Overview talk on meV-eV scale particle energy deposition detectors R&D

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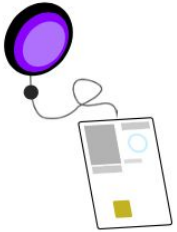
U.S. Department of Commerce

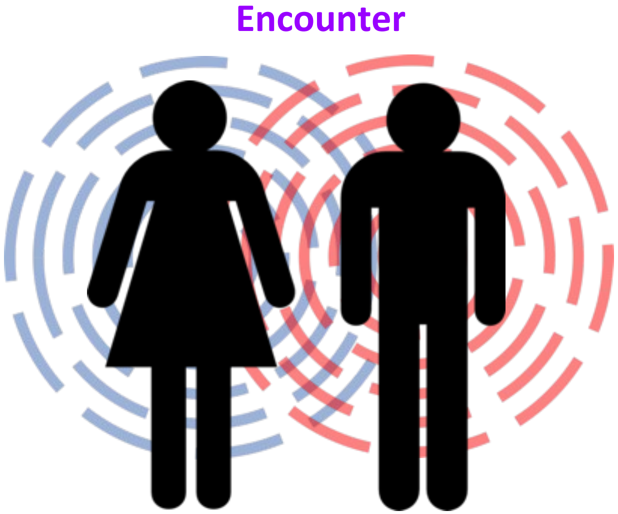
Aside: COVID-19 response
Open Source Hardware and Software for exposure tracing

CONTACT ME: If interested in helping or testing: nams@nist.gov



NIST Privacy-preserving system

- Bluetooth Dev boards, coin-cell battery
- Proximity via Bluetooth RSSI
- Ultrasonic, BT radar under development
- Public-private key cryptography to generate an encounter an ID per encounter
- 3rd Computing platform for interface to the cloud
- System testing with Human Subjects underway



From Dark to Light

looking for dark matter led to photonic tests of local realism (EPR)

back to Dark

can advances in photonics for QIS help dark matter / fundamental physics

Detector Technologies

- “Room Temperature”
  - Photomultiplier Tube + Scintillator
  - Solid-state photomultiplier
  - Skipper CCD
  - HgCdTe detectors
- Superconductivity
  - MKID
  - TES
  - Superconducting Nano-strip/wire Single Photon Detector

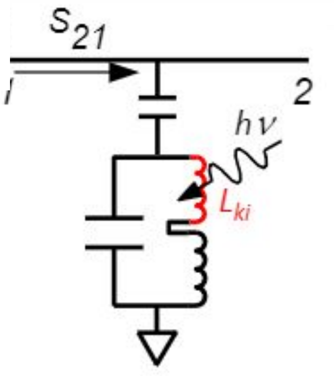
Superconductors (single pixel)

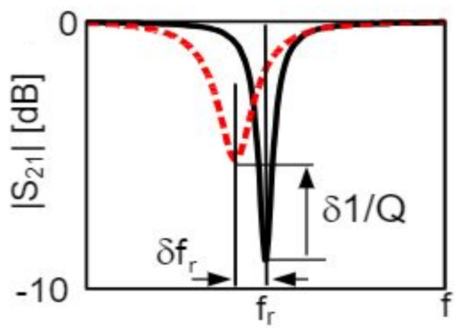
	Wavelength Range	QE (%, max)	DCR (cps)	Jitter	Max Count Rate (cps)
W-TES (NIST)	UV-1850 nm+	>98%	<<1	10-100 ns	100×10^3
SNSPD: NbN	UV-5 um	>90%	100-1000	~3 ps	100×10^6
SNSPD: WSi	UV-5 um	~98%	$<<10^{-5}$	~5 ps	10×10^6
MKID	UV-2um	~40%	<<1	1 us	10×10^3

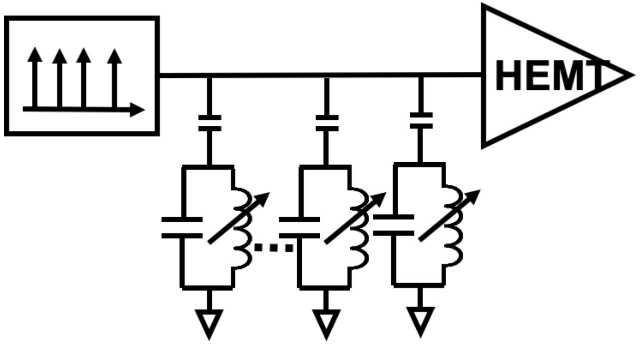
TES: Transition Edge Sensor
SNSPD: Superconducting Nanowire Single Photon Detector
MKID: Magnetic Kinetic Inductance Detector

- No afterpulsing problems
- Excellent prospects for longer wavelengths

MKID: principle of operation



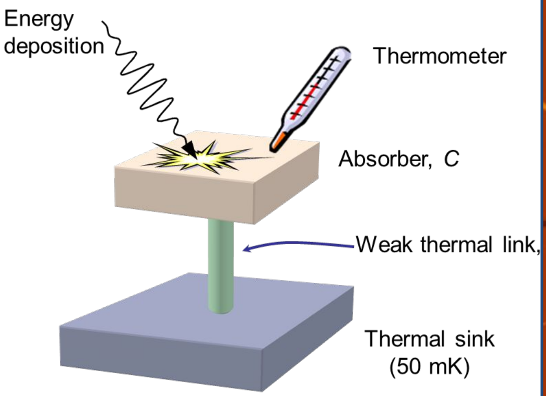


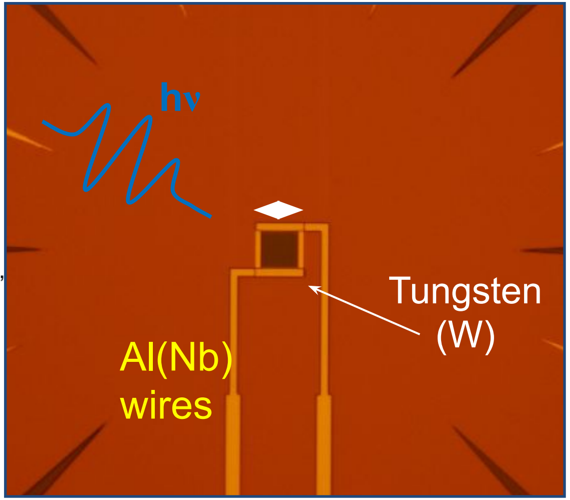


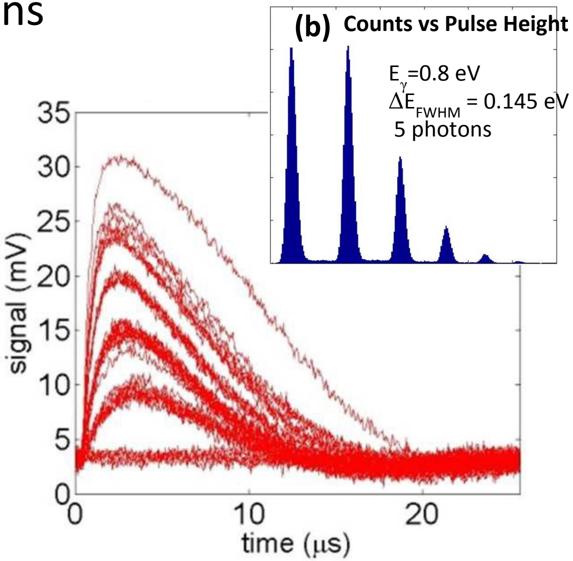
- Absorbed energy converted to excitations in the superconductor – called quasiparticles.
- Increase in quasiparticle population changes the kinetic inductance of the supercondcutor
- Use a microwave resonant circuit to detect changes in the inductance

Transition Edge Sensor (TES) Technology

Calorimetric detection of UV/optical/IR photons

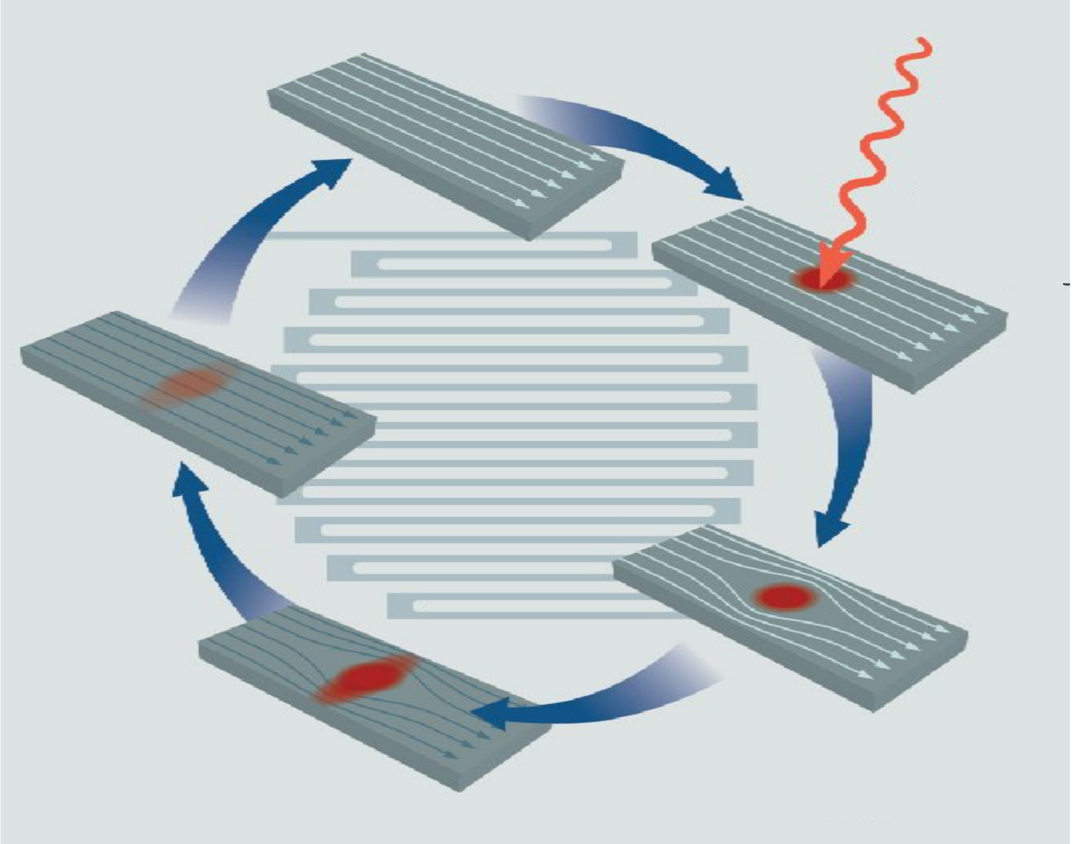






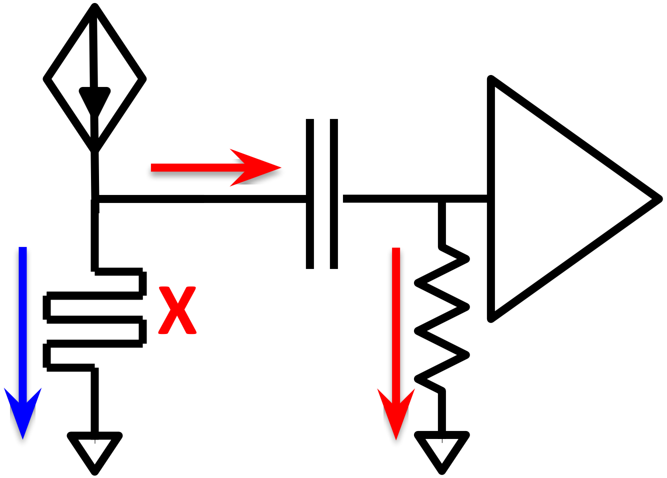
- Photon(s) are absorbed by an absorber (Tungsten (W) e^- system)
- An ultra-sensitive thermometer measures the temperature change due to absorption of energy (superconducting-to-normal transition)
- A weak thermal link enables the cooling of the absorber to base temperature (W e^- -*phonon* coupling)
- Temperatures are ~100 mK to ensure low noise and high sensitivity

Superconducting Nanowire Single Photon Detectors:



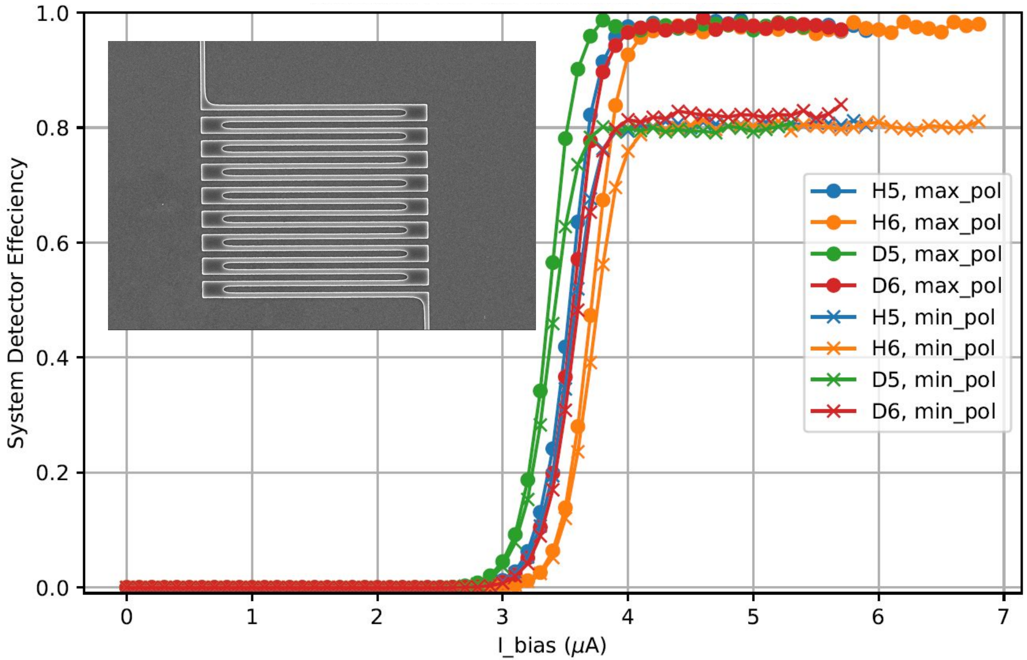
- ultra-thin (4 to 8nm, 2nm)
- Anomolously large kinetic inductance (non-linear)
- NbN, NbTiN
  - Polycrystalline
  - 2K operating temperature
  - ~80nm wide
- W-Si, Mo-Si, Mo-Ge
  - Amorphous
  - 1K operating temperature
  - ~150nm wide

Simplicity of Superconducting Nanowire Single Photoncs Detectors

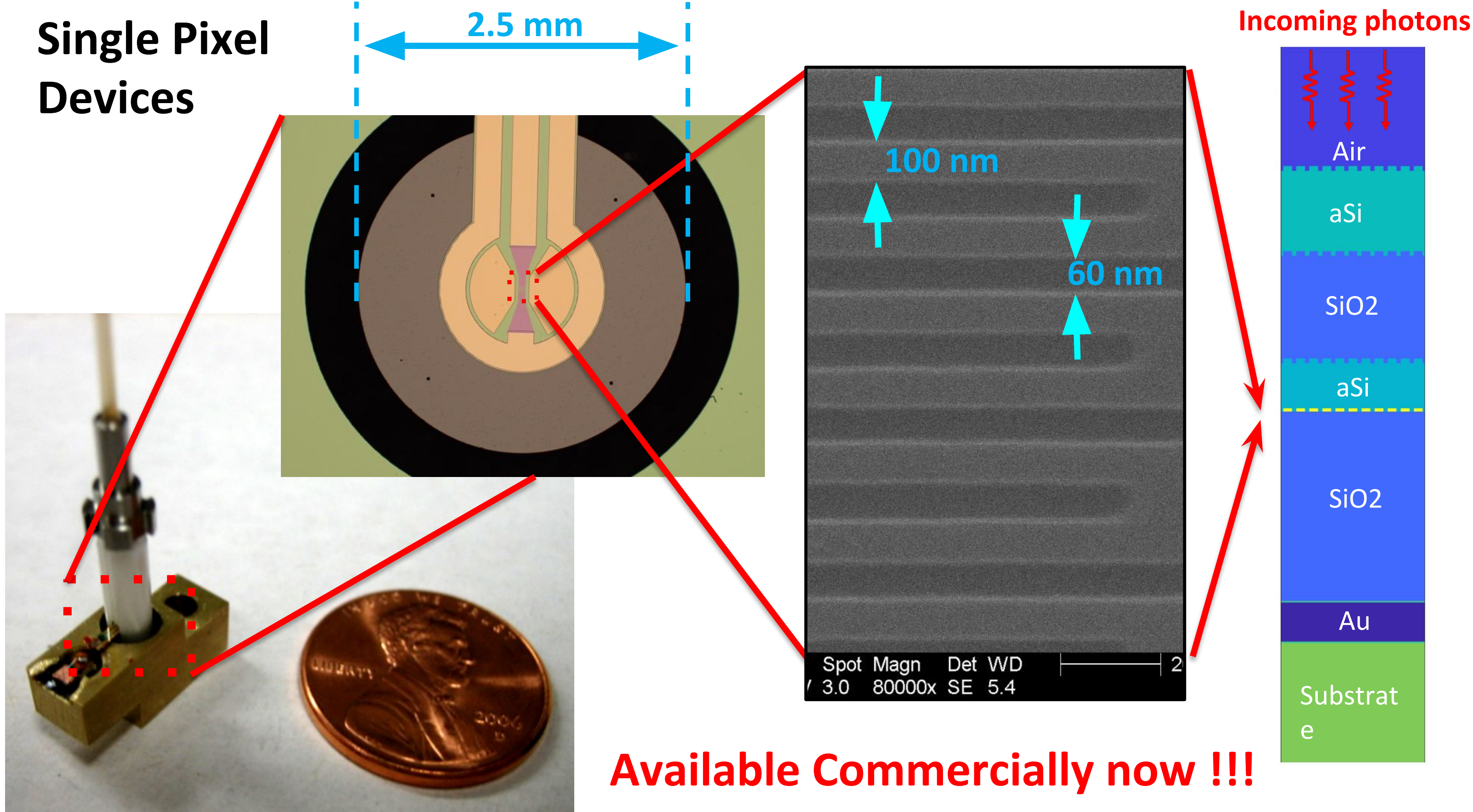


Simple Readout

Bias versus Efficiency / counts



Single Pixel Devices



Available Commercially now !!!

Single-Photon Detectors

- Key metrics:
  - Wavelength range
  - System detection efficiency
  - Dark count rate
  - Timing jitter
  - Maximum count rate
- Other considerations:
  - Optical Packaging/Coupling
  - Operating temperature
  - C-SWaP

SNSPDs:

10 µm to 100nm

~98% @ 1550nm

~ 1 count per day

2.7ps FWHM

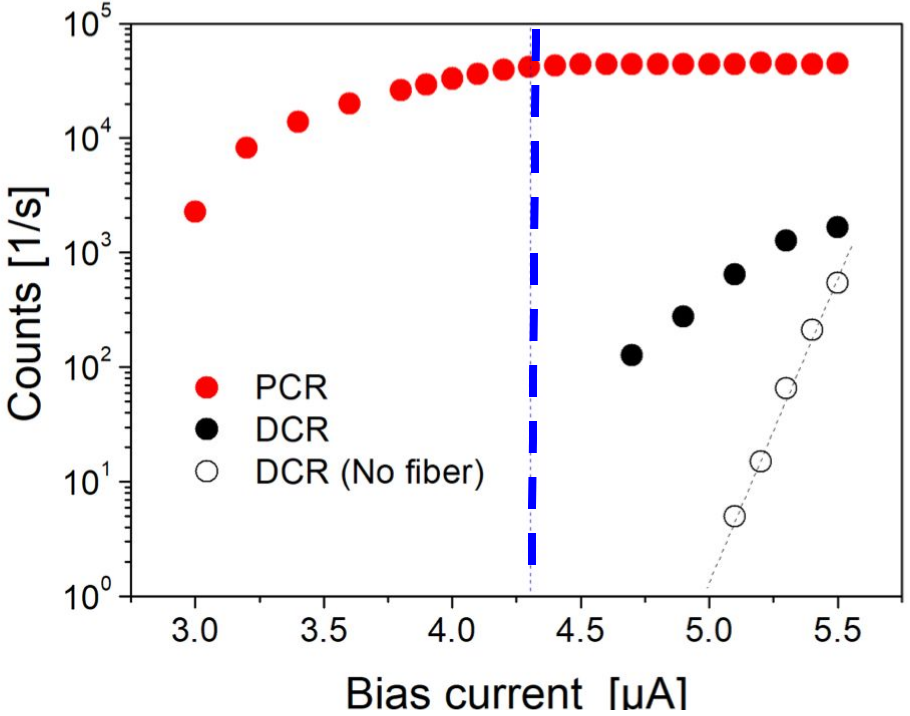
100 Mcps

Arrays

Not all in one device yet

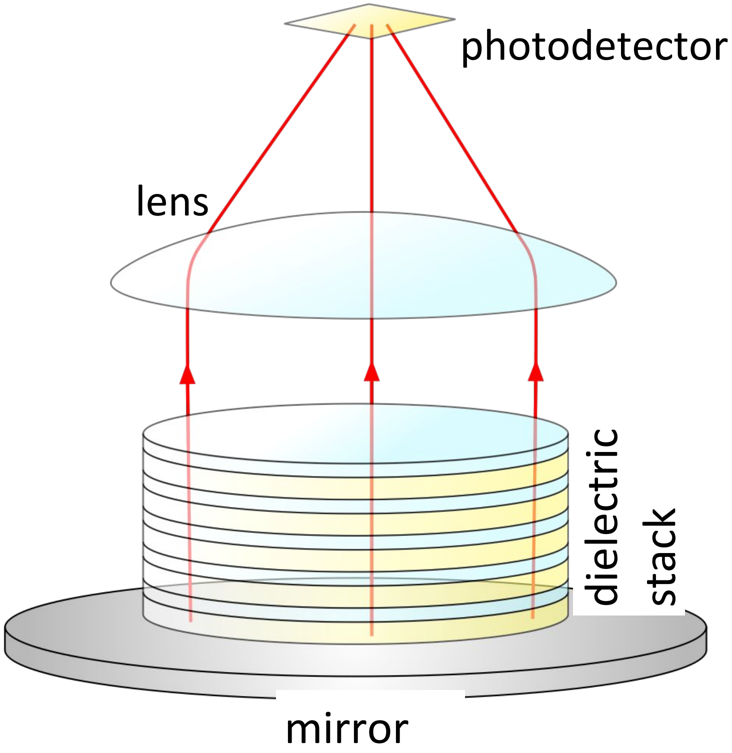
Detector for Dark Matter searches

- Based on WSi thin film from Varun Verma, NIST
- Detector fabricated by Ilya Charaev, MIT
- 400 x 400 μm^2 area
- Illuminated with 1550nm light
- 1 count in 11 hours



Y. Hochberg et al., PRL, 123 141802

Detecting Dark Photons

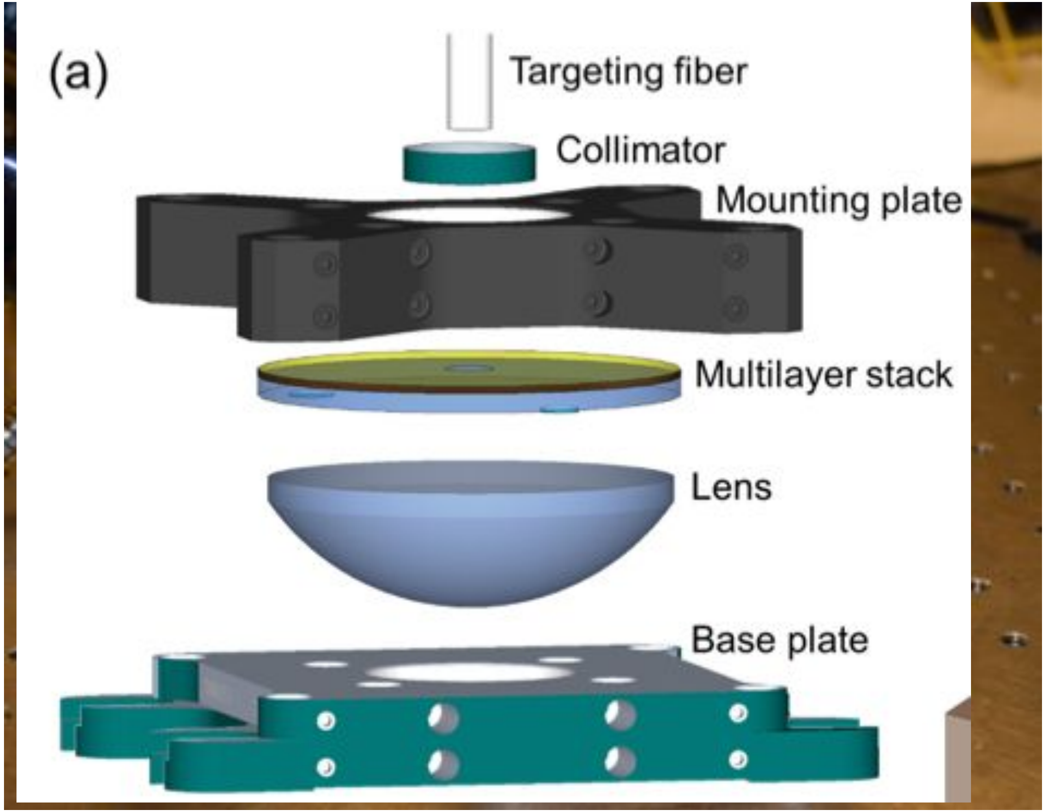


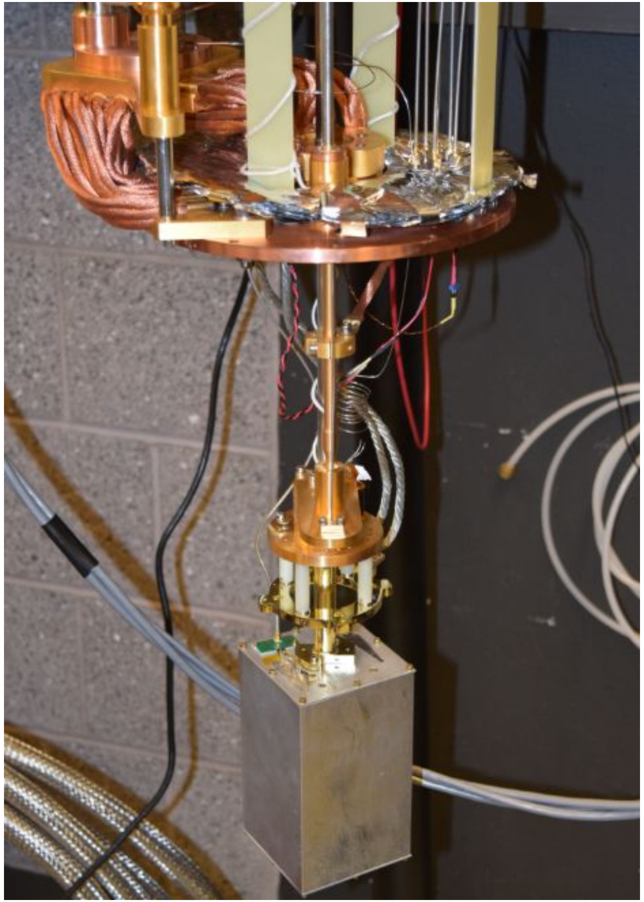
- Dark photons are “cousin” hypothetical particle to axions
- “Phase matching” via dielectric stack
- Emission of “Dark Photon” perpendicular to te dielectric stack

M. Baryakhtar et al. Phys. Rev. D 98, 035006
dark photon, dielectric stack

K. Van Tillburg et al. Phys. Rev. X, 8, 041001
molecular absoprtion

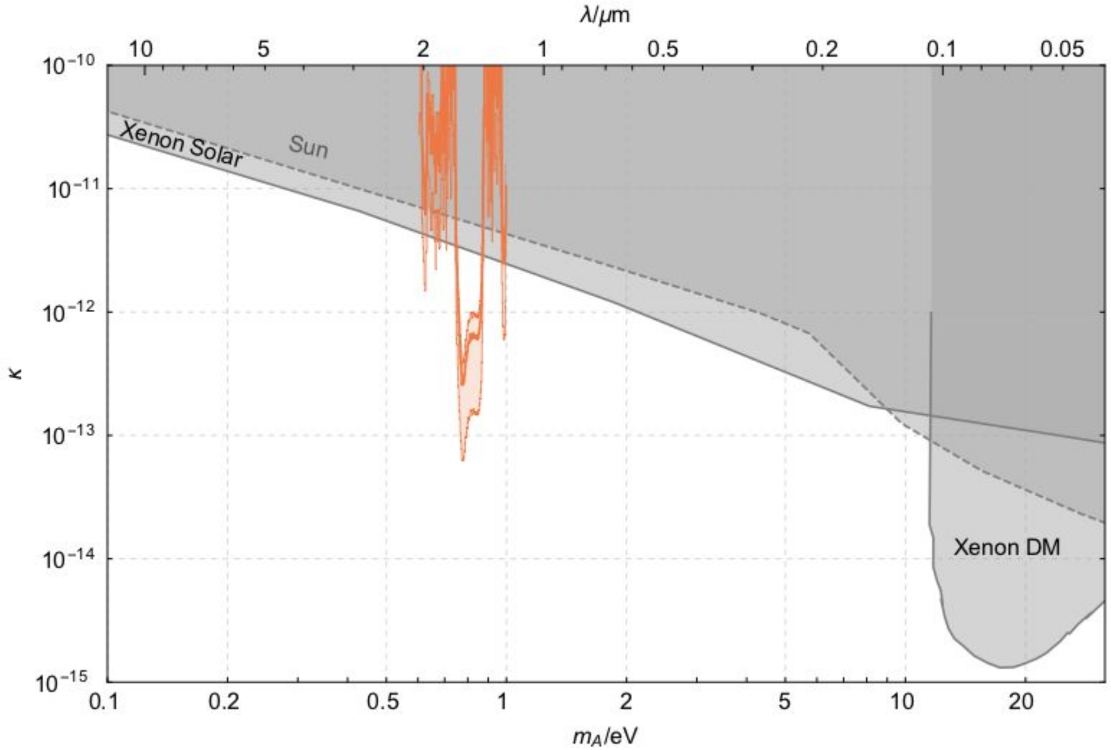
First Prototype Experiment





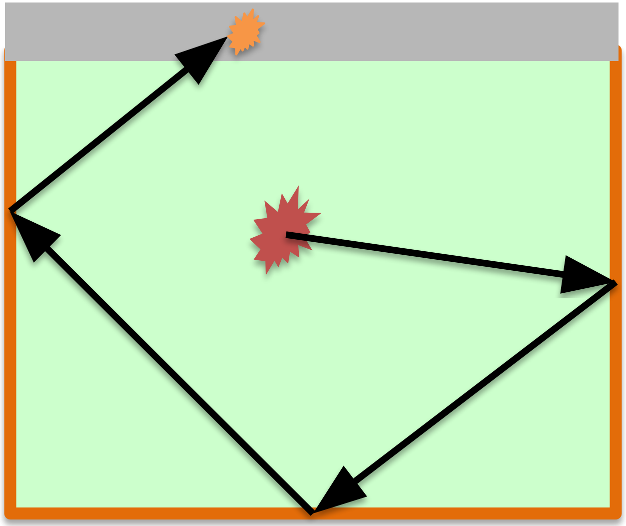
Example projected exclusion plot

Si/SiO_ halfwave
stack
5 layer pairs
~1550 nm,
2 inch diameter
DCR: 9.77x10^-6 cps



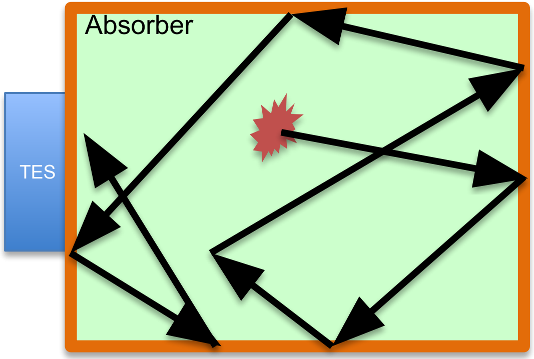
Masha Baryakhtar et al., Phys. Rev. D **98, 035006**

Inelastic recoils generating photons



- Use a low bandgap scintillating / floresence material
  - Crystal: GaAs, NaI
  - Liquid: liquid helium
  - Gas: Molecular species
- Couple to a single photon sensitive large area detector with no dark count rate

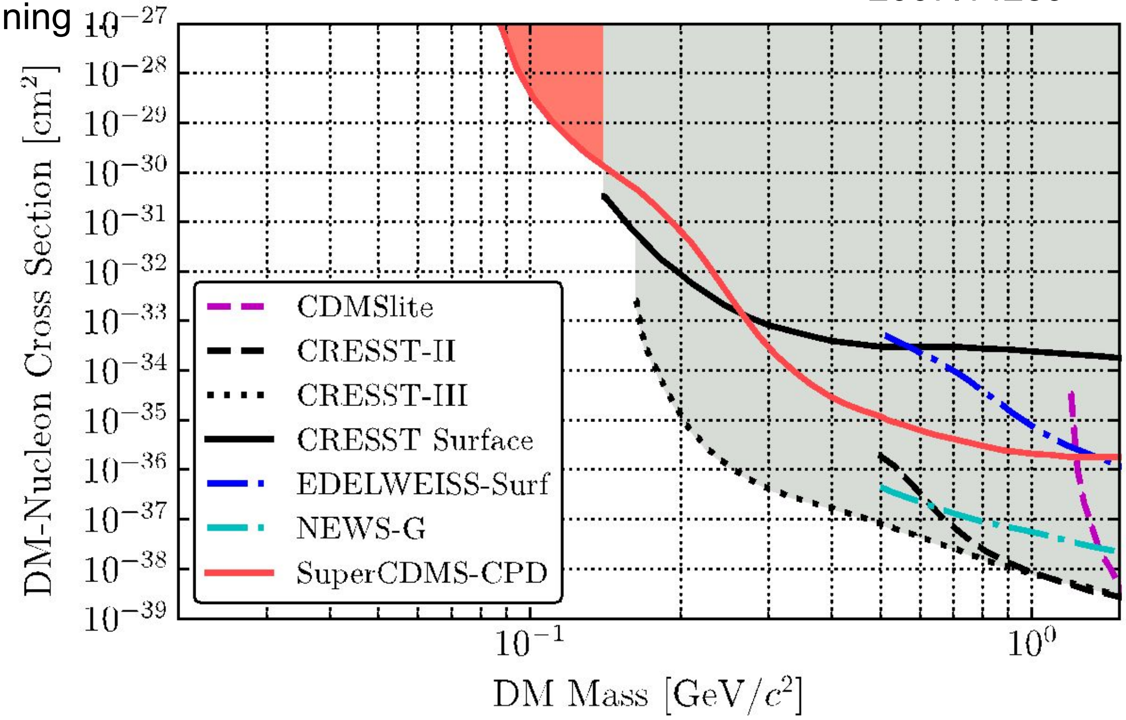
Phonons instead photons



First Dark Matter Search

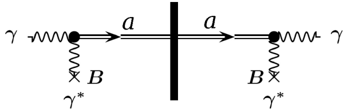
- In collaboration with SuperCDMS, we ran the CPD detector at the SLAC surface test facility
  - Significantly limited by cosmogenic backgrounds
  - 10gd exposure
- World leading DM sensitivity from 87-140 MeV
- Just the beginning

2007.14289

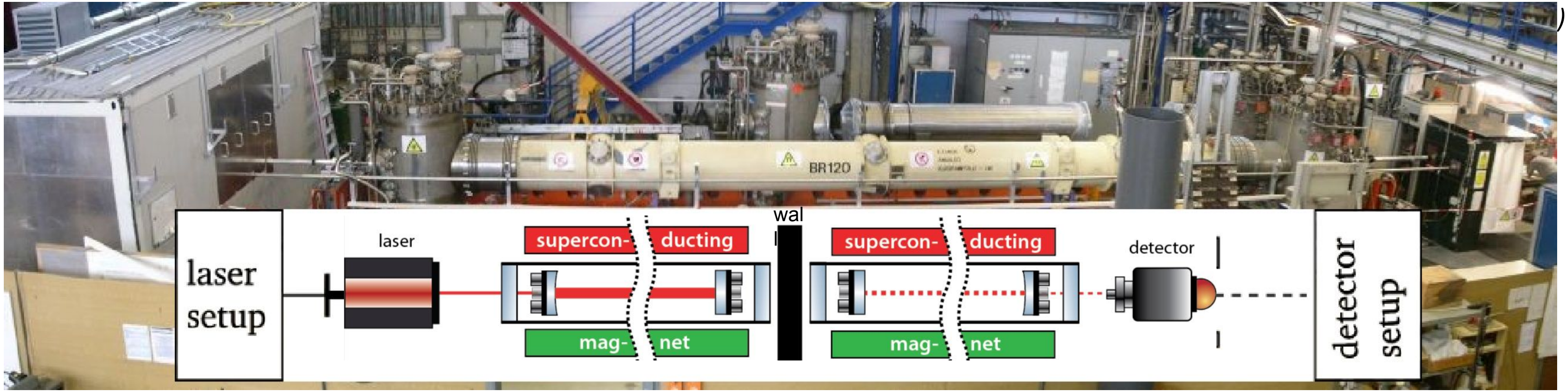


TES for Any Light Particle Search (ALPS II)

DESY, Hamburg, Germany

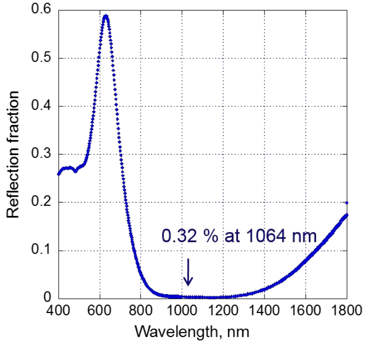


Light shinning through a wall

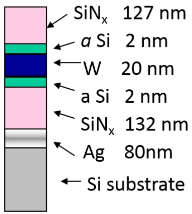


Detection of low rates of single infrared photons 1064 nm (< 1/h)

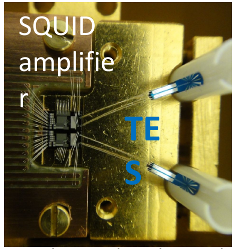
- High system detection efficiency (97.5% ± 2%)
- Low dark/background count rate (10^{-4} s^{-1})
- Good energy resolution (~ 0.15 eV)



Optical stack



TES Package



J. Dreyling-Eschweiler et.al., *Journal of Modern Optics*, 2015

With investments detectors will improve

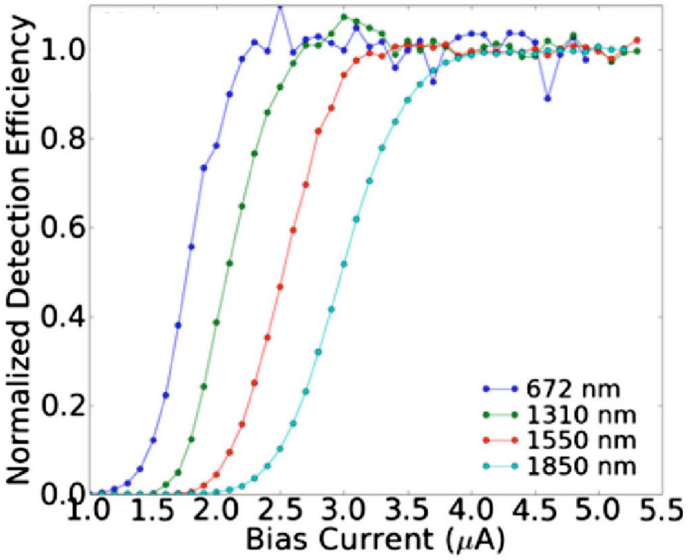
Wavelength: How low in energy (long in wavelength)?

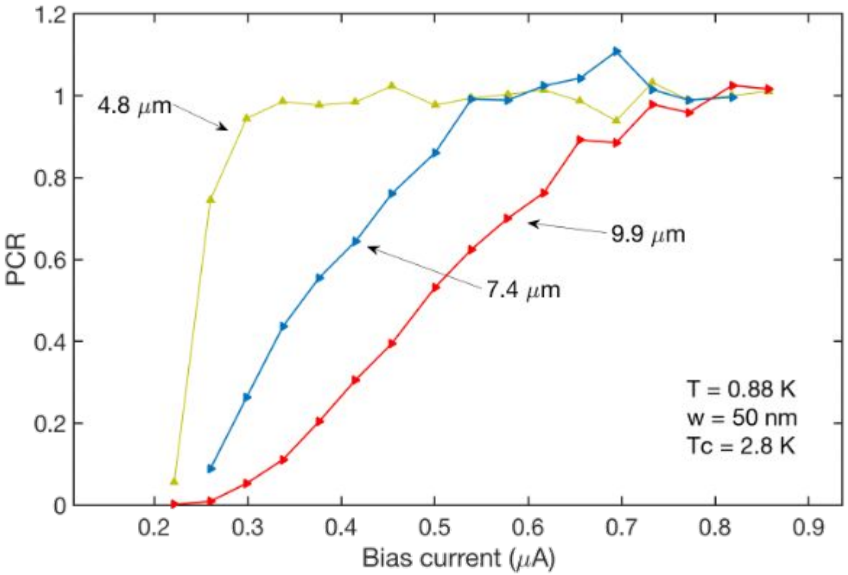
Pixel size: How large can we make a single pixel?

Arrays: Cameras or Spectroscopy arrays?

Extra

Lower threshold energy / color





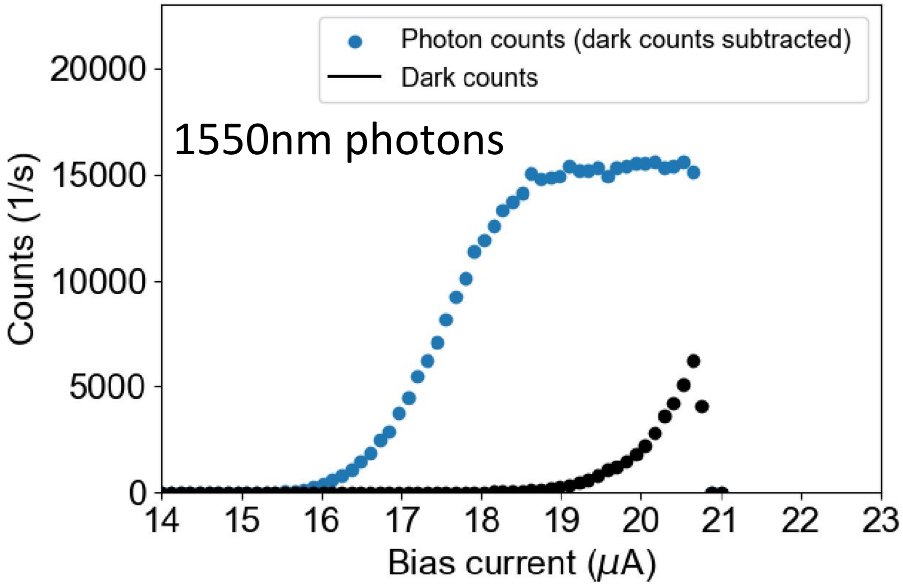
Today, 10μm = 30 THz = 124 meV

MIT JPL NIST

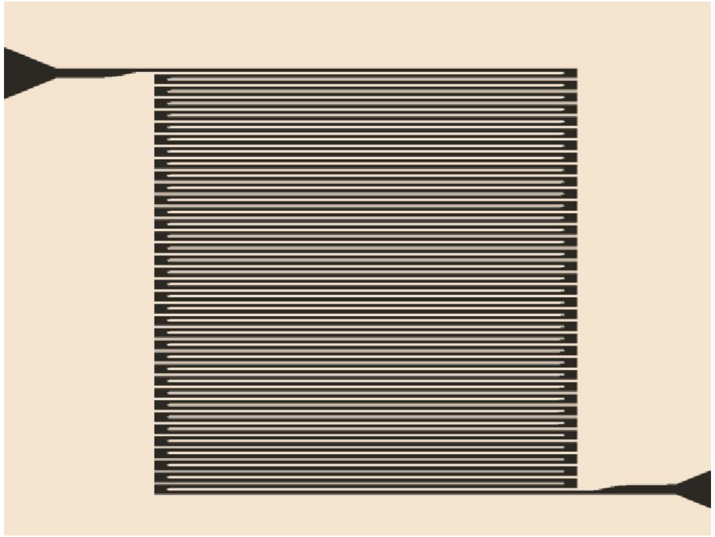
Materials, Operating Temperature

“micron” wire detectors: 150nm to 2000nm

2 μm wide wires

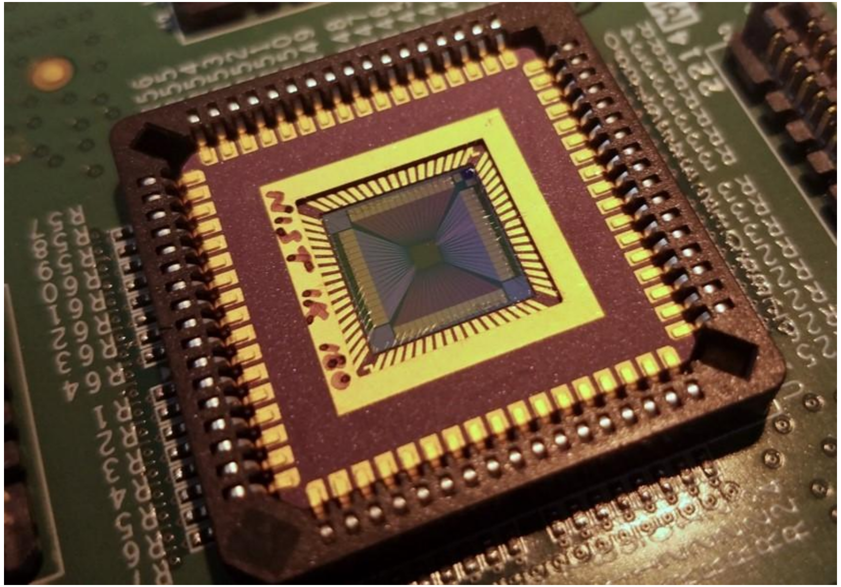


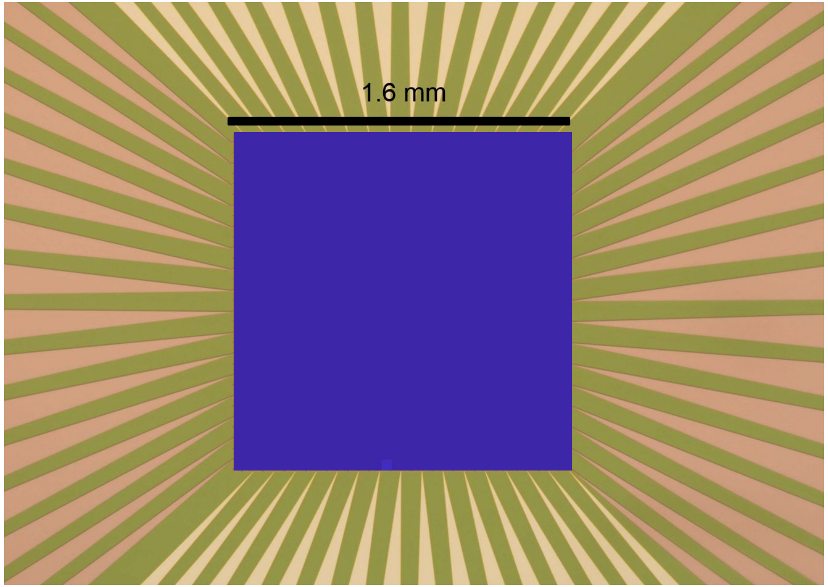
360 μm x 360 μm area



4nm x 150nm -> 2nm x 2000 nm

Larger Areas: N^2 pixels with 2N readout





1 kilopixel today, new architectures for 1 Megapixel, 100 Megapixel...

JPL NIST

Food for thought / Conclusions:

- Tweak materials and operating temperature: 3 Thz / 100µm / 12 meV
    - Still need to demonstrate on a large pixel
    - Need cryo-amps to amplify small signals
- Wide wires
    - Large area pixels (1cm scale should be possible now)
    - Wide wires work … easier to detect lower energy?
- Arrays
    - Cover 300mm wafers?!?

Food for thought continued

- Can we exploit picosecond timing?
  - *e.g.* Cherenkov radiation, smaller size?

- Non-linear inductors (like Josephson junctions)
  - Quantum limited amps?
  - Low-threshold amps
  - Frequency multiplex like MKIDs and microwave SQUIDs