Superconducting nanowire detectors for rare event searches

Sae Woo Nam (NIST) and Ilya Charaev (MIT)

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

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JPL
Jet Propulsion Laboratory

Superconducting nanowire detectors for fundamental physics

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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

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Perimeter, NYU, Stanford, IAS

Outline

- Single Photon Detection Technologies
  - Quantum Information Applications
  - Semiconductors
  - Superconductors
- Superconducting Nanowire Detectors
  - How they work…
- Dark Matter Detection
  - Dark Photons
- Prospects for improving detectors
- Summary

Quantum Information Requirements

	Quantum Communication	Quantum Computing (Photonic)	Quantum Computing (atoms)	Entanglement-based random numbers
Wavelength	1550 nm	Visible, Near-IR	UV	Near-IR
Detection Efficiency	As high as possible	As high as possible	>80%	>67%

Dark / Background counts	As low as possible
Timing jitter	As low as possible
Maximum count rate	As high as possible

Conventional Single-Photon Detectors

	Wavelength Range	QE (%, max)	DCR (cps)	Jitter	Max Count Rate (cps)
PMT (visible)	400-900 nm	40	100	300 ps	10×10^6
PMT (IR)	1000-1600 nm	2	200K	300 ps	10×10^6
Silicon (thick)	400-1050 nm	65	25	400 ps	10×10^6
Silicon (thin)	400-1000 nm	49	25	35 ps	10×10^6
InGaAs APD	950-1600 nm	20	75K	350 ps	10×10^3

- Commercially available
- Relatively inexpensive

M. D. Eisaman, J. Fan, A. Migdall, and S. V. Polyakov, Rev. Sci. Instrum. 82, 071101

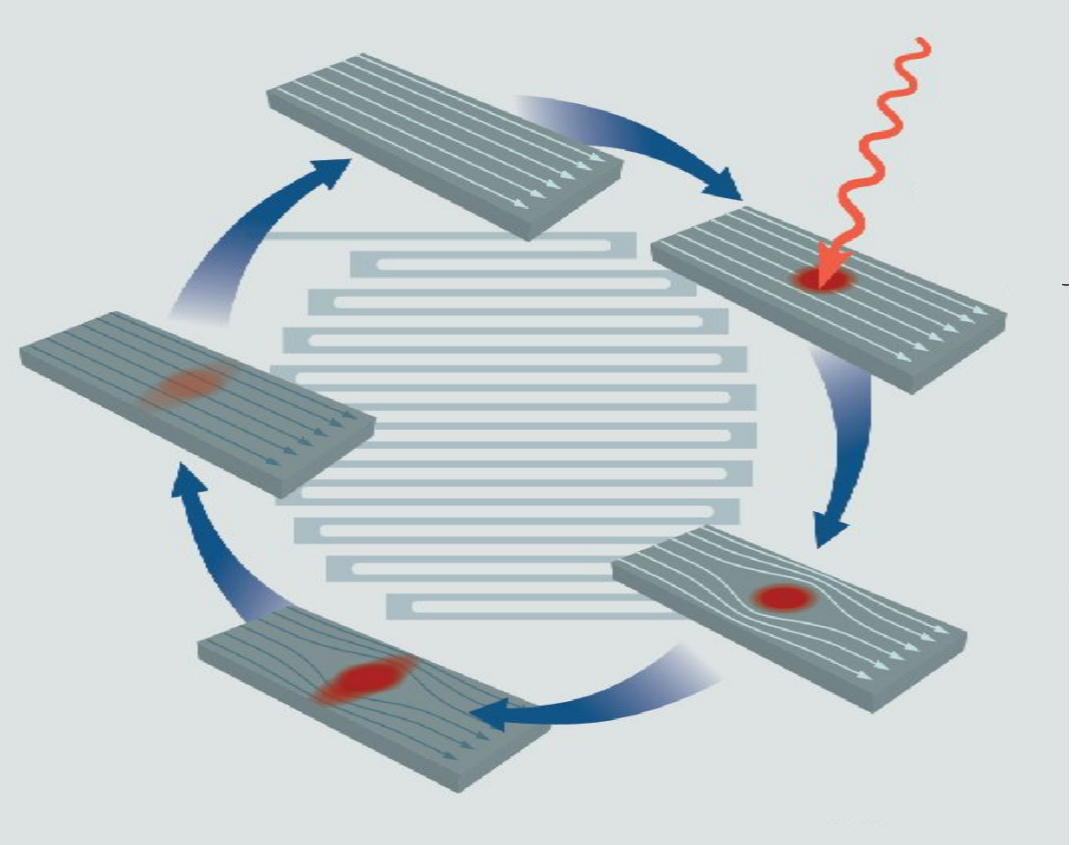
Superconductors

	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

TES: Transition Edge Sensor
SNSPD: Superconducting Nanowire Single Photon Detector

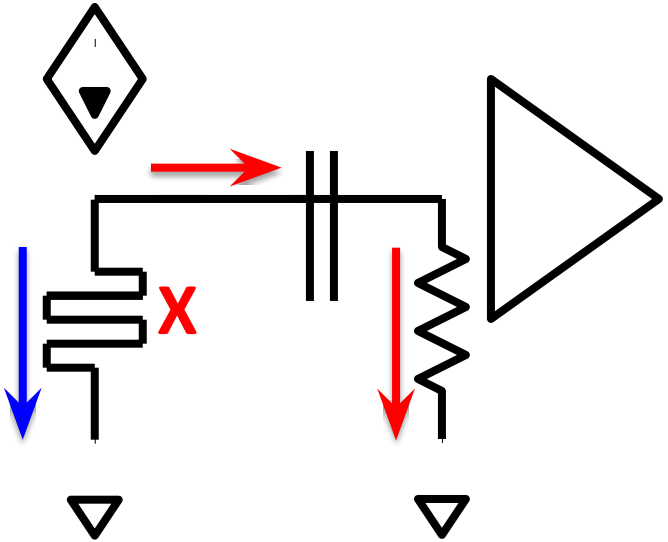
- No afterpulsing problems
- Excellent prospects for longer wavelengths

Superconducting Nanowire Single Photon Detectors:



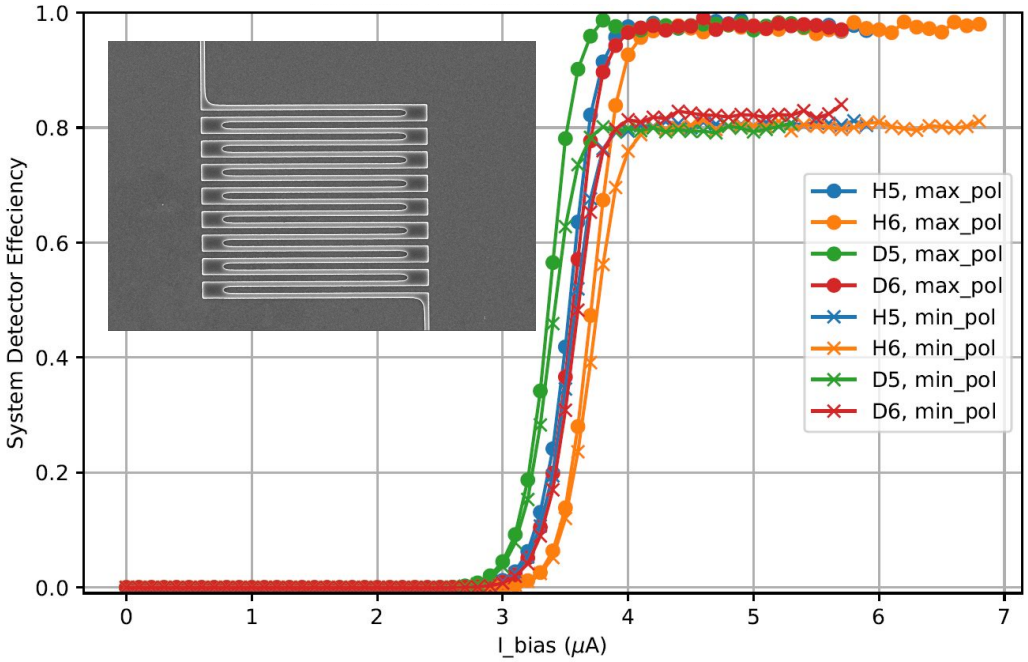
- ultra-thin (4 to 8nm, 2nm)
- Anomolously large kinetic inductance (non-linear)
- NbN, NbTiN
  - Polycrystalline
  - 2K operating temperature
  - ~80nm wide
- W-Si, Mo-Si, Mo-Ge
  - Amorphous
  - 1K operating temperature
  - ~150nm wide

Simplicity of Superconducting Nanowire Single Photoncs Detectors

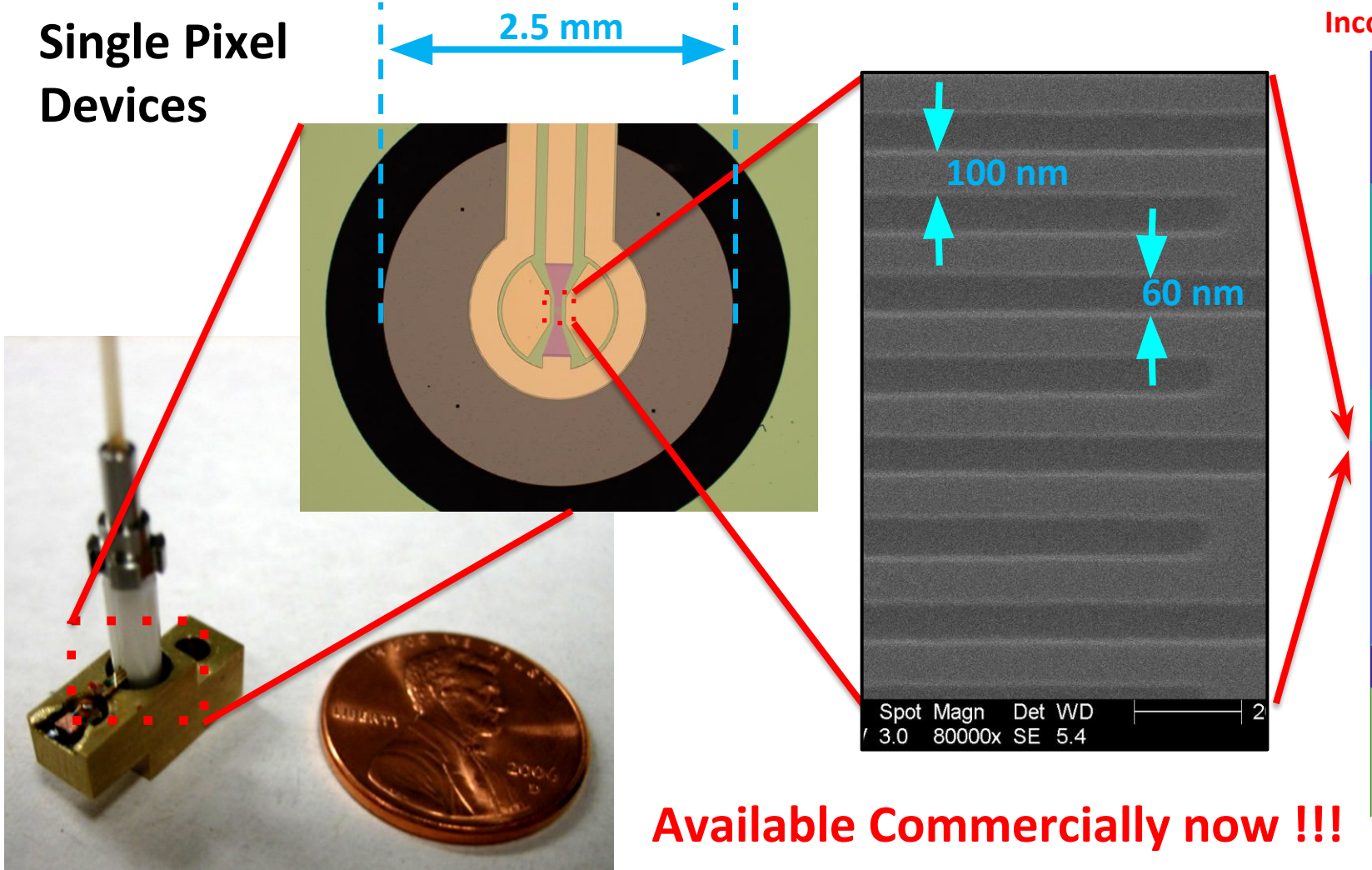


Simple Readout

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:

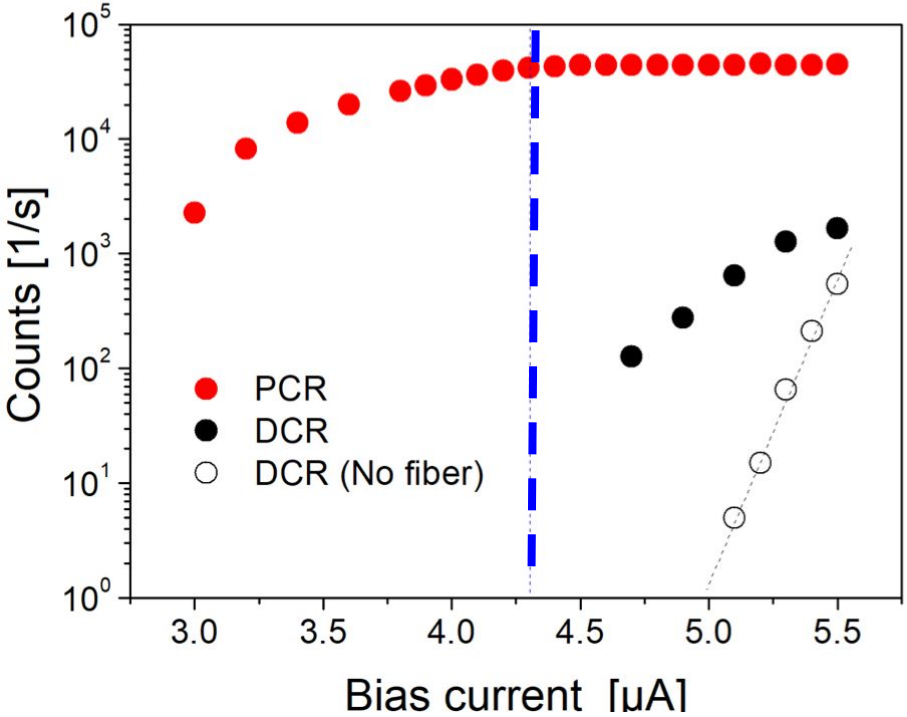
10 µm to 100nm
~98% @ 1550nm
~ 1 count per day
2.7ps FWHM
100 Mcps

Arrays
Not all in one device yet

MIT JPL NIST

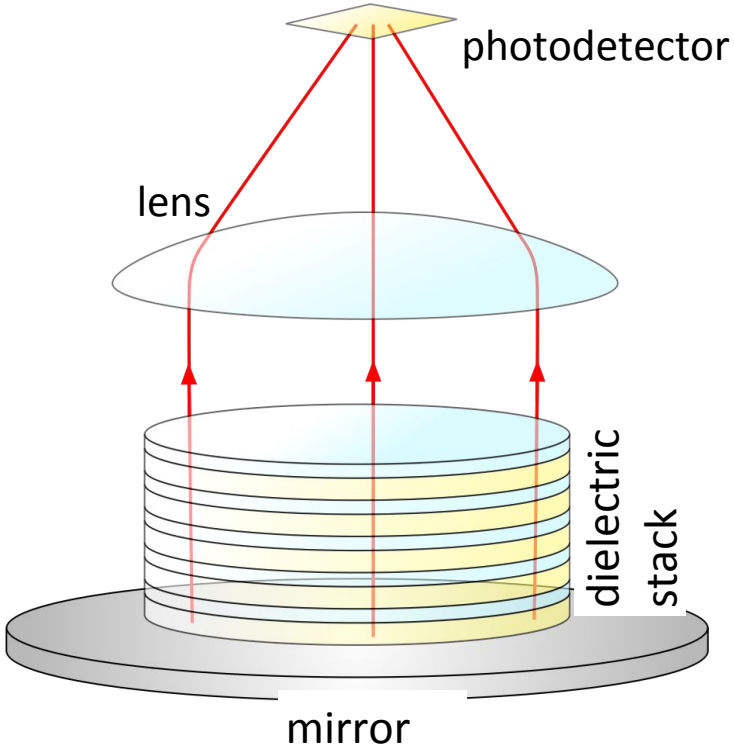
Detector for Dark Matter searches

- 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

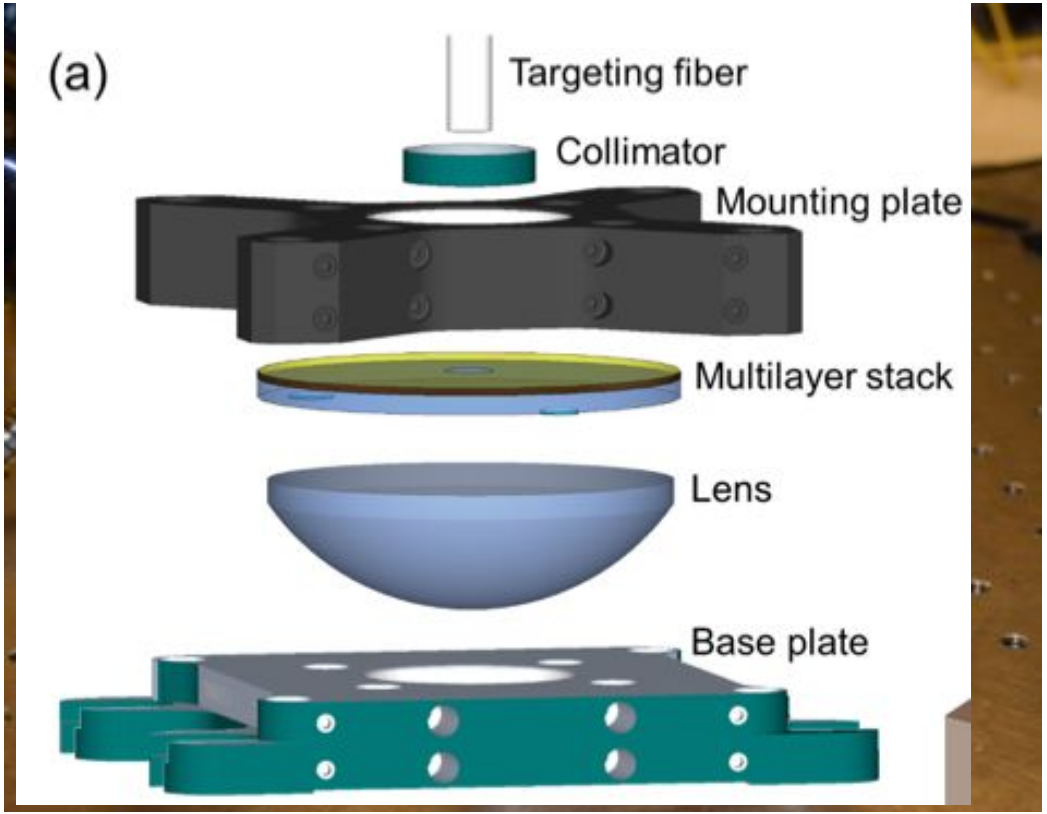


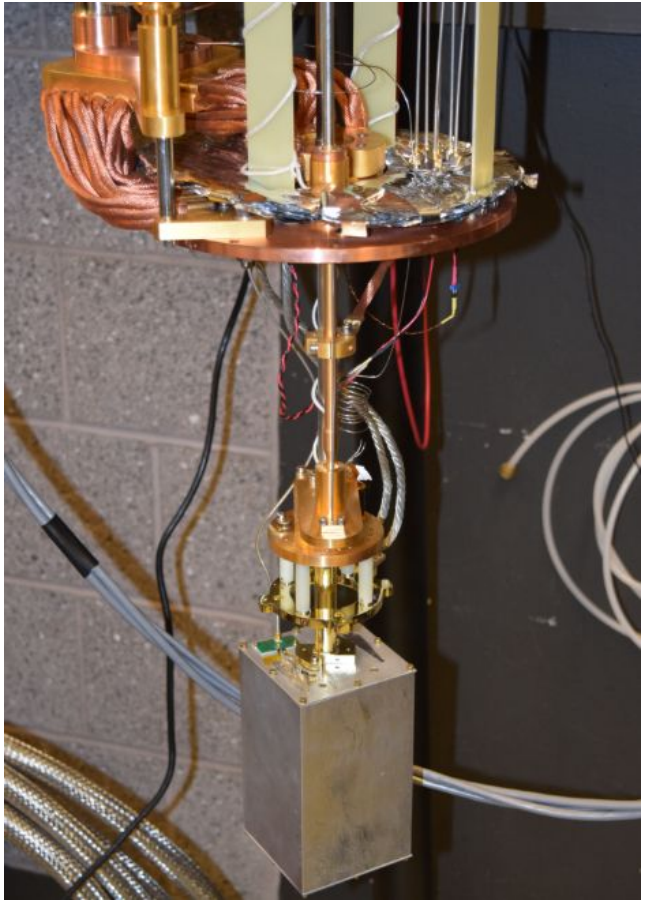
- Dark photons are “cousin” hypothetical particle to axions
- “Phase matching” via dielectric stack
- Emission of “Dark Photon” perpendicular to te dielectric stack

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

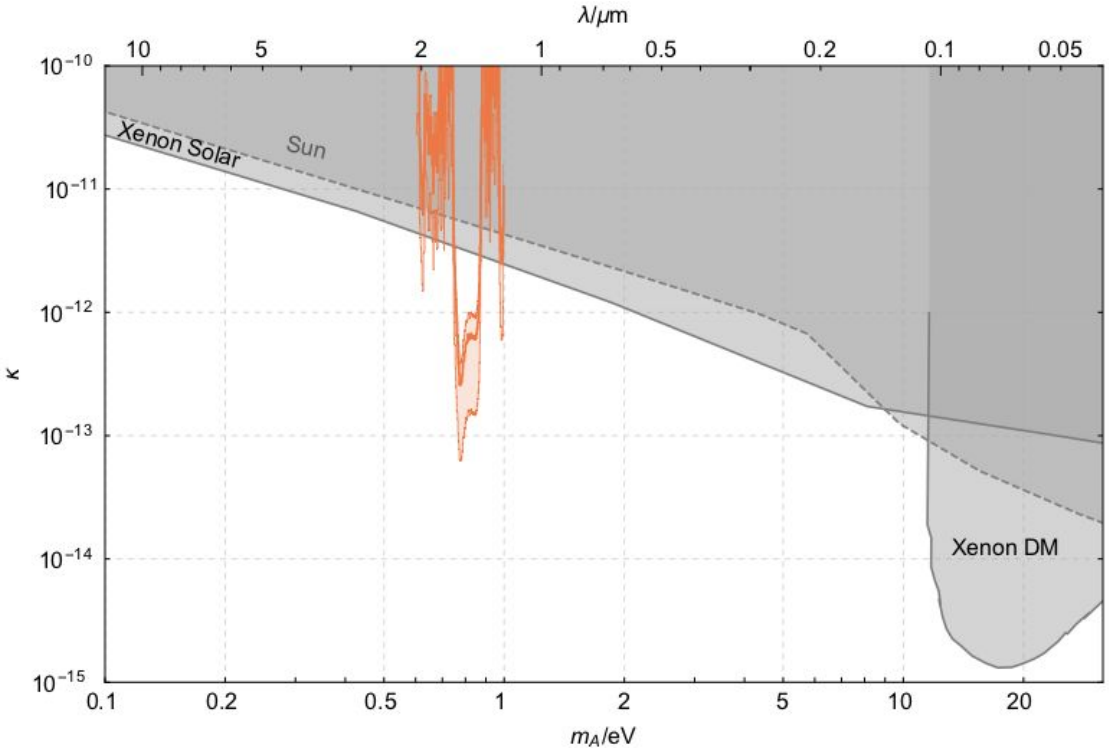
First Prototype Experiment





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**

Detector Improvements

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

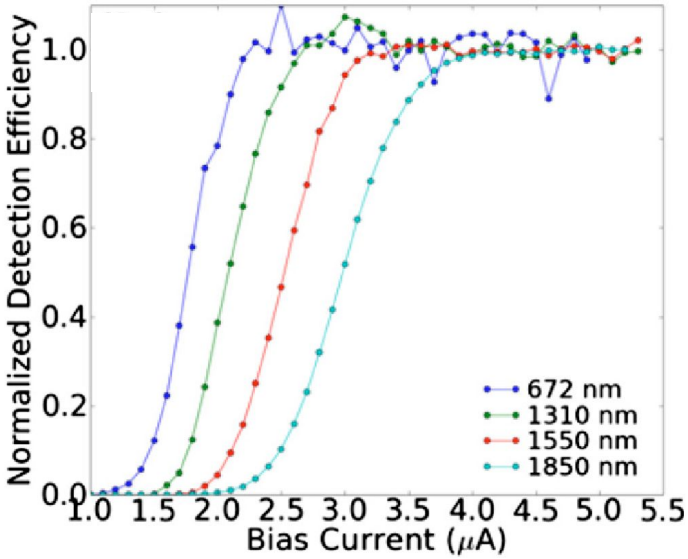
Pixel size: How large can we make a single pixel?

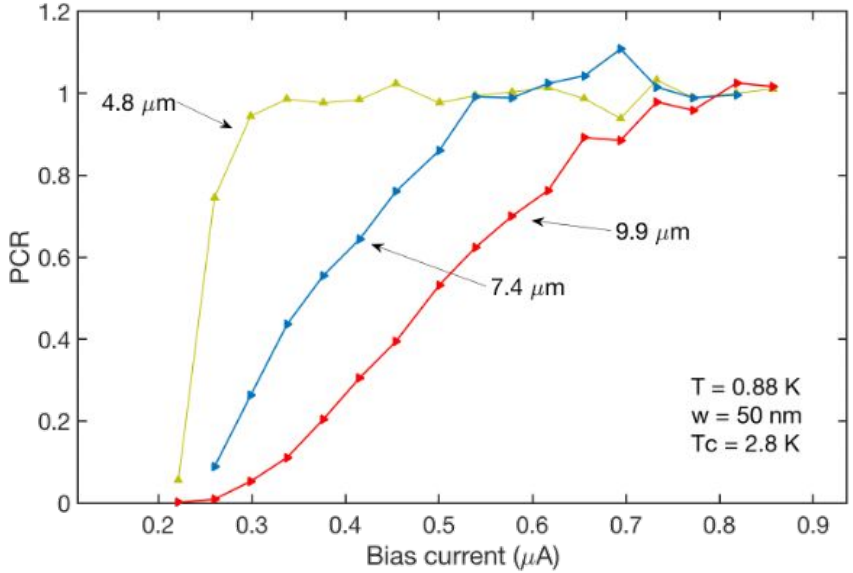
Arrays: Cameras or Spectroscopy arrays?

Timing: 2.7ps at 400nm, Can we go sub-picosecond?

Operating Temperature: Higher Tc?

Lower threshold energy / color



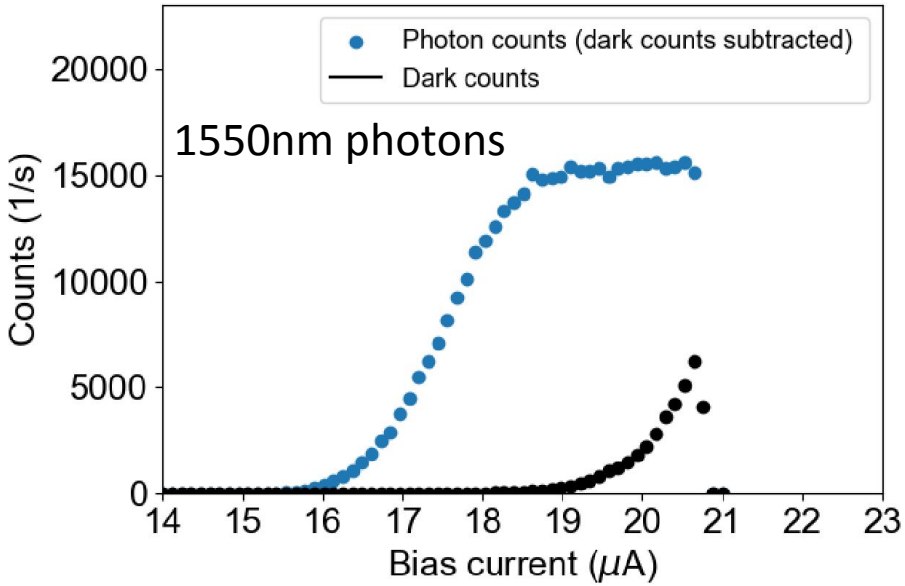


Today, 10μm = 30 THz = 124 meV

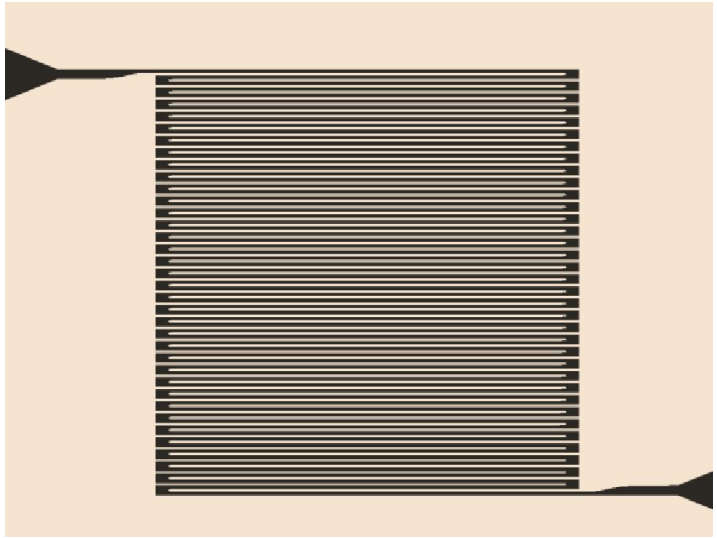
Materials, Operating Temperature

“micron” wire detectors: 150nm to 2000nm

2 μm wide wires

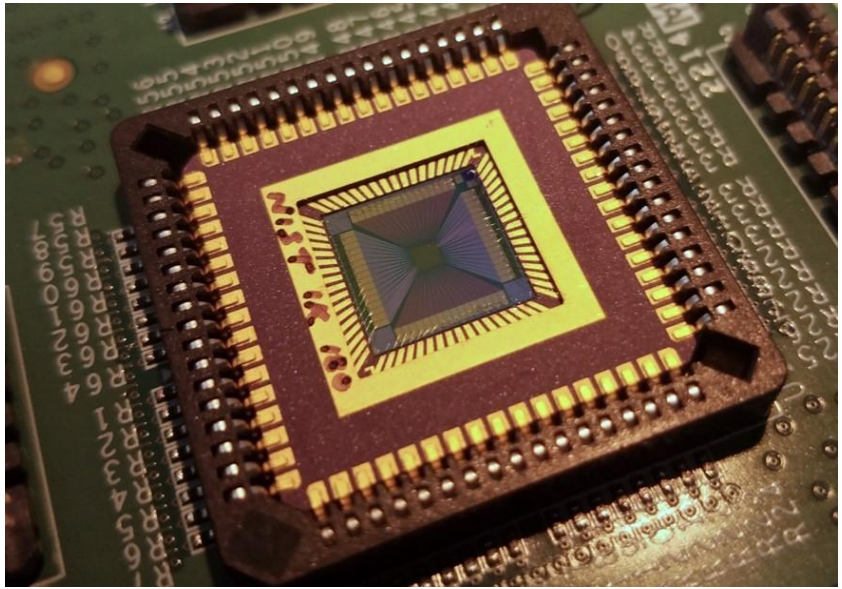


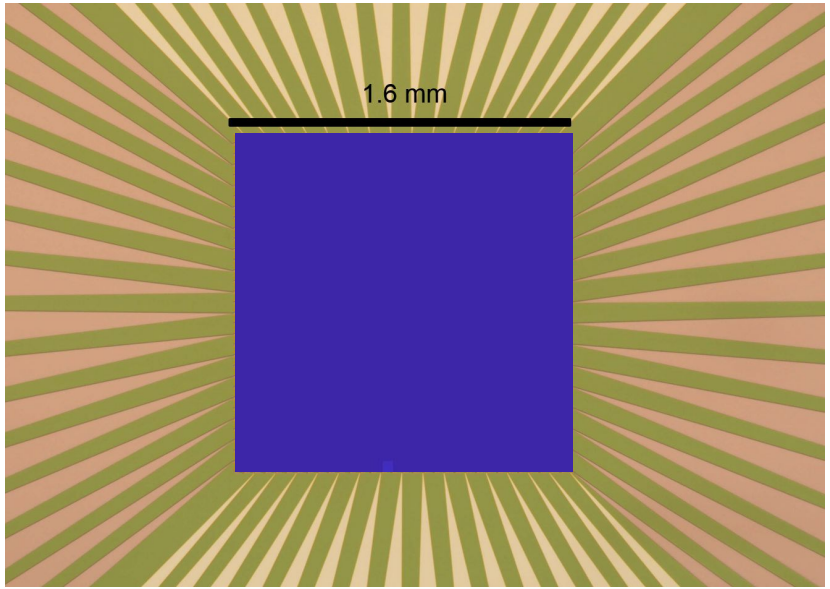
360 μm x 360 μm area



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

Postdoctoral Opportunities

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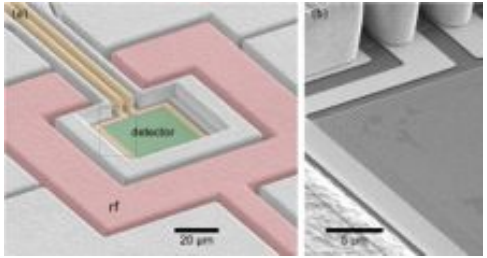
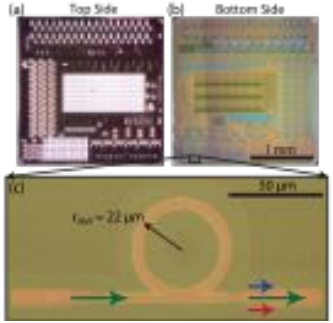
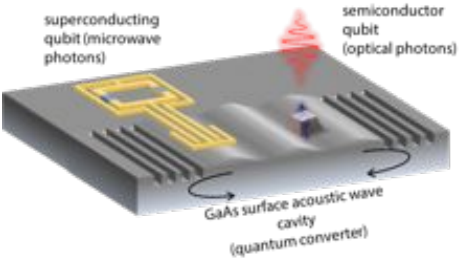
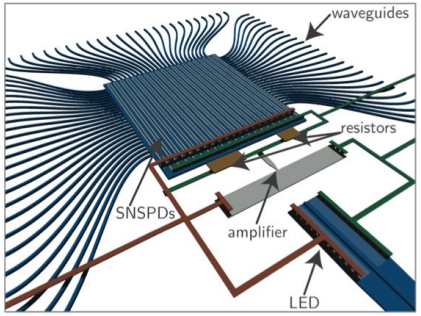
richard.mirin@nist.gov









Optical photon sources and detectors

Quantum Optics

Integrated Photonics, frequency combs, lasers

Quantum dot devices

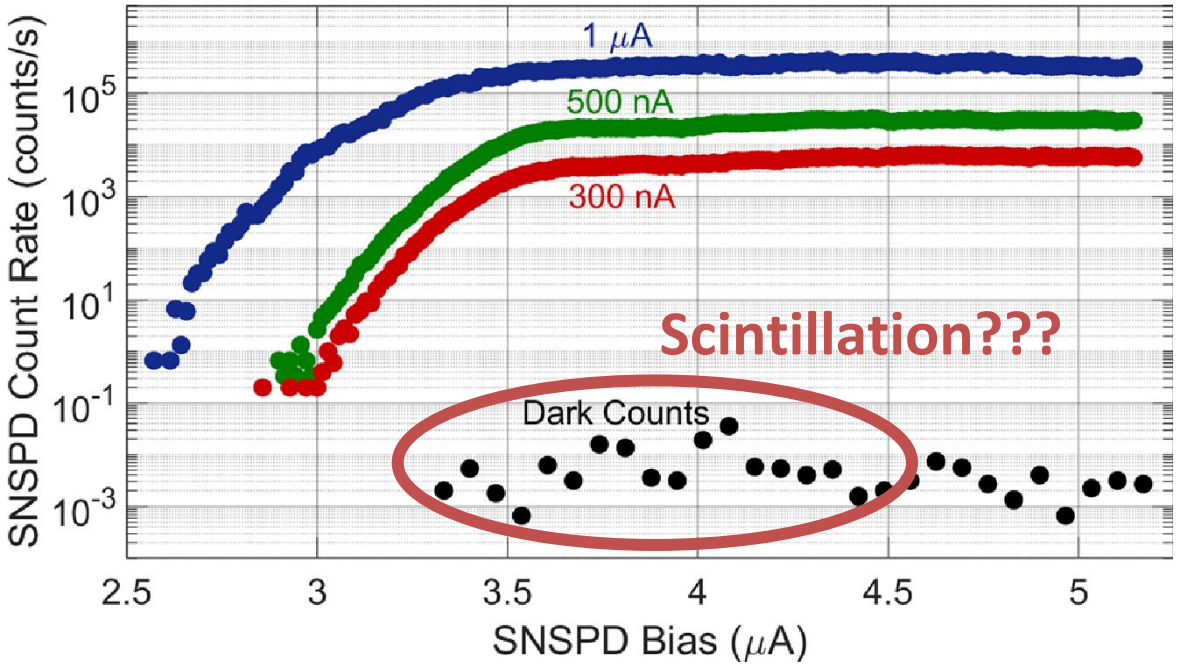
Optical power metrology

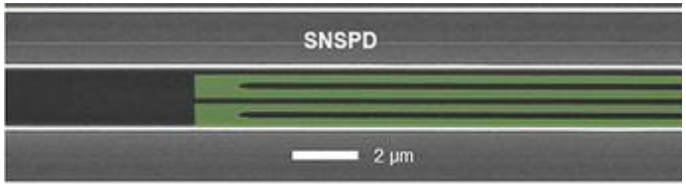
Superconducting Optoelectronics for Neuromorphic Computing

Advanced Cryogenic Systems

Unvconventional Superconducting electronics

GaAs wafer as a scintillator detector of muons???

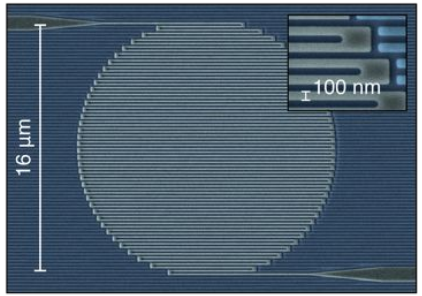


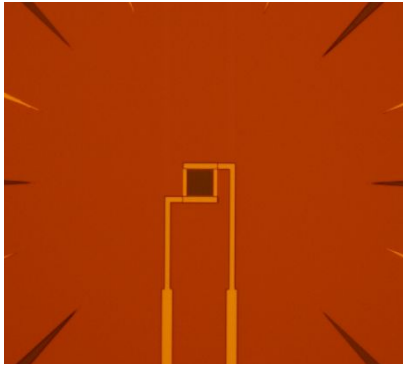


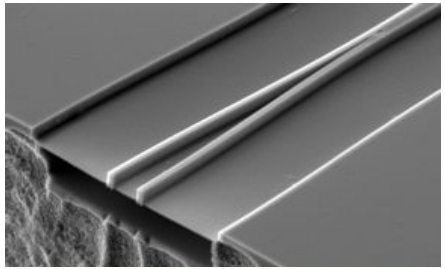
McDonald, C et al., Appl. Phys. Lett. **115**, 081105 (2019)

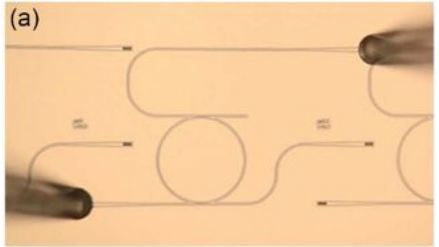
Nb wires

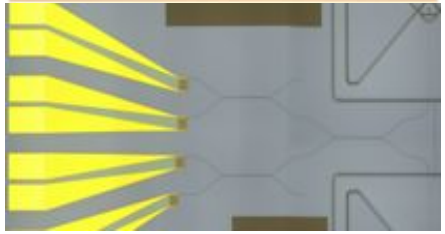
Boulder Microfabrication Facility





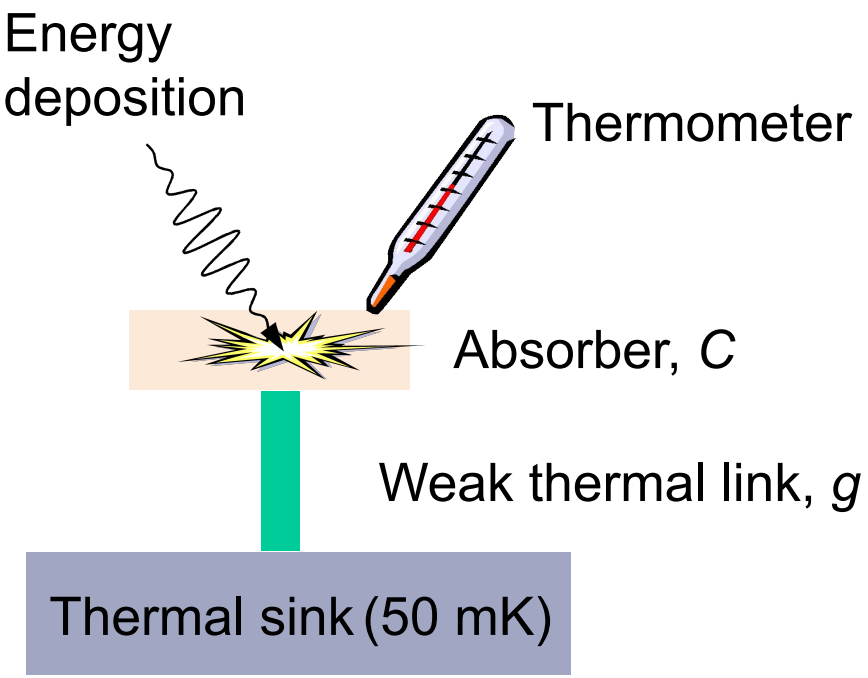






1700 sq. meter (18,000 square ft), class 100

Transition Edge Sensor (TES)

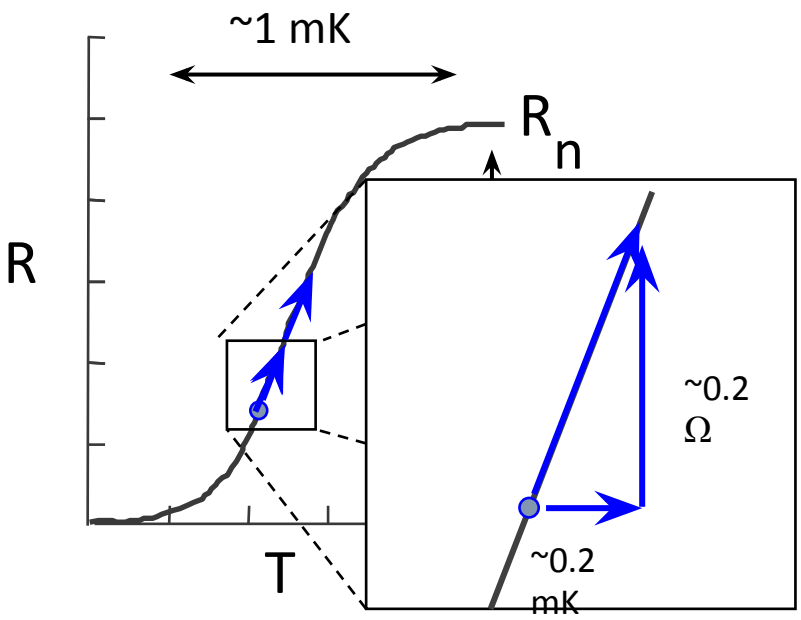


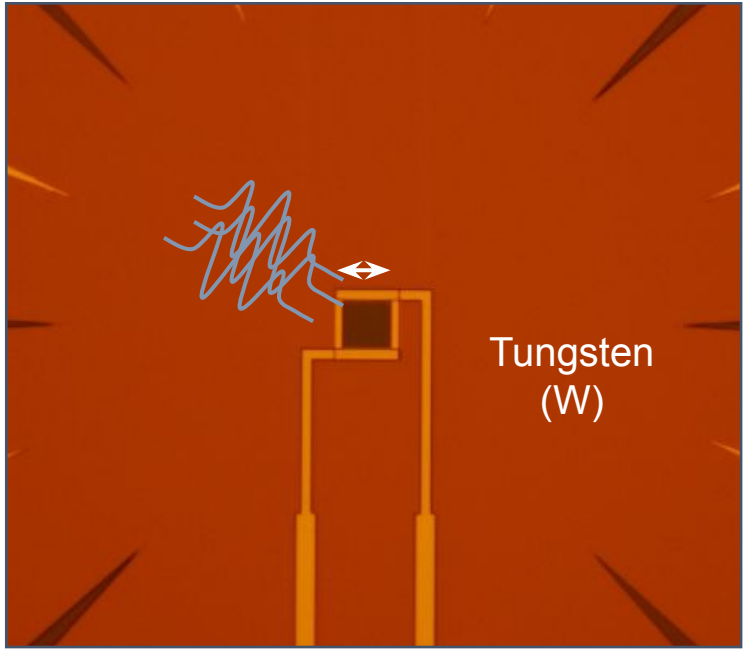
- Calorimetric detection of UV/optical/IR photons
- Temperatures are ~100 mK
  - low noise
  - high sensitivity.
- NIST – Tungsten Superconductor
- AIST – Titanium Superconductor

Nb wires

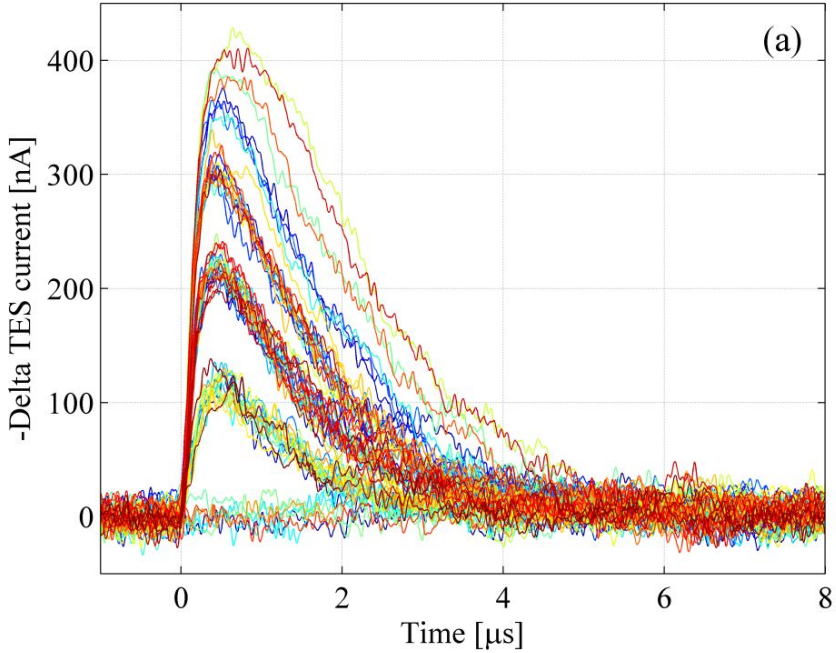
Transition Edge Sensor (TES)

Superconducting-to-normal transition as ultra-sensitive thermometer





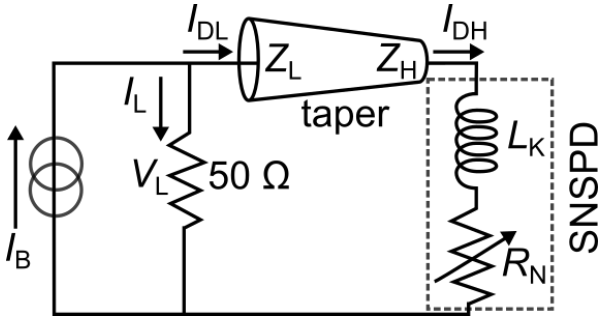
Photon Number Resolution

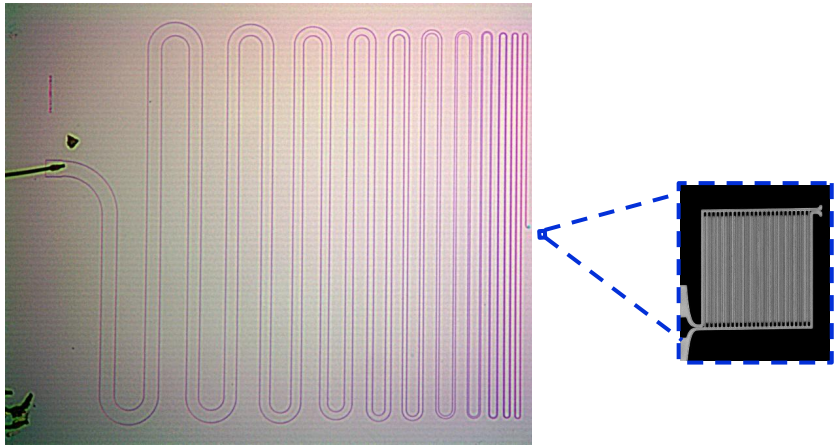


- Measurement non-linearity
- Gaussian Boson Sampling
- >95% system DE
- 24 / 7 operation

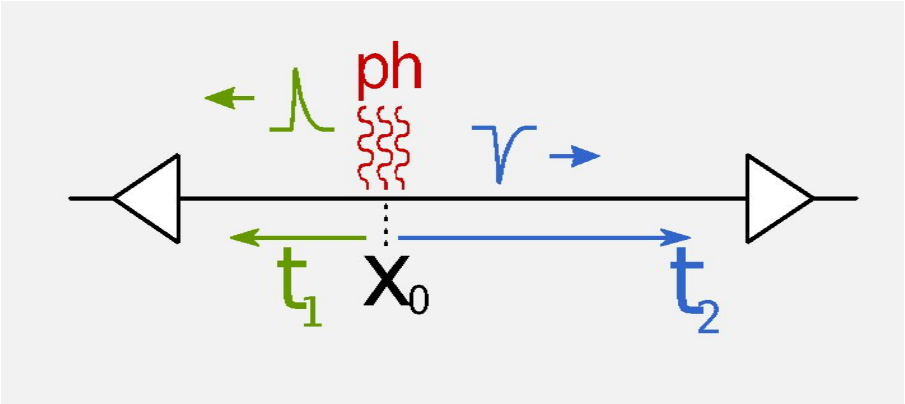
XANADU

Taper readout





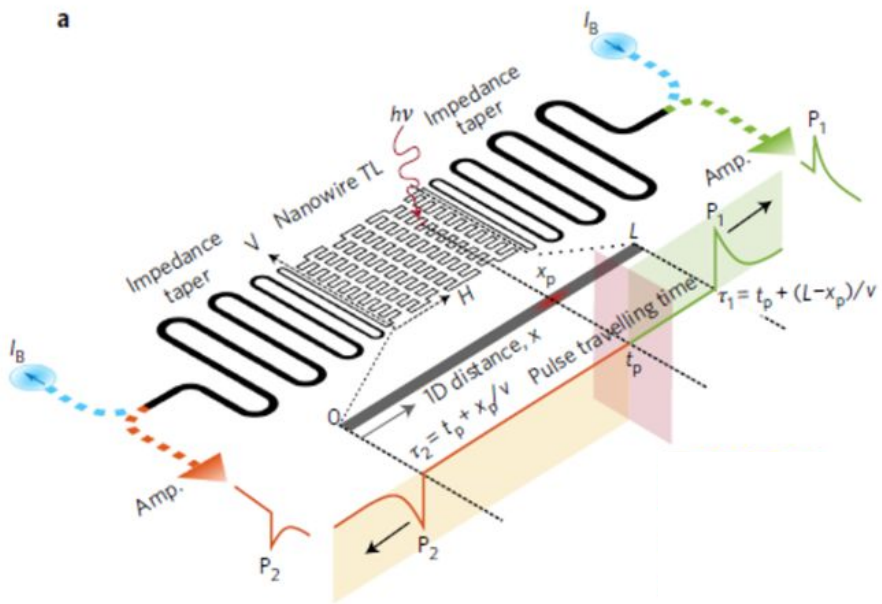
Transmission line imager



- Use relative time delay to determine where a photon is detected
- Requires dual readout

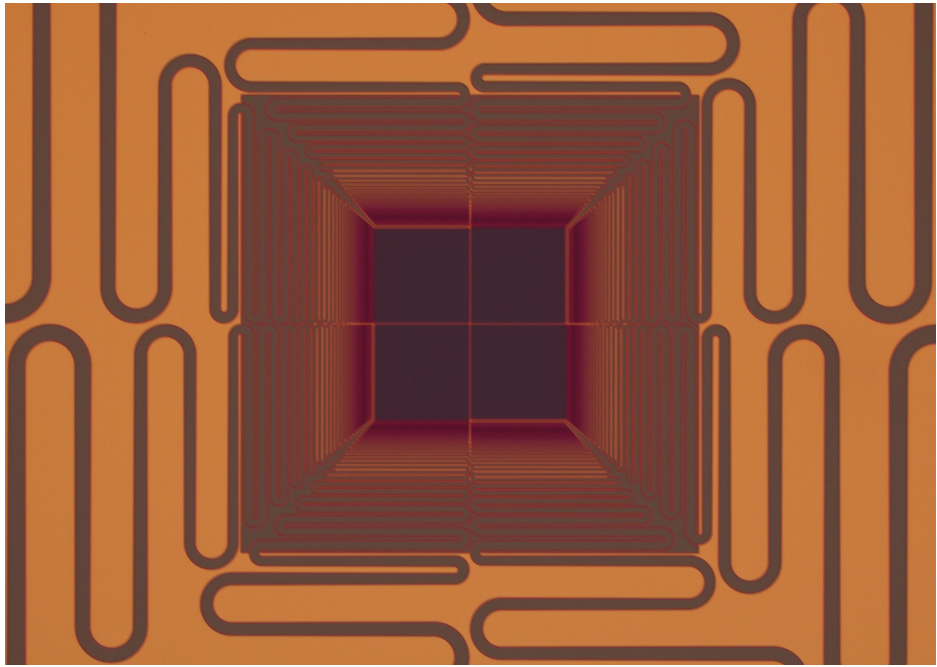
Q. Zhao et. al, Nature Photonics 11, 247 (2017)

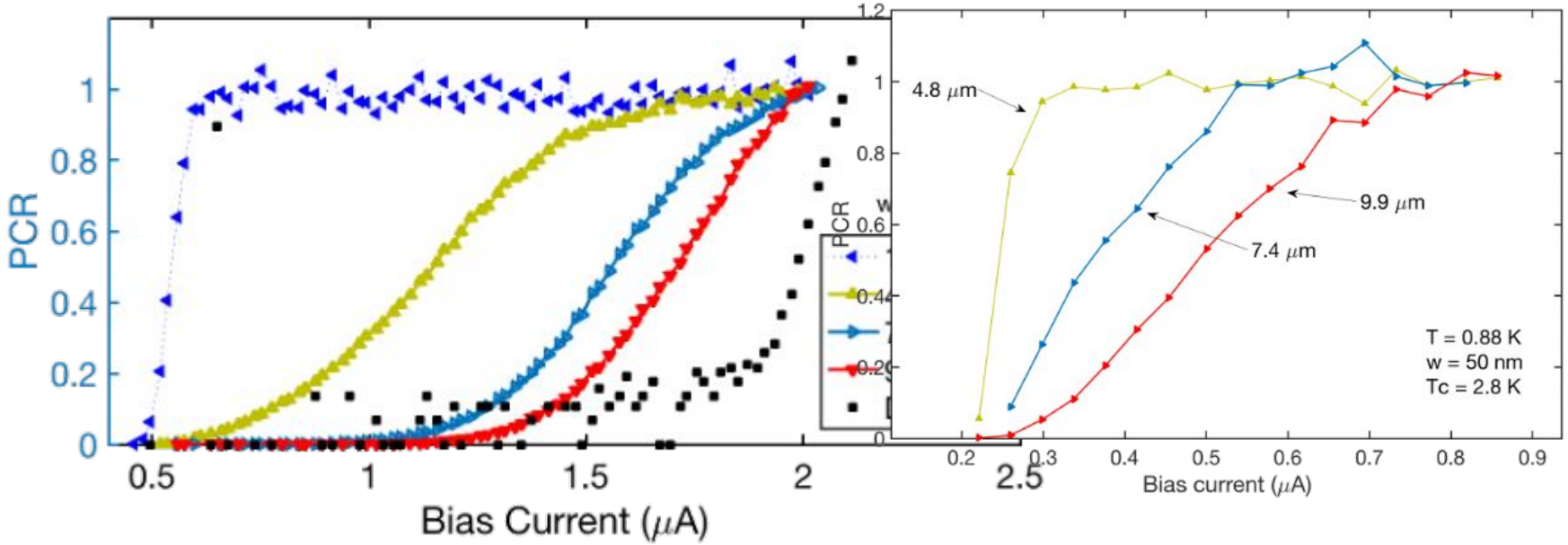
Delay line imager



Q. Zhao et. al, Nature Photonics 11, 247 (2017).

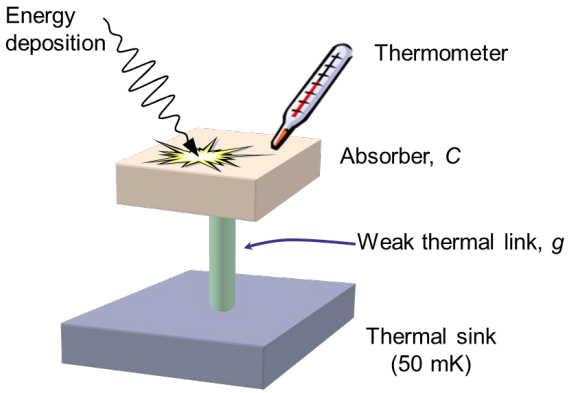
NIST Quad Delay line imager

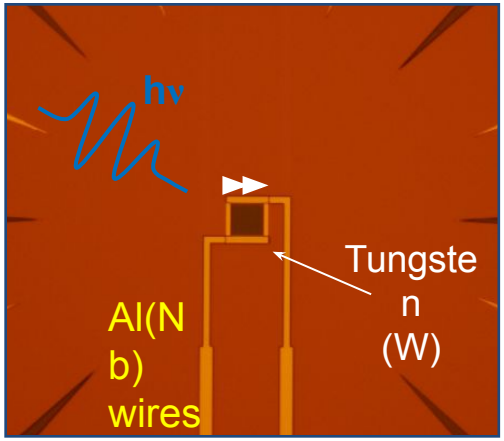


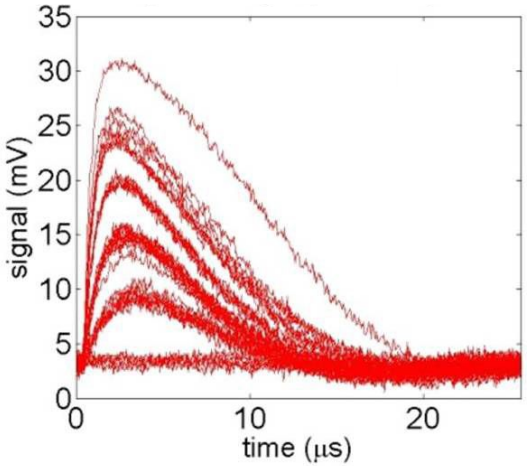

PCR
Bias Current (μA)
0.5
1
1.5
2
2.5
0
0.2
0.4
0.6
0.8
1
1.2
4.8 μm
7.4 μm
9.9 μm
T = 0.88 K
w = 50 nm
Tc = 2.8 K
Bias current (μA)
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Transition Edge Sensor (TES) Technology

Calorimetric detection of UV/optical/IR photons



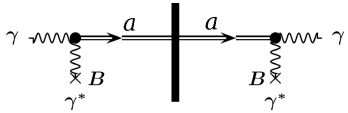




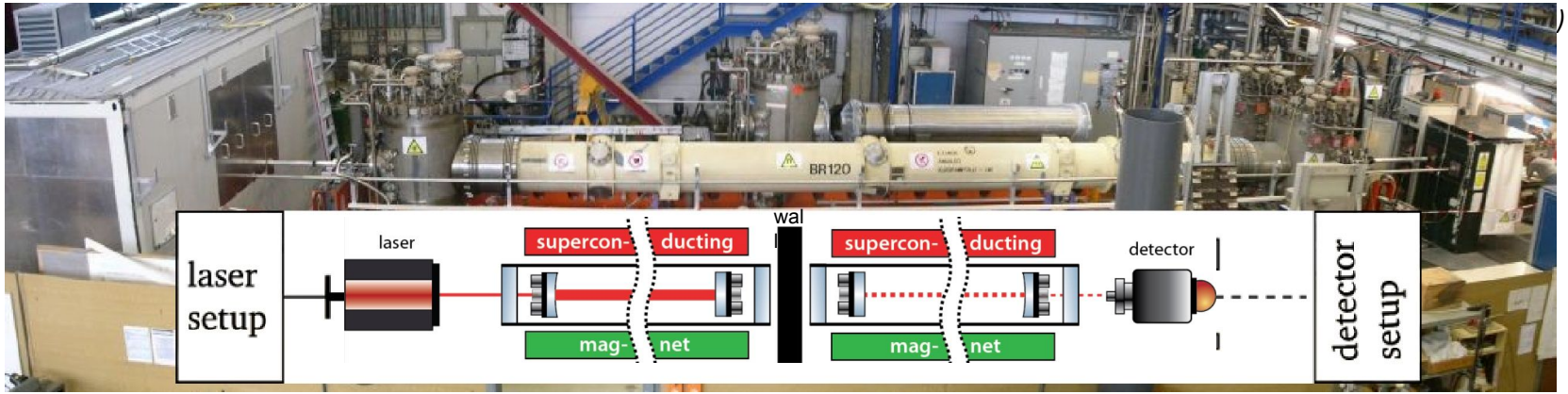
- Photon(s) are absorbed by an absorber (Tungsten (W) e^- system)
- An ultra-sensitive thermometer measures the temperature change due to absorption of energy (superconducting-to-normal transition)
- A weak thermal link enables the cooling of the absorber to base temperature (W e^- *-phonon* coupling)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

TES for Any Light Particle Search (ALPS II)

DESY, Hamburg, Germany

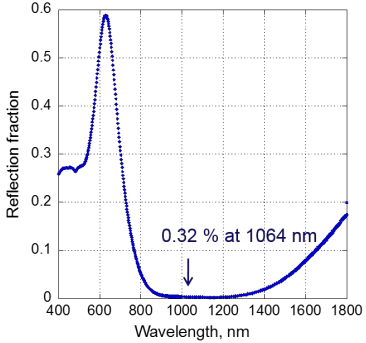


Light shinning through a wall

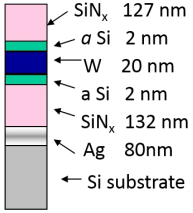


Detection of low rates of single infrared photons 1064 nm (< 1/h)

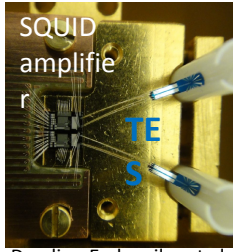
- High system detection efficiency (97.5% ± 2%)
- Low dark/background count rate (10^{-4} s^{-1})
- Good energy resolution (~ 0.15 eV)



Optical stack

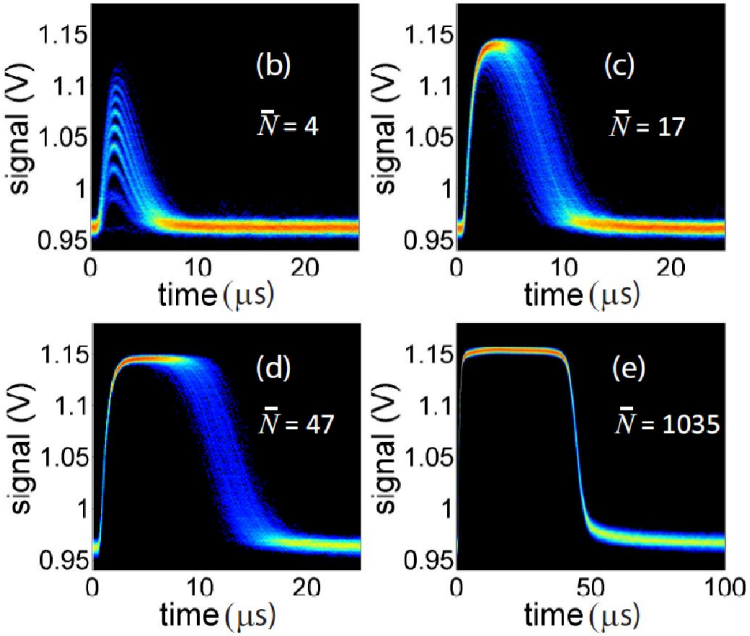


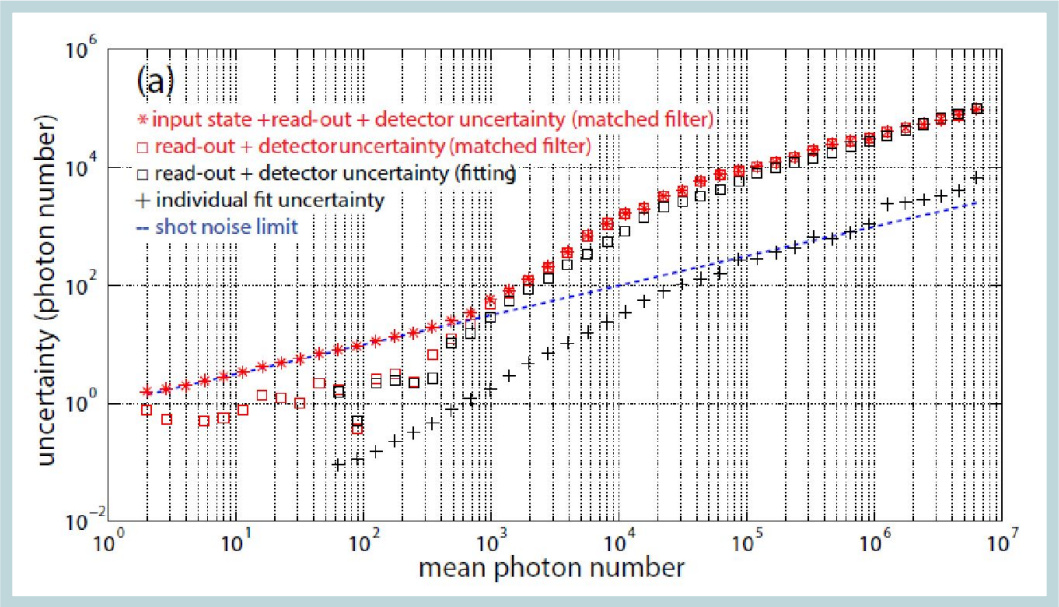
TES Package



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

Explore Quantum to Classical Transition
Large Photon Number Counting



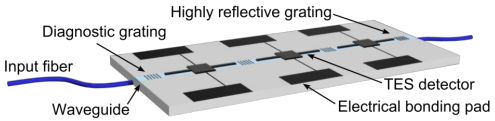


Gerrits et al., *Opt. Expr.* **20**, 23798 (2012)

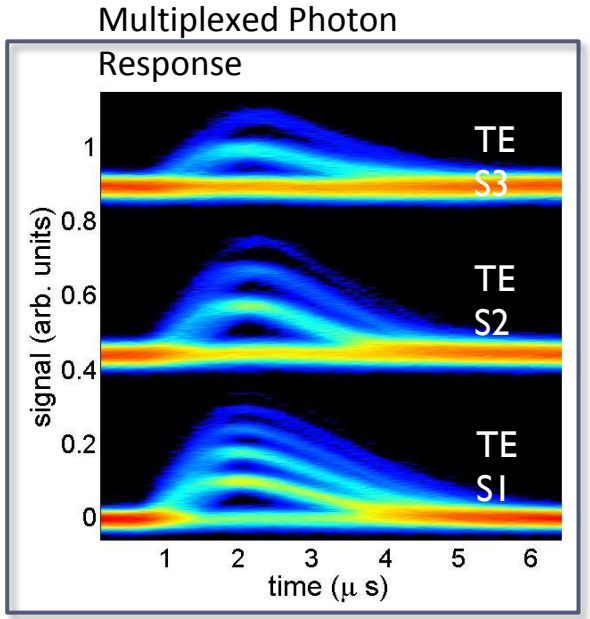
TESs can display large dynamic range due to their low uncertainty thermal response
Potentially advantageous for photon pulses calibration in the mesoscopic regime between single photon detection and conventional photodiodes

TES Waveguide Integration : Evanescent Coupling

SiO_2 waveguide

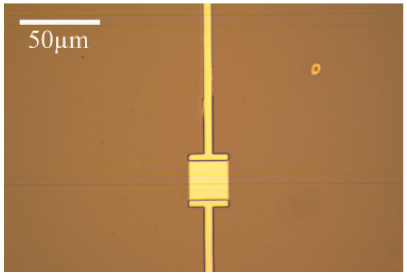


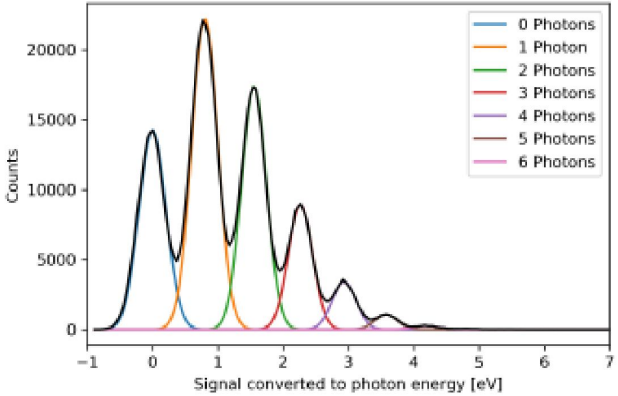
79% total detection efficiency



B. Calkins et al, *Opt. Expr.* **19**, 22657 (2013)

$LiNbO_3$ waveguide



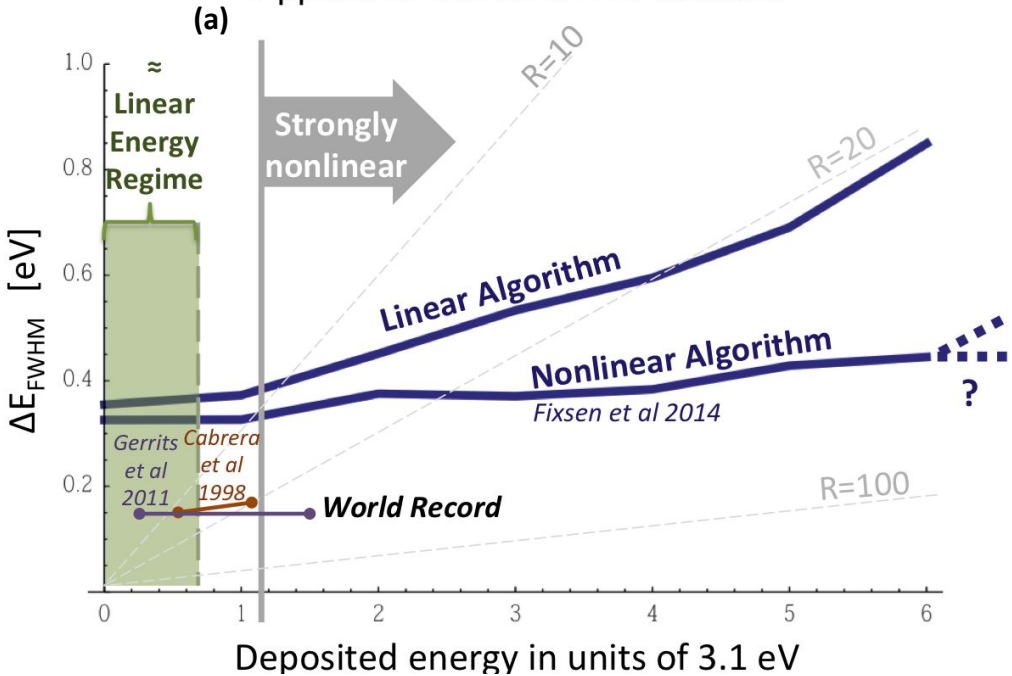


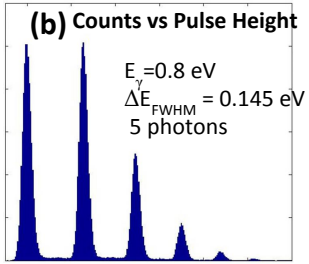
: J-P. Hoepker et al, APL Photonics 4, 056103 (2019)

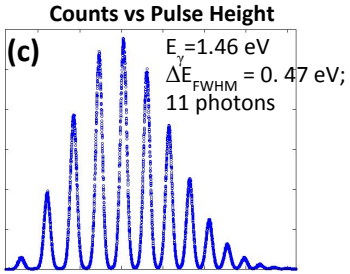
Single-Photon Spectroscopy

TES Energy Resolution

Two Different Pulse Processing Algorithms
Applied to the same TES dataset.

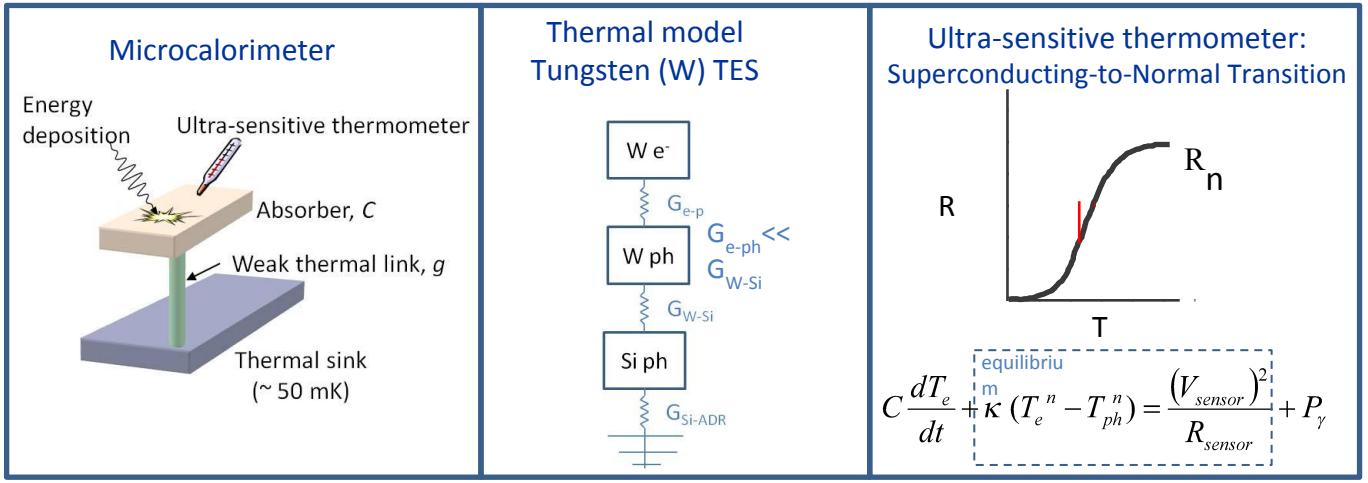






Transition Edge Sensor (TES)

Calorimetric detection of UV/optical/IR photons



- A general microcalorimeter device consists of
  - Absorber for the incident energy (W e^- system)
  - A thermometer to measure the temperature increase from absorption of energy (superconducting transition)
  - A weak thermal link enabling the cooling of the absorber to base temperature (W e^- *-phonon* coupling)
- Temperatures are ~100 mK to ensure low noise and high sensitivity