Wilson Hall, inspired by a Gothic cathedral in Beauvais, France, is the focal point for administrative and scientific activity at Fermilab.

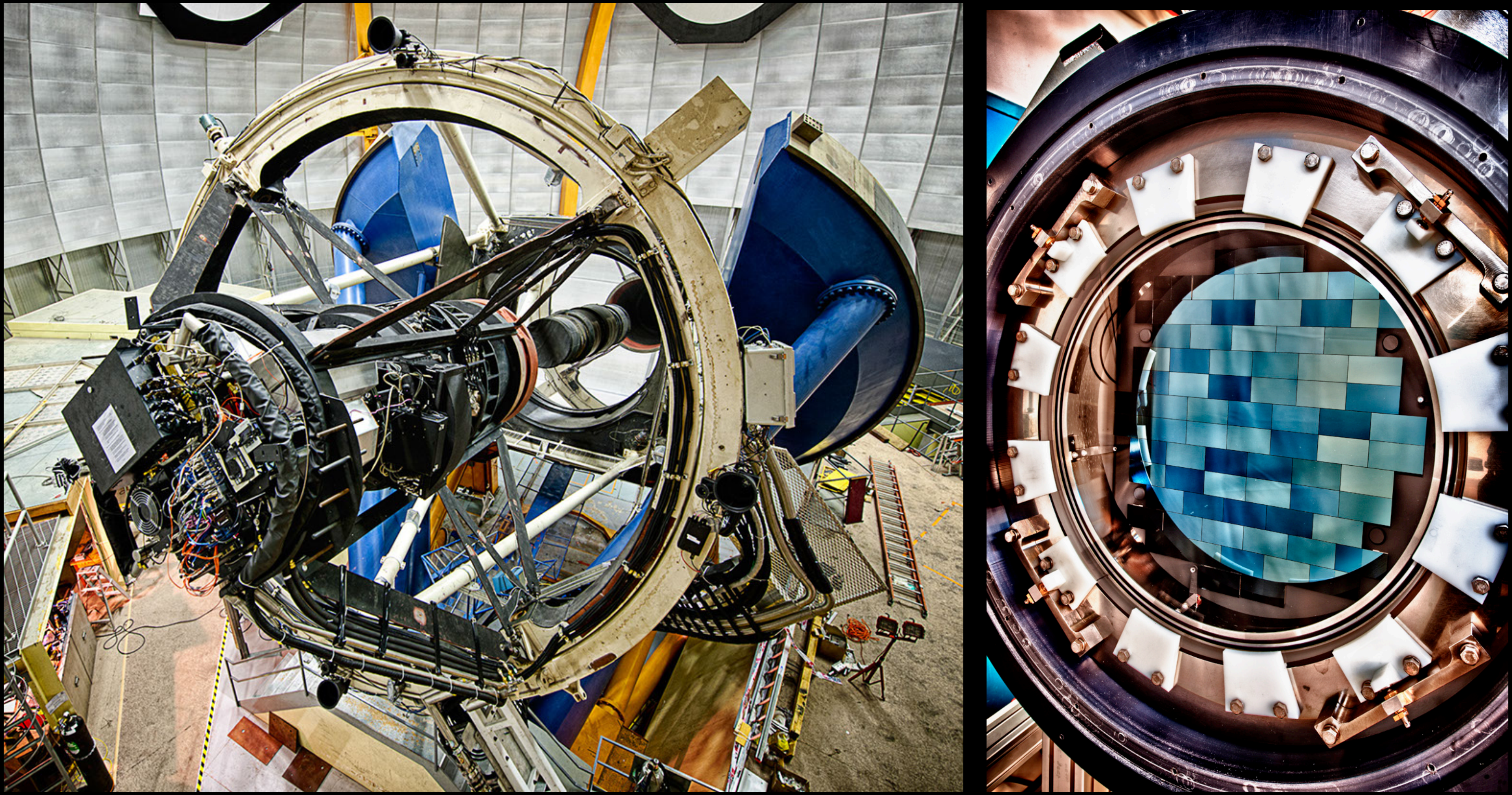
Next generation of instrumentation with scientific imaging sensors for astrophysics

Juan Estrada
Fermilab

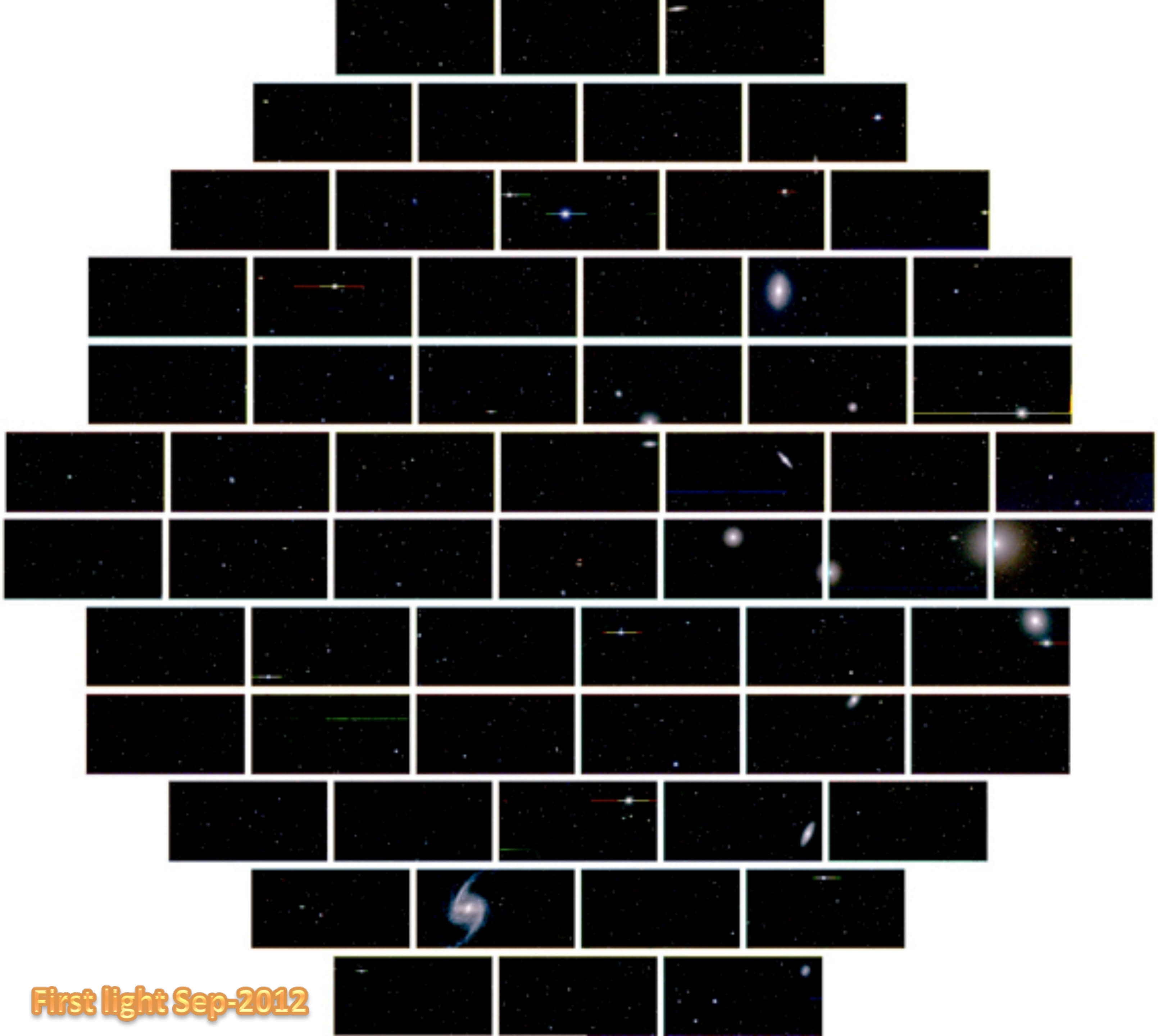
Thick CCD detectors

- Dark Matter Search
- Neutrino-nucleus coherent scattering
- Neutron Imaging

Microwave Kinetic Inductance Detectors (MKIDs)
- Photo-z machine for DES and LSST
- Lyman alpha intensity mapping



Dark Energy Camera



First light Sep-2012

Focal Plane Detectors

Science goal for DES: z~1

~50% of time in z-filter

825-1100nm

Astronomical CCDs are usually thinned to 30-40 microns (depletion):

Poor 900nm response

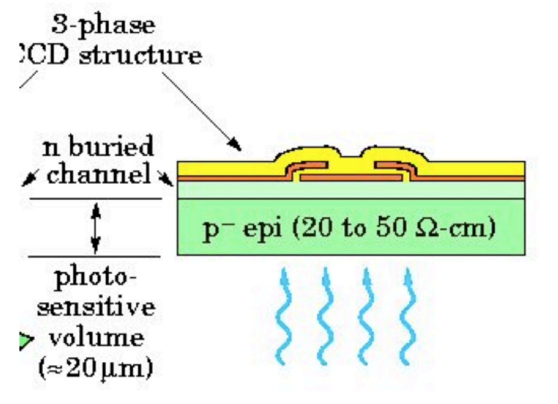
LBNL full depletion CCD

–250 microns thick

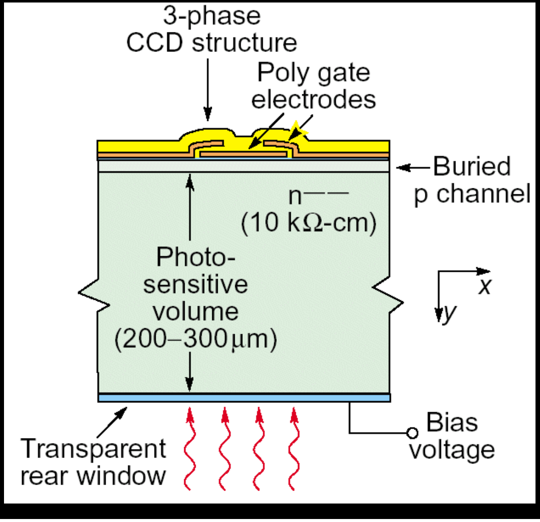
–high resistivity silicon

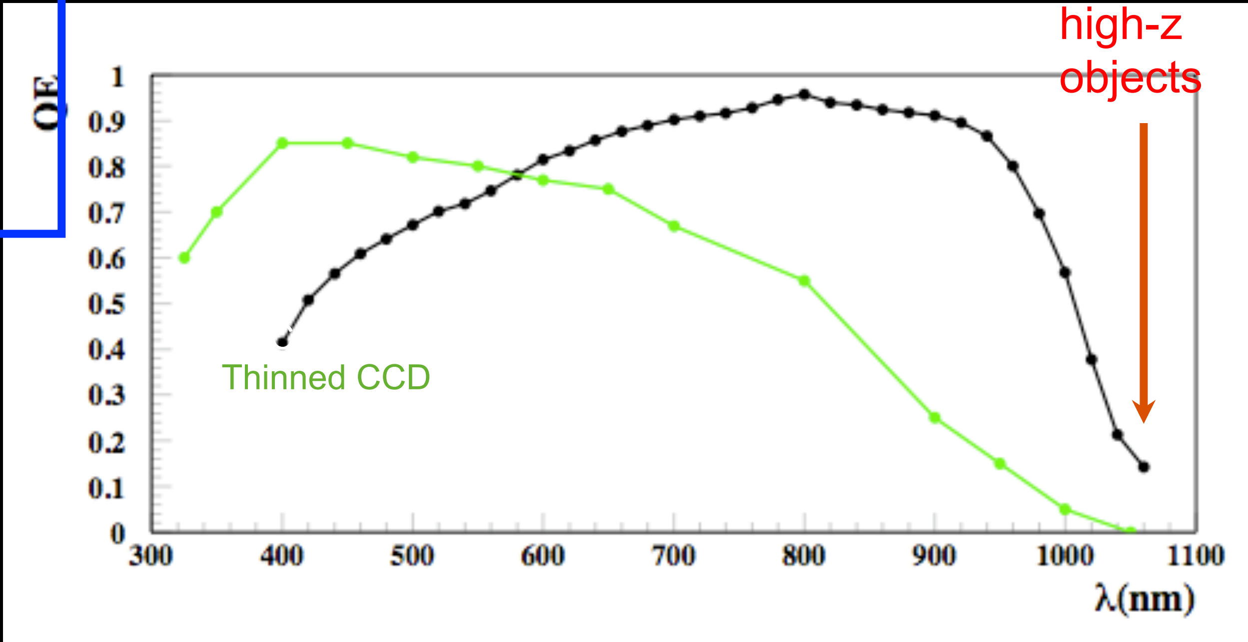
–QE> 50% at 1000 nm

thin CCD

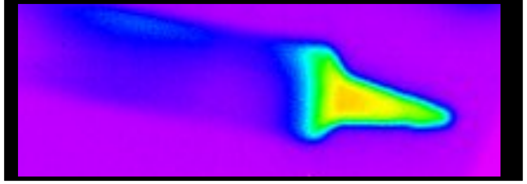


DECam CCD





IR image of soldering iron with a DECam CCD (K.Kuk)

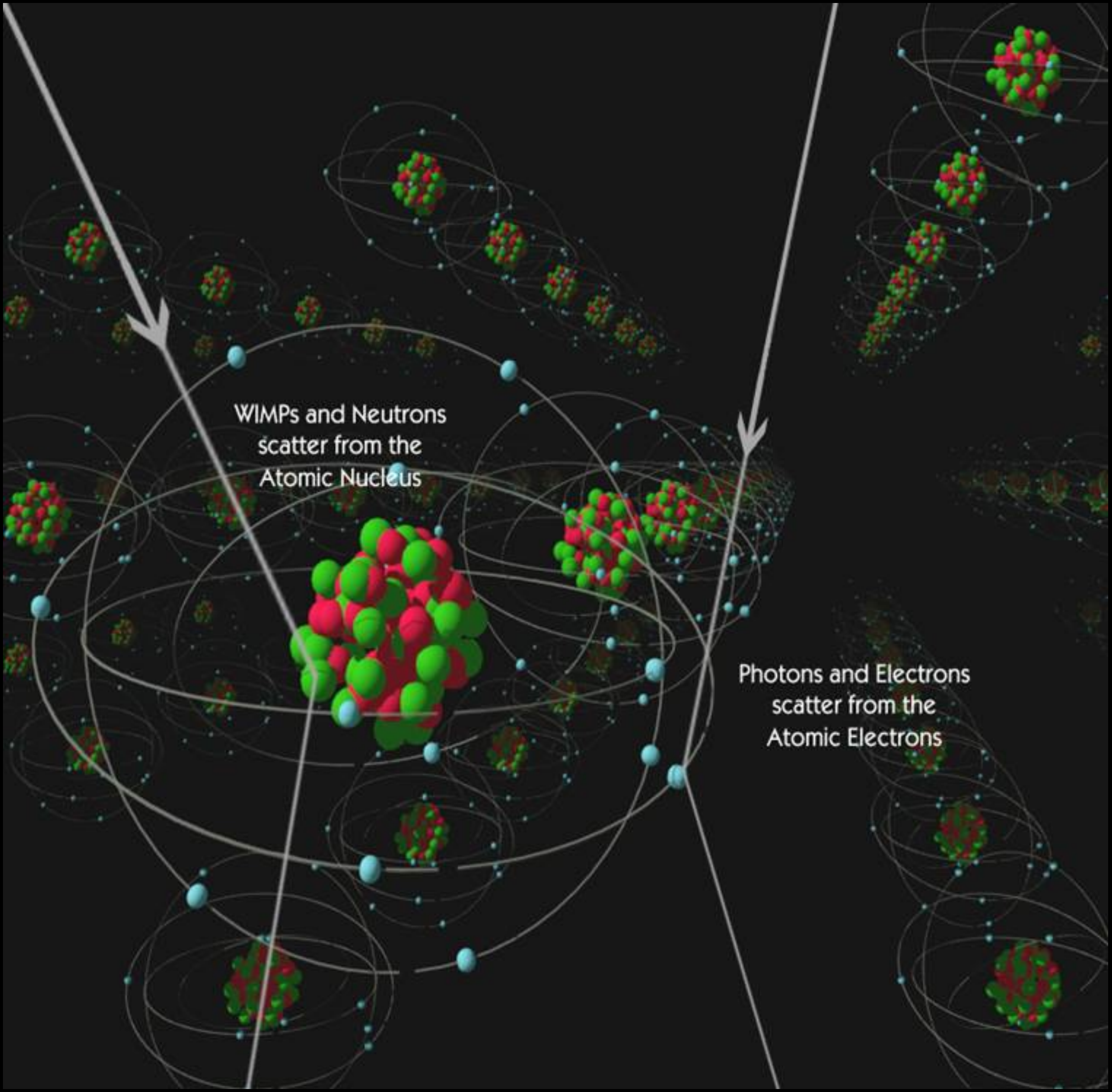


The beautiful images of the sky obtained with CCDs show only 15% of the matter in the universe. We are going for the not so shinny 85%.

Cerro Tololo Observatory
2200 m above see level

SNOLAB Underground Laboratory
2000 m underground.

Good detectors go to heaven, others go everywhere and have more fun...

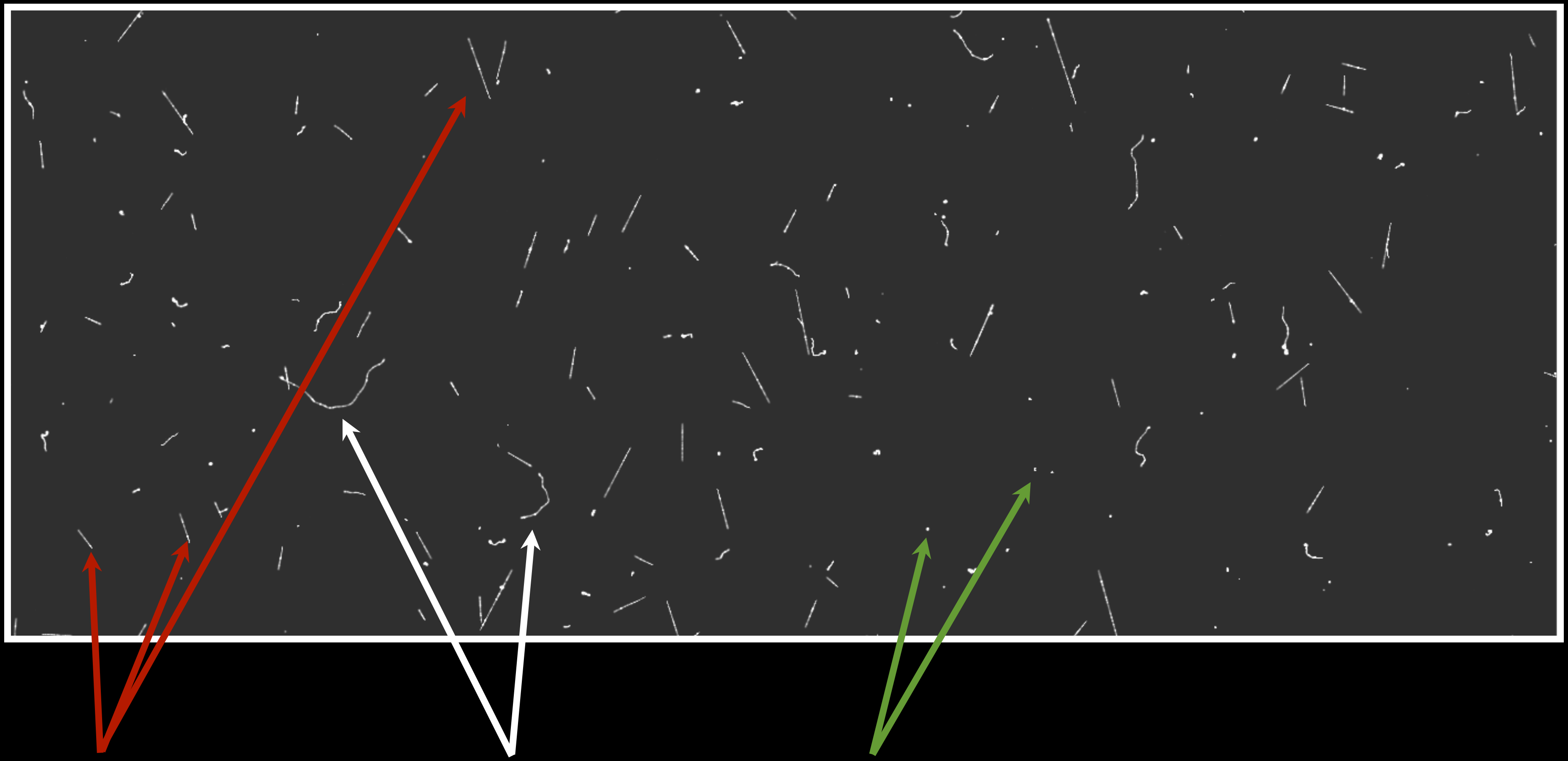


DM properties:
Small cross section for interaction with standard matter. Electrically neutral.

Recipe:

1) Choose a detector that can see neutral particles
2) Install it in a location where you will see small background from non DM particles
3) Wait for a DM particle to hit your detector

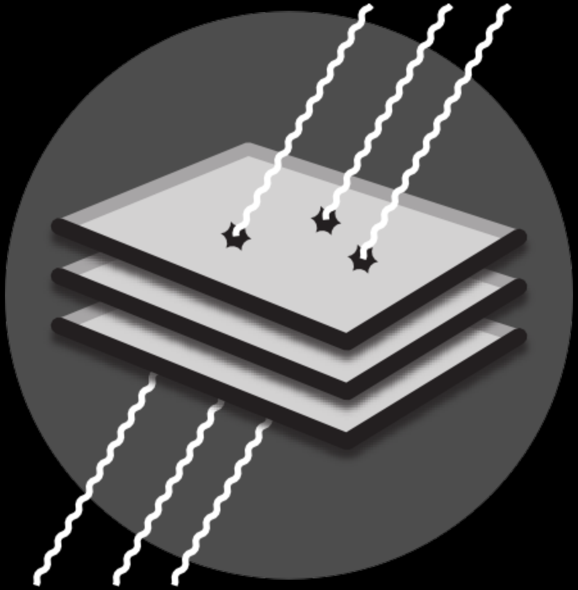
CCD as particle detector



muons, electrons and diffusion limited hits.

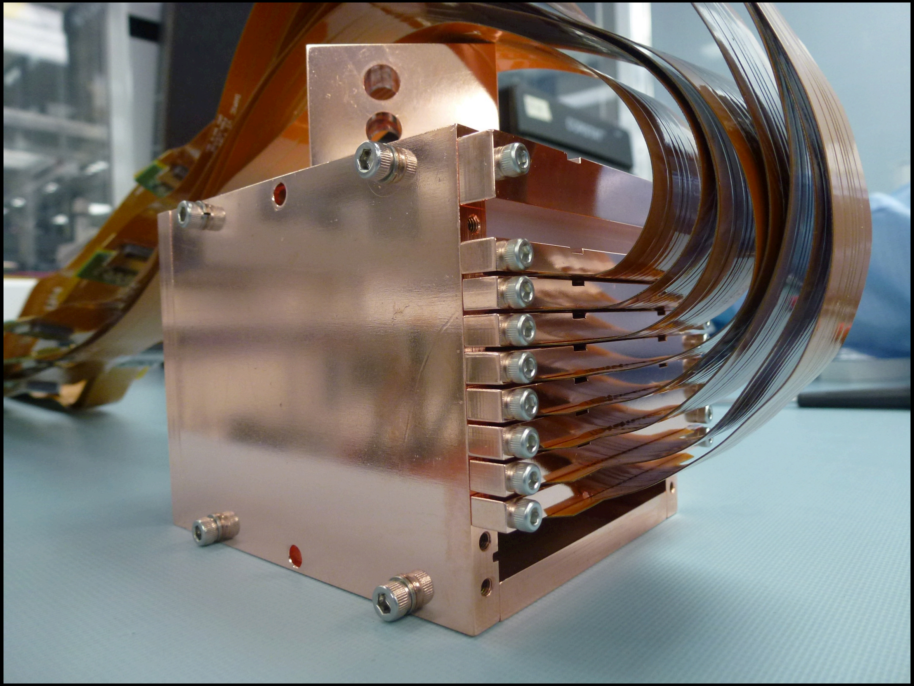
nuclear recoils will produce diffusion limited hits
Dark Matter is expected to produce nuclear recoils

DAMIC Collaboration



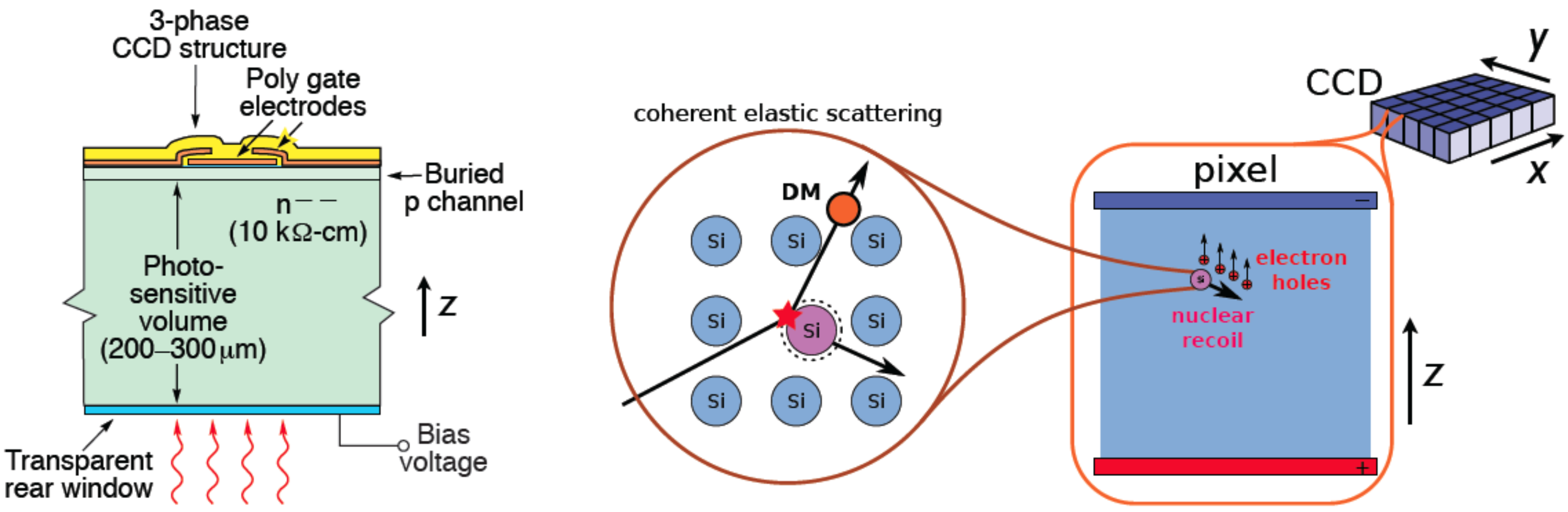
Fermi National Accelerator Laboratory, Universidade do Estado do Rio de Janeiro, Universidad Nacional Autonoma de Mexico, Universidad Nacional de Asuncion, University of Chicago, University of Michigan, University of Zurich.

12 faculty, 3 postdocs, 6 graduate students, undergraduate students



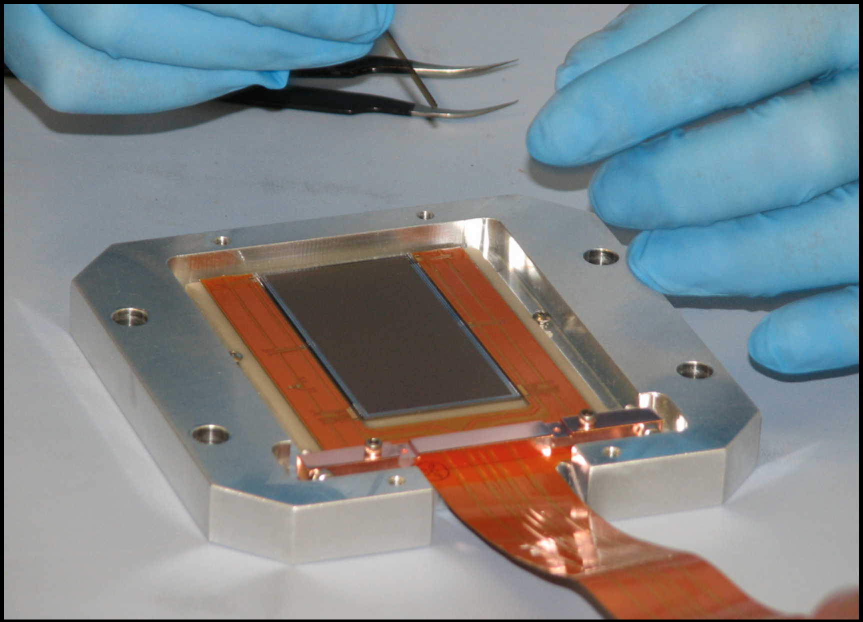
- CCDs developed for astronomy can be operated with a **40eV threshold**!
- Thick sensors recently developed for near-IR imaging have a large active mass, ~ 10g/CCD.

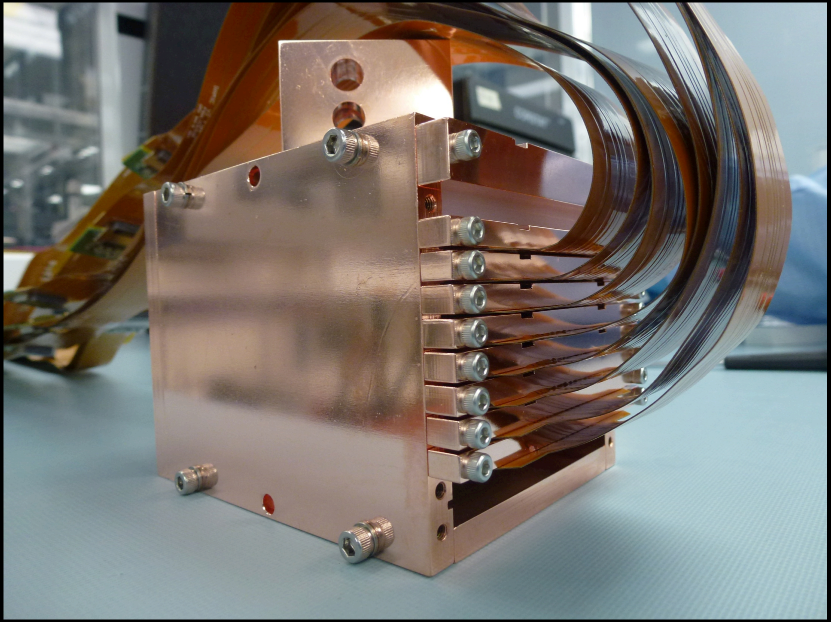
We installed an array 2000m underground to look for nuclear recoils produced by Dark Matter particles. Current best limit in the world for low energy recoils.

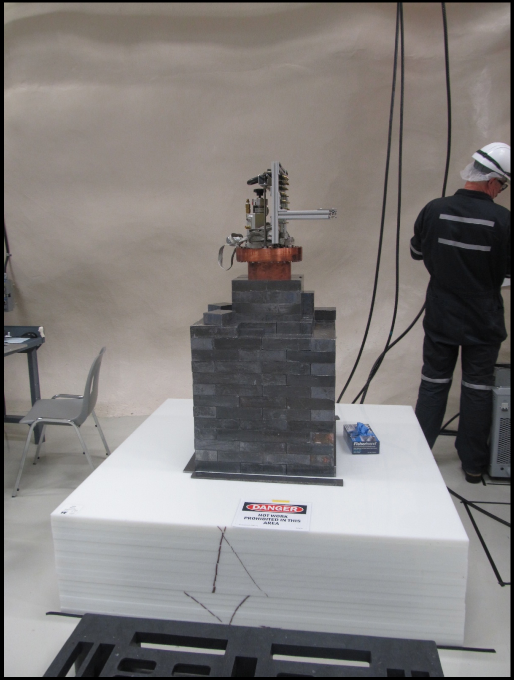


(a) A CCD pixel

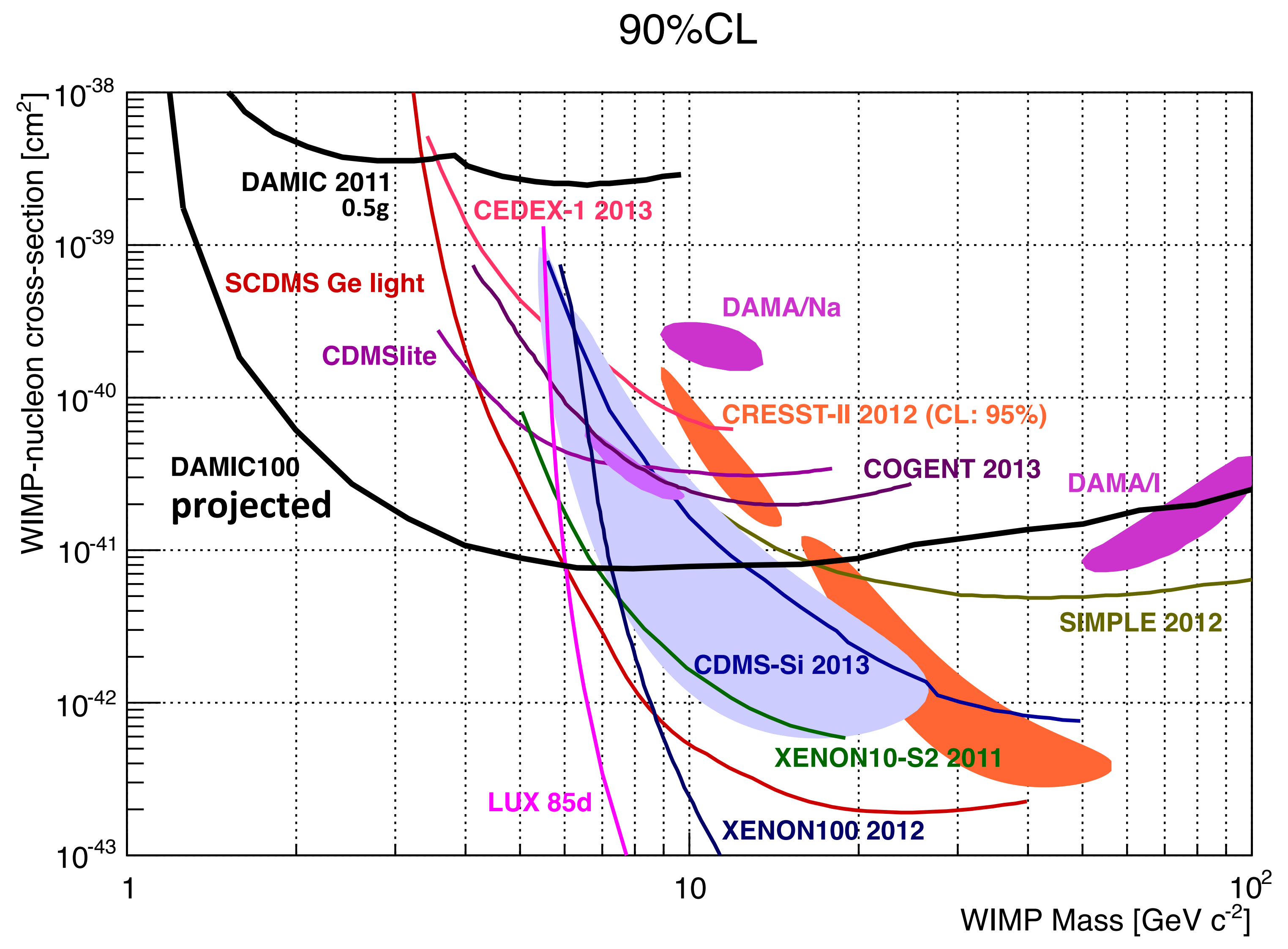
(b) WIMP detection principle





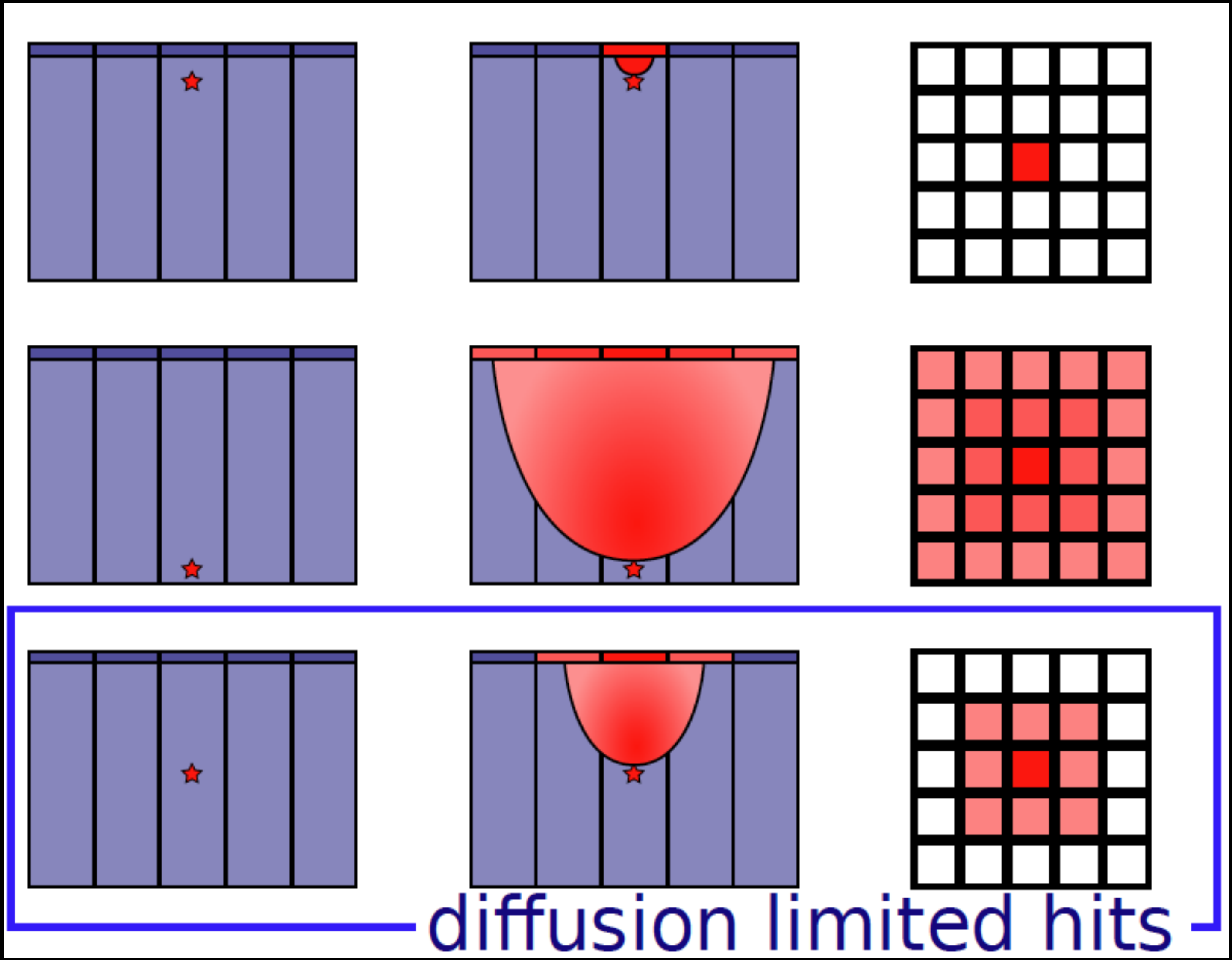


At SNOLAB underground lab.

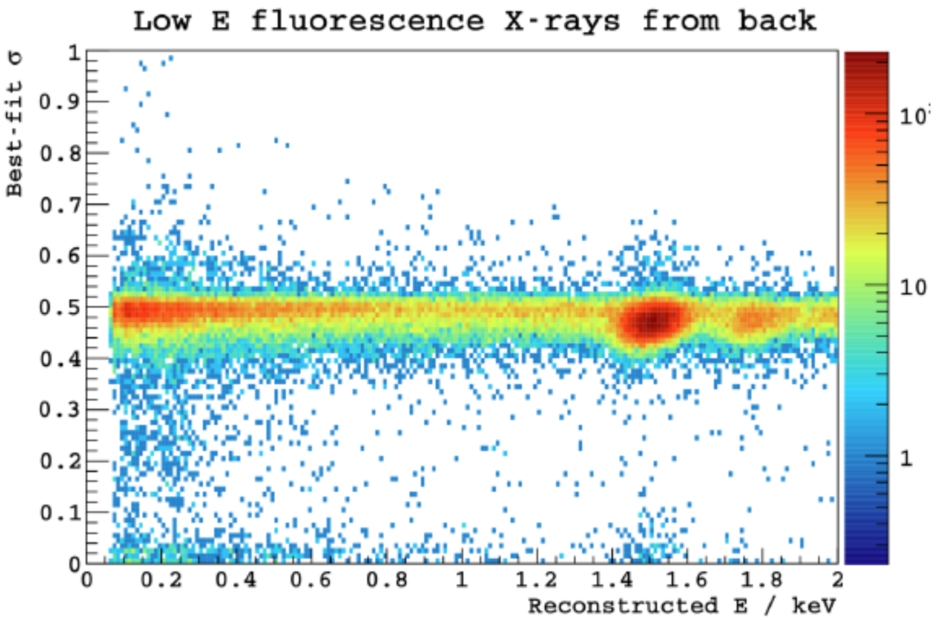


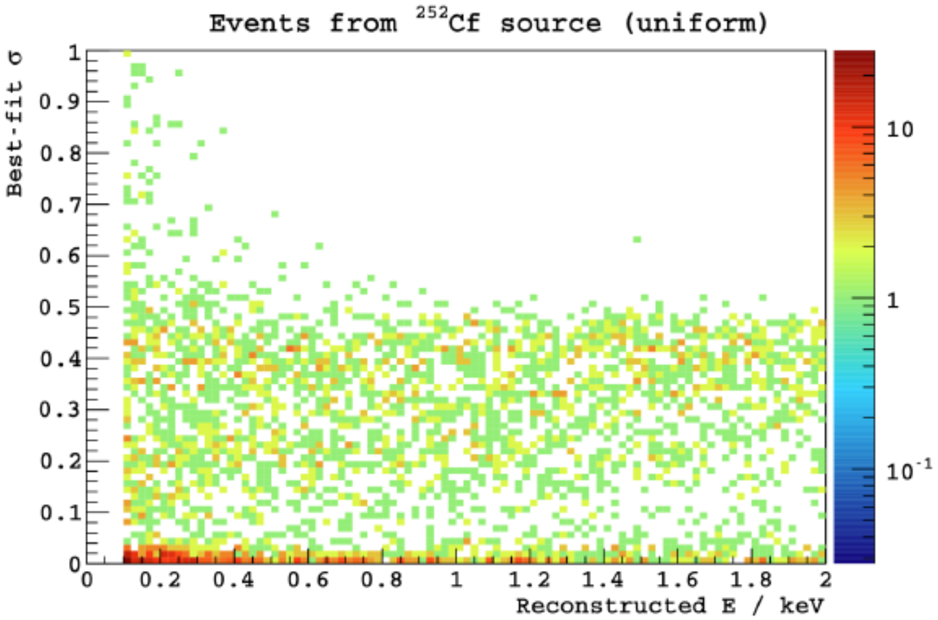
Lot's of activity in the low mass dark matter region.
Thick CCDs have role here because they have very low readout noise (x50 lower than other radiation detectors with a similar mass).

Diffusion gives us 3D hit reconstruction



CCD is not a 2D sensor anymore…

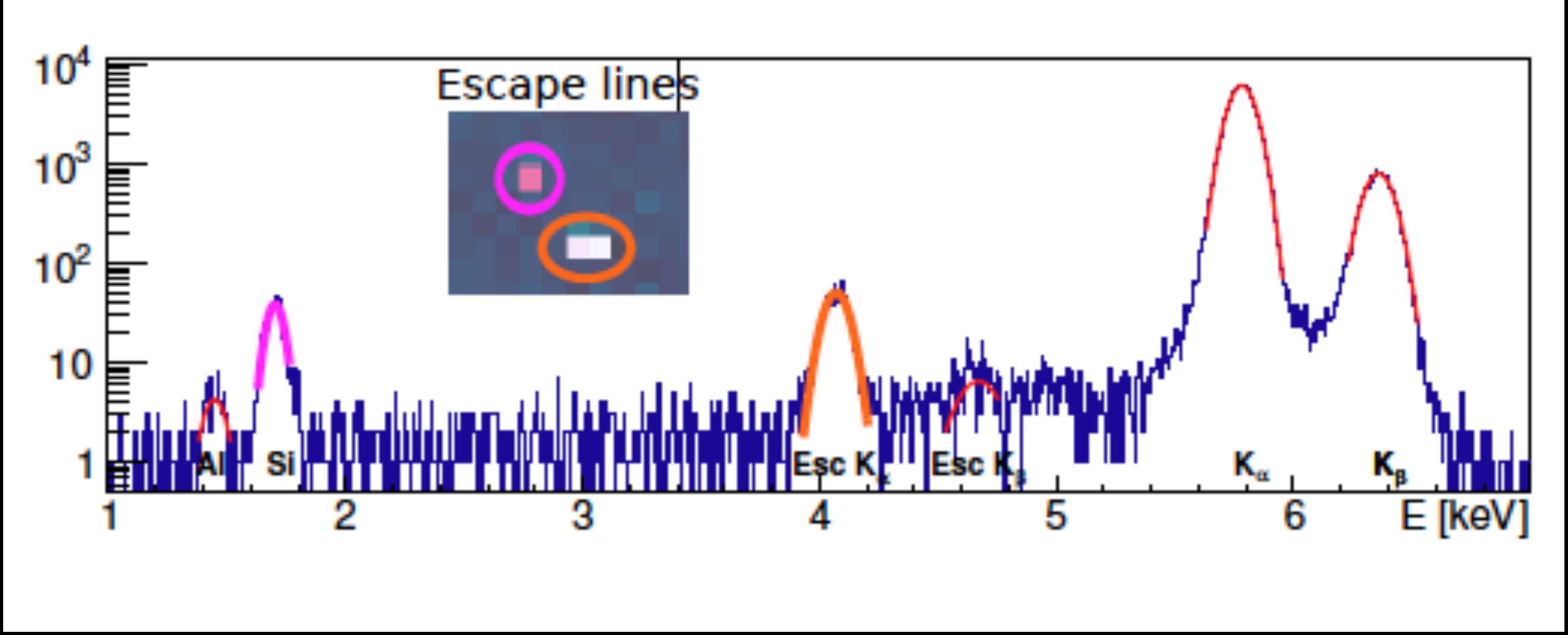




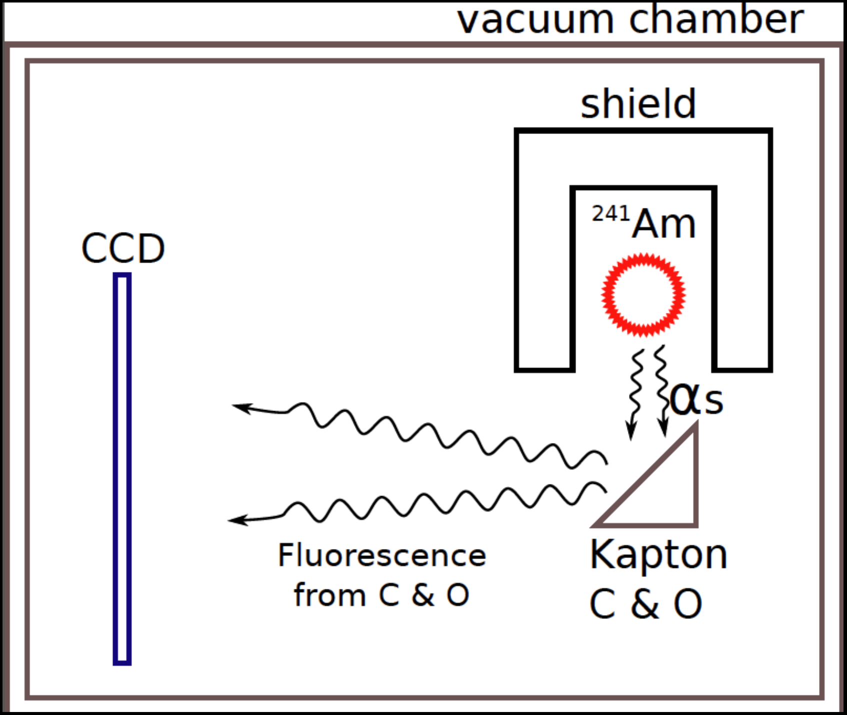
X-ray penetrate few um into the silicon.
Neutrons interact everywhere in the bulk.

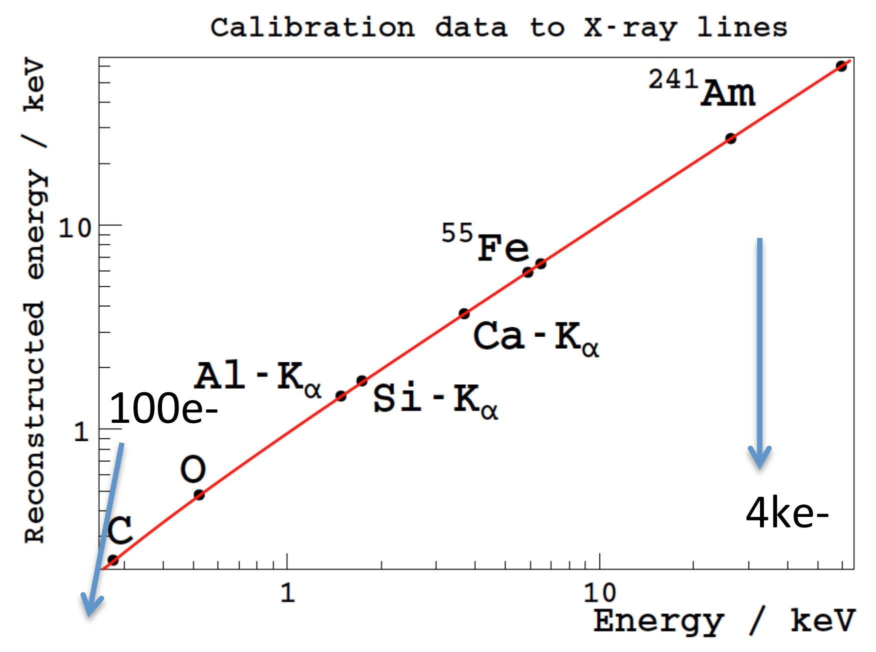
The density of hits for neutrons should be constant (only depend on the mass of each pixel). This is a nice way to measure the 3D volume of each pixel.

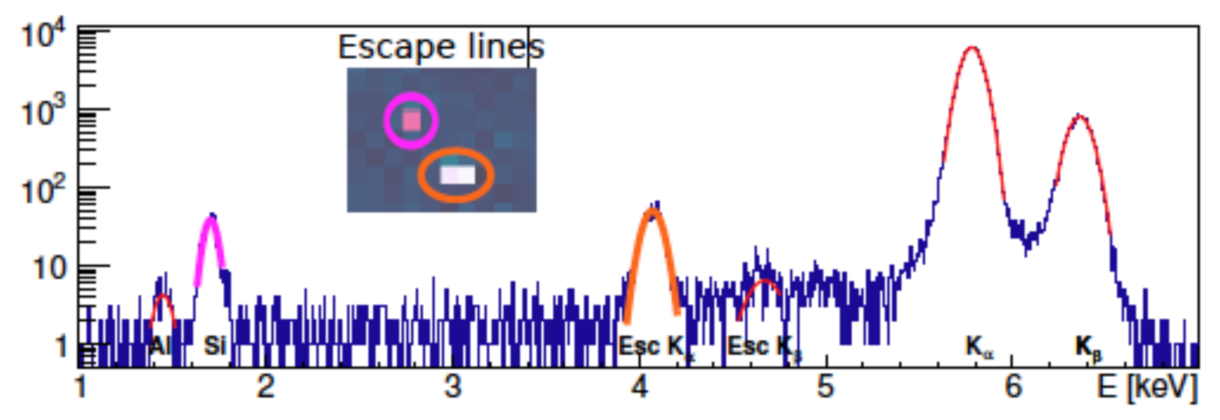
X-rays

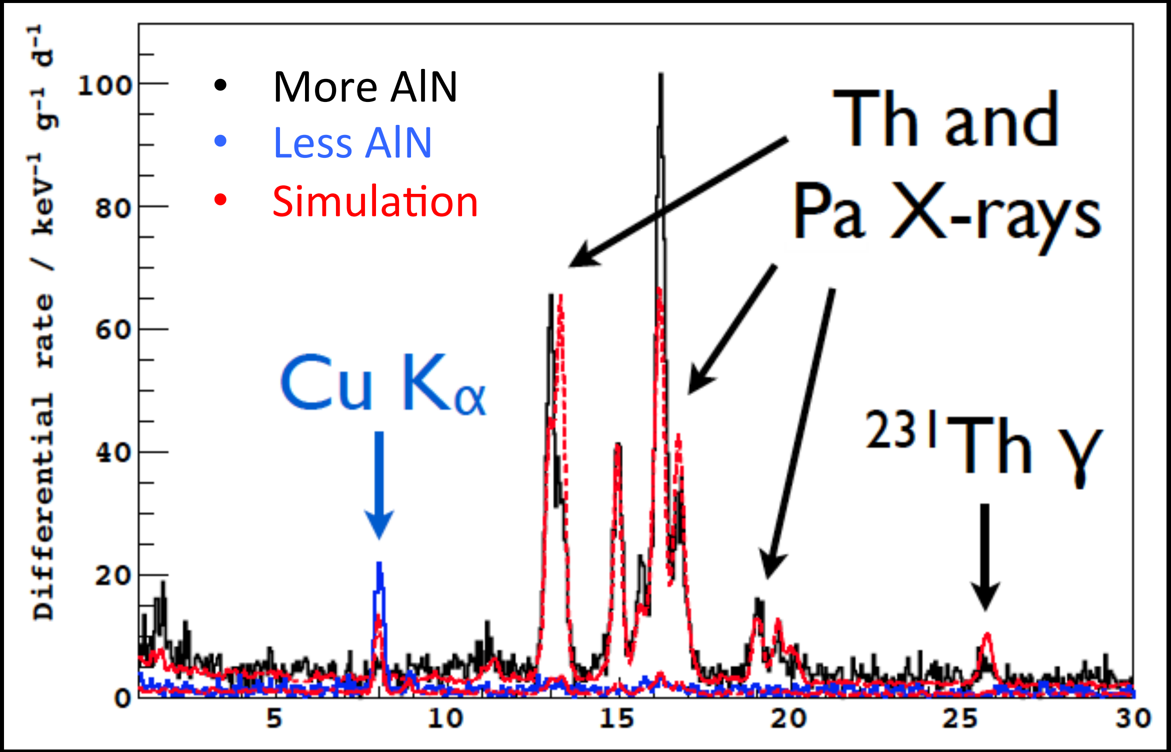

Escape lines
10^4
10^3
10^2
10
1
Al
Si
Esc K_α
Esc K_β
K_α
K_β
1
2
3
4
5
6
E [keV]

X-rays – calibrations

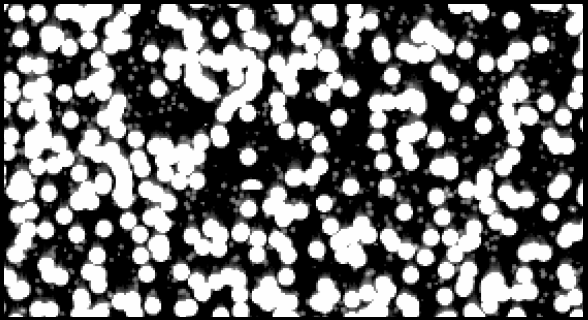


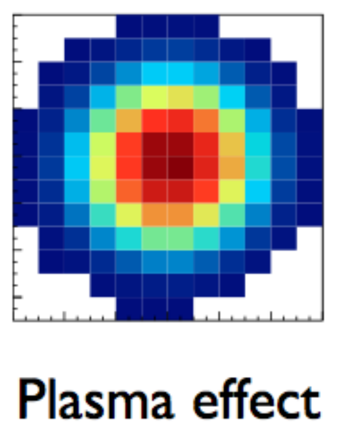






We are also starting to get a very good idea about which parts of the package are radioactive. The electronics next to the CCD is the largest offender, the AlN comes next.





Alpha particles produce plasma effect in silicon, and the signature is very easy to identify in the images.

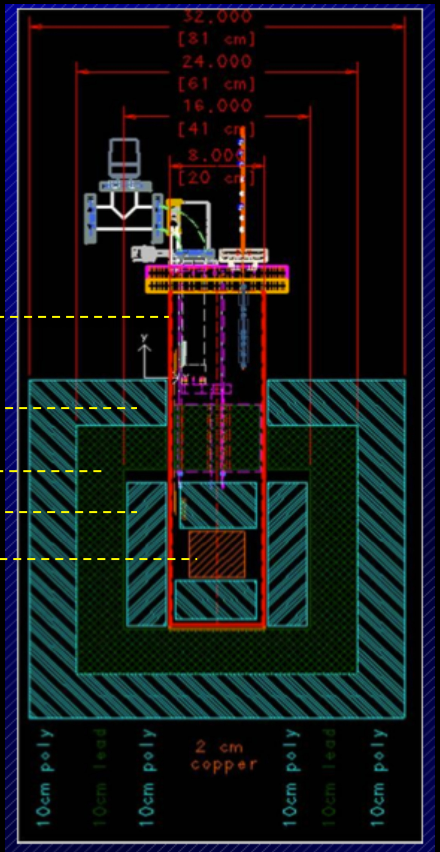
U and Th contamination in the Silicon would produce these, and they will not escape detection. Short range. We get **<10-4 Bq/kg of U + Th. Nice!**

Coherent Neutrino-Nucleus Interaction Experiment (CONNIE)

Fermilab CONICET CBPF Centro Brasileiro de Pesquisas Físicas UFRJ

Detection of coherent neutrino-nucleus scattering interaction using CCD, at Angra nuclear reactor, Brazil.

CCD System

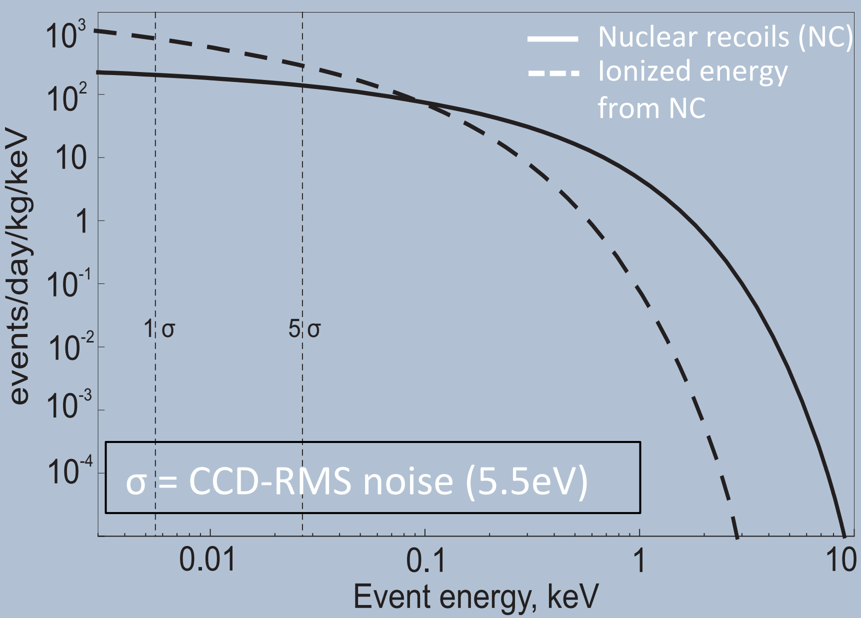


Container

Polyethylene
Lead
Polyethylene
CCD

Nuclear Plant

Spectrum of events expected in the CCD



Event Rate

Events/year for 52g of Si and different energy thresholds.

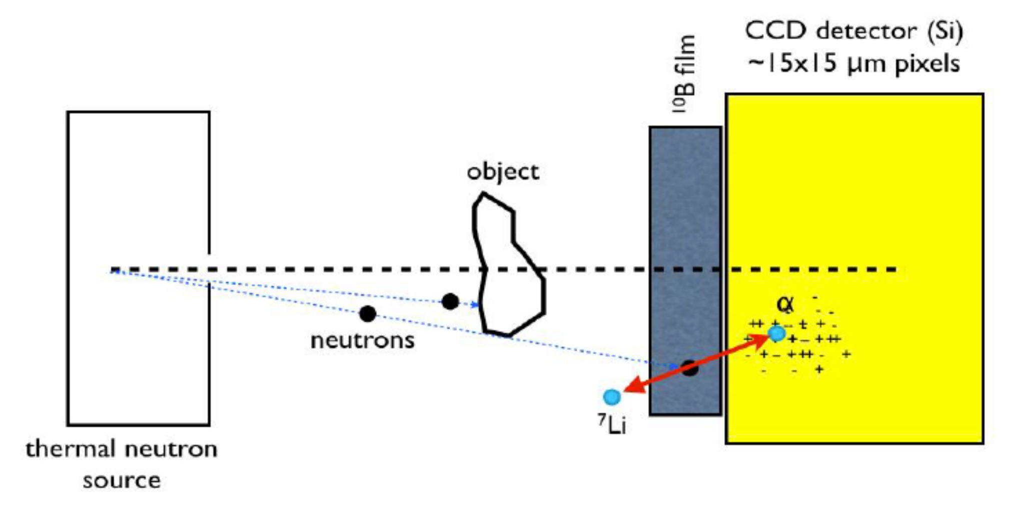
E_{th}	events/year
1σ (5.5eV)	532
5σ (28eV)	343

Running forecast

Running time, assuming: 52g of detecting mass, background of ~600 events/day/kg/keV (Heusser G., 1995), energy range: 28-300 eV.

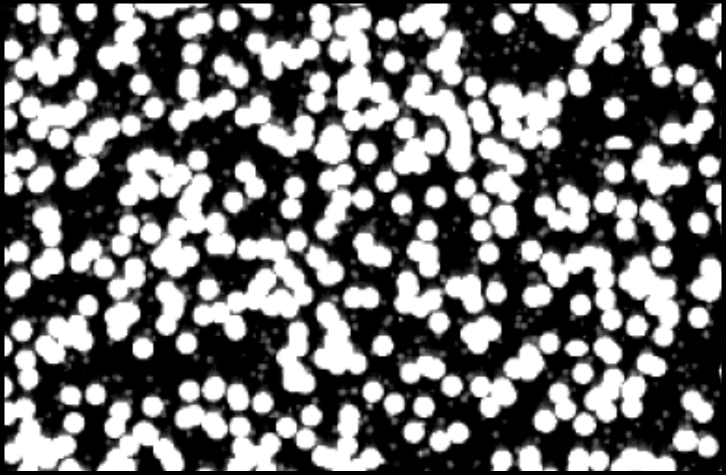
C. L. [%]	90	95	98	99.87
days	16	27	44	87

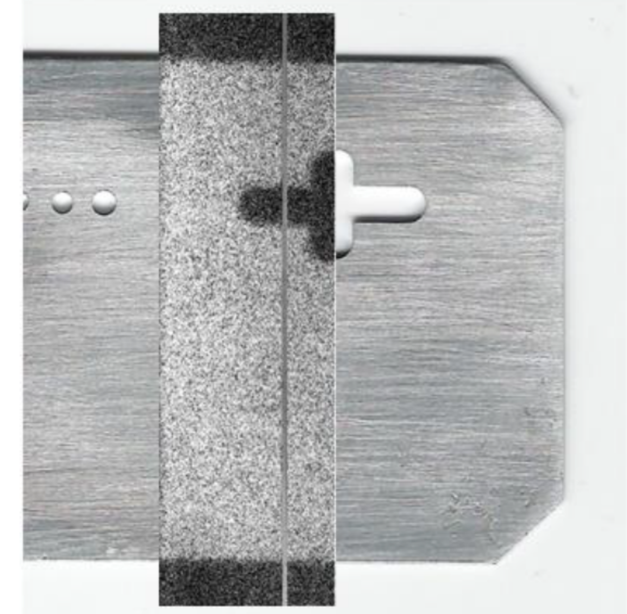
Currently inside a container in a ship off the coast of Brazil. Arriving at Rio next Monday. We are traveling to Brazil to start the installation next week.



Neutrons a background in our Dark Matter experiment, so we try to measure them. For this we coated a CCD with Boron-10 film.

The thermal neutron is captured, converts into an alpha, a we can clearly see the alpha.



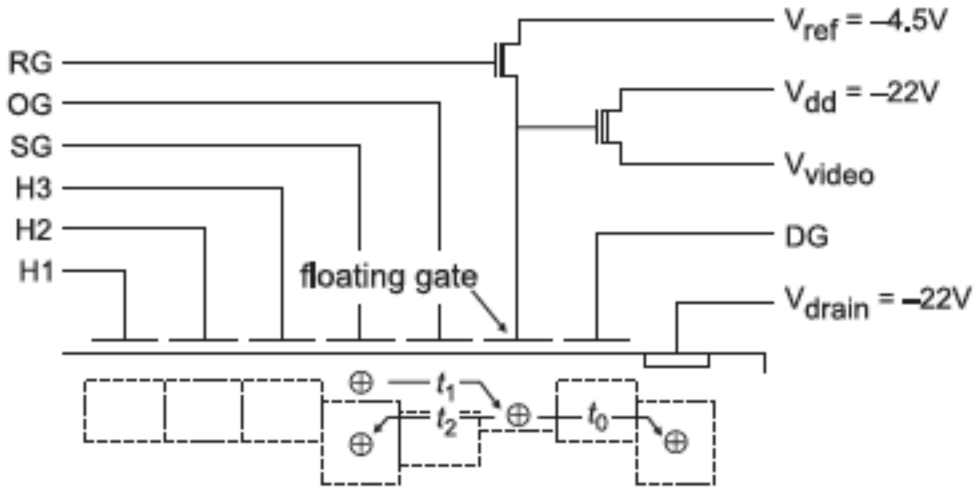


Neutron imaging of Cd plate @ FNAL.

Charge cloud produced by alpha is distributed over many pixels (plasma effect inside silicon). **Thermal neutron detector with spatial resolution of a few microns.**

arXiv:1408.3263, arXiv:1105.3229, DOE patent application

Arxiv: 1106.1839



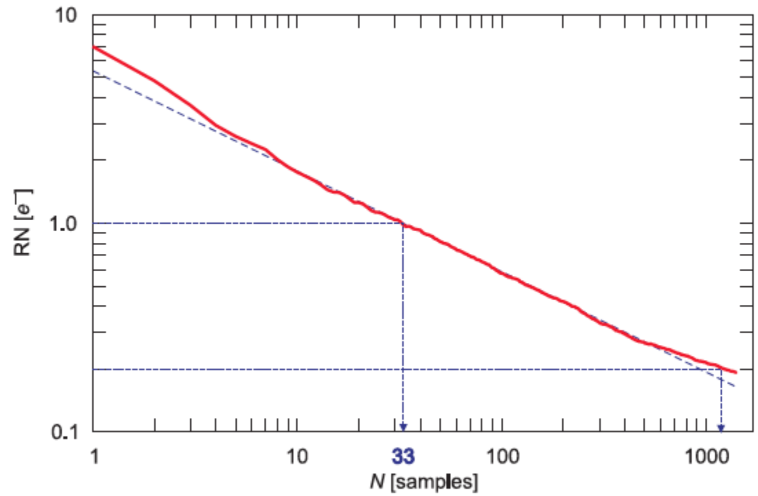


Figure 9: Skipper CCD RN as a function of the number of averaged samples N. Continuous line: RN measured from images. Dashed line: theoretical white noise fit for the image RN.

By changing the output stage on the CCD, we can read the charge on each pixel multiple times (N~1000), and reduce the readout noise by 1/√N.

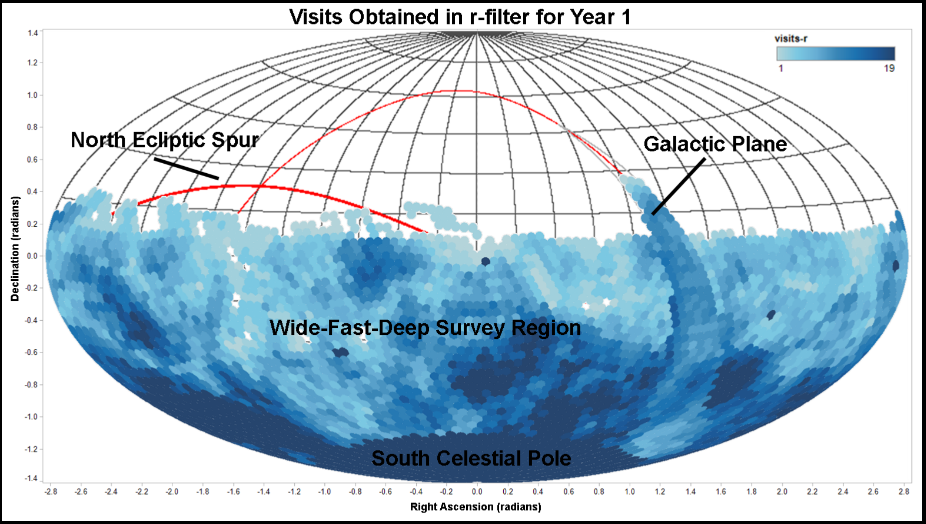
Background experiments with single electron threshold.

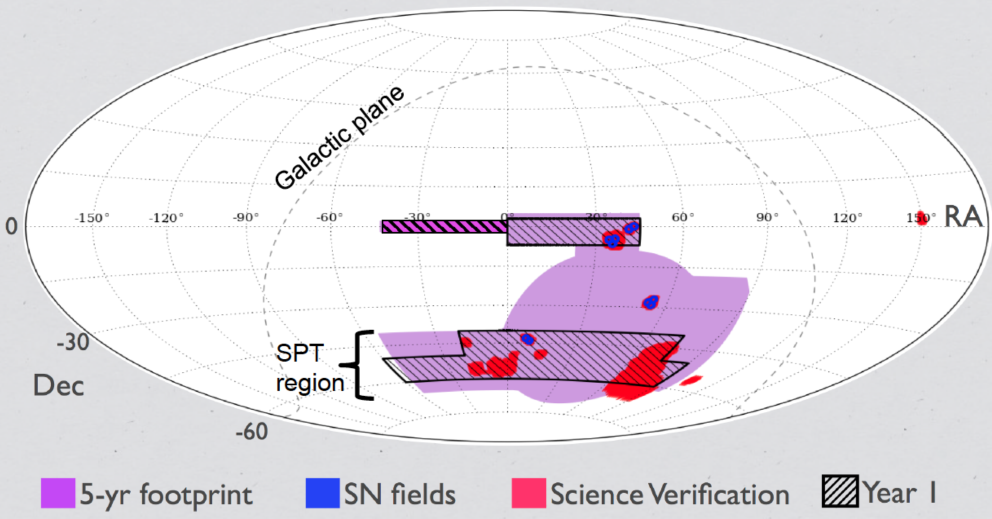
We know in Silicon at -100C you can get a single electron with ~1eV of deposited energy (near IR).

Prototype sensors fabricated by LBNL, large mass detector coming.

Technology to detect Sub GeV dark matter, by looking a very low energy electron recoils.

DES + LSST imaging surveys

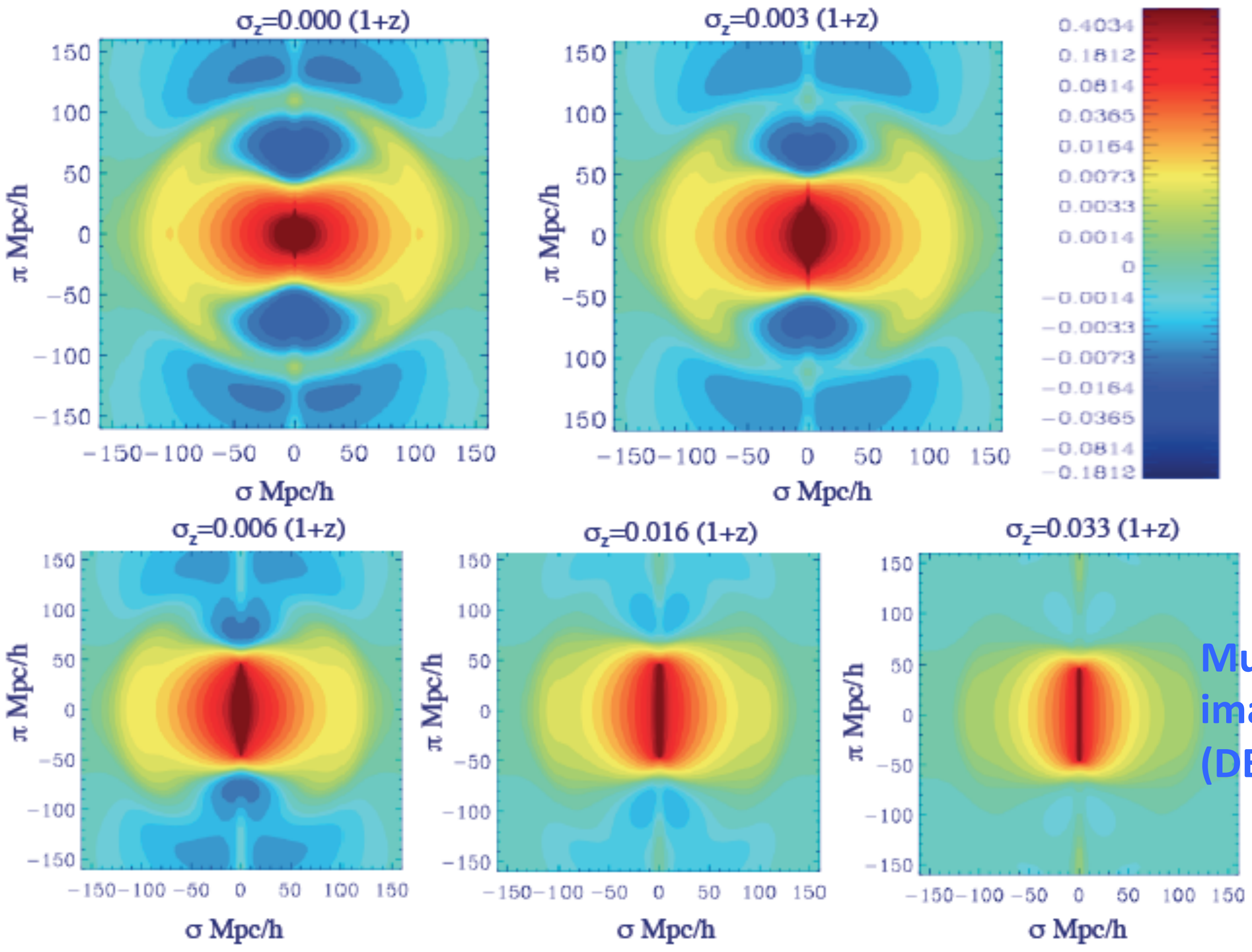




Will count photons in filter 5 filters from a large fraction of the sky. We will not have spectra for the observed objects.

Cosmology would benefit from spectra.

Cosmological information lost due to photo-z error

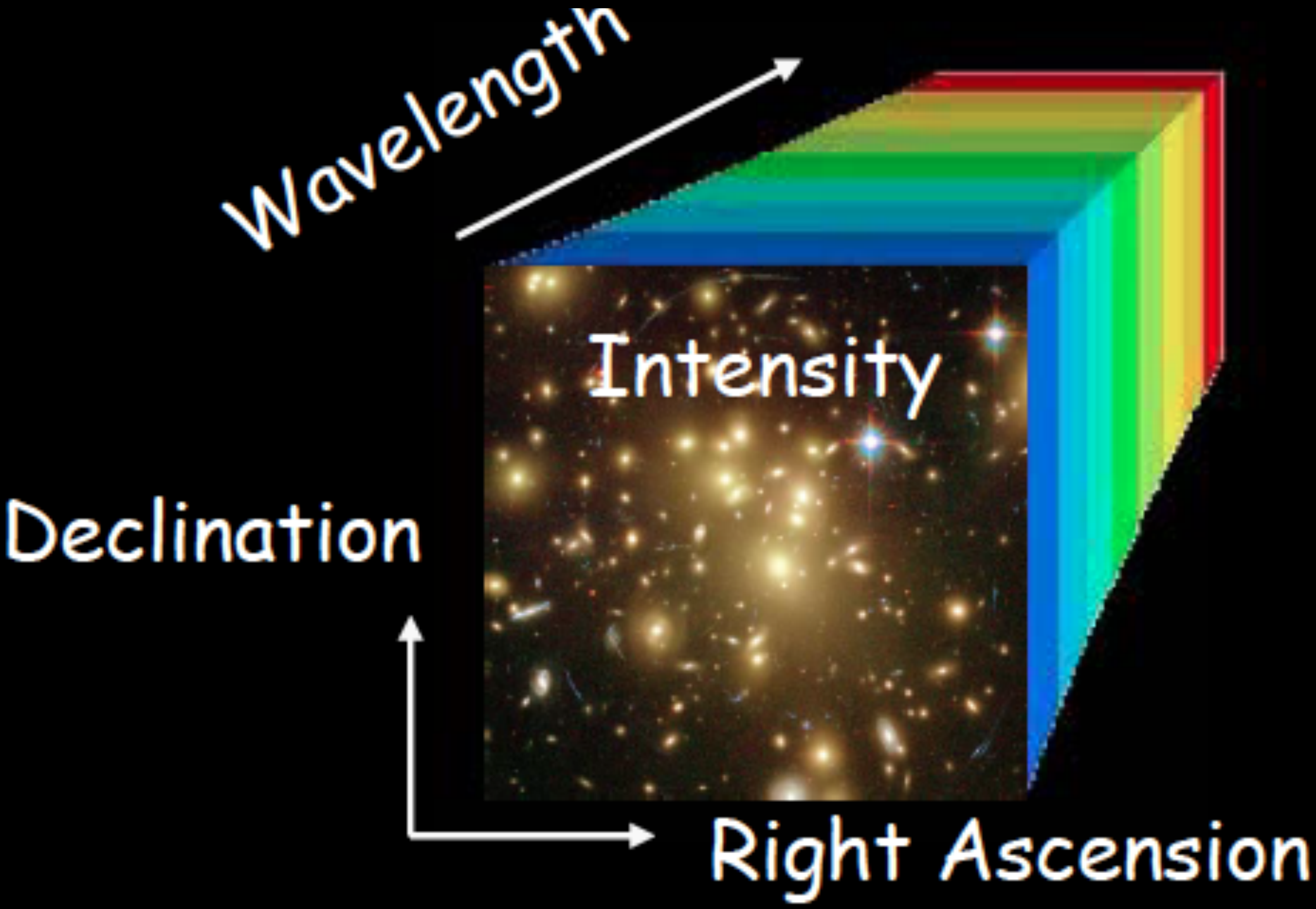


Hi-res Spectrum (DESI)

Multi filter imaging (DES, LSST)

Figure 2. Top left panel shows the $\xi(\pi,\sigma)$ correlation in the Kaiser model with no photo-z error, i.e. $\sigma_z = 0$ (from Gaztañaga, Cabré & Hui 2009). The correlation is clearly squashed in the radial direction with a region of negative correlation (in blue) between $\pi = 50 - 100$ Mpc/h. Top right panel shows the same model but with a photo-z degradation of $\sigma_z = 0.003(1+z)$, corresponding to the PAU Survey. The difference is small and is mostly confined to small radial scales. Bottom panels show how the results are degraded as we increase σ_z to 0.006 (left), 0.016 (center) and 0.033 (right panel). As the photo-z increases the radial squashing disappears, turning instead into a radial elongation. Note also how the region of negative correlation vanishes as we increase the photo-z error.

Gastanaga et al, Monthly Notices of the Royal Astronomical Society, Volume 422, Issue 4, pp. 2904-2930.


Wavelength
Intensity
Declination
Right Ascension

Semiconductor (CCDs)

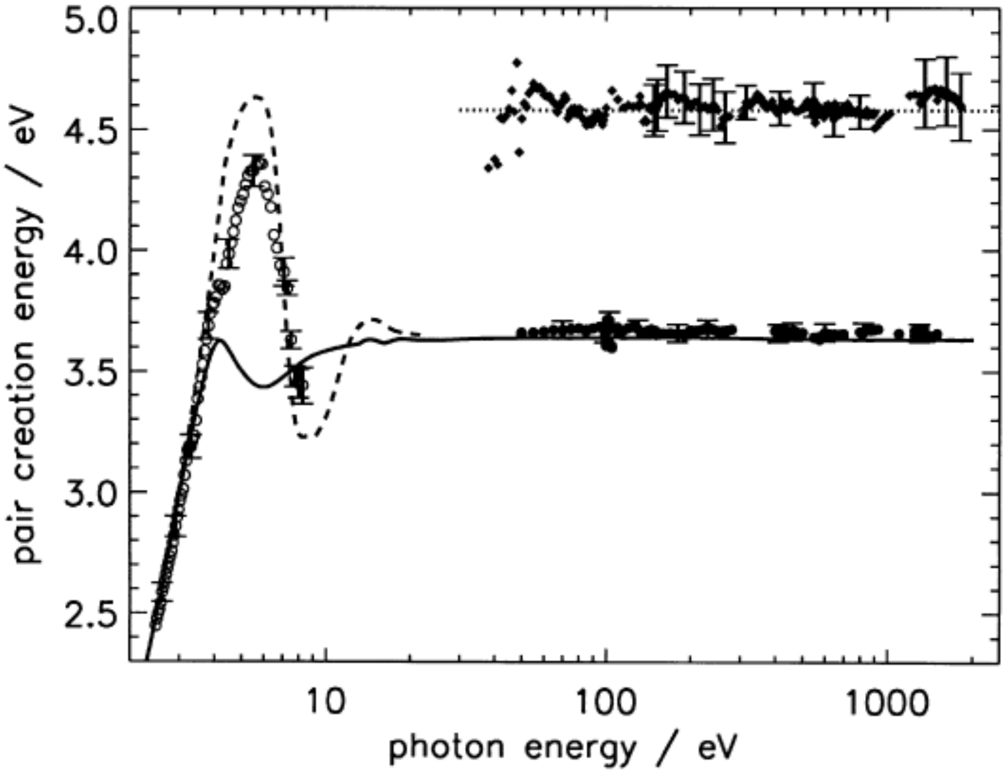
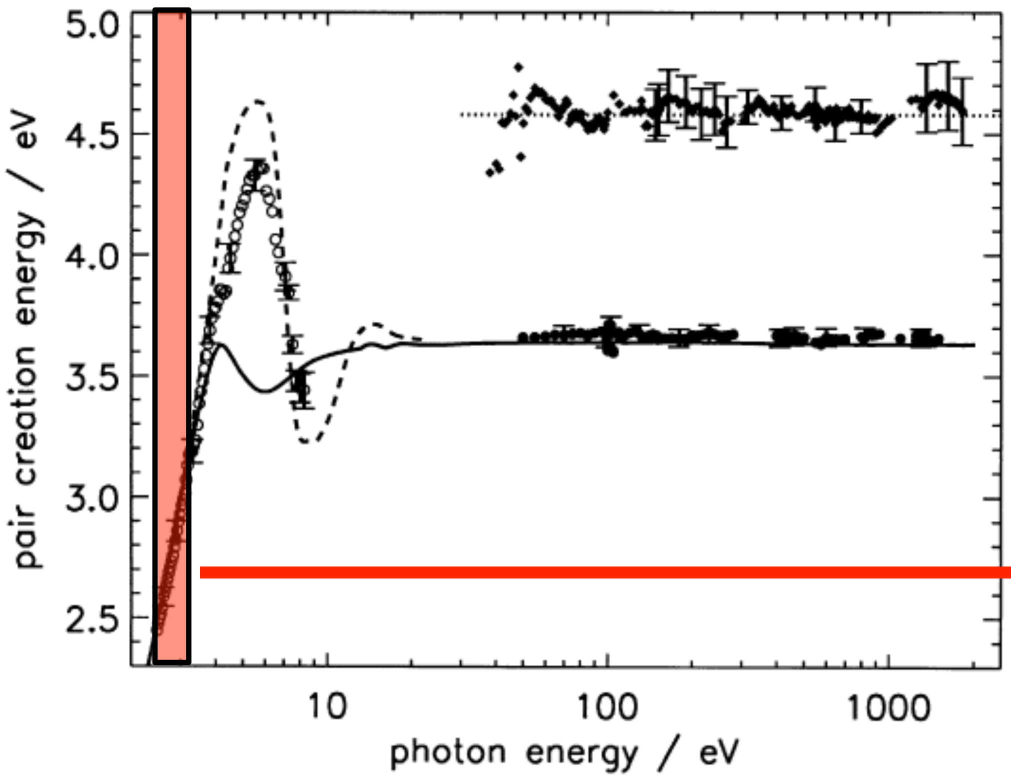


Fig. 5. Mean energy *W* required for creating an electron-hole pair determined from s_r and s: for silicon in the soft X-ray region [14] (closed circles) and UV and VUV region [21] (open circles) and for GaAsP in the soft X-ray region (diamonds). Typical experimental uncertainties are indicated. For silicon, calculations from Ref. [14] are shown as solid line and dashed line (see text). The points indicate the mean value of 4.58 eV for GaAsP.

Semiconductor (CCDs)



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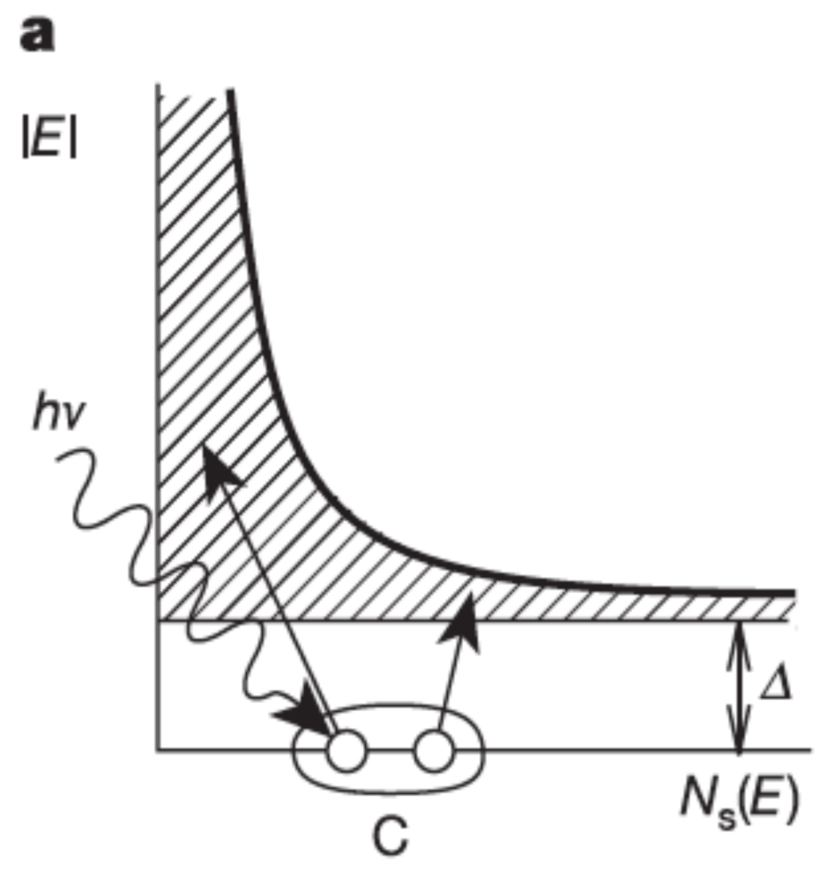
This is the optical range… unfortunately the 1e/photon here. That is why we a need spectrograph to follow up.

Superconductor



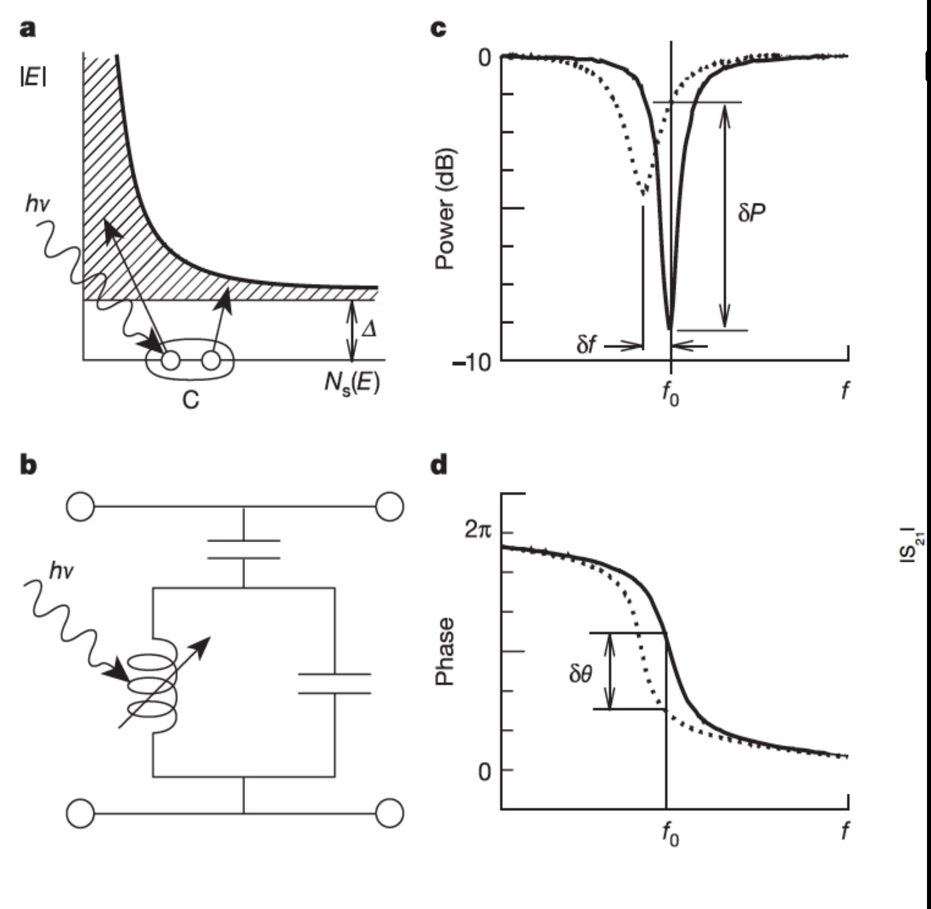
~5000 quasiparticles/ visible photon !

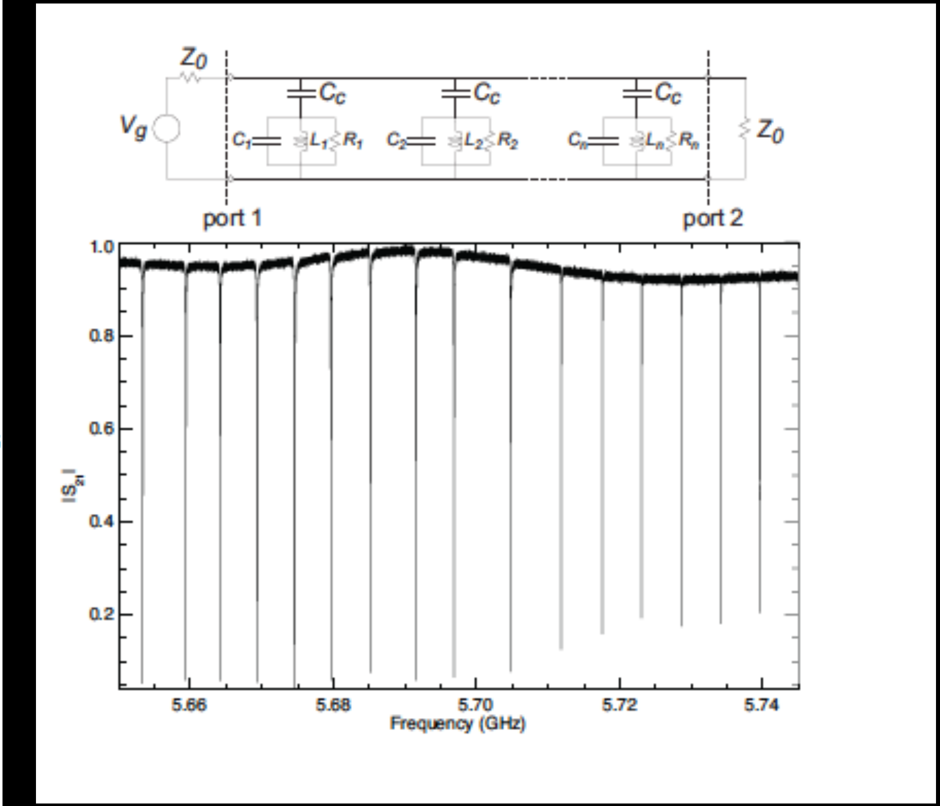
quasiparticles:

$$N_{qp} = \eta h \nu / \Delta$$

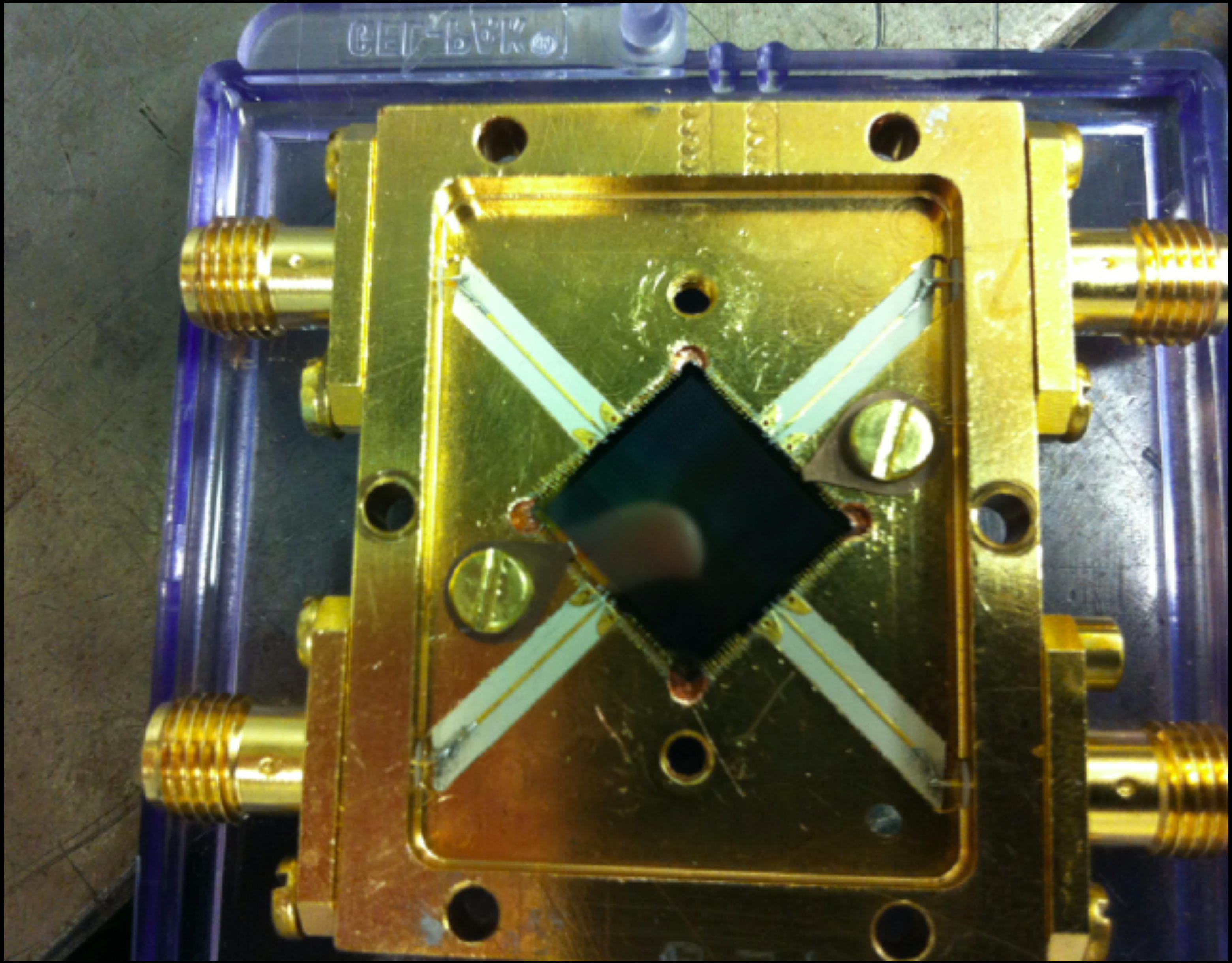
Δ : Energy gap
~ 0.001 eV

η: is an efficiency
~ 0.6



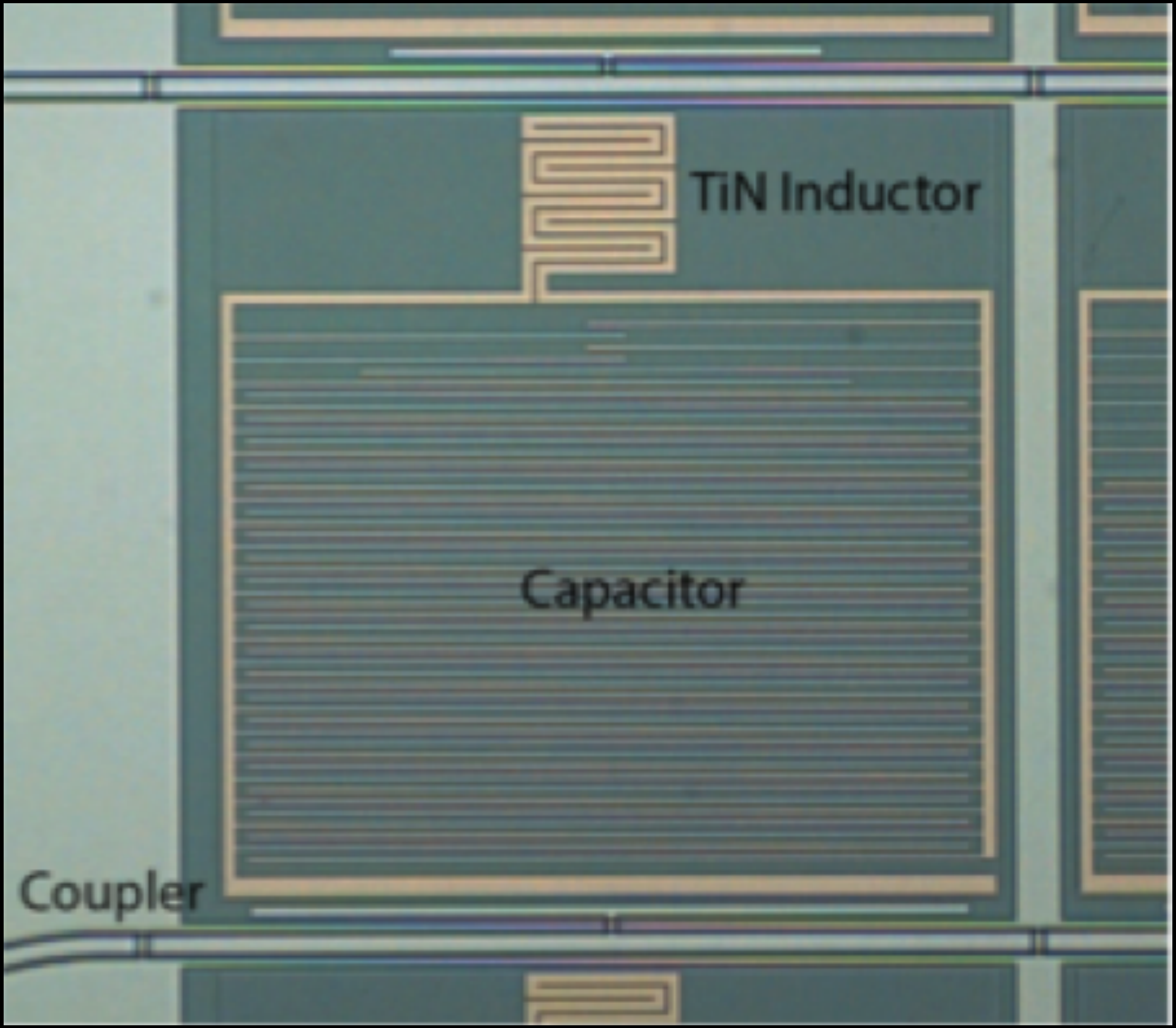


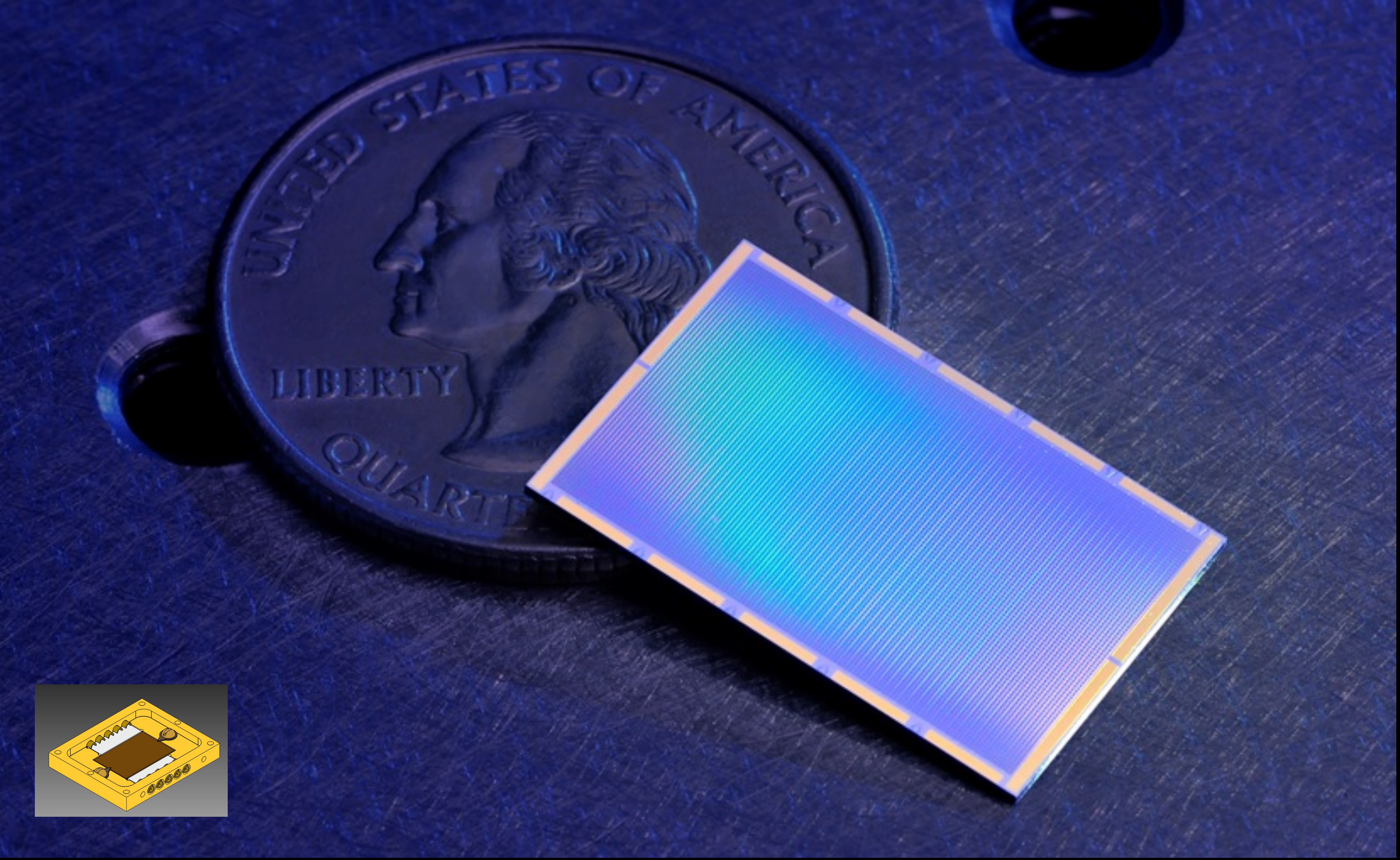
There are a few talks about Kinetic Inductance Detectors today, here will concentrate on the application for optical and near-IR astronomy.



2K pixels detector designed at UCSB (Prof. Mazin)

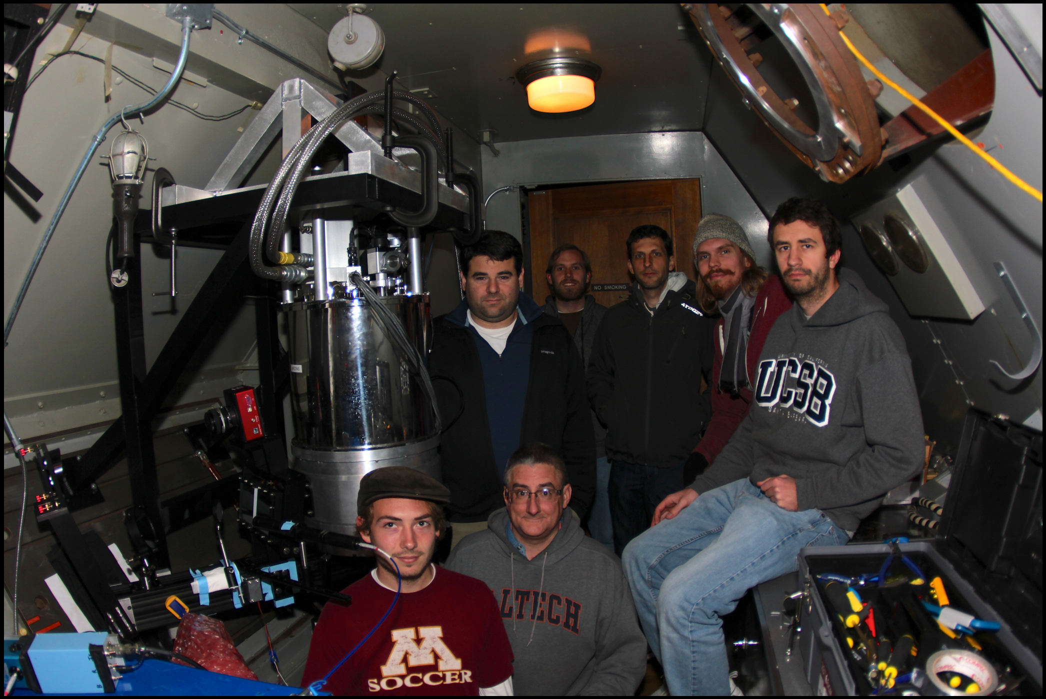
MKID pixel

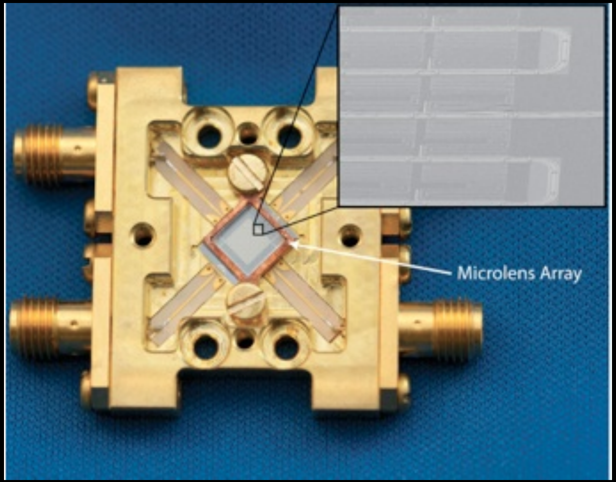


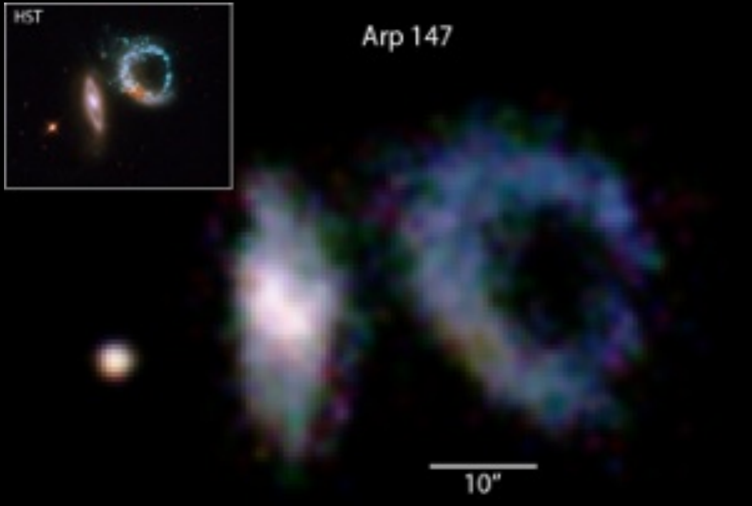


10 K resonators device (B.Mazin UCSB)

Optical MKIDs developed by tested in a small stronomical instrument 1k pixels in 2011, “2k” pixels in 2012. Going to the telescope again now.







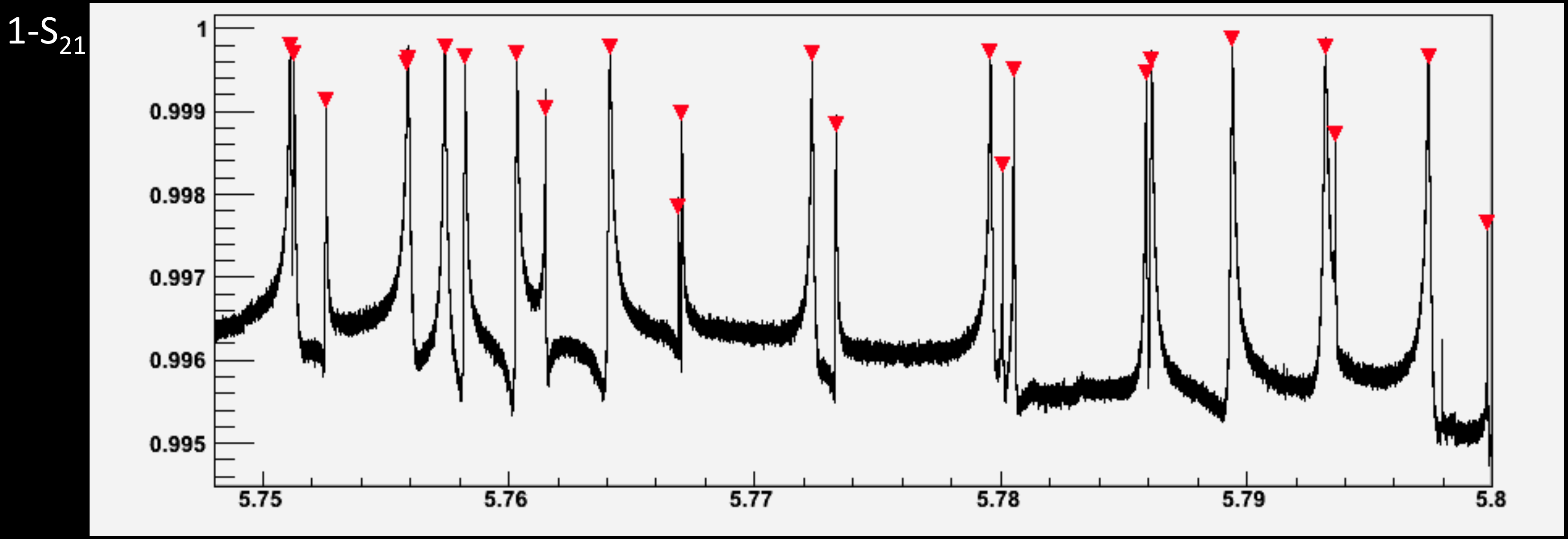
operating temperature = 100 mK

UCSB, JPL, OXFORD, FNAL.

preliminary mosaic of Arp 147 taken with ARCONS at the Palomar 200”

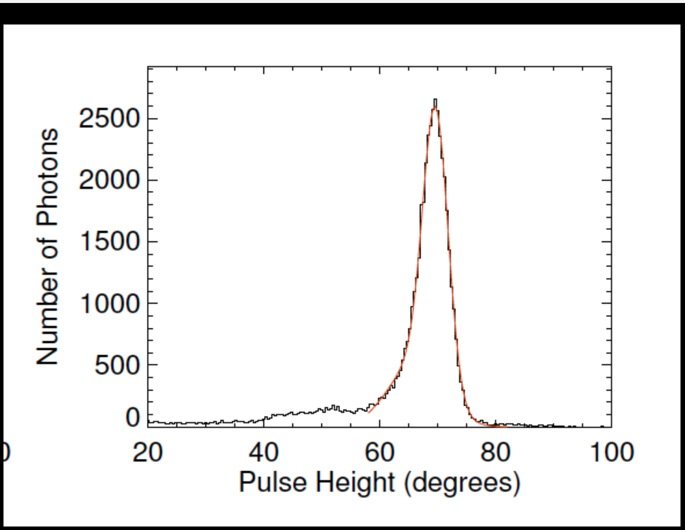
There is still a lot of work to do

- Pixel overlap
- Pixel non-uniformity (Q)
- Pixel spacing

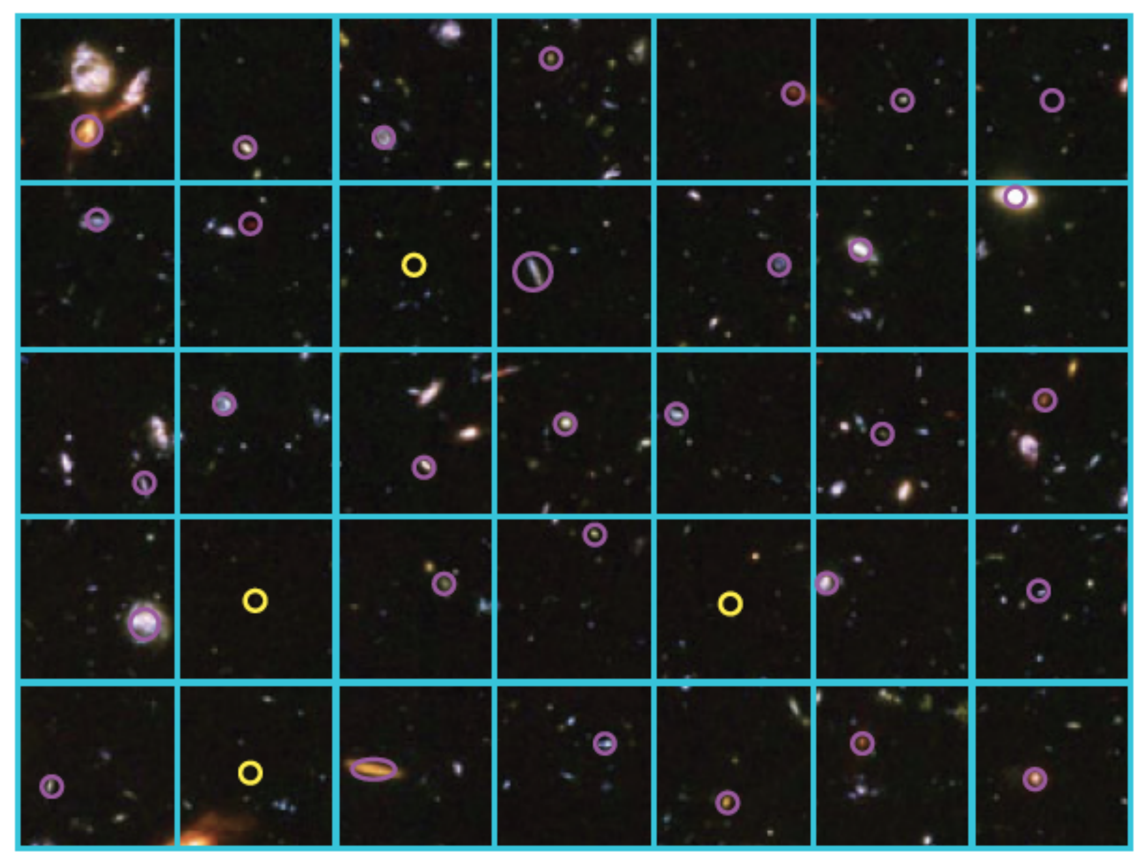


$R = E/\delta E = 16$ @250nm

Theoretical limit for the MKIDs is R=180 (quasiparticle statistics). There is still a long way to go before we reach this limit.

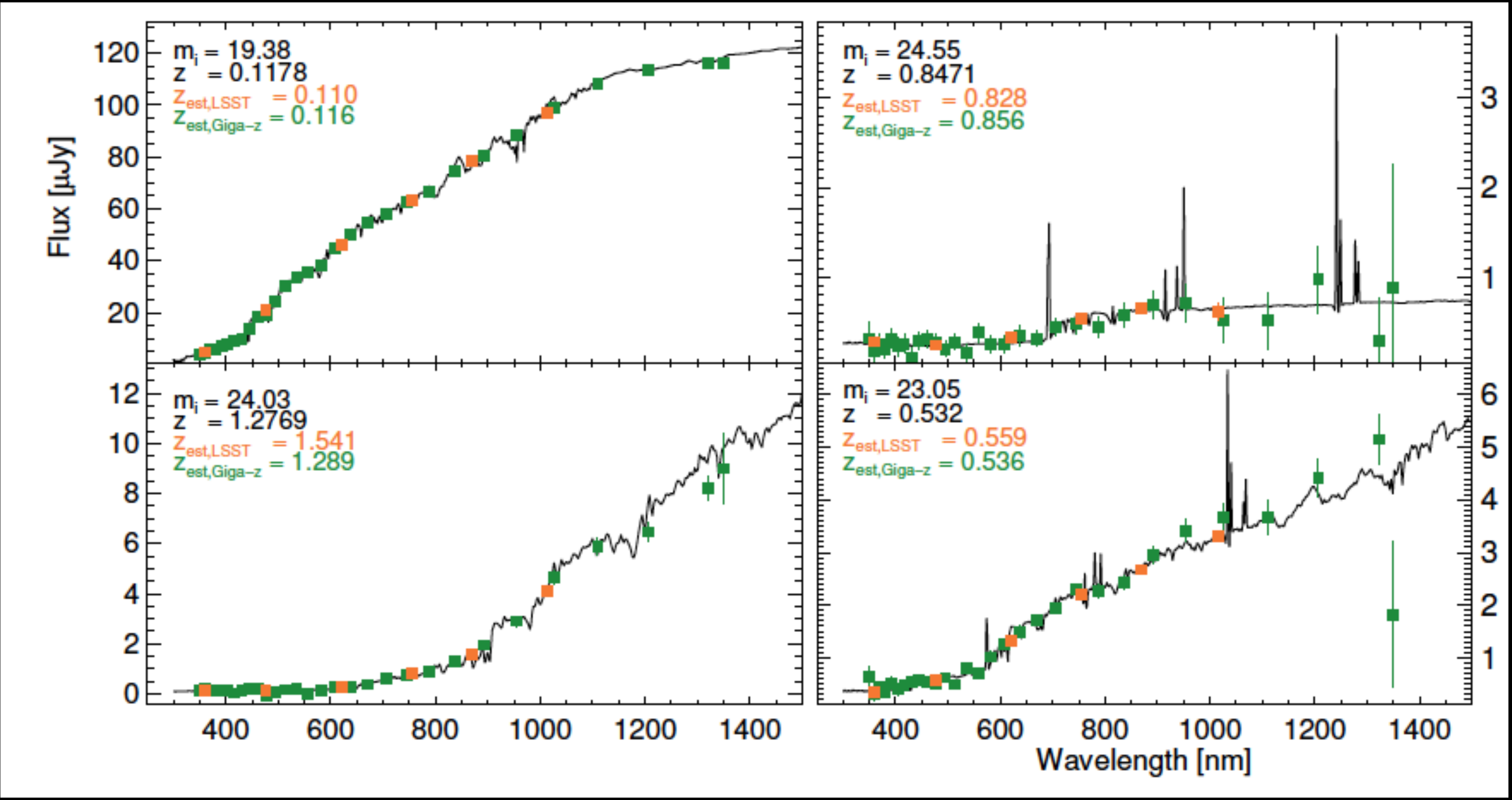


GigaZ concept (Marsden et al 2013)



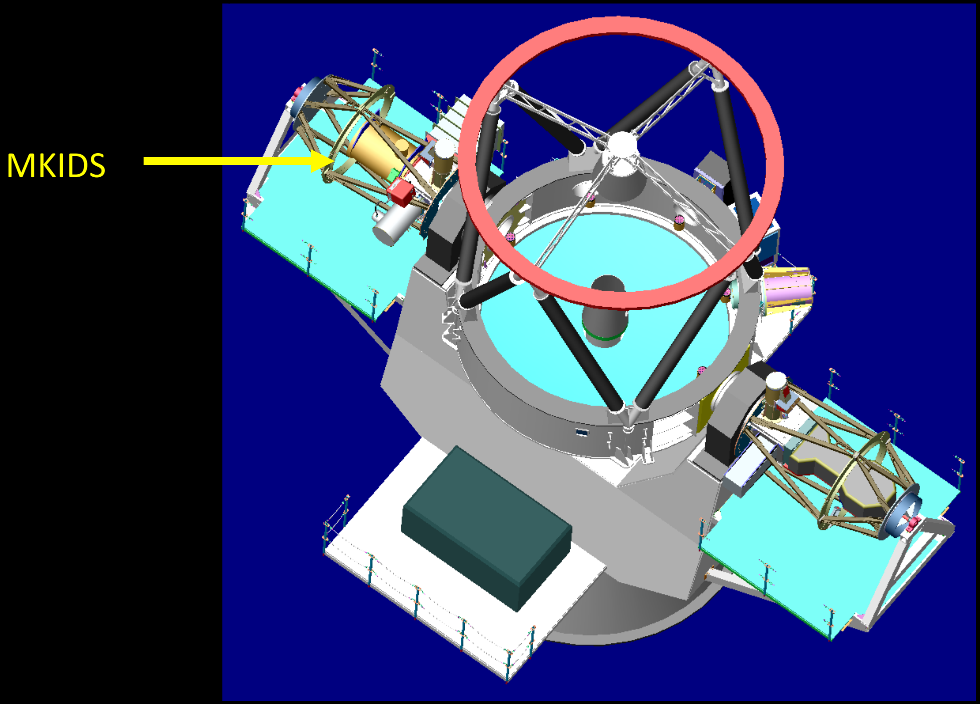
Since an MKID megapix array is still far away. We could make large pixels, and use mask to select a galaxy for each pixel. 100,000 spectroscopic channels in 1 square deg. is possible. R~30 .

GigaZ concept (Marsden et al 2013)



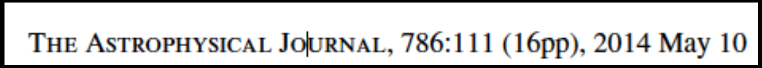
Spectrometer, DES/LSST and MKIDs
R~30 @ 428nm

SOAR 4m telescope
R&D instrument



Effort now concentrated on building an R&D instrument for the SOAR 4m telescope. Demonstrate scalability and look at obtain low resolution spectroscopy of DES objects.

Another science opportunity for MKIDs



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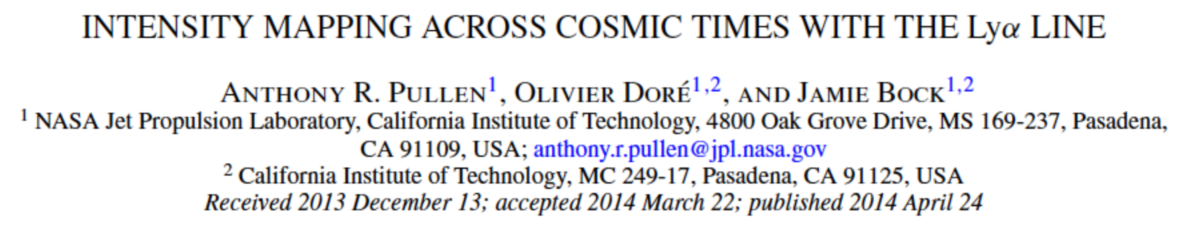

INTENSITY MAPPING ACROSS COSMIC TIMES WITH THE Lyα LINE

ANTHONY R. PULLEN[1], OLIVIER DORÉ[1,2], AND JAMIE BOCK[1,2]

[1] NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, MS 169-237, Pasadena, CA 91109, USA; anthony.r.pullen@jpl.nasa.gov

[2] California Institute of Technology, MC 249-17, Pasadena, CA 91125, USA

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Mapping the Lyman alpha line emission (122nm), maps the neutral hydrogen in he universe. Allows probes of reionization, star formation, and large-scale structure (LSS) as a function of redshift.

Large pixels would allow measuring intensity in angular scales of arcsec. Pullen et al considered a 20cm aperture instrument from space, with R~40, and surveys of ~200 deg. A MKID instrument could allow more pixels, larger field of view and possible doing this from the ground (with larger background).

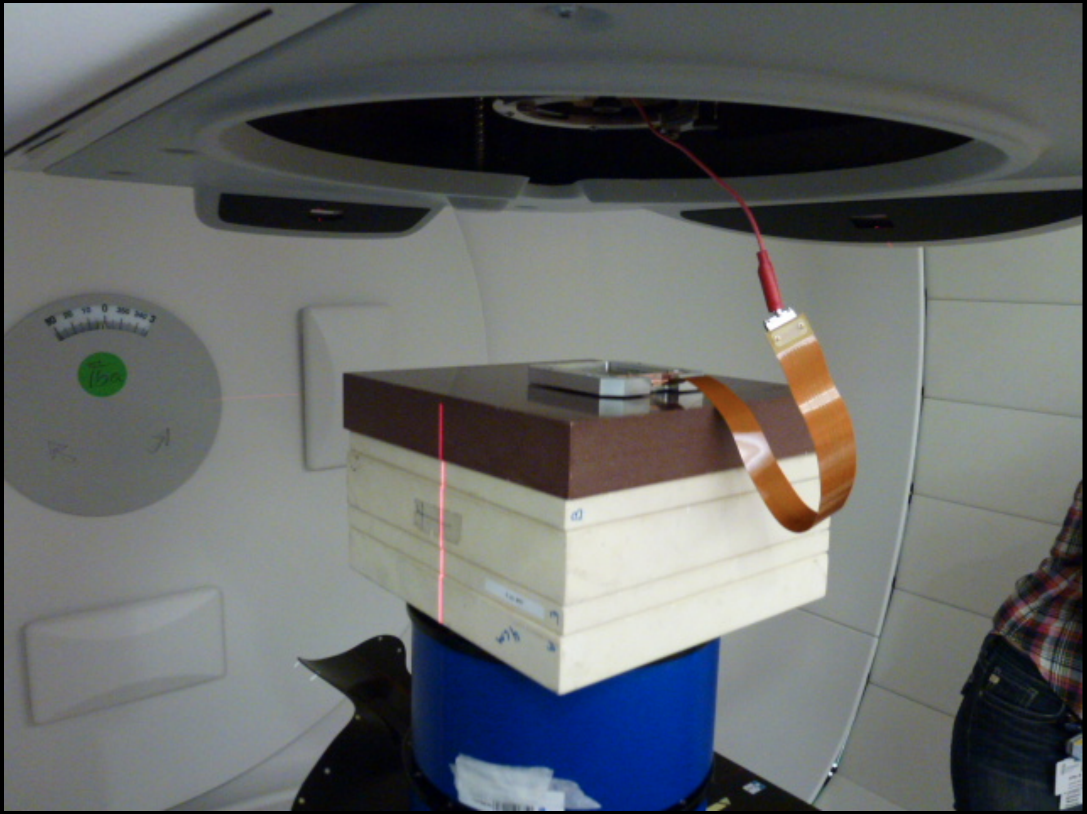
More thinking need to be done here.

Conclusion

- CCDs developed for near-IR astronomy are becoming powerful tools for low threshold detectors experiments (Dark Matter and neutrinos). Expect the best limits for low mass DM and the first detection for coherent neutrino-nucleus scattering to come from this technology.
- MKIDs for optical and near-IR provide a new tool to address the needs of spectroscopic follow-up in imaging surveys for cosmology. Huge R&D effort still needed to make this happen.

backup

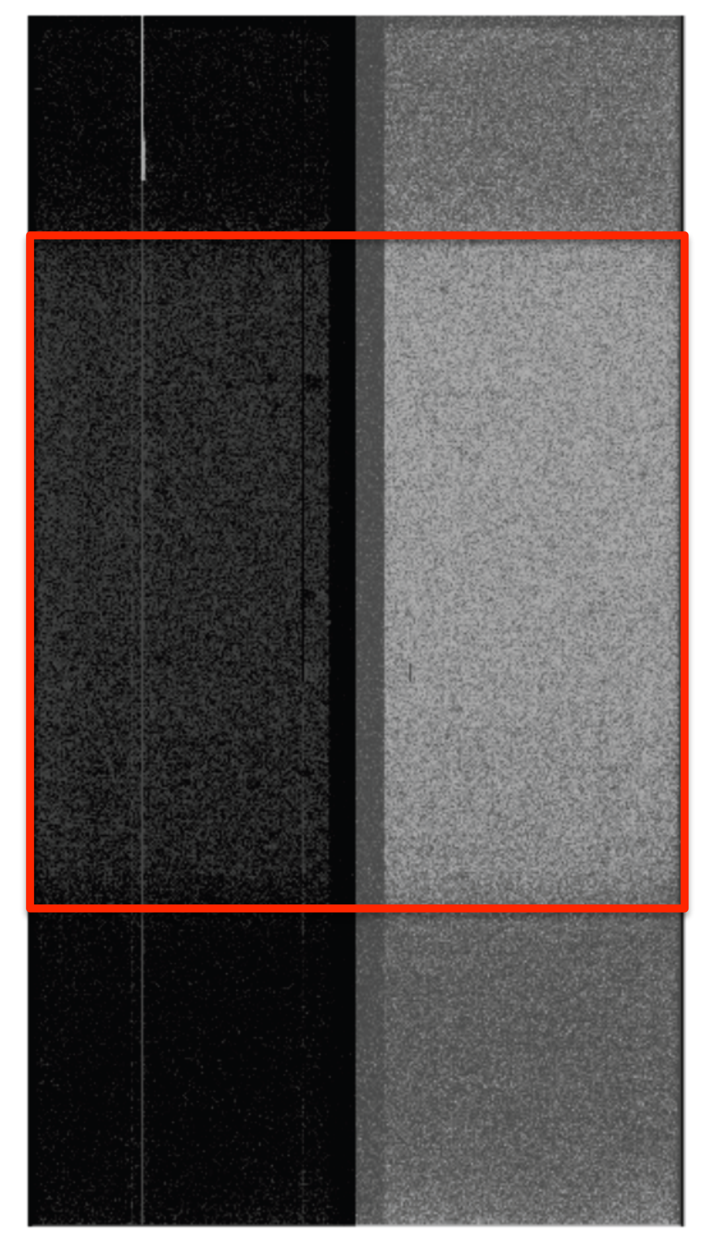
Nuclear recoil calibration at very low energies



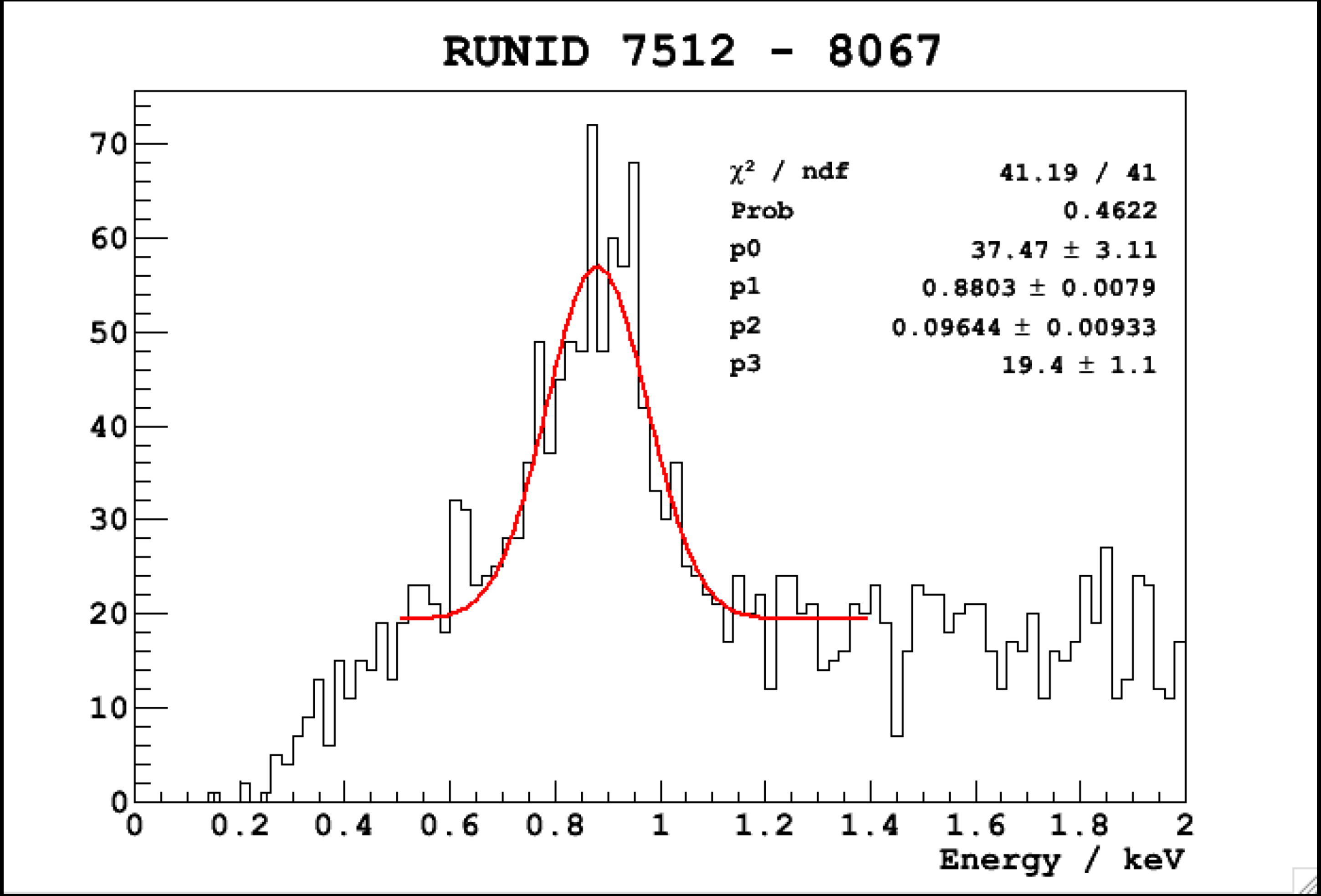
We produced ^{22}Na in our detector ~0.6 Bq (with 2E10 p/cm2)
Electron Capture decay:

$$^{22}\mathrm{Na} + e^- \longrightarrow {}^{22}\mathrm{Ne} + \nu_e + \gamma$$

The emission of neutrino and gamma produces a nuclear recoil followed by an X-ray at about 1 keV. This is produced inside the detector!



The irradiated area of the detector has higher dark current, as expected.

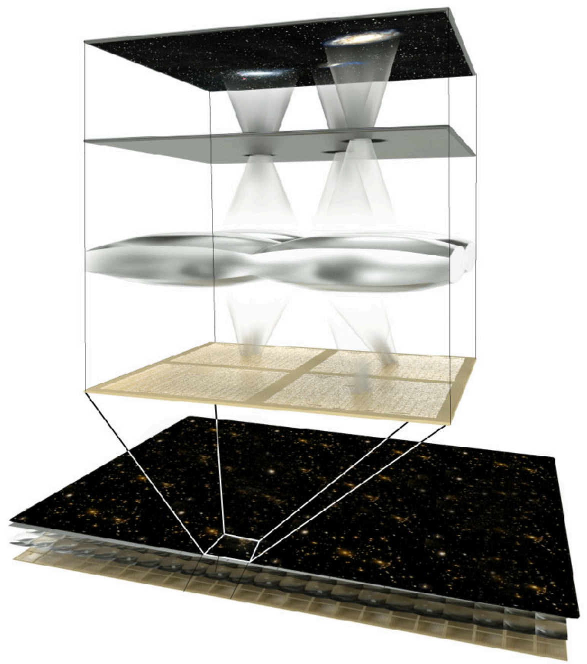


Shifted 880 eV due to recoil which (244e- object). Probably about 150e- in the brightest spot, 2e- of error in this calibration! Nice tool for low signal studies (important for DM)

GigaZ's little sister:

MEGA-Z; the MKID Extra-GAlactic redshift (Z) survey

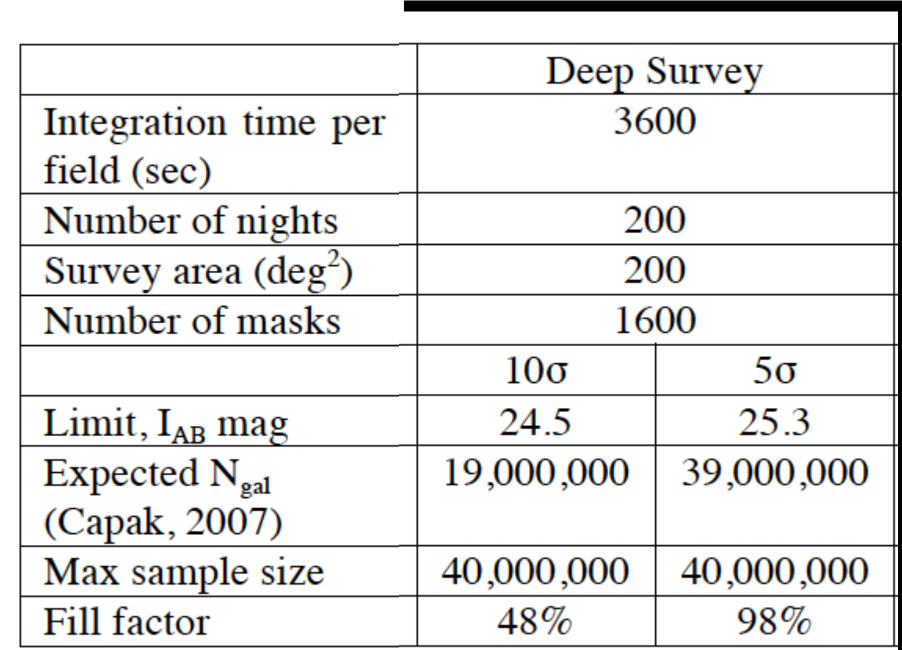
PI: Kieran O'Brien, University of Oxford, UK (Instrument lead)
Co-I: Juan Estrada, Fermilab National Laboratory, USA (Operations lead)
Co-I: Matt Jarvis, University of Oxford, UK (Survey lead)
Co-I: Benjamin Mazin, University of California Santa Barbara, USA
Co-I: Ian Hepburn, Mullard Space Science Laboratory, UK
Team Members: Gavin Dalton, Roger Davies, Isobel Hook, Mike Jones, Lance Miller, Pat Roche, Ian Shipsey, Angela Taylor, Niranjan Thatte, Aprajita Verma (University of Oxford), Joshua Frieman, Marcelle Soares (FNAL), Jo Bartlett, Graham Hardy (MSSL)



25,000 MKID pixels
1/8 sq.degree
4M telescope (NTT)

Something like this could meet the DES photo-z calibration needs, and impact also LSST.

(LOI sent to ESO in March-2014)
Possible with a good R&D program.



	Deep Survey	
Integration time per field (sec)	3600	
Number of nights	200	
Survey area (deg^2)	200	
Number of masks	1600	
	10σ	5σ
Limit, I_{AB} mag	24.5	25.3
Expected N_{gal} (Capak, 2007)	19,000,000	39,000,000
Max sample size	40,000,000	40,000,000
Fill factor	48%	98%

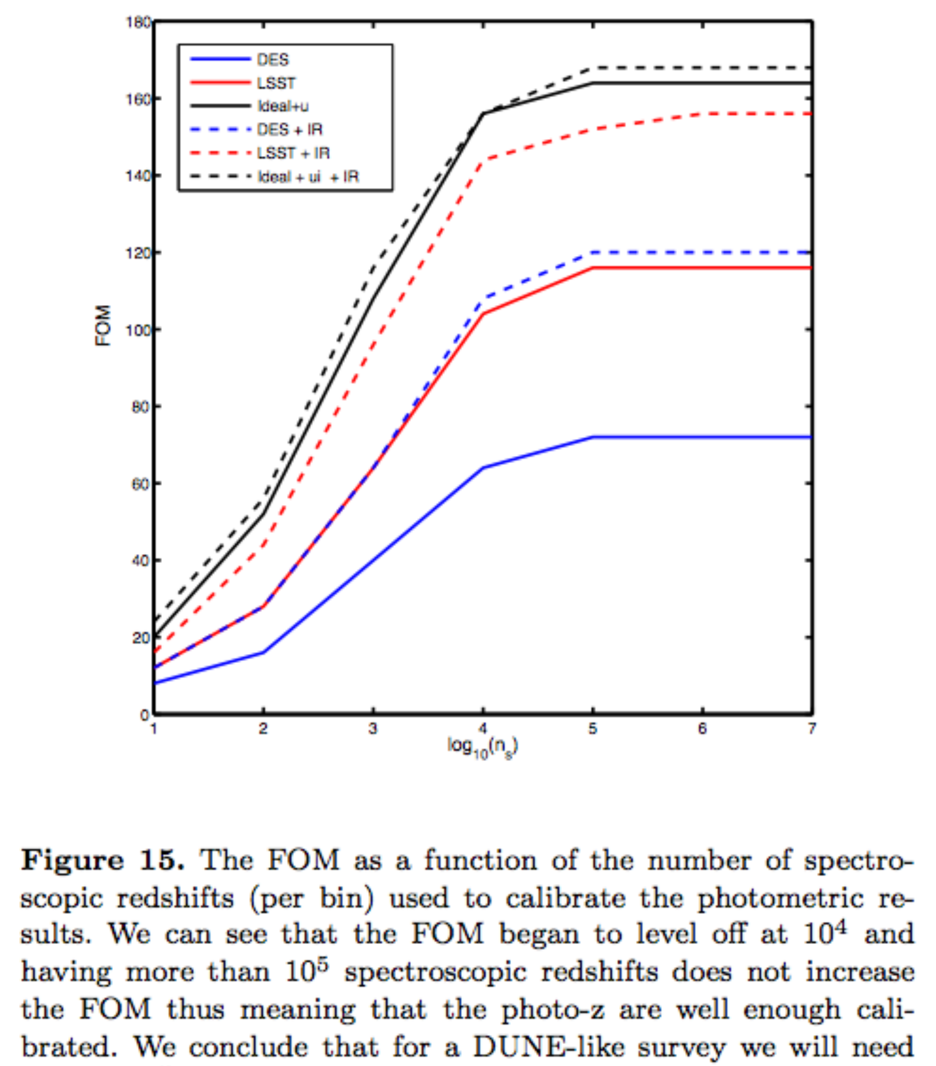


Figure 15. The FOM as a function of the number of spectroscopic redshifts (per bin) used to calibrate the photometric results. We can see that the FOM began to level off at 10^4 and having more than 10^5 spectroscopic redshifts does not increase the FOM thus meaning that the photo-z are well enough calibrated. We conclude that for a DUNE-like survey we will need

Needs
10,000 per z-bin
10 bins

Total= 100,000 spectra

Abdalla et al, 0705.1437

GigaZ concept (Marsden et al 2013)

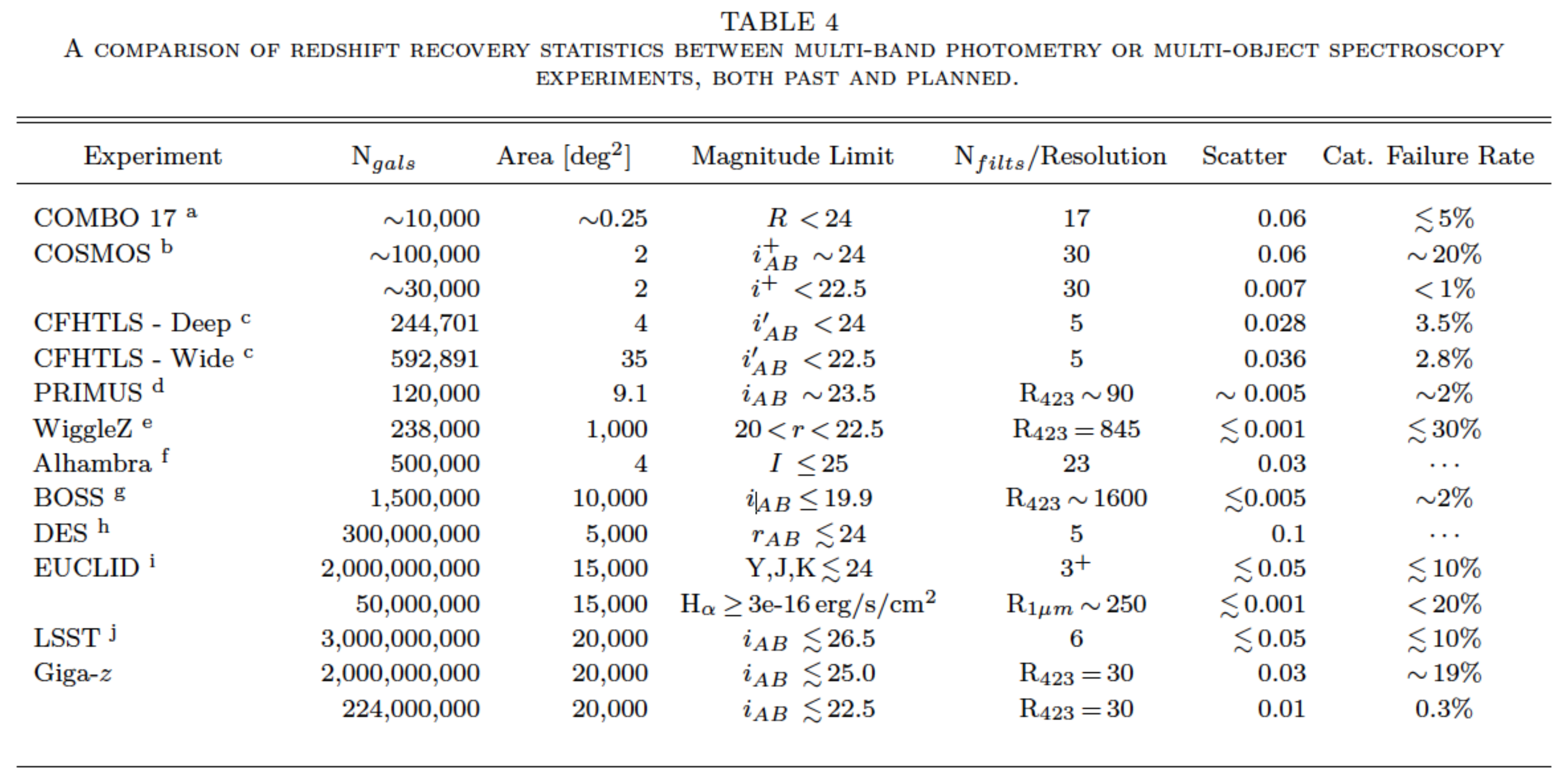
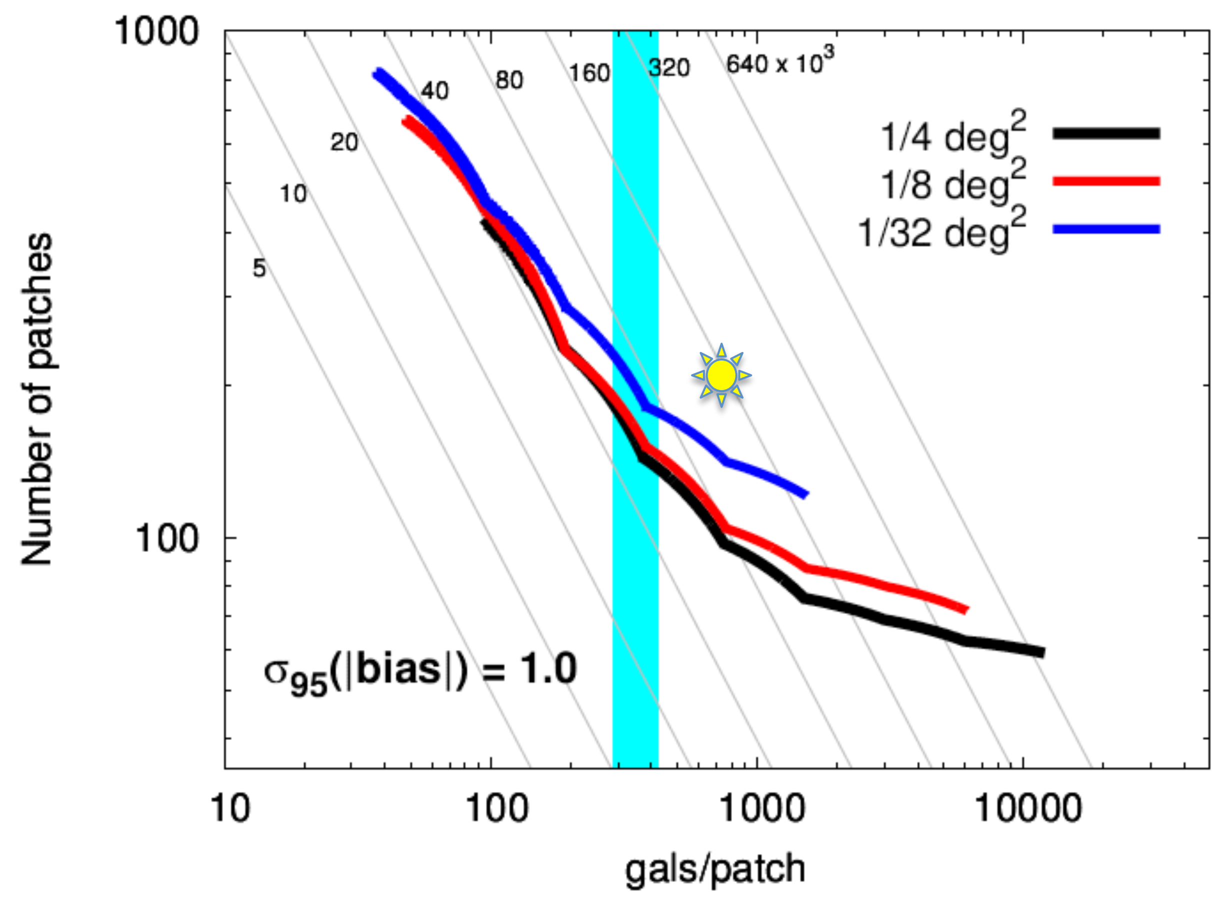


TABLE 4

A COMPARISON OF REDSHIFT RECOVERY STATISTICS BETWEEN MULTI-BAND PHOTOMETRY OR MULTI-OBJECT SPECTROSCOPY EXPERIMENTS, BOTH PAST AND PLANNED.

Experiment	N_{gals}	Area [deg^2]	Magnitude Limit	N_{filts}/Resolution	Scatter	Cat. Failure Rate
COMBO 17 [a]	~10,000	~0.25	$R < 24$	17	0.06	$\lesssim 5\%$
COSMOS [b]	~100,000	2	$i^+_{AB} \sim 24$	30	0.06	$\sim 20\%$
	~30,000	2	$i^+ < 22.5$	30	0.007	$< 1\%$
CFHTLS - Deep [c]	244,701	4	$i'_{AB} < 24$	5	0.028	3.5%
CFHTLS - Wide [c]	592,891	35	$i'_{AB} < 22.5$	5	0.036	2.8%
PRIMUS [d]	120,000	9.1	$i_{AB} \sim 23.5$	$R_{423} \sim 90$	~ 0.005	~2%
WiggleZ [e]	238,000	1,000	$20 < r < 22.5$	$R_{423} = 845$	$\lesssim 0.001$	$\lesssim 30\%$
Alhambra [f]	500,000	4	$I \leq 25$	23	0.03	···
BOSS [g]	1,500,000	10,000	$i_{AB} \leq 19.9$	$R_{423} \sim 1600$	$\lesssim 0.005$	~2%
DES [h]	300,000,000	5,000	$r_{AB} \lesssim 24$	5	0.1	···
EUCLID [i]	2,000,000,000	15,000	Y,J,K $\lesssim 24$	3^+	$\lesssim 0.05$	$\lesssim 10\%$
	50,000,000	15,000	$H_\alpha \geq$ 3e-16 erg/s/cm^2	$R_{1\mu m} \sim 250$	$\lesssim 0.001$	$< 20\%$
LSST [j]	3,000,000,000	20,000	$i_{AB} \lesssim 26.5$	6	$\lesssim 0.05$	$\lesssim 10\%$
Giga-*z*	2,000,000,000	20,000	$i_{AB} \lesssim 25.0$	$R_{423} = 30$	0.03	$\sim 19\%$
	224,000,000	20,000	$i_{AB} \lesssim 22.5$	$R_{423} = 30$	0.01	0.3%

DES redshift estimation needs to be calibrated using a spectrograph (same for LSST). The calibration sample needed is big, and has to cover a large area.



DES needs: Cunha et al 2012

MKIDs provide an efficient way to collect a high quality sample for calibration.

☀ With 1/8 sq-deg, you need about 200 pointings with 1000 galaxies on each.

DES follow-up needs

What kind of spectroscopic survey is needed to maximize the science output from DES?

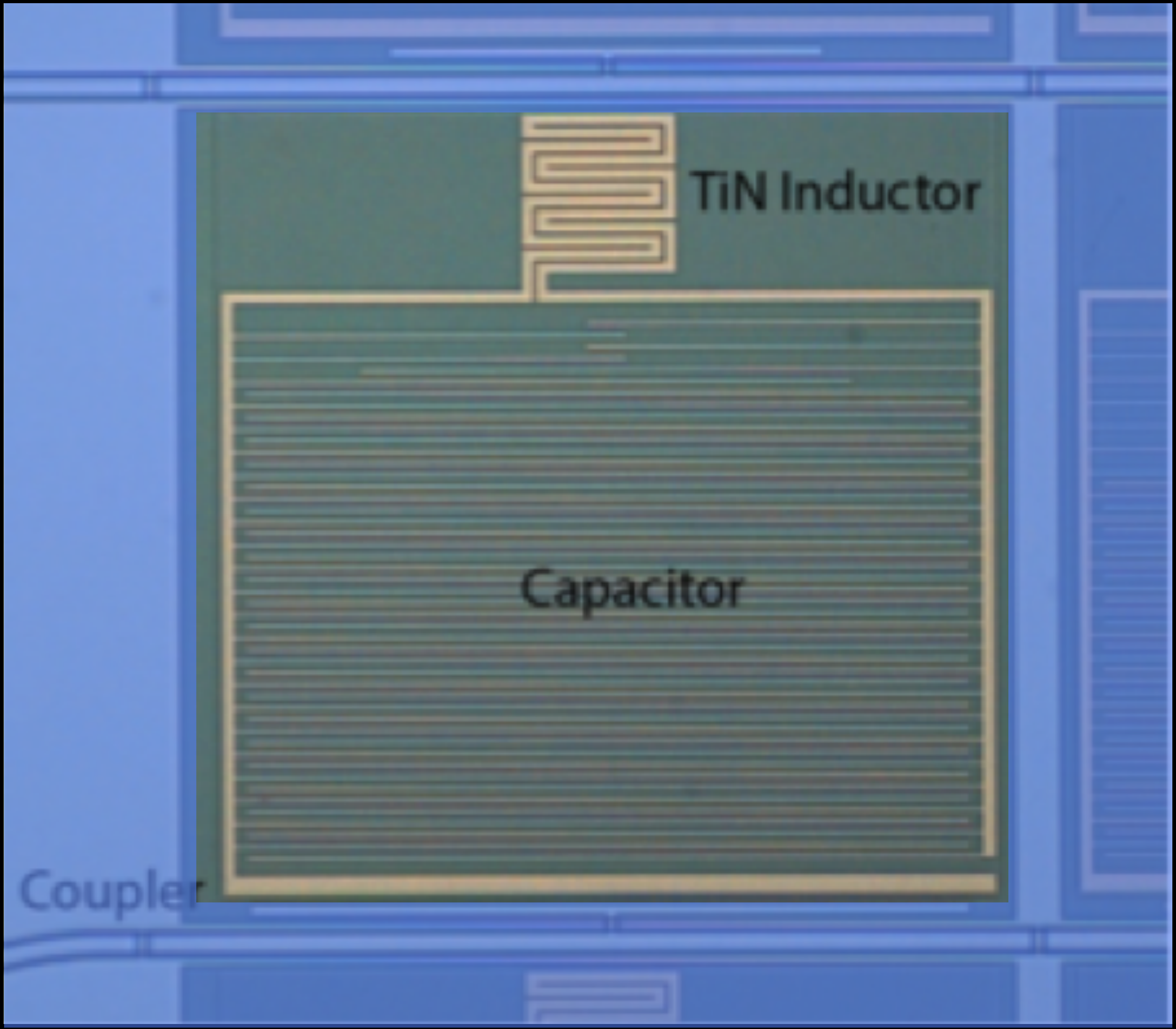
Few main ideas:

- We need to get to 10^5 per z bin beat the shot noise.
- Cosmic variance is a big deal. Need to attack this problem by distributing the sample over many patches in the sky.
- Failures in the spectroscopic determination of redshifts are a big issue (large bias in w), a lot more important that the precision of successful redshifts.

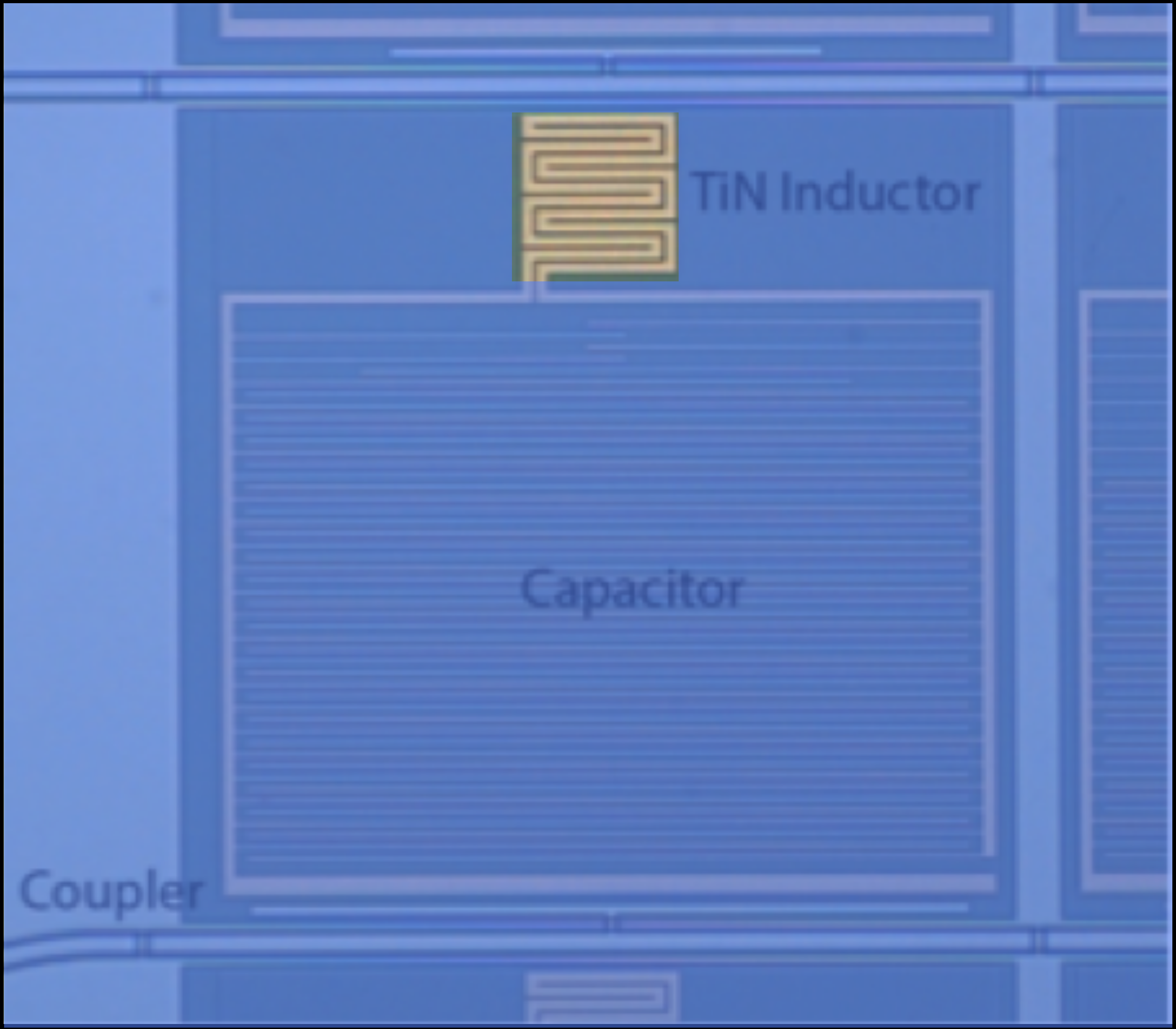
This is were we believe MKIDs could help. Get a huge sample with low failure rate.

- **Failures in the spectroscopic determination of redshifts are a big issue (large bias in w), a lot more important that the precision of successful redshifts.**

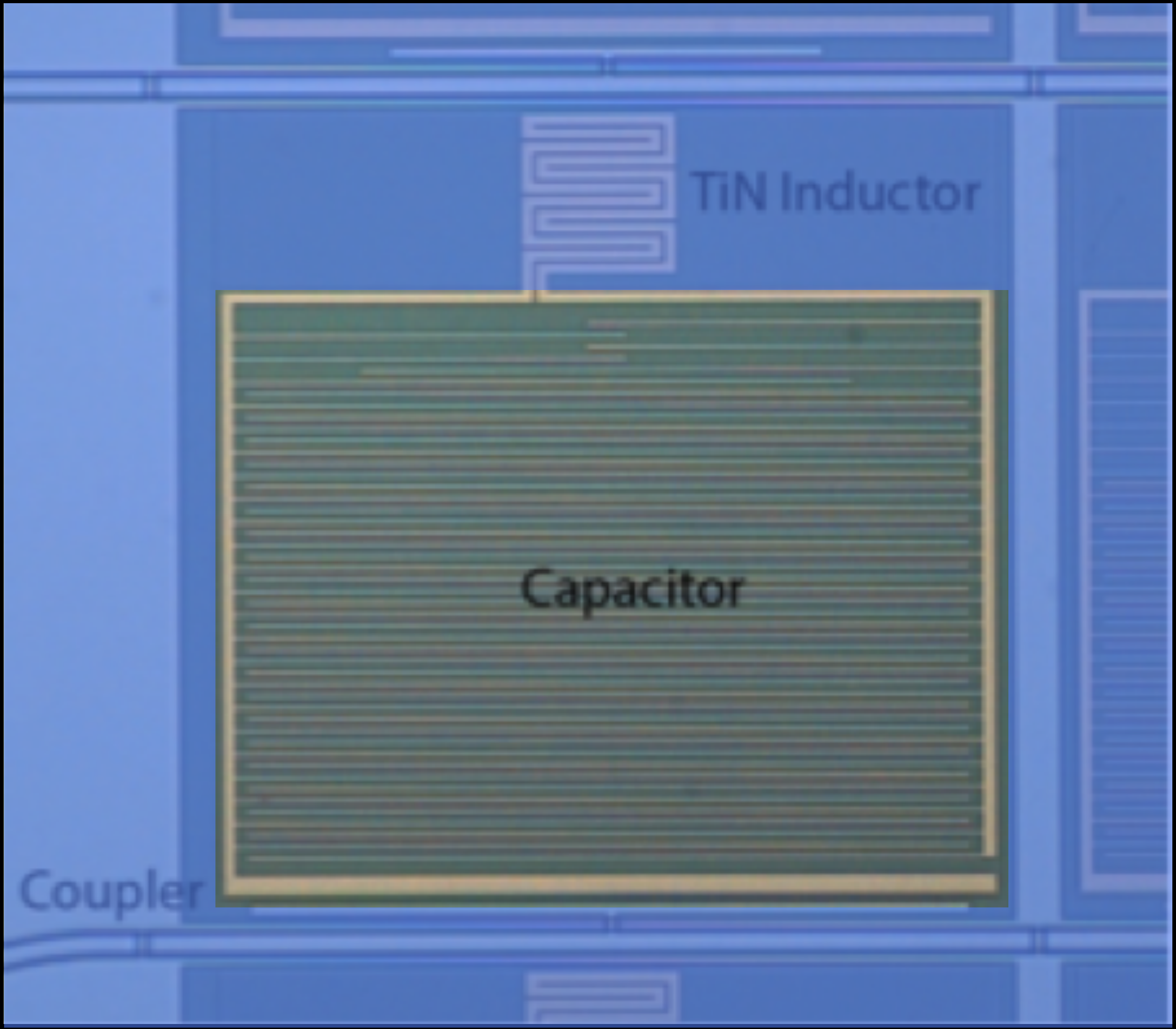
Single pixel has an inductor and a capacitor

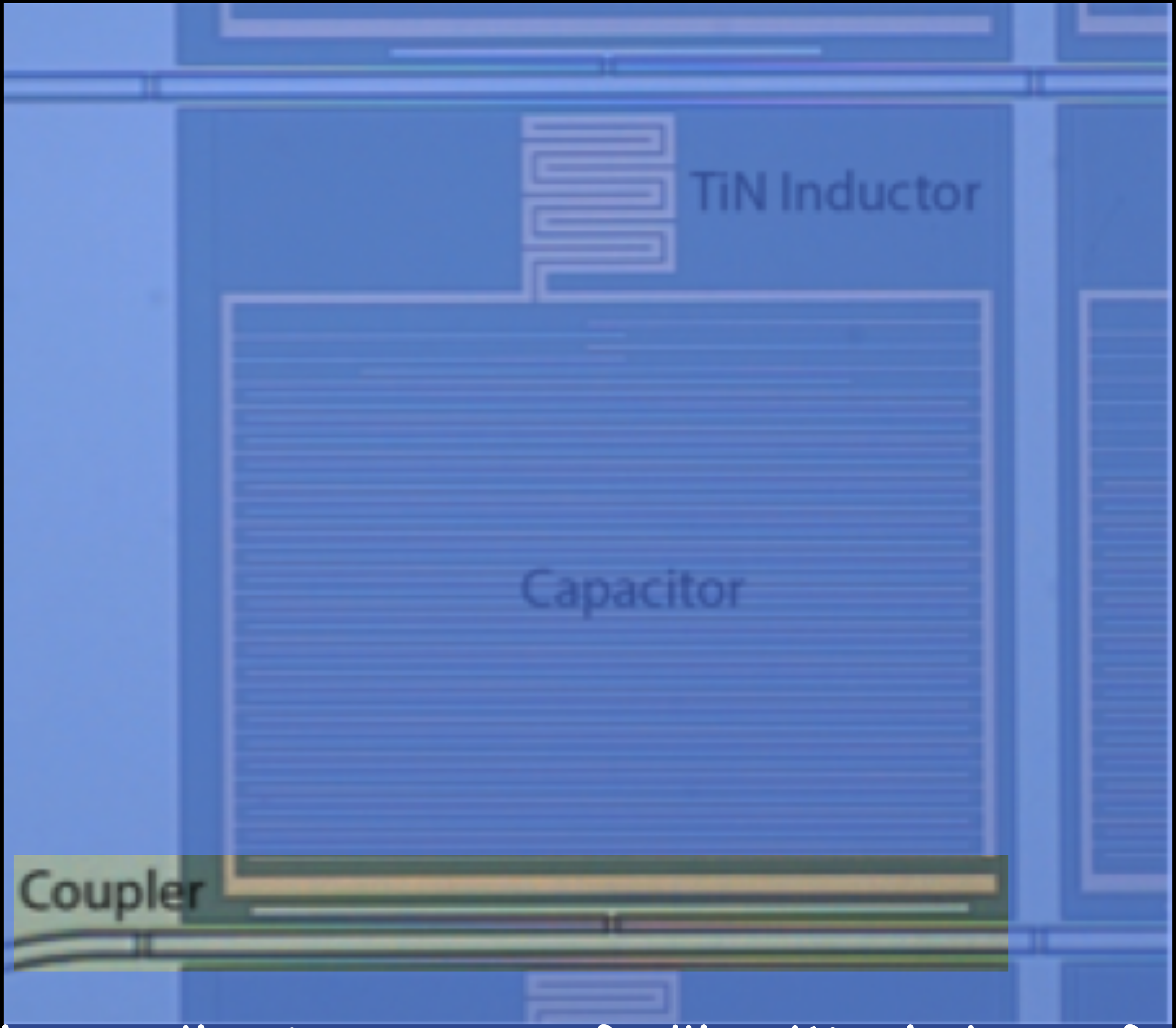


Light is collected at the inductor



Capacitor is tuned to give a different resonance frequency to each pixel



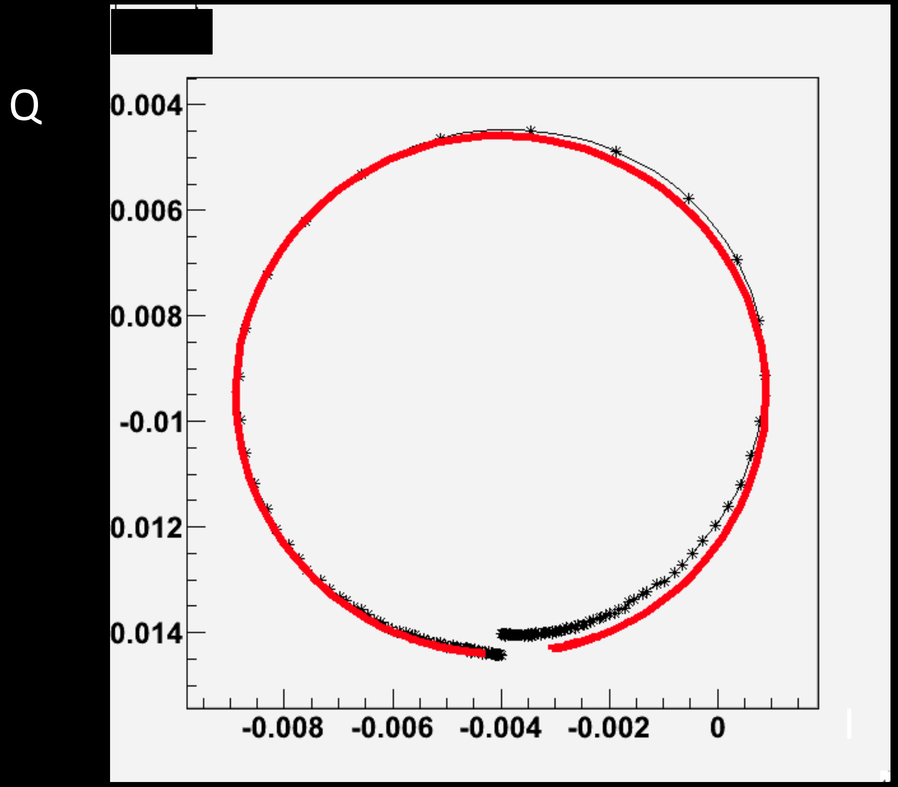


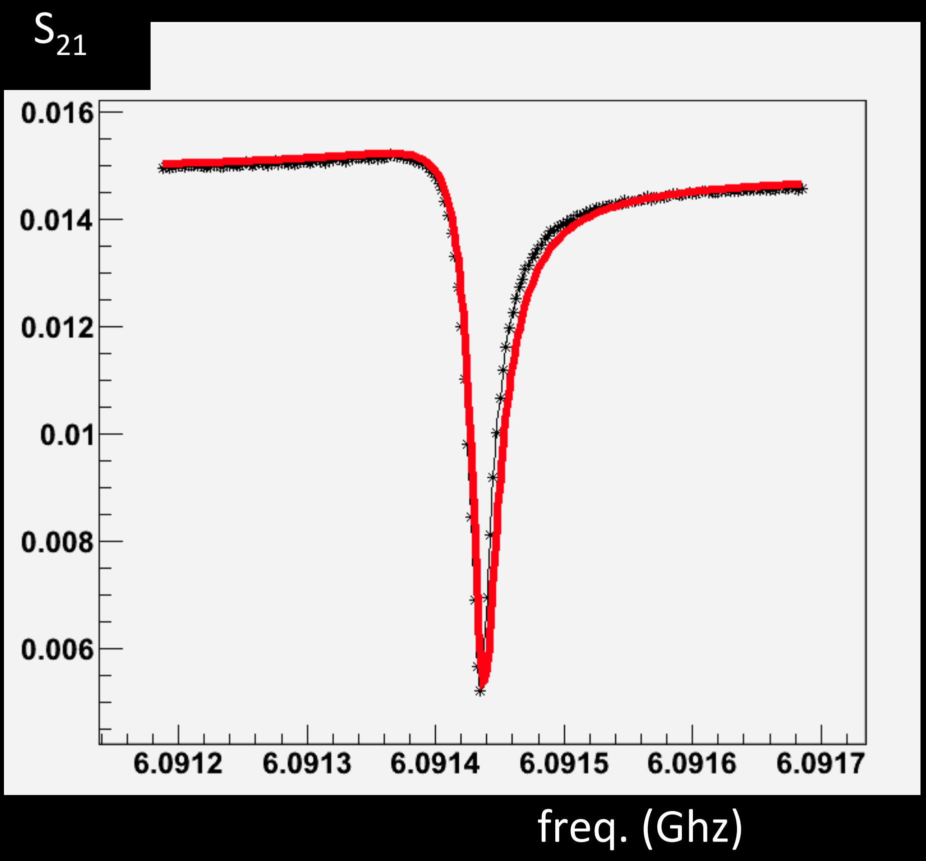
Capacitive coupling to a common feedline (1K pixels per feedline)

I : in phase with S1

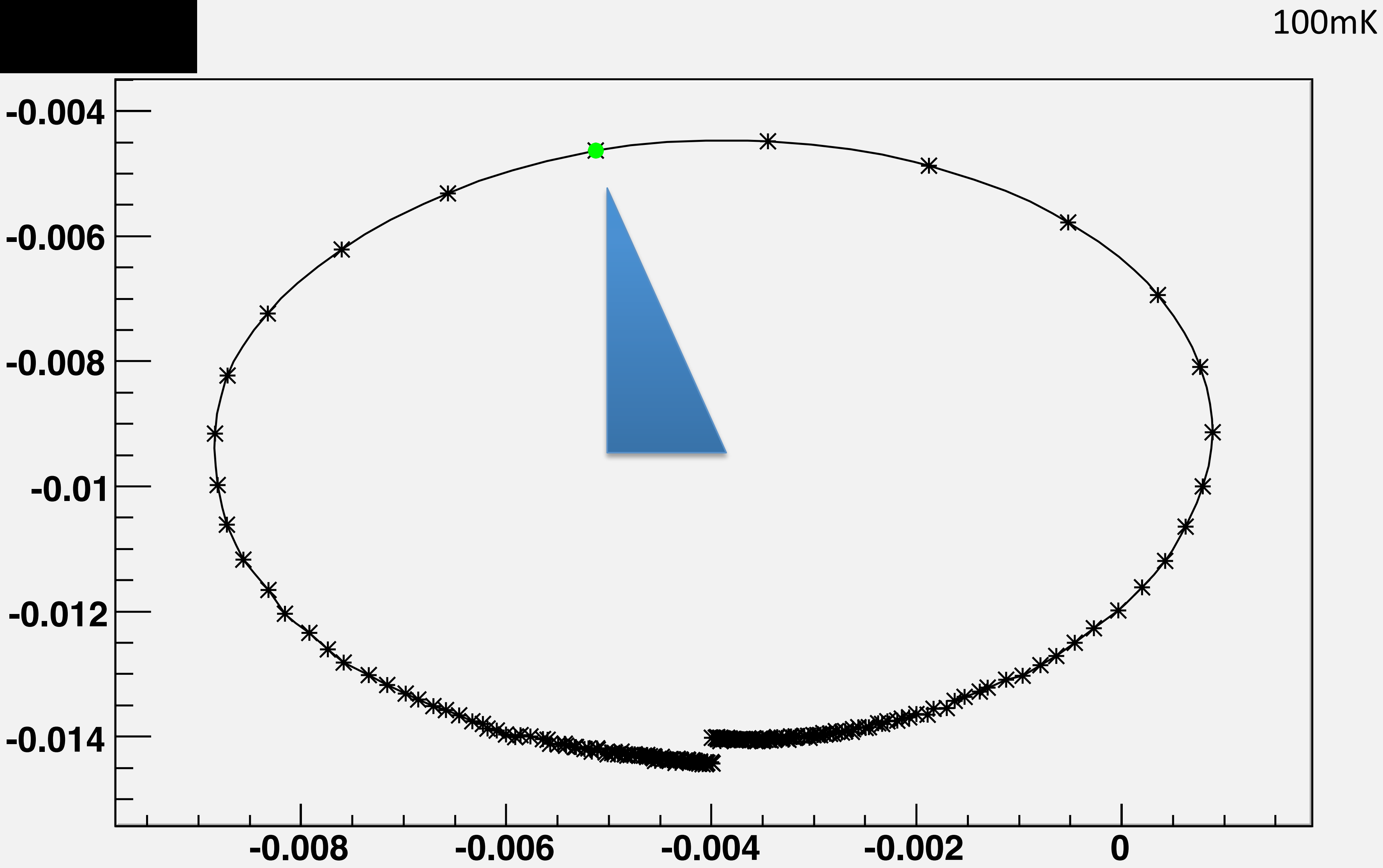
Q : 90° with respect to S1

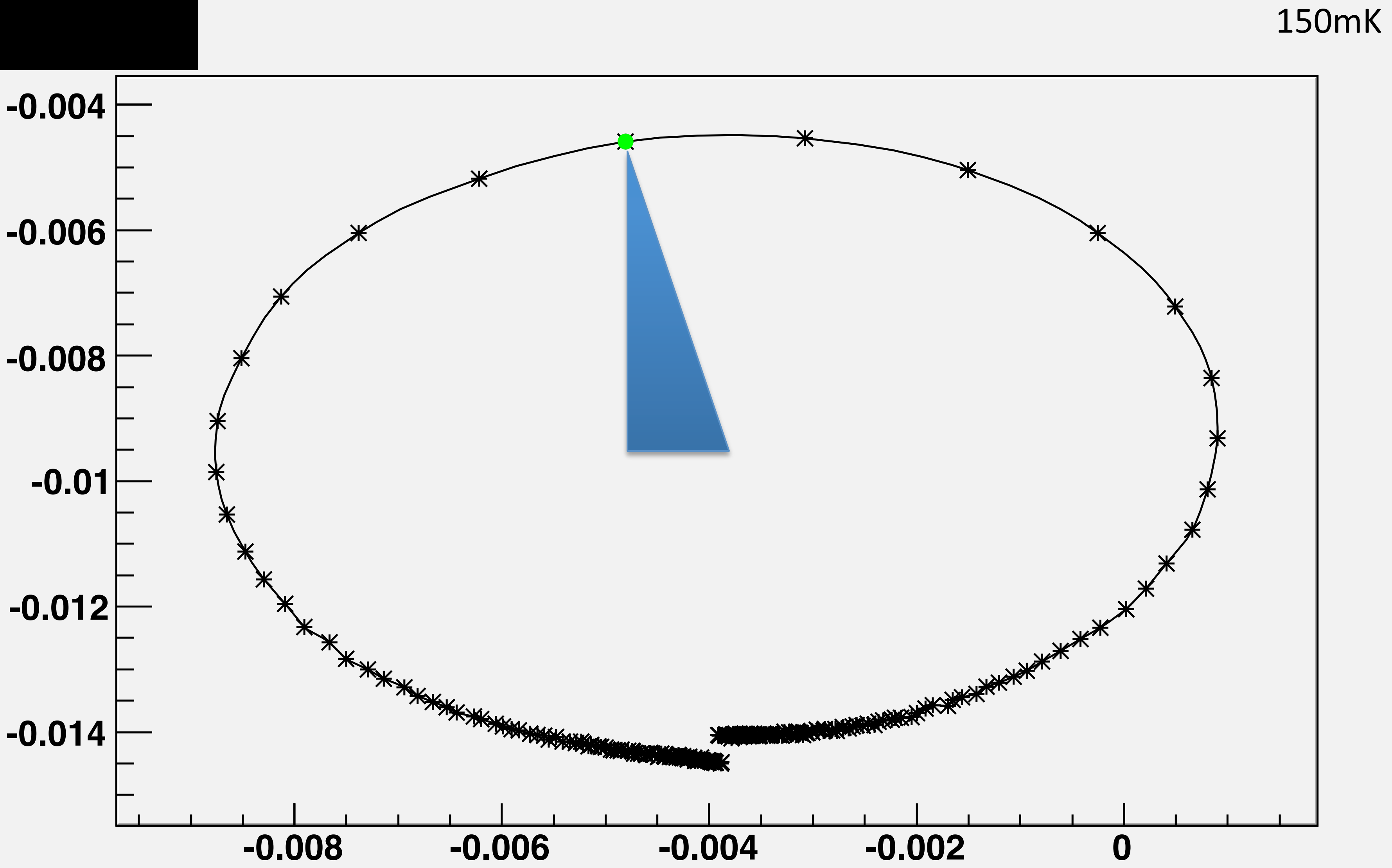
Q & I measured relative to S1
S_{21} is the sum in quadrature of Q & I





Pixel 1: Q=187k , f0=6.09143 Ghz


100mK
-0.004
-0.006
-0.008
-0.01
-0.012
-0.014
-0.008
-0.006
-0.004
-0.002
0



Change in quasi-particle density equivalent to low Energy X-ray photon (~3keV)