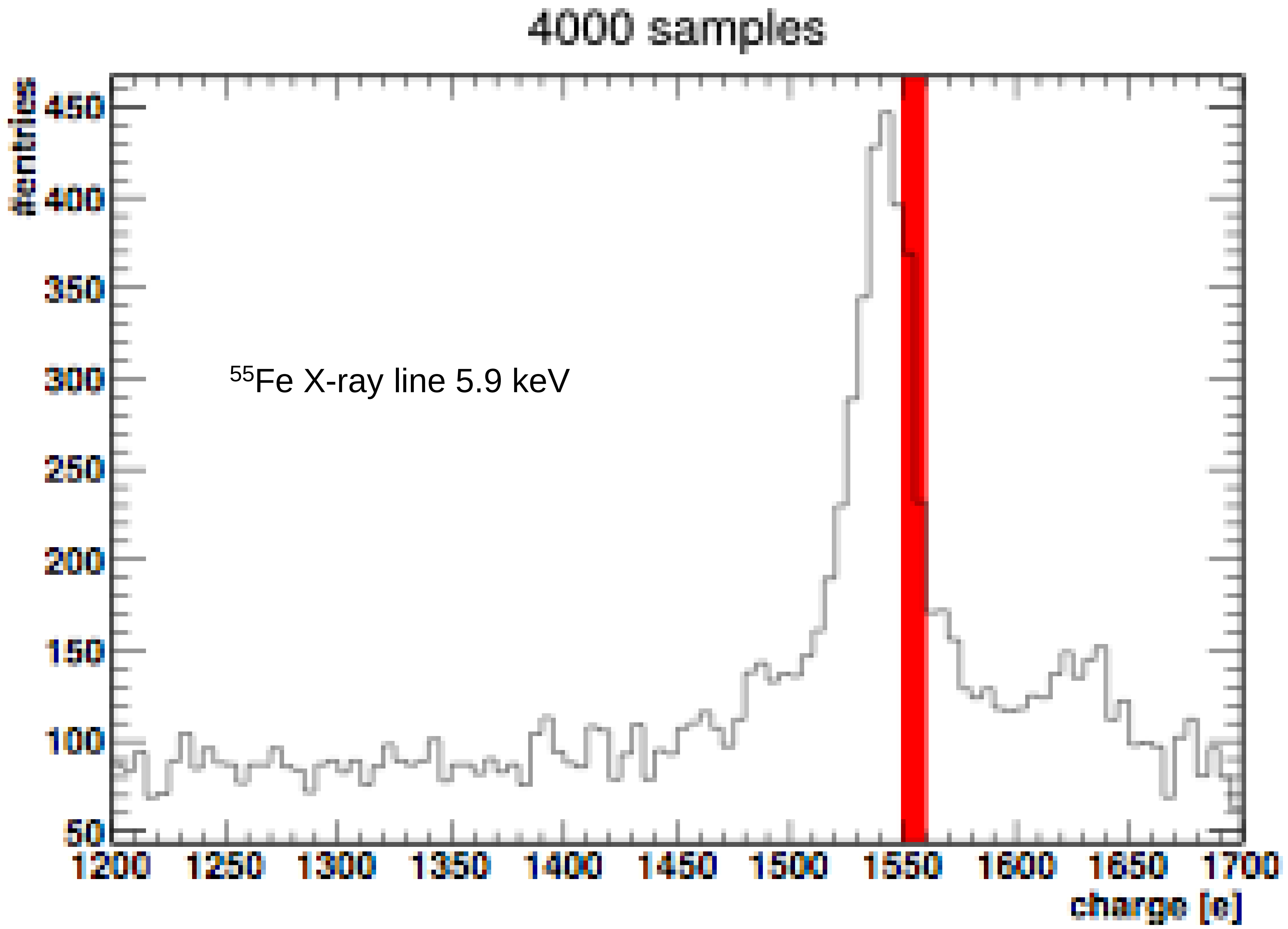
skipper CCD



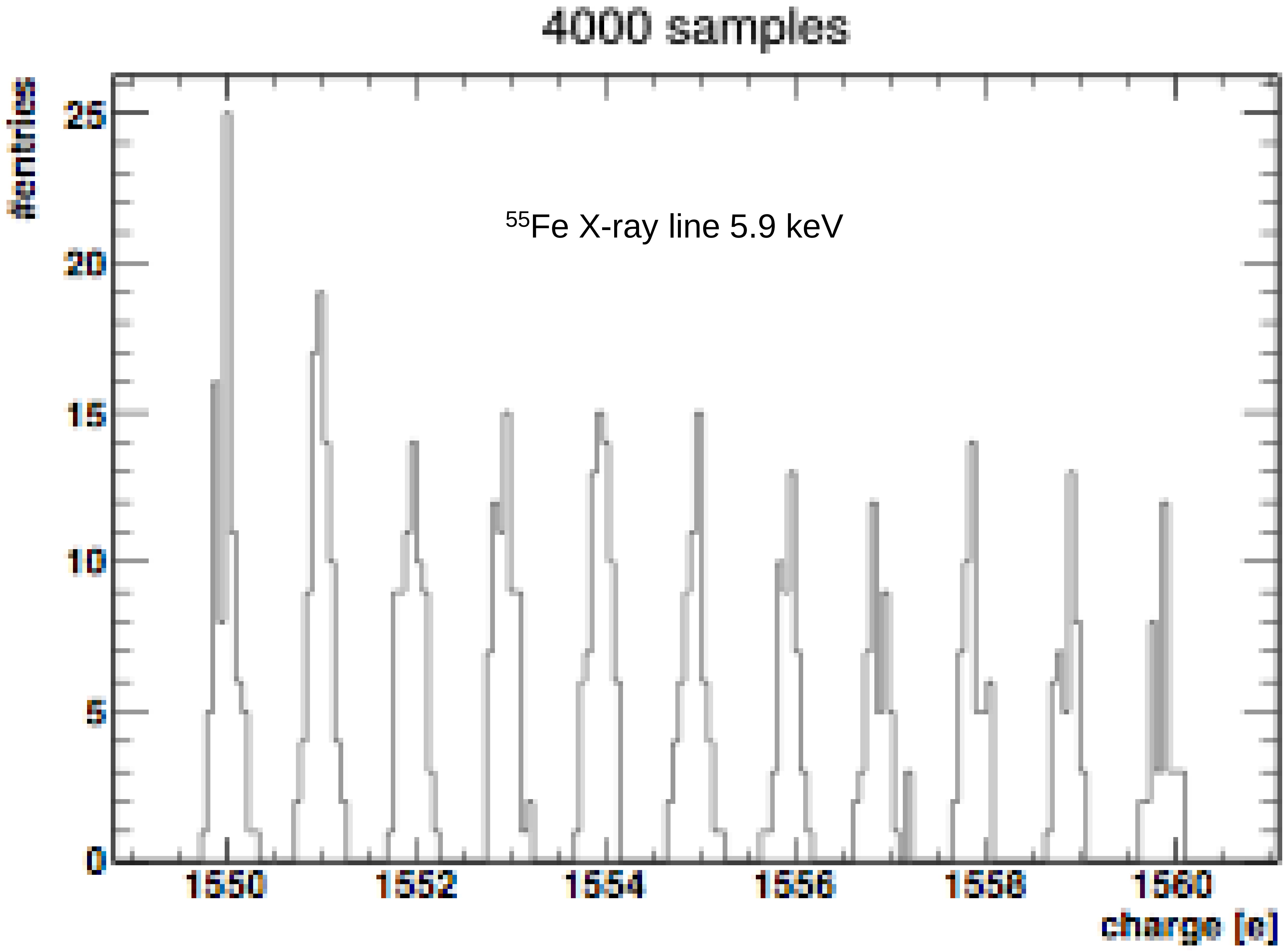
Designed ~30 years ago, but technology first demonstrated summer 2017 by Javier Tiffenberg et al (arXiv:1706.00028) [FNAL+LBNL R&D effort over several years] allows reduction of the threshold by another factor of 2. The plan is to install a couple of these detectors in CONNIE also. Will need a new ionization efficiency measurement.



4000 samples
entries
450
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
charge [e]
impressive ability to count electrons!



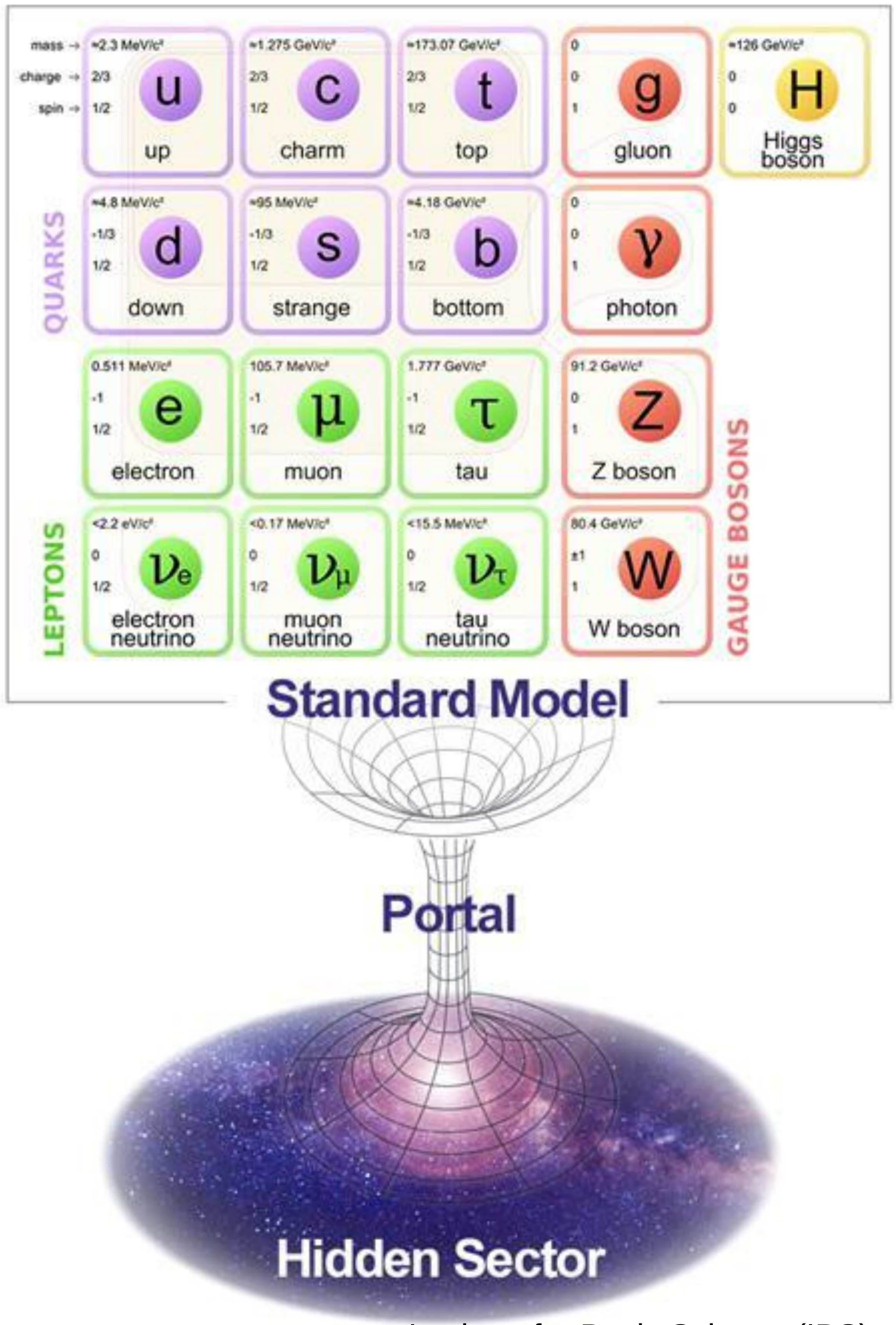
4000 samples
entries
450
400
350
300
250
200
150
100
50
^{55}Fe X-ray line 5.9 keV
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700
charge [e]



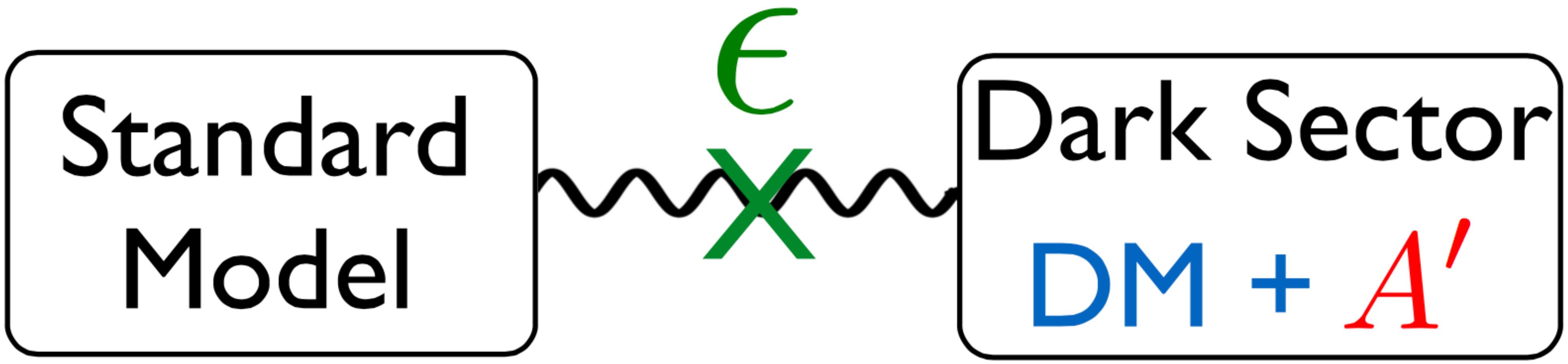
4000 samples
#entries
25
20
15
10
5
0
55Fe X-ray line 5.9 keV
1550
1552
1554
1556
1558
1560
charge [e]

dark sector search

here will focus on the hidden sector



DM w/ dark photon (A′) mediator

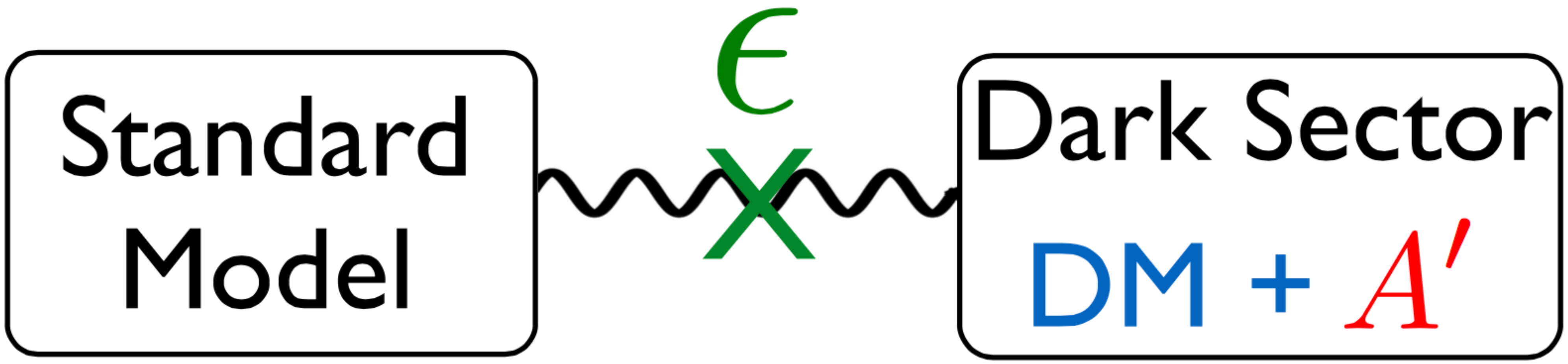


- light A′ (~m_{DM})
- ultra-light A′ (≪keV)

DM w/ dark photon (A′) mediator

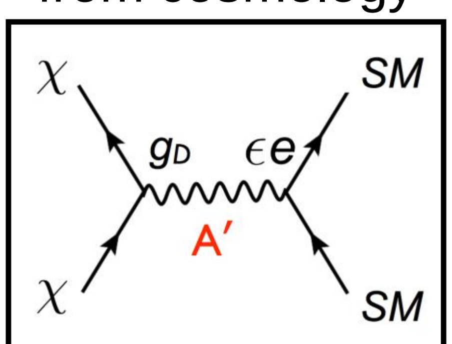
R. Essig

nice predictive model to target!



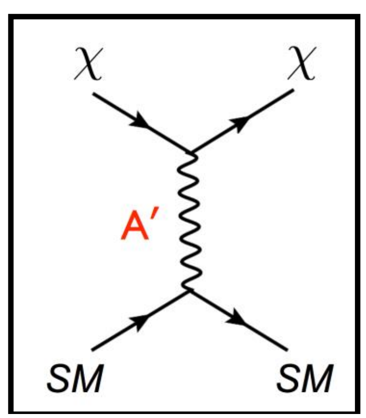
- light A′ (~m_{DM}) ⟶ $m_{A'} > 2m_\chi$
- ultra-light A′ (≪keV)

constrains from cosmology

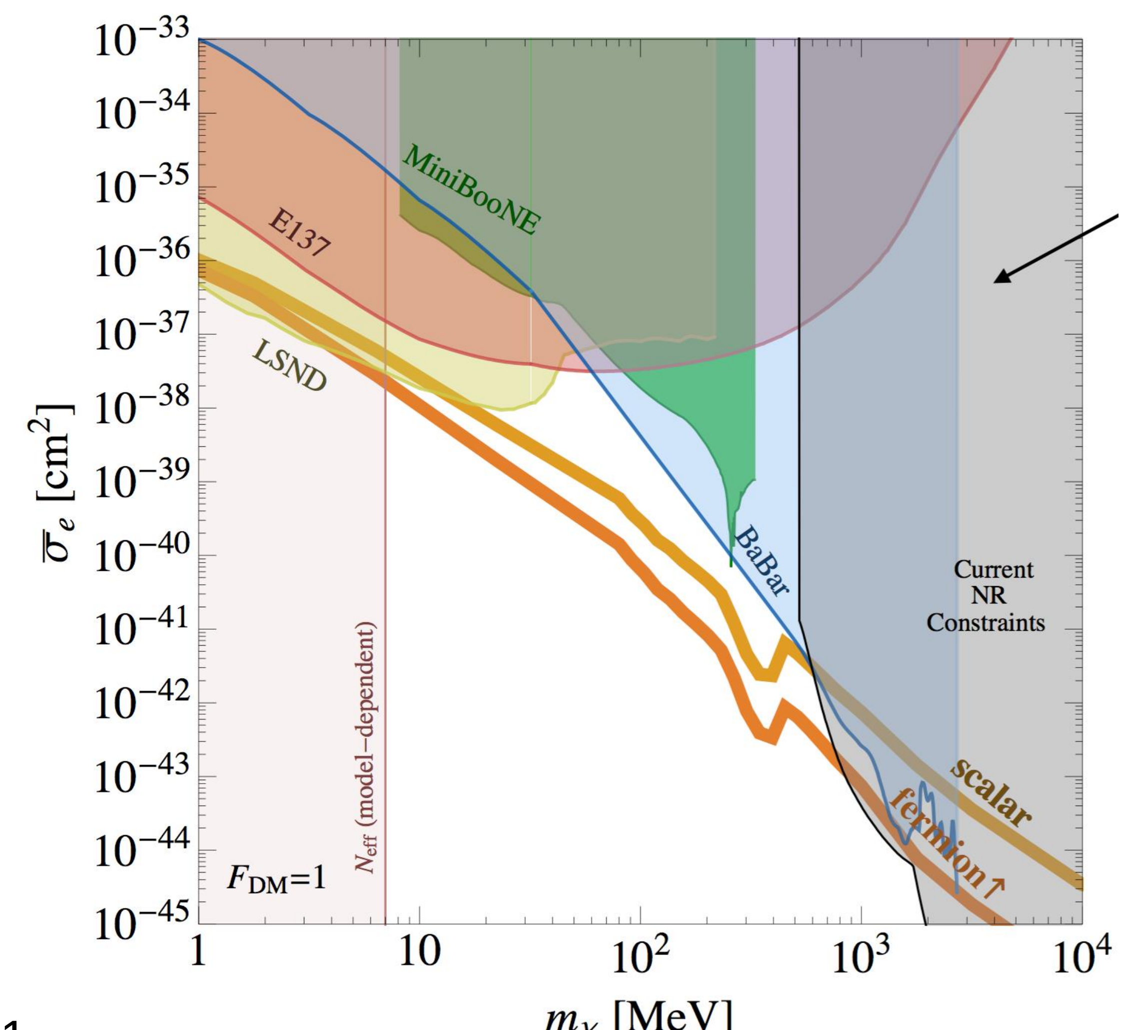


freeze out

direct detection



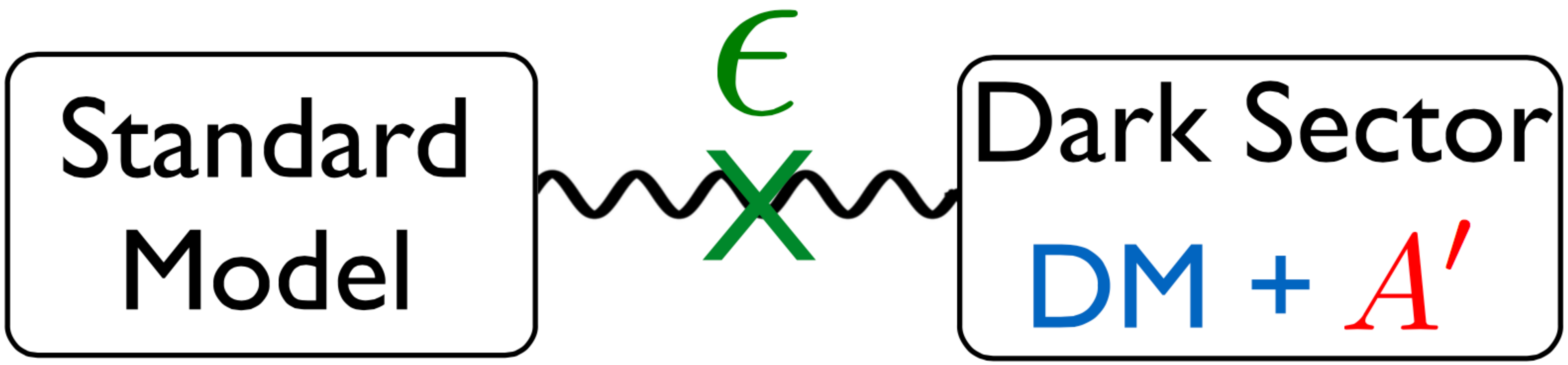
$$\bar{\sigma}_e \propto \frac{\epsilon^2 \alpha_D}{m_{A'}^4} \mu_{\chi e}^2$$



R. Essig

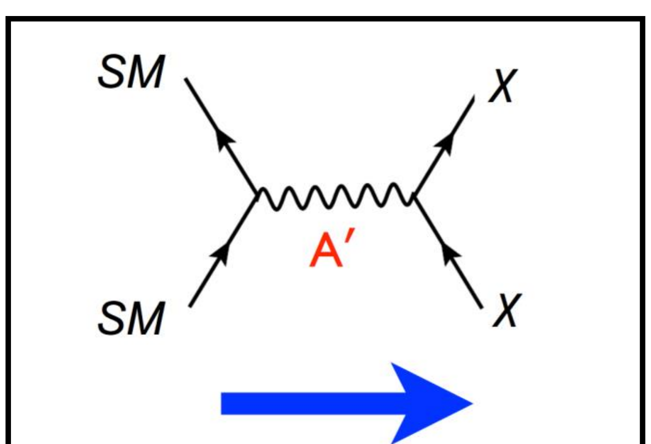
DM w/ dark photon (A′) mediator

nice predictive model to target!

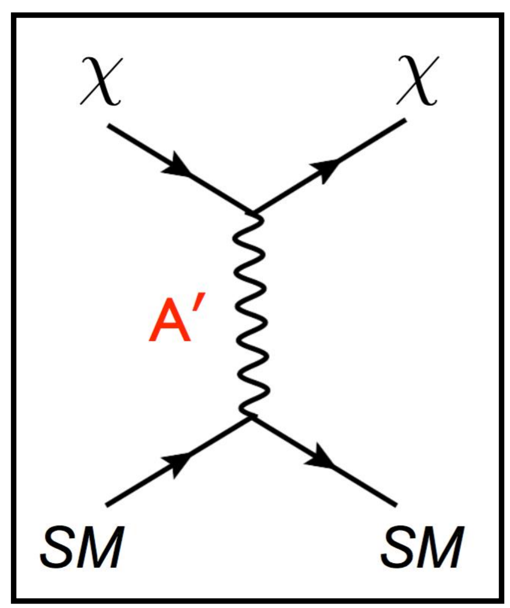


- light A′ (~m$_{DM}$)
- ultra-light A′ (≪keV)

freeze IN
(build up abundance during cool-down)

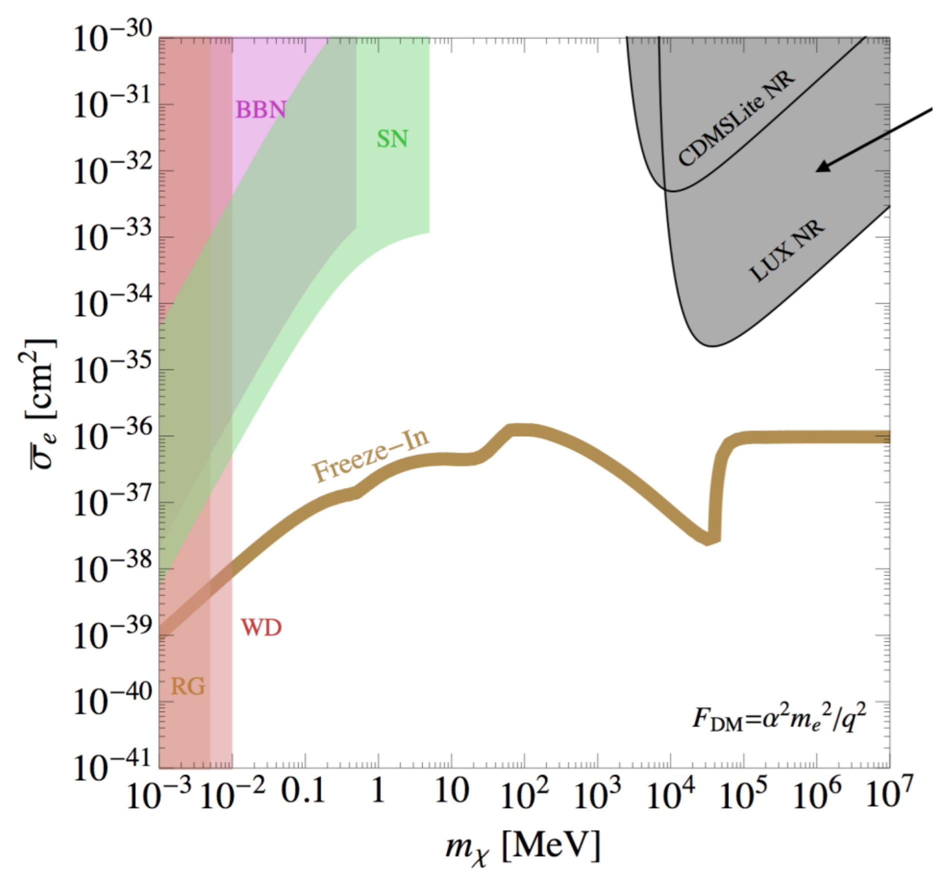


direct detection

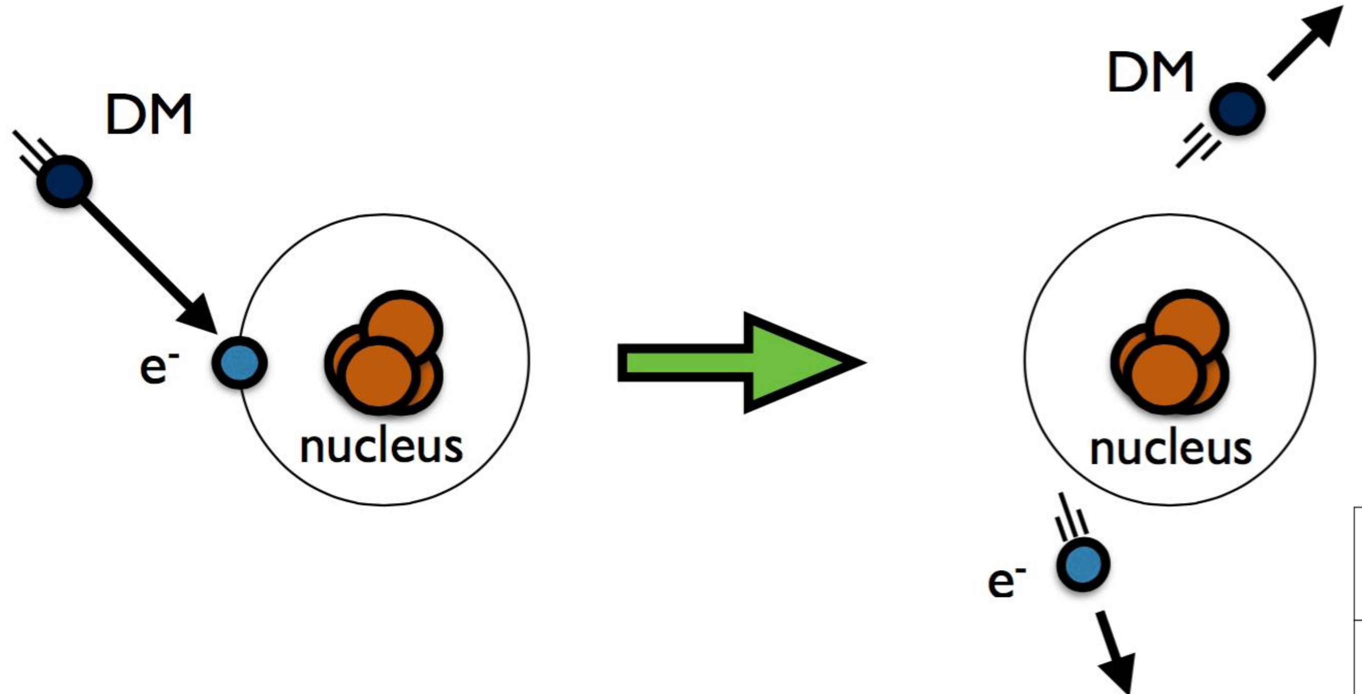


$$\sigma \propto \frac{16\pi\mu_{\chi e}^2 \alpha \alpha_D \epsilon^2}{q^4}$$

enhanced a low Q



the “classic” search for wimps looks for nuclear recoil, but when looking at lower mass particles the e-recoil channel is more competitive.



Type	Examples	E_{th}	mass threshold	Status
Noble liquids	Xe, Ar, He	~10 eV	~5 MeV	Done w/ XENON10+100 data; improvements possible
Semi-conductors	Ge, Si	~1 eV	~200 keV	E_{th} ~ 40 eV (SuperCDMS, DAMIC*) E_{th} ~ 1 eV (SENSEI) R&D ongoing
Scintillators	GaAs, NaI, CsI, …	~1 eV	~200 keV	R&D required

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

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

for outer shell e-

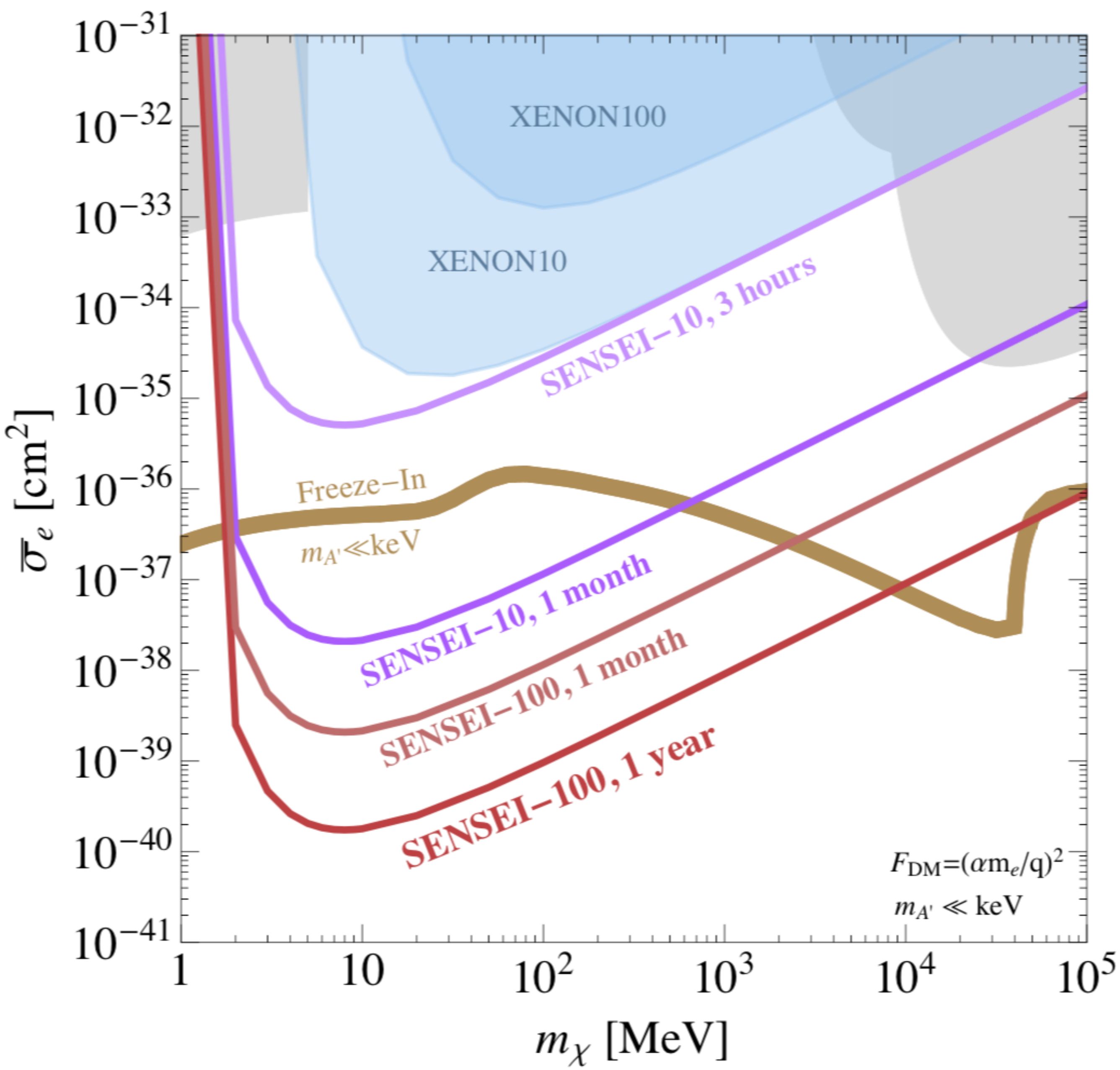
$$q_{\rm typ} \sim \alpha m_e \sim 4\ {\rm keV}$$

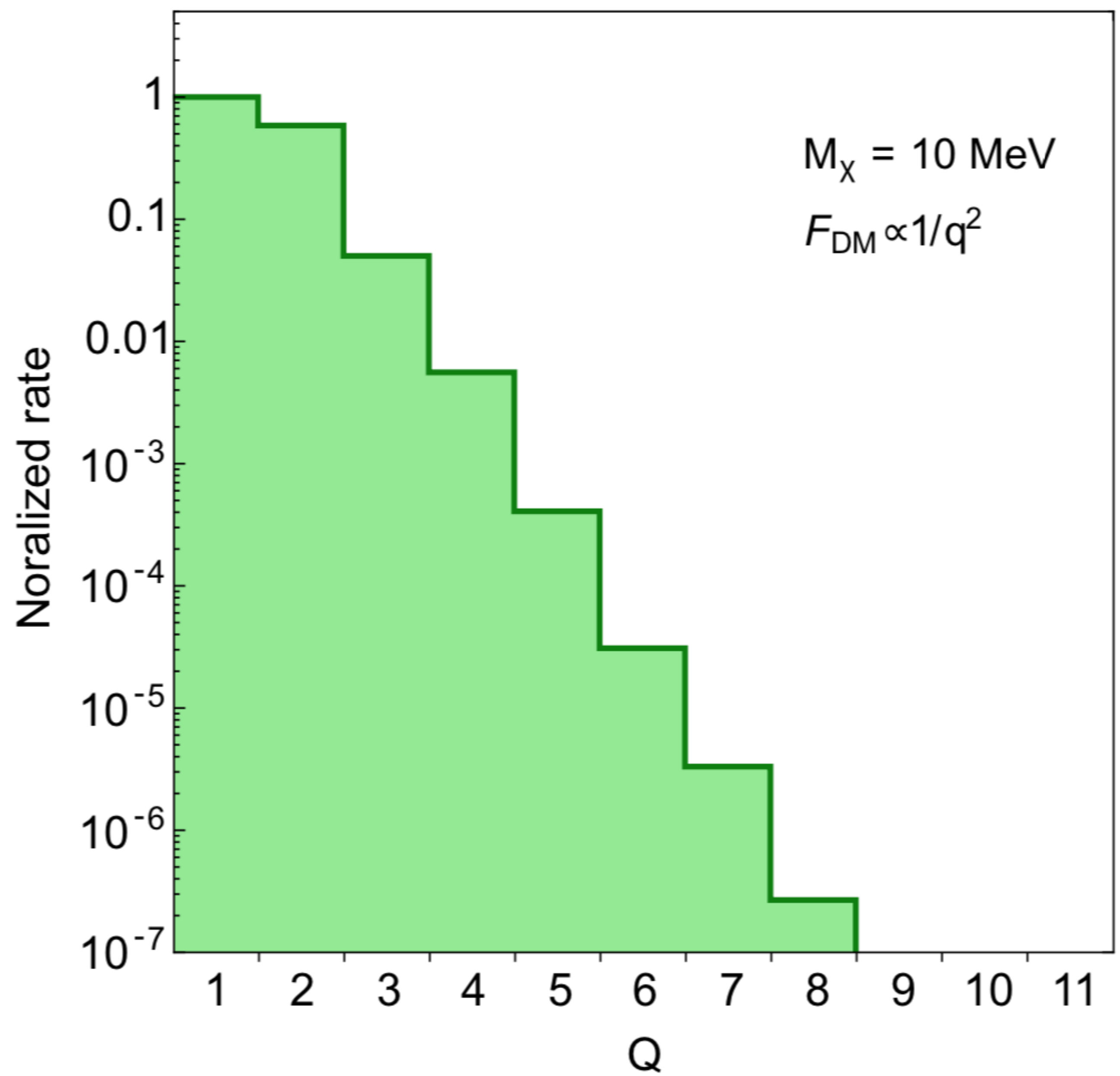
$$\Delta E_e \sim \vec{q} \cdot \vec{v}_{\rm DM}$$

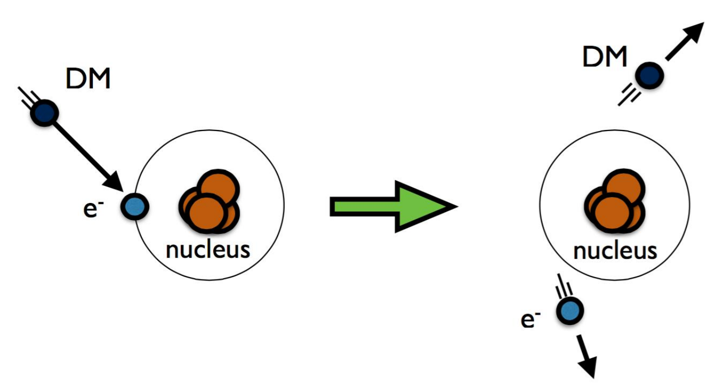
typical recoil energy: $\Delta E \sim 4\ {\rm eV}$

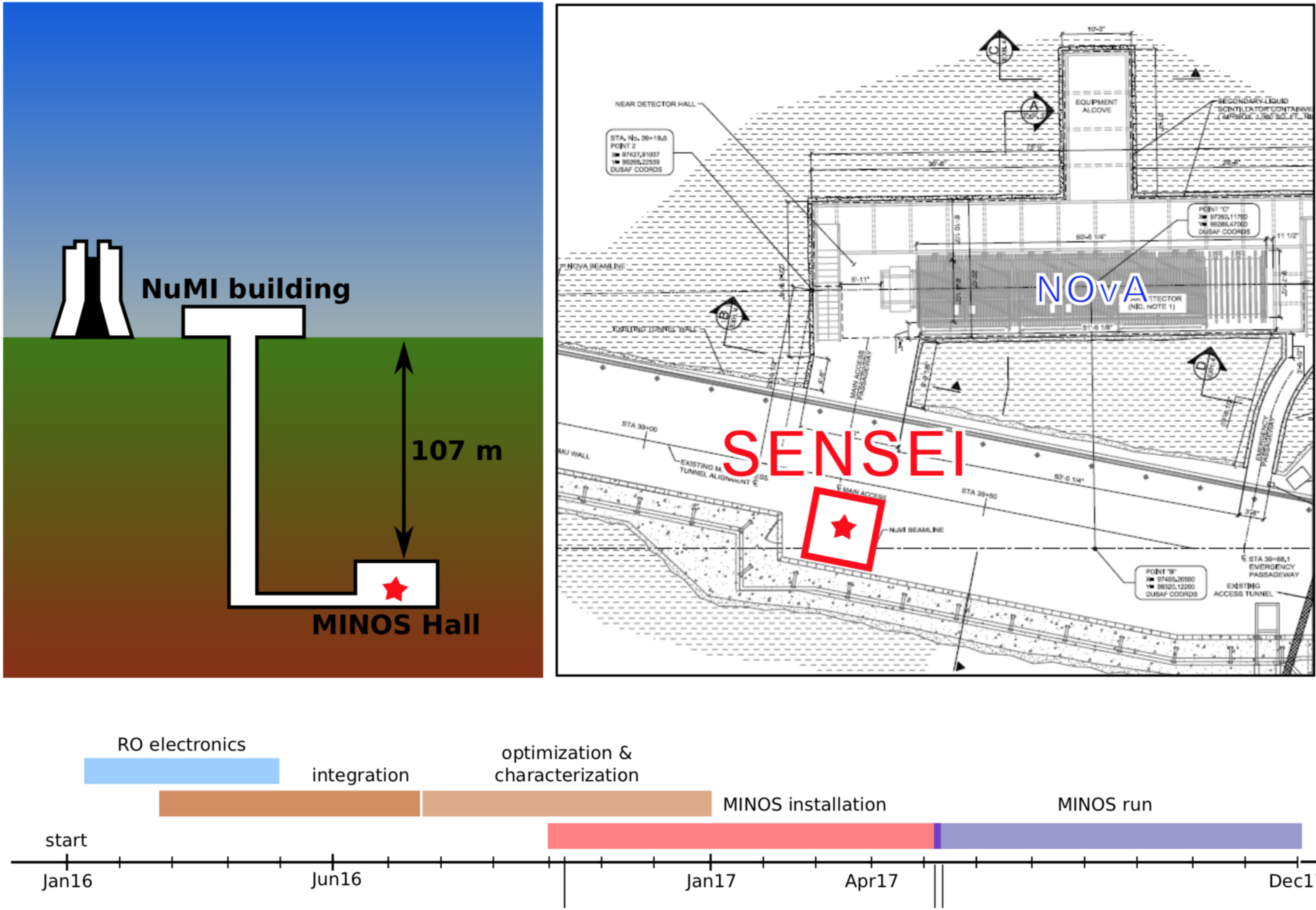
credit: R. Essig - Stony Brook University

Once you can count electrons, you can search for electron recoils produced by very low mass dark matter (dark sector searches). This is what we are planning to do with the skipper-CCD in the **SENSEI experiment.**

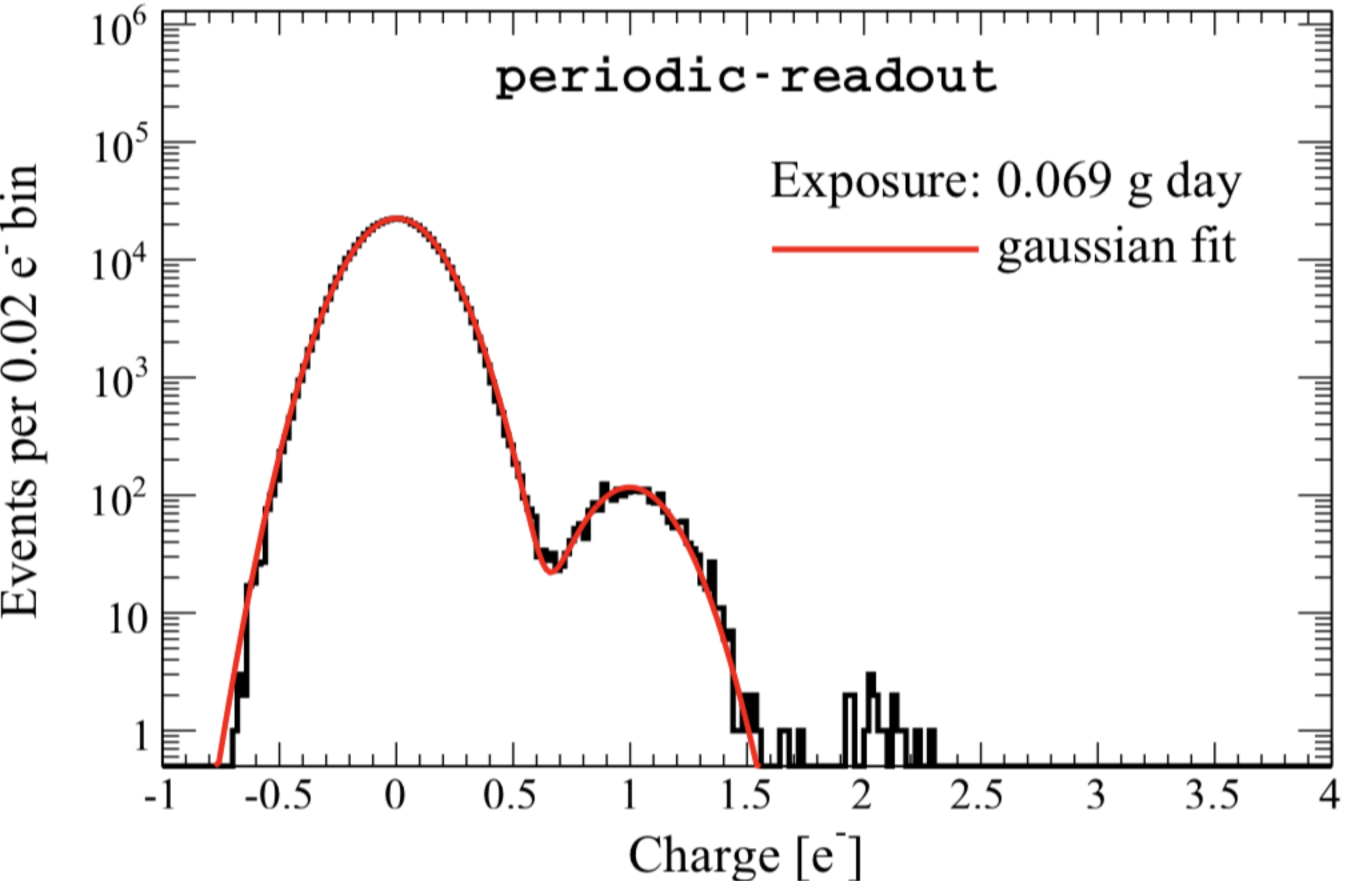






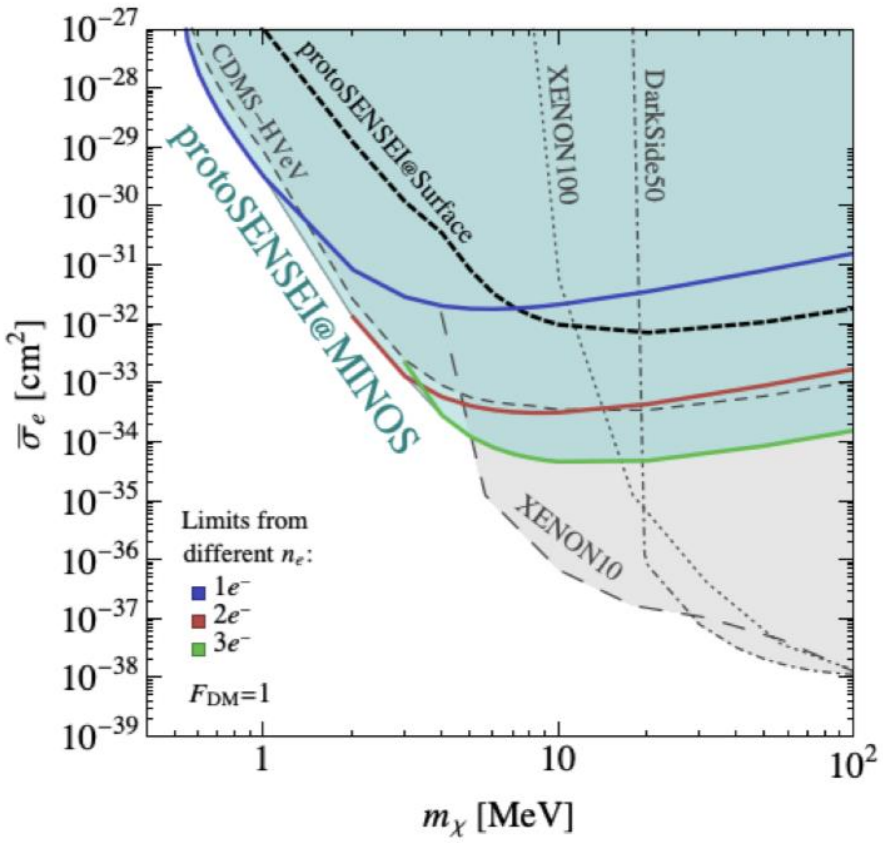

NuMI building
107 m
MINOS Hall
NOvA
SENSEI
RO electronics
integration
optimization &
characterization
MINOS installation
MINOS run
start
Jan16
Jun16
Jan17
Apr17
Dec17

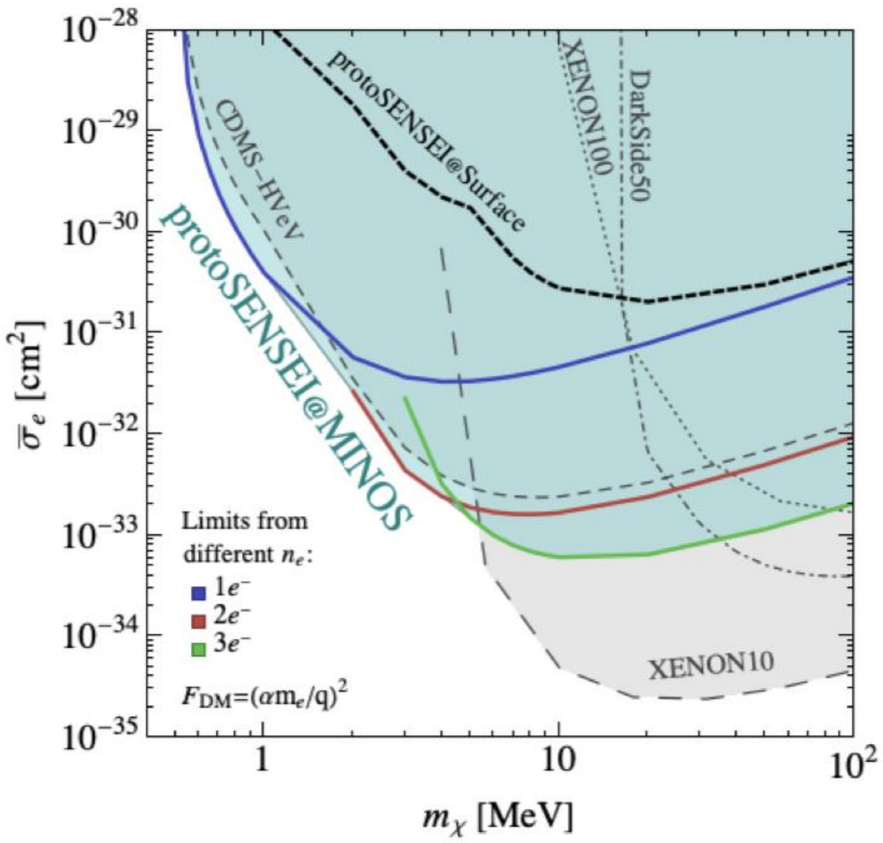
SENSEI 2019 Result
arXiv:1901.10478 [hep-ex]

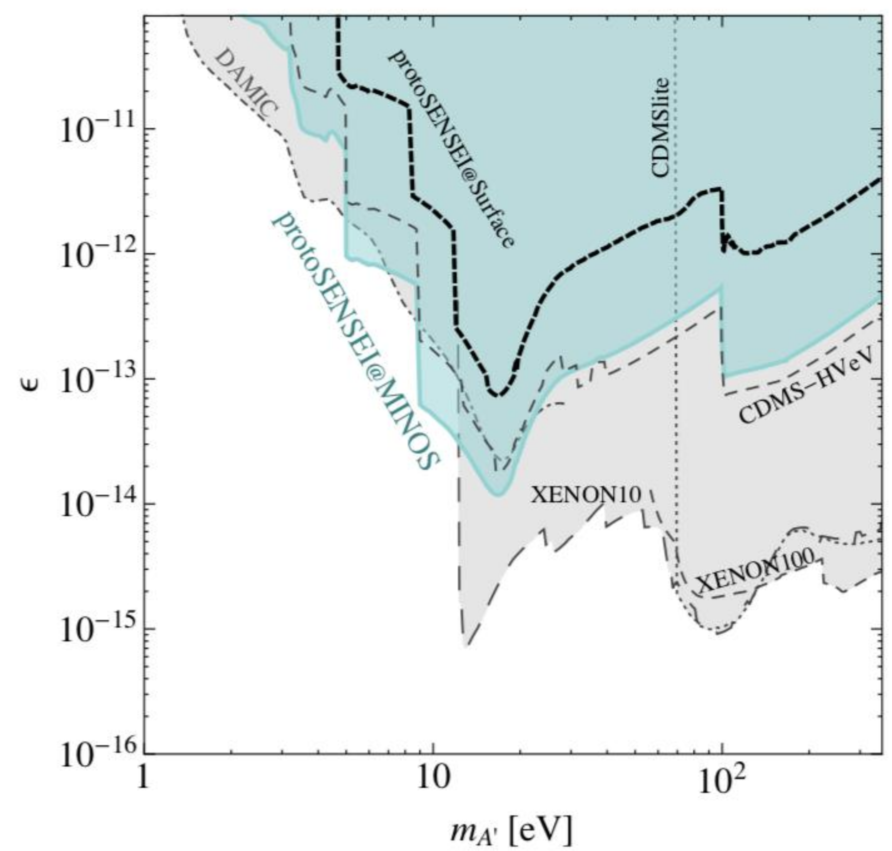


with a very modest exposure we are leading the world in the search for e-recoil dark sector particles.

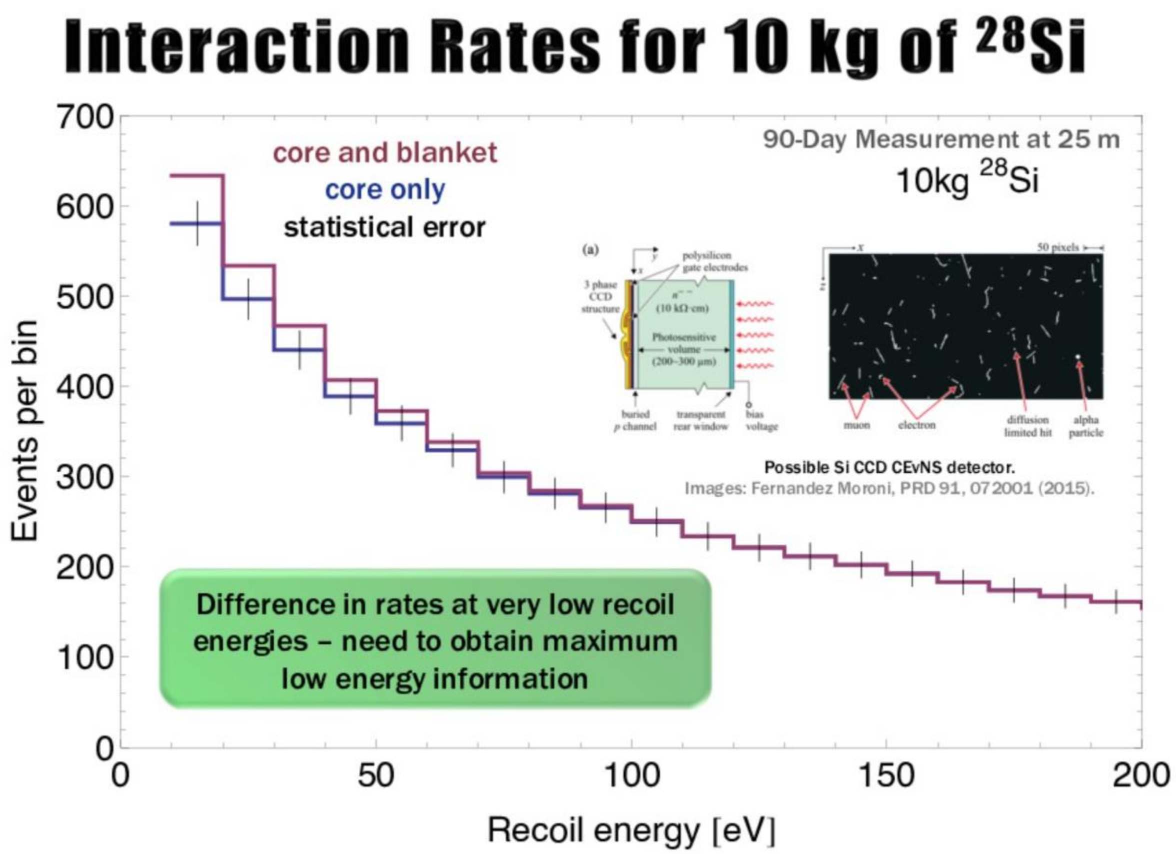
dark rate : 3.68×10^{-3} events/pixel/day

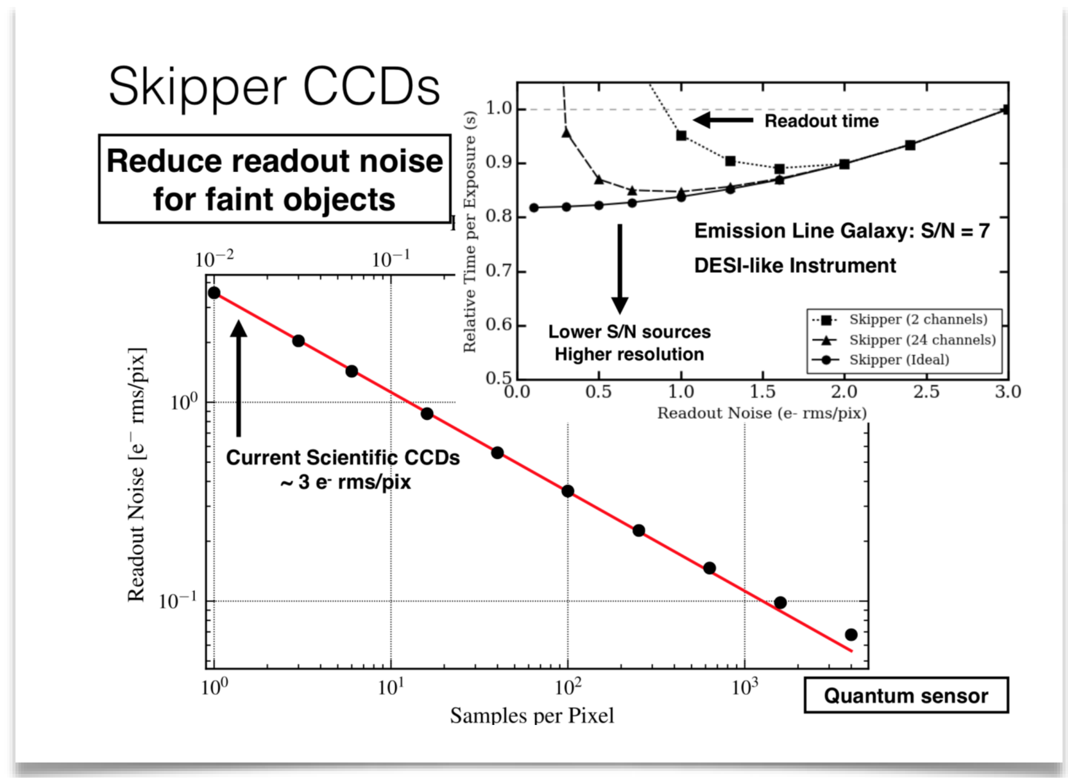


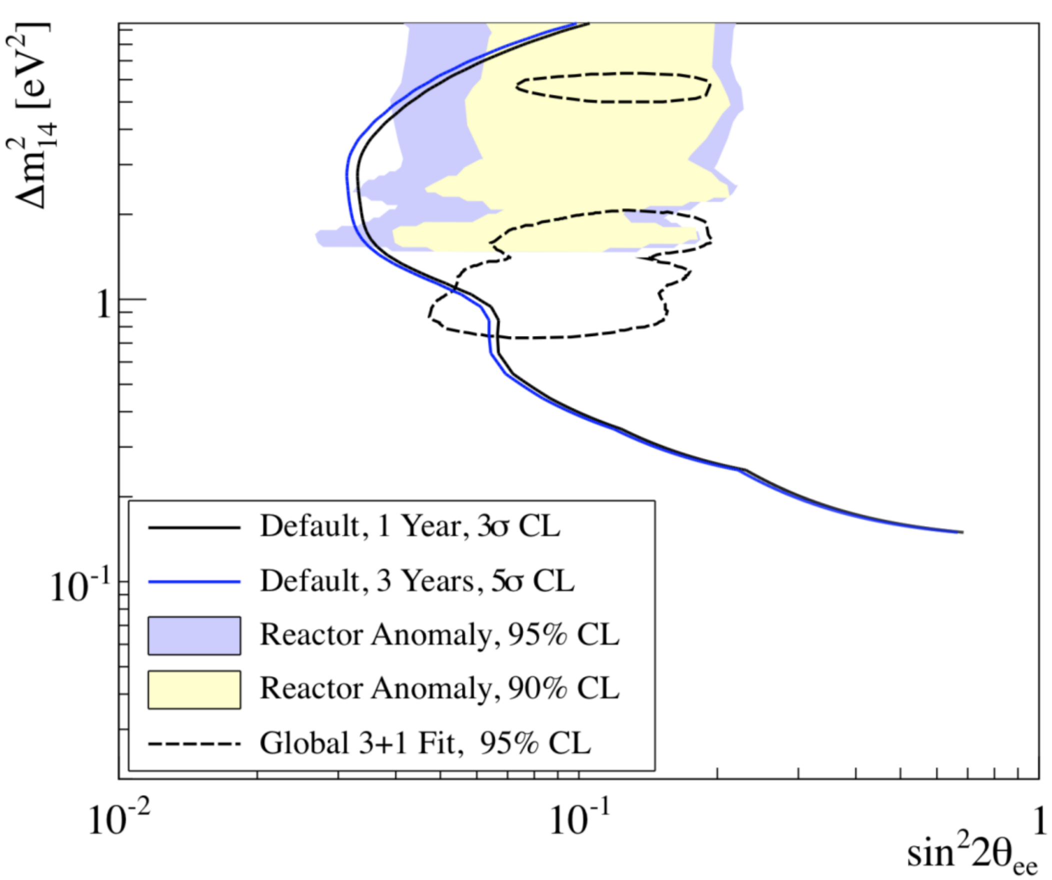


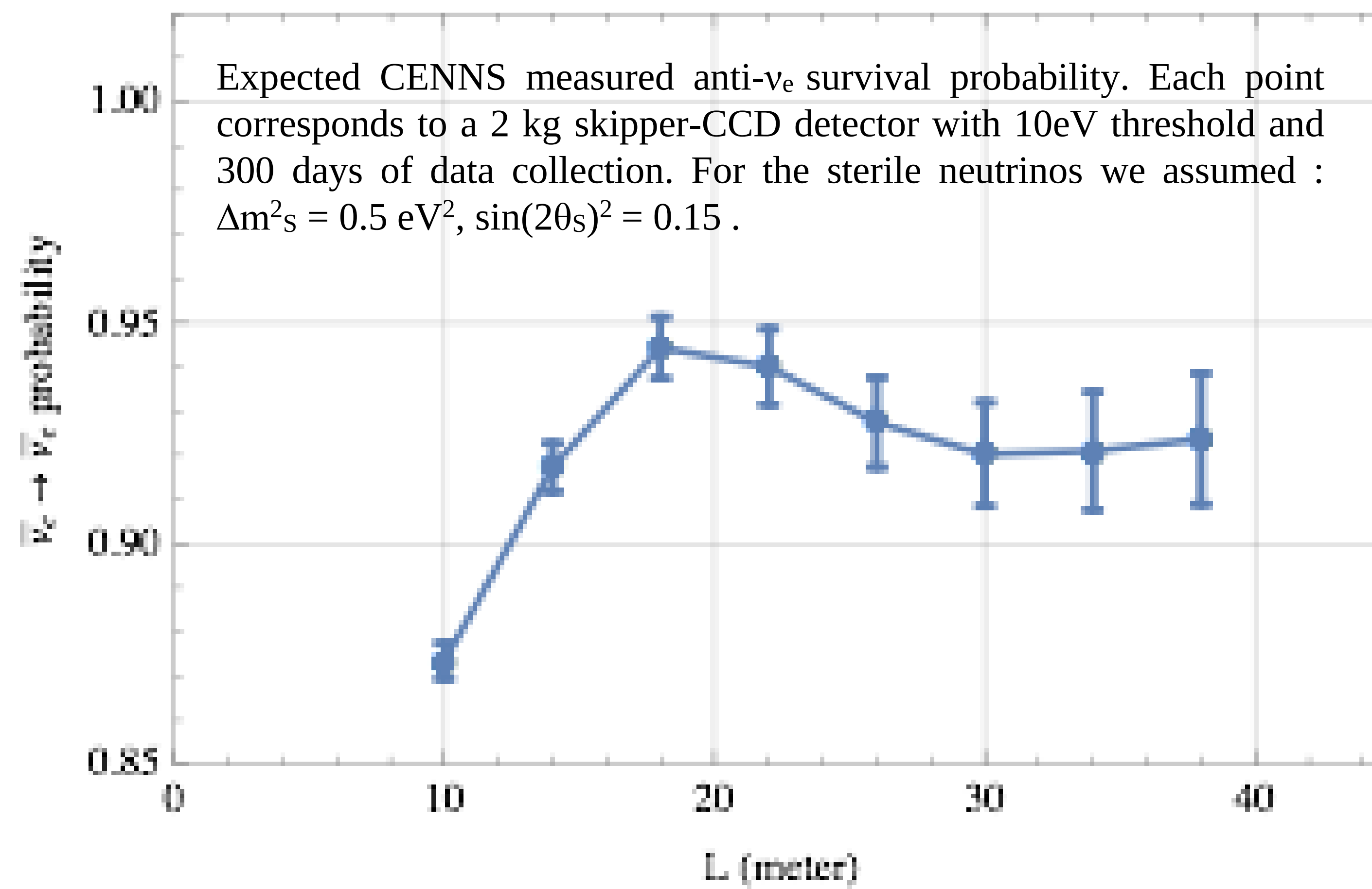


the future is all skipper…









news & views

QUANTUM IMAGING

Beating the classical camera

By utilizing the spatial quantum correlations of light, Italian researchers have now performed imaging at significantly higher signal-to-noise ratios than those possible through classical techniques.

Stefanie Barz and Philip Walther

Image sensors based on CCD arrays are an important part of daily life and are found at the heart of digital cameras, including those in cellular phones and other portable electronic devices. There is a strong and continual technological trend for manufacturers to reduce the size of CCD pixels, thereby allowing more pixels to be squeezed onto a sensor and thus in principle increasing the imaging resolution.

However, as the pixel size shrinks so does the amount of light illuminating each individual pixel. Ultimately, at low enough light levels the quantum nature of light becomes dominant, with single-photon fluctuations inherently limiting the quality of the detected image. This is typically defined as the shot-noise limit, and presents a fundamental challenge when working with low photon flux illuminations[1].

Now, writing in *Nature Photonics*, Giorgio Brida and co-workers report

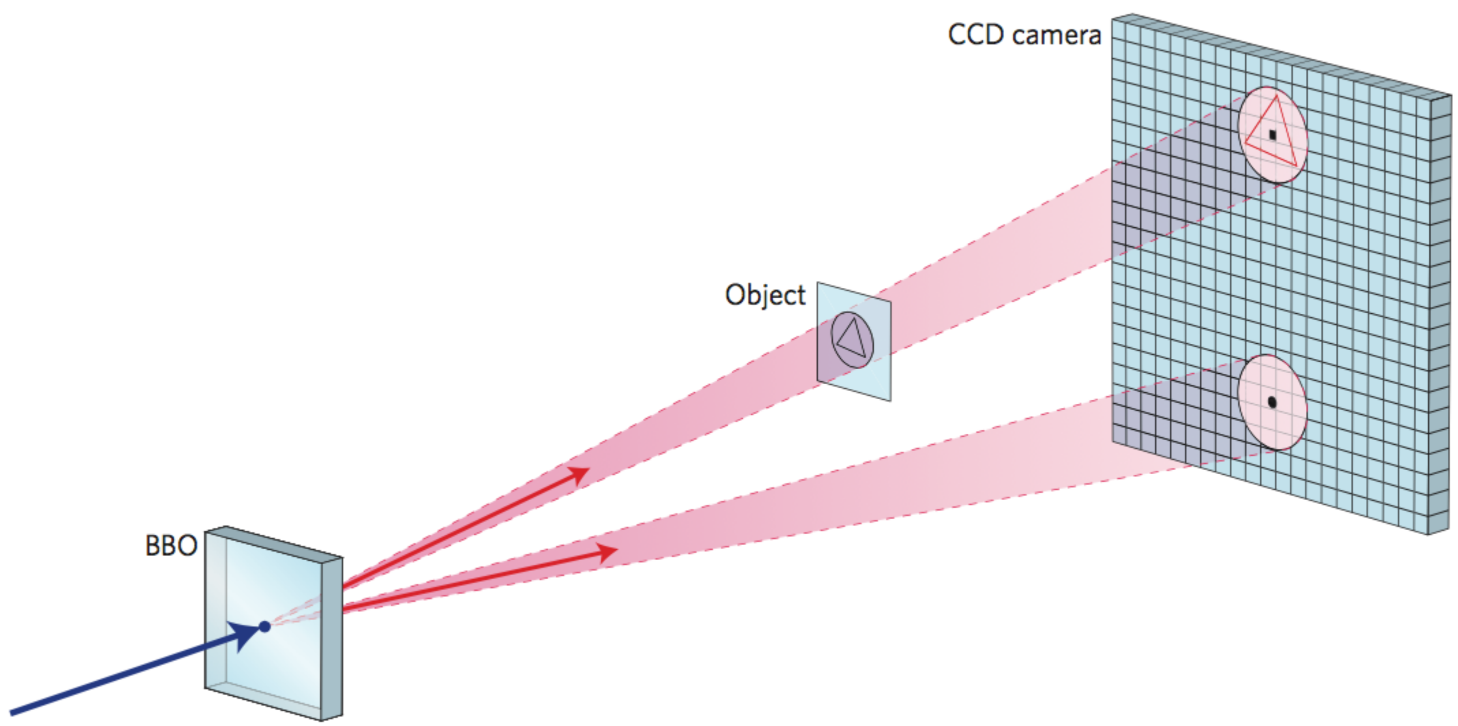
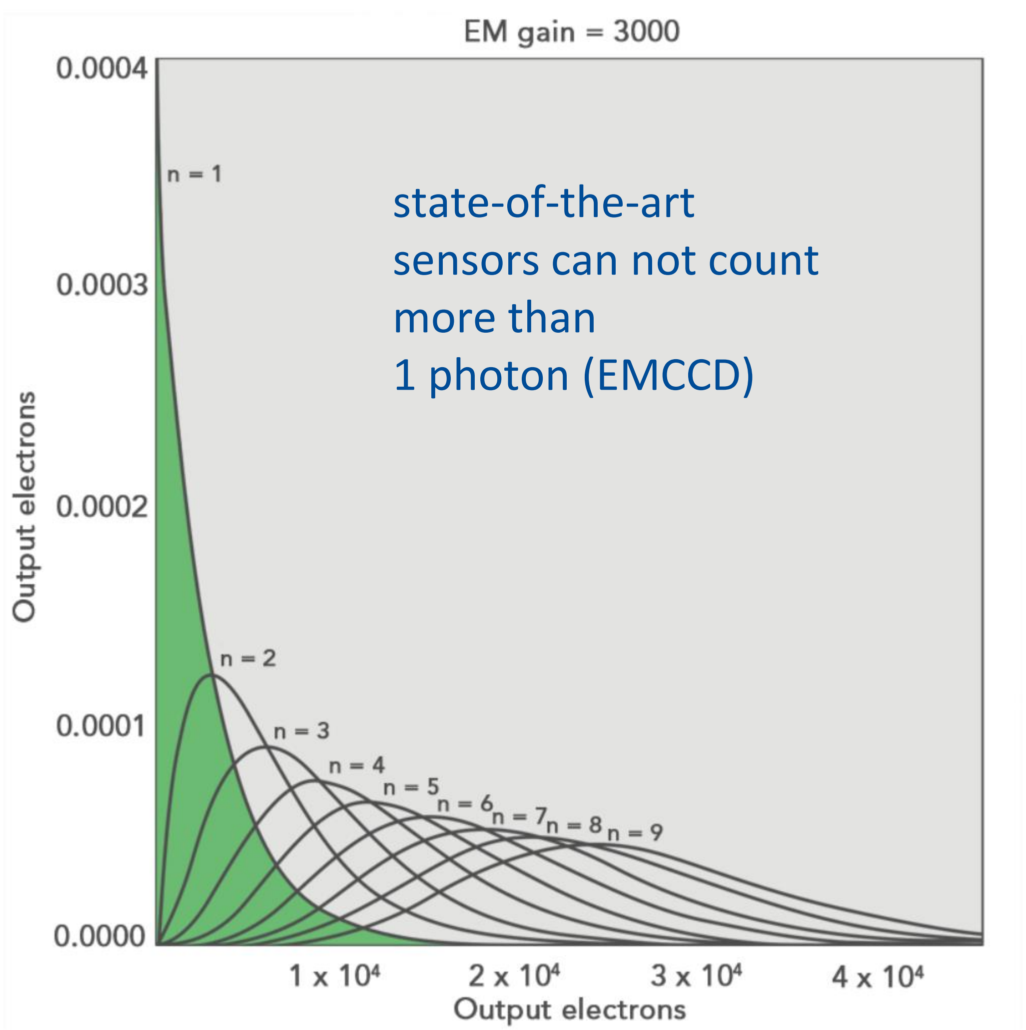


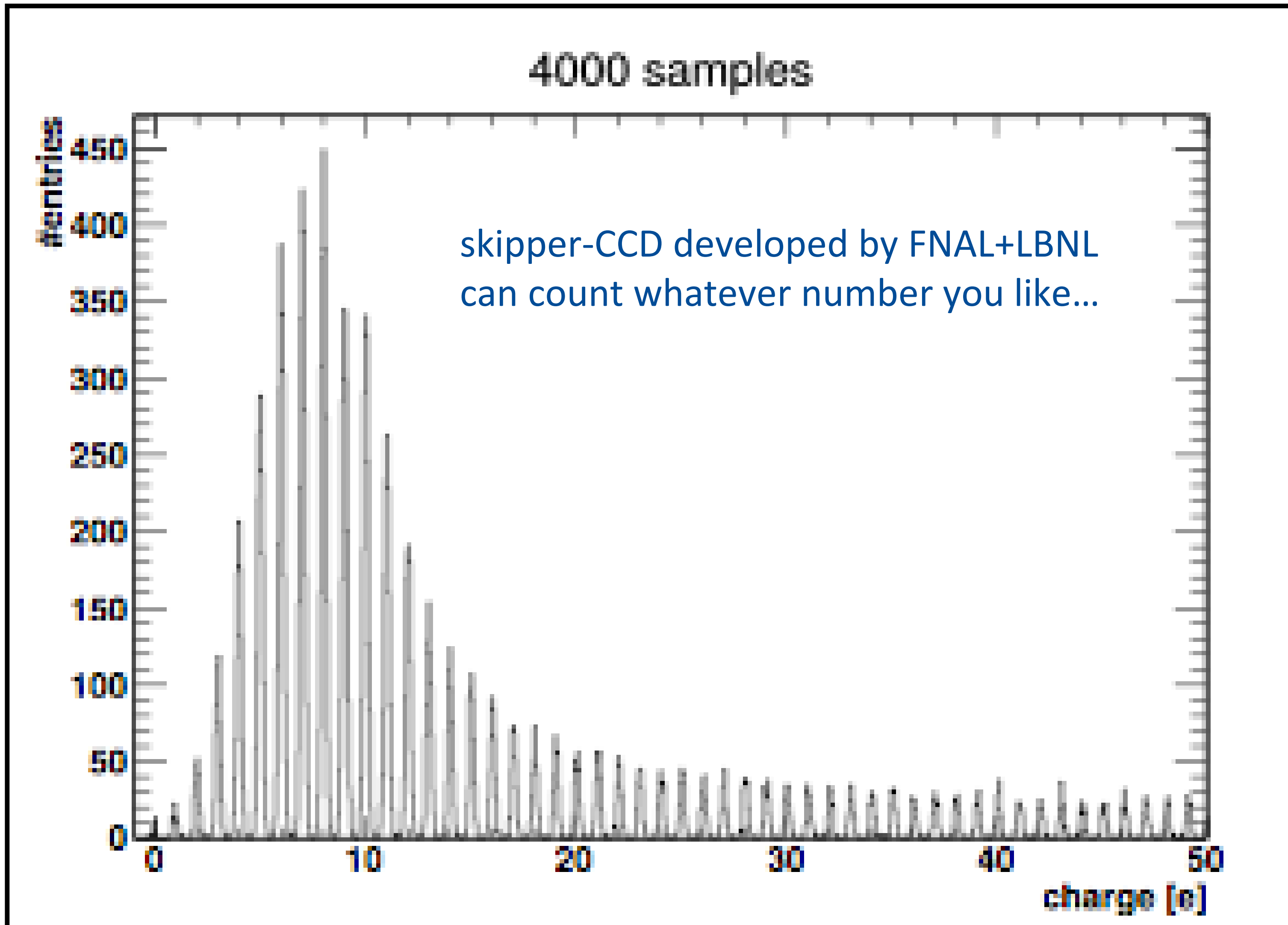
Figure 1 | The differential quantum imaging experiment of Brida and colleagues. The β-barium borate (BBO) crystal converts one laser photon into two photons that are quantum correlated in momentum and position. These non-classical correlations are used for the improved differential imaging of a weakly absorbing object.

entangled photons produced with non-linear crystal and imaged with CCDs.
[sub-shot noise imaging]

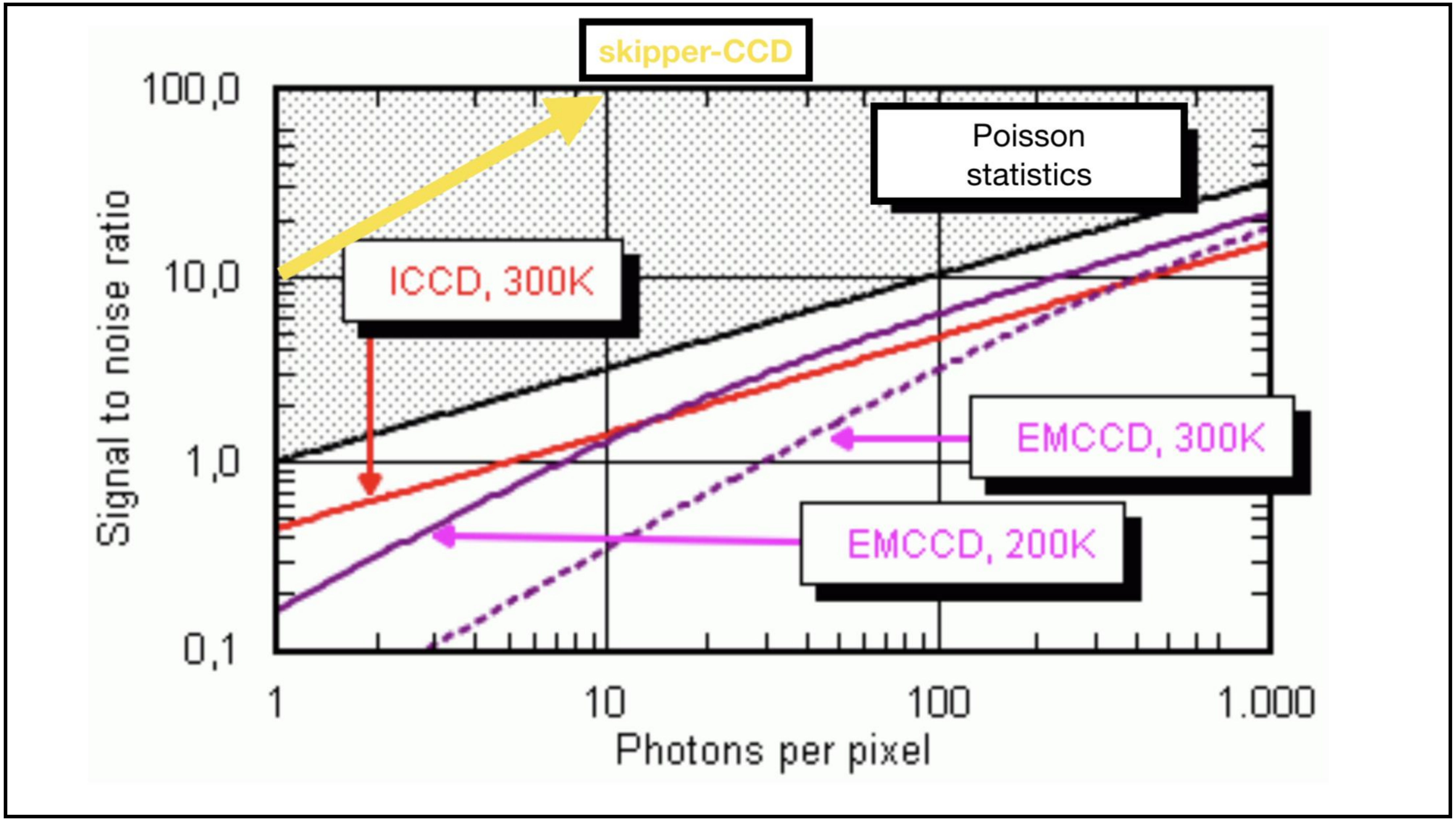
skipper for quantum imaging



Electron distribution after the avalanche process in the EM register. The output probability distribution is plotted against the output electrons for a value of the EM gain of 3,000. The n values correspond to the number of electrons in a pixel before traveling through the EM register.

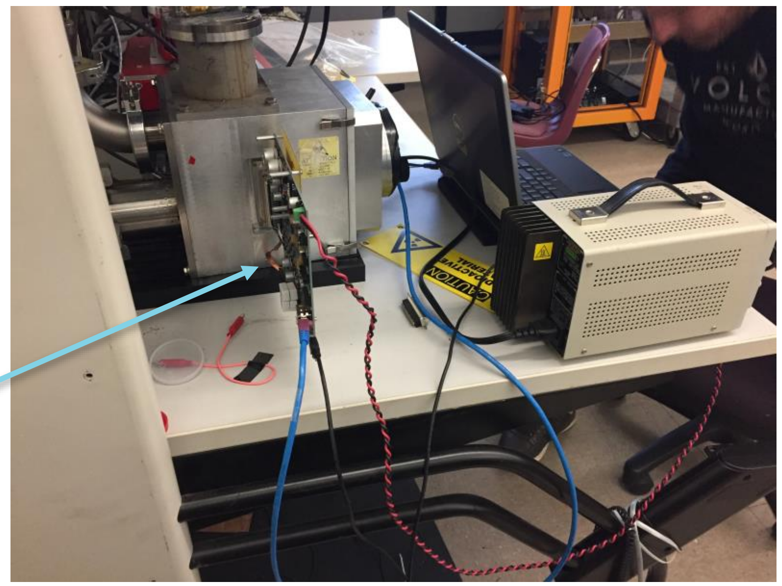


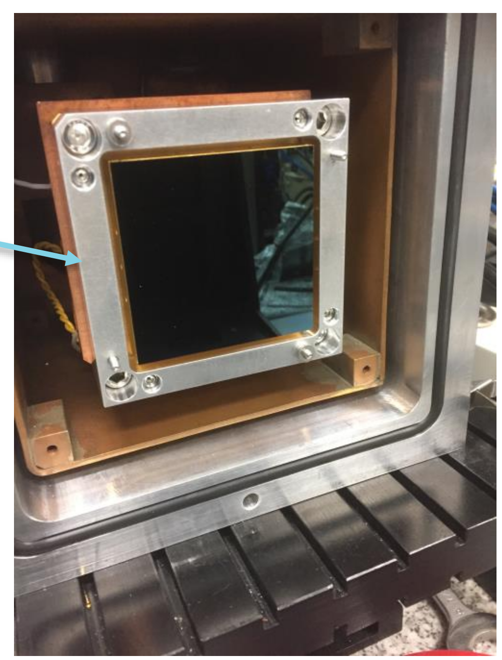
skipper provides an opportunity for increasing signal to noise in quantum imaging

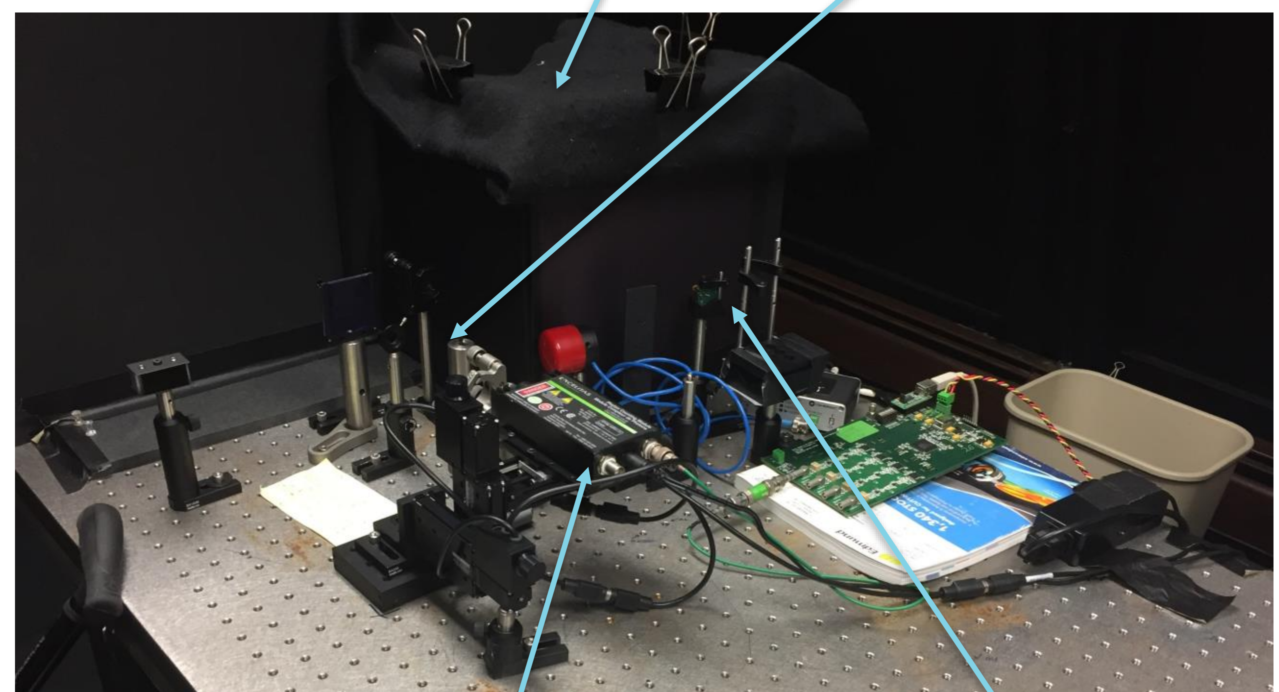


it is slow…

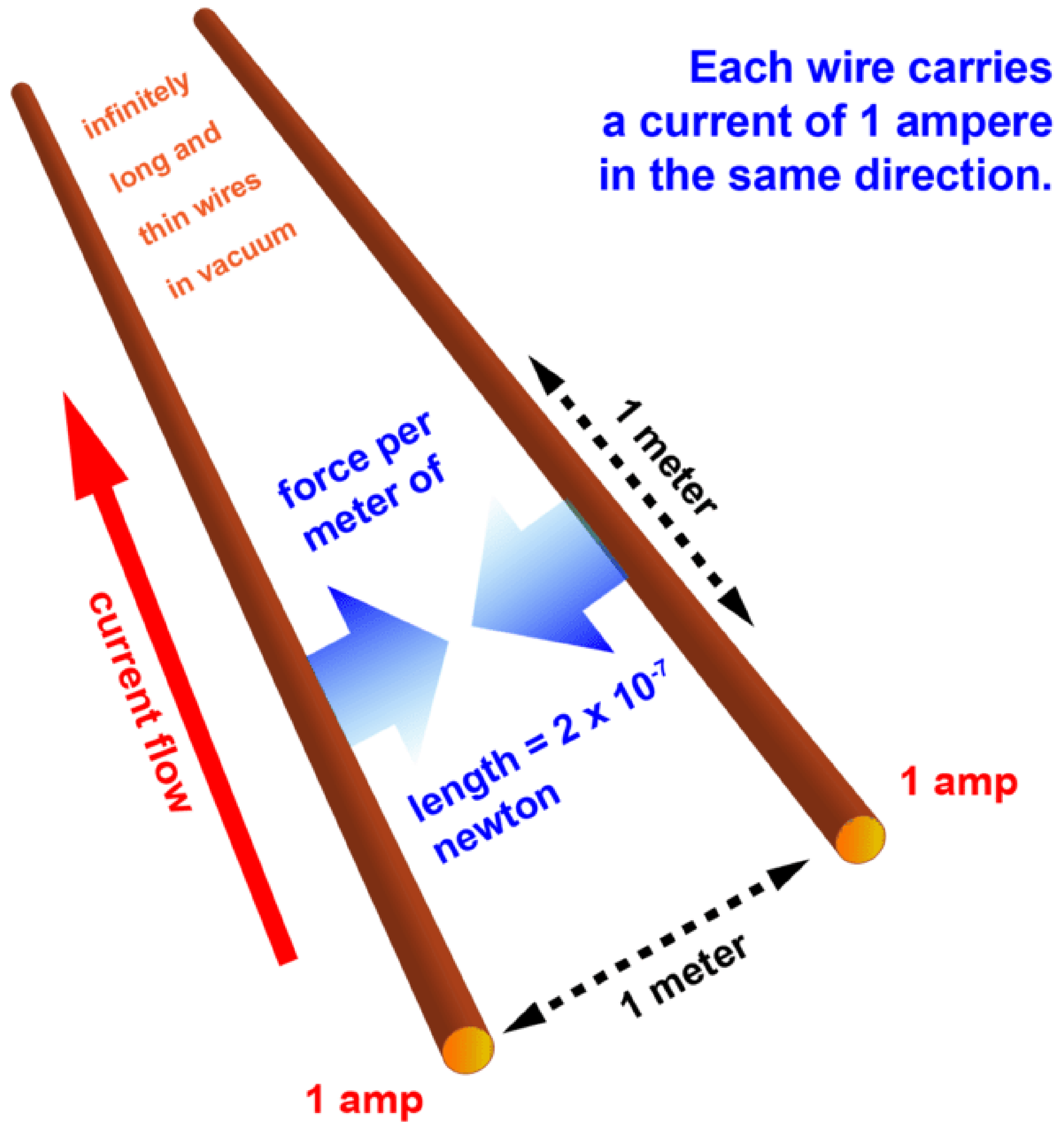
setting up the lab to test skipper CCDs for this application, and also develop faster skippers (FNAL, LBNL, Caltech)





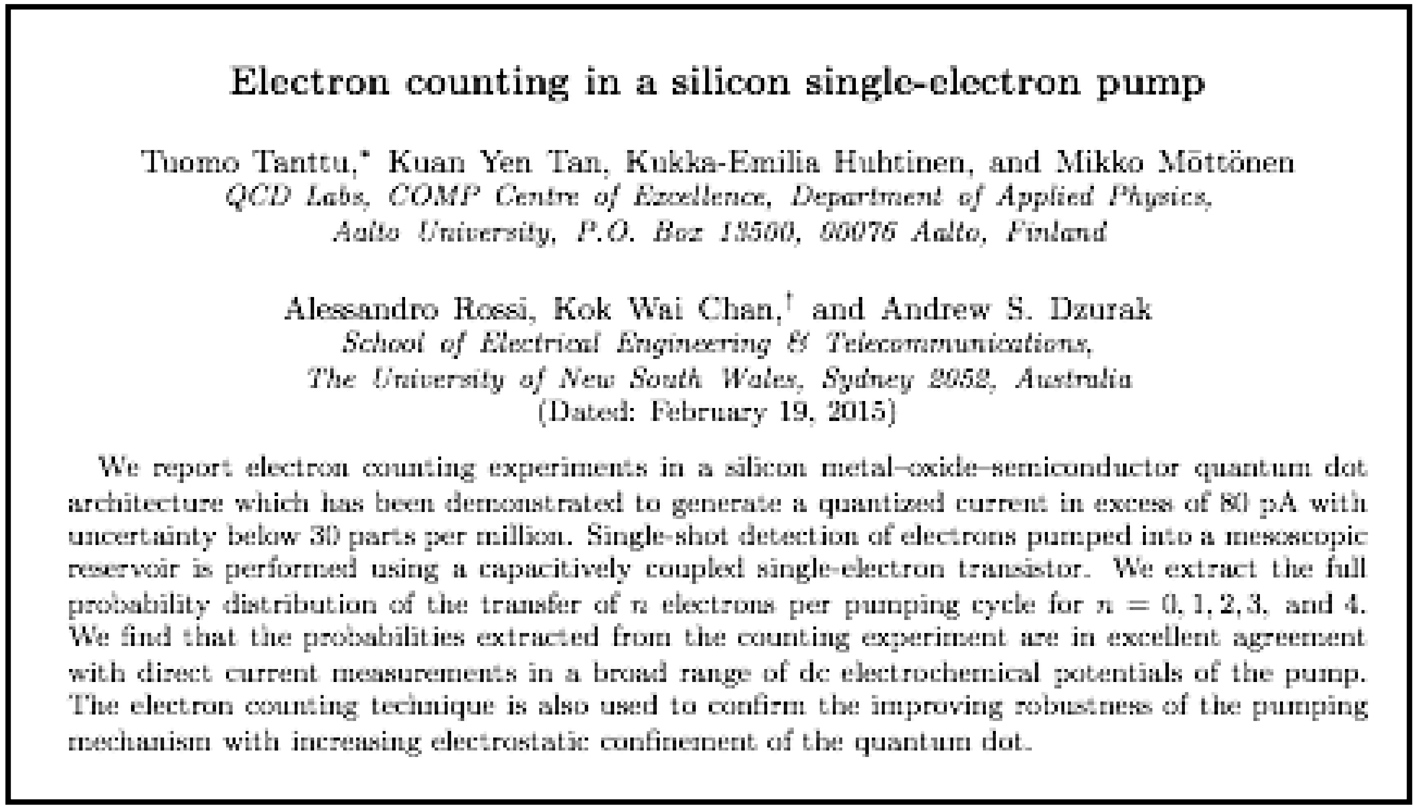


Metrology : definition of the ampere until Nov-2018



André-Marie Ampère's 200-year old experiment

The ampere has been redefined in terms of the electron charge per unit time. Quantum devices are used to realize this standard: single electron pumps.



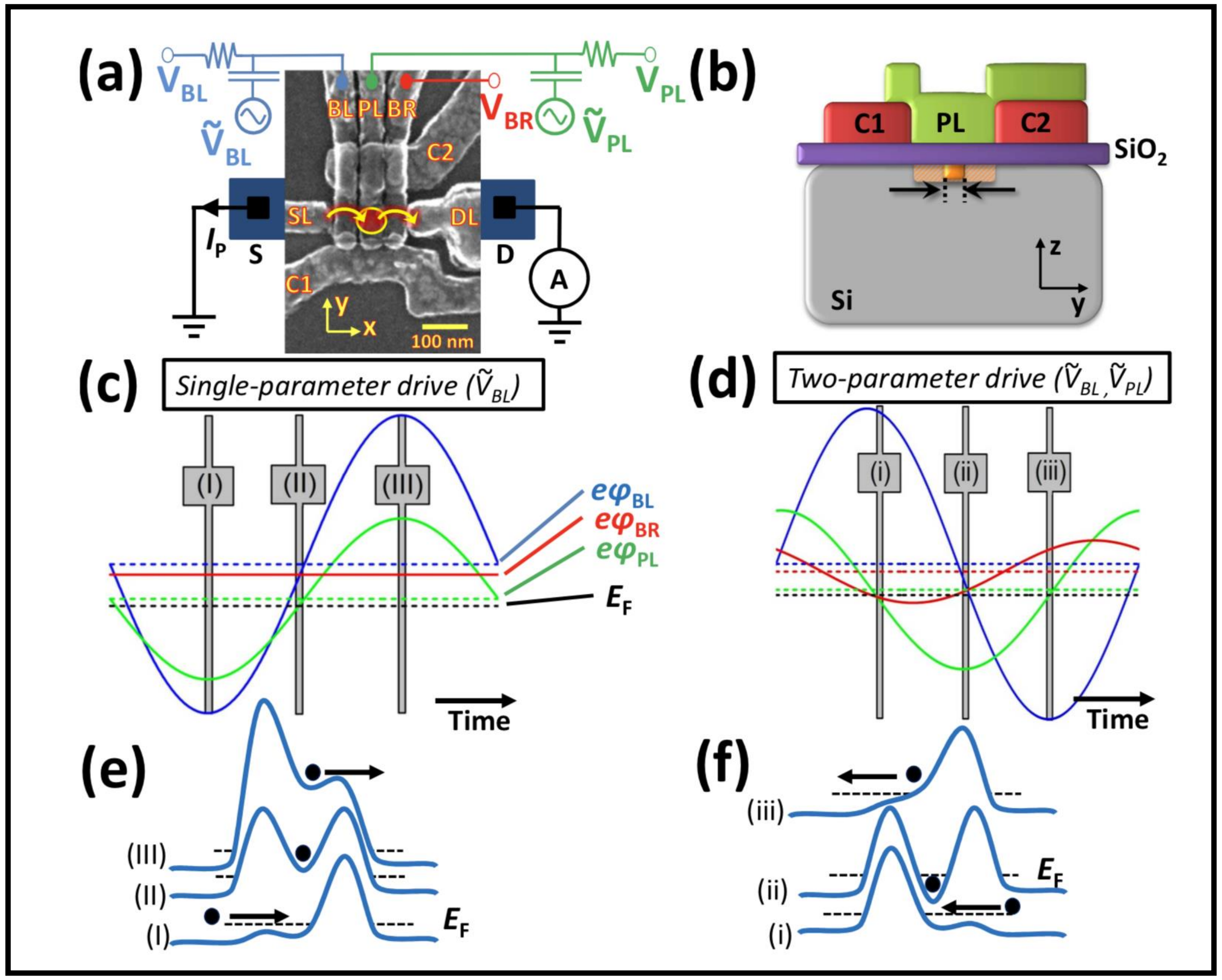
Electron counting in a silicon single-electron pump

Tuomo Tanttu,* Kuan Yen Tan, Kukka-Emilia Huhtinen, and Mikko Möttönen
QCD Labs, COMP Centre of Excellence, Department of Applied Physics, Aalto University, P.O. Box 13500, 00076 Aalto, Finland

Alessandro Rossi, Kok Wai Chan,† and Andrew S. Dzurak
School of Electrical Engineering & Telecommunications, The University of New South Wales, Sydney 2052, Australia

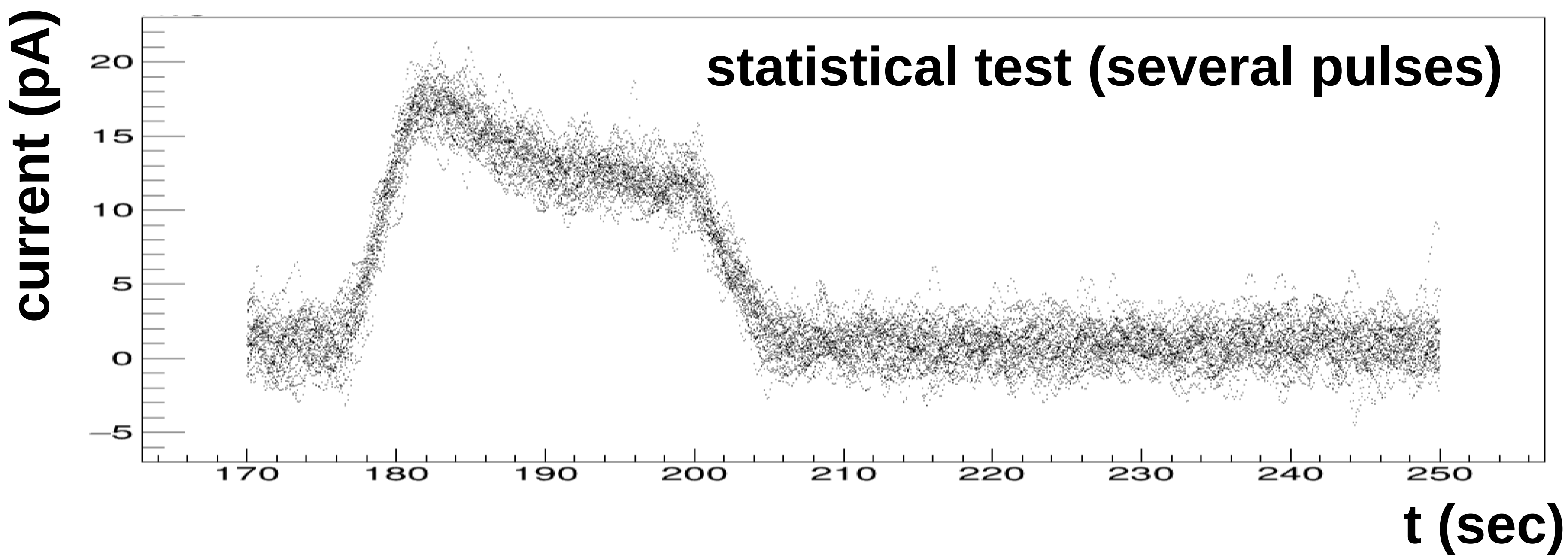
(Dated: February 19, 2015)

We report electron counting experiments in a silicon metal–oxide–semiconductor quantum dot architecture which has been demonstrated to generate a quantized current in excess of 80 pA with uncertainty below 30 parts per million. Single-shot detection of electrons pumped into a mesoscopic reservoir is performed using a capacitively coupled single-electron transistor. We extract the full probability distribution of the transfer of n electrons per pumping cycle for $n = 0, 1, 2, 3$, and 4. We find that the probabilities extracted from the counting experiment are in excellent agreement with direct current measurements in a broad range of dc electrochemical potentials of the pump. The electron counting technique is also used to confirm the improving robustness of the pumping mechanism with increasing electrostatic confinement of the quantum dot.

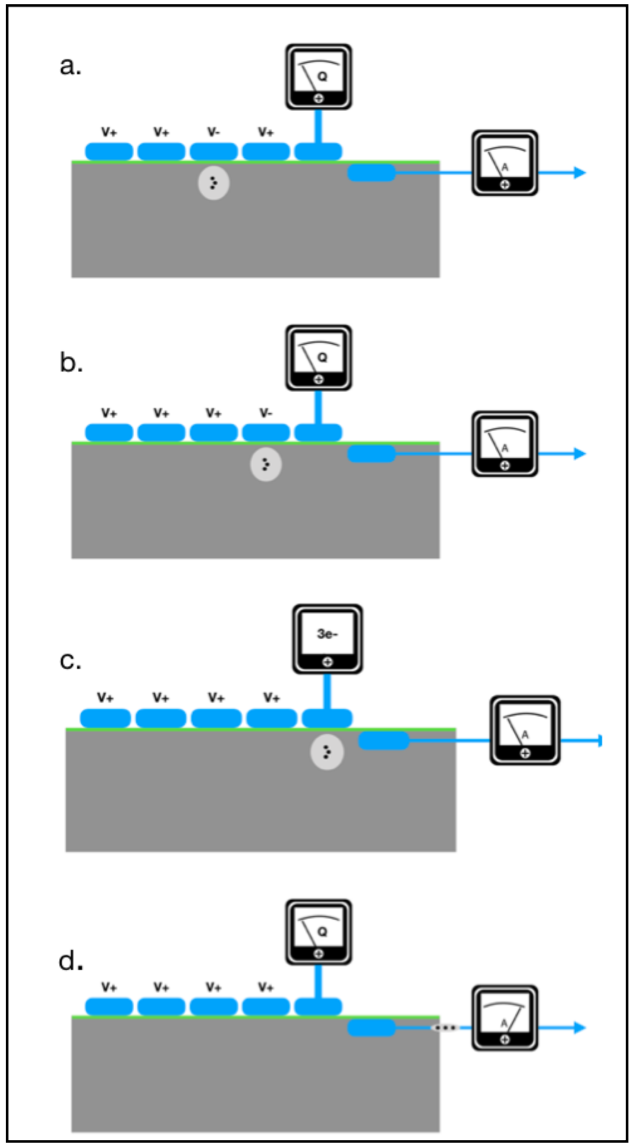


"Ultimately, a precise electron pump verified by error counting not only provides a supreme candidate for th

CCD image

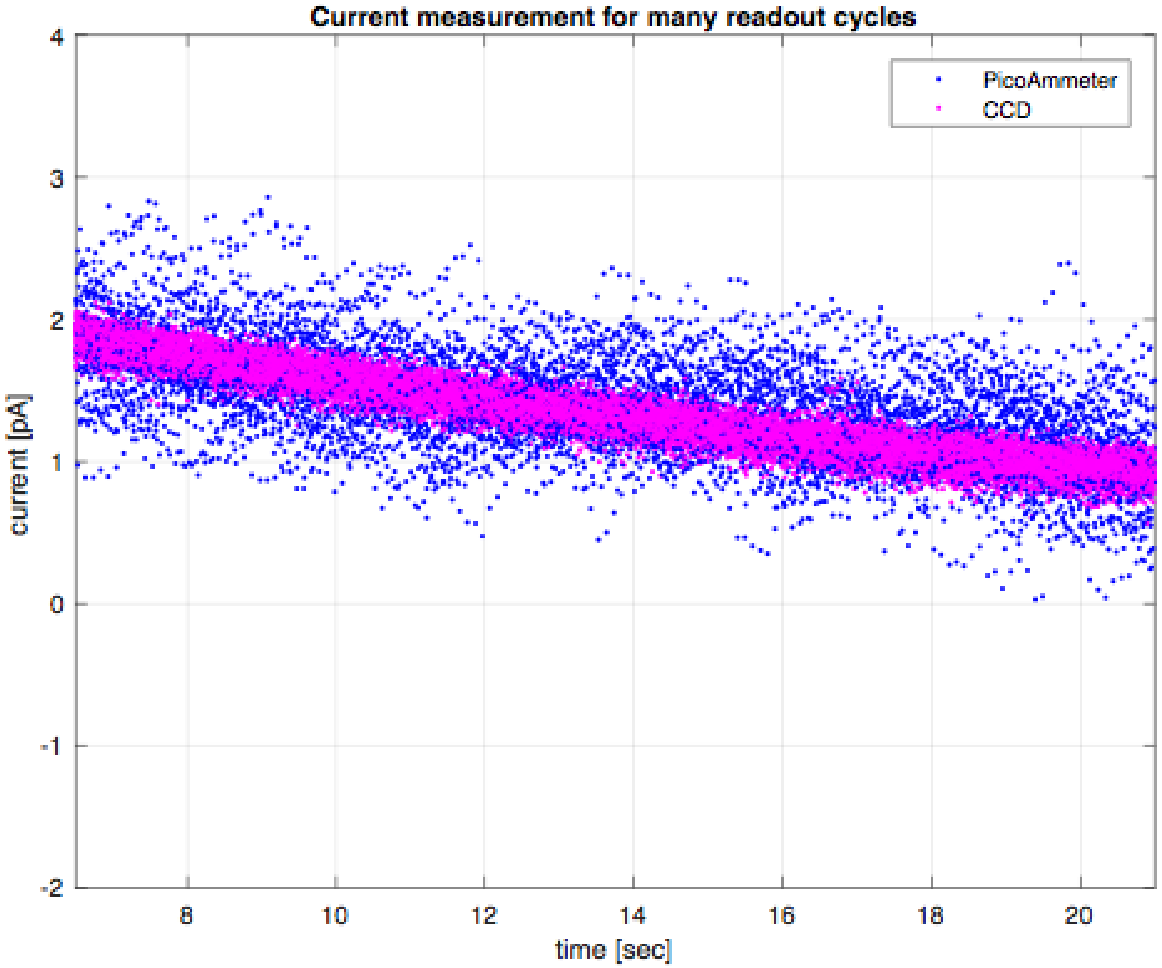


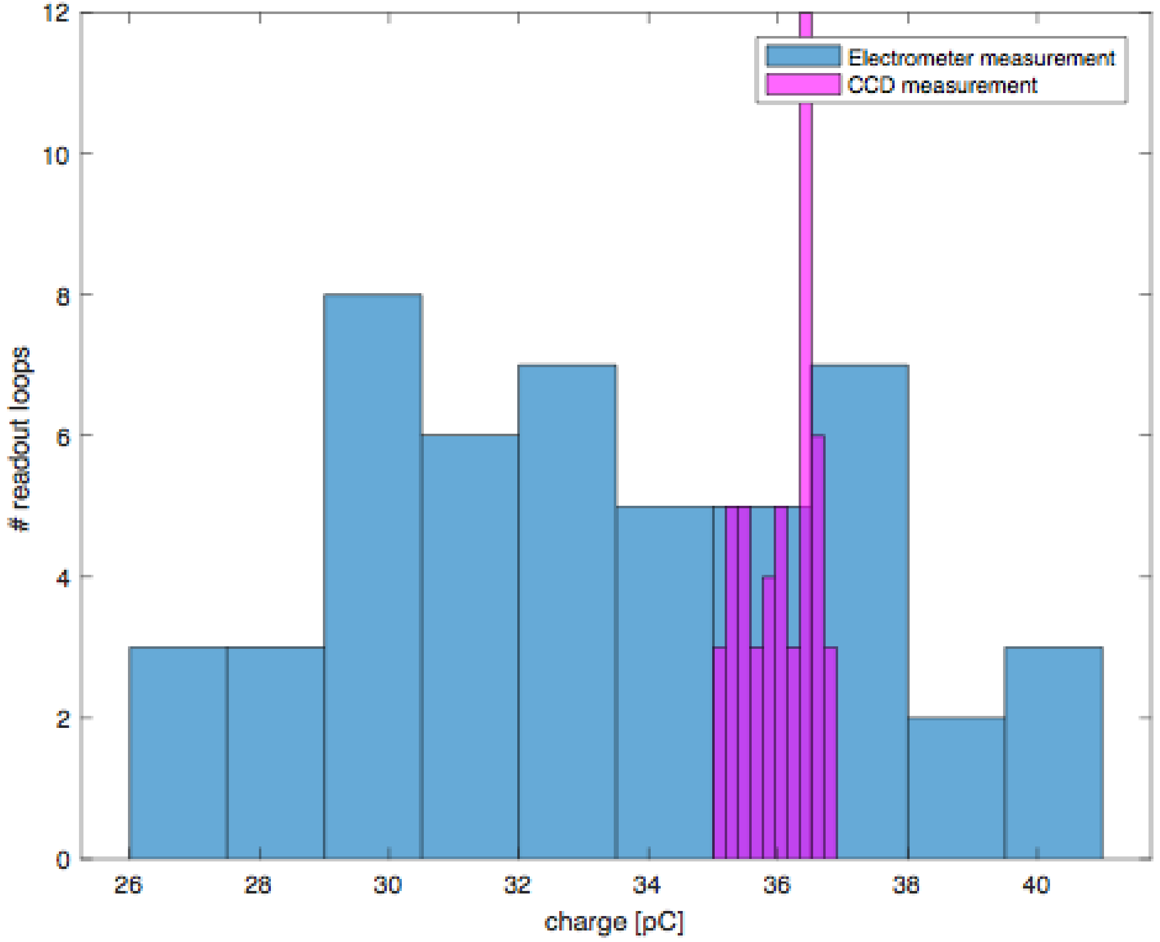
ampmeter

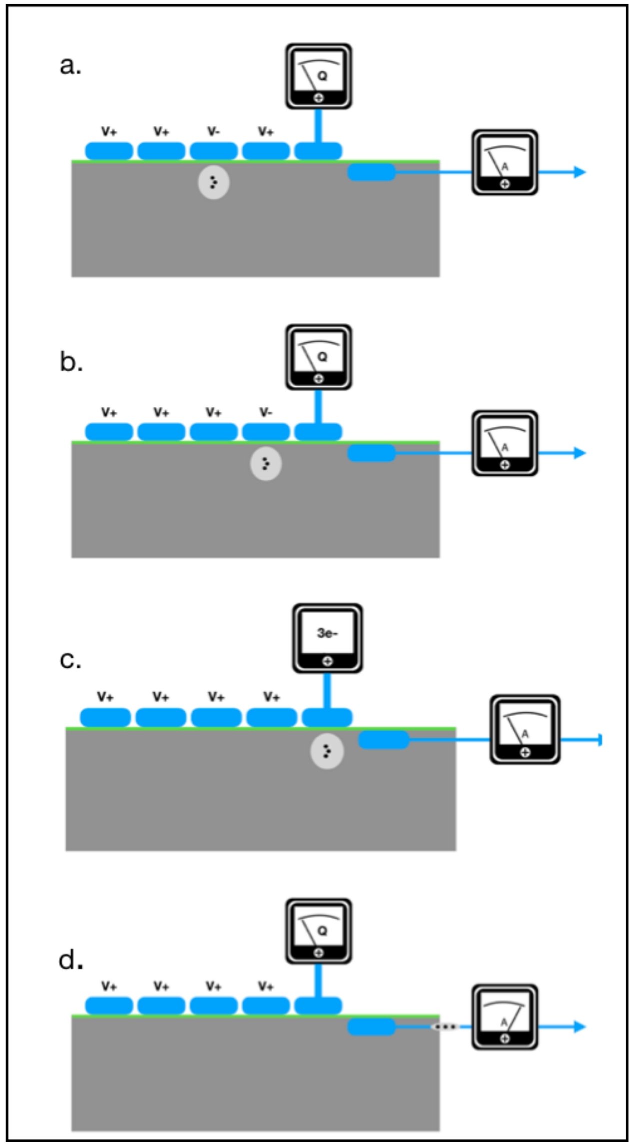


skipper-CCD developed for dark sector searches has a role to play here.

credit: G. Fernandez-Moroni - Fermilab







skipper-CCD developed for dark sector searches has a role to play here.

credit: G. Fernandez-Moroni - Fermilab

- Lots of opportunities to improve our HEP experiments with tools developed for quantum science, and also to push the limit of quantum science with HEP tools.
- The synergy goes well beyond what I have discussed here, it includes simulations and data analysis algorithms.
- Join the fun!

Thanks!

skipper for treaty verification

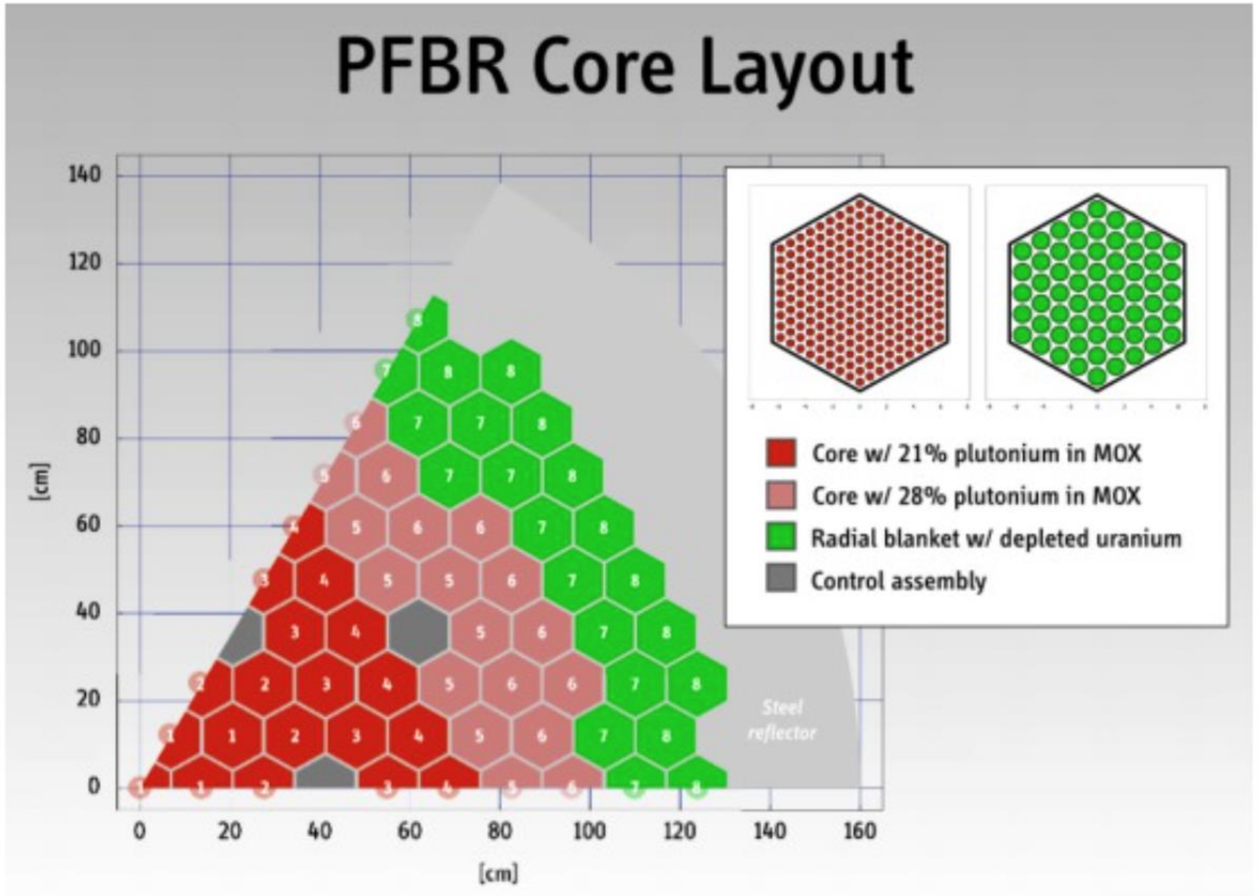


Image: Glaser *et. al*, Science & Global Security 15 (2007)

keV fast neutrons drive core fission (red hexagons) and neutron capture in a surrounding blanket (green hexagons) of natural or depleted uranium where Pu-239 breeding can occur

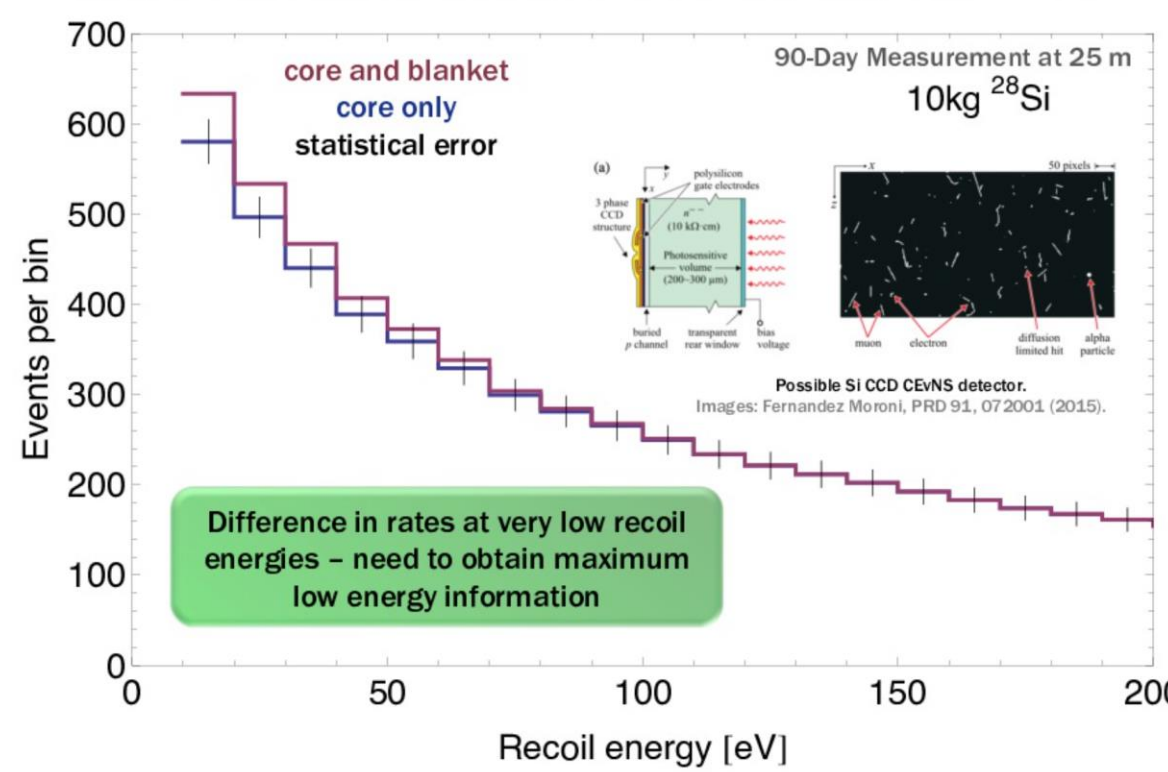
Model and data taken from:
A. Glaser and M. V. Ramana, Science & Global Security 15 (2007)

Achieved: Proof of Principle

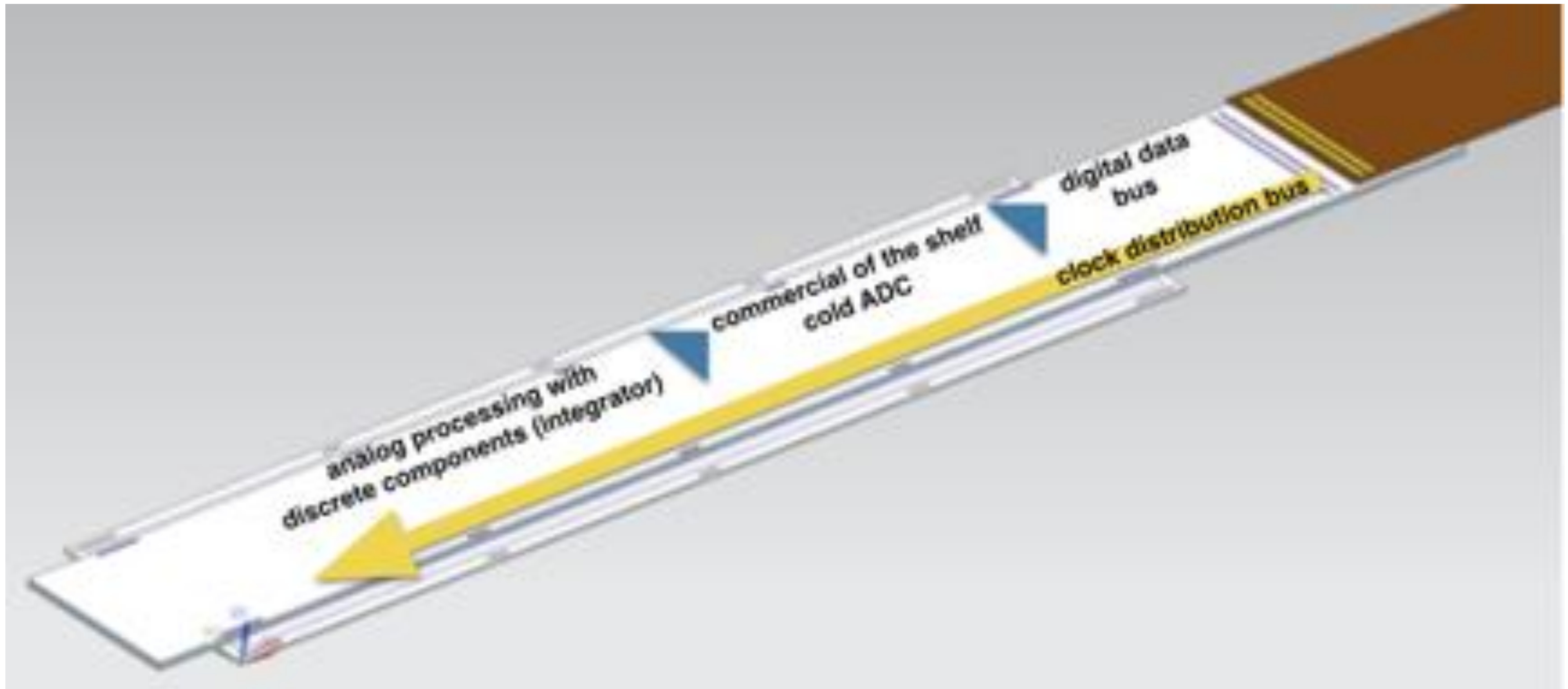
- On-going R&D on silicon-based charge coupled devices (CCDs) shows detector masses of 17-kg with 20 eV threshold may be possible in the near future[1]
- Can detect the presence of a breeding blanket at a PFBR-type fast reactor at 95% confidence level within 90 days using a 36-kg ^{28}Si CENNS detector with a threshold of 30 eV[2]

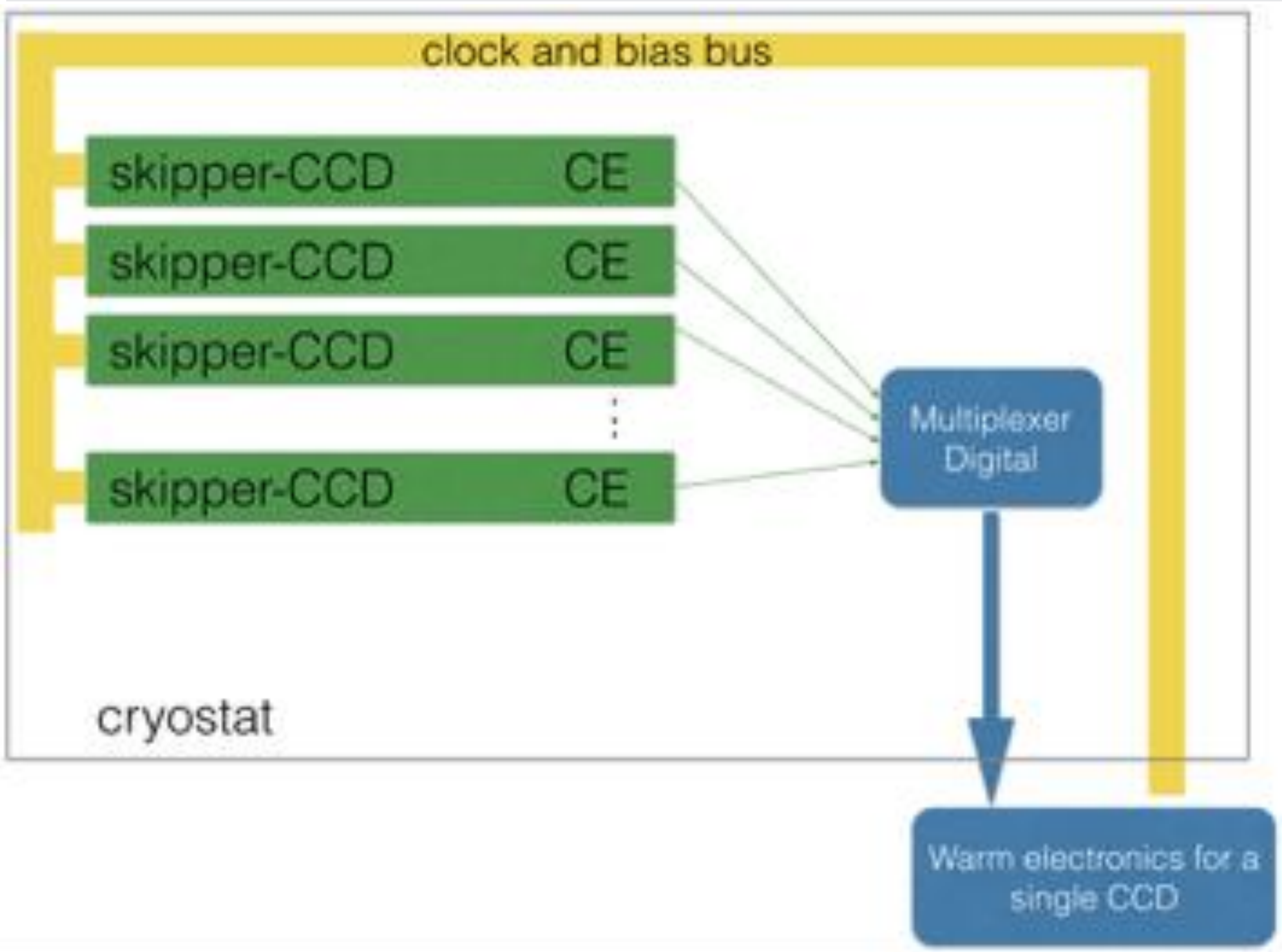
[1]G. Fernandez Moroni, J. Estrada, E. E. Paolini, et al., Phys. Rev. D 91, 072001 (2015); [2] Cogswell and Huber INMM Proceedings 2015

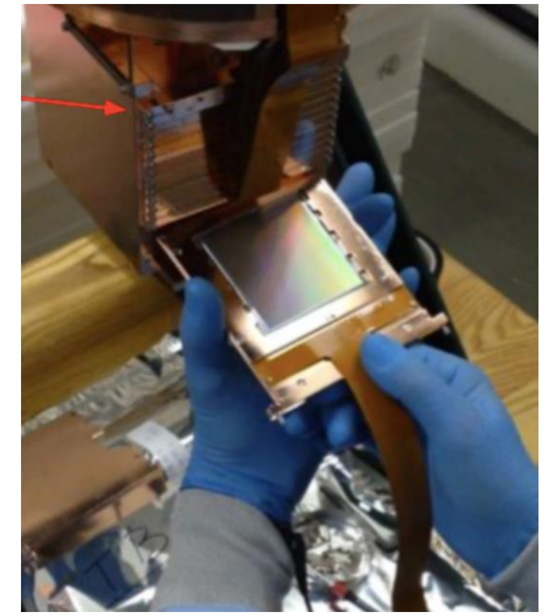
Interaction Rates for 10 kg of ^{28}Si

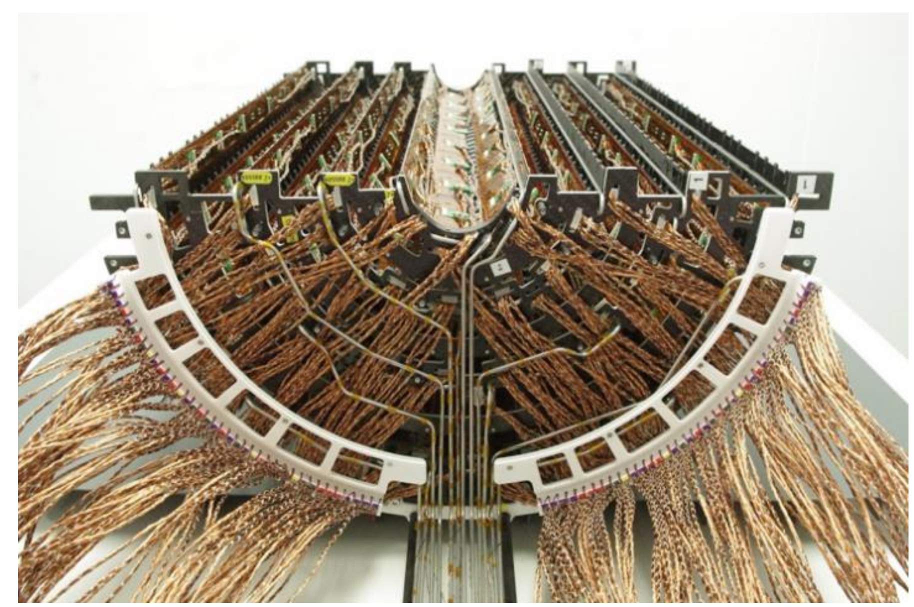


10 kg skipper Detector (4000sensors)









DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[3], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2,4], and Scott W. Randall[1]

[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA, USA
[2] CRESST and X-ray Astrophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA
[3] NASA Goddard Space Flight Center, Greenbelt, MD, USA
[4] Department of Astronomy, University of Maryland, College Park, MD, USA

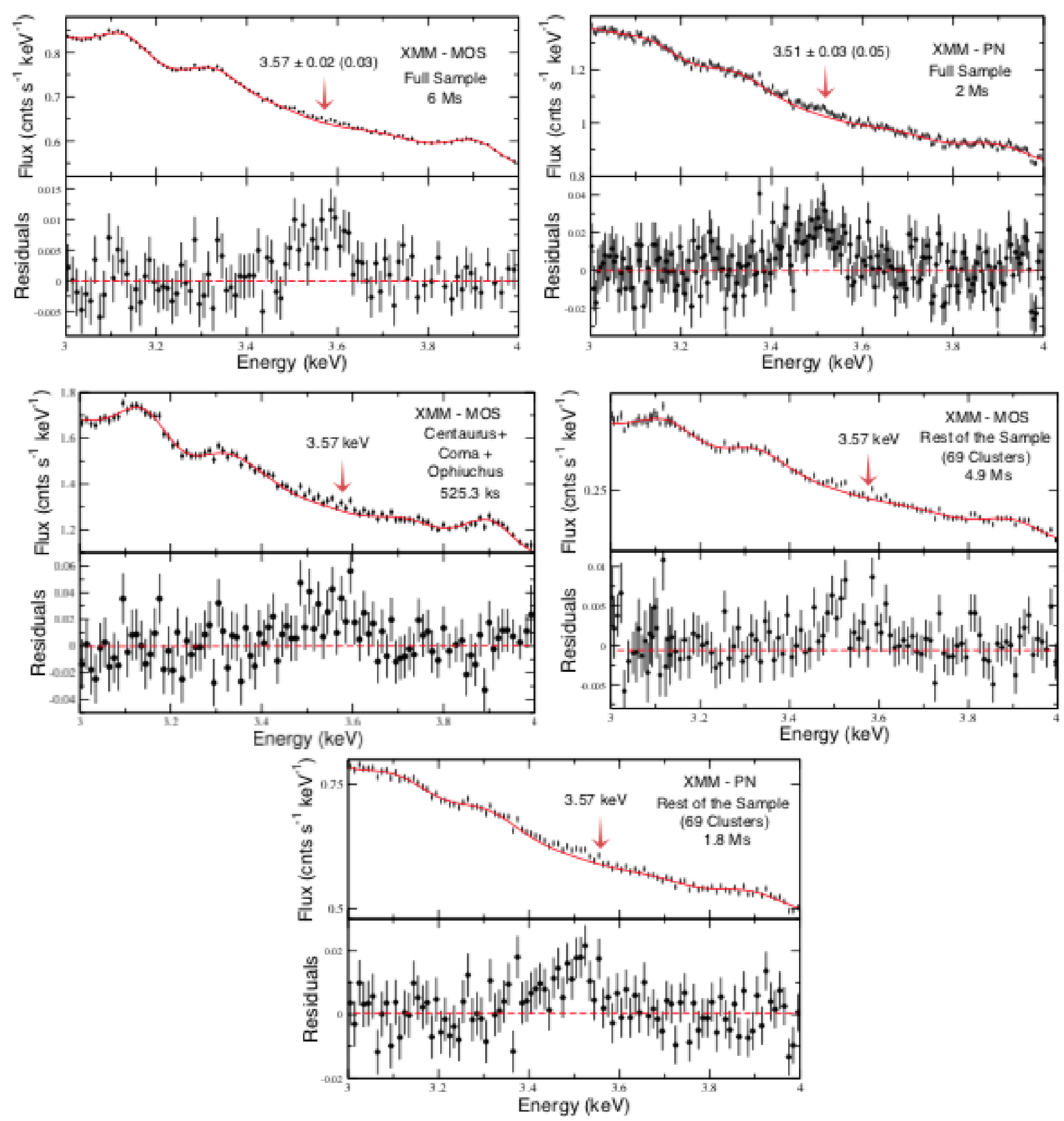


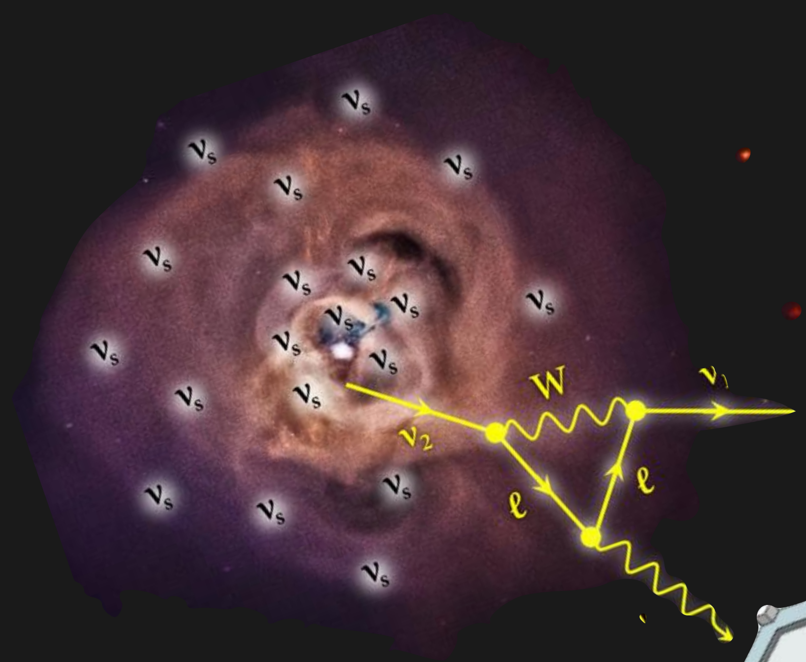
Figure 6. 3–4 keV band of the rebinned *XMM-Newton* spectra of the detections.The spectra were rebinned to make the excess at ~3.57 keV more apparent. **(APJ VERSION INCLUDES ONLY THE REBINNED MOS SPECTRUM OF THE FULL SAMPLE).**

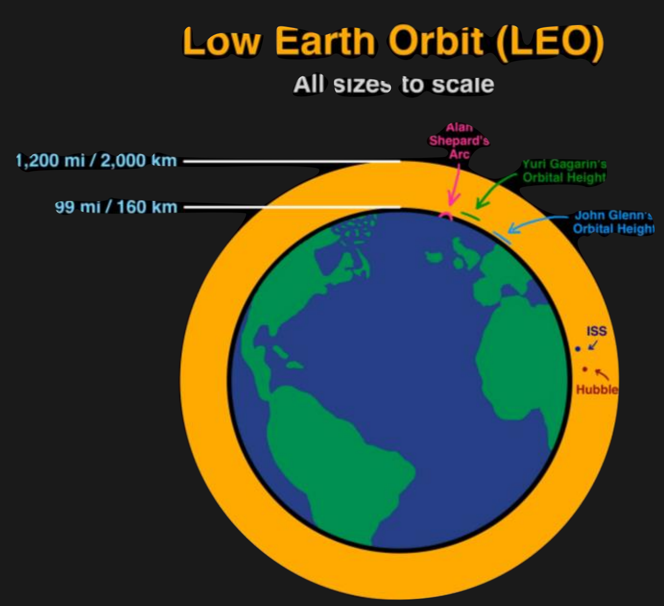
ABSTRACT

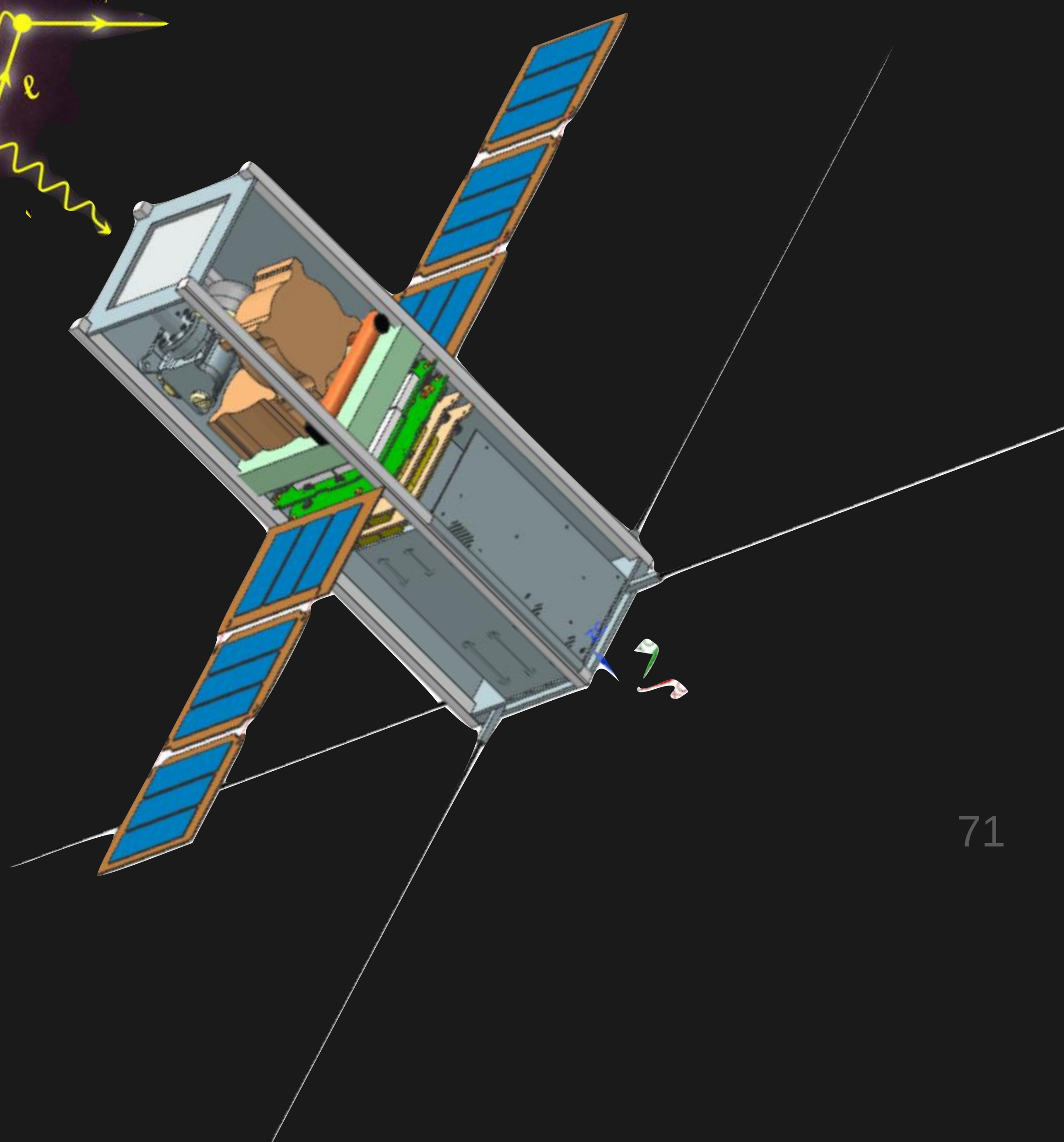
We detect a weak unidentified emission line at $E = (3.55-3.57) \pm 0.03$ keV in a stacked *XMM-Newton* spectrum of 73 galaxy clusters spanning a redshift range $0.01 - 0.35$. MOS and PN observations independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is seen at $> 3\sigma$ statistical significance in all three independent MOS spectra and the PN "all others" spectrum.

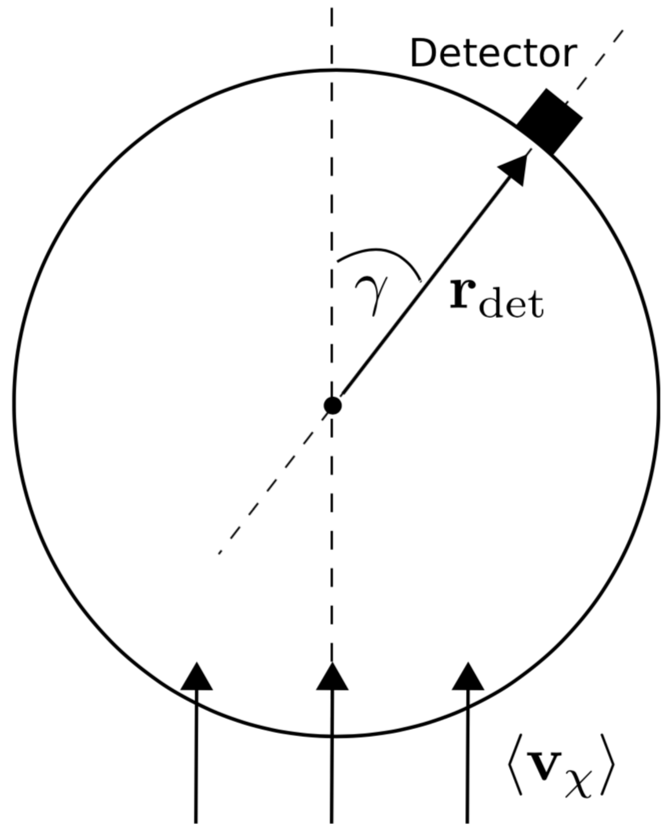
skipper in space

cubeSat for detecting the decay of dark matter in our own galaxy.

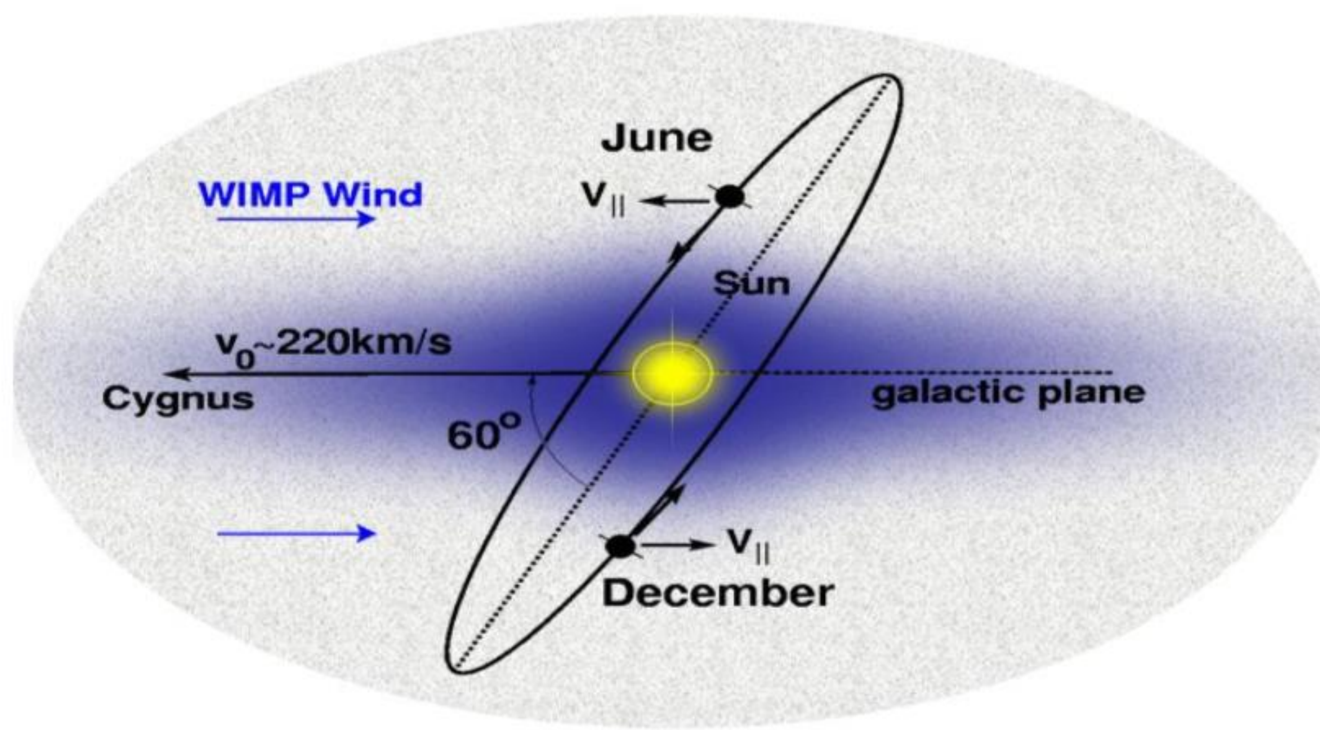




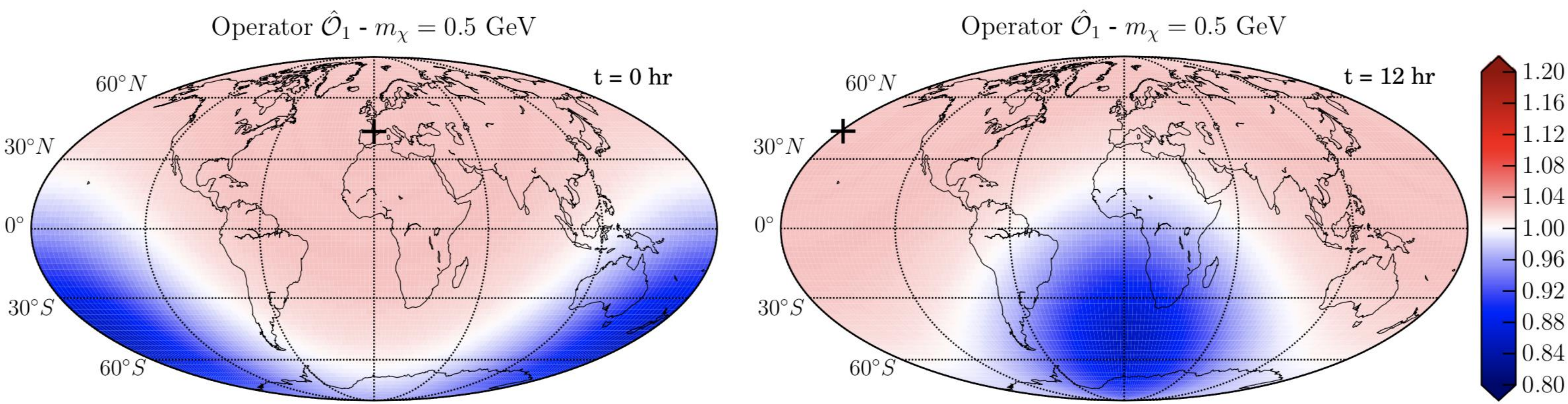




Detector
γ
$\mathbf{r}_{\rm det}$
$\langle \mathbf{v}_\chi \rangle$



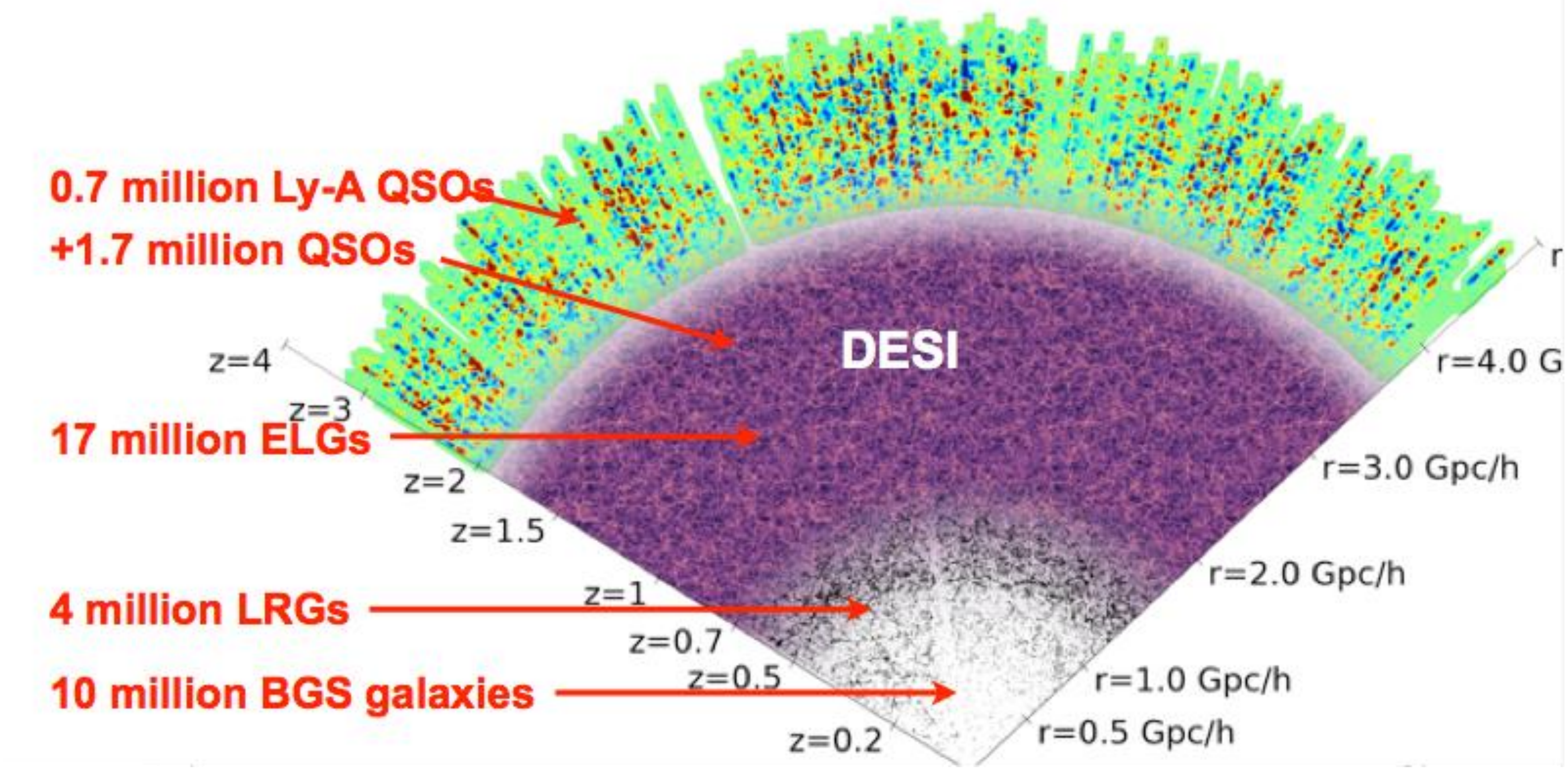
June
WIMP Wind
$v_{||}$
Sun
v_0~220km/s
Cygnus
galactic plane
60°
$v_{||}$
December

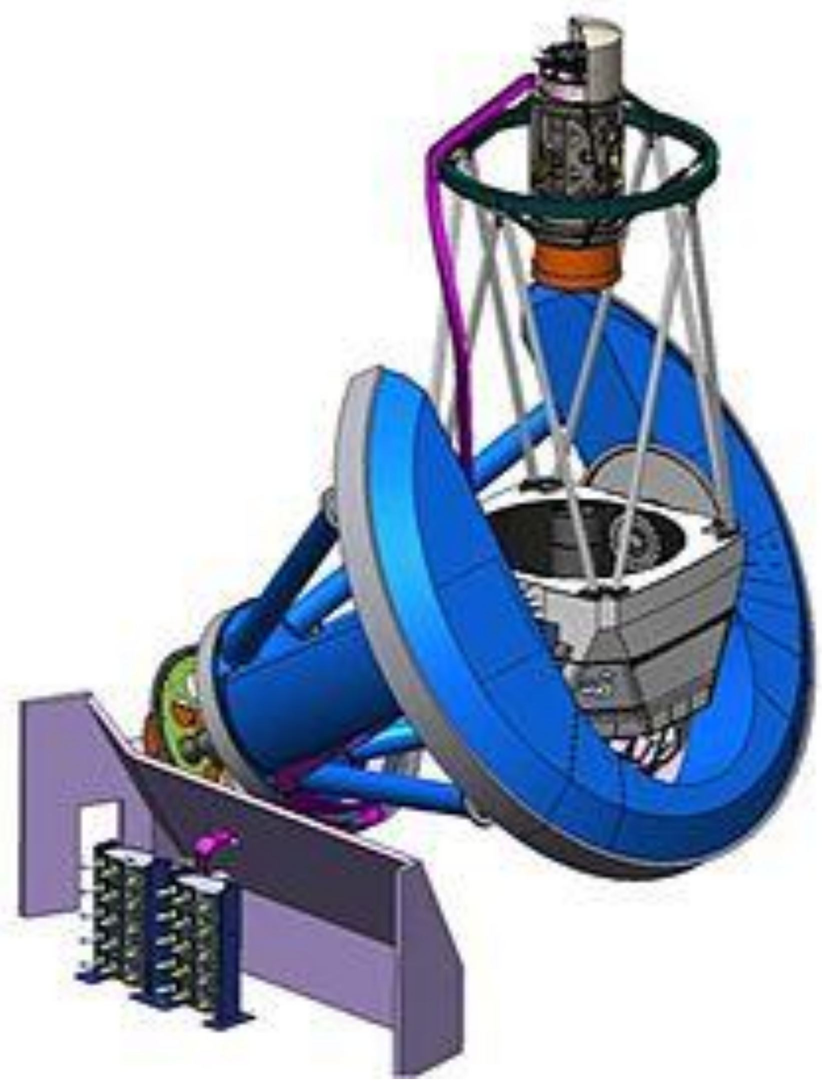


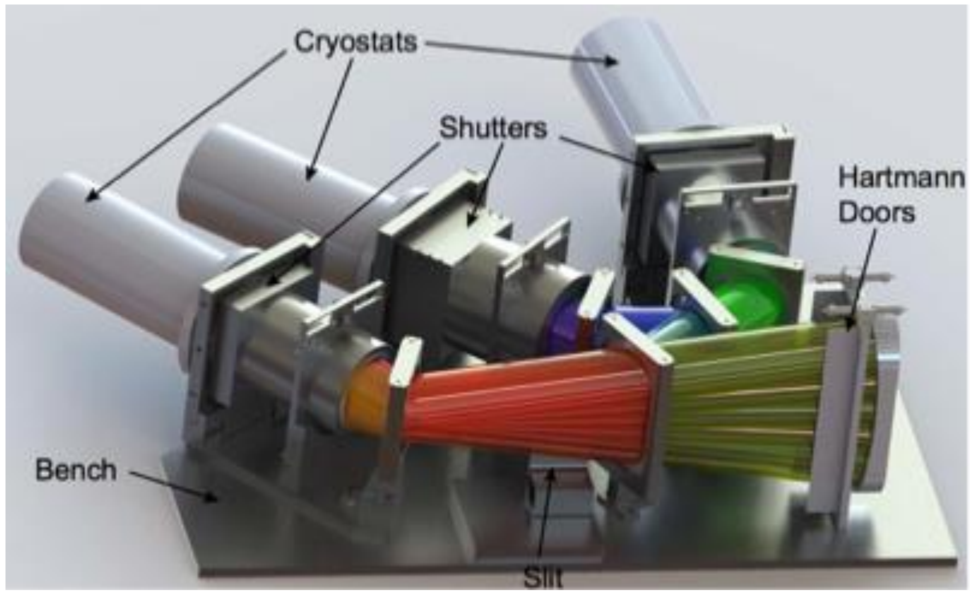
Operator $\hat{\mathcal{O}}_1$ - $m_\chi = 0.5$ GeV
t = 0 hr
60°N
30°N
0°
30°S
60°S
Operator $\hat{\mathcal{O}}_1$ - $m_\chi = 0.5$ GeV
t = 12 hr
60°N
30°N
0°
30°S
60°S
1.20
1.16
1.12
1.08
1.04
1.00
0.96
0.92
0.88
0.84
0.80

DESI: Dark Energy Spectroscopic Survey

35 million galaxy + QSO redshift survey

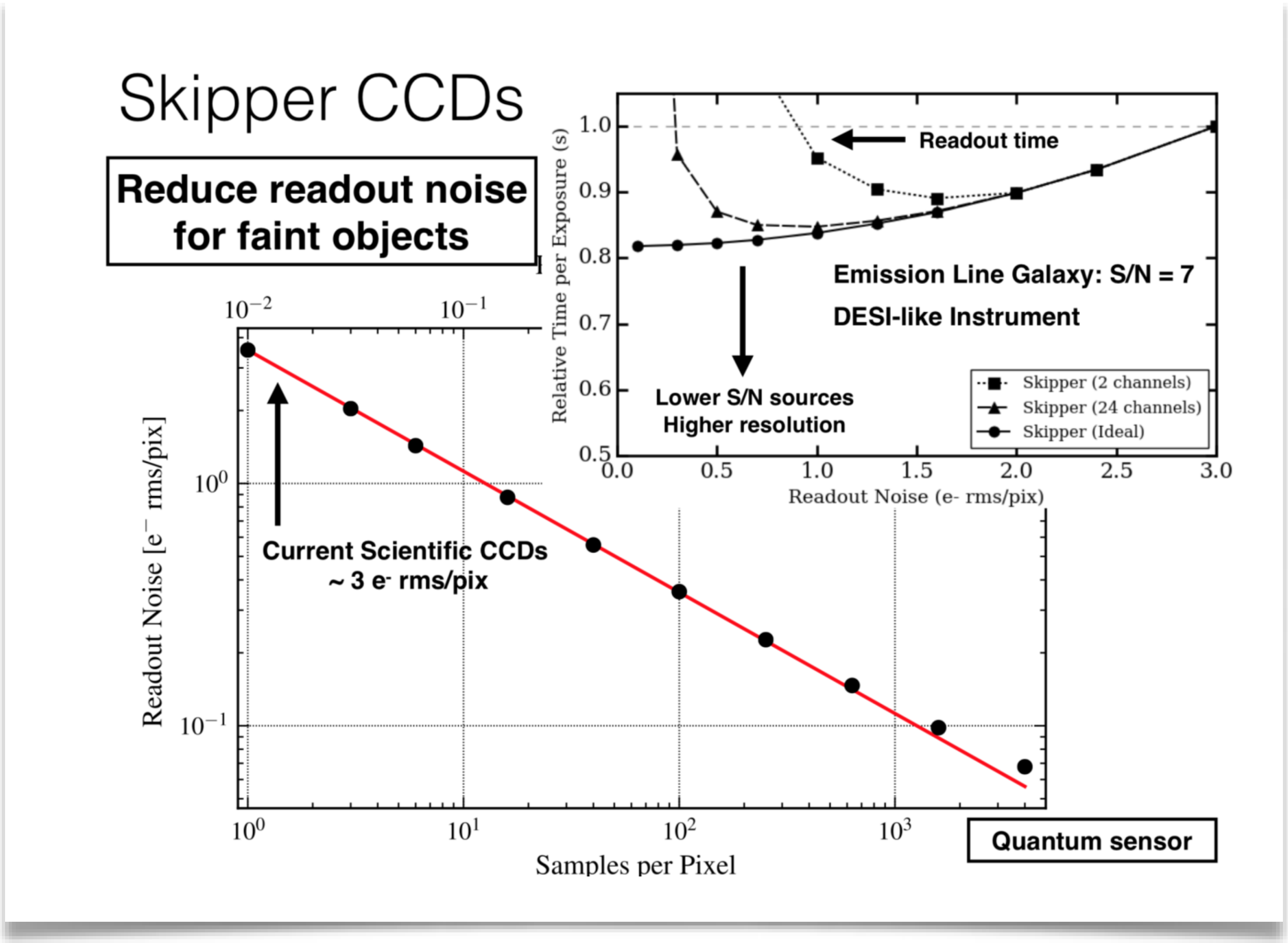


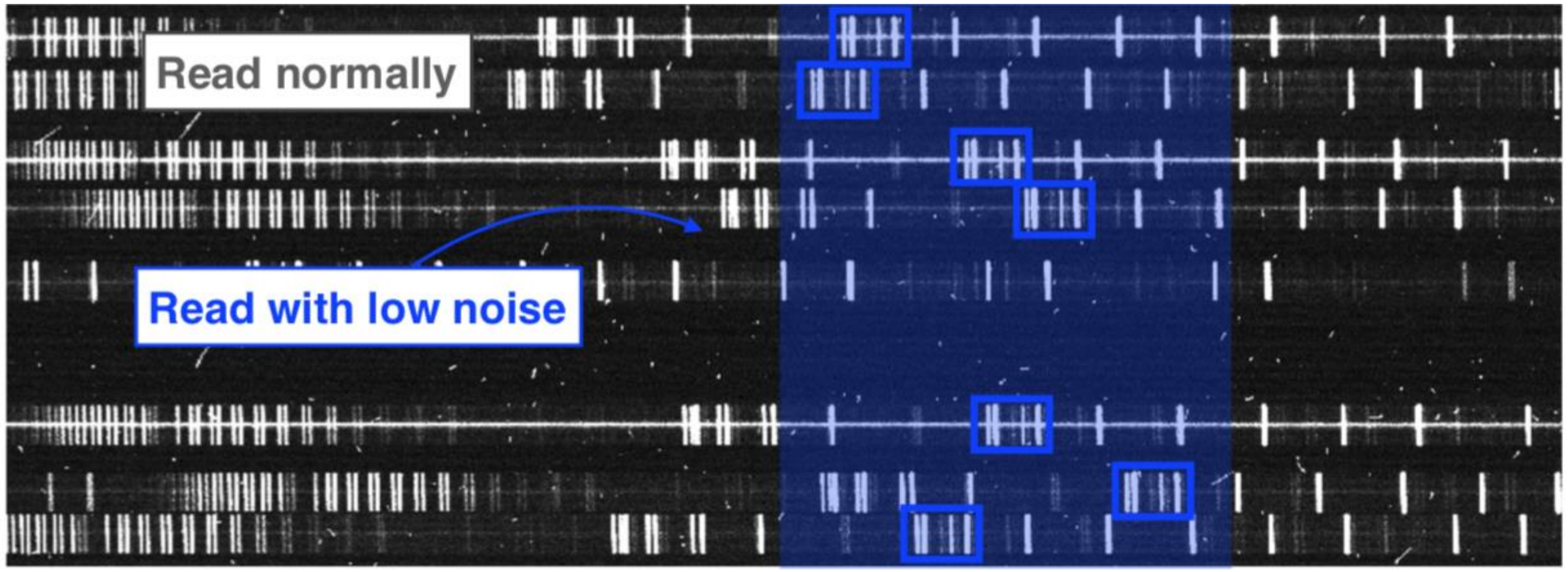




we are now building the detectors for these spectrographs, 2e- of noise.

skipper for cosmic surveys





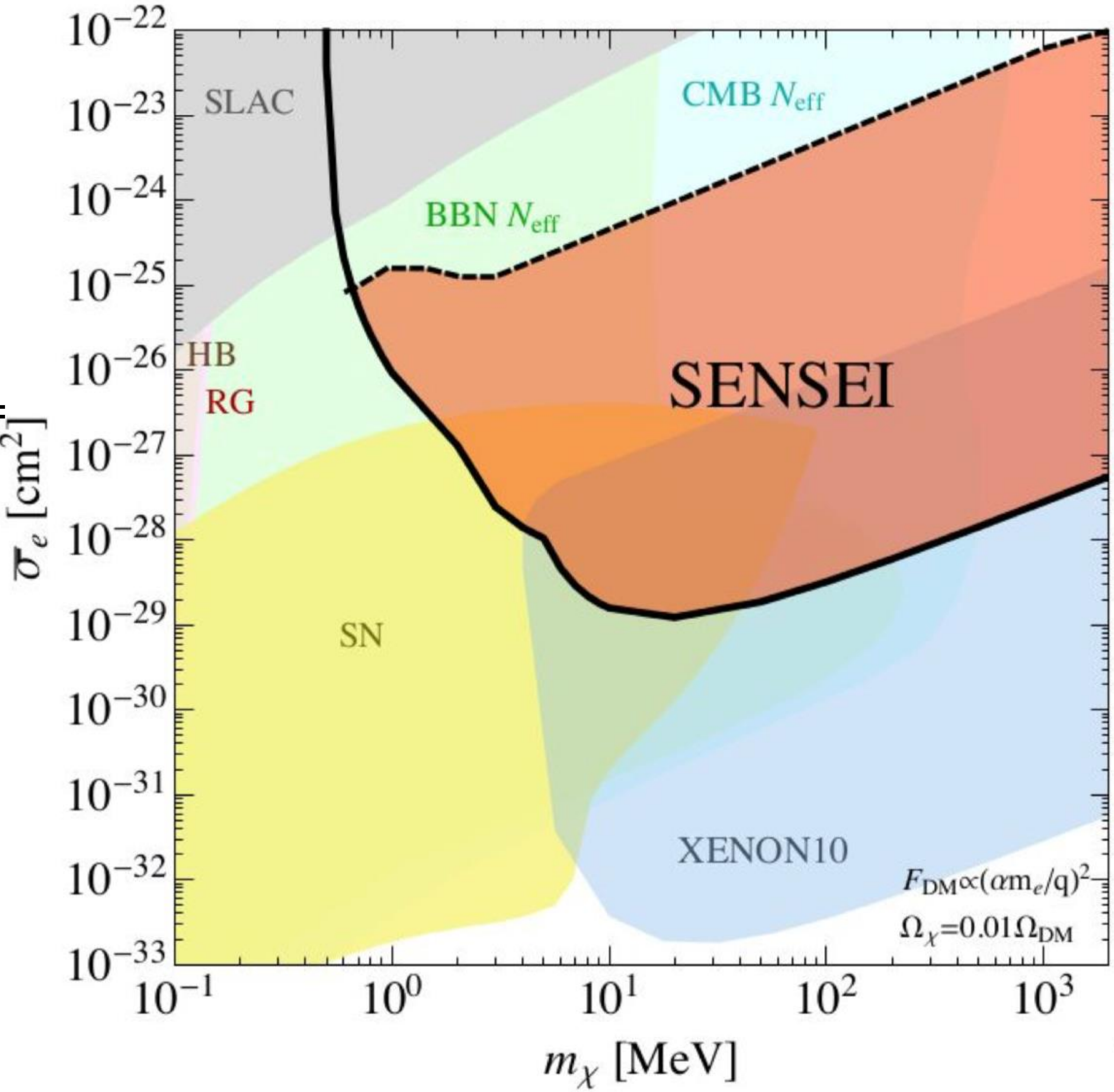
new skipper-CCD technology could improve the efficiency of a survey spectrograph reducing readout time.

Signal to noise could be tuned to optimizing readout time (target specific pixels for low noise).

(A.Drilica-Wagner)

Light mediator and Ω χ = 0.01Ω DM, which may explain the 21-cm signal observed by EDGES

We assume that a subdominant DM component, χ, interacts with an ultra-light dark photon (mA′ ≪ keV), with Ωχ = 0.01ΩDM. This model is motivated by the EDGES measurement of the 21-cm spectrum at z ≃ 17, which revealed an anomalously large absorption signal.



PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \rightarrow \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

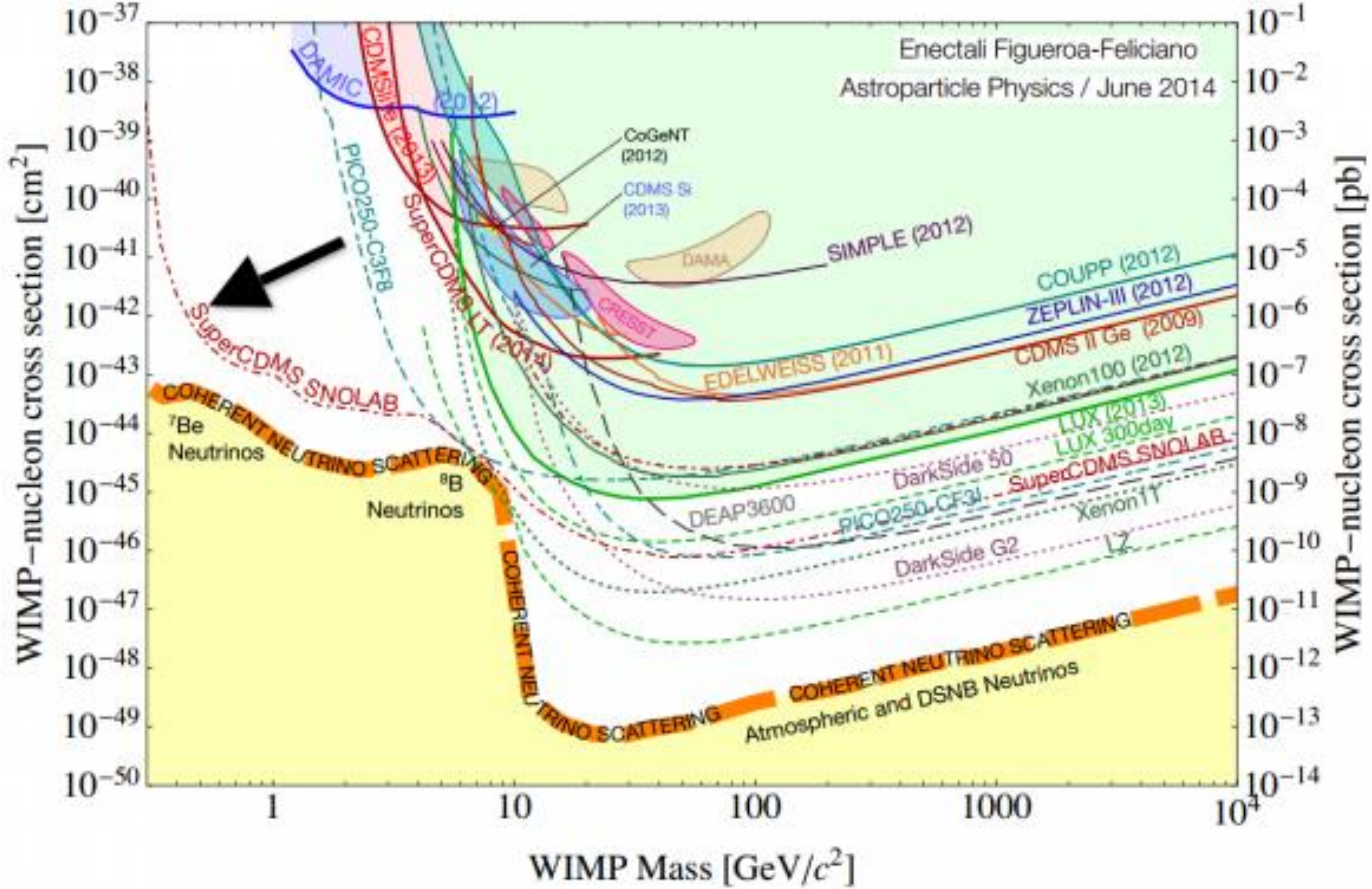
PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

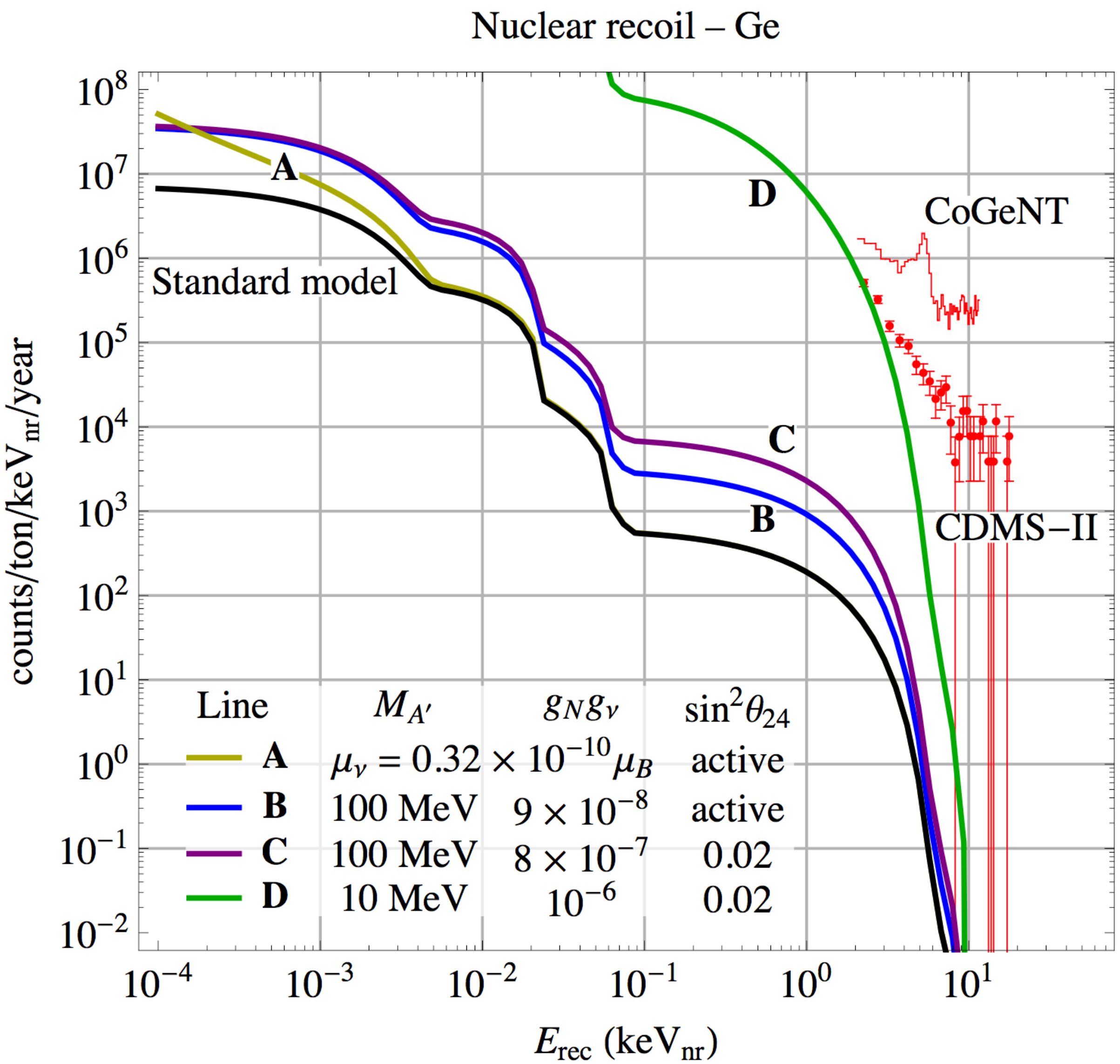
A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany

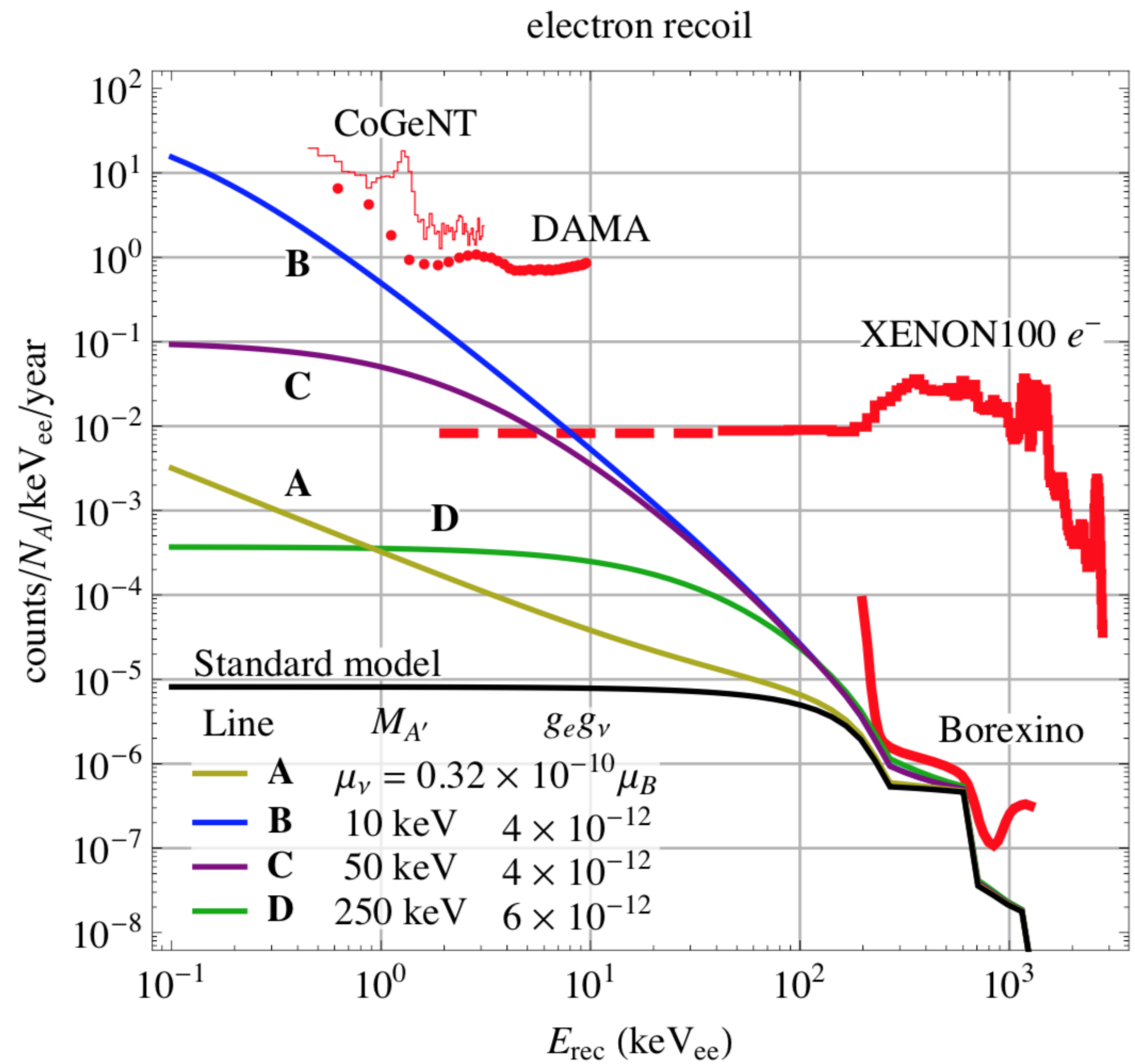
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small (10–10^3 eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.



neutrino floor…



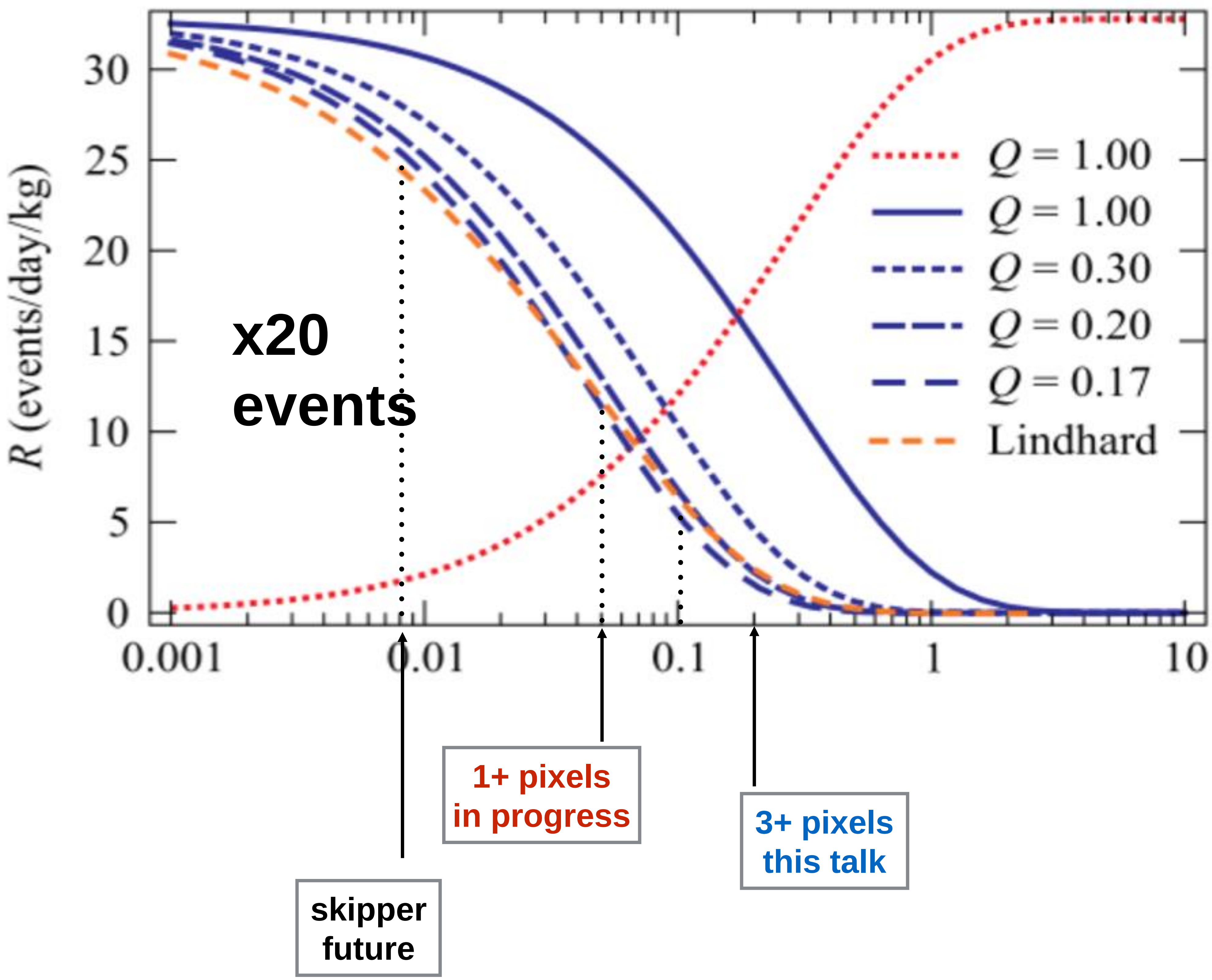


new neutrino–electron or neutrino–quark

interaction mediated by a light particle (Gauged B-

L). "Dark Photon"

understanding the new physics also important for future dark matter searches…
R. Harnik et al. (2012)



R (events/day/kg)
30
25
20
15
10
5
0
0.001
0.01
0.1
1
10
Q = 1.00
Q = 1.00
Q = 0.30
Q = 0.20
Q = 0.17
Lindhard
x20
events
1+ pixels
in progress
3+ pixels
this talk
skipper
future

$$\frac{d\sigma_W}{dT} = \frac{G_F^2 m_e}{2\pi}\left[\left(1 - \frac{T}{E_\nu}\right)^2 (1 + 2\sin^2\theta_W)^2 + \right.$$
$$\left. + 4\sin^2\theta_W - 2\,(1 + 2\sin^2\theta_W)\sin^2\theta_W \frac{m_e T}{E_\nu^2}\right], \quad (1)$$

$$\frac{d\sigma_{EM}}{dT} = \pi r_0^2 \left(\frac{\mu_\nu}{\mu_B}\right)^2 \left(\frac{1}{T} - \frac{1}{E_\nu}\right), \quad (2)$$

(3GW reactor)

To realize this useful feature in our GEMMA spectrometer[14], we use a 1.5 kg HPGe detector with the energy threshold as low as 3.0 keV. To be sure that there is no efficiency cut at this energy, the "hard" trigger threshold was twice lower (1.5 keV).

Background is suppressed in several steps. First, the detector is placed inside a cup-like NaI crystal with 14 cm thick walls surrounded with 5 cm of electrolytic copper and 15 cm of lead. This active and passive shielding reduces external γ-background in the ROI to the level of $\sim$ 2 counts/keV/kg/day. Being located just under reactor #2 of the KNPP (at a distance of 13.9 m from the reactor core, which corresponds to the antineutrino flux of $2.7 \times 10^{13}\ \bar{\nu}_e/\mathrm{cm}^2/\mathrm{s}$), detector is well shielded against the hadronic component of cosmic rays by the reactor body and technologic equipment (overburden$\simeq$70 m w.e.). The muon component is also reduced by a factor of $\sim$10 at $\pm 20°$ with respect to the vertical and $\sim$3 at $70° - 80°$, but a part of residual muons are captured in massive shielding and thus produce neutrons which scatter elastically in Ge and give rise to a low-energy background. To

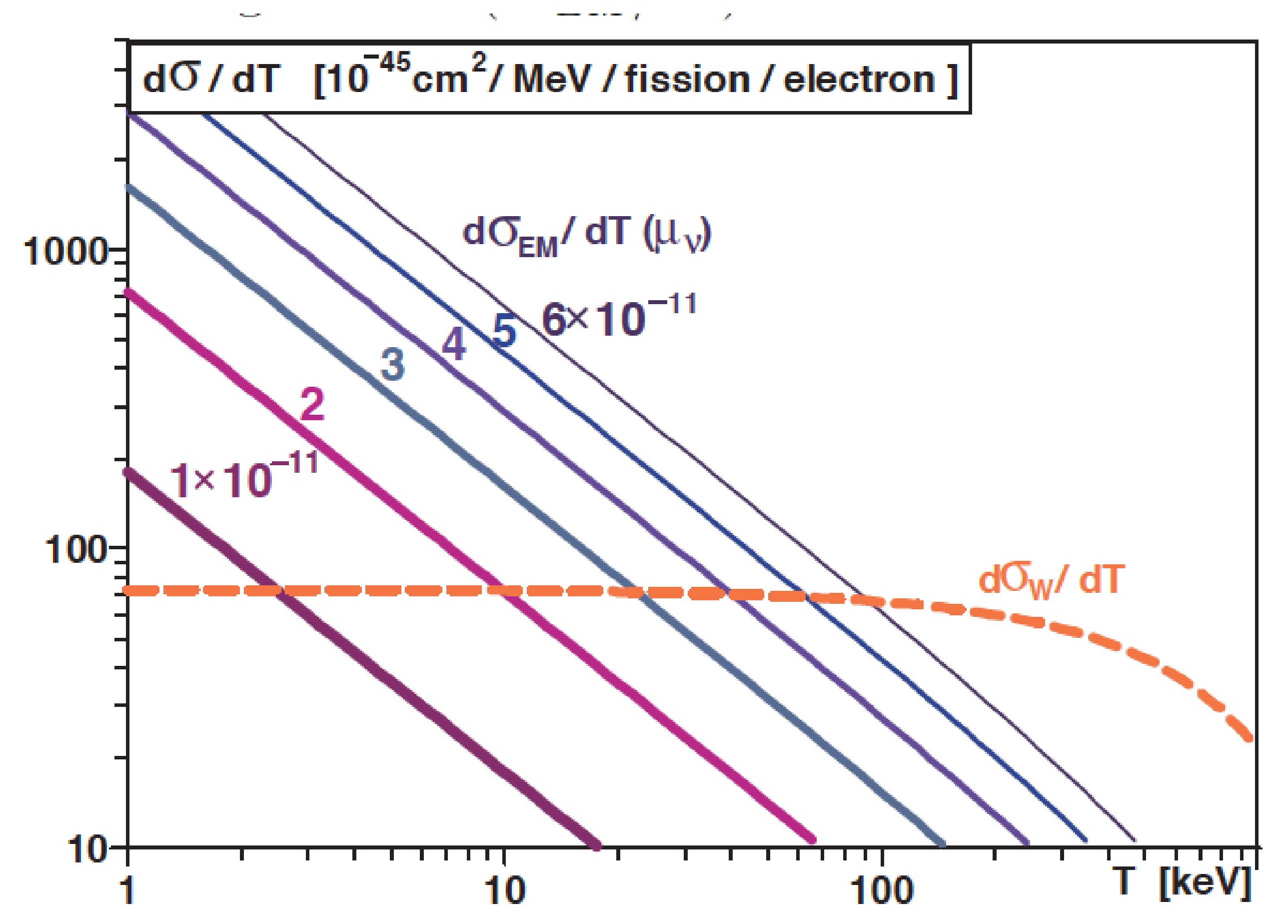
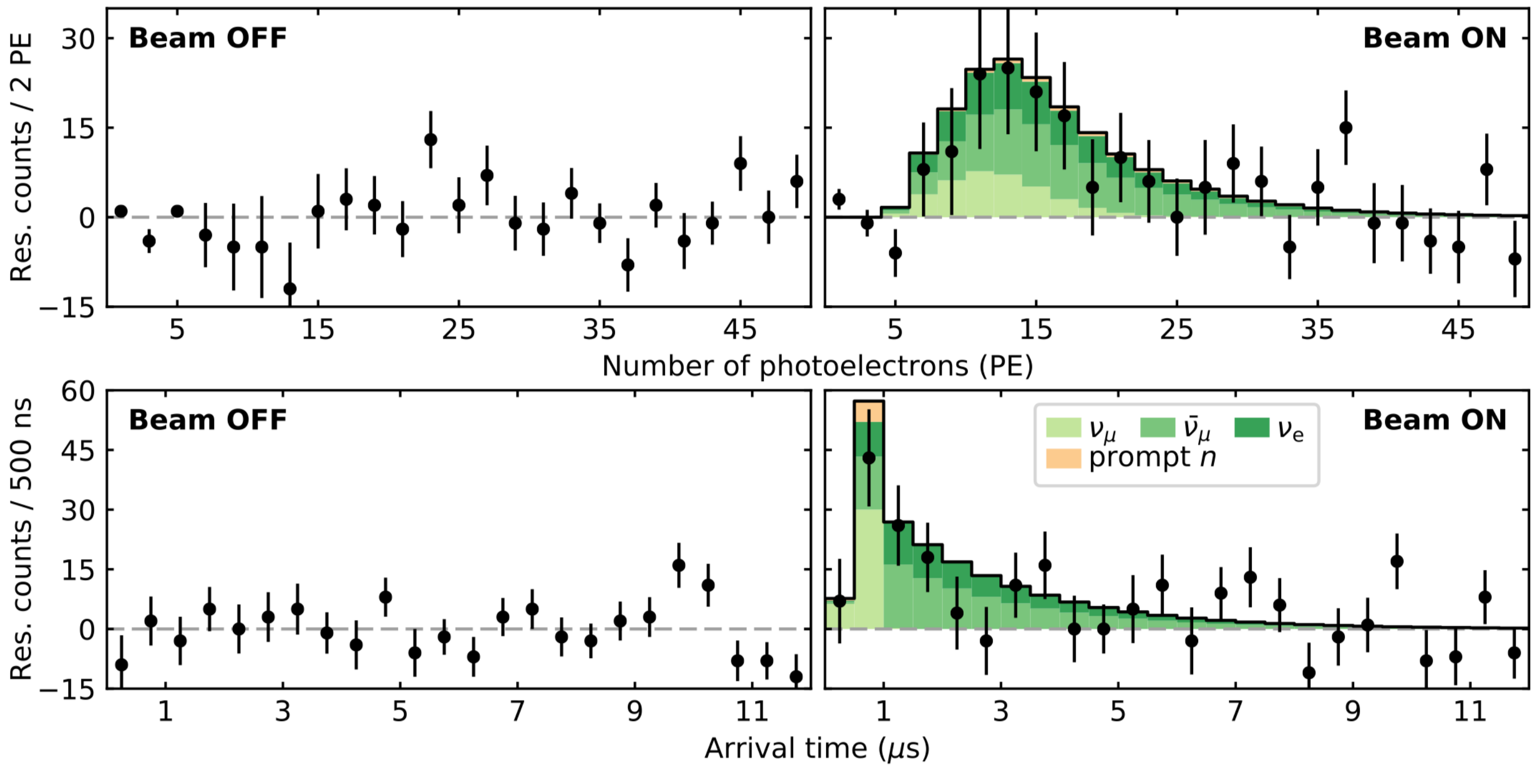


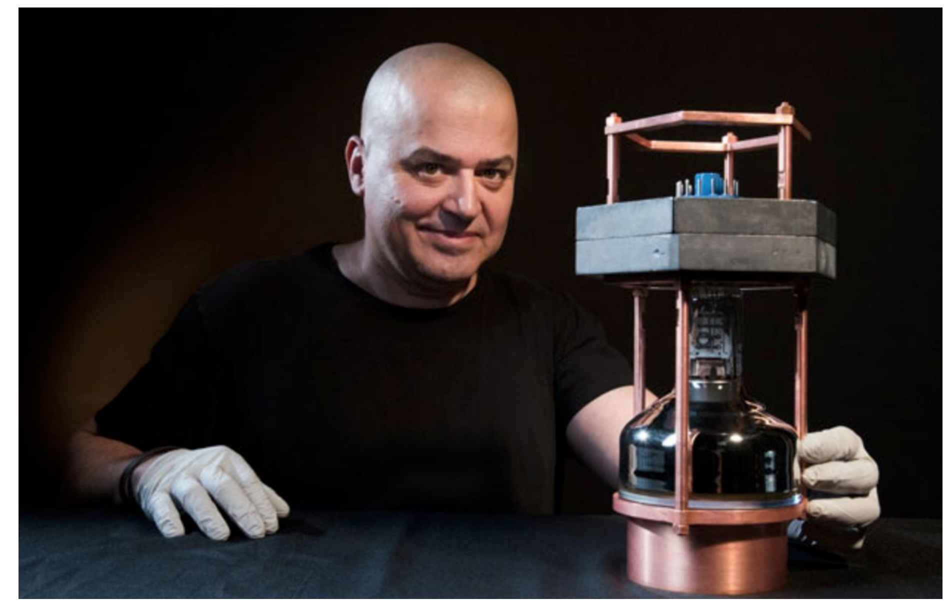
FIG. 1: Weak (W) and electromagnetic (EM) cross-sections calculated for several NMM values.

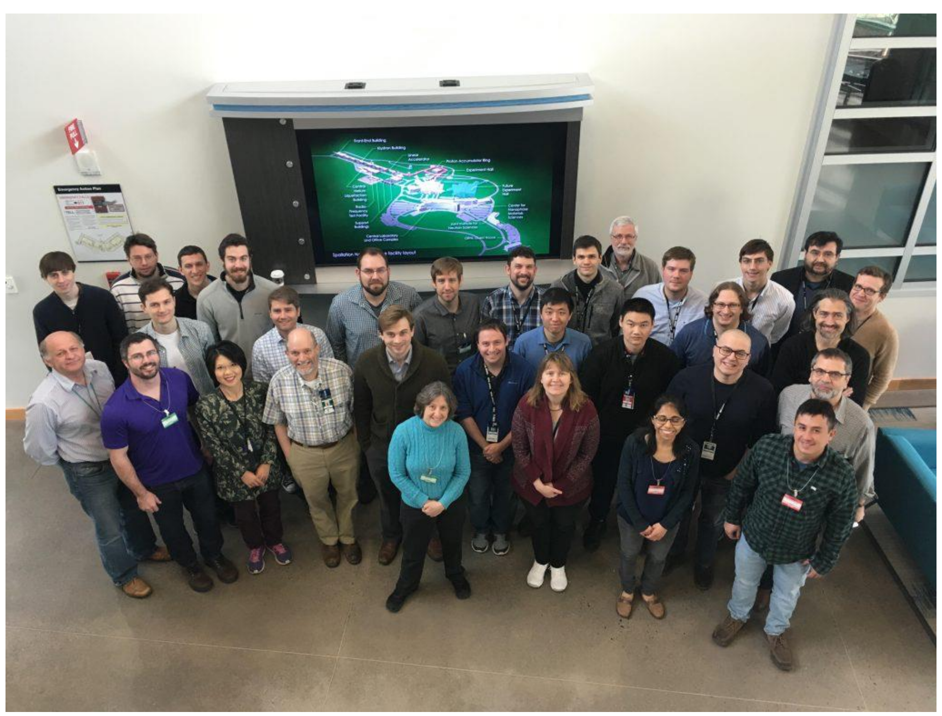
$$\mu_\nu^a < 2.9 \times 10^{-11} \mu_B.$$

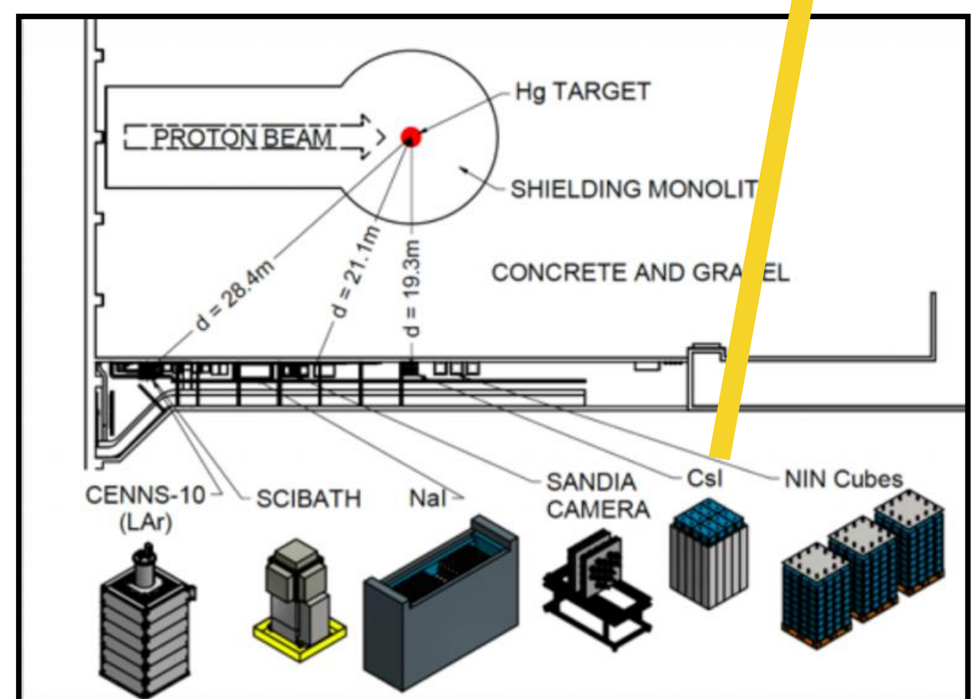
Current best limit comes from GEMMA (using Ge detector at reactor) $3.2\text{x}10^{-11}\ \mu_B\ m_\nu/\mathrm{eV}$

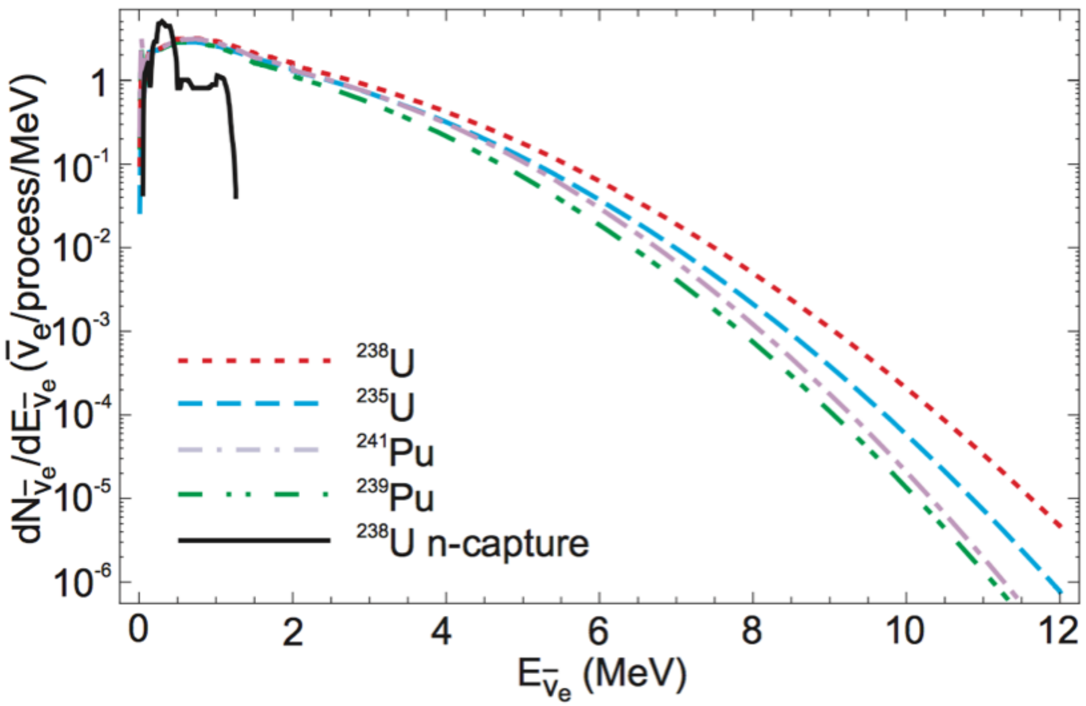
NEWS: First light for CEvNS, “Observation of coherent elastic neutrino-nucleus scattering” by the COHERENT collaboration, published in Science, August 3, 2017





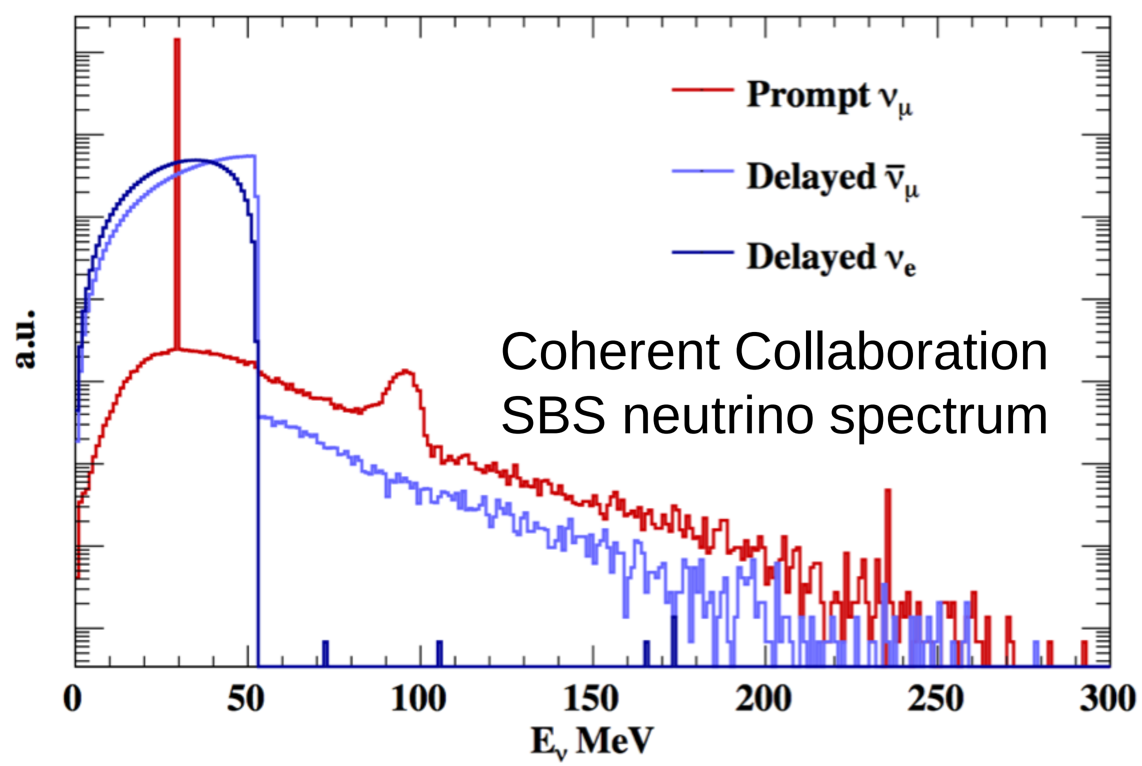






Neutrinos from a nuclear reactor

- Very large flux, close to core.
- Low energy recoils, harder to see.
- Deal with background by shielding.
- A window to very low energy neutrino sector.
- MINER, **CONNIE**

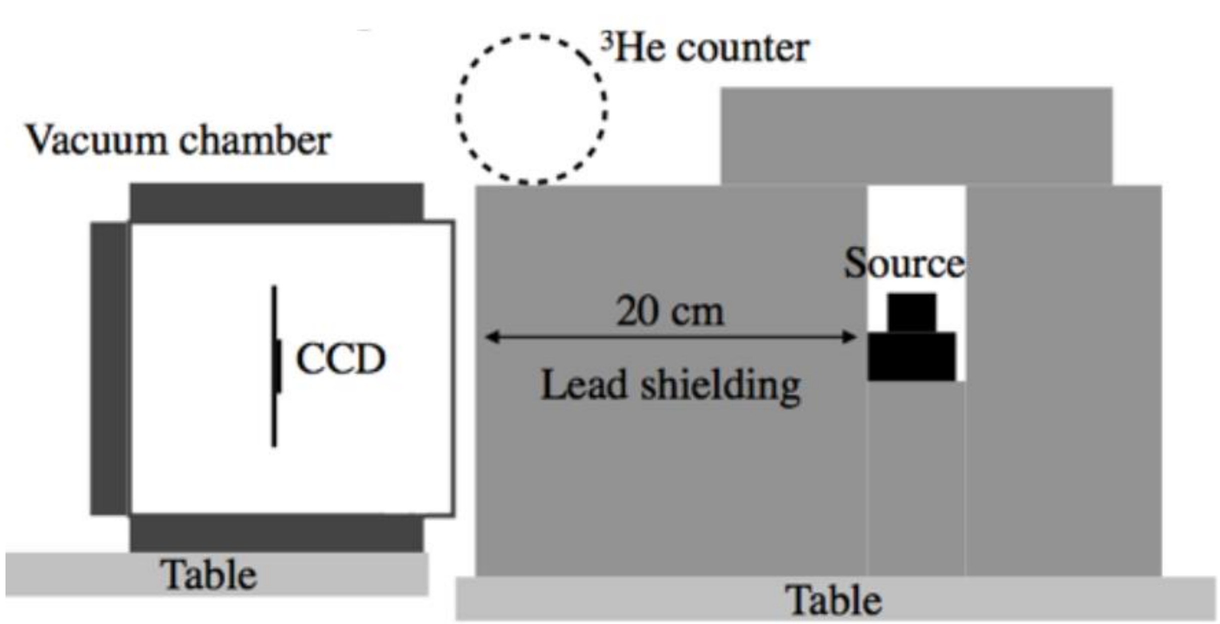


Neutrinos produced by stopped pions (decay at rest).

- Higher energy recoils, easier to see
- Pulsed to control background.
- Has to deal with beam associated background.
- COHERENT

Nuclear Recoil Calibration (A.Chavarria et al)

arXiv:1608.00957



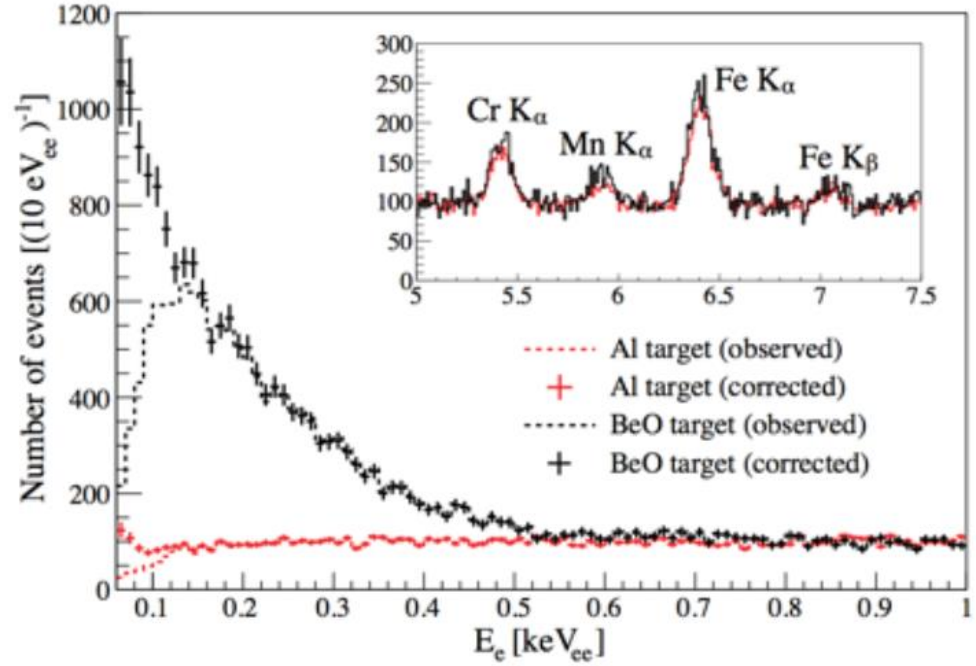


FIG. 2. Measured ionization spectra with the full BeO and Al targets (dashed lines). Solid markers represent the spectra corrected for the energy-dependent event selection acceptance. The inset shows the spectra in the 5.0–7.5 keV$_{ee}$ range, with in-run calibration lines from fluorescence x rays originating in the stainless steel of the vacuum chamber.

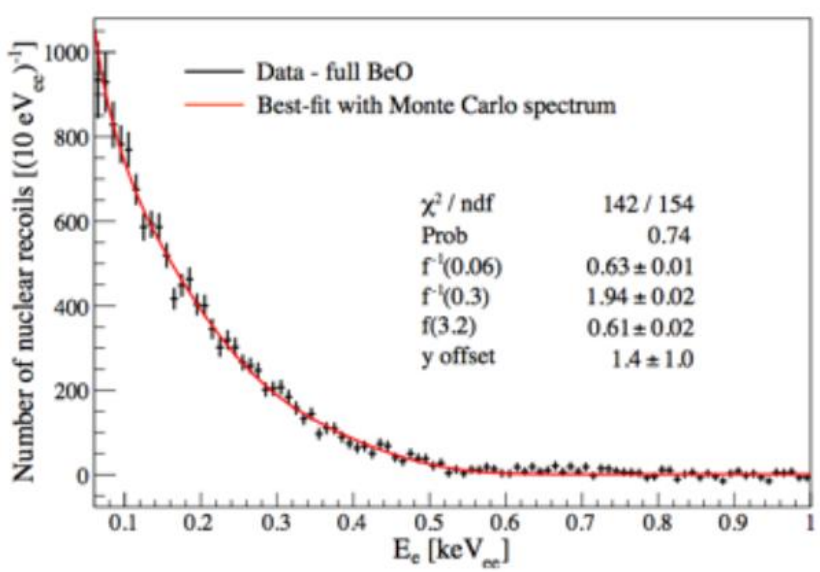
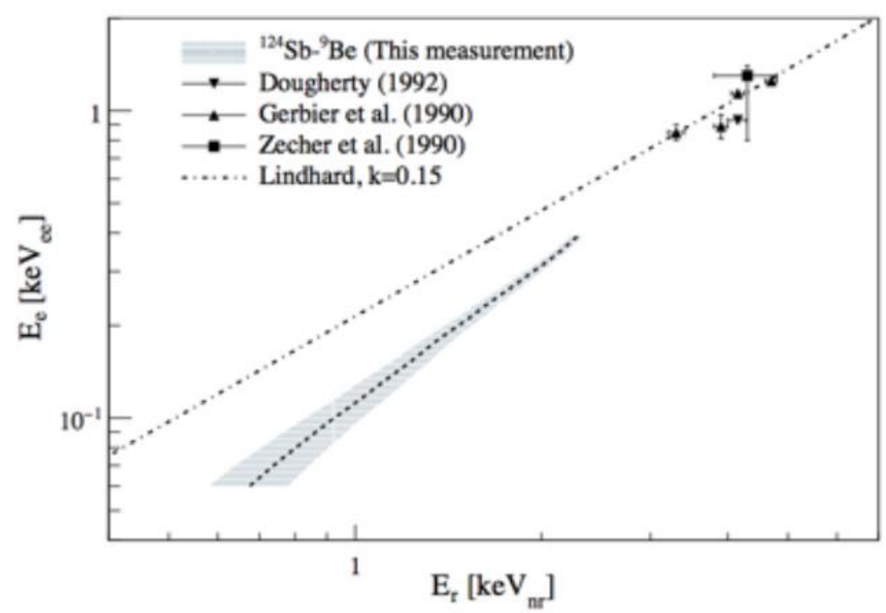


FIG. 4. Ionization spectrum of nuclear recoils induced by neutrons from the full BeO target source (black markers) and best fit to the data (solid line). The fitting function was obtained by applying a cubic spline model f of the nuclear recoil ionization efficiency to the simulated recoil spectrum and convolving with the detector energy resolution. The best-fit parameters of the spline are given in the legend.



Nuclear Recoil Calibration (F. Izraelevitch et al)

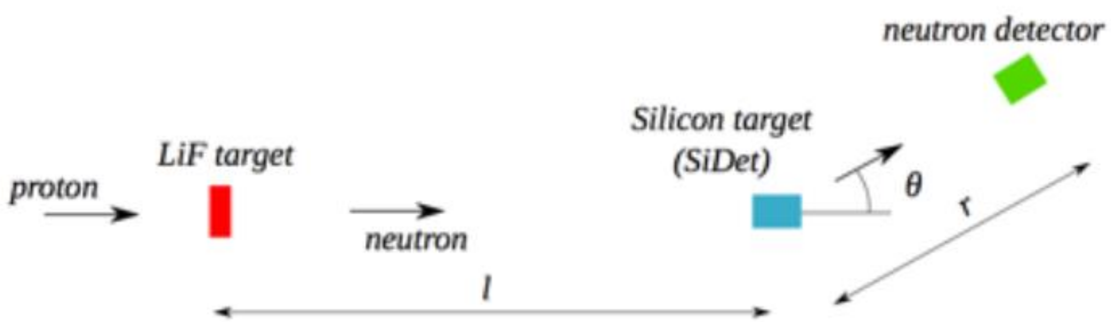
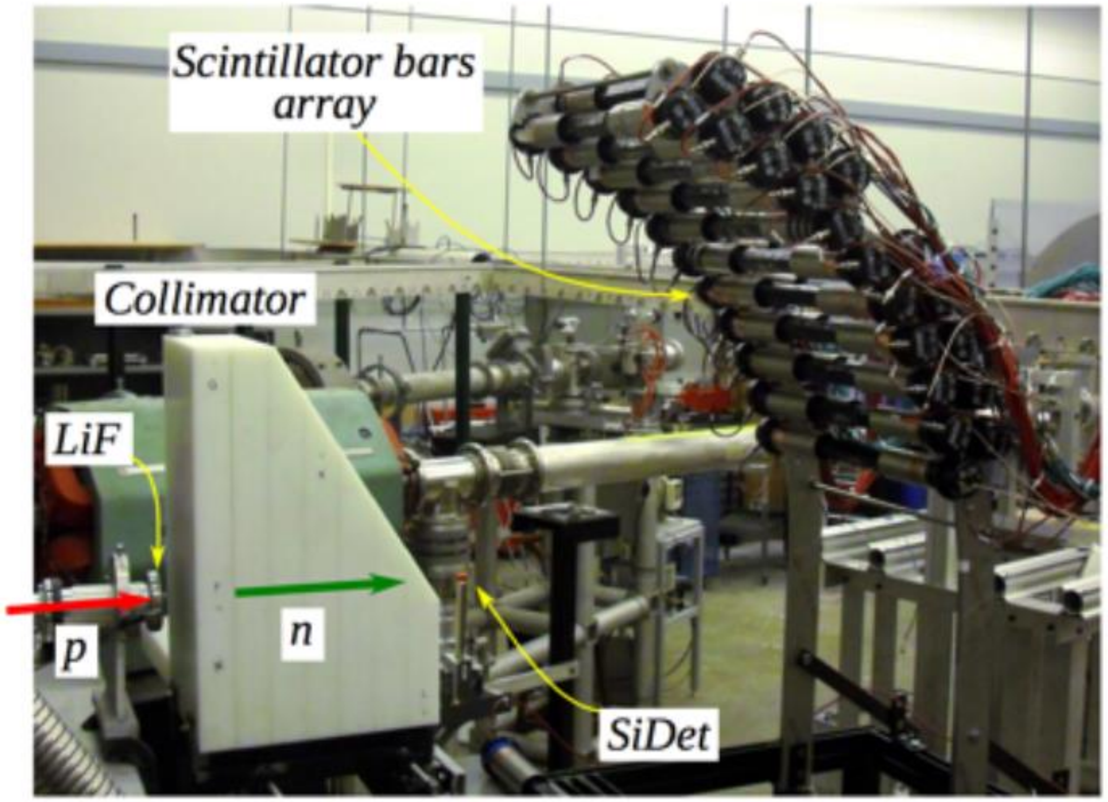
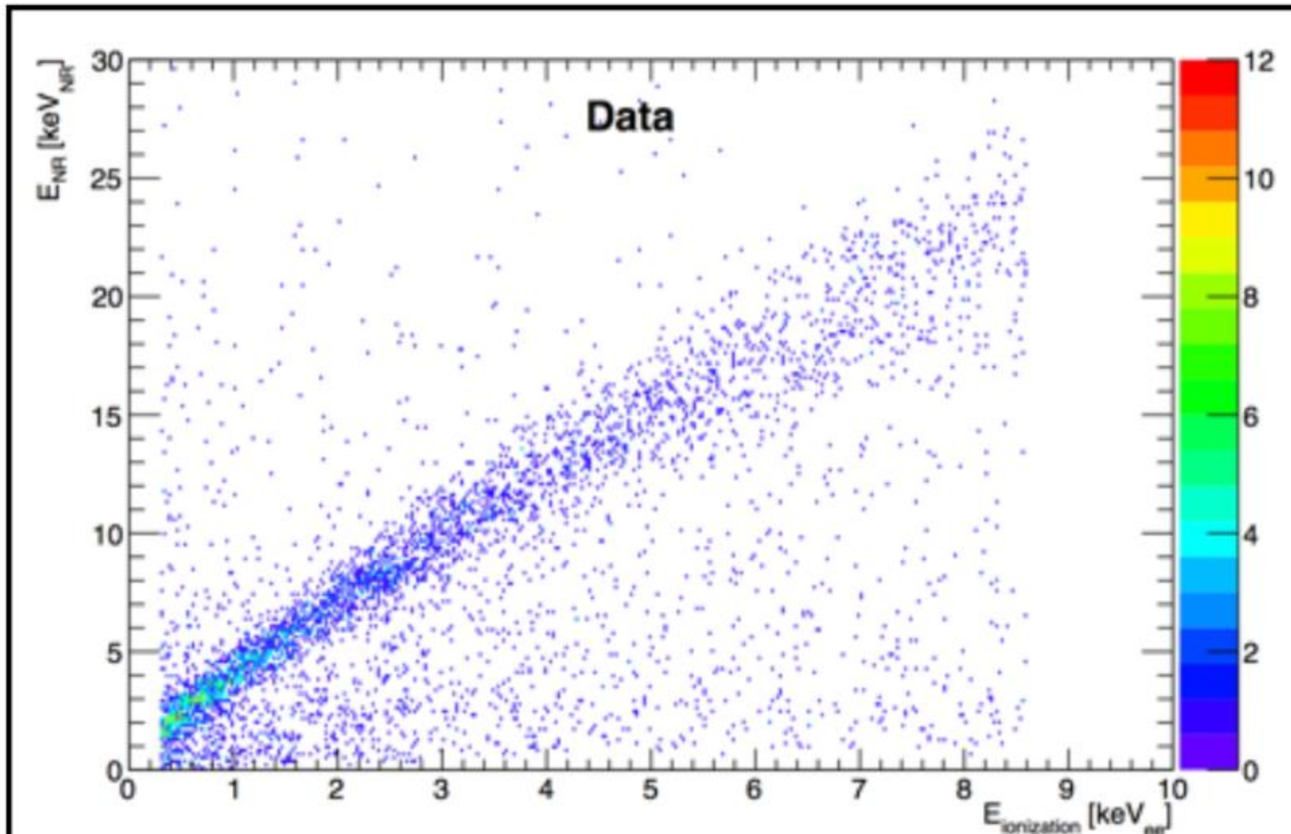
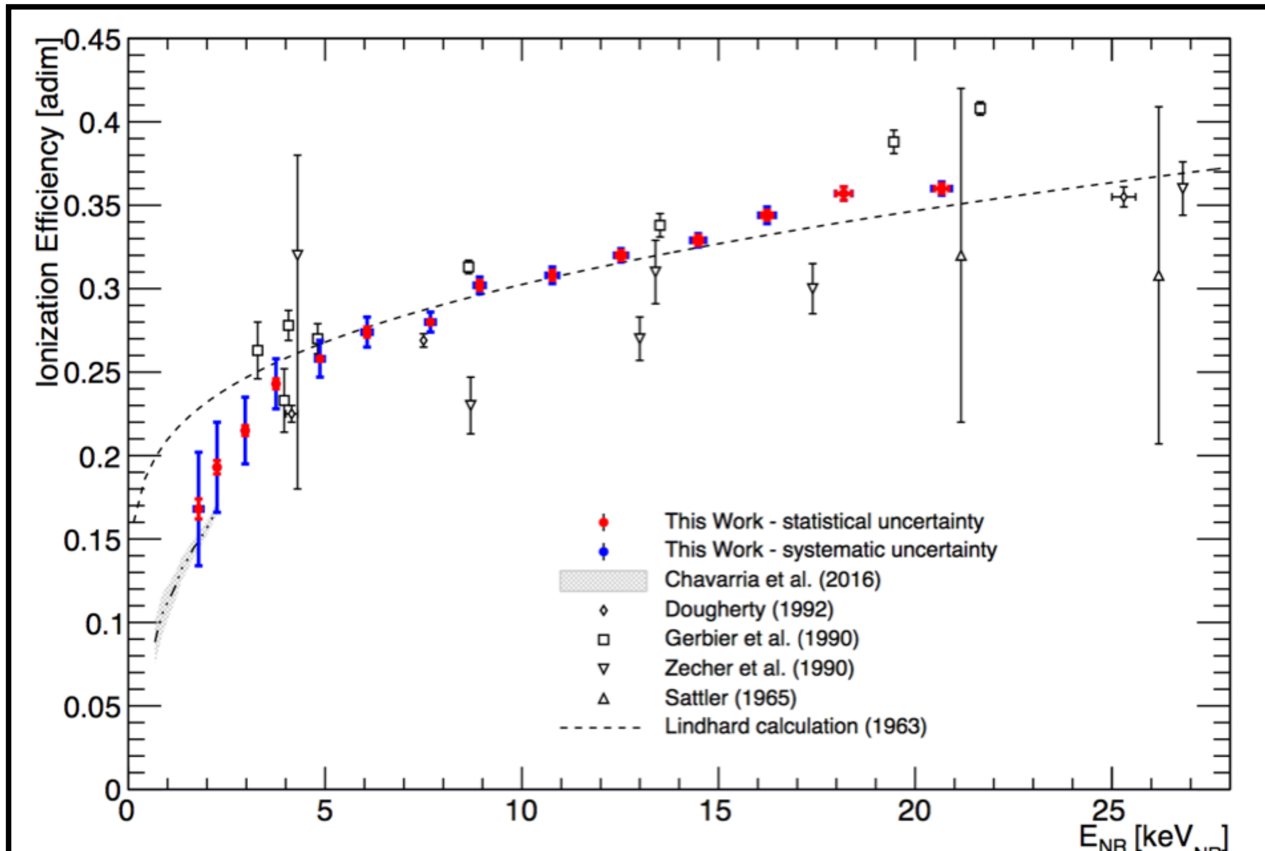


Figure 1: Schematic layout of the experimental arrangement.



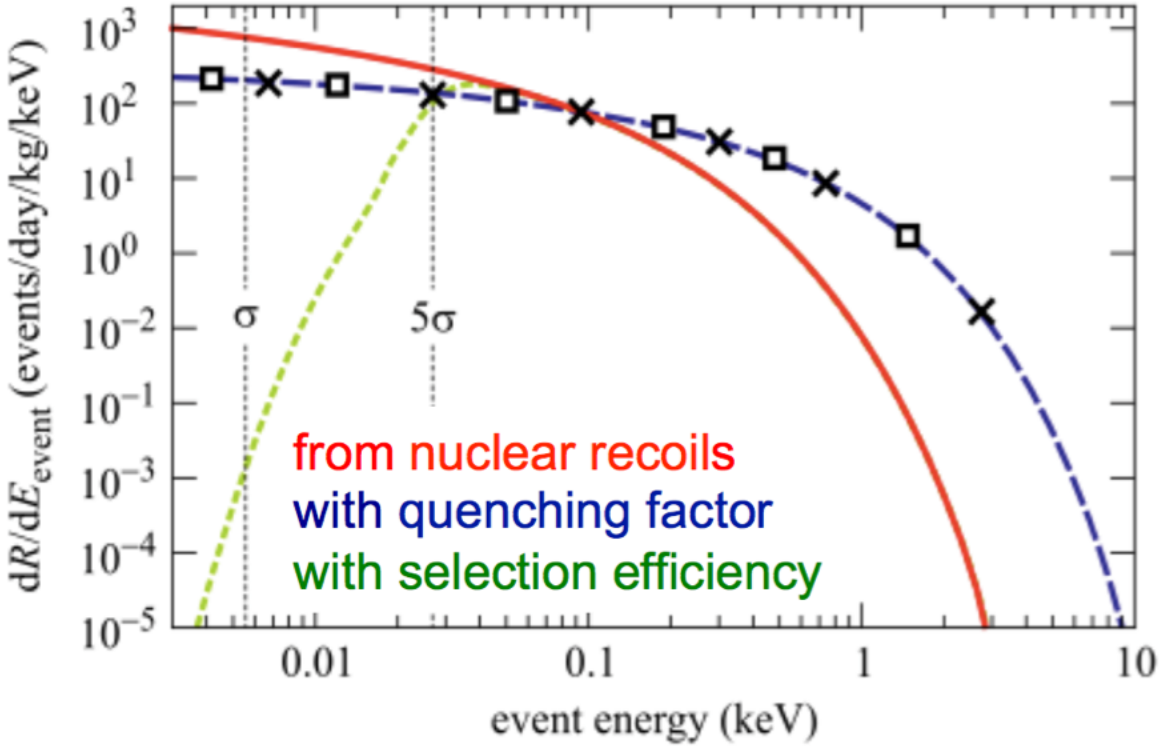




<u>Complete calibration down to our threshold for CONNIE.</u>

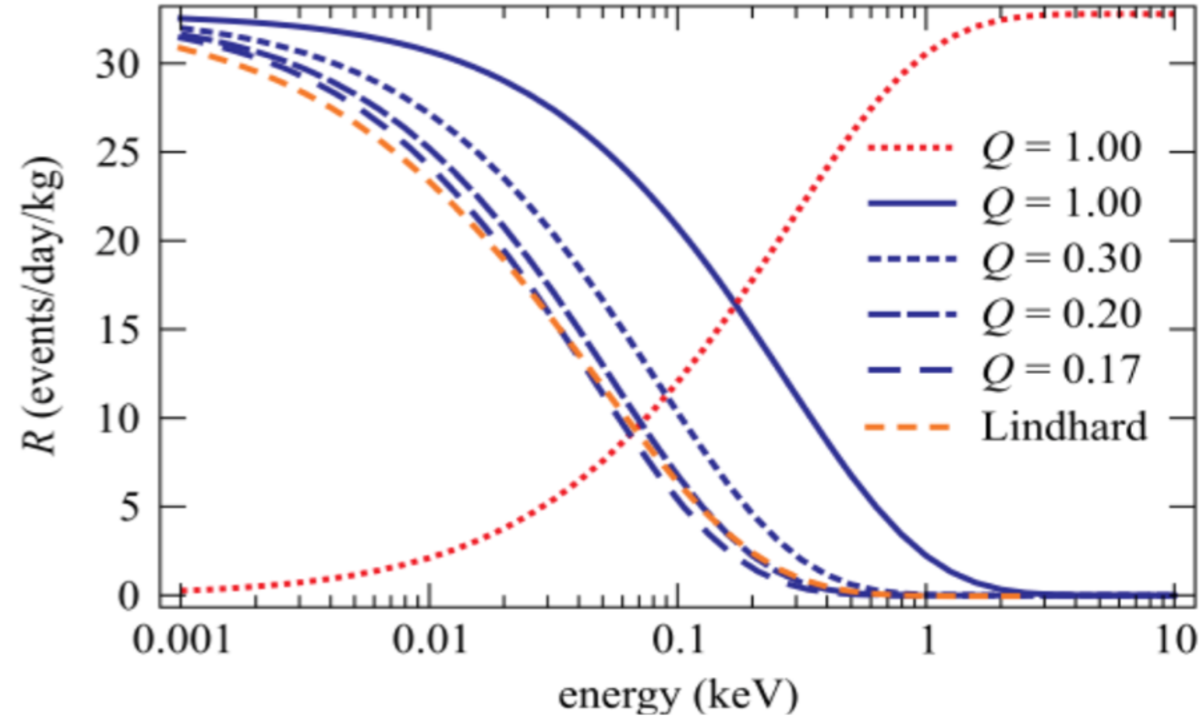
CONNIE rates

Energy spectra in silicon detectors



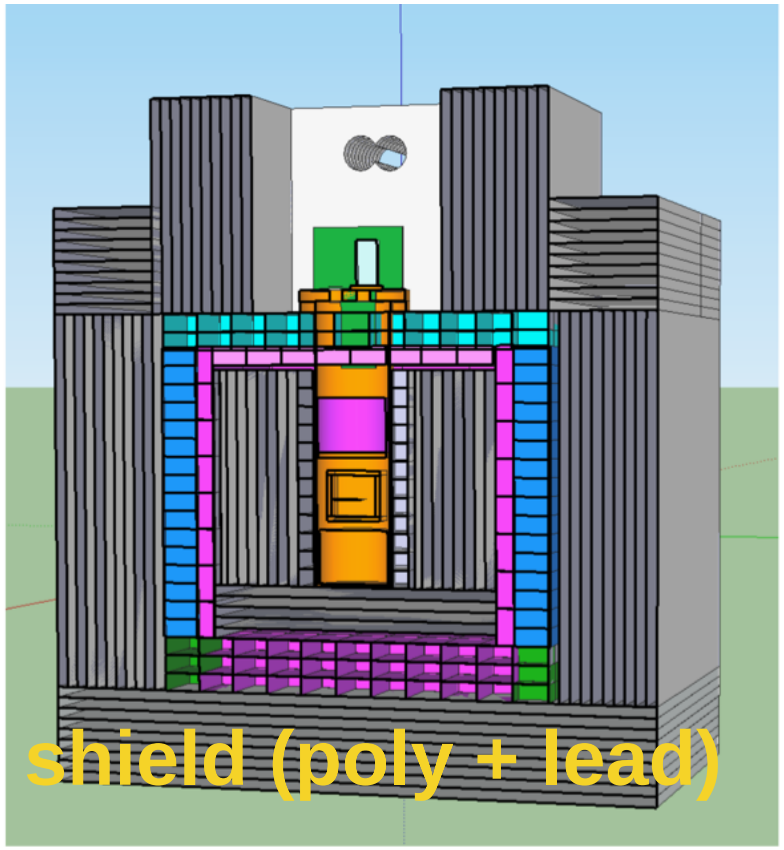
Phys.Rev. D 91, 072001 (2015)

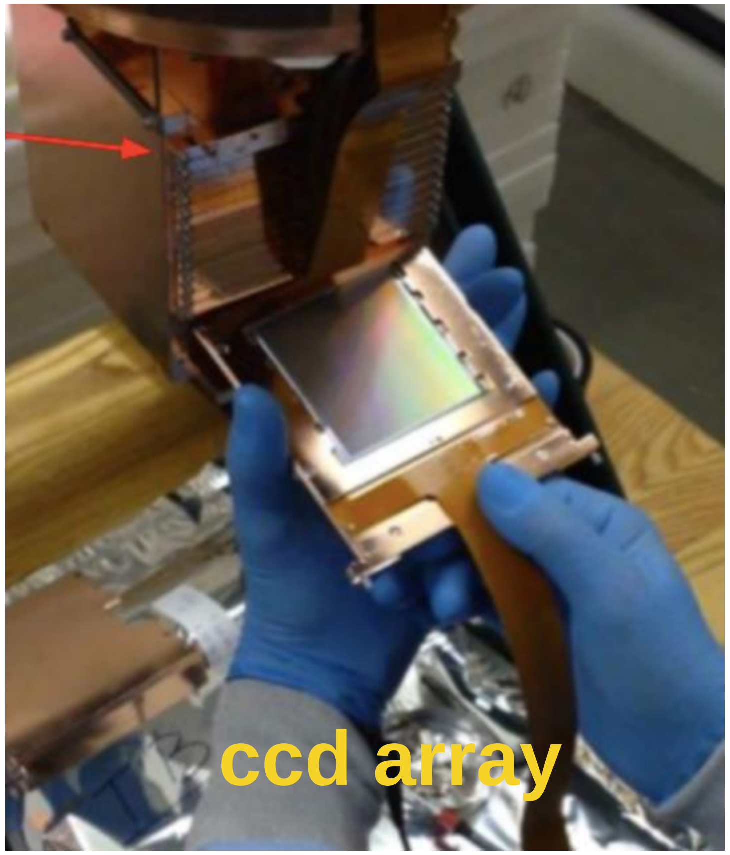
Total number of events vs threshold energy for different quenching factors

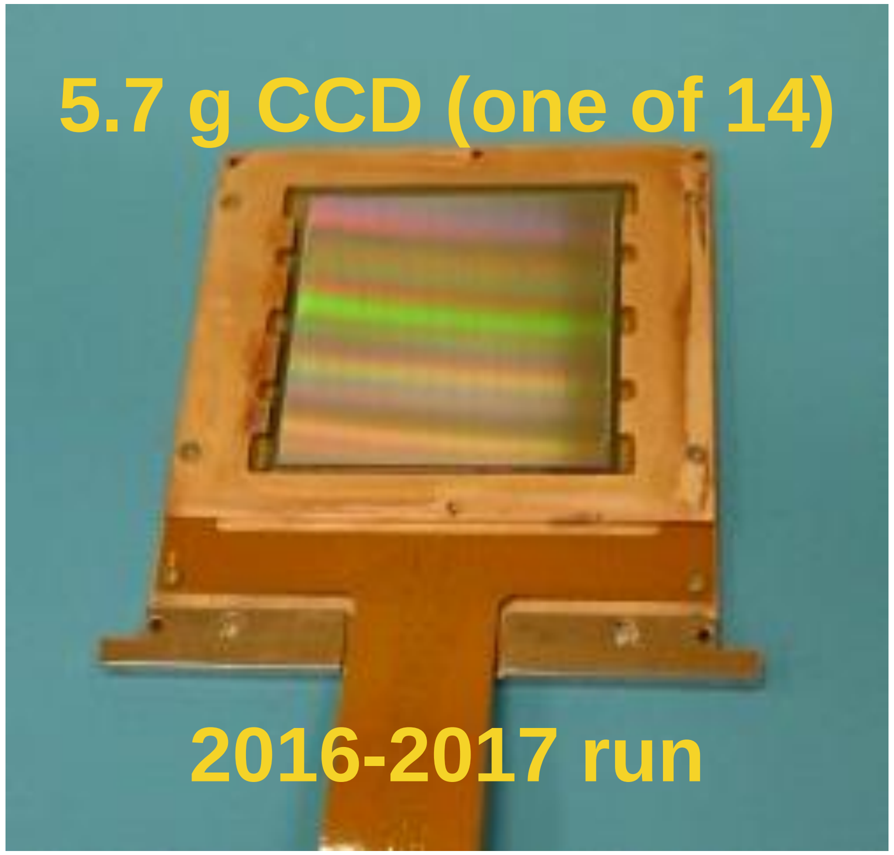


Total events vs max. detectable recoil for Q=1

	Q = 0.20
Expected number of events (event/kg/day)	
E_{th} = 5.5 eV ($1\sigma_{RMS}$)	~ 28.3
E_{th} = 28 eV ($5\sigma_{RMS}$)	~ 18.1

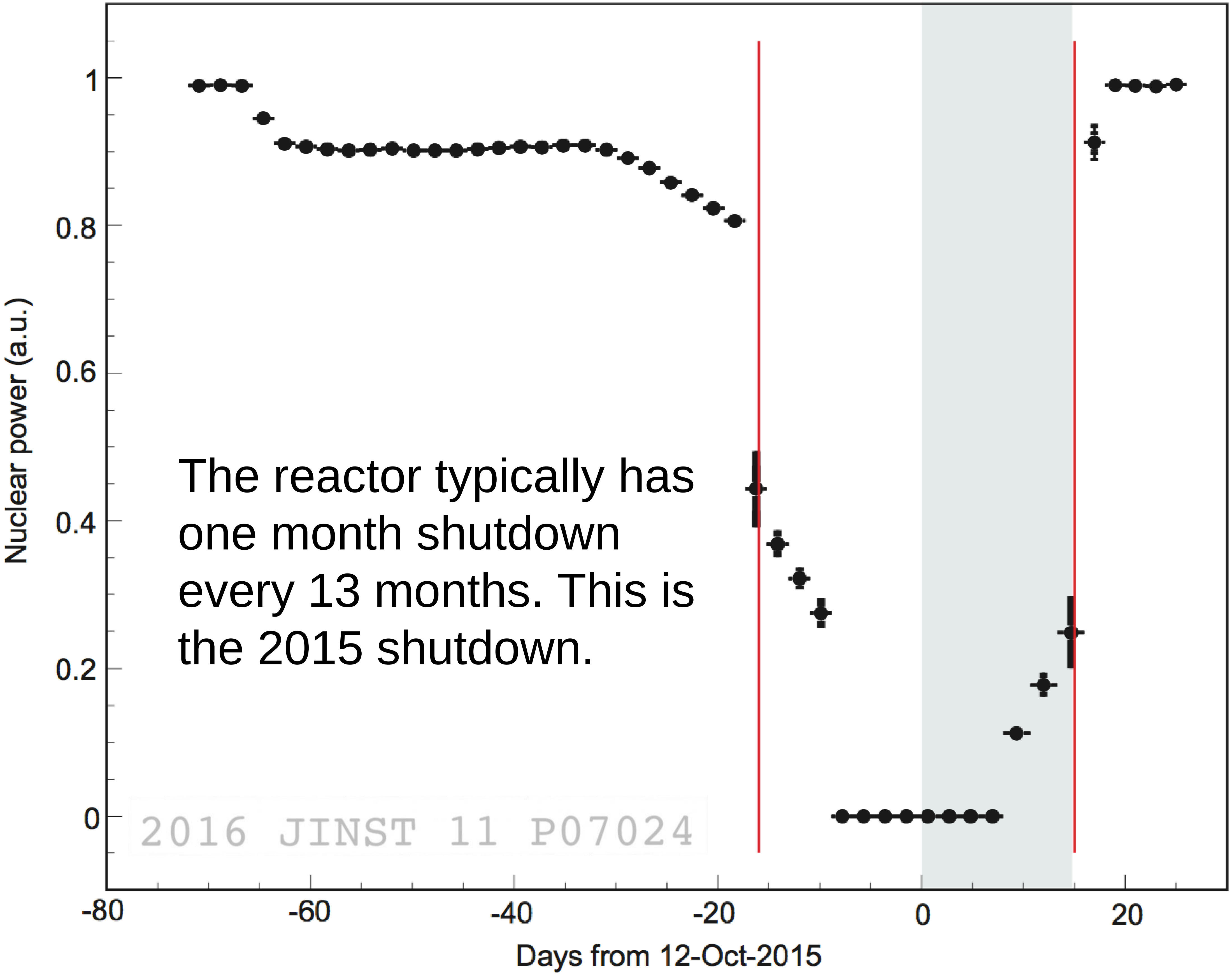






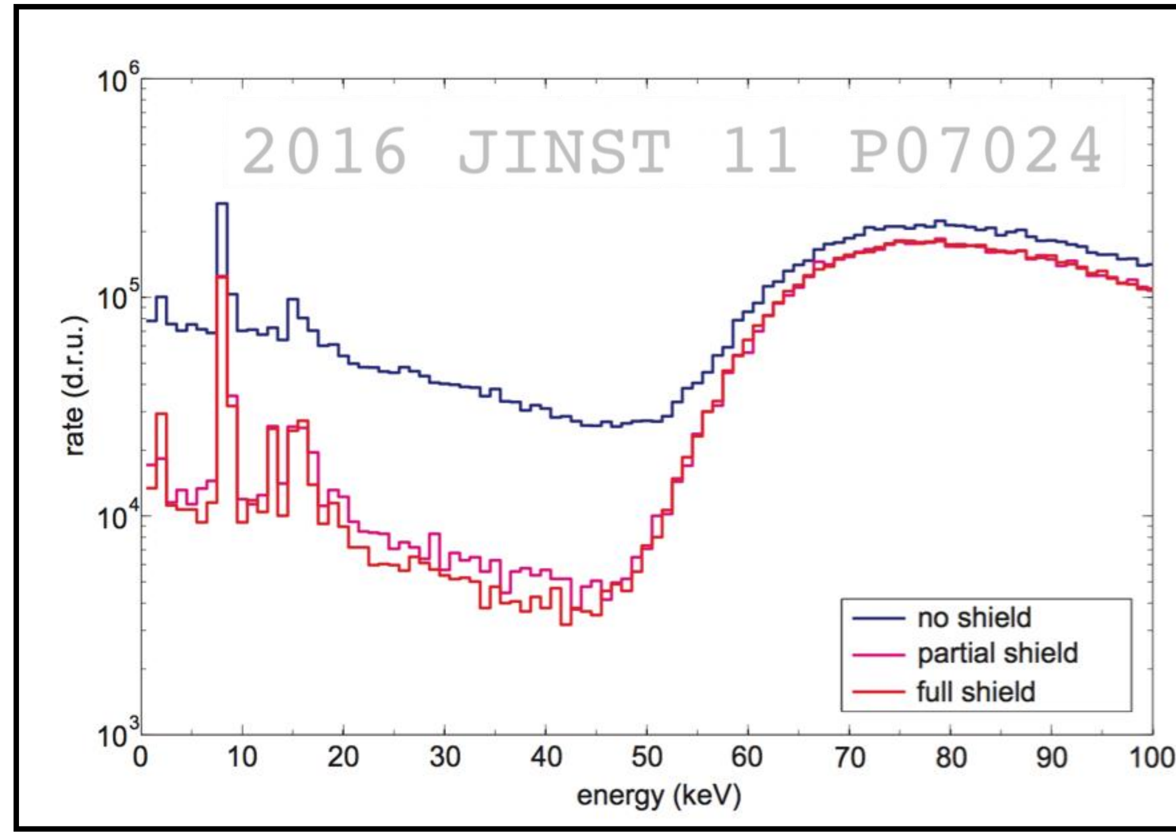
originally we developed this technology for DAMIC (dark matter search)

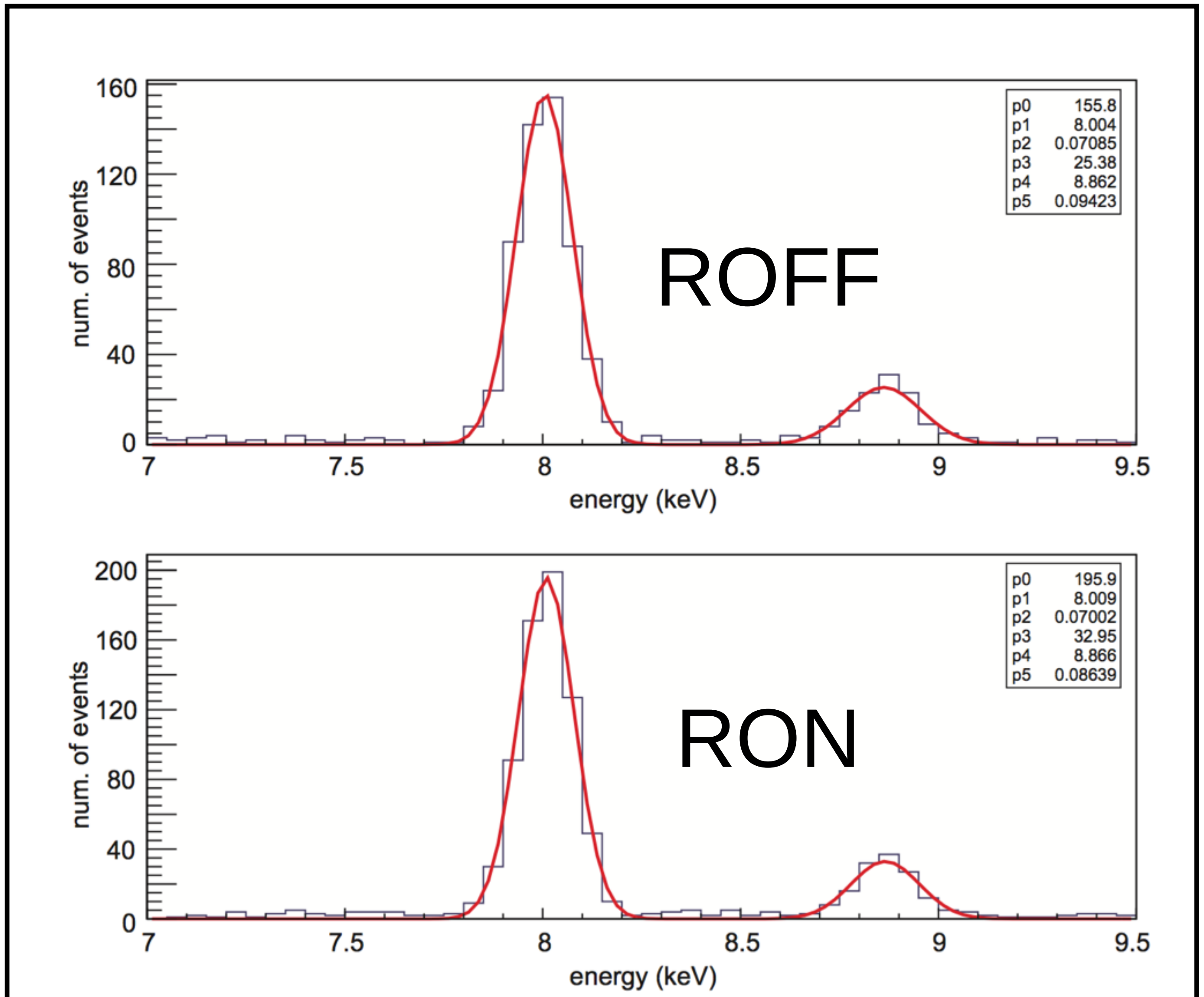
2015 Engineering Run

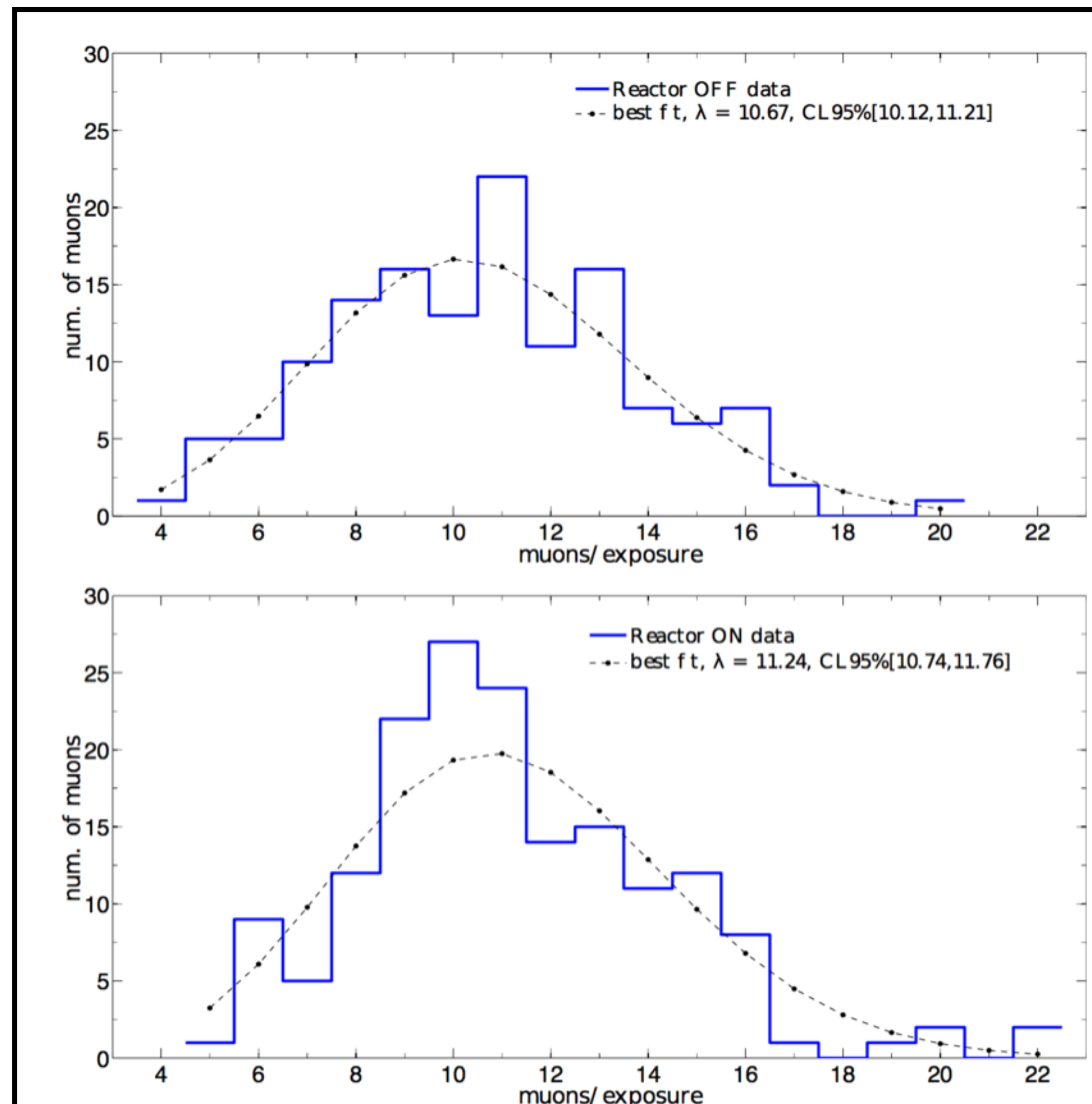


2015 engineering run FNAL-LDRD program (1g active mass, 1 CCD)

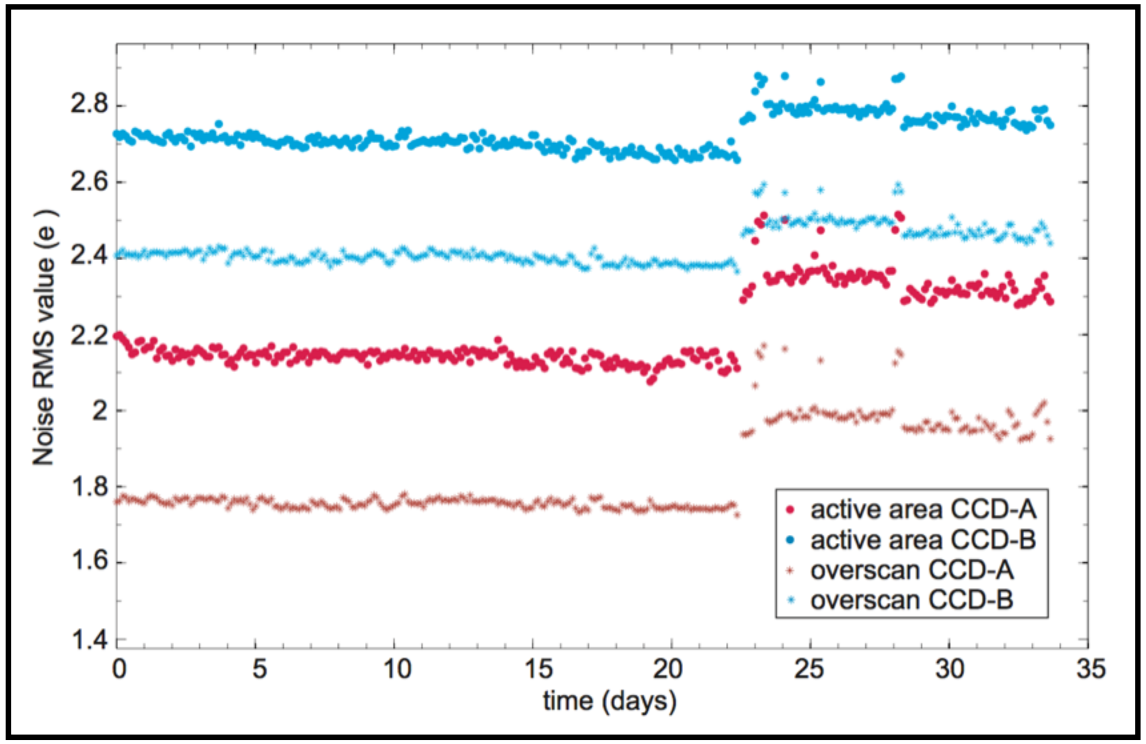
Reactor	counts (7.8-8.2 keV)	exposure (day)	rate (counts/day)
RON	693	18.0	38.5 ± 1.46
ROFF	557	14.8	37.6 ± 1.61







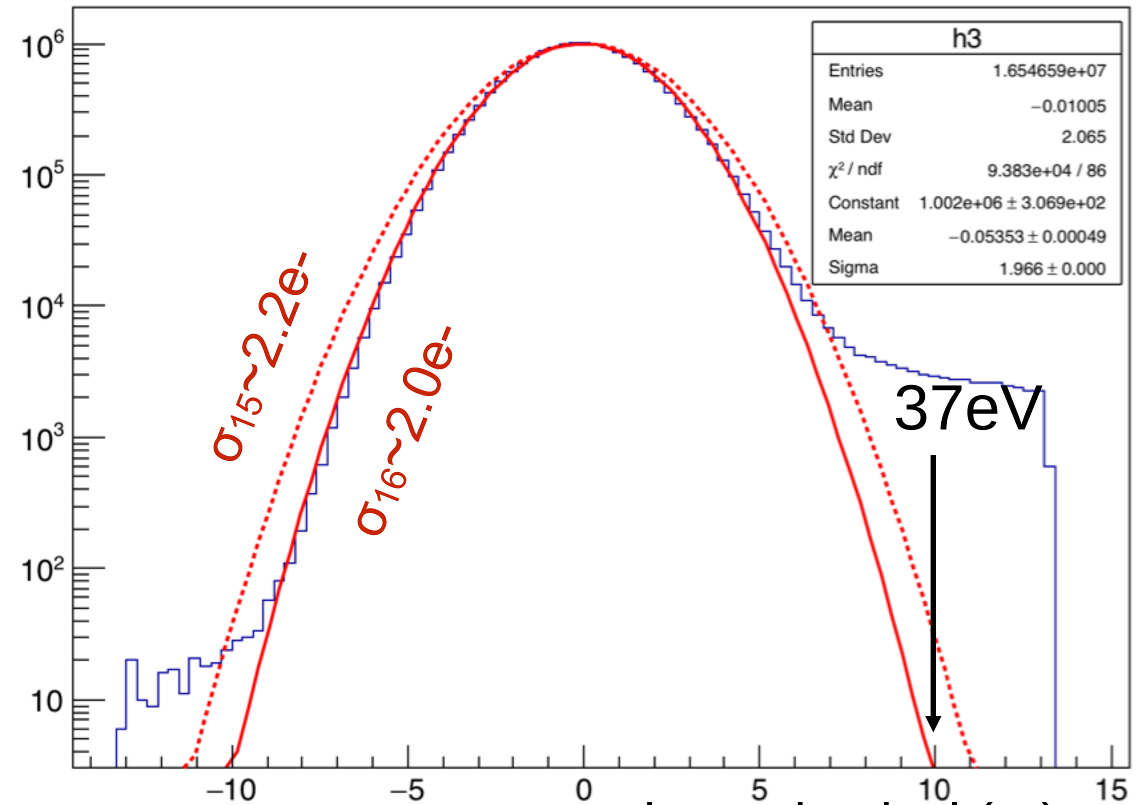
2015 engineering run

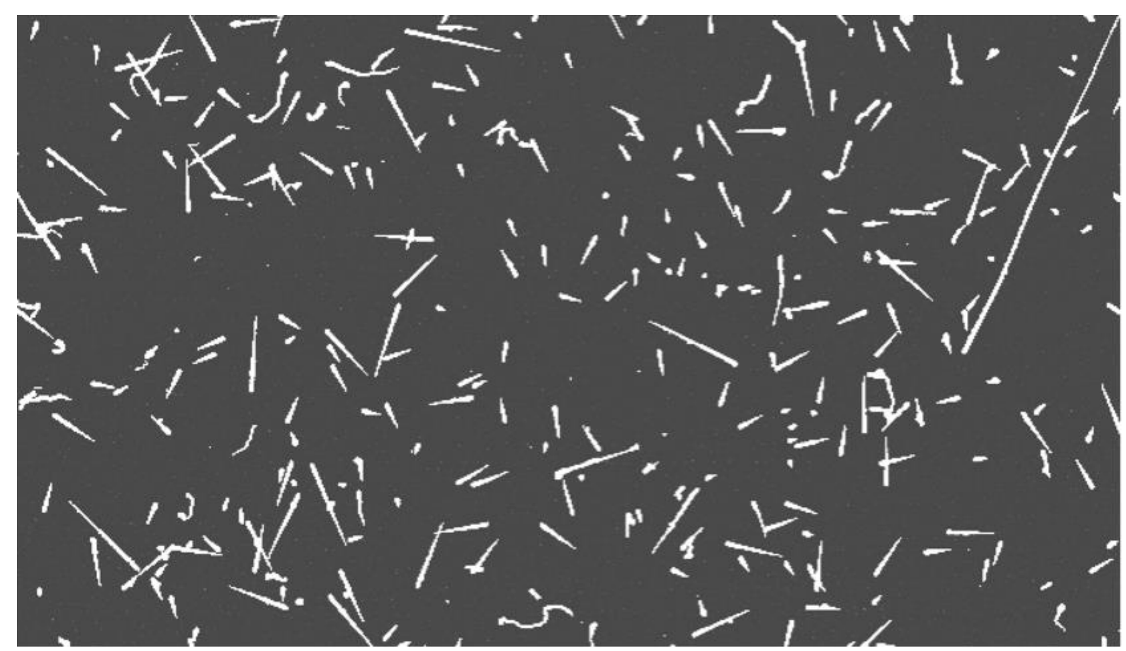


2015 we had a 2.2e- noise in the best CCD for the active area of the detector. This means that we had dark current, or IR photons hitting the detectors.

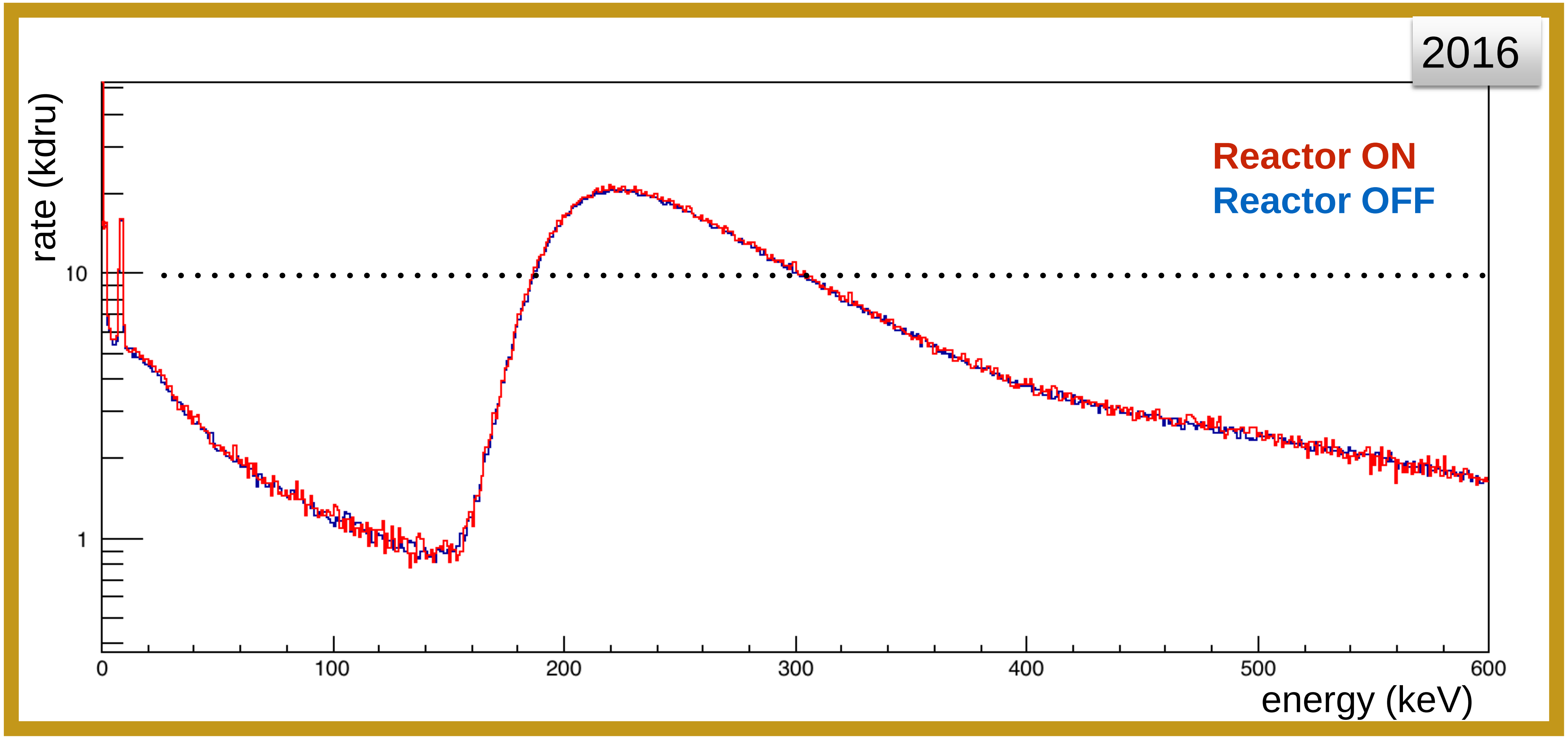
This 10% decrease in the noise is a big deal. It corresponds to ~10 increase in the rate of noise hits at ~35 eV.

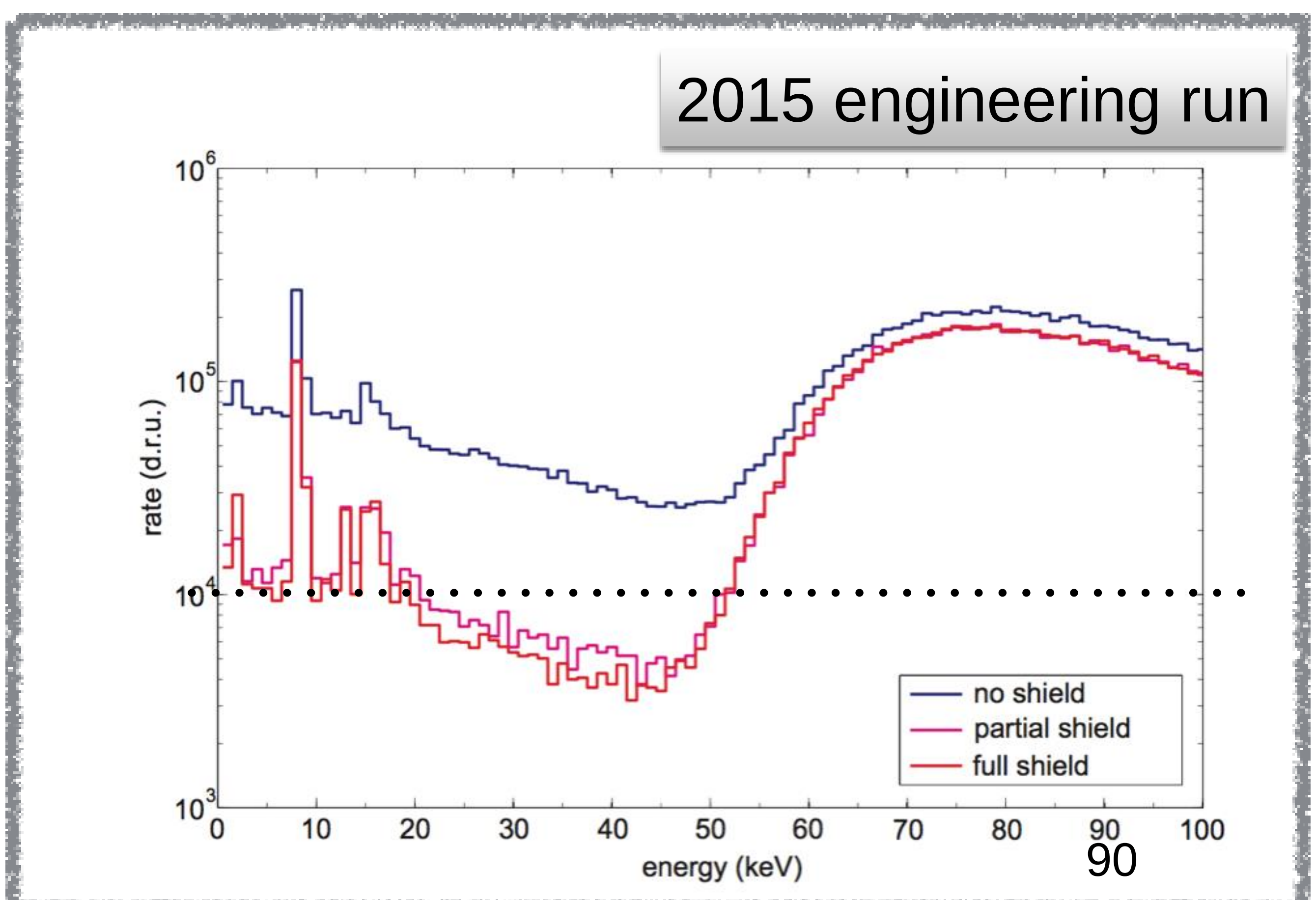
2016 image example





the histogram above also shows the hits from real tracks.





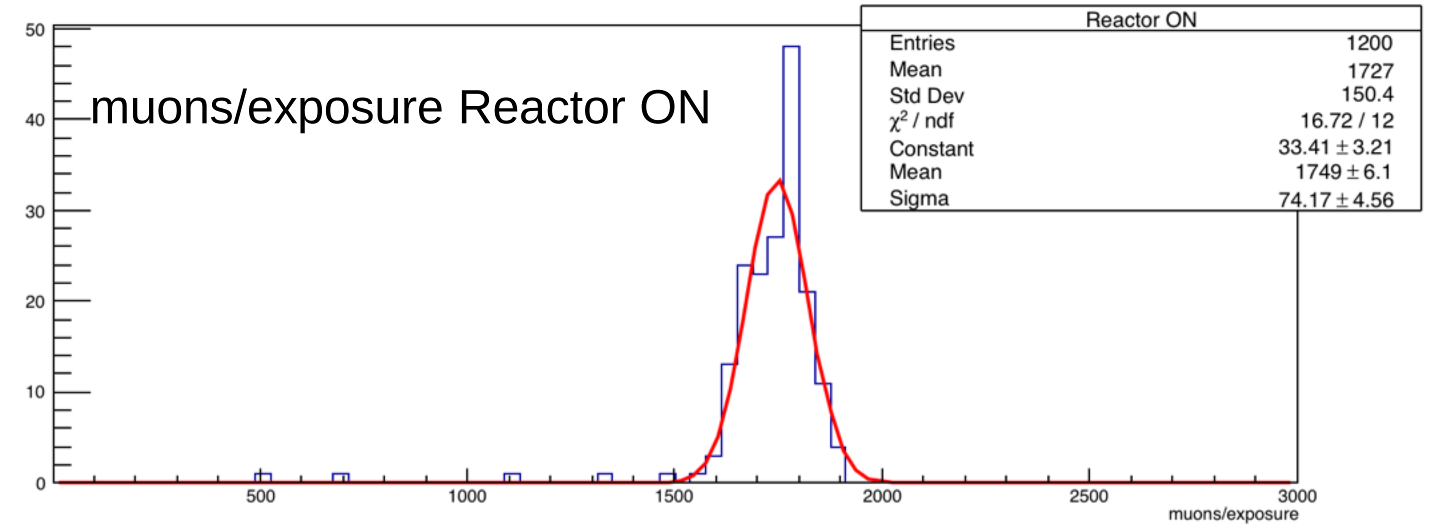
background improvement in the new configuration. We eliminated ceramic spacer (AlN) in the detector package. This eliminated all the ~15 keV lines produced by the U and Th decays. It also lowered the background significantly.

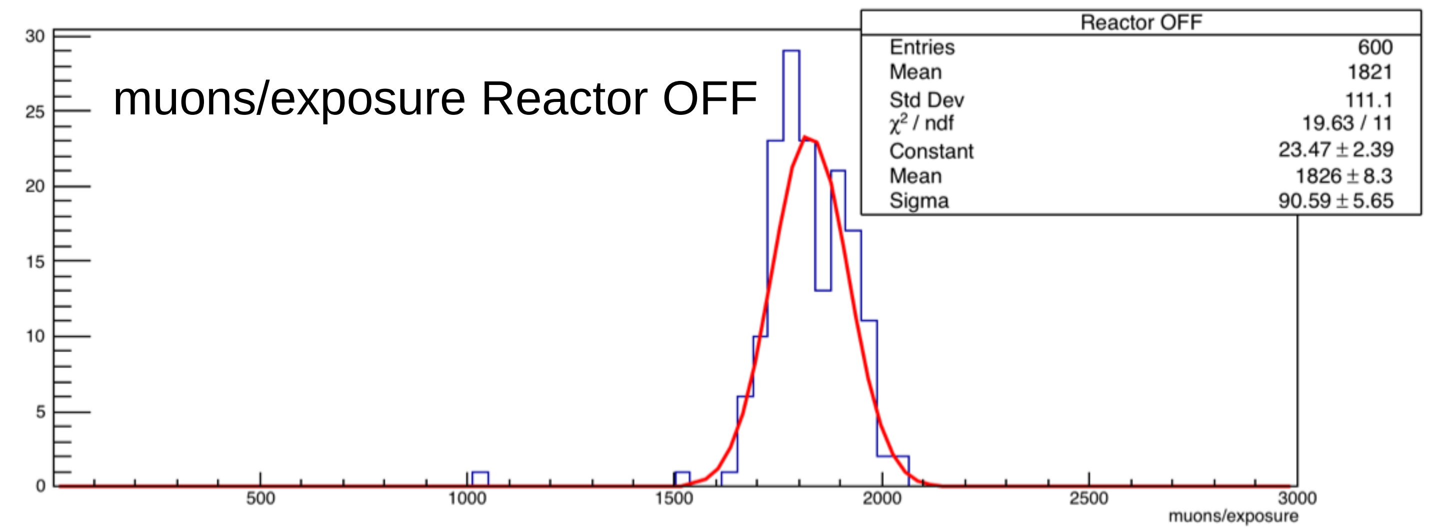
The bump from muon tracks is now at 250 keV because we went from 250um silicon to 675 um.

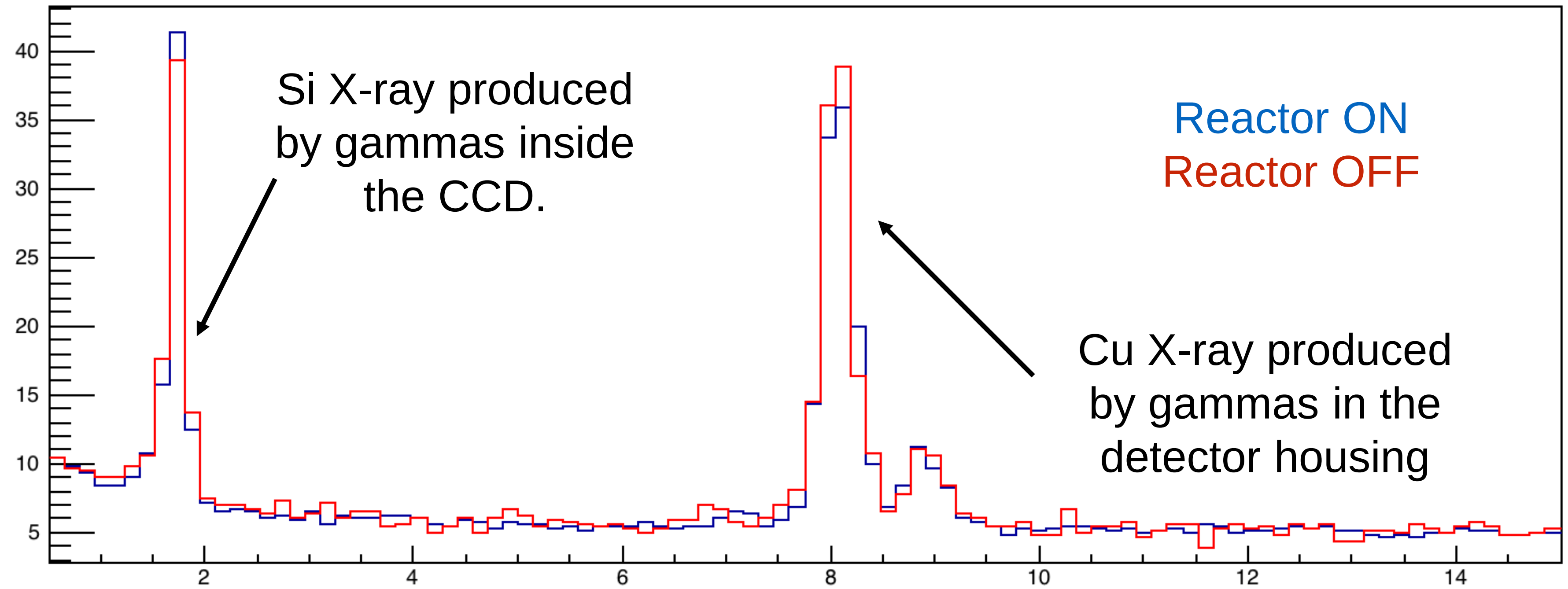
Comparing Reactor ON/OFF backgrounds.

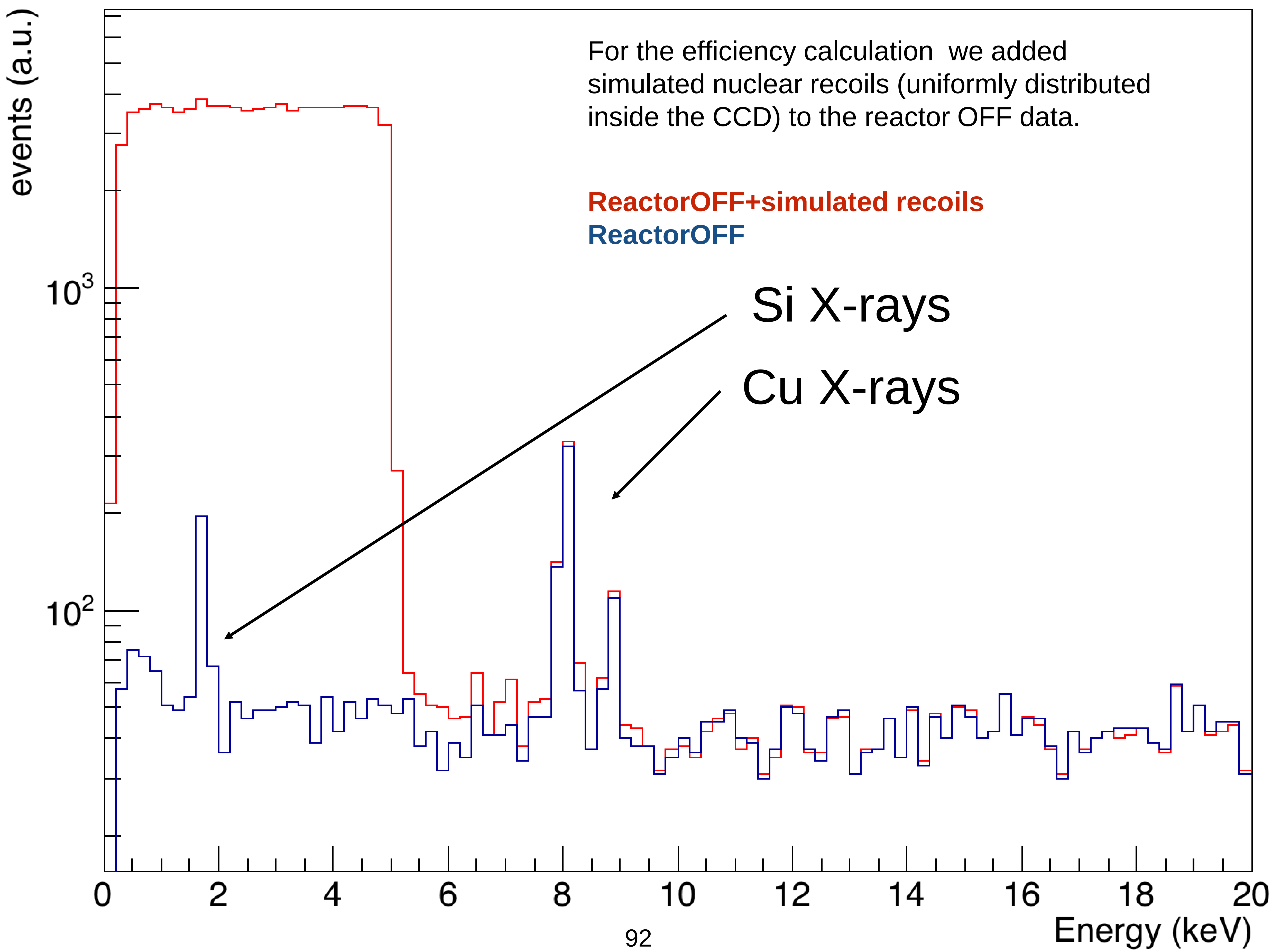
the muon flux is not the same, it is higher when the reactor is OFF. Makes sense due to weather.

fluorescence X-rays are the same reactor ON/OFF. This point to a stable gamma background.



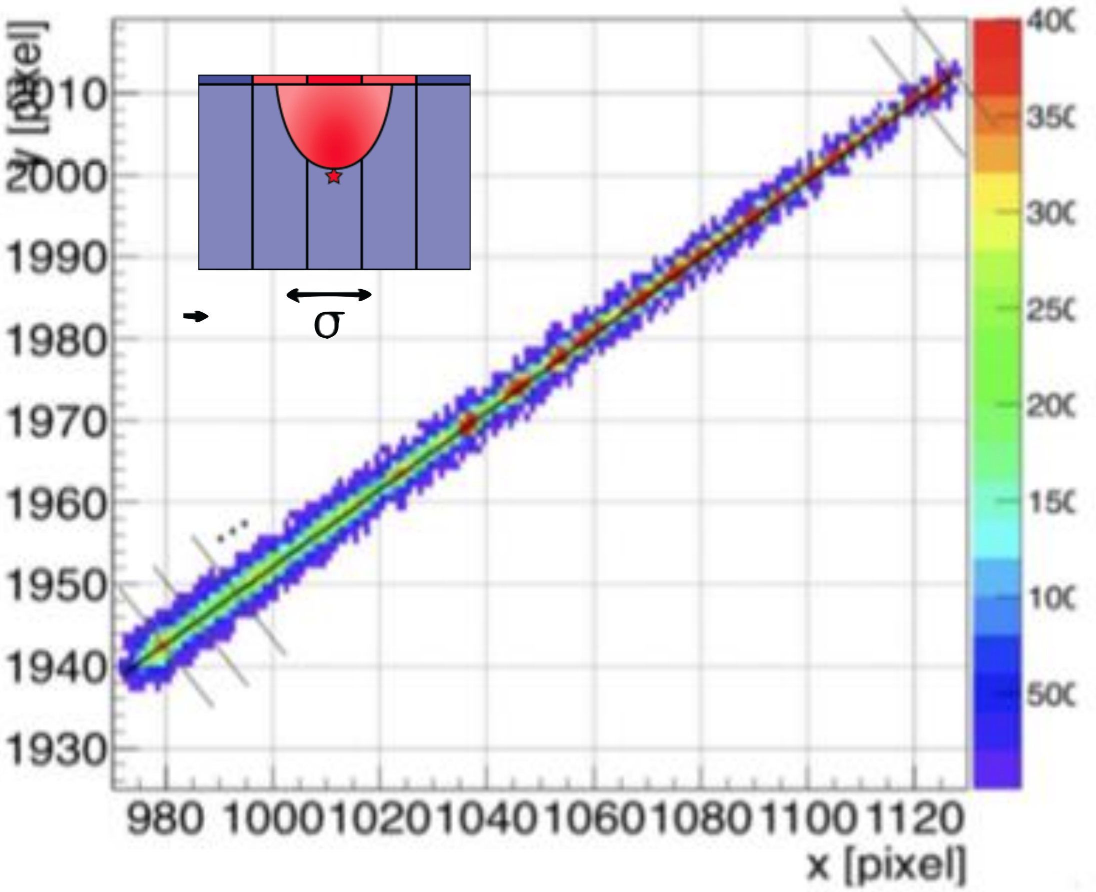


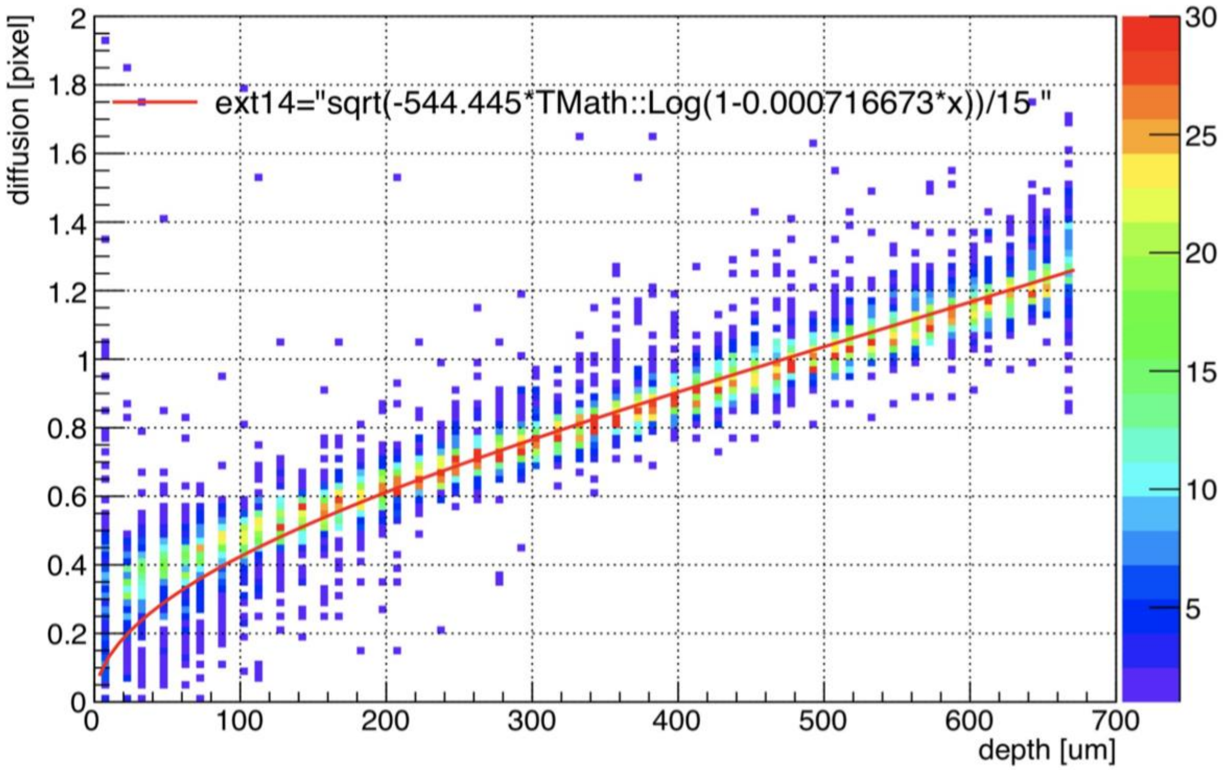




events (a.u.)
For the efficiency calculation we added simulated nuclear recoils (uniformly distributed inside the CCD) to the reactor OFF data.
ReactorOFF+simulated recoils
ReactorOFF
Si X-rays
Cu X-rays
10^3
10^2
0
2
4
6
8
10
12
14
16
18
20
Energy (keV)

now selecting the low energy events….

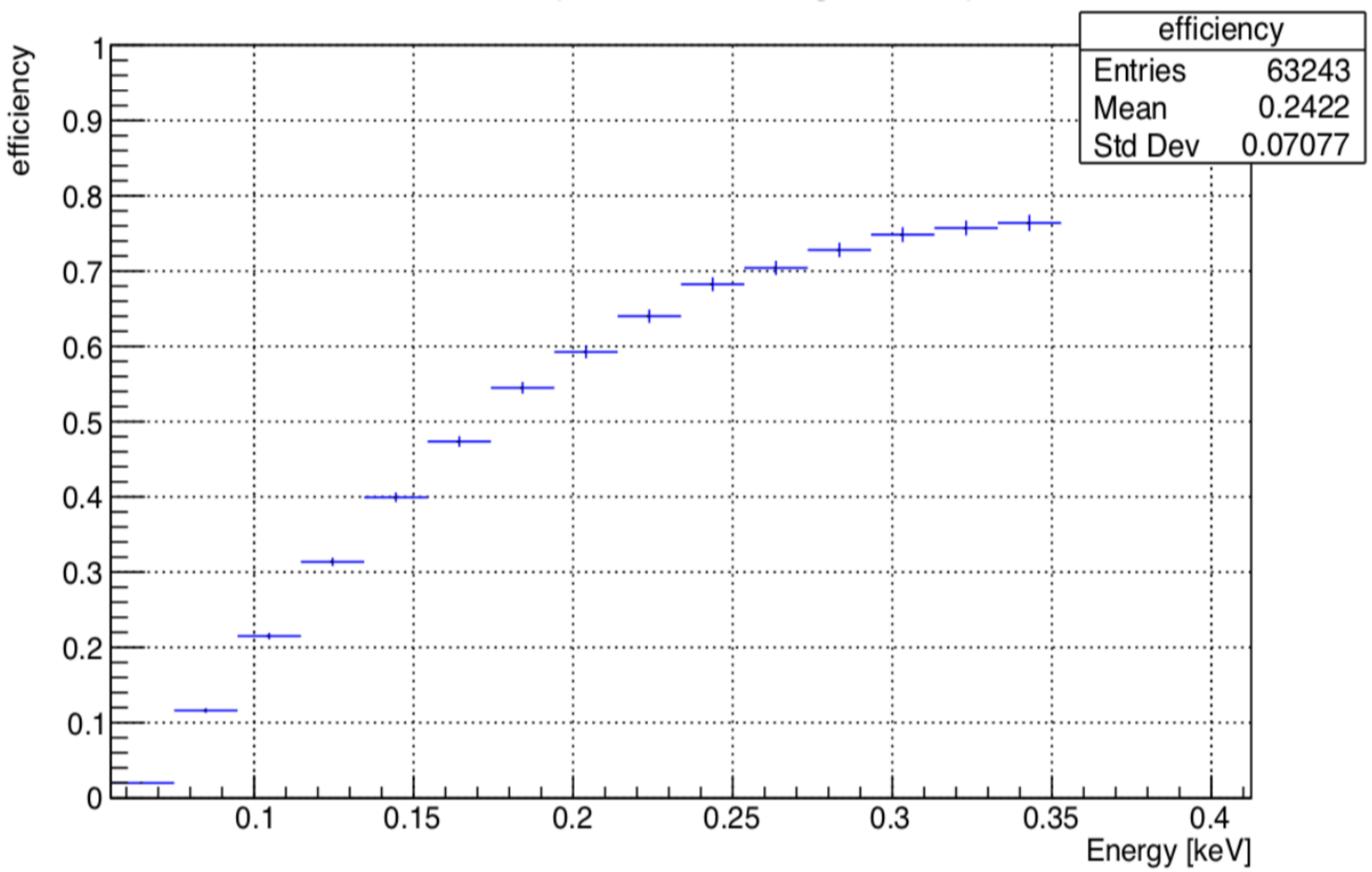




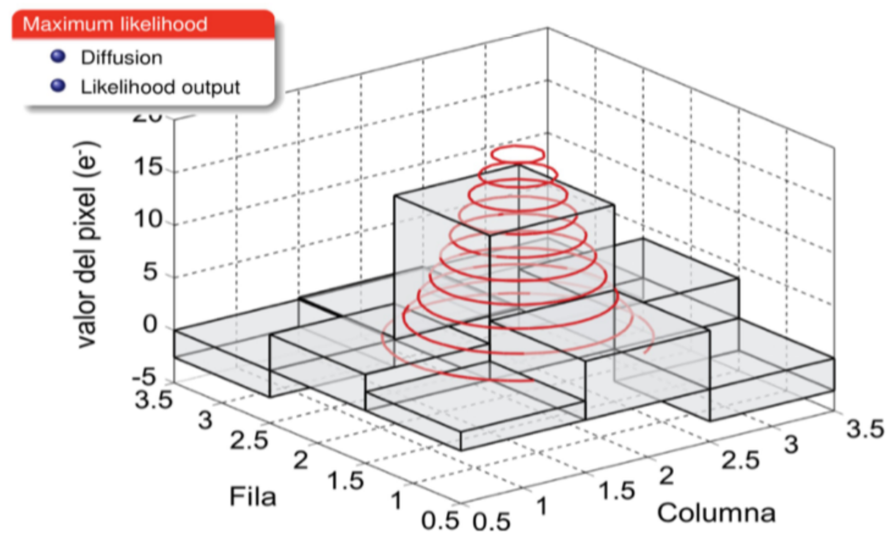
- For each muon measure make a measurement of charge diffusion in the CCD
- Using all the muons in a 10 day period make a model for the detector
- Use this model to eliminate surface events.

coming soon…

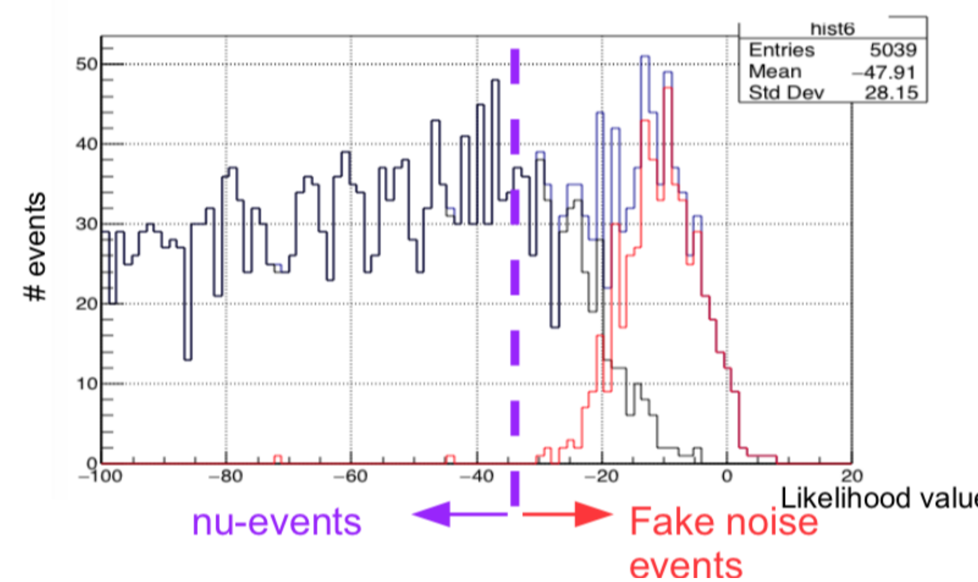
now selecting the low energy events…



- **Need to improve our low energy extraction**
- **Higher efficiency can be get using binning, with the drawback of loosing spatial information of the events.**

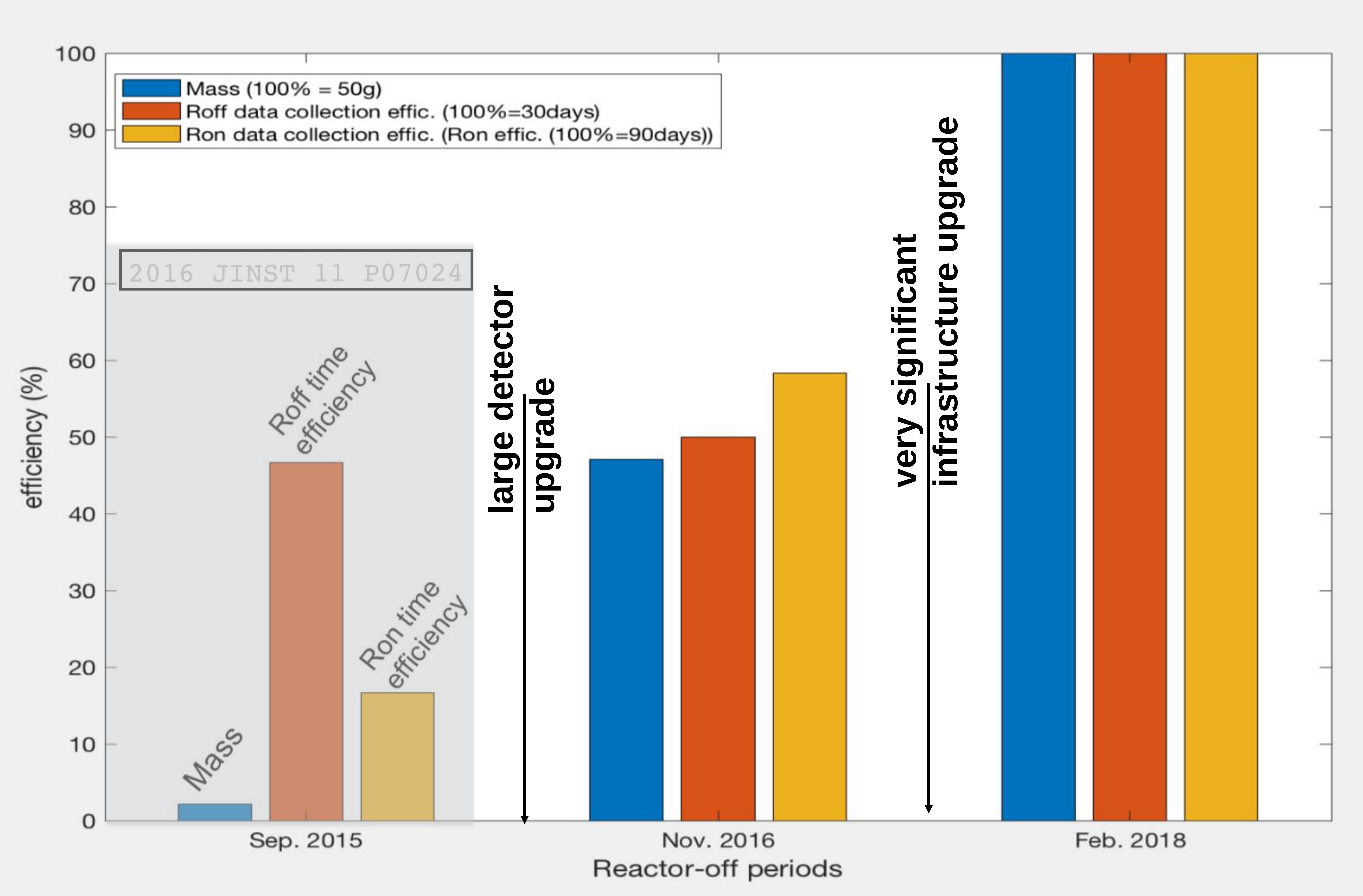


Simulation of nu events + noise

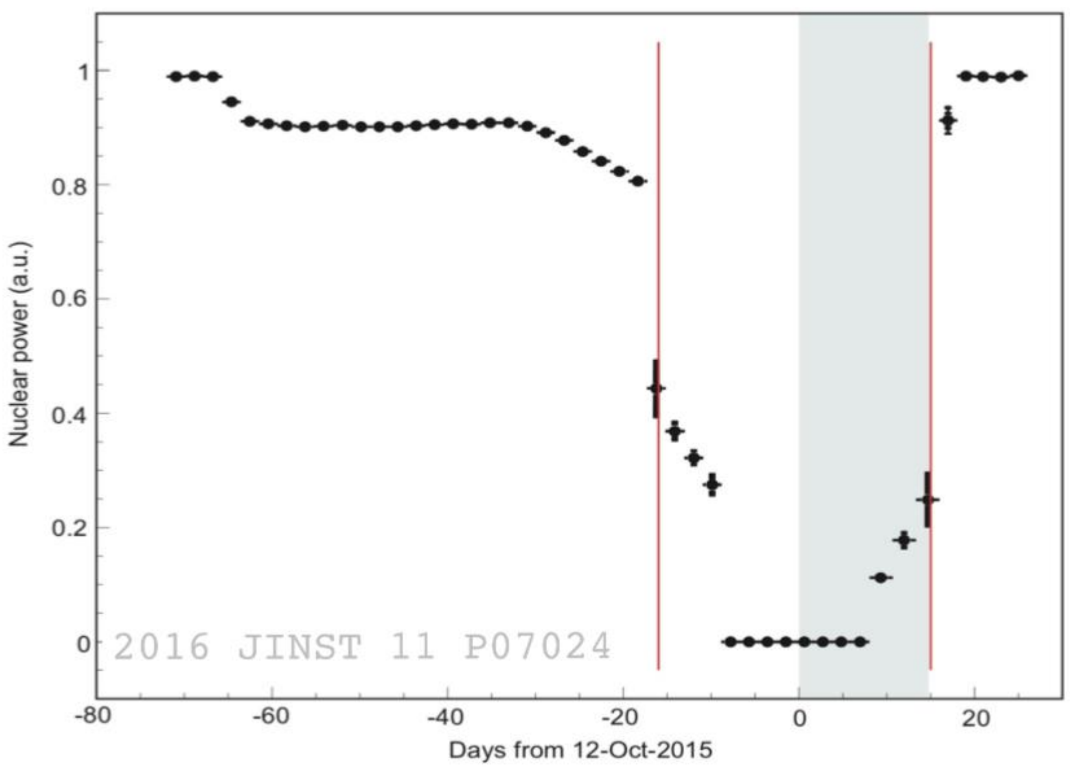


Likelihood measures the probability of the event being compatible with a noise fluctuation. Selection cut in this likelihood variable.

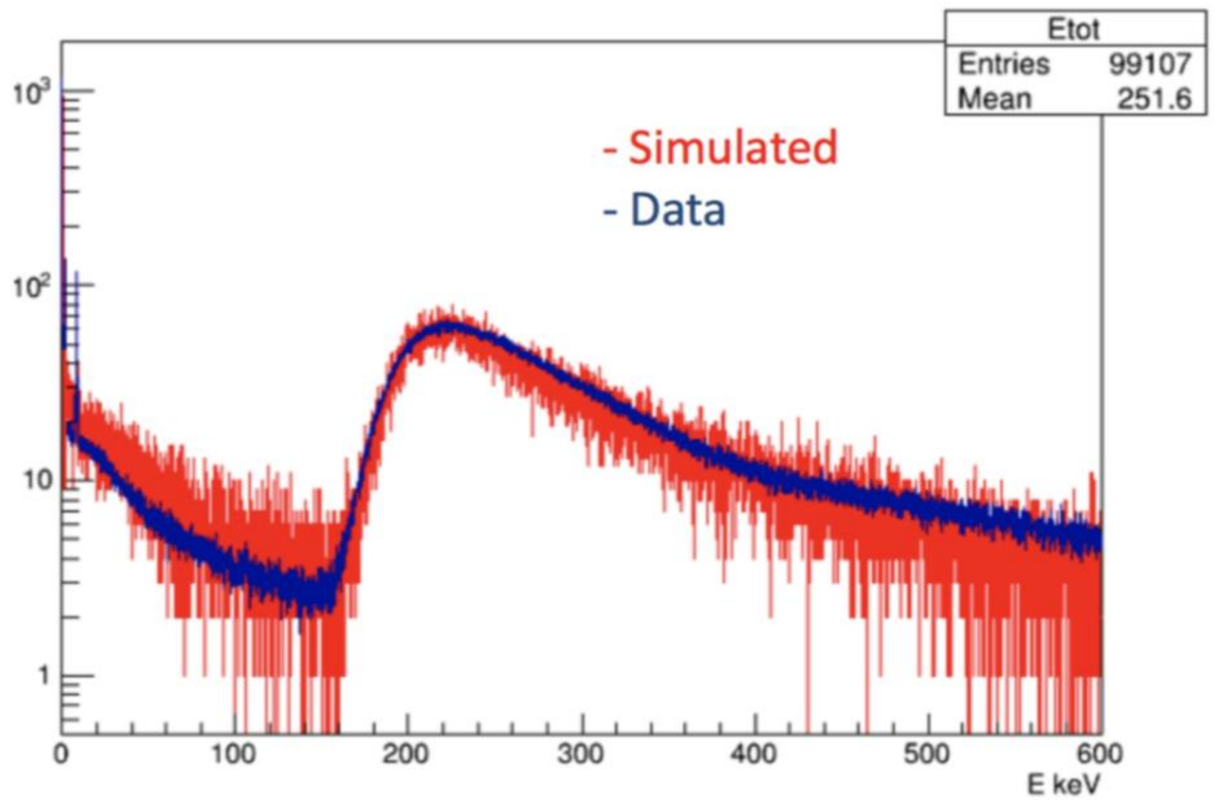
operation improvements in CONNIE : **statistics going up fast. By this time next year we will have 5 times the statistics.**



- Statistic limited by the reactor OFF data
- 30 days every ~year

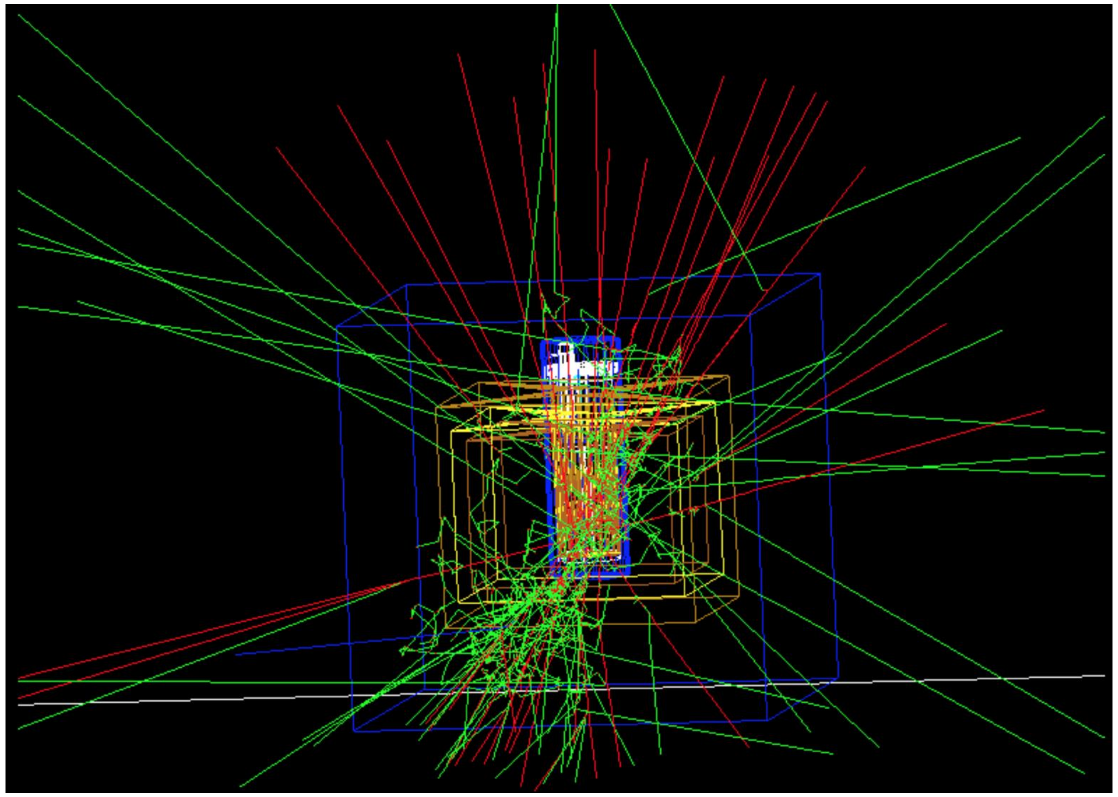


- ~10 times more statistics.
- Extra uncertainty associated with the background model



Until now we have been doing RON-ROFF analysis. This is limited by the ROFF statistics.

Now with full geant4 simulations doing modeling the background. **With a solid background model the statistic uncertainty drops by a factor of 10!!!**



- Counting electrons $\Rightarrow$ **noise has zero impact**
- It can take about 1h to read the sensors
- **Dark Current is the limiting factor**

It's better to readout continuously to minimize the impact of the DC

Dark Current $[e^{-} pix^{-1} day^{-1}]$	$\geq 1e^{-}$ [pix]	$\geq 2e^{-}$ [pix]	$\geq 3e^{-}$ [pix]
10^{-3}	1×10^{8}	3×10^{3}	7×10^{-2}
10^{-5}	1×10^{6}	3×10^{-1}	7×10^{-8}
10^{-7}	1×10^{4}	3×10^{-5}	7×10^{-14}

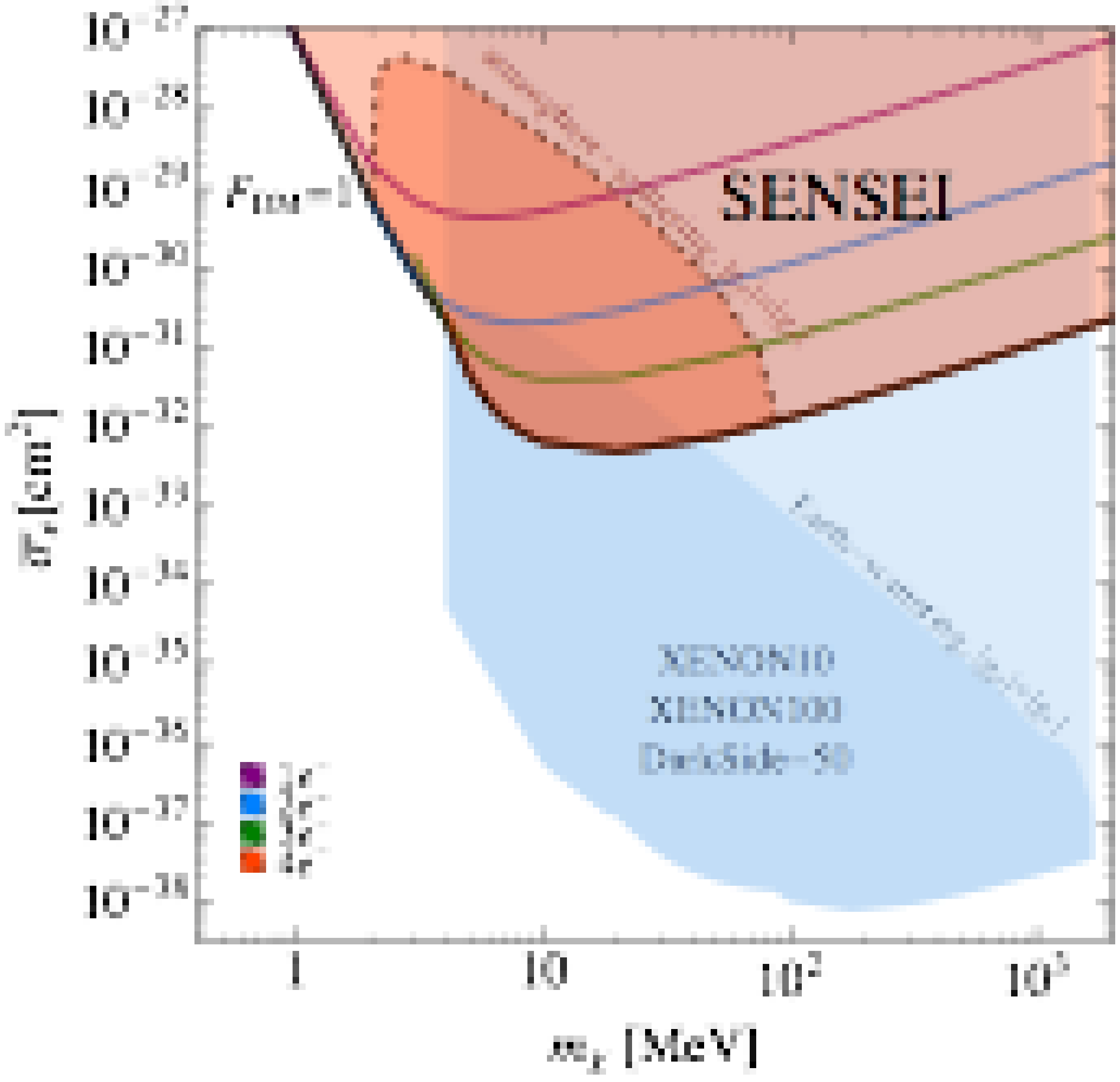
Measured upper limit for the DC in CCDs is:

$$1 \times 10^{-3} \ e \ pix^{-1} day^{-1}$$ arXiv:1611.03066

Could be orders of magnitude lower. **Theoretical prediction is $O(10^{-7})$**

SENSEI commissioning run at surface: arXiv:1804.00088

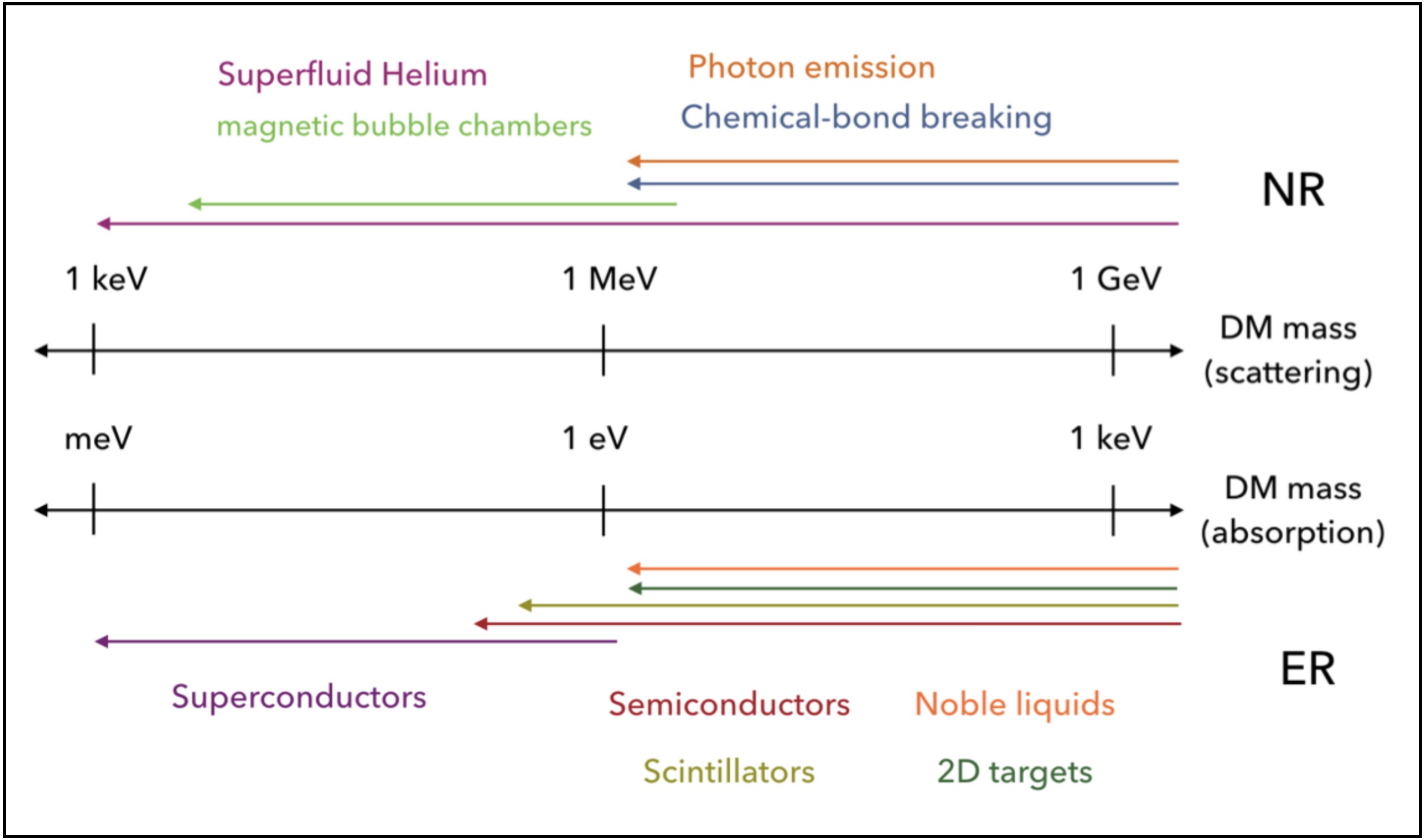
First direct-detection constraints between ~500 keV to 4 MeV!



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

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

arXiv:1707.04591



lots of ideas to scan the low mass parameter space

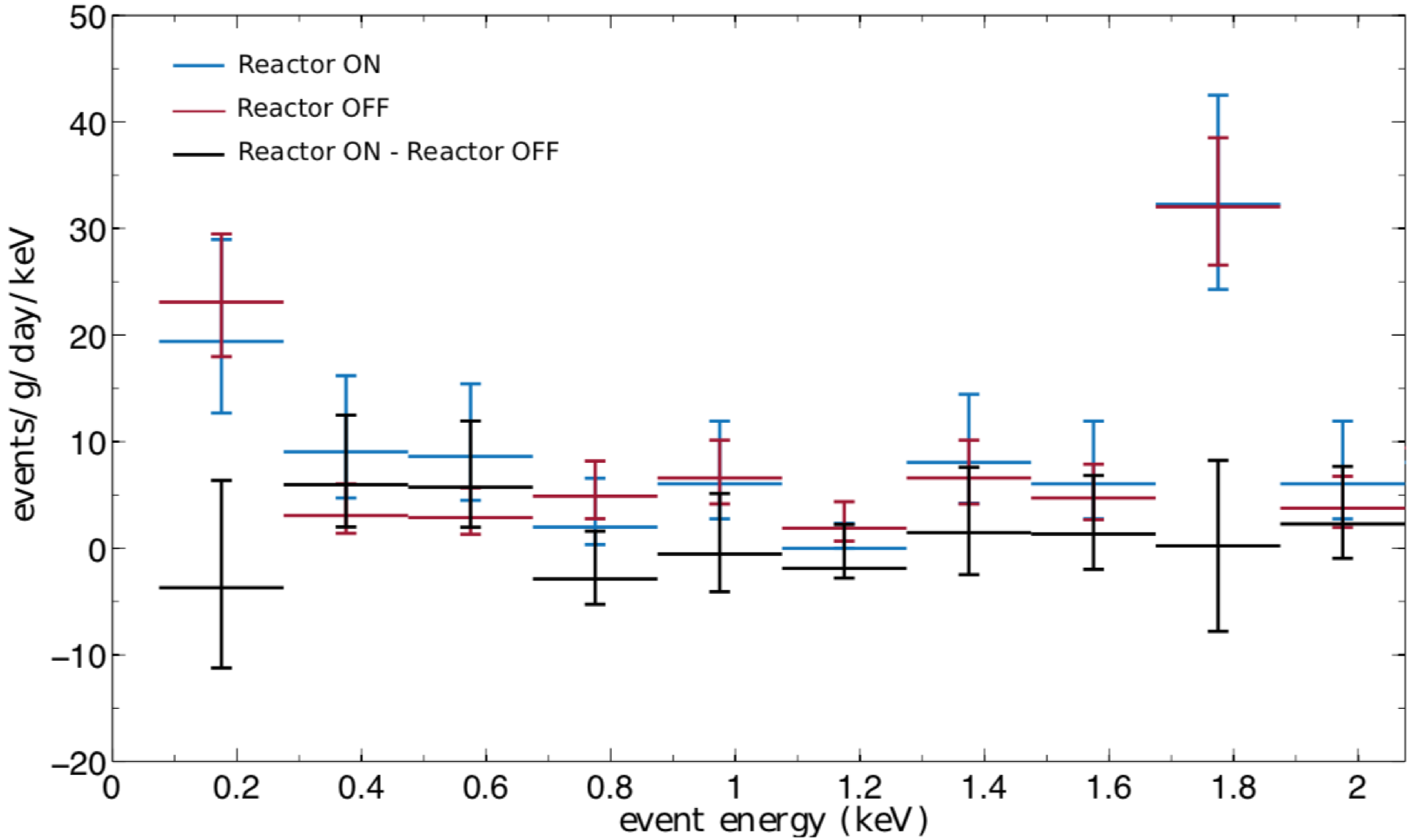


Figure 16: Energy spectrum measured with Reactor on, Reactor off and their difference. Events are selected as discussed in the text, and the rate is corrected for the efficiency of the selection criteria. The error bars correspond to 68.27% probability assuming a Poisson distribution for each energy bin. The higher rate of events at 1.8 keV is produced by the silicon fluorescence X-ray.

Scientific
Charge-Coupled Devices

James R. Janesick
Editor

2000 CCD textbook

skipper-CCD is not a new invention, but their performance has not been pushed to the limit until now

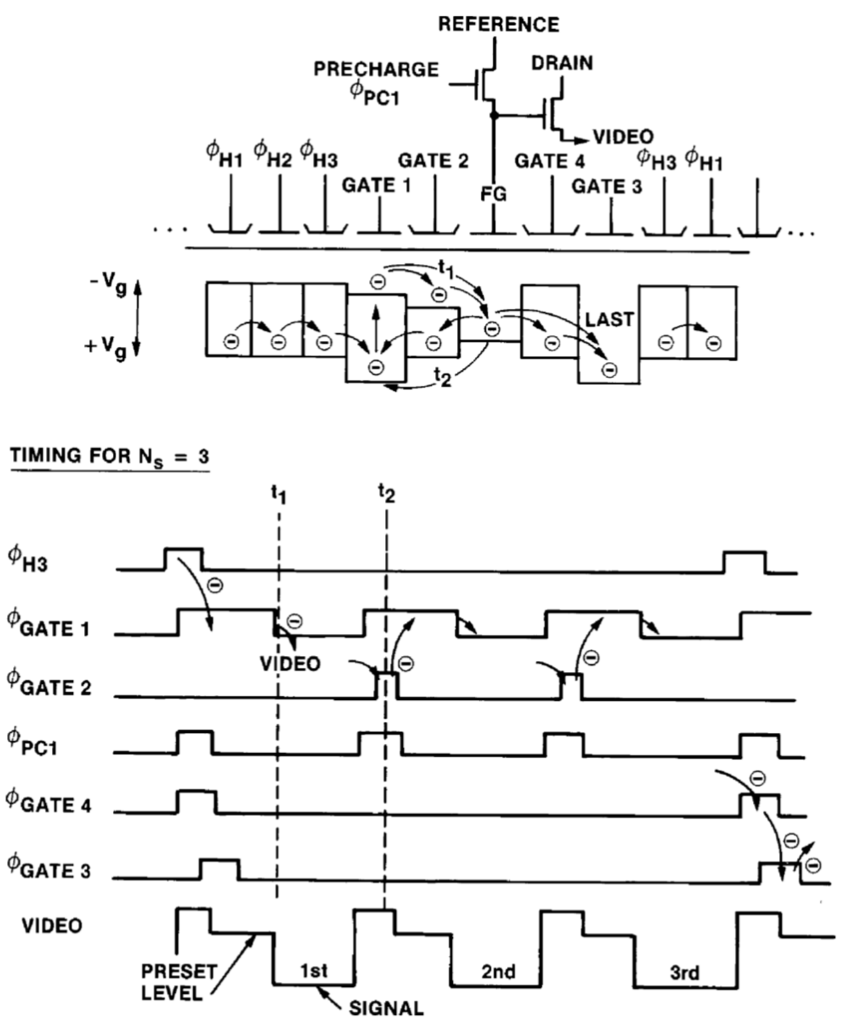


Figure 6.55 Timing diagram for Skipper operation.

- •Used these papers as the basis of our first FG amplifier
- •Chandler et al, 1990 SPIE
- •Janesick et al, 1990 SPIE

- •First reports of FG amplifiers (Fairchild R&D Laboratory)

—Wen and Salisbury, ISSCC, 154, 1973

—Wen, IEEE JSSC, 410,1974

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

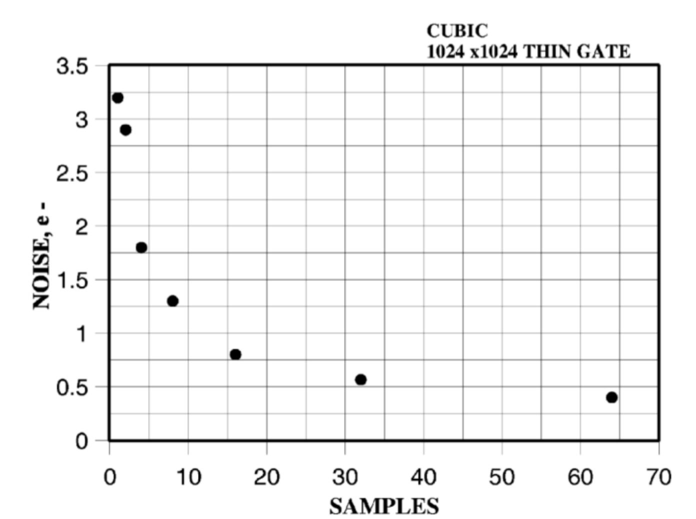
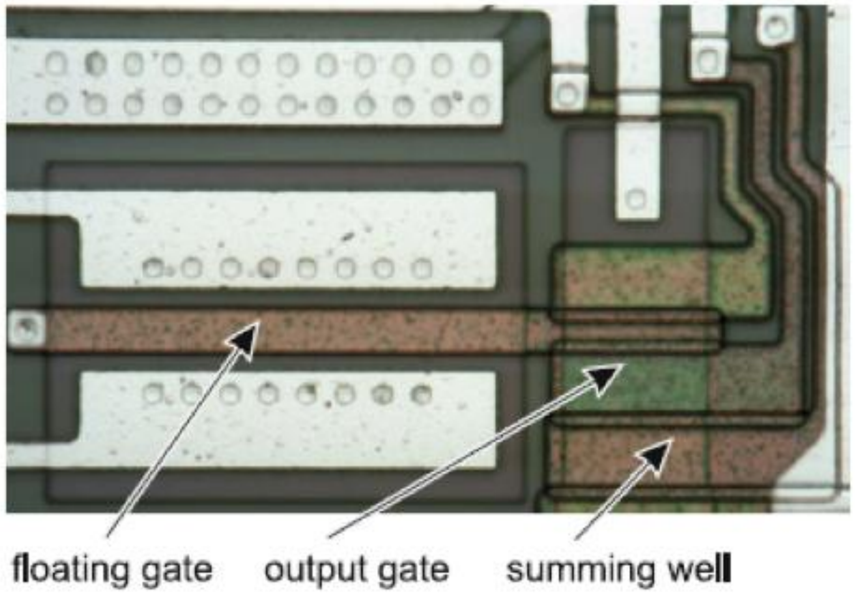


Figure 6.59 Read noise as a function of number of samples for a 1024 × 1024 Skipper CCD.

R&D development @ FNAL/LBNL (G.Fernandez-Moroni)

Fig. 4 L2 amplifier layout. The floating gate, the output gate and the summing well gate are shown



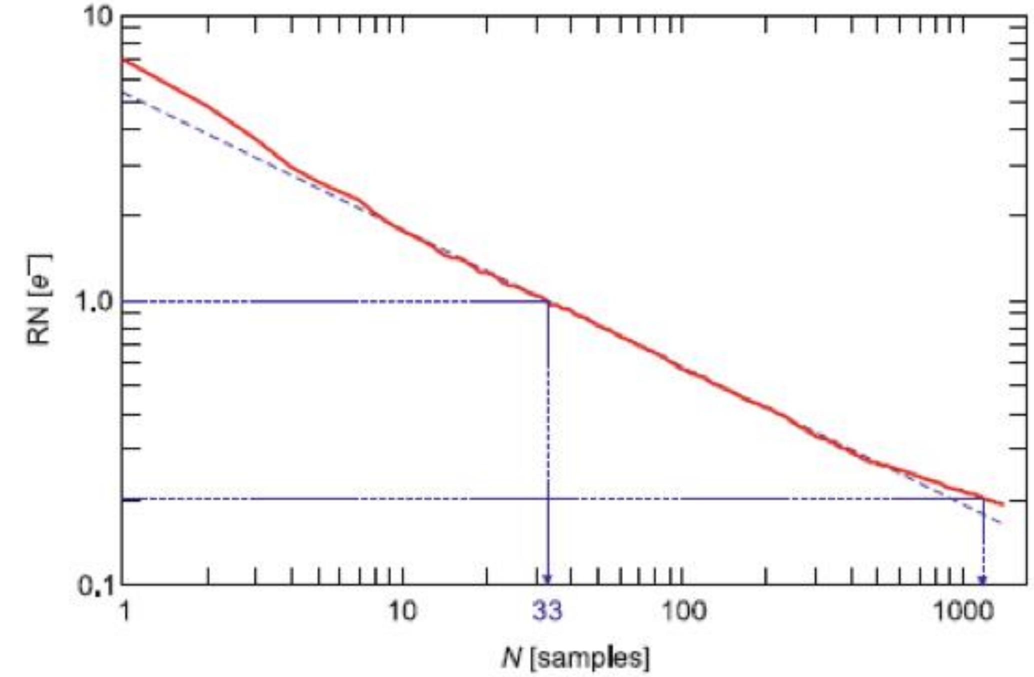


Fig. 10 Skipper CCD RN in the overscan region as a function of the number of averaged samples *N*. *Continuous line* RN measured from images. *Dashed line* theoretical RN reduction fit for white or $1/f^2$ noise

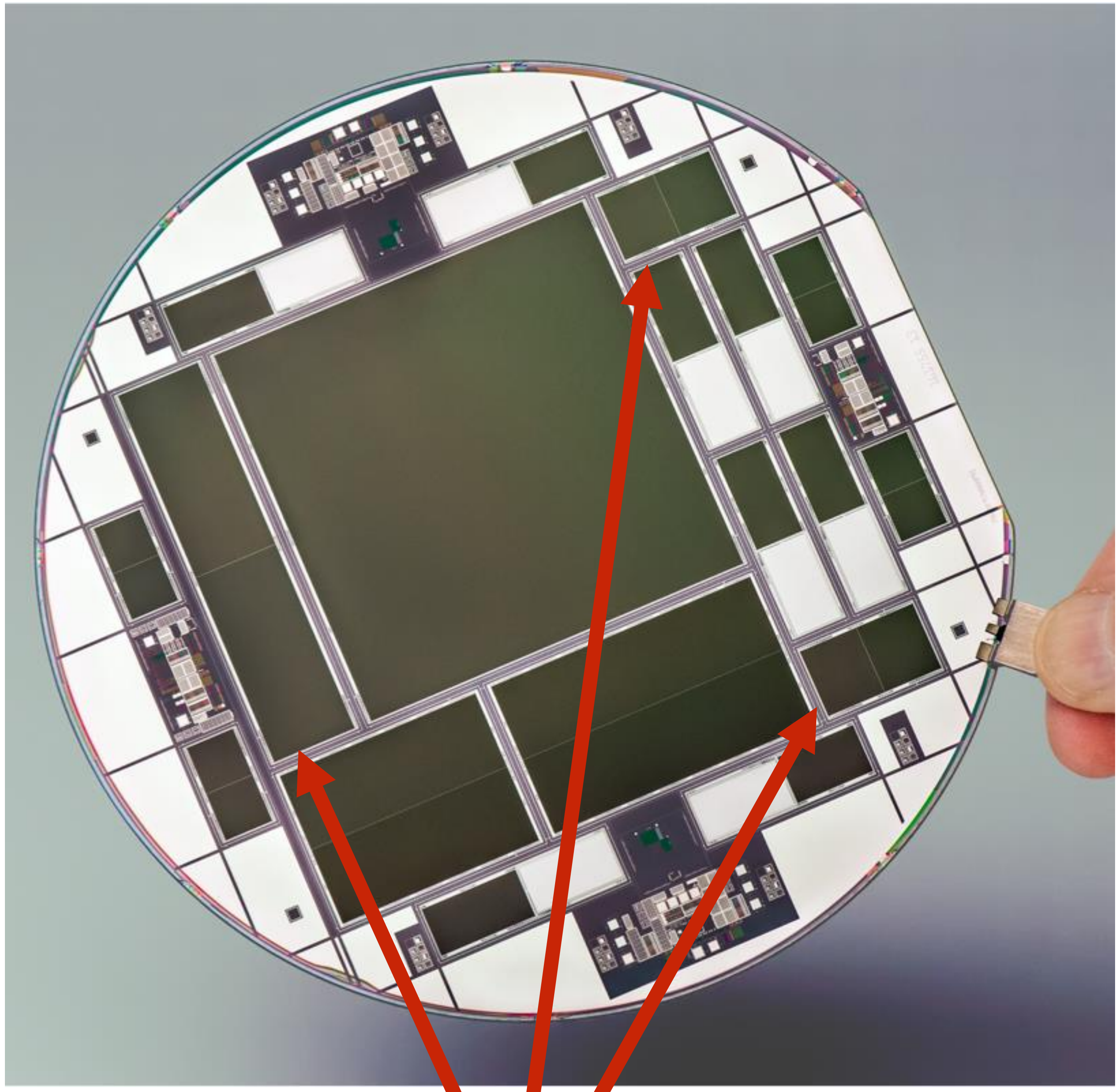
Exp Astron (2012) 34:43–64
DOI 10.1007/s10686-012-9298-x

ORIGINAL ARTICLE

Sub-electron readout noise in a Skipper CCD fabricated on high resistivity silicon

Guillermo Fernández Moroni · Juan Estrada · Gustavo Cancelo · Stephen E. Holland · Eduardo E. Paolini · H. Thomas Diehl

R&D development @ FNAL/LBNL (S.Holland)



floating gate
skipper-CCDs