Quantum Sensors for HEP and HEP technology for Quantum Science.

Juan Estrada
February 2019
Vienna
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 \(\sim 100\) GeV.

\[
\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}
\]

\[
< \sigma v >_{ann} \approx 3 \times 10^{-26} \text{cm}^3\text{sec}^{-1}
\]

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
beyond wimps
for low mass (axions)

\[ \Delta x = \frac{1}{\Delta p} = \frac{1}{m_a} \Delta v \approx 100 \text{ m} \]

\[ v \approx \Delta v \approx 300 \text{ km/s} \]

(stadium-sized regions of coherently oscillating classical waves slowly drifting through detectors.)
Haloscope technique (Sikivie -1983) axion wave drives RF cavity mode coupling that allows detection

oscillation axion in magnetic field produces a current

\[ \mathbf{J}_a(t) = -g \theta \mathbf{B}_0 m_a e^{im_\alpha t} \]

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

\[ \mathbf{E} \times \mathbf{H} = \frac{d}{dt} \mathbf{D} = \mathbf{J}_a \]

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

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.
Dig out the signal buried beneath the noise

Each tuning \( \sim 100 \text{ s.} \)
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.**

\[
SNR = \frac{P_{\text{signal}}}{\sqrt{2kT \Delta f}} \sqrt{2\Delta f t}
\]

Require \( 10^6 \) averages
it is hard now, but it will get a lot worse as get move towards higher mass

$dN/dt [s^{-1}]$

DFSZ Signal, $\mathcal{T}_I, 1\lambda^3$

$\frac{dN_{SQL}}{dt} = 2 \times \Delta f = 2 \times \frac{m_a}{2\pi Q_a} \propto f$

Detection bandwidth = axion kinetic linewidth

Shrinking target volume to match momentum transfer

$V \propto f^{-3}$

$Q_{cav} \propto f^{-2/3}$

(Anomalous skin effect)

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 $n^{2^n}$

Quantum computers are growing fast, but they are still in their infancy.

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

\[ \langle \alpha | P | \alpha \rangle = |\alpha| \sin \theta \]

\[ \langle \alpha | X | \alpha \rangle = |\alpha| \cos \theta \]

\[ \frac{1}{2} \hbar = \text{quantum of phase space area.} \]

Simultaneous measurement of wave amplitude and phase gives irreducible zero-point noise in measurement. (Caves, 1982)

Thermal noise = \( kT \) of energy per resolved mode

\[ \text{Quantum noise} = 1 \text{ photon per resolved mode in the T=0 limit.} \]

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 $\Rightarrow$ all backreaction is put into the unobserved phase $\Rightarrow$ which we don’t care about...

Phase space area is still $\frac{1}{2}\hbar$ 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

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.

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

B. R. Johnson¹, M. D. Reed², A. A. Houck², D. I. Schuster³, Lev S. Bishop¹, E. Ginossar³, J. M. Gambetta³, L. DiCarlo³, L. Frunzio³, S. M. Girvin¹ and R. J. Schoelkopf¹*

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
Resolving photon number states in a superconducting circuit


CPW cavity 5.7 GHz

Cooper Pair Box qubit “cavity QED”

0 1

populate cavity

probe
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.


state-of-the-art in QC: Quality factor $\sim 10^8$
Superconducting RF cavities for accelerators

High frequency alternating current voltage is used to create magnetic fields. Drift tubes increase acceleration by managing the magnetic fields. Electromagnets keep the particle beams in the center of the pipe.

credit: A. Romanenko - Fermilab
Potential of up to ~10 seconds of coherence

\[ Q > 10^{11} \]


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
big push for quantum, and interesting opportunities to work with HEP
now let’s look at another regime…
Charge-coupled devices: CCDs

photon detector
Charge-Coupled Device (CCD)

Charge coupling makes the detectors ideal for low noise measurements, typical noise for scientific CCDs is $2e^-\text{ RMS (7.2eV)}$. Very recent work pushing this to “0” noise.
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...
CONNNIE-DAMIC 2016 sensors

- 16 Mpix
- 6g
- 4 amplifiers
- 2e^- noise
- low background package
Particle identification in a CCD image

- **muons**, electrons and diffusion limited hits.
Calibration using X-rays

- Mn Kα: 63 eV RMS at 5.9 keV
- Mn Kβ
- Al K
- Mn K escape lines

Energy / keV

- 4.2 keV: pe from Si fluorescence X-ray absorption
- 1.7 keV: pe from Mn Kα X-ray absorption

Reconstructed energy / keV

Energy / keV

var(E) = 0.16 \times 3.62 \text{ eV} \times E

RMS = 30 \text{ eV (from noise)}
CCD for Dark Matter search and neutrino nucleus elastic coherent scattering

2014

CCD for Dark Matter search and neutrino nucleus elastic coherent scattering

2016

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


(DAMIC Collaboration)

FIG. 5. Exclusion plot (90% C.L.) for the hidden-photon kinetic mixing $\kappa$ 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.

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

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.
the new skippers

$N_{\text{smpl}} = 1$

$\sigma_{\text{noise}} = 3.5$
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 Yu⁶

scientific CCDs now

![Graph showing pixel value vs. charge for scientific CCDs]

skipper CCD

![Graph showing distribution of entries for 4000 samples]

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.
impressive ability to count electrons!
$^{55}$Fe X-ray line 5.9 keV
$^{55}$Fe X-ray line 5.9 keV
dark sector search
here will focus on the hidden sector
DM w/ dark photon ($A'$) mediator

- light $A'$ ($\sim m_{DM}$)
- ultra-light $A'$ ($\ll \text{keV}$)
DM w/ dark photon ($A'$) mediator

nice predictive model to target!

Standard Model $\xrightarrow{\epsilon}$ Dark Sector $\text{DM} + A'$

- light $A'$ ($\sim m_{\text{DM}}$)
- ultra-light $A'$ ($\ll$ keV)

$M_{A'} > 2m_\chi$

direct detection

constrains from cosmology

freeze out

credit: R. Essig - Stony Brook University
DM w/ dark photon ($A'$) mediator

nice predictive model to target!

- light $A'$ ($\sim m_{\text{DM}}$)
- ultra-light $A'$ ($\ll \text{keV}$)

freeze IN (build up abundance during cool-down)

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

enhanced a low $Q$

credit: R. Essig - Stony Brook University
the “classic” search for wimps looks for nuclear recoil, but when looking at lower mass particles the e-recoil channel is more competitive.

\[ E_{DM} \sim \frac{1}{2} m_{DM} v_{DM}^2 > \Delta E \]

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

**typical recoil energy:**

\[ \Delta E \sim 4 \text{ eV} \]

**Table:**

<table>
<thead>
<tr>
<th>Type</th>
<th>Examples</th>
<th>( E_n )</th>
<th>mass threshold</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noble liquids</td>
<td>Xe, Ar, He</td>
<td>~10 eV</td>
<td>~5 MeV</td>
<td>Done w/ XENON10+100 data; improvements possible</td>
</tr>
<tr>
<td>Semiconductors</td>
<td>Ge, Si</td>
<td>~1 eV</td>
<td>~200 keV</td>
<td>( E_n \sim 40 \text{ eV (SuperCDMS, DAMIC^*)} ) ( E_n \sim 1 \text{ eV (SENSEI)} ) R&amp;D ongoing</td>
</tr>
<tr>
<td>Scintillators</td>
<td>GaAs, NaI, CsI</td>
<td>~1 eV</td>
<td>~200 keV</td>
<td>R&amp;D required</td>
</tr>
</tbody>
</table>

For outer shell e-

\[ q_{typ} \sim \alpha m_e \sim 4 \text{ keV} \]

\[ \Delta E_e \sim q \cdot \vec{v}_{DM} \]

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

dark rate : $3.68 \times 10^{-3}$ events/pixel/day
the future is all skipper…

Expected CENNS measured anti-νe survival probability. Each point corresponds to a 2 kg skipper-CCD detector with 10eV threshold and 300 days of data collection. For the sterile neutrinos we assumed: Δm^2_S = 0.5 eV^2, sin(2θ_S)^2 = 0.15.
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.

Now, writing in Nature Photonics, Giorgio Brida and co-workers report entangled photons produced with non-linear crystal and imaged with CCDs. [sub-shot noise imaging]
skipper for quantum imaging

State-of-the-art sensors can not count more than 1 photon (EMCCD)

Skipper-CCD developed by FNAL+LBNL can count whatever number you like...
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

Each wire carries a current of 1 ampere in the same direction.

Force per meter of

length = $2 \times 10^{-7}$ newton

1 meter

1 amp
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.

"Ultimately, a precise electron pump verified by error counting not only provides a supreme candidate for the definition of the ampere but also provides an accurate way to measure the charge and resistance of materials."
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!
**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.

- 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.

---

10 kg skipper Detector (4000 sensors)
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.
cubeSat for detecting the decay of dark matter in our own galaxy.
DESI: Dark Energy Spectroscopic Survey

35 million galaxy + QSO redshift survey

0.7 million Ly-A QSOs
+1.7 million QSOs

17 million ELGs

4 million LRGs

10 million BGS galaxies

we are now building the detectors for these spectrographs, 2e- of noise.
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 $\Omega \chi = 0.01 \Omega \text{DM}$, which may explain the 21-cm signal observed by EDGES.

We assume that a subdominant DM component, $\chi$, interacts with an ultra-light dark photon ($m_{A'} \ll \text{keV}$), with $\Omega \chi = 0.01 \Omega \text{DM}$. This model is motivated by the EDGES measurement of the 21-cm spectrum at $z \approx 17$, which revealed an anomalously large absorption signal.
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.

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)
This talk is about events in progress. The graph shows the relationship between \( R \) (events/day/kg) and \( Q \) with several curves indicating different values of \( Q \) (e.g., \( Q = 1.00 \), \( Q = 0.30 \), \( Q = 0.20 \), \( Q = 0.17 \)). The legend includes a line labeled "Lindhard." The graph highlights 1+ pixels in progress and 3+ pixels this talk. Additionally, there is a mention of skipper future.
(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 $\gamma$-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 $2.7 \times 10^{13} \bar{\nu}_e$/cm$^2$/s), detector is well shielded against the hadronic component of cosmic rays by the reactor body and technologic equipment (overburden $\approx 70$ m w.e.). The muon component is also reduced by a factor of $\sim 10$ at $\pm 20^\circ$ with respect to the vertical and $\sim 3$ at $70^\circ - 80^\circ$, 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

$$\mu^a_\nu \ < \ 2.9 \times 10^{-11} \mu_B.$$
Two ways to get high flux low energy neutrinos

**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)

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)

Complete calibration down to our threshold for CONNIE.
CONNIE rates

Energy spectra in silicon detectors

![Graph showing energy spectra in silicon detectors with different quenching factors.](image)

- From nuclear recoils
- With quenching factor
- With selection efficiency


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)

- $E_{th} = 5.5 \text{ eV (1\sigma_{RMS})}$ ~ 28.3
- $E_{th} = 28 \text{ eV (5\sigma_{RMS})}$ ~ 18.1
originally we developed this technology for DAMIC (dark matter search)
The reactor typically has one month shutdown every 13 months. This is the 2015 shutdown.
2015 engineering run
FNAL-LDRD program (1g active mass, 1 CCD)

<table>
<thead>
<tr>
<th>Reactor</th>
<th>counts (7.8-8.2 keV)</th>
<th>exposure (day)</th>
<th>rate (counts/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RON</td>
<td>693</td>
<td>18.0</td>
<td>38.5 ± 1.46</td>
</tr>
<tr>
<td>ROFF</td>
<td>557</td>
<td>14.8</td>
<td>37.6 ± 1.61</td>
</tr>
</tbody>
</table>
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.

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.
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
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…

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

- Need to improve our low energy extraction
- Higher efficiency can be get using binning, with the drawback of loosing spatial information of the events.
operation improvements in CONNIE: statistics going up fast. By this time next year we will have 5 times the statistics.
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 ⇒ 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

<table>
<thead>
<tr>
<th>Dark Current ( [e^- \text{pix}^{-1}\text{day}^{-1}] )</th>
<th>( \geq 1e^- ) [pix]</th>
<th>( \geq 2e^- ) [pix]</th>
<th>( \geq 3e^- ) [pix]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^{-3} )</td>
<td>( 1 \times 10^8 )</td>
<td>( 3 \times 10^3 )</td>
<td>( 7 \times 10^{-2} )</td>
</tr>
<tr>
<td>( 10^{-5} )</td>
<td>( 1 \times 10^6 )</td>
<td>( 3 \times 10^{-1} )</td>
<td>( 7 \times 10^{-8} )</td>
</tr>
<tr>
<td>( 10^{-7} )</td>
<td>( 1 \times 10^4 )</td>
<td>( 3 \times 10^{-5} )</td>
<td>( 7 \times 10^{-14} )</td>
</tr>
</tbody>
</table>

Measured upper limit for the DC in CCDs is:

\[ 1 \times 10^{-3} \text{ e pix}^{-1}\text{day}^{-1} \quad \text{arXiv:1611.03066} \]

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 $\sim 500$ keV to 4 MeV!

Terrestrial effects: Timon Emken, RE, Kouvaris, Mukul Sholapurkar (to appear)
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.
• 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 6.55 Timing diagram for Skipper operation.

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