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Quantum Sensors - Fundamental Experiments and Infrastructure

William Wester

Physics Advisory Meeting

8 Jul 2017

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Thanks to A. Chou, A. Sonnenschein, D. Bowring, A. Moretti, A. Tollestrup, A. Grasselino, A. Romanenko, B. Benson, A. Anderson, S. Rahlin, J. Tiffenberg, J. Estrada, D. Kubic, S. Chattopadhyay, plus all the associated University colleagues and others not at Fermilab.

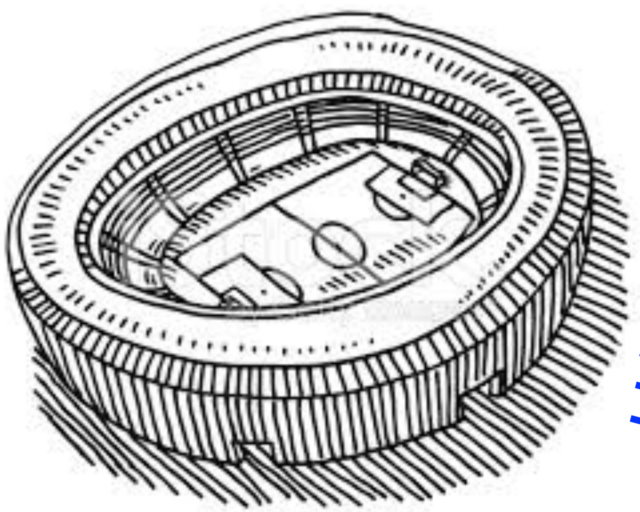
Axions first! ADMX: axion dark matter experiment

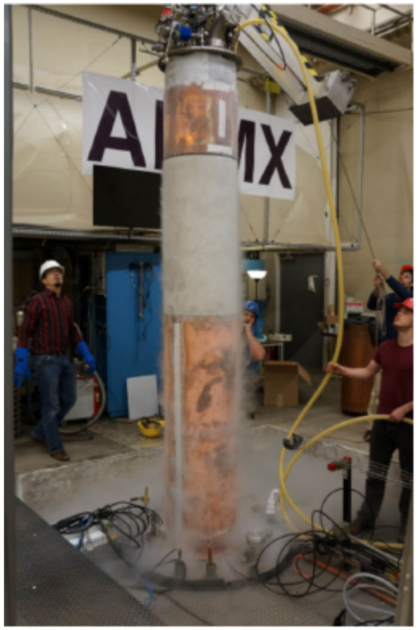
- For the first time, an experiment has sensitivity to the QCD axion that solves the strong-CP problem and could account for the dark matter in the universe.

- Over 20 years of R&D, but now a 1) high magnetic field surrounds a 2) high-Q and tunable copper cavity with 3) superconducting quantum interference device (SQUID) readout at 4) sub-kelvin temperatures. This is ADMX in the context of the DOE gen2 dark matter program.

- Sensitivity to possible 10^{-23} W of power from dark matter axions converting into detectable single microwave photons.

ADMX – direct detection of axionic dark matter



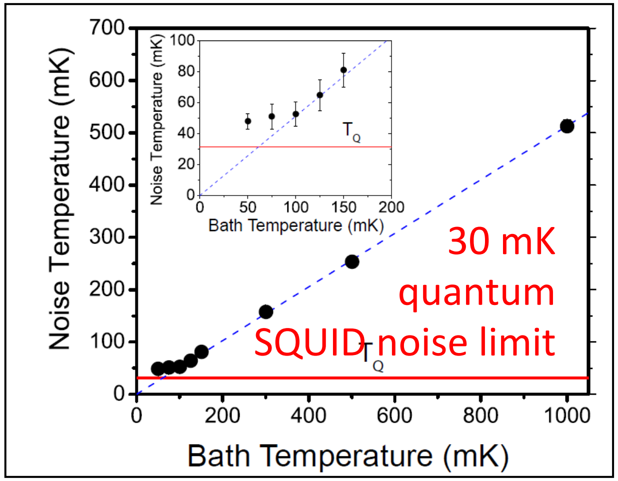


Tune the μ-wave cavity to the frequency corresponding to the kinetic energy of the axion.

Scan in frequency for sensitivity as a function of the mass of the axion.

λ = h/p ~ 100m coherent cloud of an axion field making up the dark matter halo, passing through the ADMX apparatus.

$$\frac{df}{dt} \approx 1.68\ \mathrm{GHz/year}\ \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1\ \mathrm{GHz}}\right)^2 \left(\frac{\rho_0}{0.45\ \mathrm{GeV/cc}}\right)^2 \cdot \left(\frac{5}{SNR}\right)^2 \left(\frac{B_0}{8\ \mathrm{T}}\right)^4 \left(\frac{V}{100\mathrm{l}}\right)^2 \left(\frac{Q_L}{10^5}\right) \left(\frac{C_{010}}{0.5}\right)^2 \left(\frac{0.2\ K}{T_{sys}}\right)^2$$



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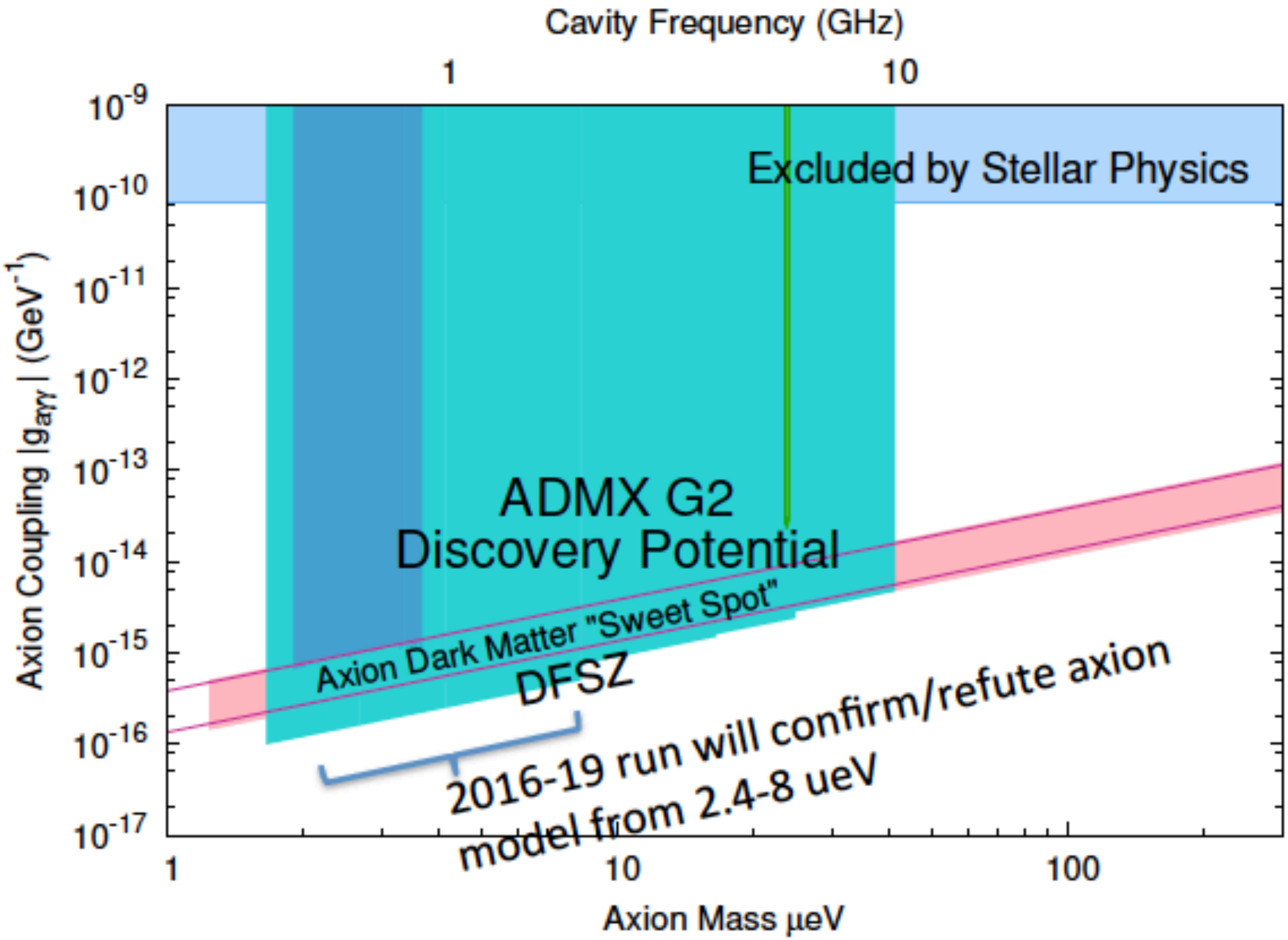
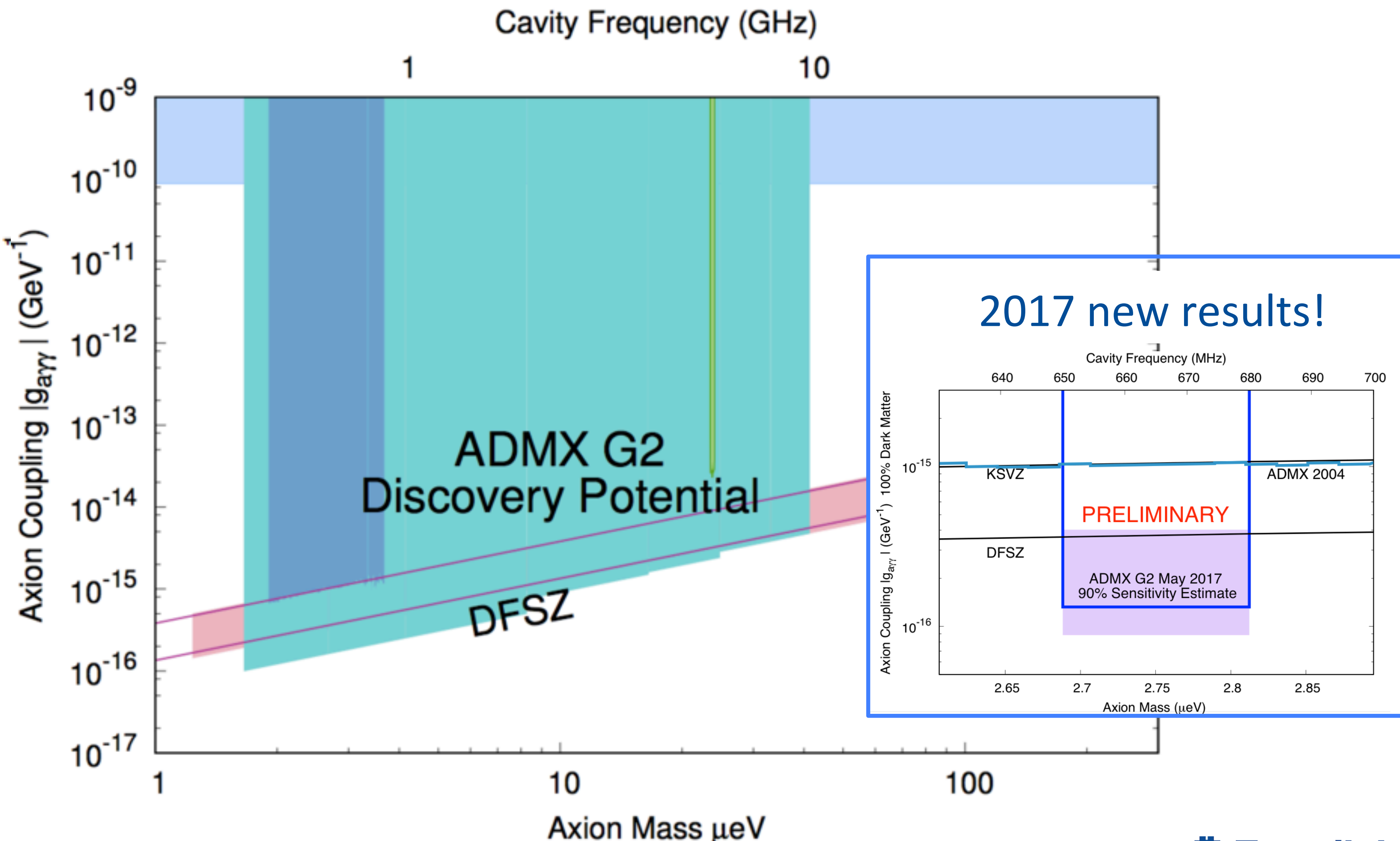
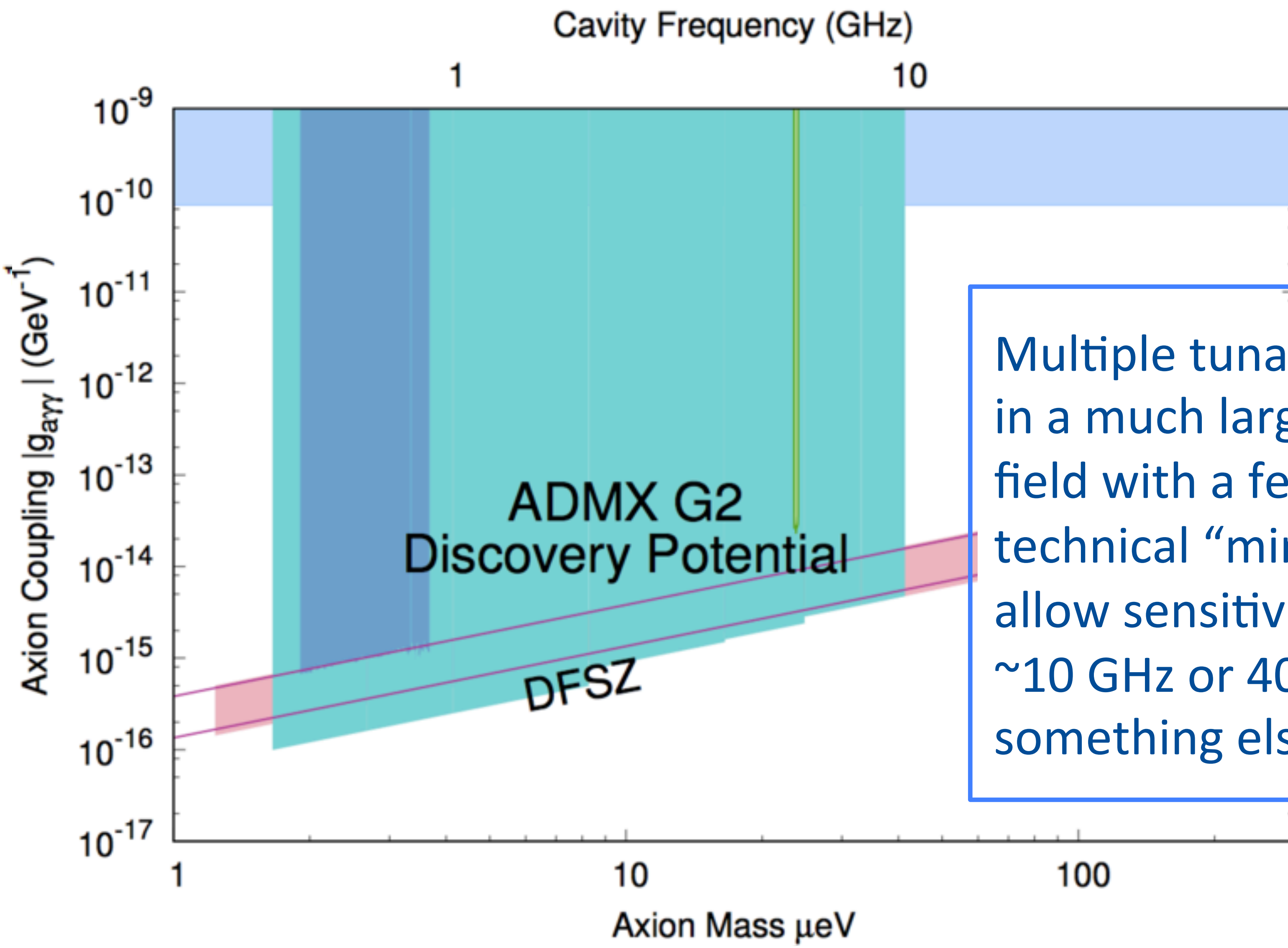
ADMX - gen2 discovery potential



ADMX – Initial results for gen2 project



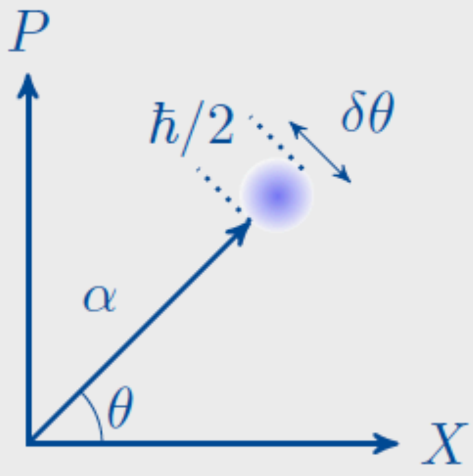
ADMX – possible to use multiple cavities to ~ 10 GHz



Multiple tunable cavities in a much larger magnetic field with a few other technical "miracles" may allow sensitivity up to ~10 GHz or 40μeV. Need something else for > m_a.

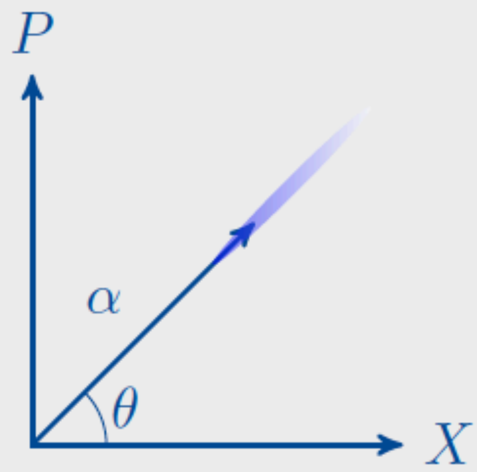
Quantum “Miracles”

Coherent State



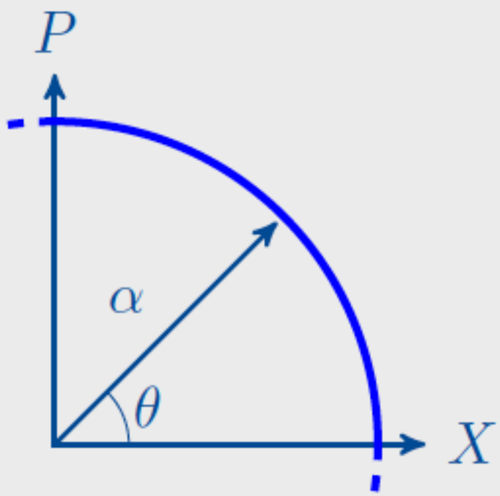
$$\Delta P \Delta X \gtrsim \hbar/2$$

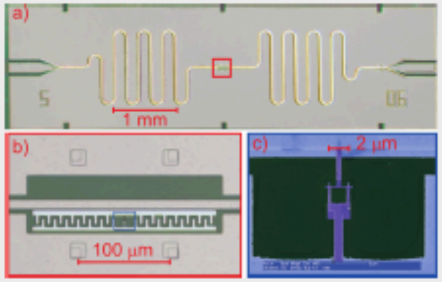
Squeeze θ



LIGO

Squeeze $|\alpha|$





http://schusterlab.uchicago.edu/

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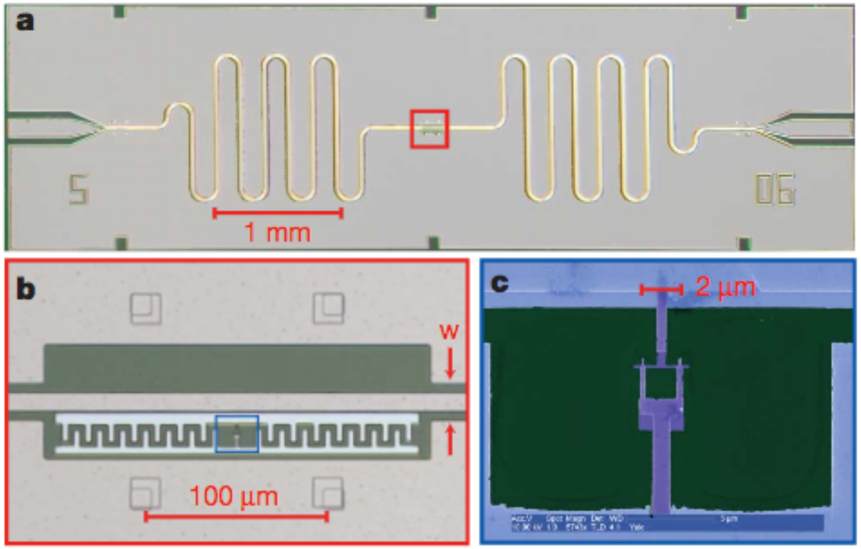
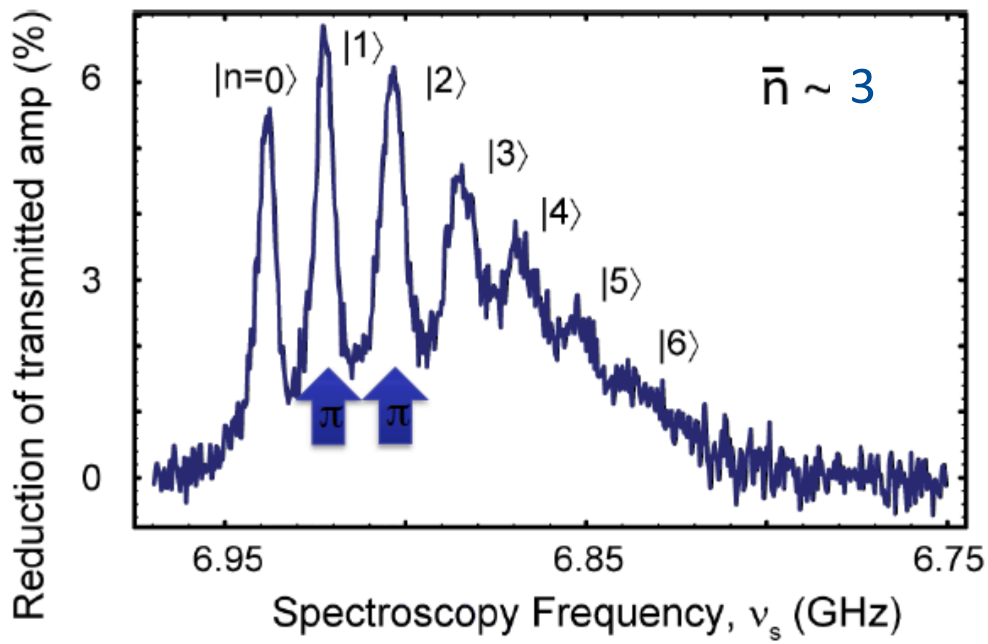
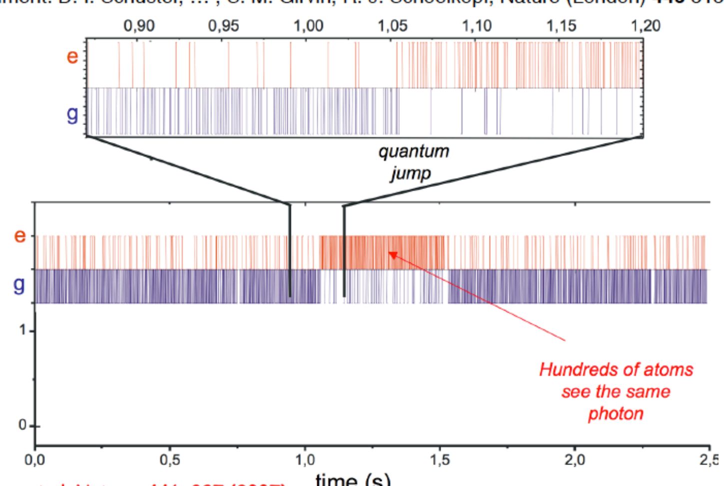
Qubits – non-destructive single microwave photon detector



Theory: J. Gambetta, A. Blais, …, S. Girvin, and R. J. Schoelkopf, *PRA 94 123602 (2005)*
Experiment: D. I. Schuster, … , S. M. Girvin, R. J. Schoelkopf, Nature (London) **445** 515 (2007)



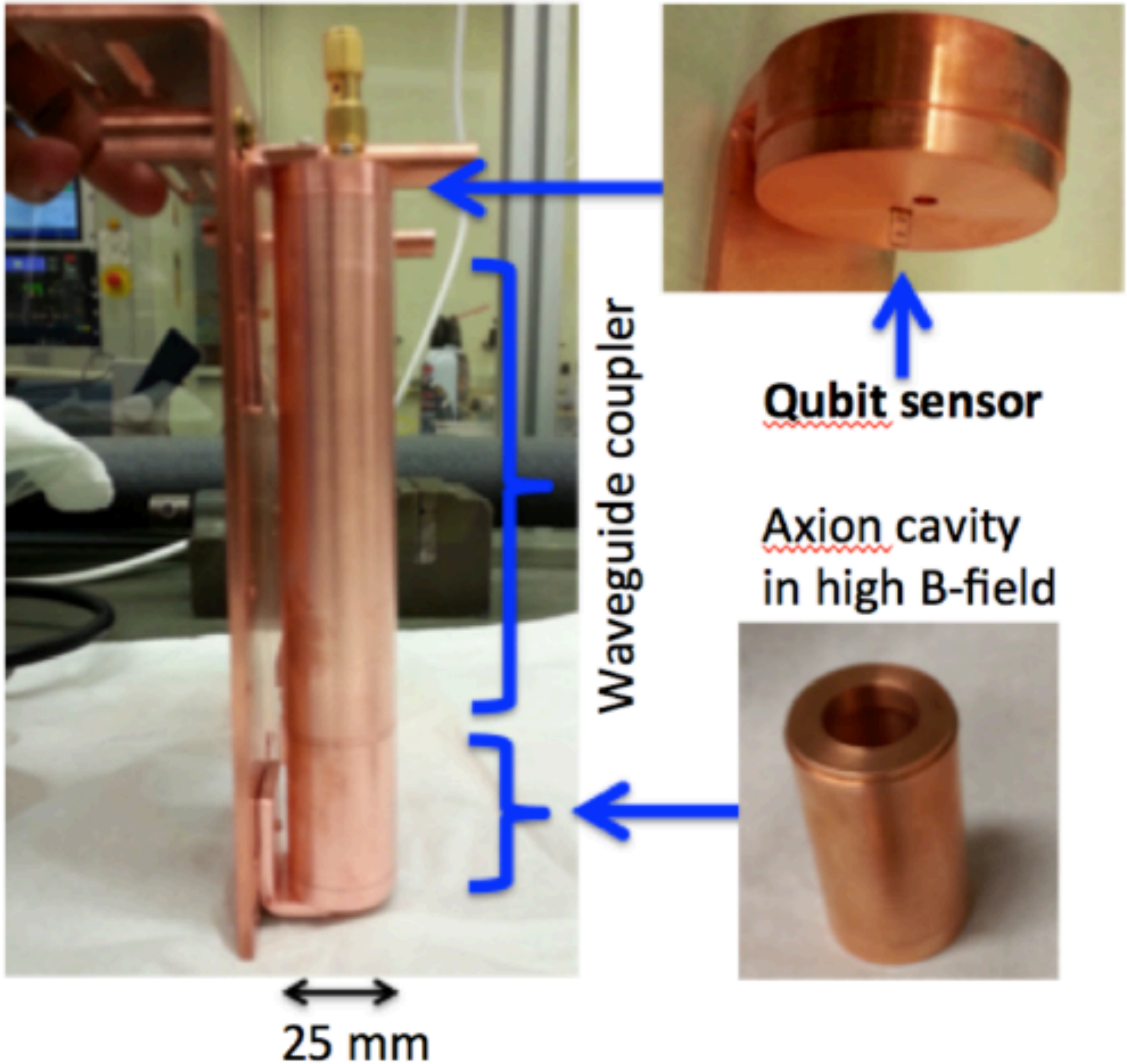


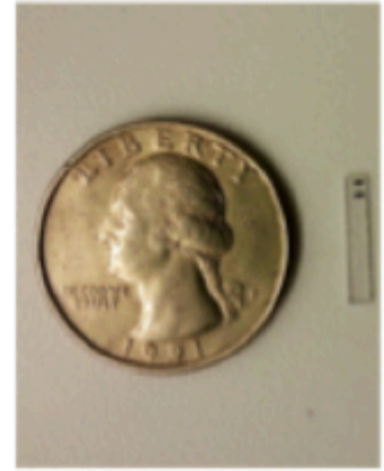
S.Gleyzes et al, Nature, 446, 297 (2007)

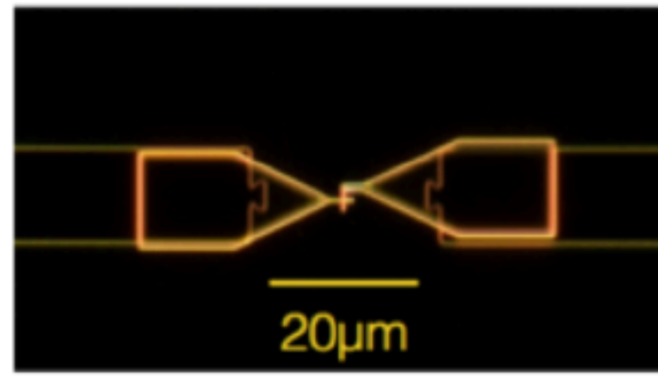
Aaron Chou's LDRD: detect single microwave photons in a high magnetic field using qubits with particular emphasis on improving the bit error rate -> enable high mass axion search.

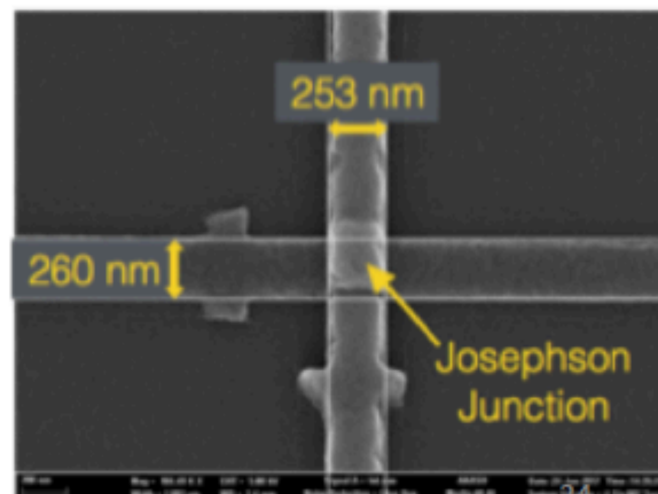
3D Qubit-based detector prototype

AC, Akash Dixit, D.Schuster (U.Chicago)





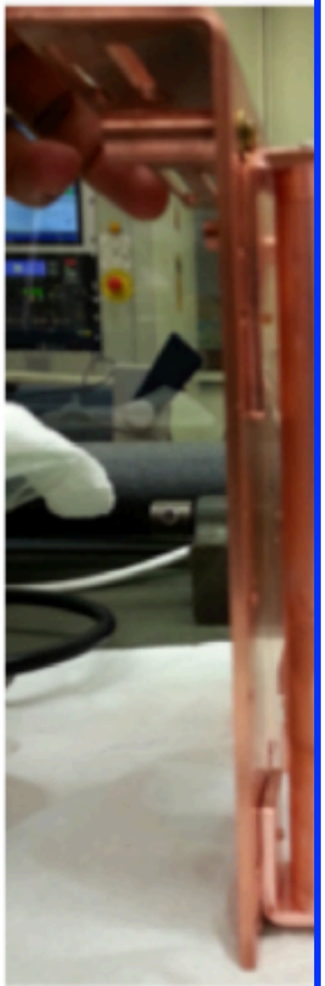




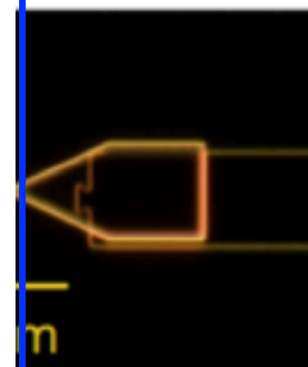
R&D supported by Heising-Simons Foundation.

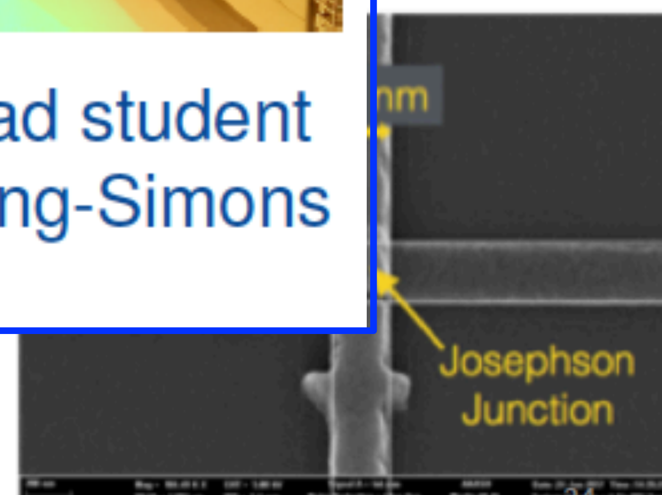
3D Qubit-based detector prototype

AC, Akash Dixit, D.Schuster (U.Chicago)



Akash Dixit, U. Chicago grad student with funding from the Heising-Simons Foundation.





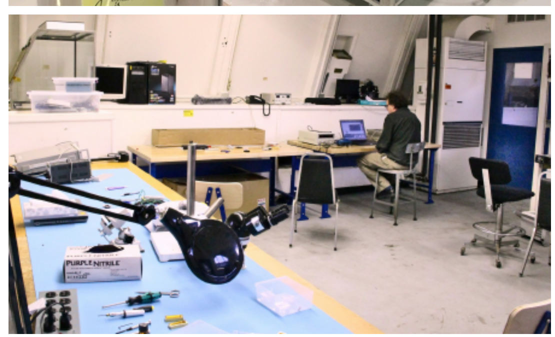
25 mm

R&D supported by Heising-Simons Foundation.

Measurement in high field to be done with LDRD support

- Dilution refrigerator for sub-K operation with associated high field magnet. Plan to locate in the SiDet facility.

SiDet – technical area used for silicon particle trackers, CCDs, CMB sensors, etc.



Newly obtained test cryostats and lab space for LDRD project studying fine tuning of cavities using dielectrics with applied voltage. (A. Sonnenschein)

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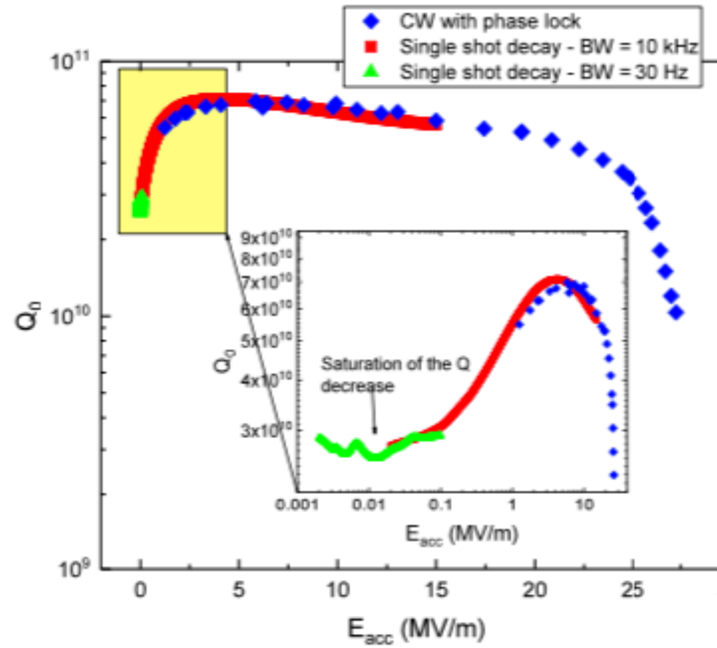
2nd effort: Study qubit lifetime in high Q SRF cavities

- We have begun R&D toward higher Q cavities for quantum computers, which translates e.g. to longer coherence times
- Supported by LDRD (A. Romanenko)

From PIP-2, LCLS-2 to Quantum Computing



Nature of the Low Field *Q* Degradation in Superconducting Niobium Cavities

A. Romanenko†
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

D. I. Schuster‡
The James Franck Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637, USA

(Dated: May 31, 2017)

Joe Lykken discussed this effort in his talk. Large volume dilution refrigerator leverages existing cavities

Sub-kelvin research at Fermilab

What:	Target R&D	Unique Capability	Funding source
ADR (50 mK)	MKIDs for optical cosmo.	SiDet focal plane packaging	KA25
ADR (50 mK), He-3 fridges (1K)	SPT, CMB-S4	SiDet detector integration	LDRD
Dilution fridge (10 mK)	Qubit-based photon detectors for axions	High field magnet* (>14 T)	LDRD
Dilution fridge (10 mK)	Materials studies for high Q SRF cavities	SRF surface processing facility	LDRD
Dilution fridge (10 mK)	Active veto for WIMP detectors, low threshold calorimetry	Underground** in NUMI (30 m.w.e.)	Northwestern, KA25 (install) KA23 (G3 DM)

FY17-18 (last three rows)

*NHFML is good for quick sample testing, FNAL magnetic test stand is for device development.
**Stanford underground test stand (Cabrera) no longer exists.

MKIDs: Microwave kinetic inductive detectors

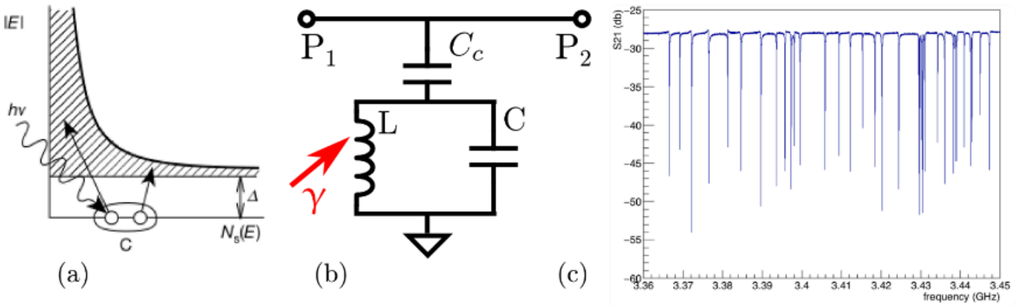
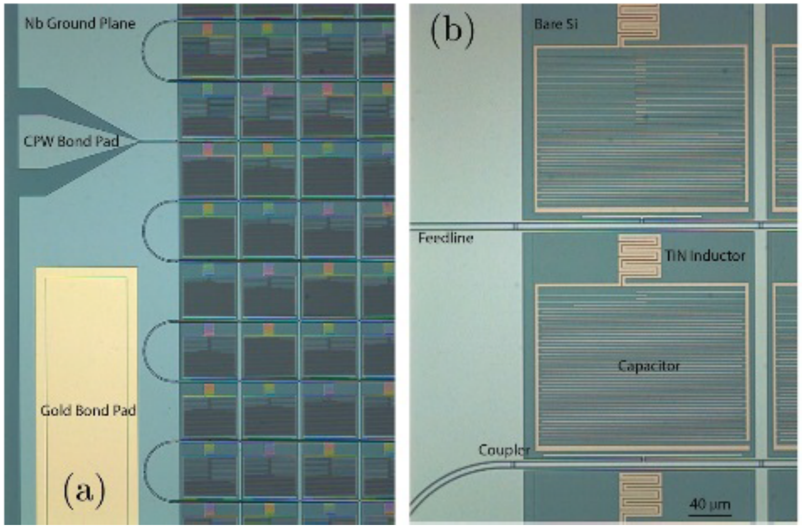


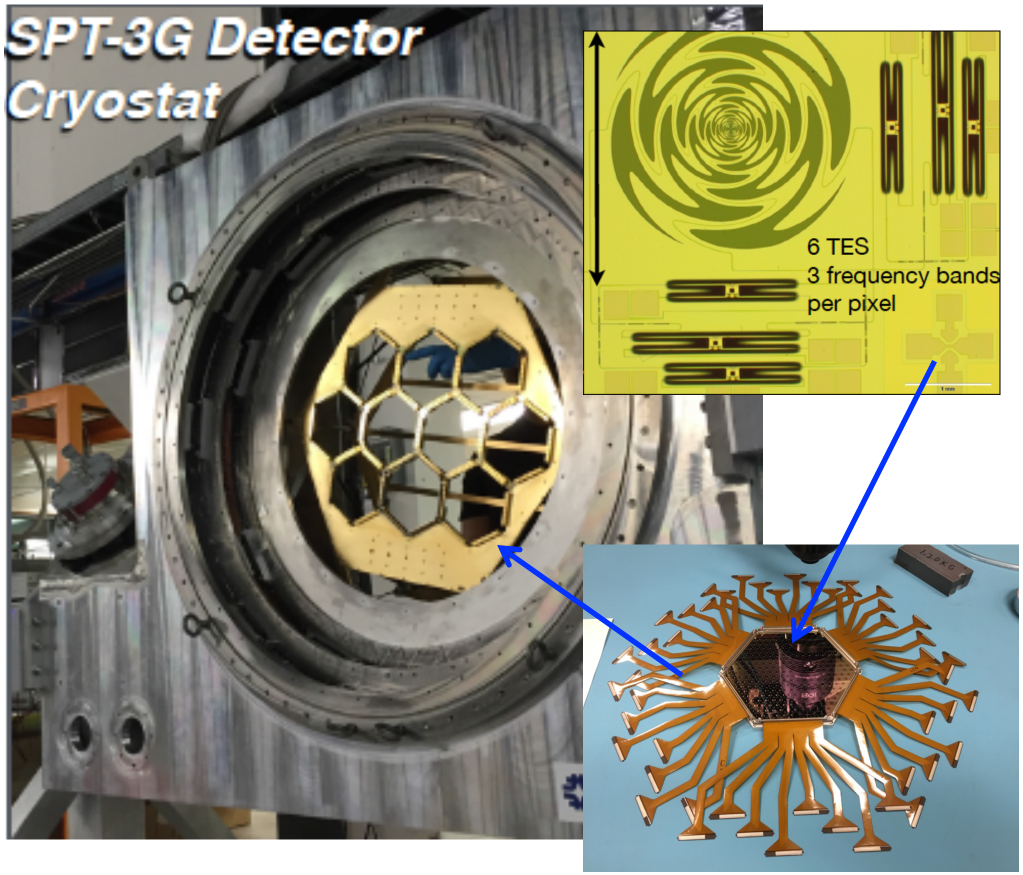
Figure 3 (a-b) When photons strike the inductor of an MKID, they break Cooper pairs and generate quasiparticles, changing the frequency of an LC circuit. (c) A measured microwave sweep across part of an existing optical MKID array, showing multiple frequency collisions and wide variation in the depth of resonances, both of which we propose to remedy.

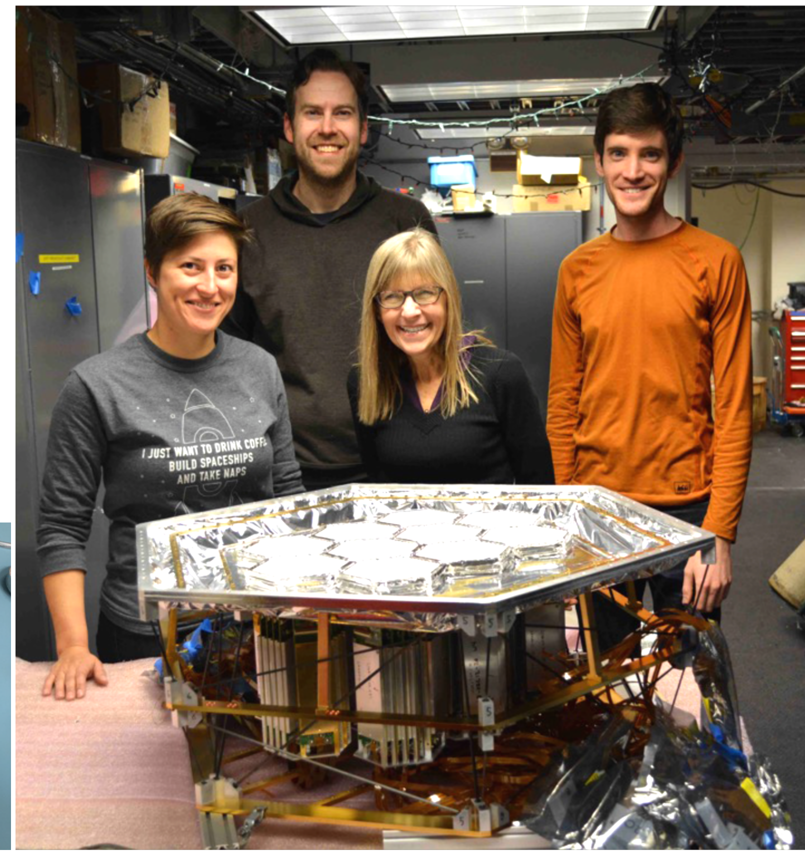


Single photon detection by MKIDs for optical / near-IR has been demonstrated, but continued R&D towards realizing a viable device -> goal towards using for cosmology where photons are collected and have an energy (wavelength) measured. Iteration on a next optimized devices supported through LDRD (J. Estrada).

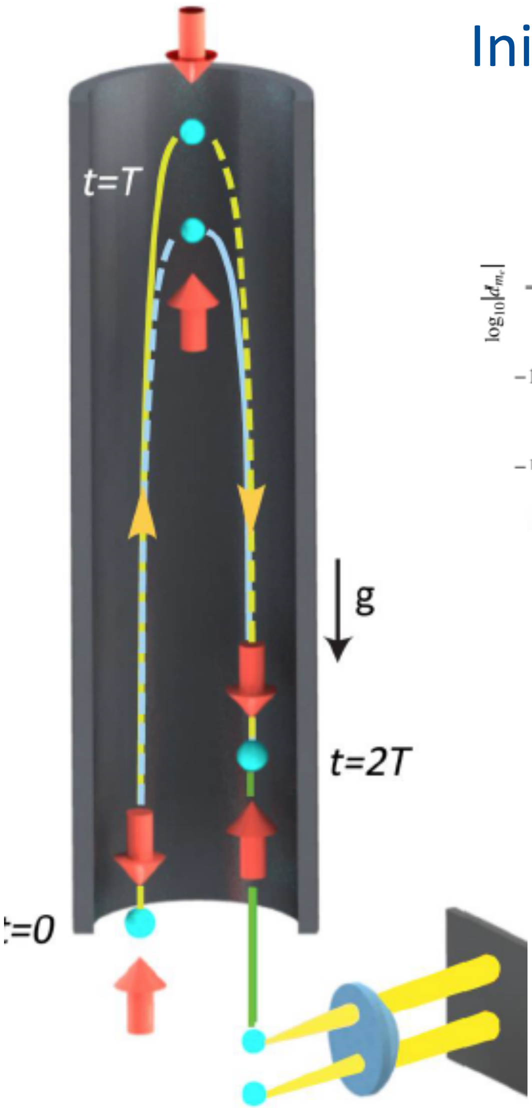
CMB R&D towards S4

For 3 years, B. Benson and his team have been working on R&D related to large scale focal plane assembly and testing for CMB. This effort lead to delivery of the S3 South Pole Telescope focal plane.

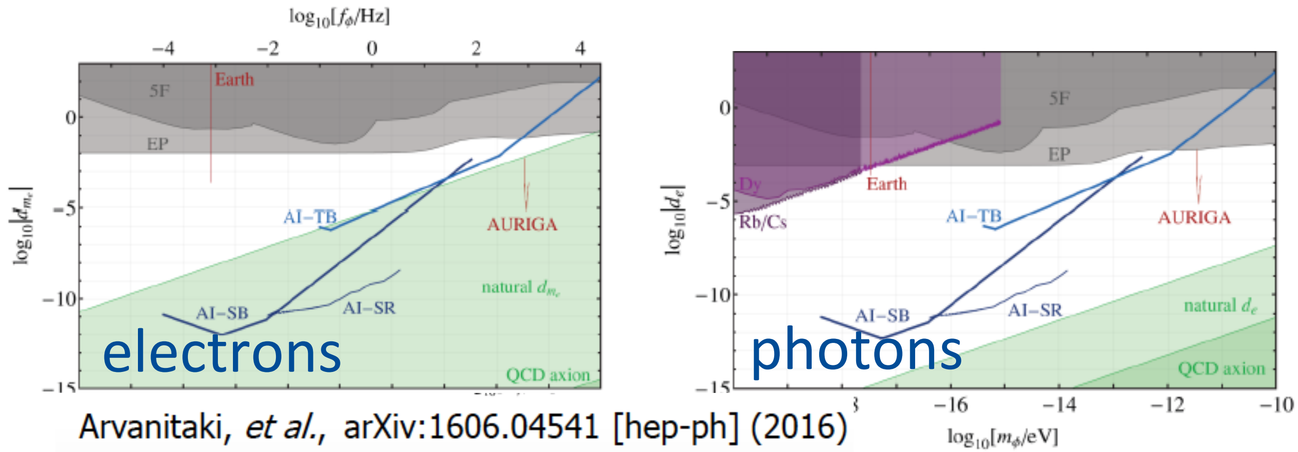




Atom Interferometry for new scalars – ultra light DM

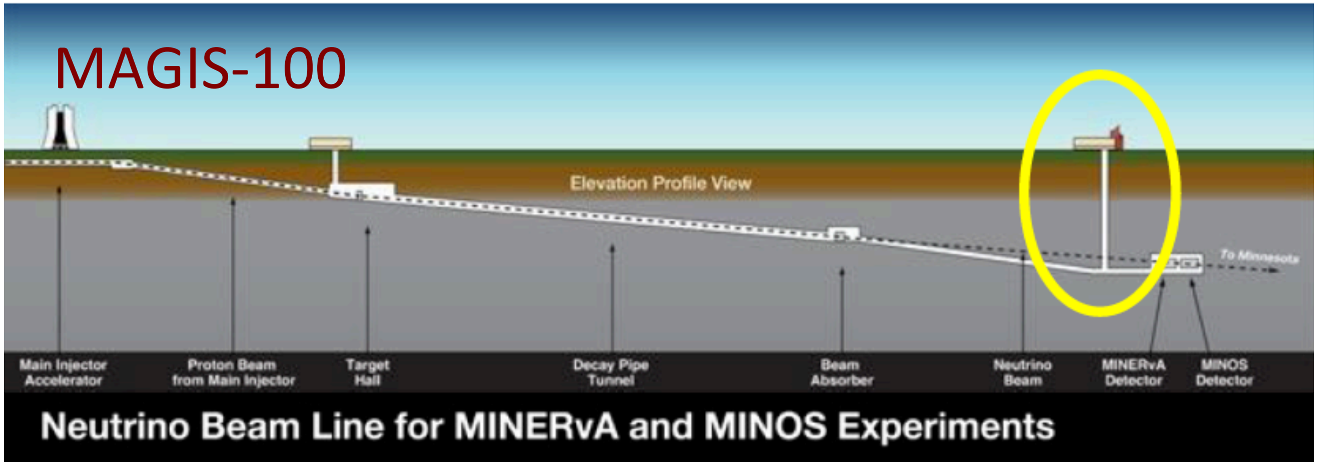


Initial SLAC effort … possible sensitivity to scalar DM



Arvanitaki, *et al.*, arXiv:1606.04541 [hep-ph] (2016)

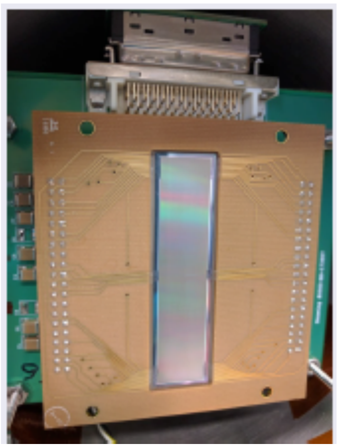
Proposal: 100 meter detector at Fermilab

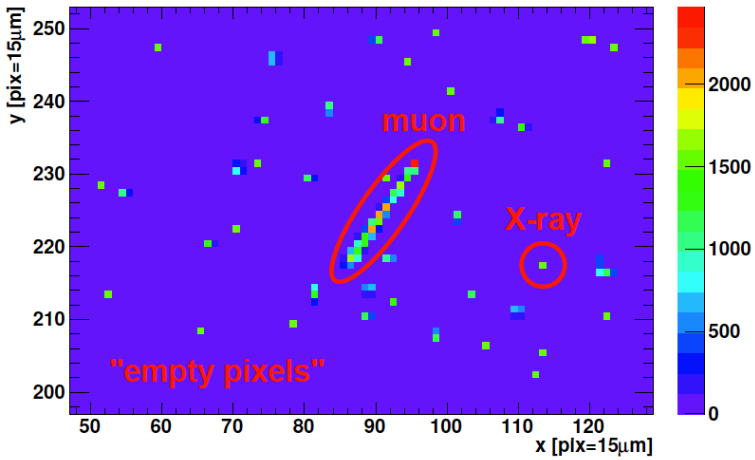


SENSEI – Sub-Electron Noise SkipperCCD Exp. Instrument

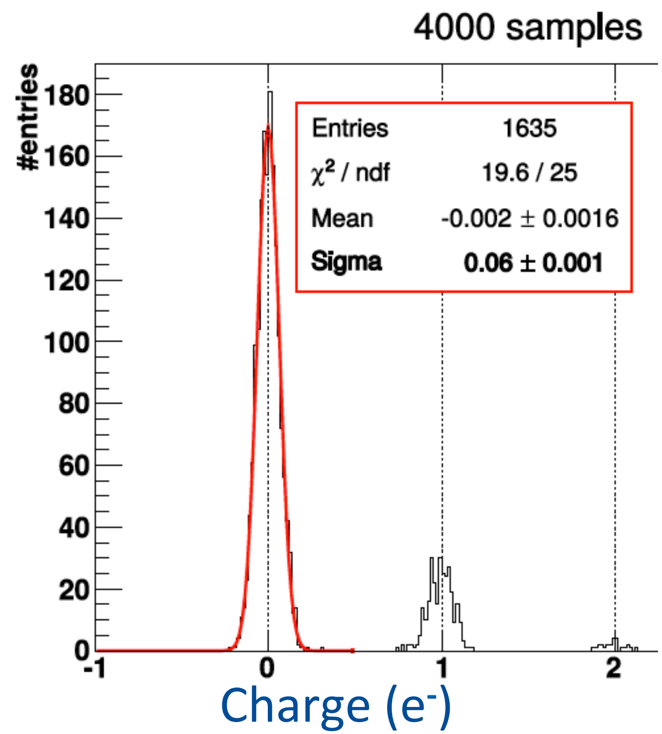
- New CCD device with novel architecture that allows multiple reads of the same pixel to reduce noise.

(J. Tiffenberg)



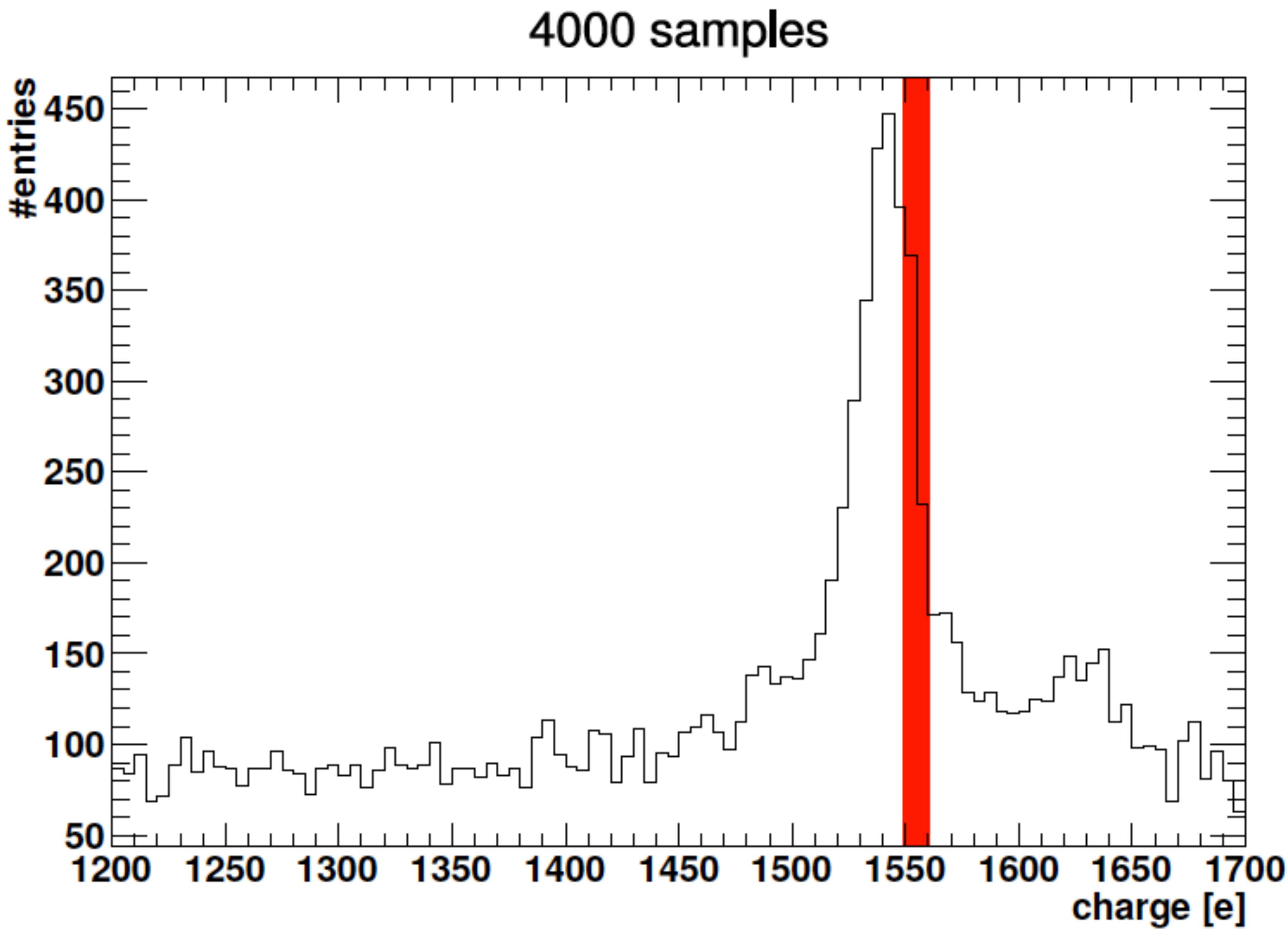


Skipper device and detector along with an exposure with 4000 reads/pixel

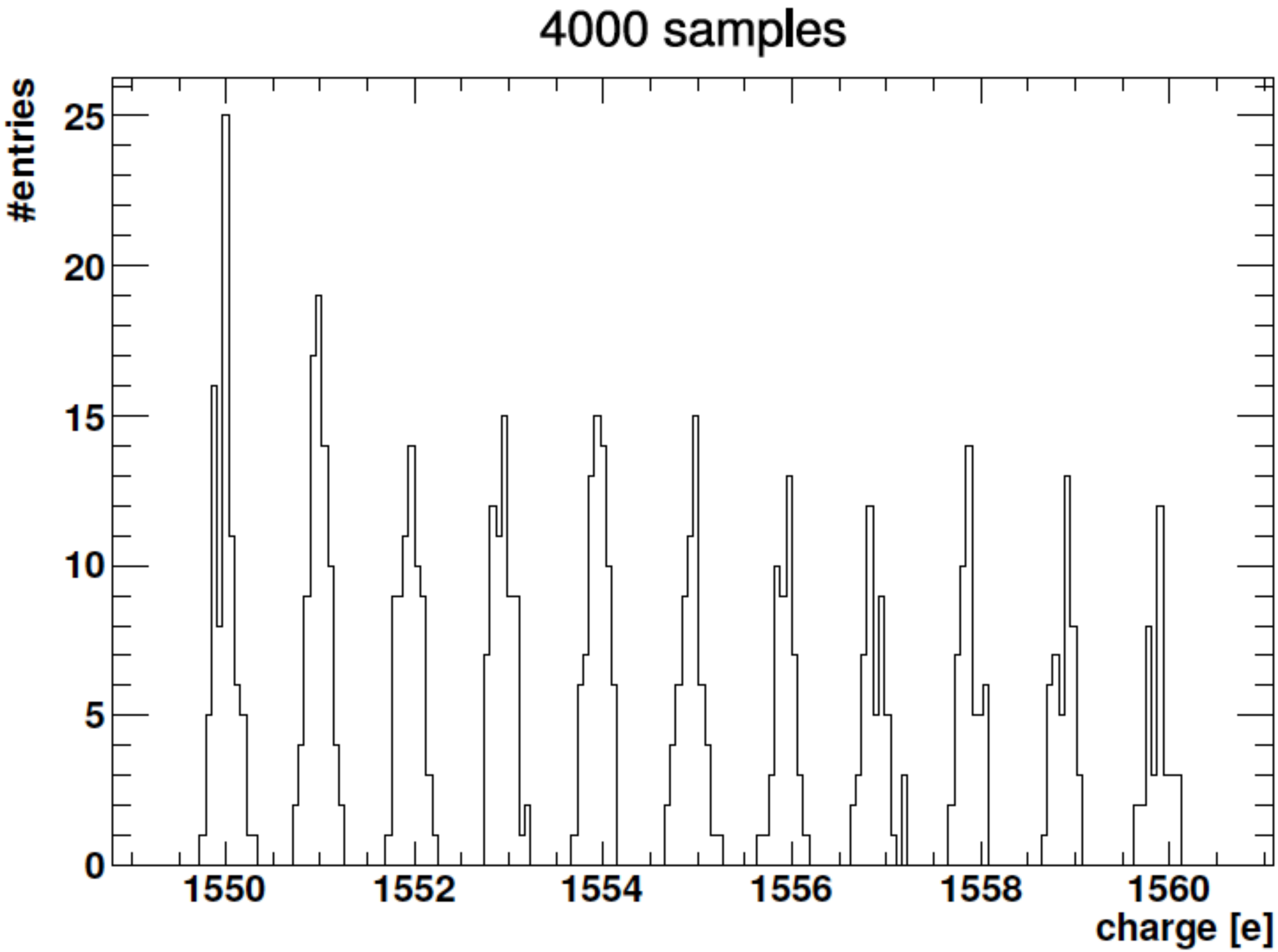


Sub-electron noise!

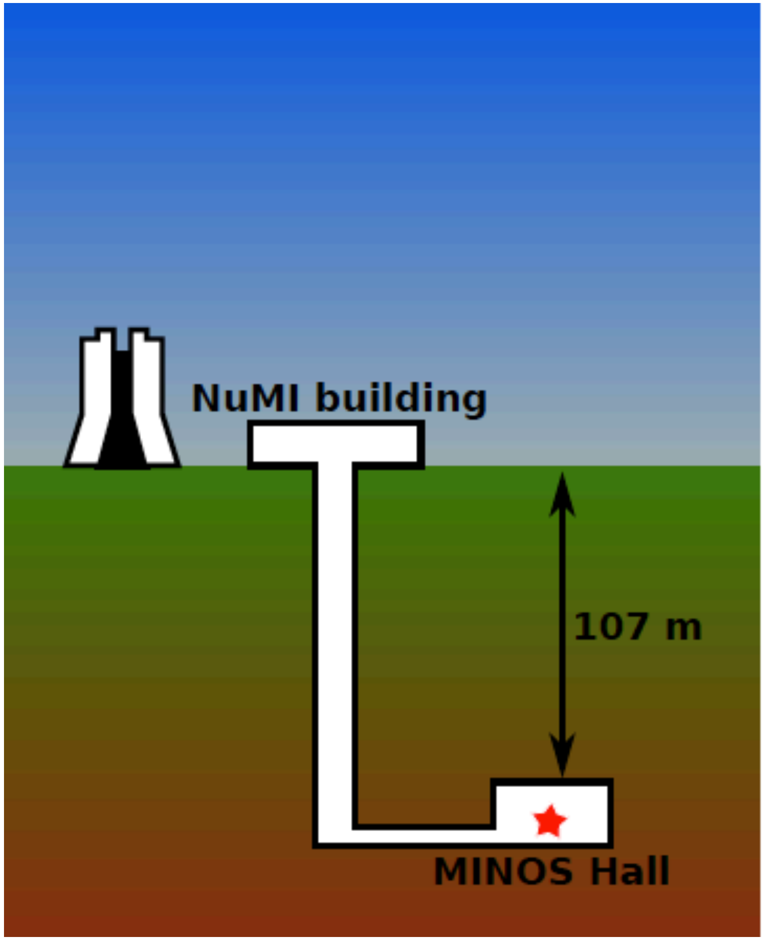
^{55}Fe X-ray source

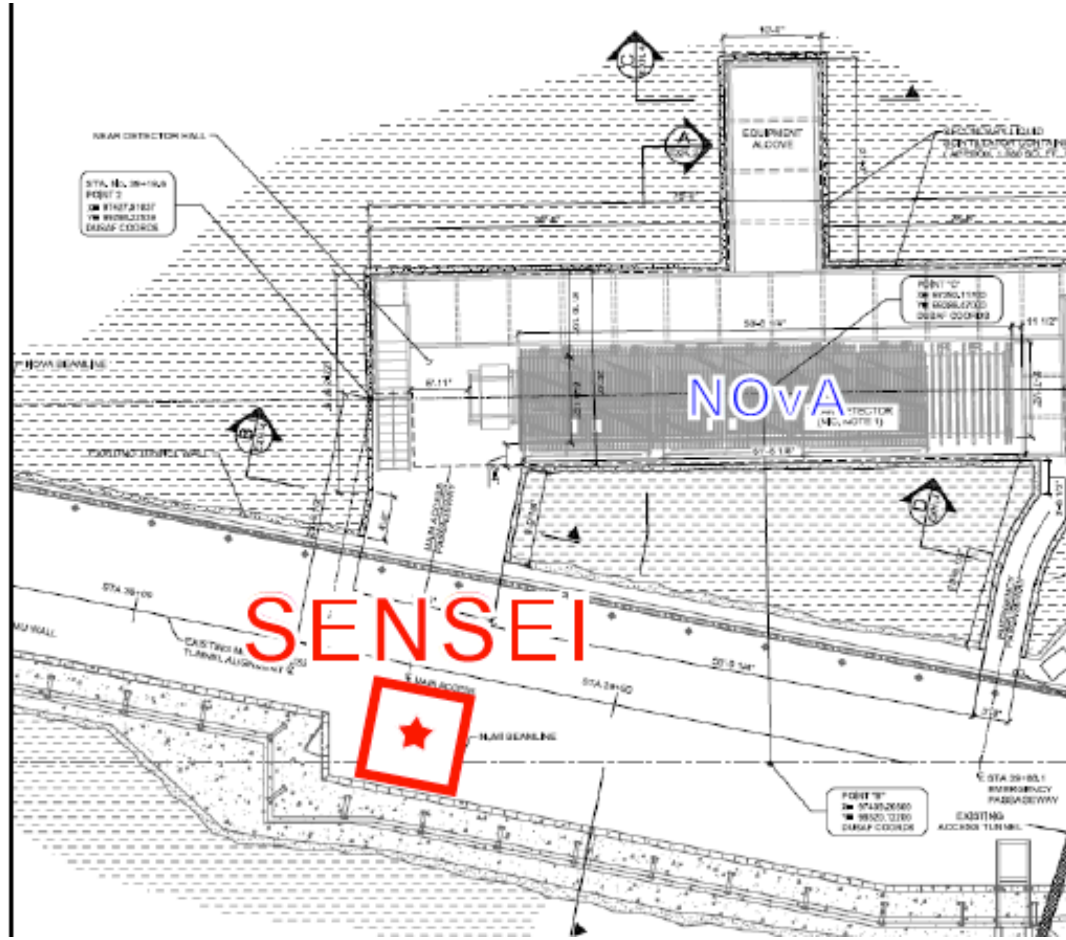


keep counting: ..1550, 1551, 1552..



Technology and background demonstrator at FNAL



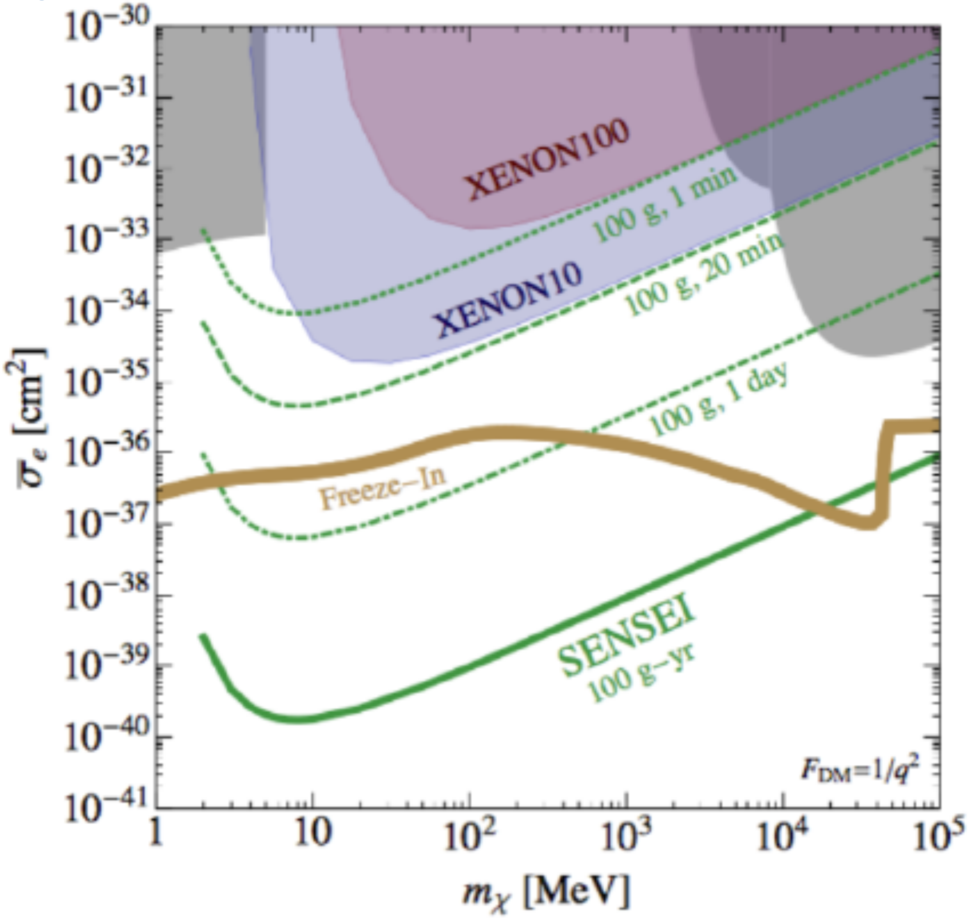


New low radiation package and clean room area in the MINOS hall

Low mass WIMP Dark Matter last!

New unexplored parameter space for low mass WIMP dark matter utilizing electron recoils is enabled by sub-electron noise using CCD with skipper readout.

In addition, skipper CCDs improve the prospects of detecting coherent neutrino interactions at a reactor (CONNIE)



Rouven Essig, Tomer Volansky & Tien-Tien Yu

Conclusions

- Sensors leading to quantum sensors have been at Fermilab
  - Silicon Detectors, Low temperatures devices (Super-CDMS)
  - CMB S3 deployed, MKIDs R&D leadership for cosmology
- New activities in Quantum Sensors benefit FNAL and QIS
  - For high mass axions, need qubits to achieve low bit error rates
  - For SRF cavities, enhance the qubit lifetimes
- QIS activities are enhanced by FNAL core competencies and leverage Chicago-land strength
  - Chicagoland strength in superconducting electronics -- sensors and readout, Fermilab core capability in detector integration, test facilities
  - Facilities can attract outside users (atom interferometry, users of dilution refrigerators with unique capabilities, new experiments)