Development of X-ray Thermal Microwave Kinetic Inductance Detector (MKID) Arrays for Astrophysics, and MKID Photonic Spectrometers.

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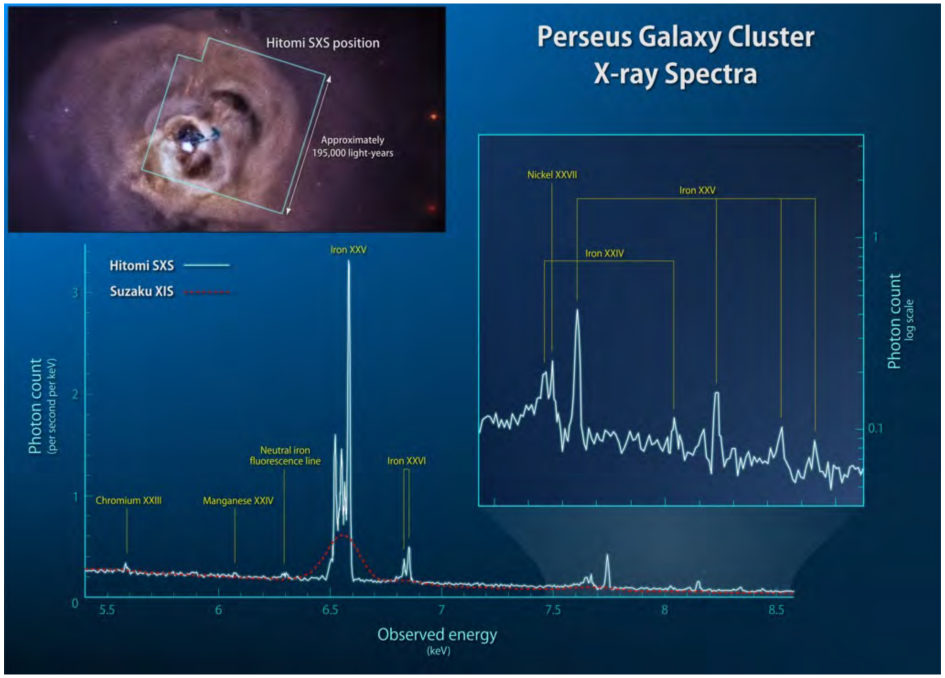
Technology & Funding Justification

- Space-Borne – For *Physics of the Cosmos* NASA needs:
  - Priority #1: fast, low-noise, megapixel X-ray imaging arrays with moderate resolution, $\Delta E \approx 5$ eV
  - Priority #2: large-format, high-spectral-resolution, small-pixel X-ray focal plane arrays
  - TKID arrays provide a path to eventually satisfying priority #1 and #2



Hitomi SXS: <7 eV @ 6 keV, 6 x 6 pixels, 50mK, Si Thermistors
Suzaku XIS: 130 eV @ 6keV, 1025 x 1024 pixels, CCD

Science Enabled with $\Delta E \approx 5$ eV micro-calorimeter array

- High Energy Astrophysics:
  - spatially resolved spectroscopy of extended sources, as well as sensitivity in the detection and spectral analysis of point-like objects
  - Understanding Cooling Flows: turbulent velocities of the gas in clusters of galaxies could be mapped with a precision of 200 km/sec. . . What keeps cluster gas hot?
  - Mapping the cosmic web and its evolution: Map Warm-Hot Intergalactic Medium (WHIM) in both emission and absorption
  - Studying Neutron Stars: can get energy-, time- and spatially- resolved pulse profile of an X-ray pulsar, to locate site of the pulsed X-ray production near the neutron star, and a thermal spectral signature at pulse minimum could indicate the surface temperature of the neutron star
- Materials Analysis:
  - Synchrotron beam-line studies and x-ray microanalysis
  - Micro-calorimeter array provides faster acquisition than scanning crystal diffractometers for similar energy resolution, and added time-resolution.

Funded Objectives

NASA APRA Funding for:

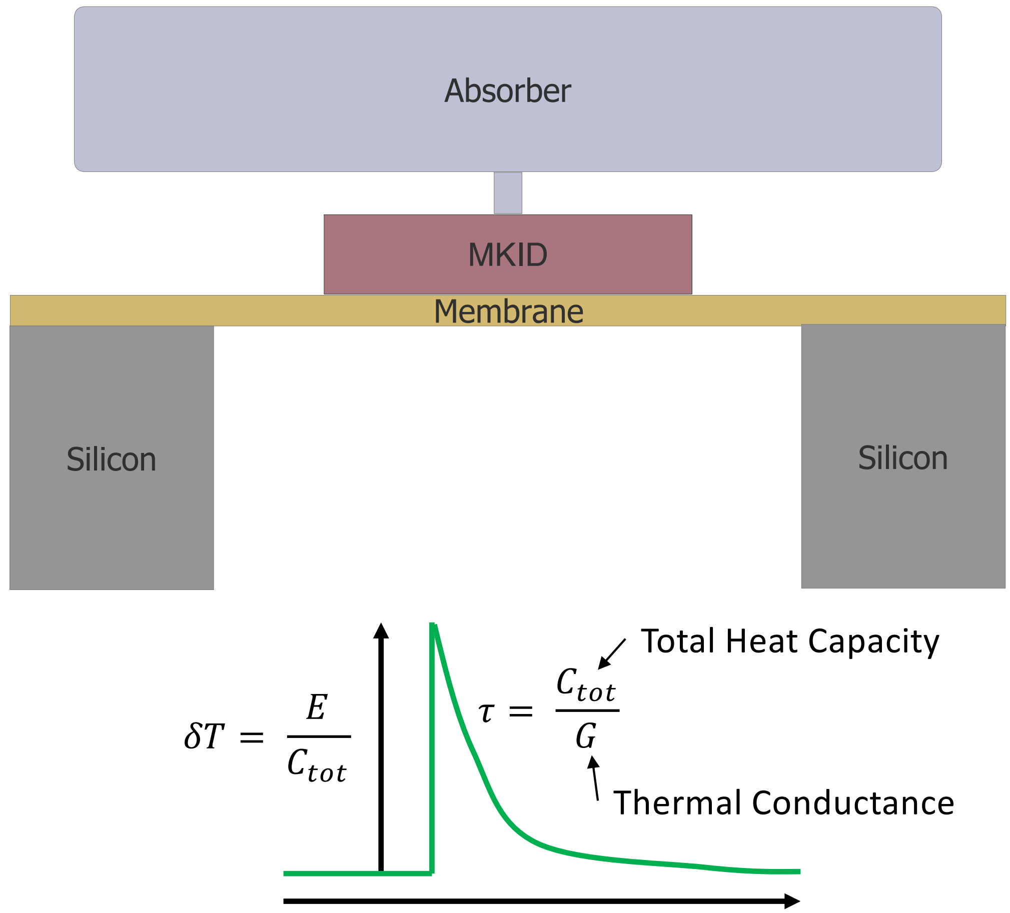
- X-Ray detector array, > 1,000 pixels
- Multiplex factor, 1 signal line : ≥ 250 pixels
- Soft x-rays, 0.2 - 10 keV
- Moderate energy resolution, $\Delta E \leq 5$ eV @ 6 keV
- Moderate fill factor, ≥ 75%
- Pixel quantum efficiency (QE), ≥ 95% @ 6 keV
- Microsecond photon arrival time resolution

Resources

- 1 Full-time postdoc
- UCSB Nanofab
- Dedicated UHV sputter system
- Two Dilution Fridges

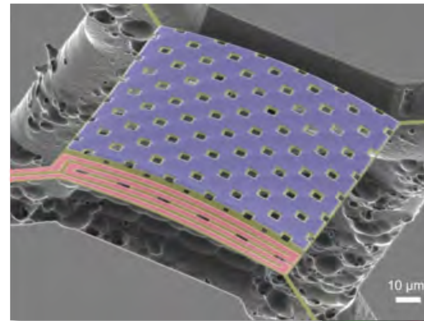
Approach

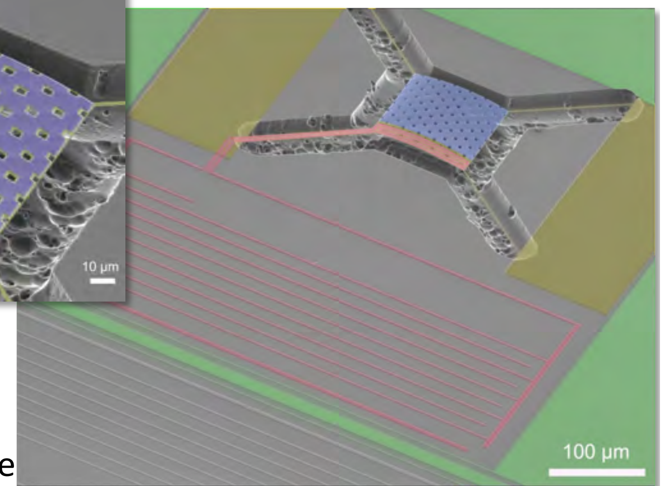
- Use microcalorimeter format to couple an x-ray absorber to an MKID.
- X-rays warm up absorber which warms up MKID.
- Use temperature rise to measure x-ray energy.



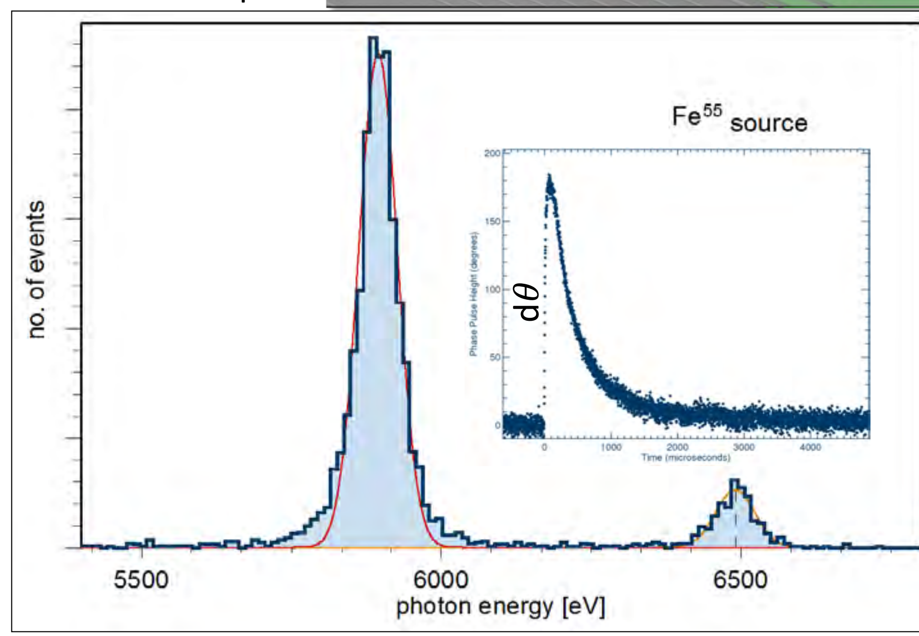
Development History 1

- 75 eV at 5.9keV
    - Ulbricht *et al*., APL, 106, 251103, 2015
- Long rise time, ≈45 µs, ⇒ degraded energy resolution
    - Probably due to perforated absorbers, necessary or XeF_2 etch
    - Membrane conductance too low giving ≈500 µs fall times ⇒ low count rate
- Resonator phase sensitivity (dθ per dT) was too high resulting in easy saturation
- 2D format did not provide path for high fill factor and rapid absorber thermalization



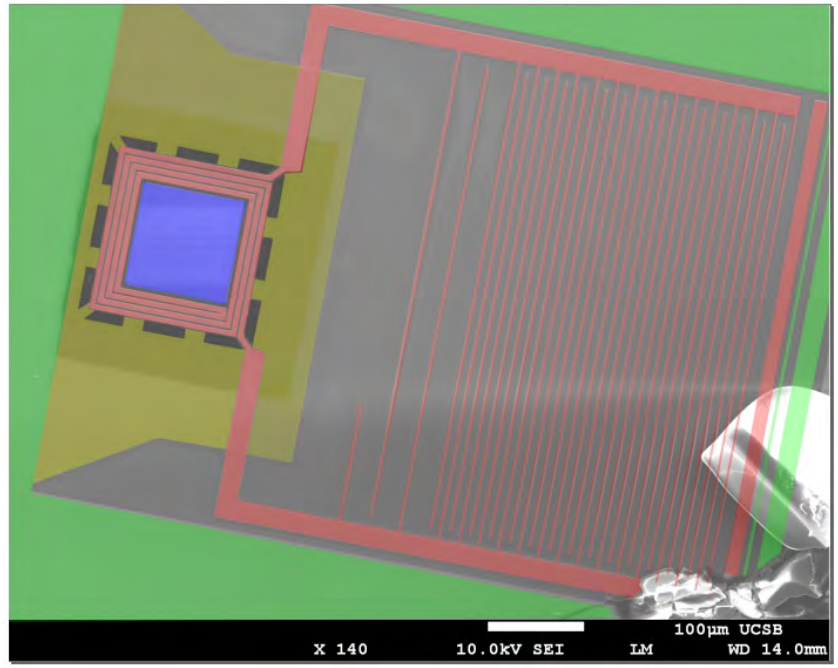


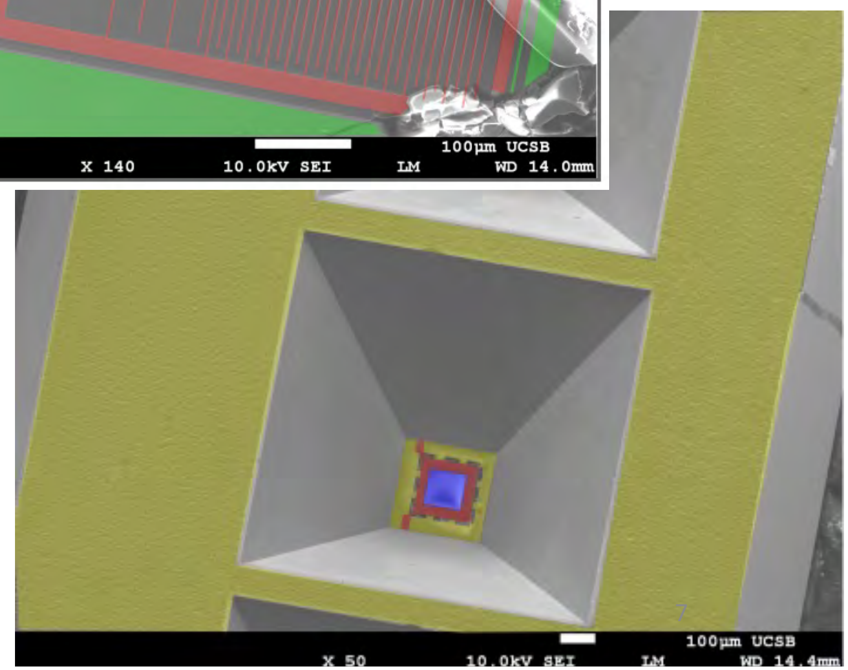
: TiN_x
: Si_3N_4 (etched with XeF_2)
: Ta absorber
: Nb feedline & GND plane



Development History 2

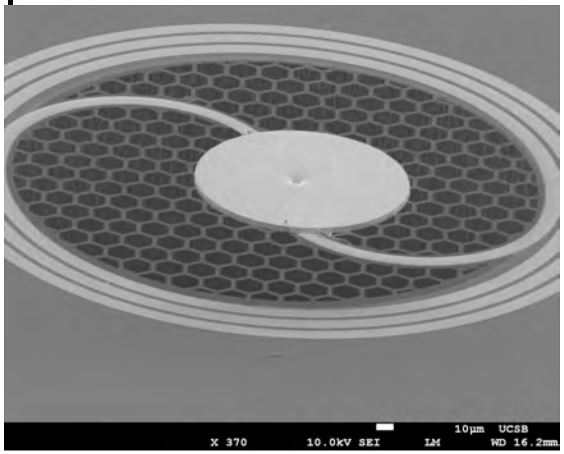
- Switched to WSi_x
  - TiN_x sputter system repossessed by DOE!
- Switched to KOH etch
  - Allow for non-perforated absorbers to speed up rise time
  - Avoids excess heat capacity due to XeF_2 etch
- This design was unsuccessful
  - KOH attacked resonators
  - WSi_x found to have anomalously high heat capacity. (W has high C)

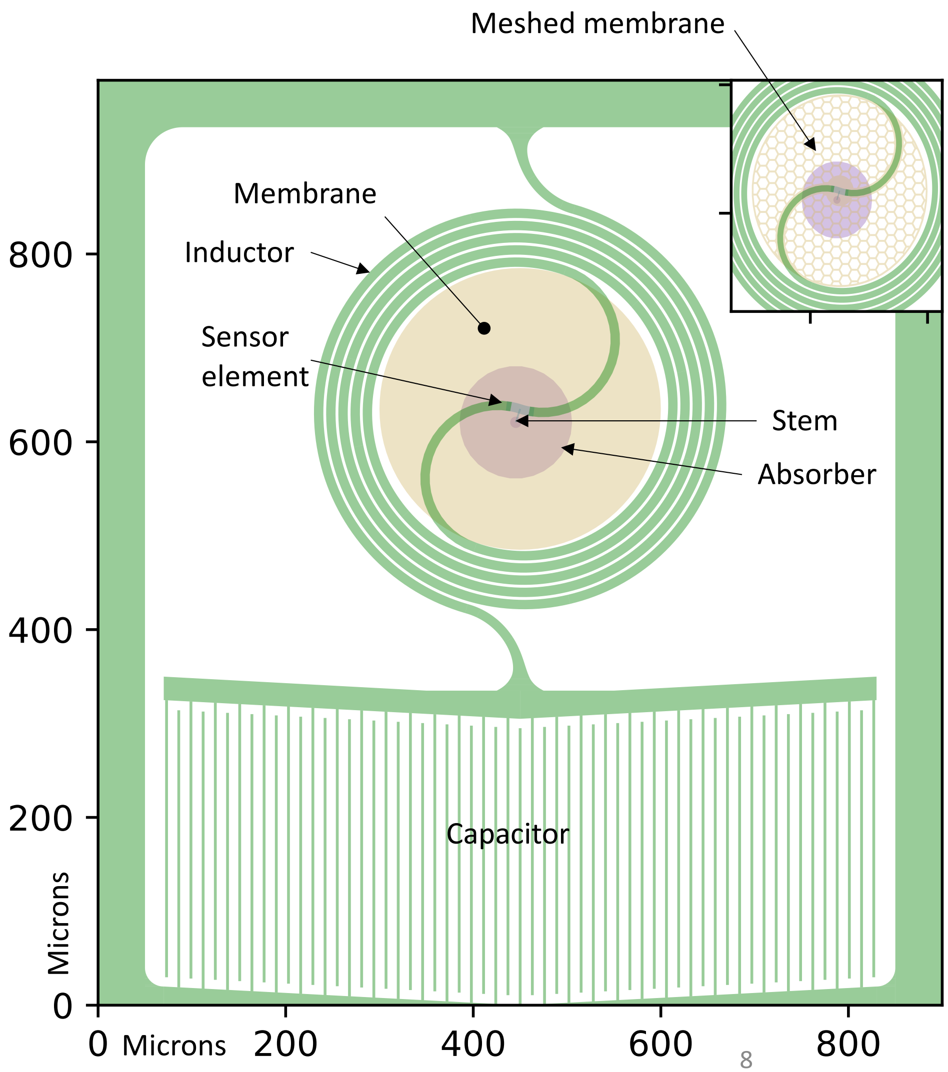




Goals for Current Design Iteration

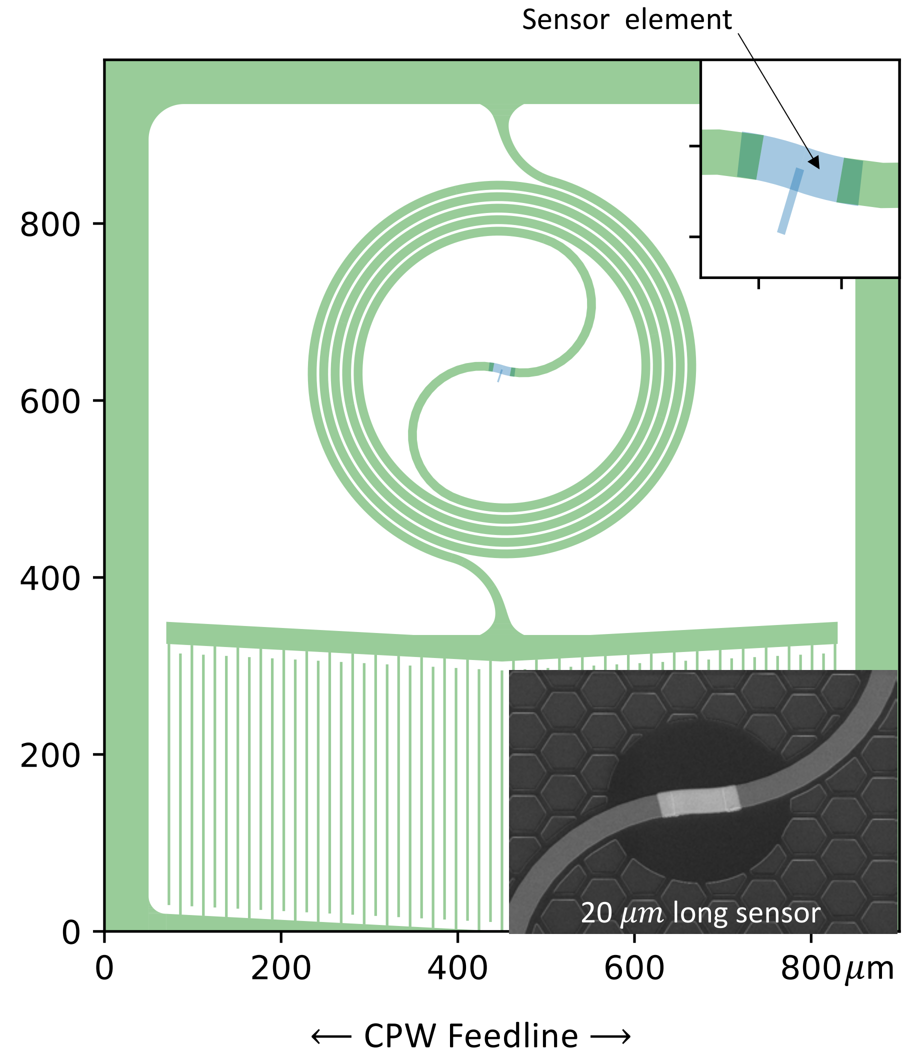
- Thick, cantilevered (3D) absorbers
  - Faster thermalization
  - X-ray stopping power
  - Admits high fill factor
- Hybrid resonators
  - Disentangle phase sensitivity, f_0 & Qc control, heat capacity, and readout power
- Suppress TLS noise using large capacitor and high readout power
  - **Go to ~20x smaller pixels later**





Resonator Design

- Wide inductor for high current operation
- Low T_c, High L_{Kin} 'Sensor element'
  - β-Tantalum
- High T_c, Low L_{Kin} ground, capacitor, inductor, feedline
  - α-Tantalum
- Tapers and Fillets to control current density
- Q_c controlled by distance to feedline
- f_0 controlled by inductor length
  - Capacitor geometry/TLS-noise fixed across array



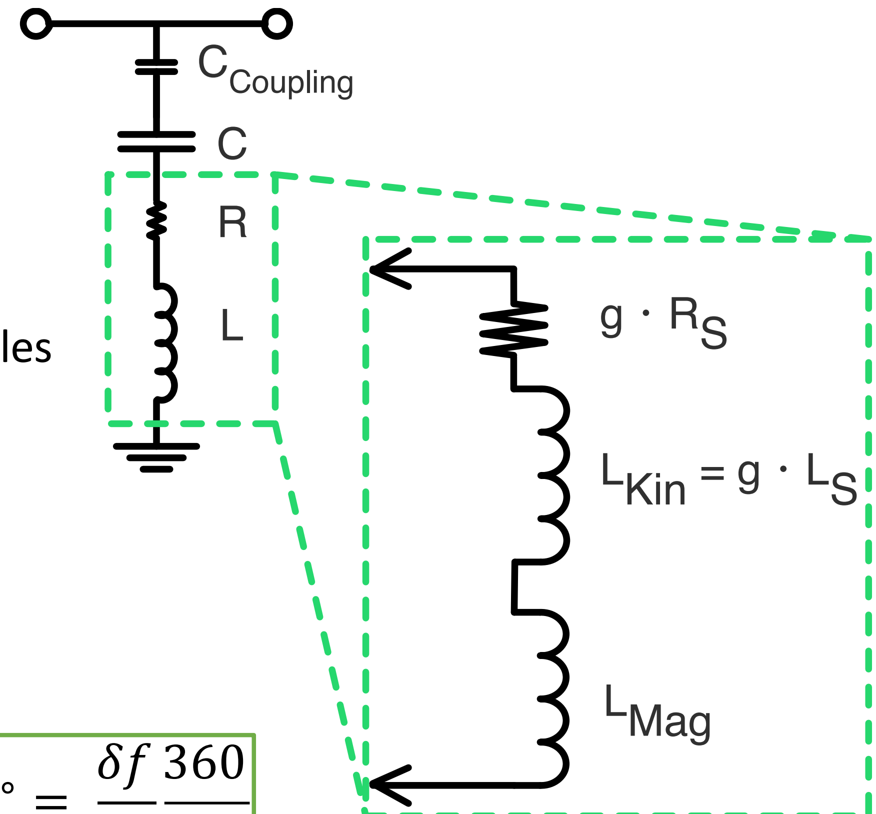
MKIDs read out surface impedance changes

- Shunt Coupled Resonators made of superconducting films
- Surface impedance:
  - $Z_S(T, \omega) = R_S + j\omega\, L_S$
  - R_S, L_S change with temperature / quasi-particles
  - $L_{Kin} = g \bullet L_S$
- Resonant Frequency,

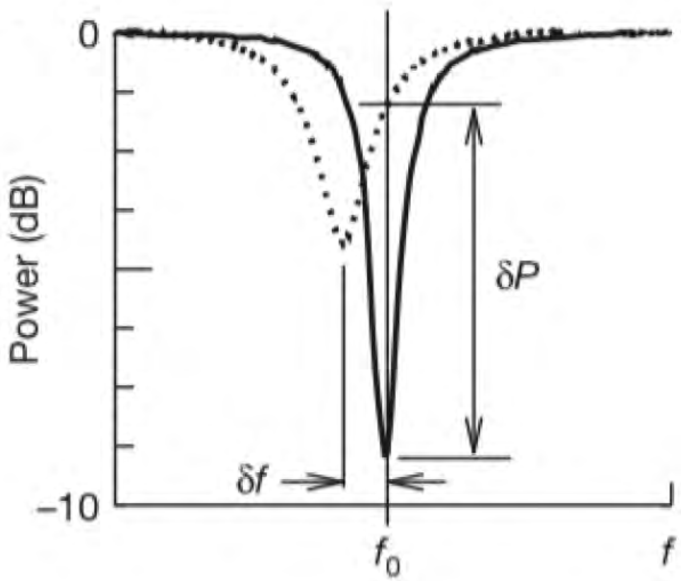
$$f_0 = \frac{1}{\sqrt{C\cdot(L_{\mathrm{Kin}}+L_{\mathrm{Mag}})}}$$

- Only dθ is measured (not dissipation)

$$\boxed{d\theta^\circ = \frac{\delta f}{f_0}\frac{360}{\pi}}$$

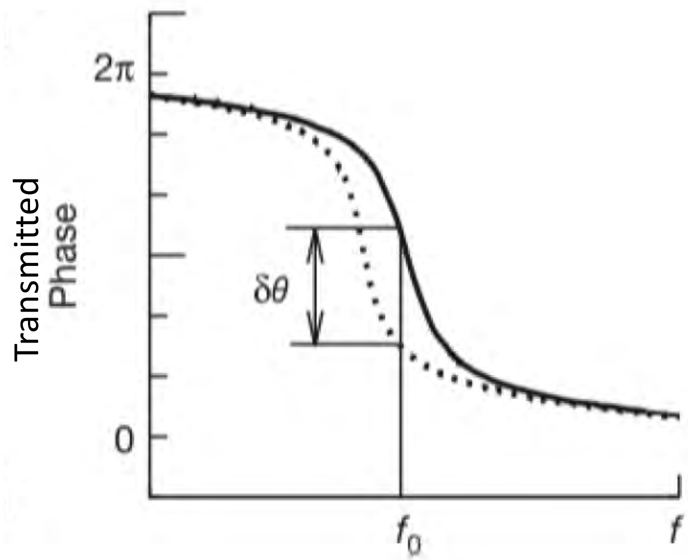


Detector Response: $df, dQ, d\theta$

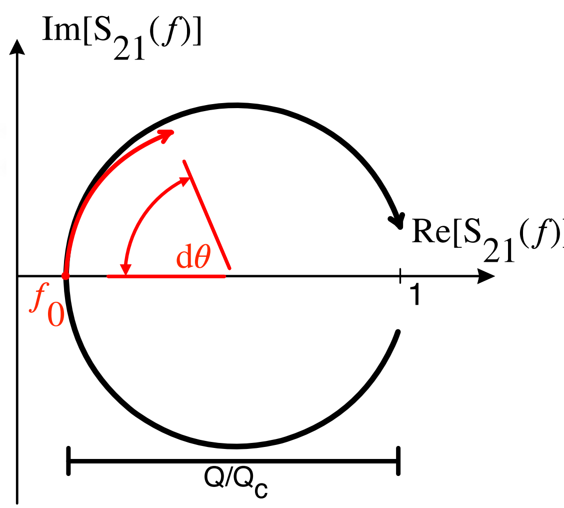


$$\frac{1}{Q} = \frac{1}{Q_i} + \frac{1}{Q_c}$$

Q_c set to 15 – 30 x 10^3

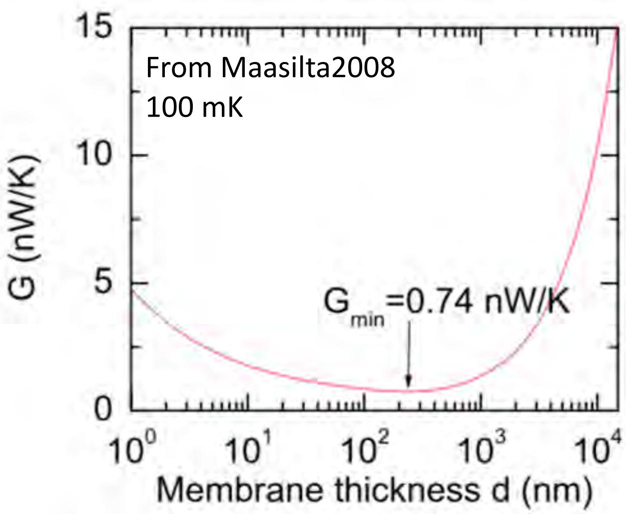


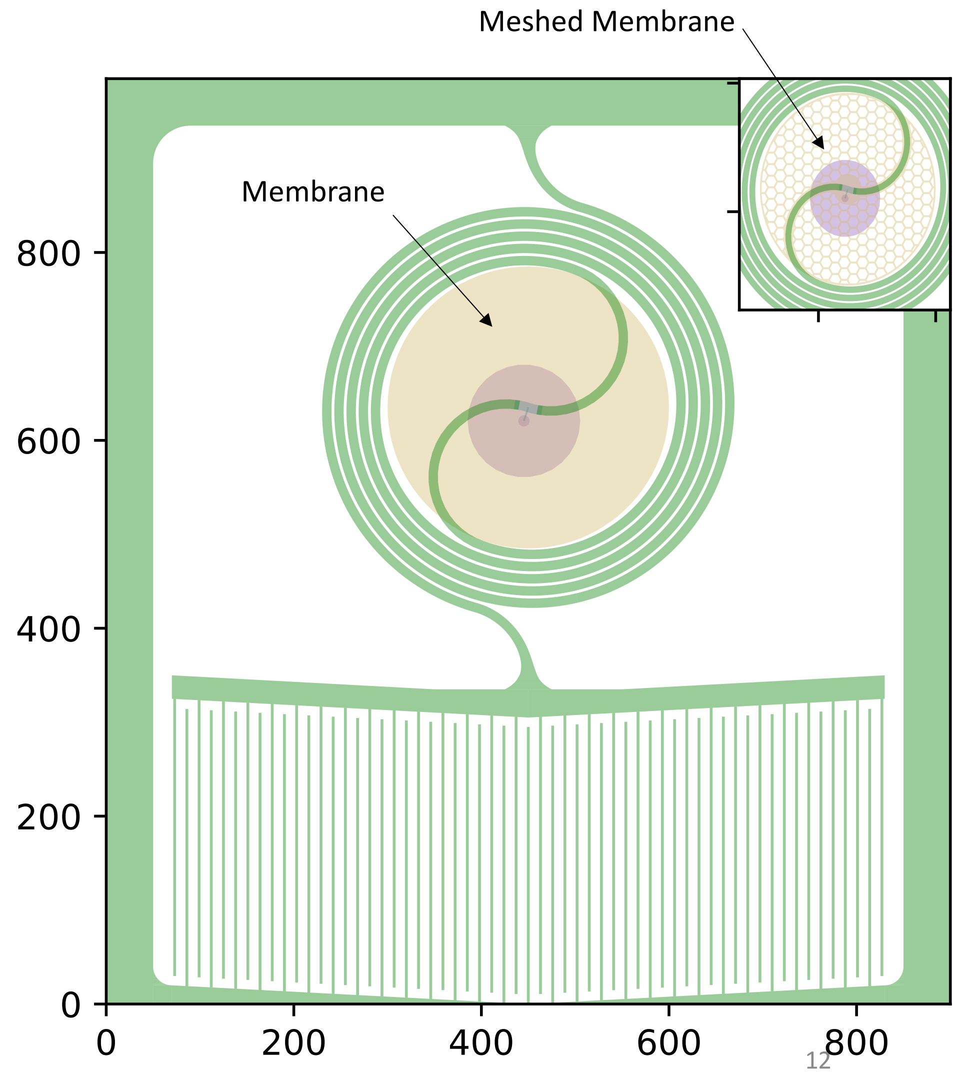
$|d\theta|$ is energy estimate



Membrane Design 1

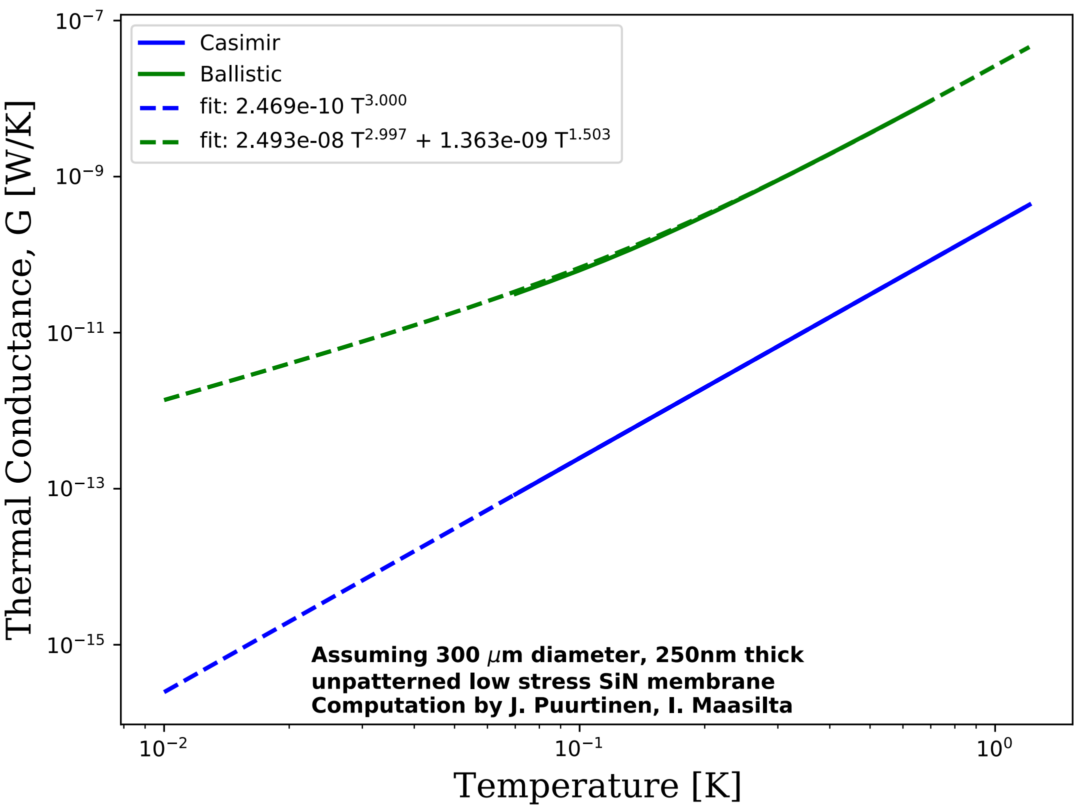
- Membrane thickness and patterning are used to control conductance
  - Using 250 nm thickness for low ballistic conductance limit





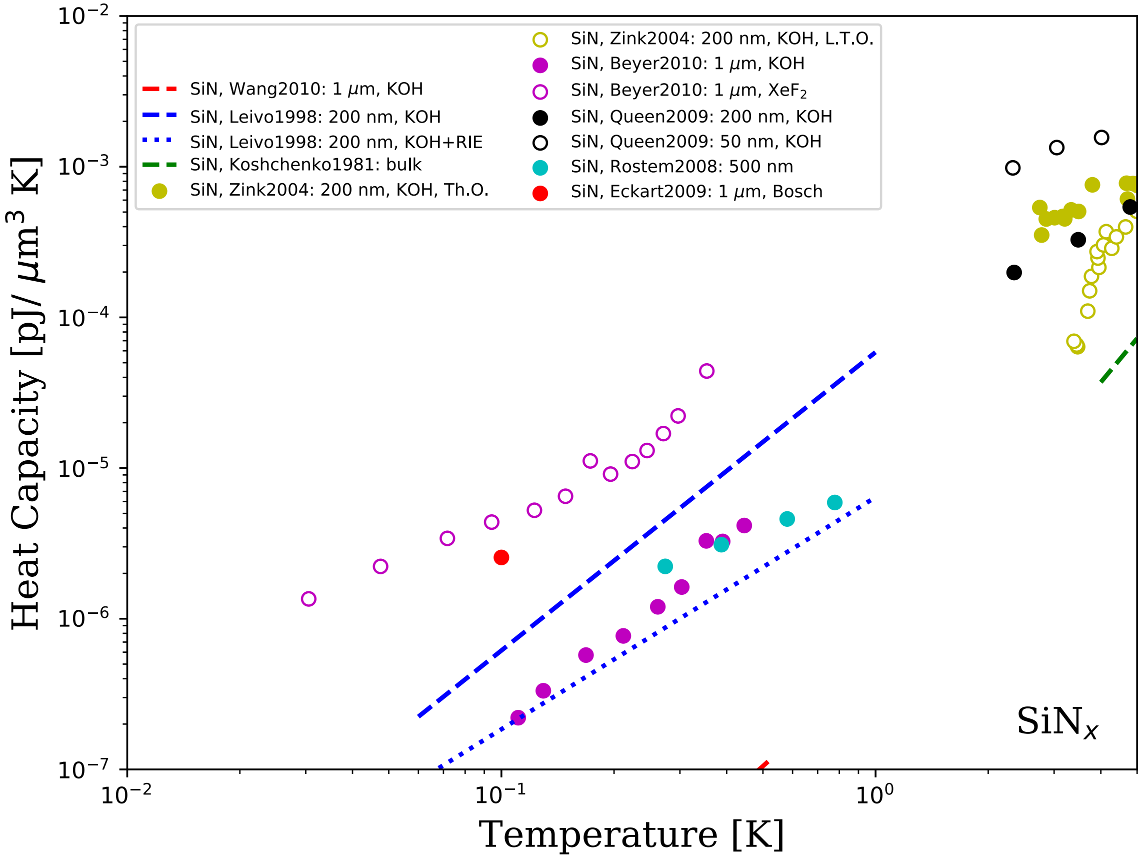
Membrane Design 2

- Estimate membrane conductance based on phonon transport **simulations**
- Test devices use solid membrane and meshed membranes
- Neglected α-Tantalum lead conductance. 🤦



Membrane Heat Capacity

- Heat capacity: α-Ta absorber $\gg$ β-Ta sensor + α-Ta + SiN membrane
- All resonators designed to have the same heat capacity (α-Ta + β-Ta +SiN + Absorber)
- Minimize SiN heat capacity using REI etch



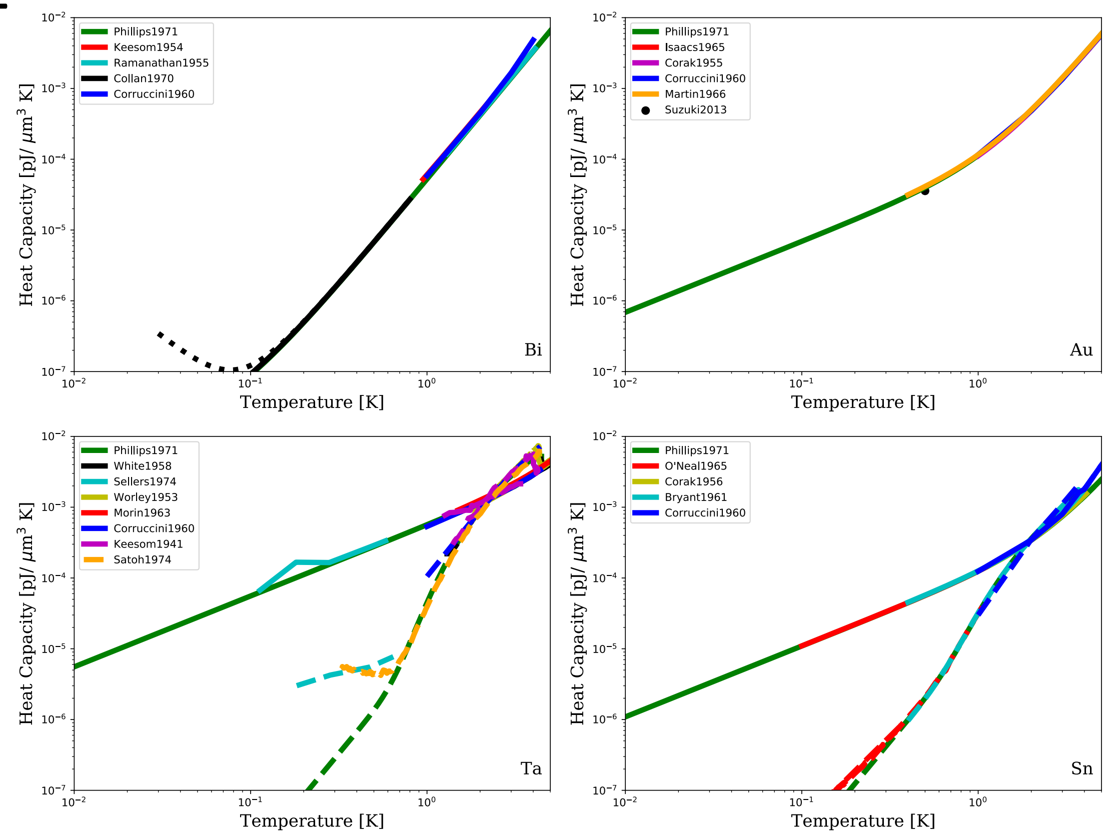
Note Higher heat capacity with XeF_2

Absorber Design: δT, QE

- Match dynamic range of resonator, total $\Delta\theta$, to δT of absorber for target energy

- Thickness chosen to achieve QE objective

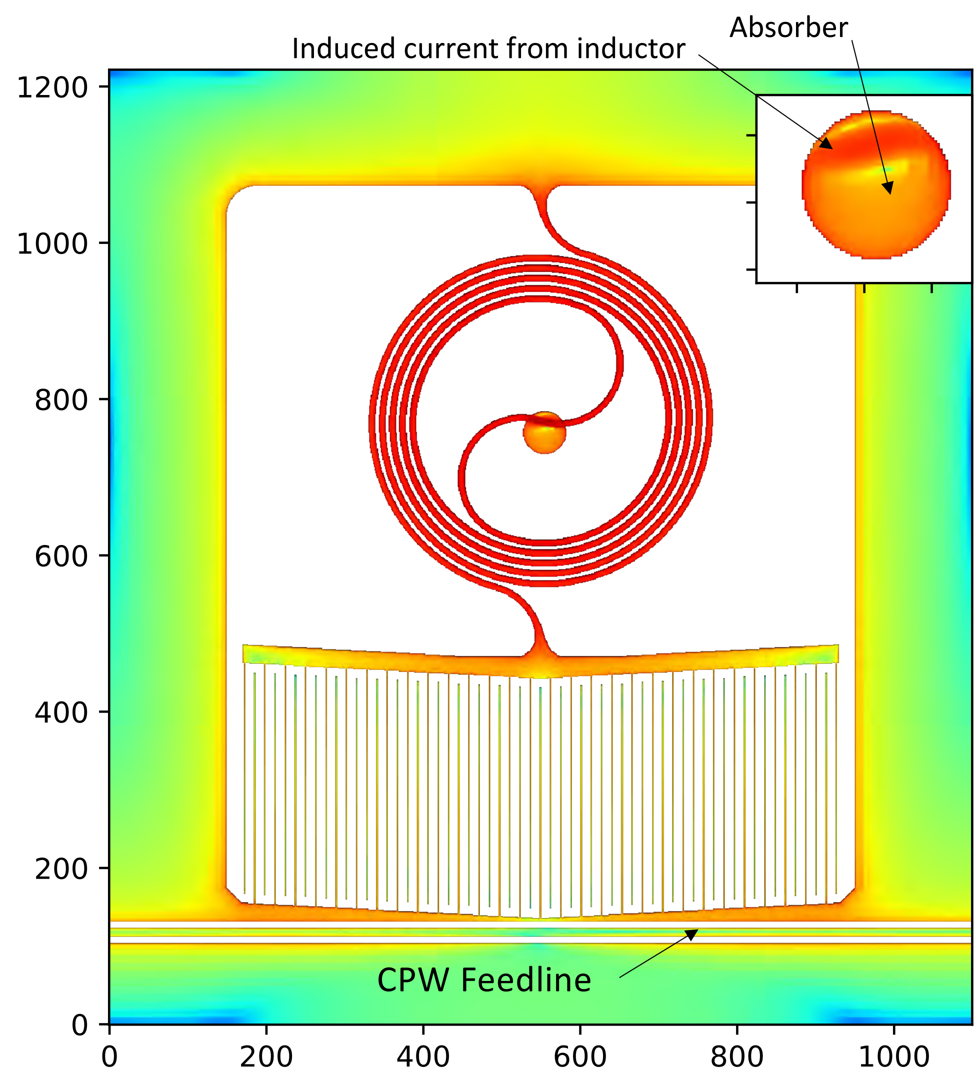
Minimum thickness, t, for 97% x-ray absorption at 6 keV	
Bi	7.41 µm
Ta	6.22 µm
Au	4.26 µm
Sn	9.06 µm



Absorber Design: Eddy Currents

- Eddy currents must not diminish Q_i
  - Use superconducting absorber
  - Possibly cap SC absorber with Au for fast & uniform thermalization.

Q with Ø40 µm absorber, 4.2 µm above inductor, Qc ≈ 42000, f_0 ≈ 3.5 GHz	
	Qi
Ta Absorber	$>10^6$
Au Absorber, (2e-9 Ω•cm)	50e3
Ta then Au (5 µm separation)	340e3

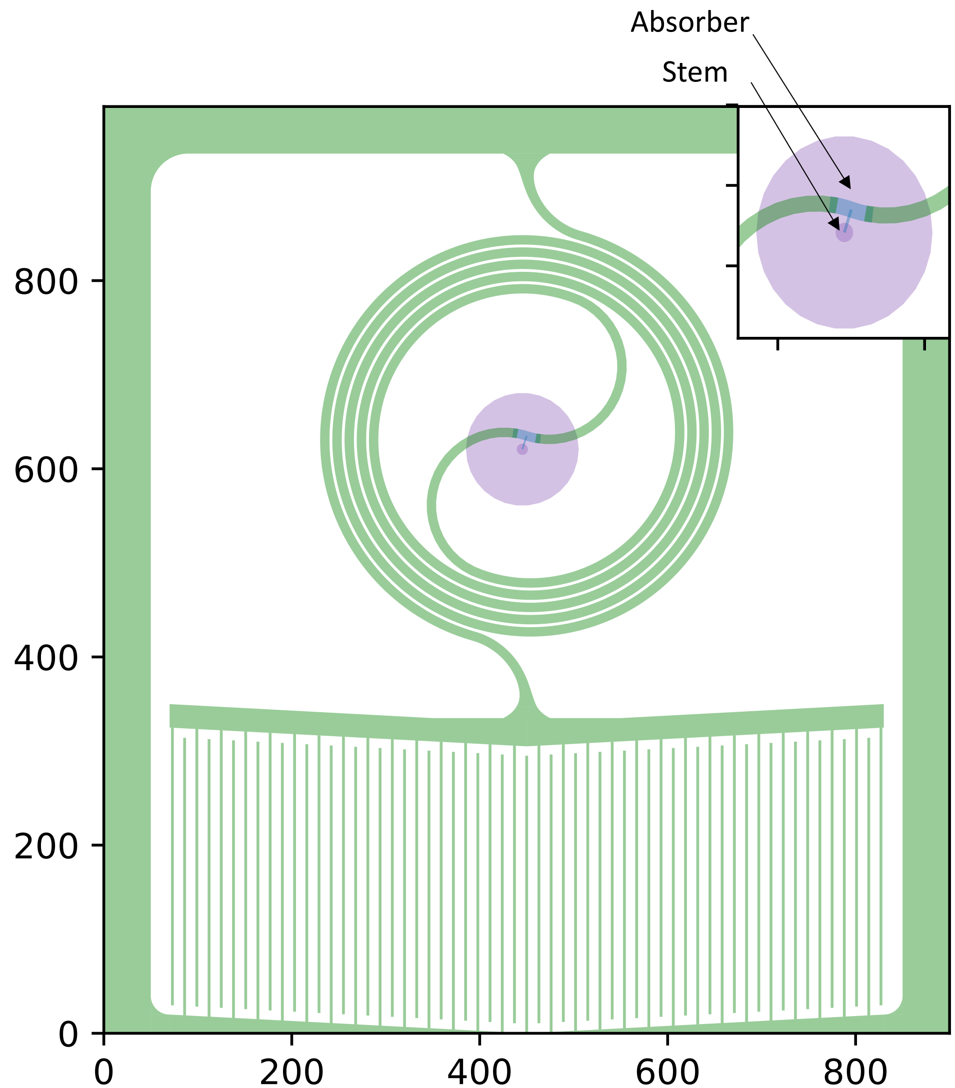


Absorber Design: Stem

- Want fast thermalization, but
  - SC have low thermal conductivity
  - qp generation slows thermalization?
    - E.g. ~35 μs qp lifetime for Ta

- Use 'Stem' size to tune conductance to 'Sensor Element' and allow for absorber thermalization

- Ring-down time, Q/ $2\pi f_0$, lower limit of rise time – shortest time scale of the resonator



Sensor Element Design

- First: Estimate dθ response from absorber $\delta T = \frac{E}{C_{tot}}$.
- Then: choose sensor element volume to avoid saturation

Assuming Ta absorber: Vol = $t \bullet \pi$ (120/2)^2 µm^3; Hf Sensor: 120 nm thick; T_{bath} = 70 mK, Q ≈ 40,000				
Sensor length	*@ 2 keV*		*@ 10 keV*	
	df/f	dθ	df/f	dθ
2 µm	2.1e-6	18˚	2.1e-5	190˚
6 µm	5.7e-6	52˚	5.9e-5	545˚
20 µm	18e-6	171˚	19e-5	1780˚

Sensor element and absorber geometry

Compute: f_0, Q @ T_{bath}
Using: Sonnet, $Z_s(T_{bath})$

↓

Compute: df/f @ T_{bath} + dT
Using: Sonnet, $Z_s(T_{bath}$ + dT)

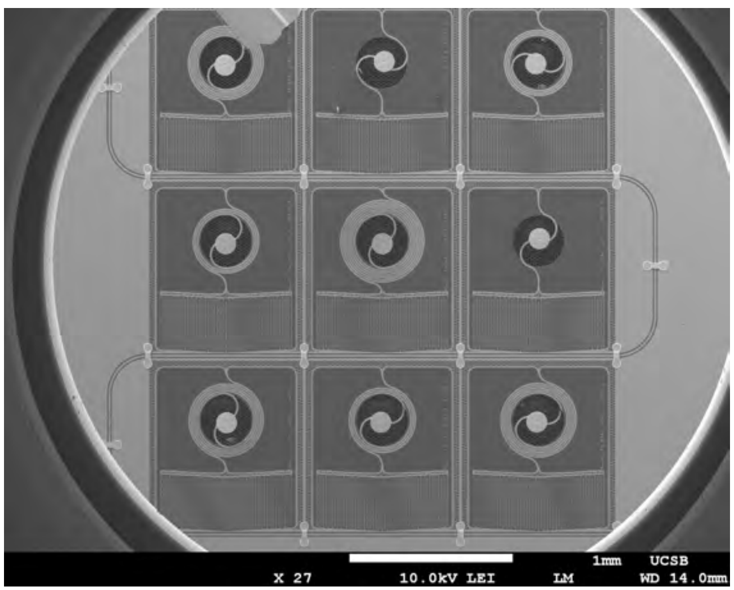
↓

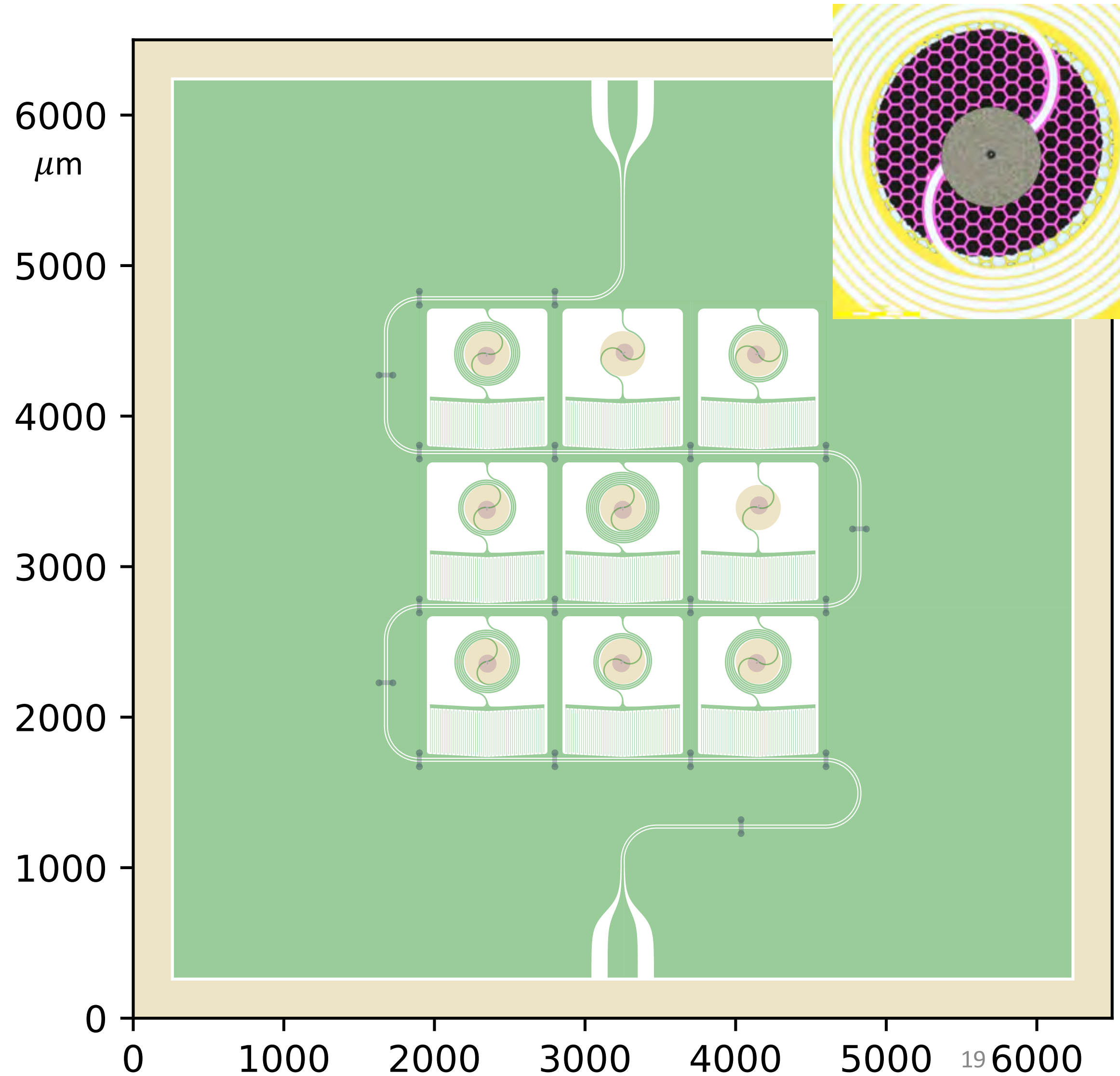
Compute: dθ
Using: df/f

Phase angle response, dθ

Test Die

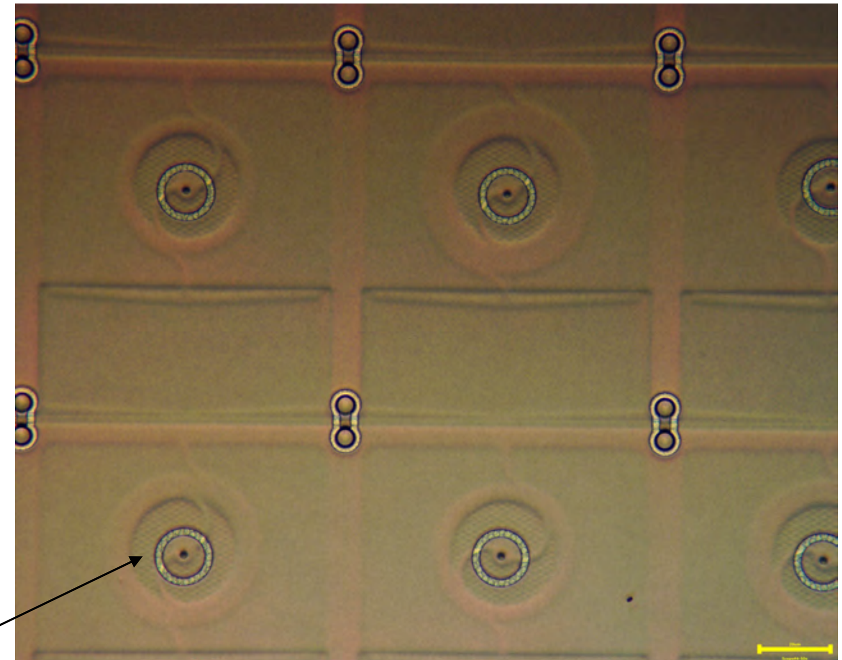
- 9 Resonators
  - Multiple absorber and stem sizes
- Air bridges
- 3 – 6 GHz

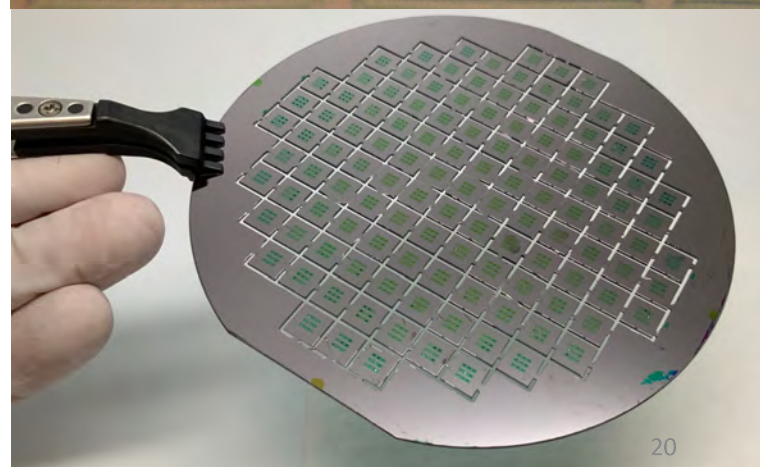




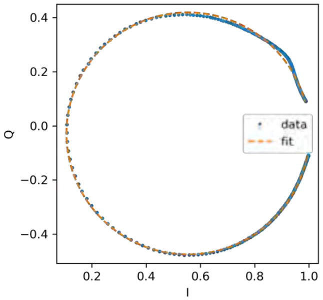
Fabrication, ~2 weeks

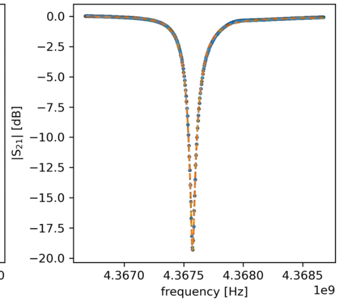
1. Start with Si wafer with 250nm SiN
2. Etch out SiN membrane patterns and capacitor area
3. Deposit α-Ta then etch out resonators/feedline
4. Lift off β-Ta sensor element
5. PR mask/sacrificial layer for absorber stems/air bridges
6. Deposit thick α-Ta for absorbers
7. Etch out absorber profile
8. Flip over wafer, attach to handle, and pattern then etch away Si from membranes
9. Release from handle and clean.

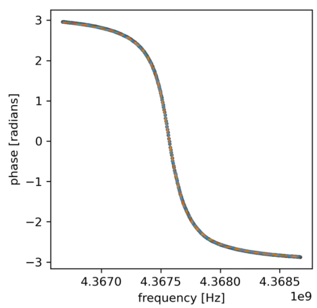




Taking Data Since Oct 2022



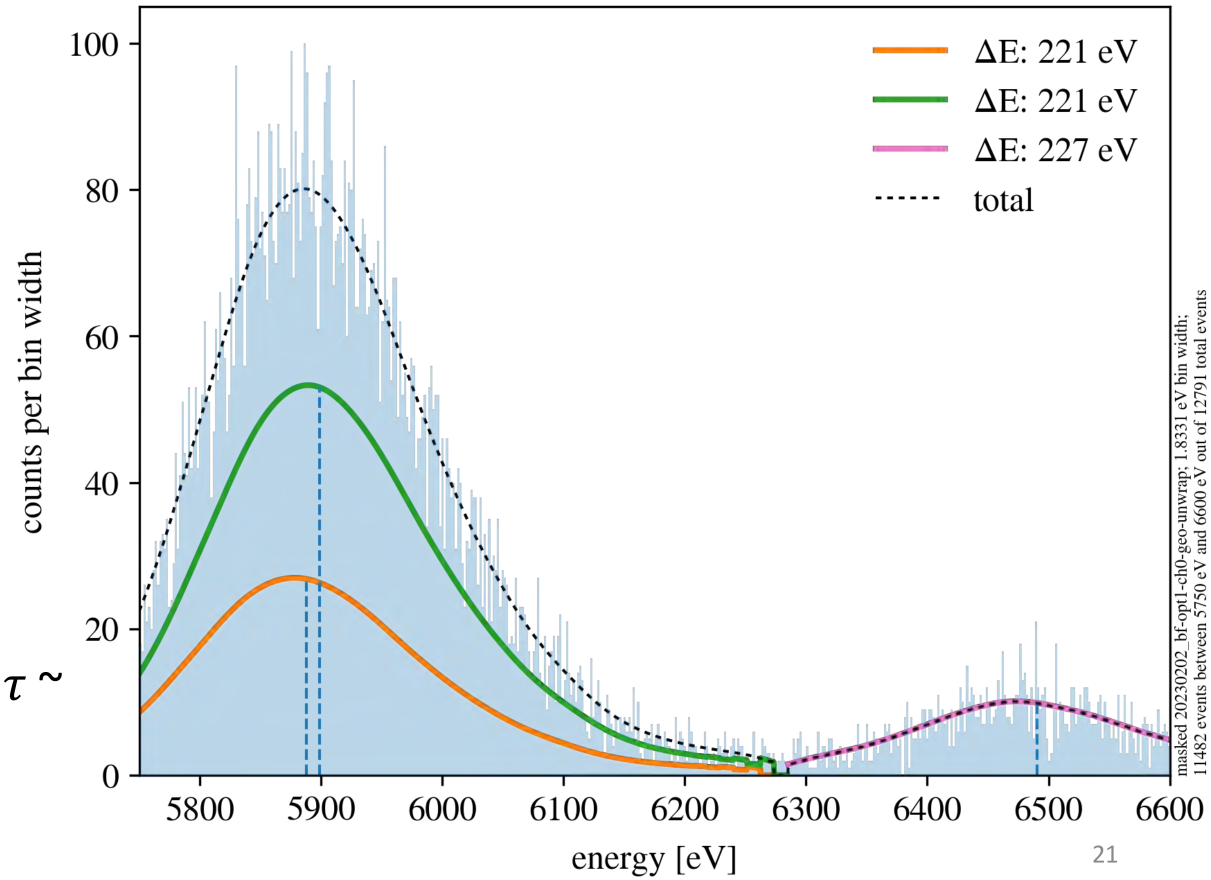


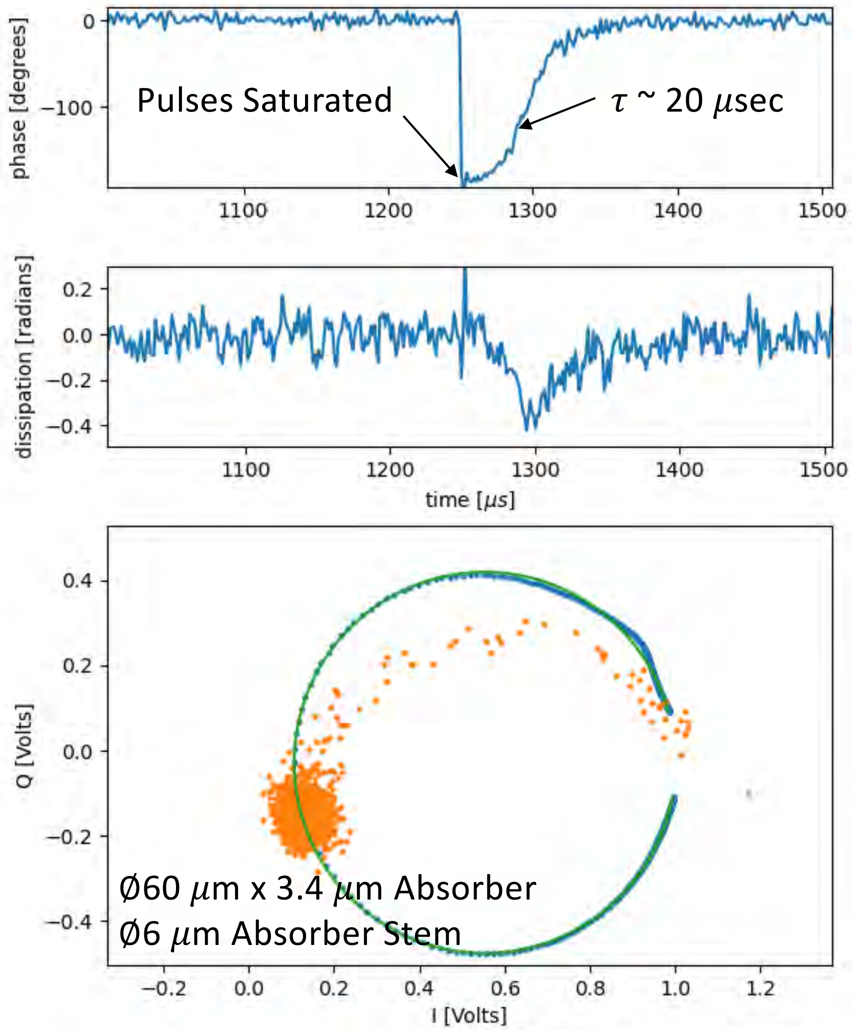


Ø60 μm x 3.4 μm Absorber
Ø6 μm Absorber Stem

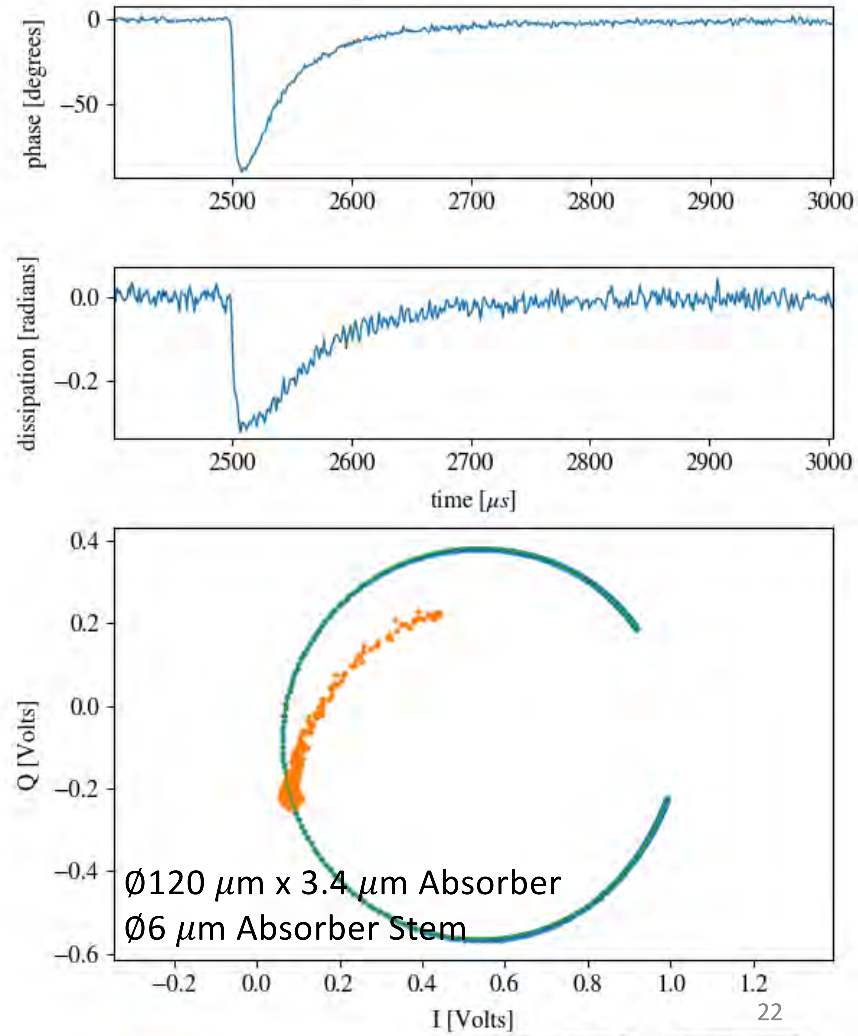
f0 = 4.36757
qi = 179017
qc = 21563.7
a = 0.0225676
beta = 3.11769
alpha = 1.15631

- Qi's ~ 100,000
- Qc's ~ 15,000
- Pulses saturated for 60 μm absorber but not for 120 μm absorber
- Expected τ ~>1 msec. Measure τ ~ 20 μsec
- 15 mK operation





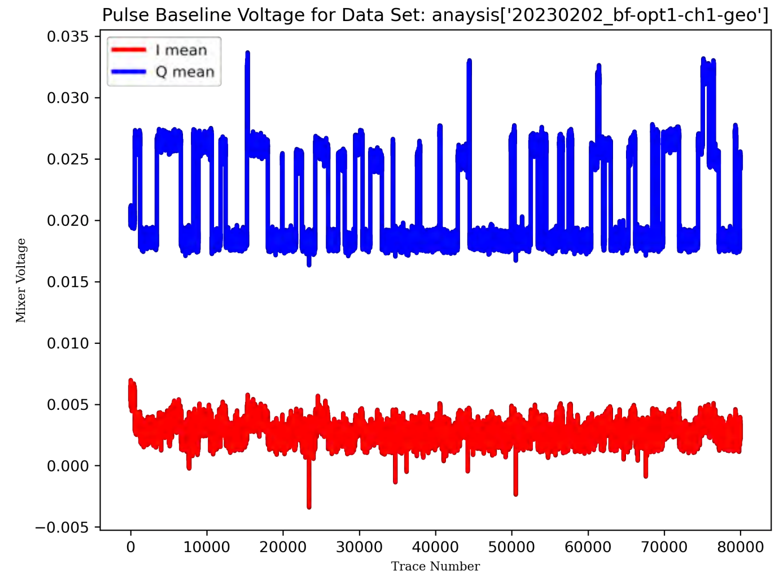
Pulses Saturated
τ ~ 20 μsec
phase [degrees]
dissipation [radians]
time [μs]
Q [Volts]
I [Volts]
Ø60 μm x 3.4 μm Absorber
Ø6 μm Absorber Stem

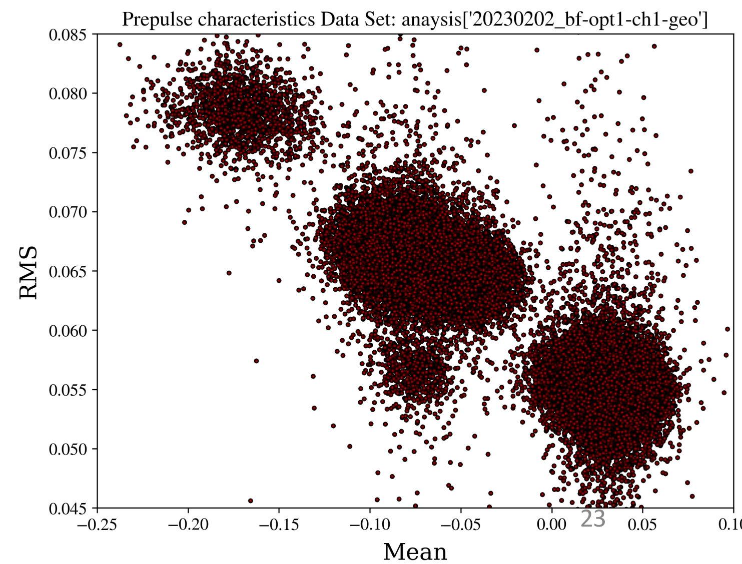


phase [degrees]
dissipation [radians]
time [μs]
Q [Volts]
I [Volts]
Ø120 μm x 3.4 μm Absorber
Ø6 μm Absorber Stem

Conclusions/Problems to Fix

- Devices work but not well
- τ too short.
  - absorber not thermalizing completely ➞ try adding gold
  - Membrane G too high ➞ increase membrane diameter
  - Heat conduction through α-Ta leads dominates
- Resonance lock point moving
  - Shifts ➞ problem in readout system
  - Drifts ➞ magnetic field susceptibility
  - Use narrower traces / magnetic shielding



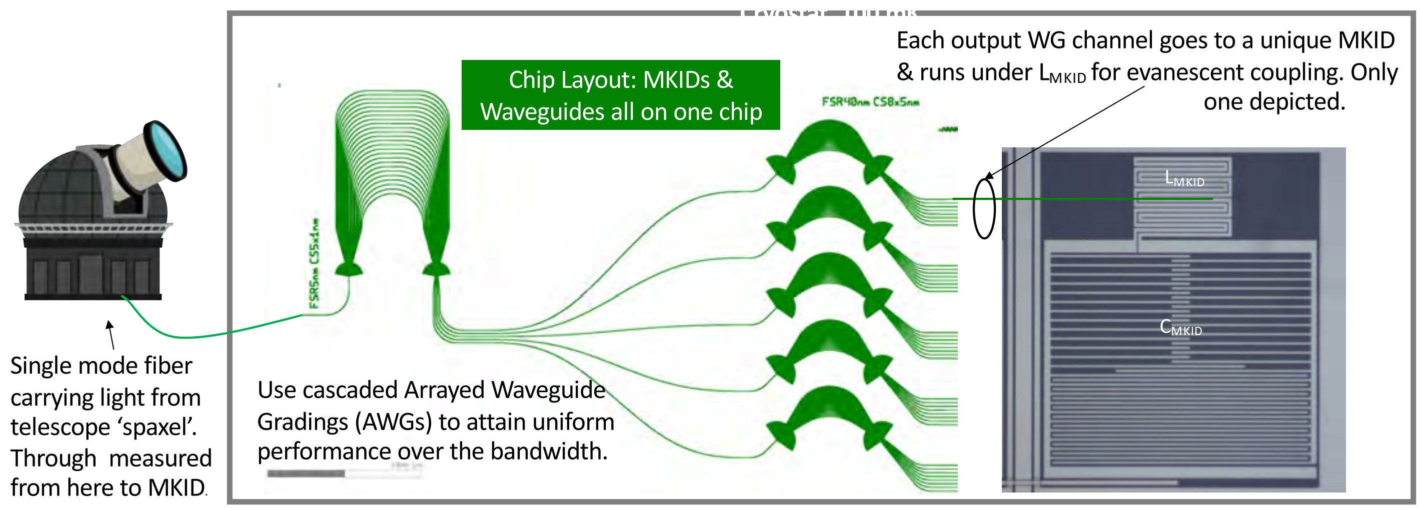


Fiber-fed spectrometer on a chip:

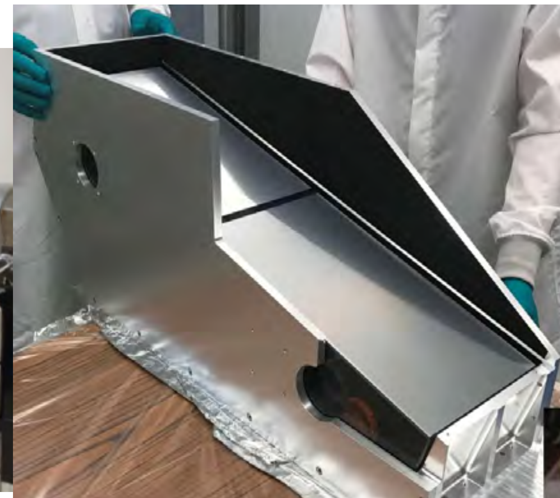
Spectral separation by photonic circuitry, then photon detection by MKIDs

Key Advantages:

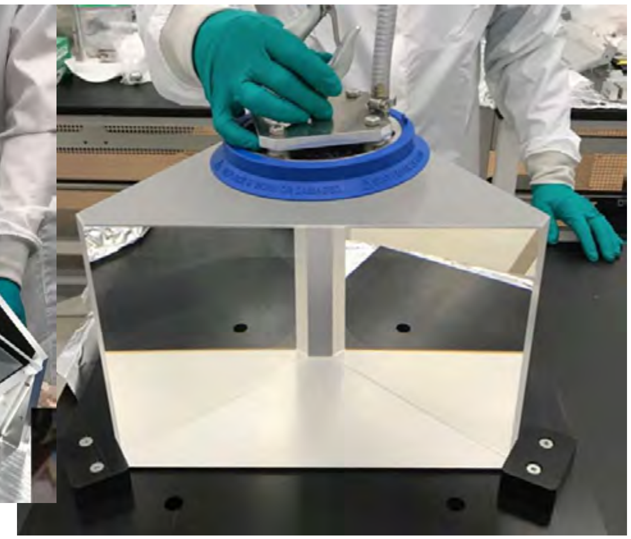
- Reduction in cost and miniaturization of MOS, IFU spectroscopy instrumentation allowing efficient use of emerging extremely Large telescopes
- Exploitation of on-chip photonic processing capabilities
- Size weight power reduction for eventual space applications
- Light detection by MKIDs at low temperature is free of dark count and read noise; affords individual photon arrival time and energy resolution



Current State of the Art: E.G. NEID Precision Radial Velocity Spectrograph at Kitt Peak National Observatory. 60k < R < 90k



Echelle Grating



Prism

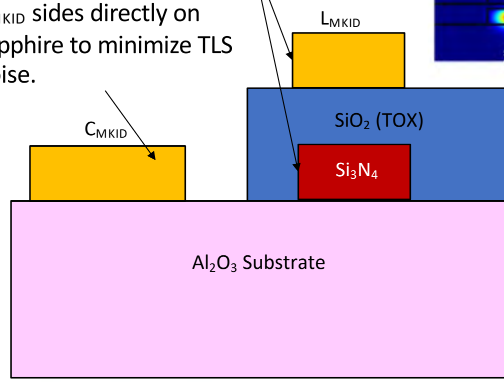
Specification Goals:

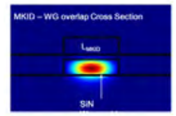
- $R = {}^{\lambda}/_{\delta\lambda} \sim 5000$
- Bandwidth: 400 nm -- 800 nm
- Fiber to MKID throughput: 60%
- Number of channels: 1024
- Operation temperature: ~100 mK
- **Integrated MKID + Waveguide Chip $\lesssim$ 10 cm^2**

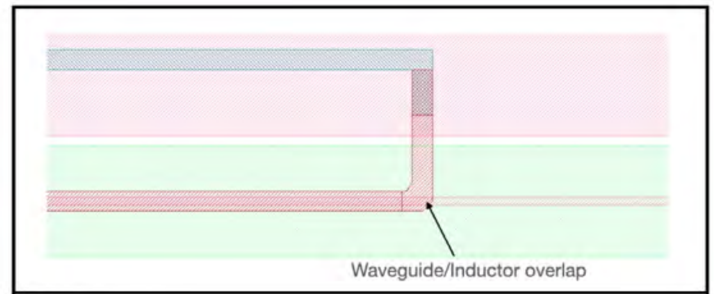
Platform Architecture

Evanescent Coupling of Waveguide light into L_{MKID}

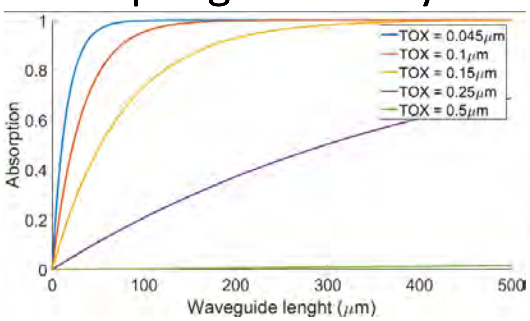
C_{MKID} sides directly on sapphire to minimize TLS noise.

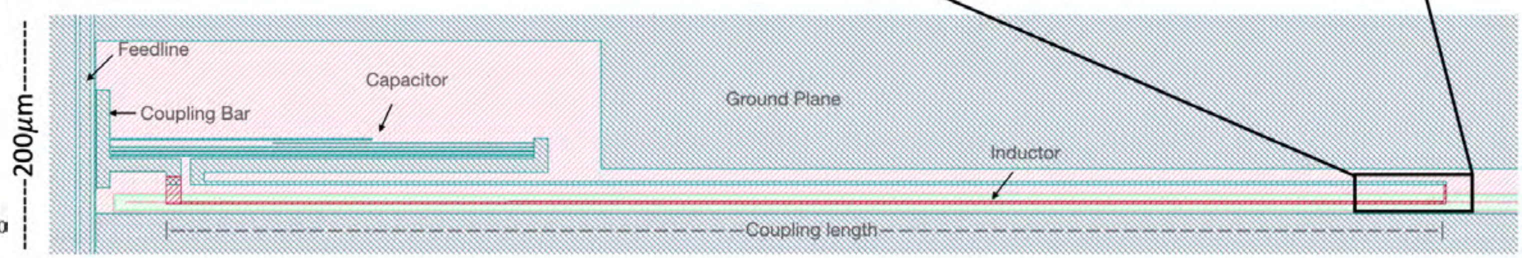






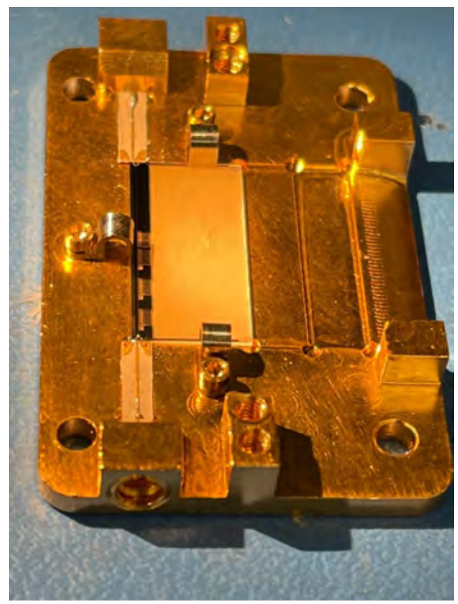
Coupling Efficiency

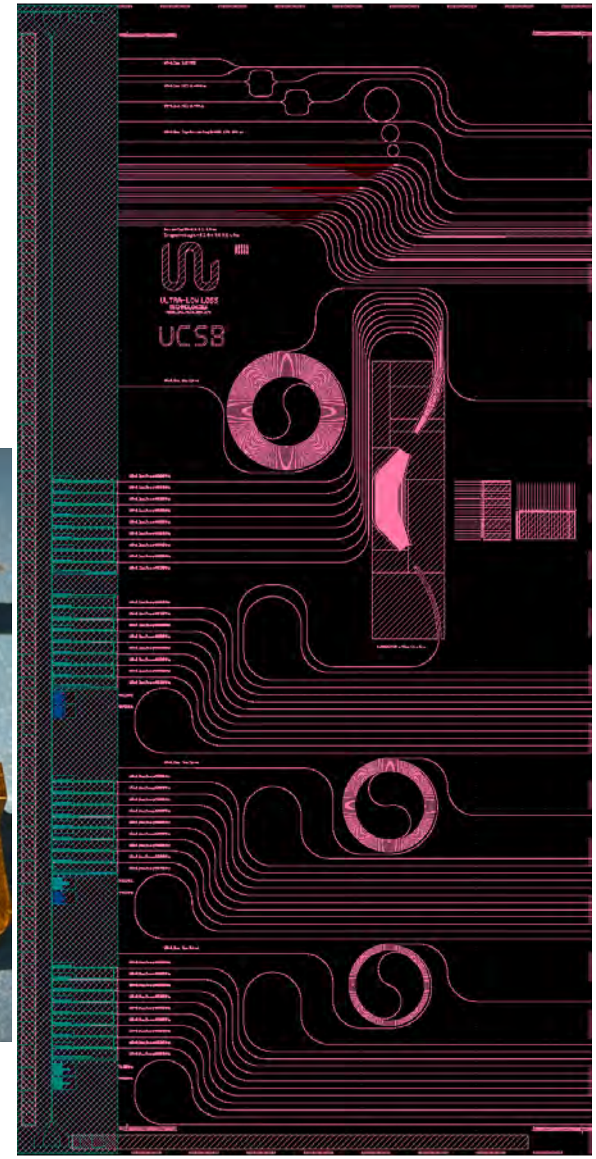




Conclusions

- WG-MKID Integration is the Challenge
- Identifying the right process and material combo so that:
  - WGs have low loss (currently > 10dB/cm)
  - MKIDs have low noise and high Q (currently Q_i > 80k)
  - Next improve WG materials / Processing to get low loss (< 5dB/cm)
- Add Fiber array to WG-MKID chip and measure photons
- Work on light channelization structures (AWGs in particular) to get high R

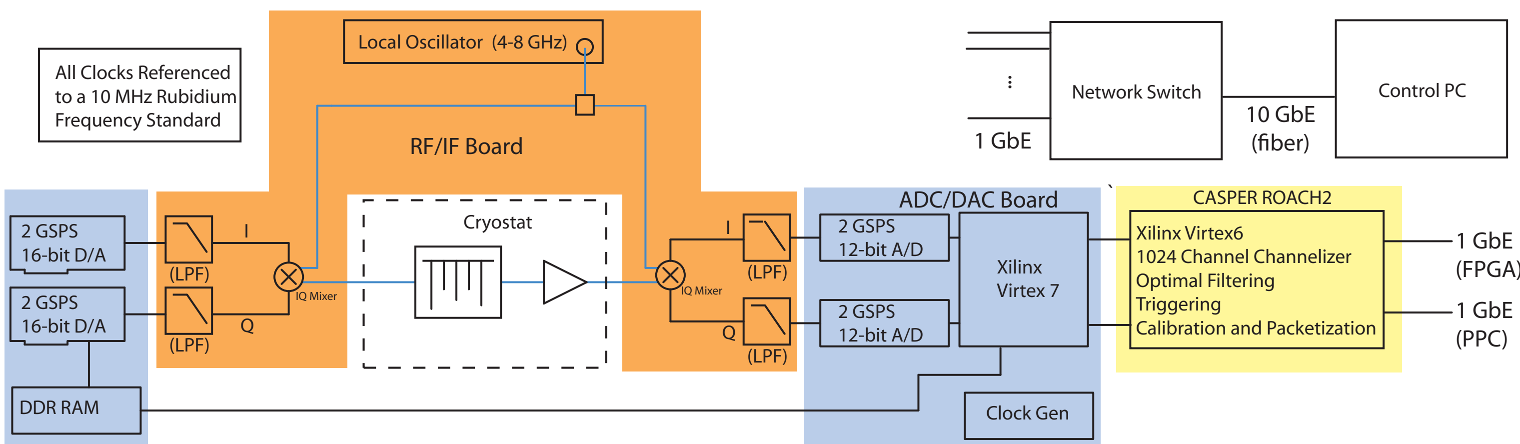




- END -

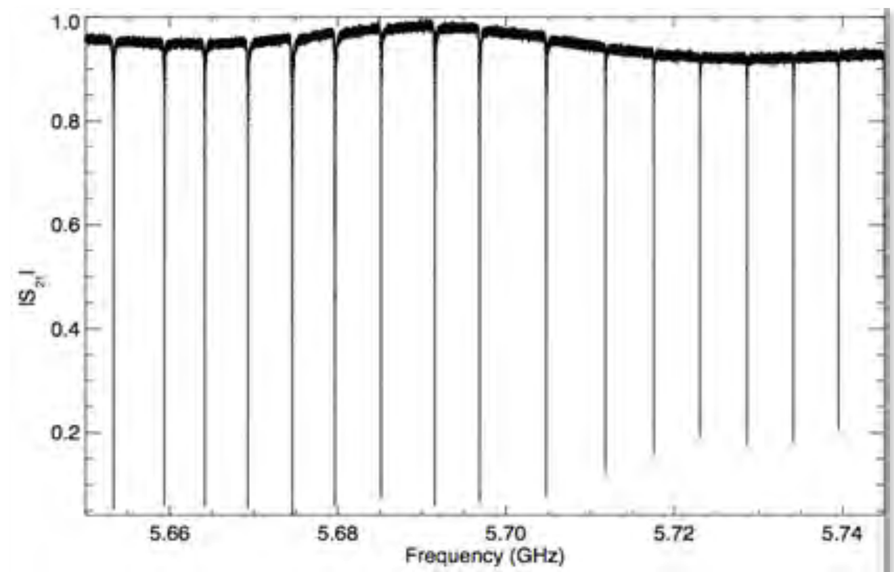
Readout

- Phase, dθ, only readout
- $\lesssim$250 resonators assuming current ROACH board readout, limited by:
  - Amplifier saturation (high power readout)
  - Relatively large ADC dynamic range (frequency shift) needed for signal band (x-ray energies)
- 2 K HEMT at low temp



Frequency Domain multiplexed

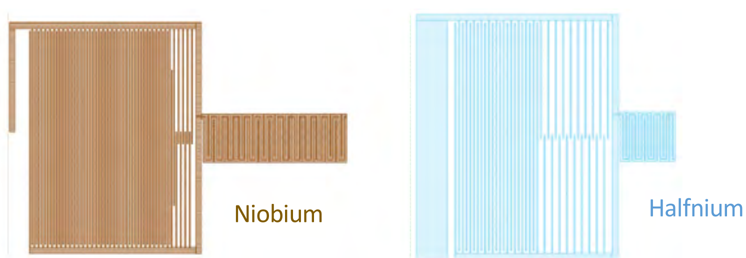
- The resonator phase is monitored at a fixed frequency.
- 1.8 – 2 MHz spacing per pixel
  - 100kHz optical pulse BW, 5000 CPS/Px
- Current readout:
  - Dual 2 GSPS 12 bit ADC per board
  - 1024 pixels in 2 GHz
  - 2 boards per feedline in 4-8.5 GHz
  - $5-$10/pixel excluding HEMT and FPGA (Free)
- Moving to RFSoC-based readout
  - $\lesssim$ 8096 pixels per board
  - 4 feedlines per board, 4 GHz each
  - 10-50% the power consumption (Flight!)
  - Tone tracking



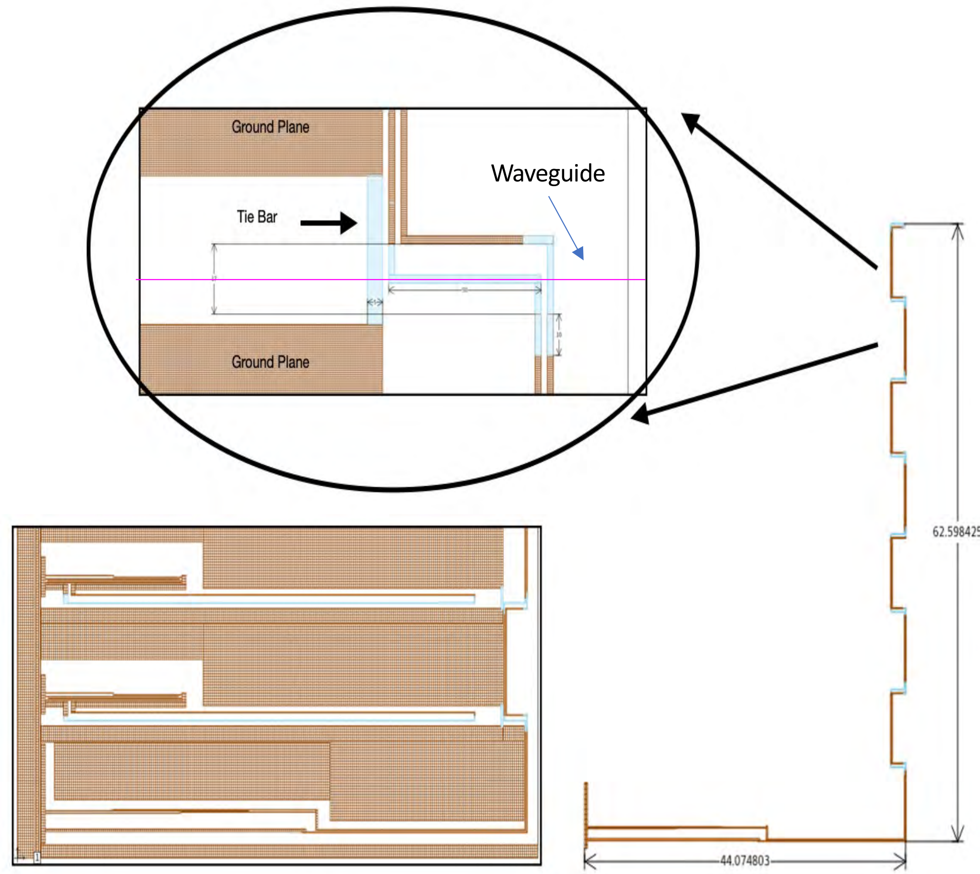
Testing

Hybrid Resonator

Reference Resonator



Sense Resonator

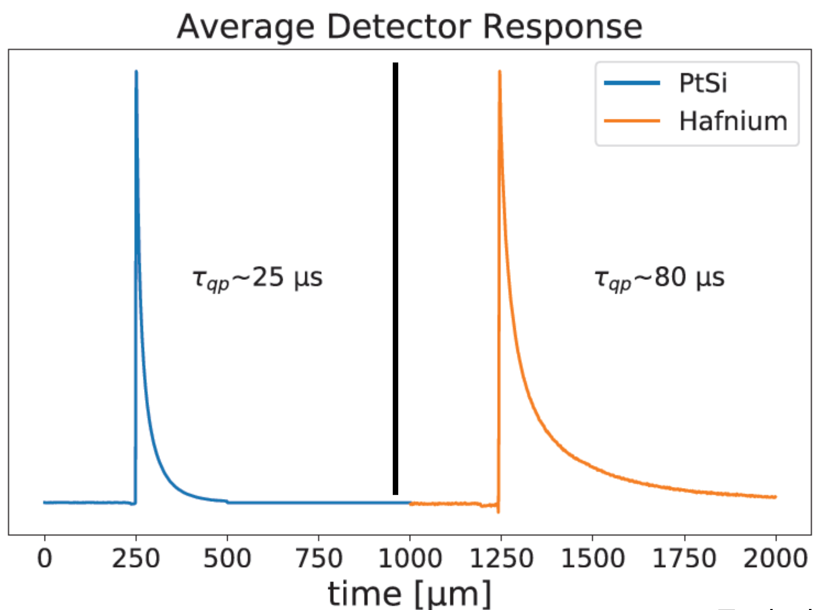


Definition: Spectral resolution $R = {}^{\lambda}/_{\Delta\lambda} = {}^{E}/_{\Delta E}$

$$R \propto \sqrt{\frac{1}{T_C}}$$

PtSi

- Tc ≈ 940 mK
- Qi ≈ 800 x 10^3
- Sputter Pt then Si then anneal
- R, τ_{qp} :...



Hafnium

- T_c≈450 mK
- Qi ≈ 200 x 103
- Sputtered
- R, τ_{qp}: ...