Quasiparticle Tunneling Measurements on an Illuminated Quantum Capacitance Detector Array

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Outline

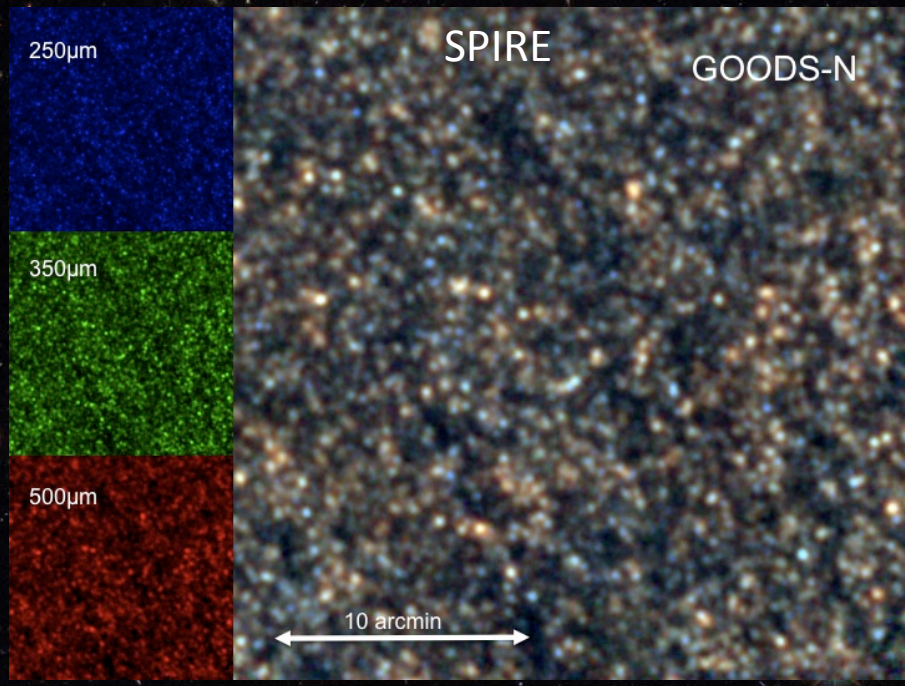
- Project Objectives
- Detector Concept
- Experimental Setup
- Noise
- Quantum Capacitance Results
- Current Work

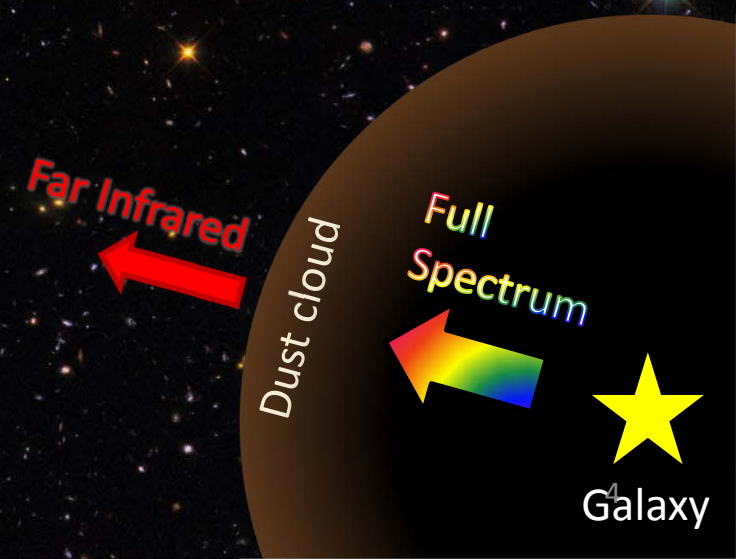
Project Objective

- Far-IR background limited detector
  - Wavelength: 35-600μm
  - Noise Equivalent Power (NEP) @ 10^{-18} to 10^{-21} W/Hz$^{1/2}$
- Applications
  - Cryogenic satellite missions
  - Aim: Background-Limited Infrared-Submillimeter Spectrograph (BLISS) on the Japanese Space Infrared Telescope for Cosmology and Astrophysics (SPICA)

Relevance to Astronomy

- Lack spectral detection sensitivities amongst the far-infrared/sub millimeter regime
  - Re-irradiation from dust surrounded galaxies
    - Ultra sensitivity not required
  - Red shifted galaxies from near-IR to the far-IR
    - z = 10 shift
    - Early galaxy formation
      ~12.5 Billion years ago
  - HUGE Discovery Space

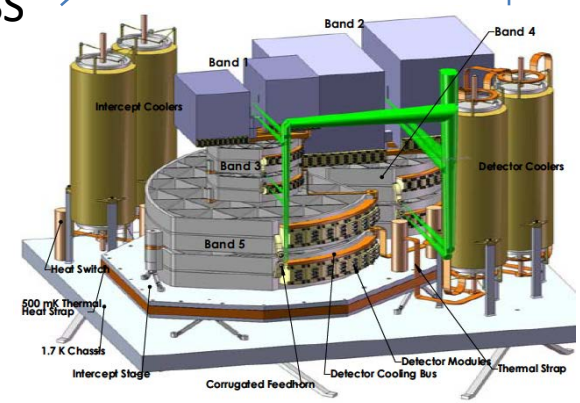


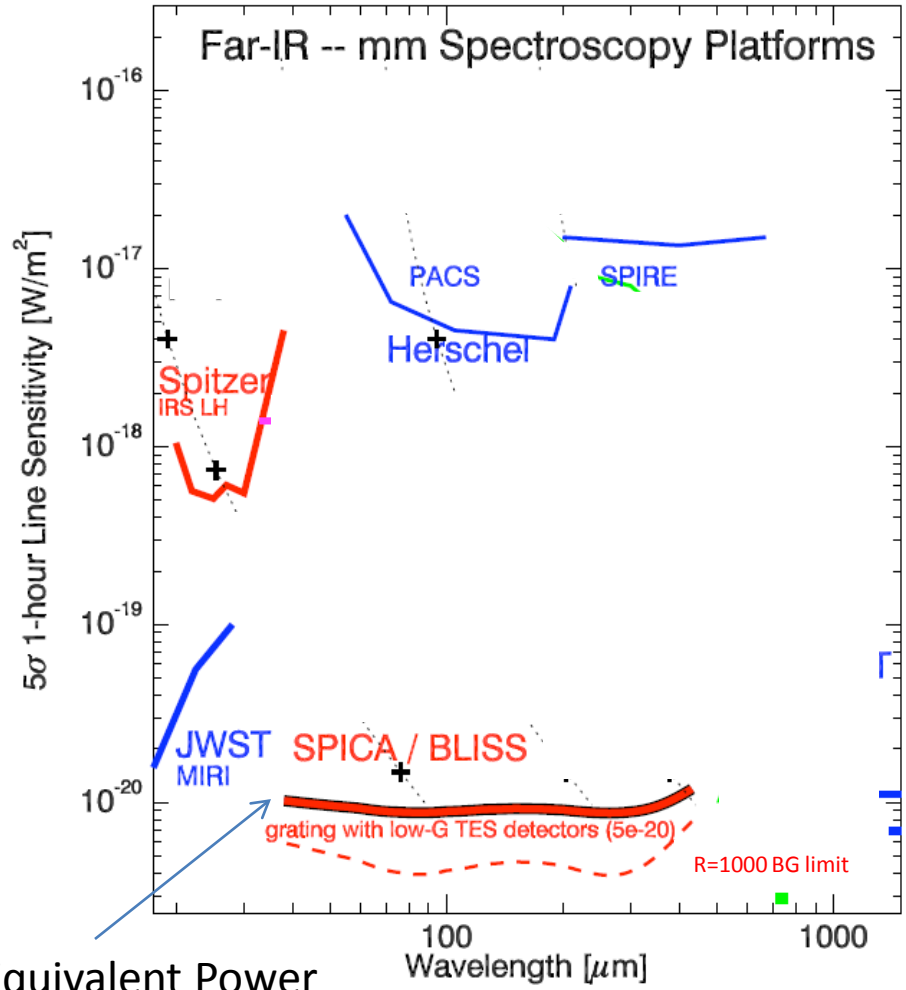


BLISS on SPICA

SPICA

BLISS





Noise Equivalent Power
$= 4\times10^{-20}$ W/Hz$^{1/2}$

Adapted from Astro 2010 Decadal Survey

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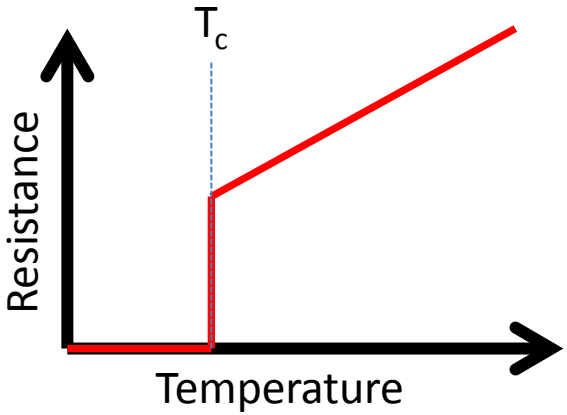
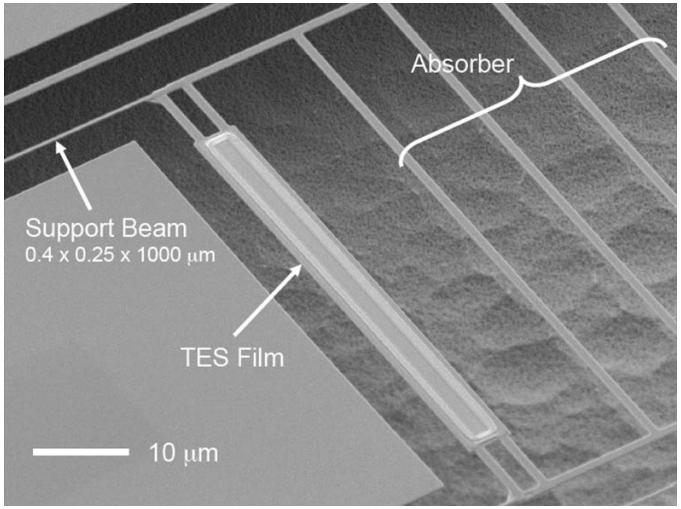
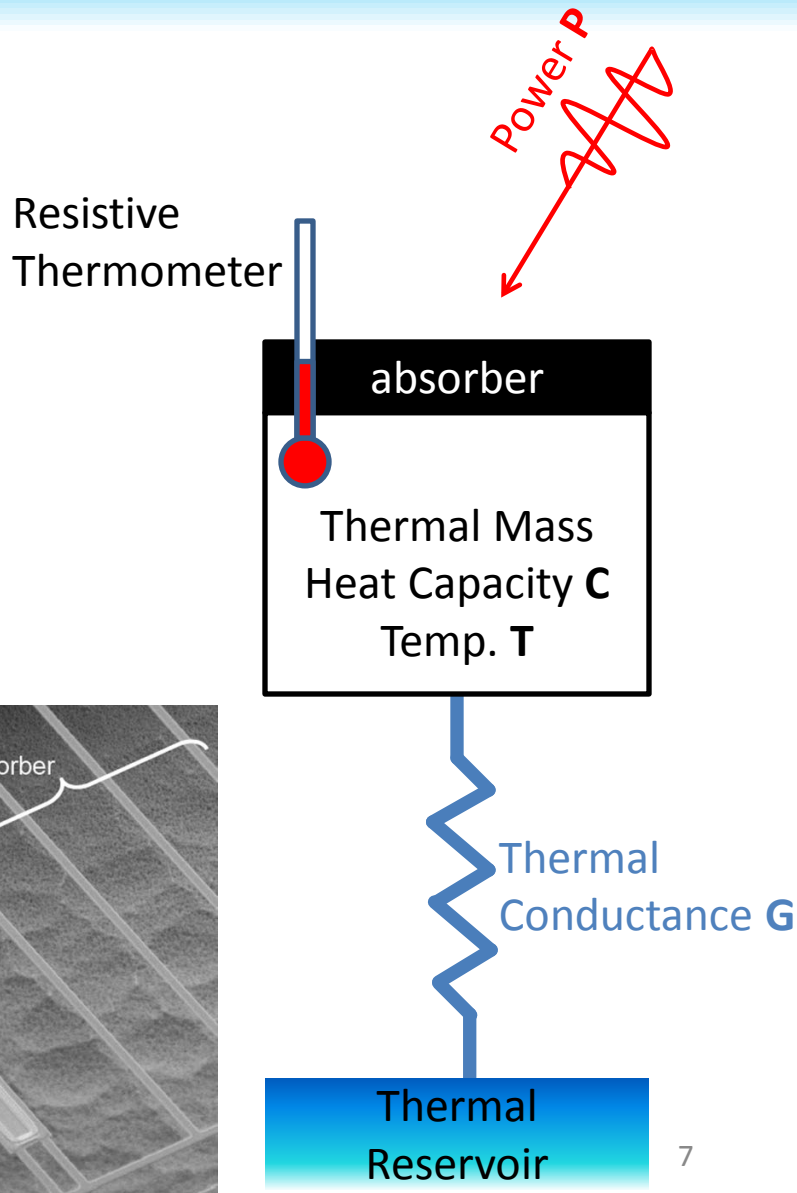
Existing technology

- Bolometers
  - Photons heat absorber
    - Temp. measured

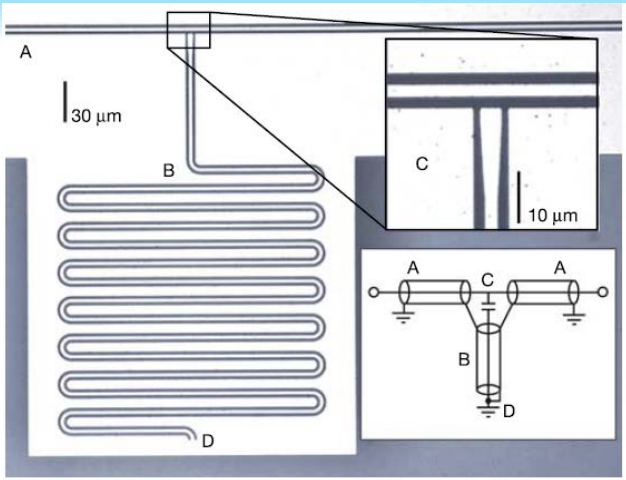


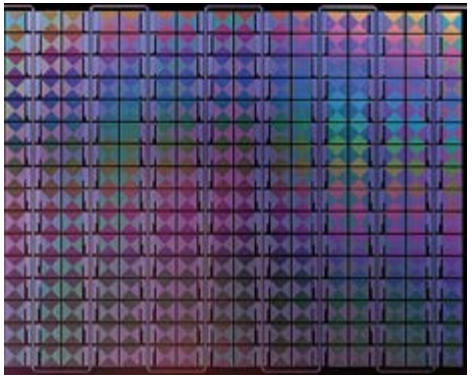




Other Options

- Superconducting Resonators
  - Microwave Kinetic Inductance Devices (MKIDs)
    - Photons detected by resonance shift
      - Variable Inductance
    - Multiplexable on single feedline





16x16 pixel MKID array

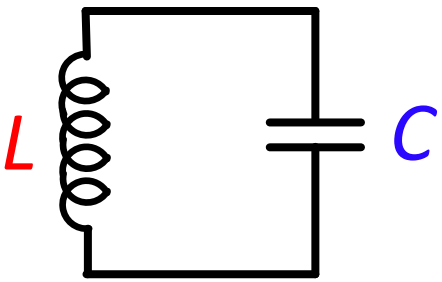
Quantum Capacitance Devices (QCD)

- Same multiplexibility as MKIDs
- 2-3 orders of magnitude more sensitive
- Operating temp. ~100mK
- Large signal to single quasiparticle tunneling event

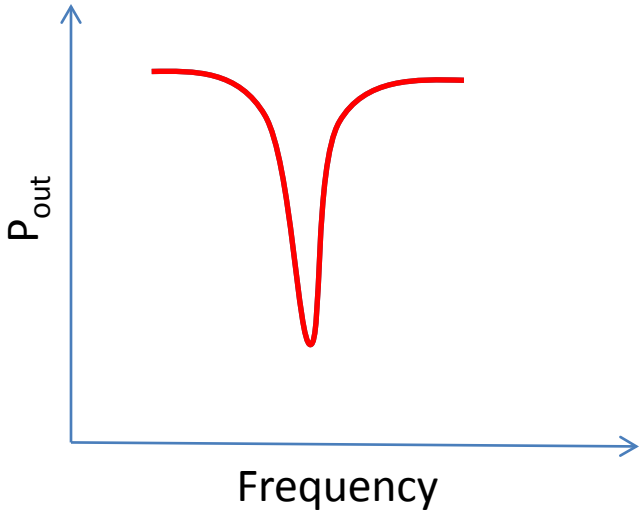
Microwave Resonators

- Energy resonates between stored Inductance and Capacitance at a specific frequency

$$\omega = \frac{1}{\sqrt{L \cdot C}}$$

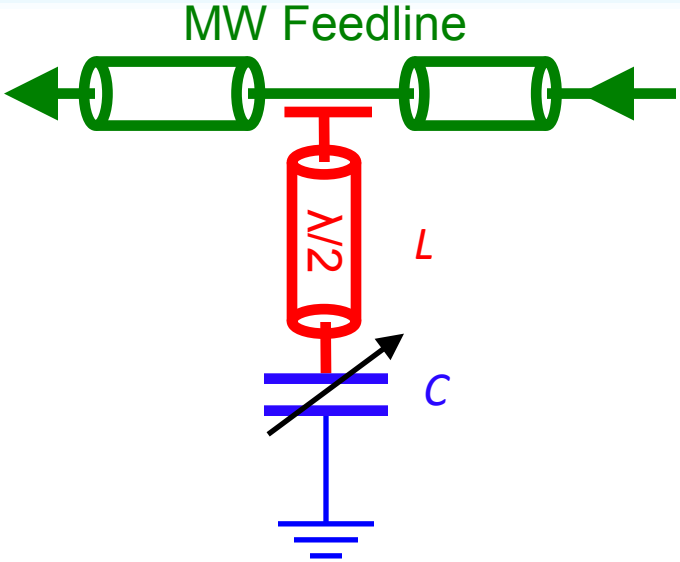


Simplest model

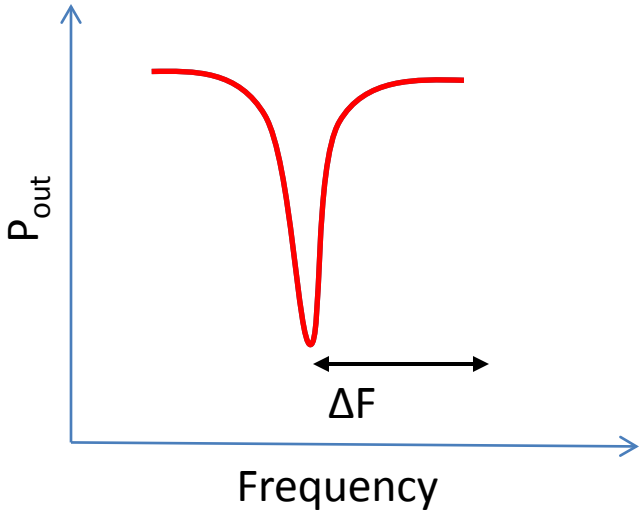


Microwave Resonators

$$\omega = \frac{1}{\sqrt{L \cdot C}}$$



- Energy resonates between stored Inductance and Capacitance at a specific frequency
- Can have analogy with microwave circuits
  - If *L* is fixed, *C* controls the resonance frequency

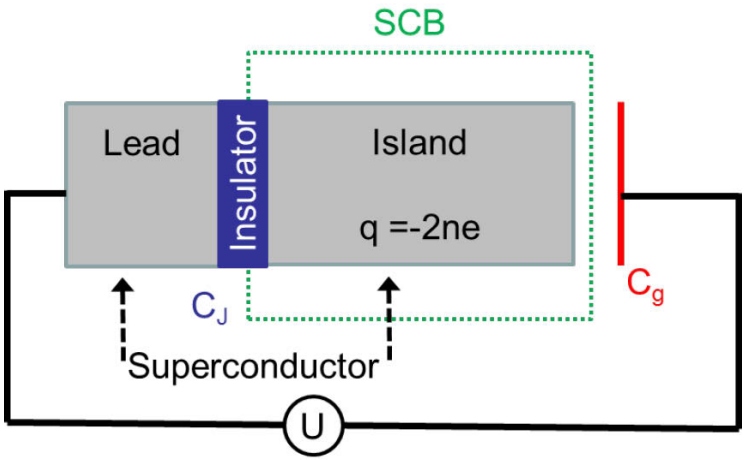


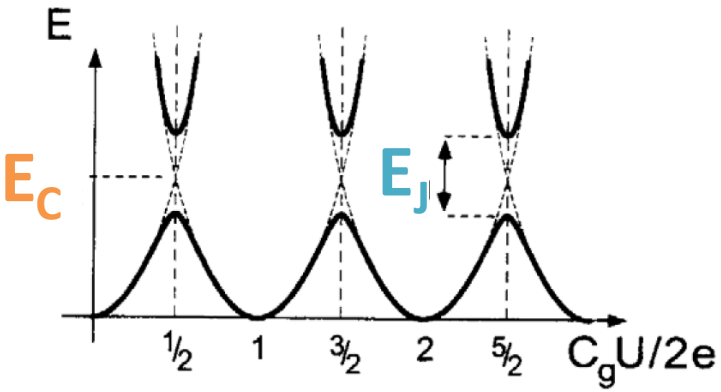
Single Cooper-Pair Box (SCB)

- Need a ***variable capacitance*** that depends on ***incident power***
- Single Cooper-pair Box (SCB)
  - Fabricated using superconductor-Insulating-superconducting (SIS) Junction
  - Initially studied for use as a quantum bit (qubit)
    - **Very sensitive to THz radiation**
    - Difficult for quantum computing
    - Turned around to make a detector for that same radiation

Single Cooper-Pair Box (SCB)

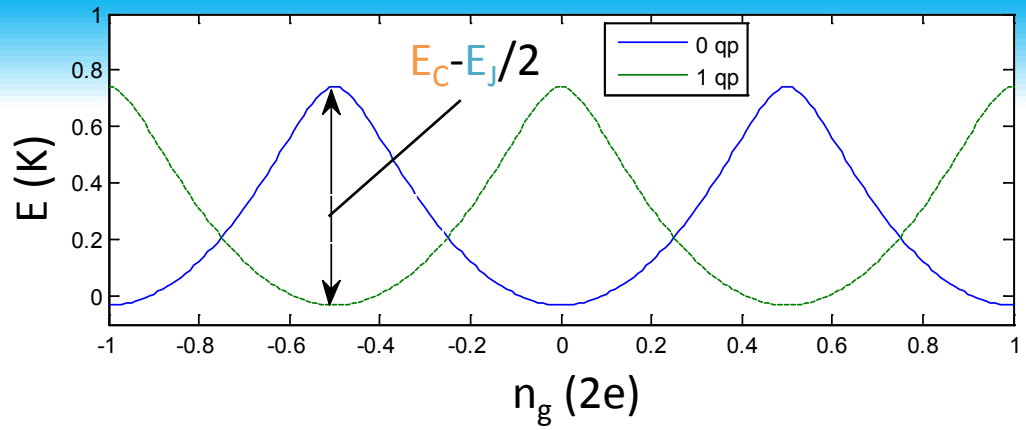
- A biased SIS junction
  - Sub-µm junction in series with gate C_g
  - Cost to add one electron
    - $\delta E = E_c - E_J/2 \quad >> k_B T$





Single Cooper-pair Box (SCB)

Electron Energy



$$n_g = \frac{C_g V_g}{2e}$$

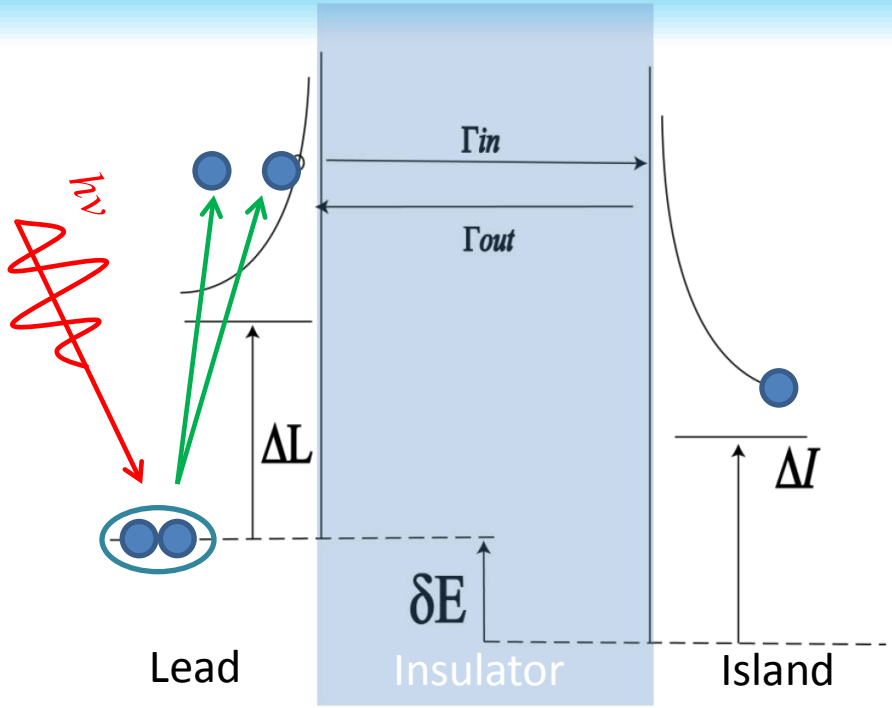
$$E_c = \frac{e^2}{2(C_J + C_g)} \sim 1\ K$$

$$E_J = \frac{h}{8e^2}\frac{\Delta}{R_n}$$

$$C = \frac{\partial \langle Q \rangle}{\partial V_g}$$

Single Cooper-Pair Box (SCB)

- SIS junction
  - Sub-µm Insulator junction
  - Incoming photon break up Cooper-pairs
    - Number quasiparticles generated
      - $n_{qp} = \eta h\nu/\Delta$
        - » $\eta = 0.57$, conversion efficiency
        - » Δ = superconducting gap energy



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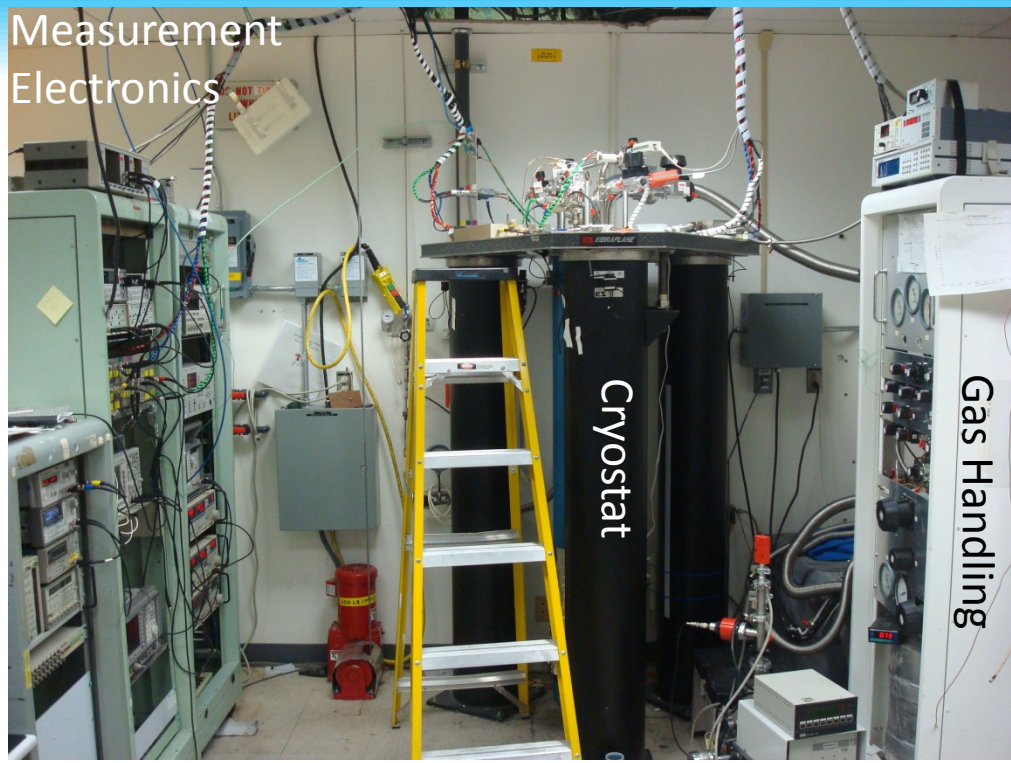
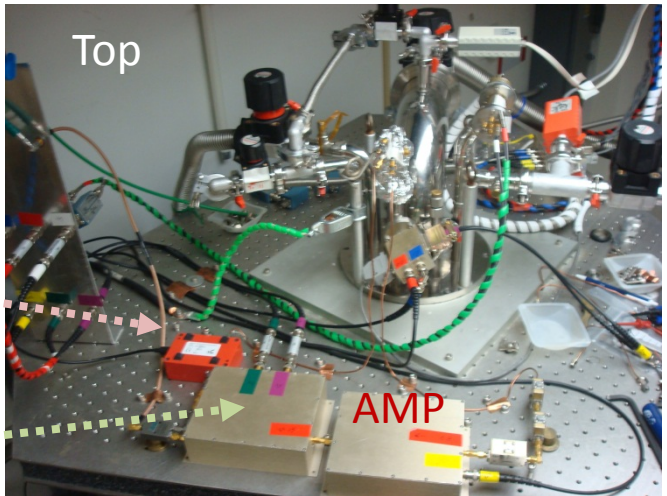
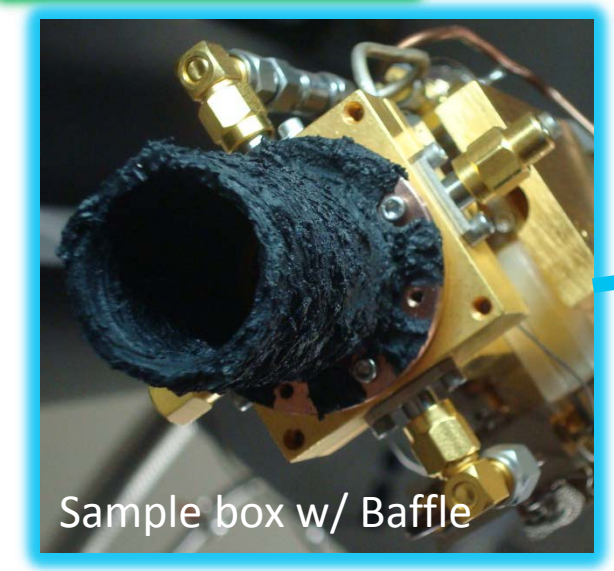
Apparatus

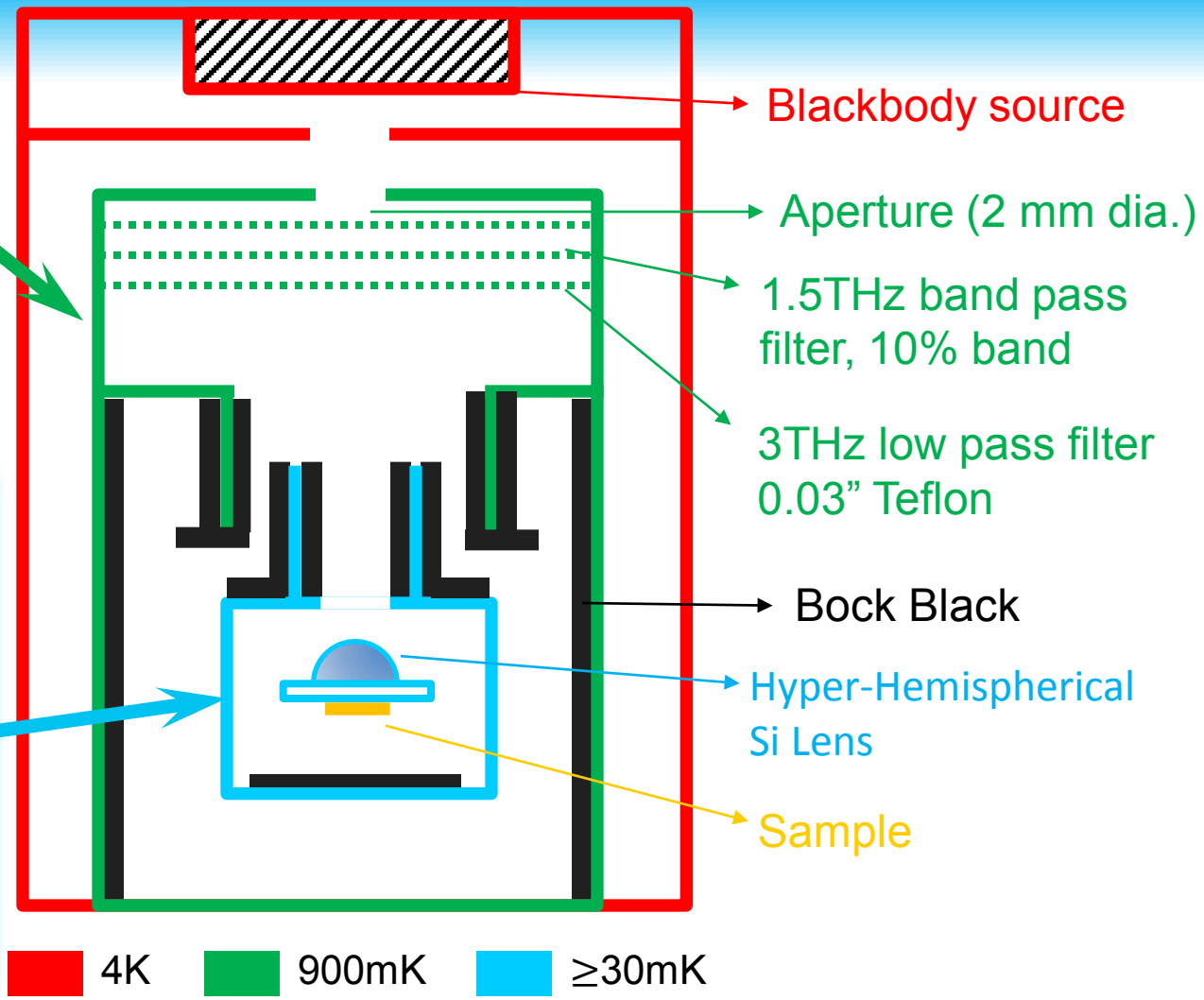
- Need:
  - Dilution refrigerator
    - ~100mK
  - RF readout capabilities
    - Single feedline
  - DC Bias
  - Source of Photons
    - Black body source





Experimental Setup

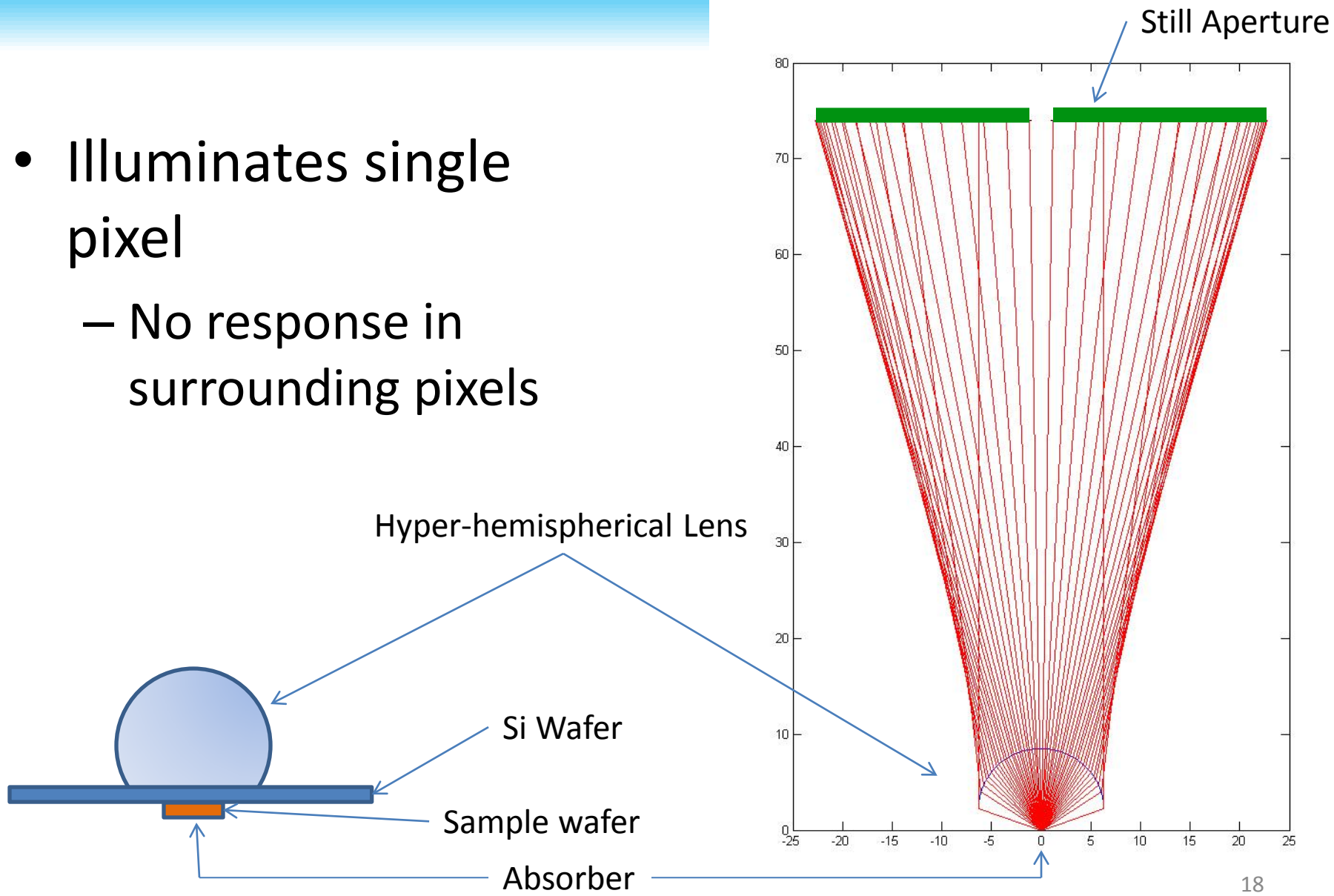




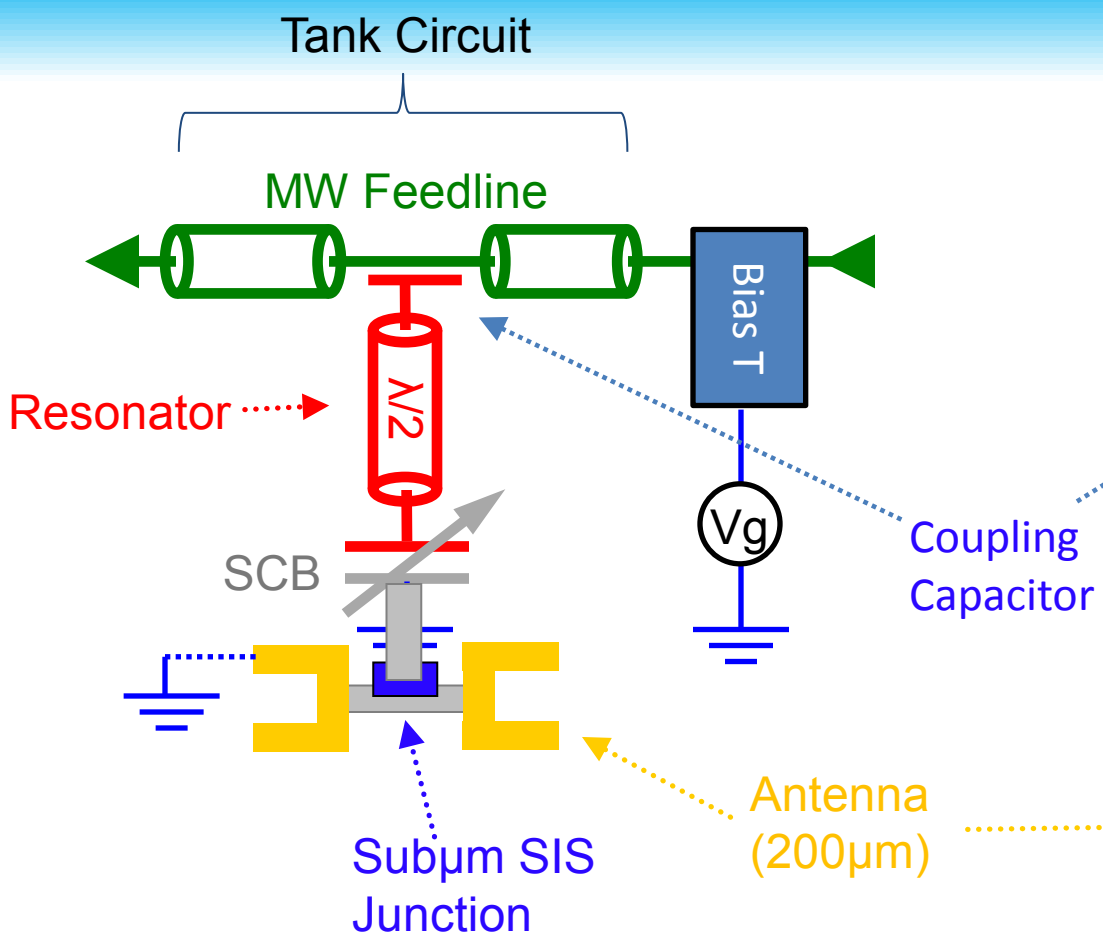
- Black body source and filters provide 1.5THz radiation from 4.2 – 40 K. The Bock Black absorbs stray 4K radiation from the fridge.

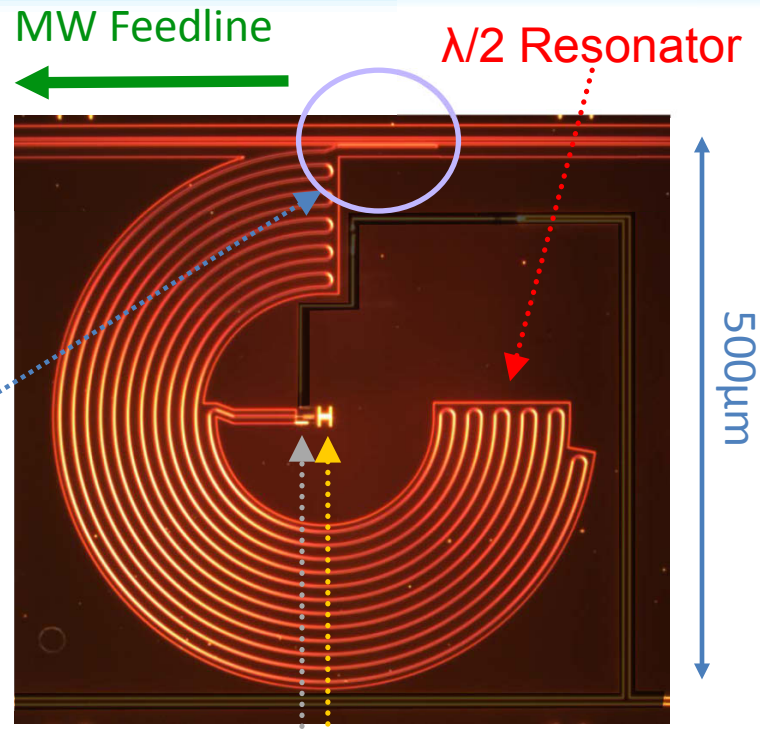
Single Si Hyper-hemispherical Lens

- Illuminates single pixel
  - No response in surrounding pixels

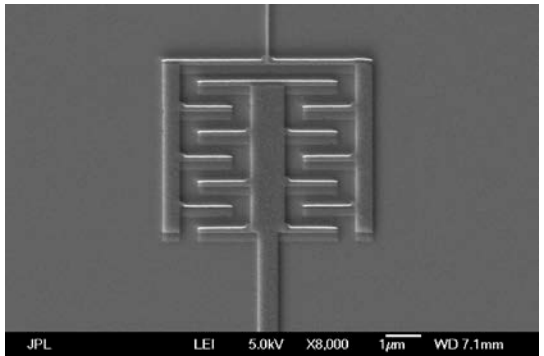


Quantum Capacitance Detector

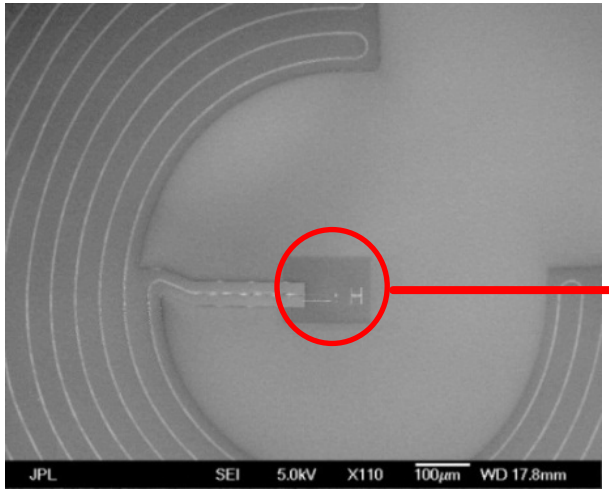


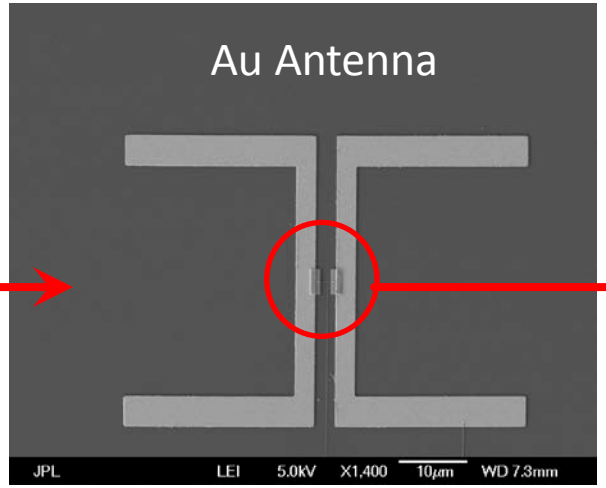


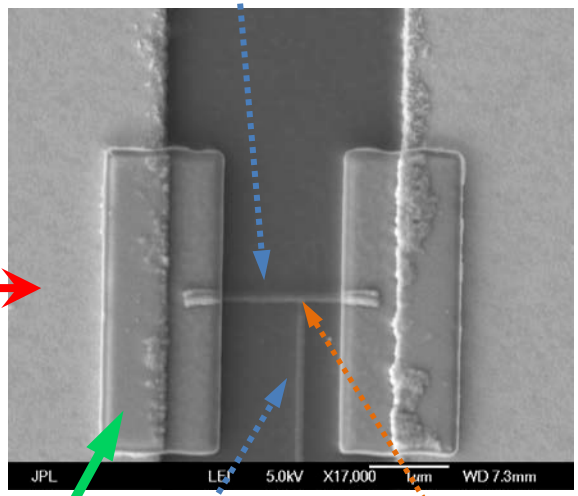
Interdigitated Capacitor (SCB)



QCD Absorber







Lead = Absorber

Island

Nb plugs

Al SIS junction

Shadow Mask
Double Angle
Evaporation

Nb plugs prevent backflow of quasiparticles into absorber, due to larger energy gap.

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Noise Sources

- Phase Noise
  - Coupling to two-level charge fluctuators on the substrate and surface
    - 1/f noise
- Generation/Recombination (GR) Noise
  - Thermal excitation and recombination of equilibrium quasiparticles
  - Mostly frozen out
- Fano Noise
  - Uncertainty of the number of quasiparticles generated
- Telegraph Noise
  - Quasiparticle shot noise
  - Largest contribution in a QCD

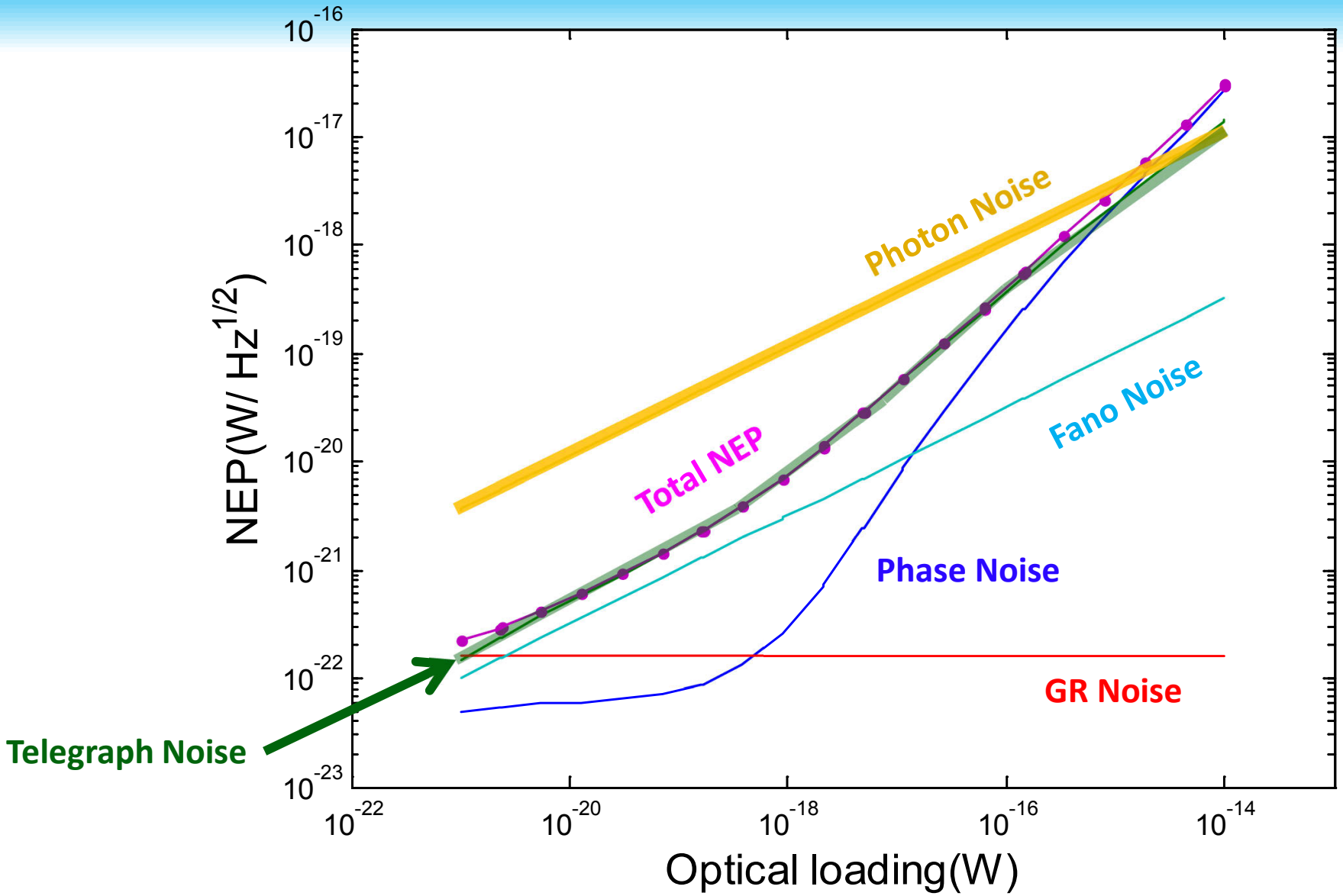
Noise Equivalent Power (NEP)

- The signal power that gives a signal-to-noise ratio = 1, within a bandwidth of 1Hz.
  - Used as a standard to compare different kinds of detectors
  - Units of $W/Hz^{1/2}$
  - Lower values = more sensitive detectors

$$NEP = \frac{Noise}{Responsivity}$$

$$Responsivity = \frac{\partial \boldsymbol{Response}}{\partial Power}$$

Theoretical Sensitivity vs. Signal Power



- *Detector is background limited over a wide range of operation*

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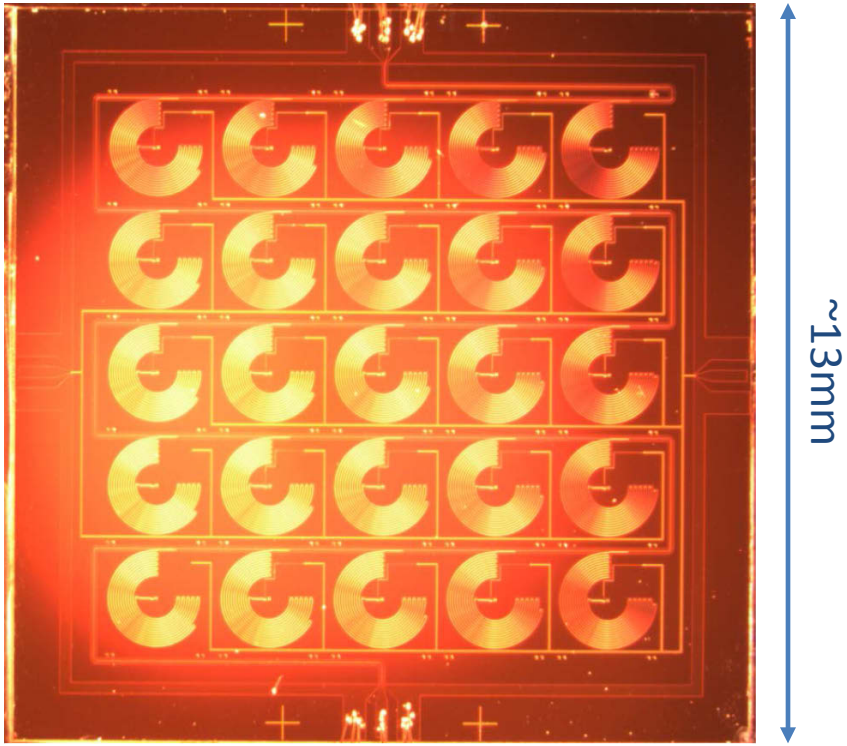
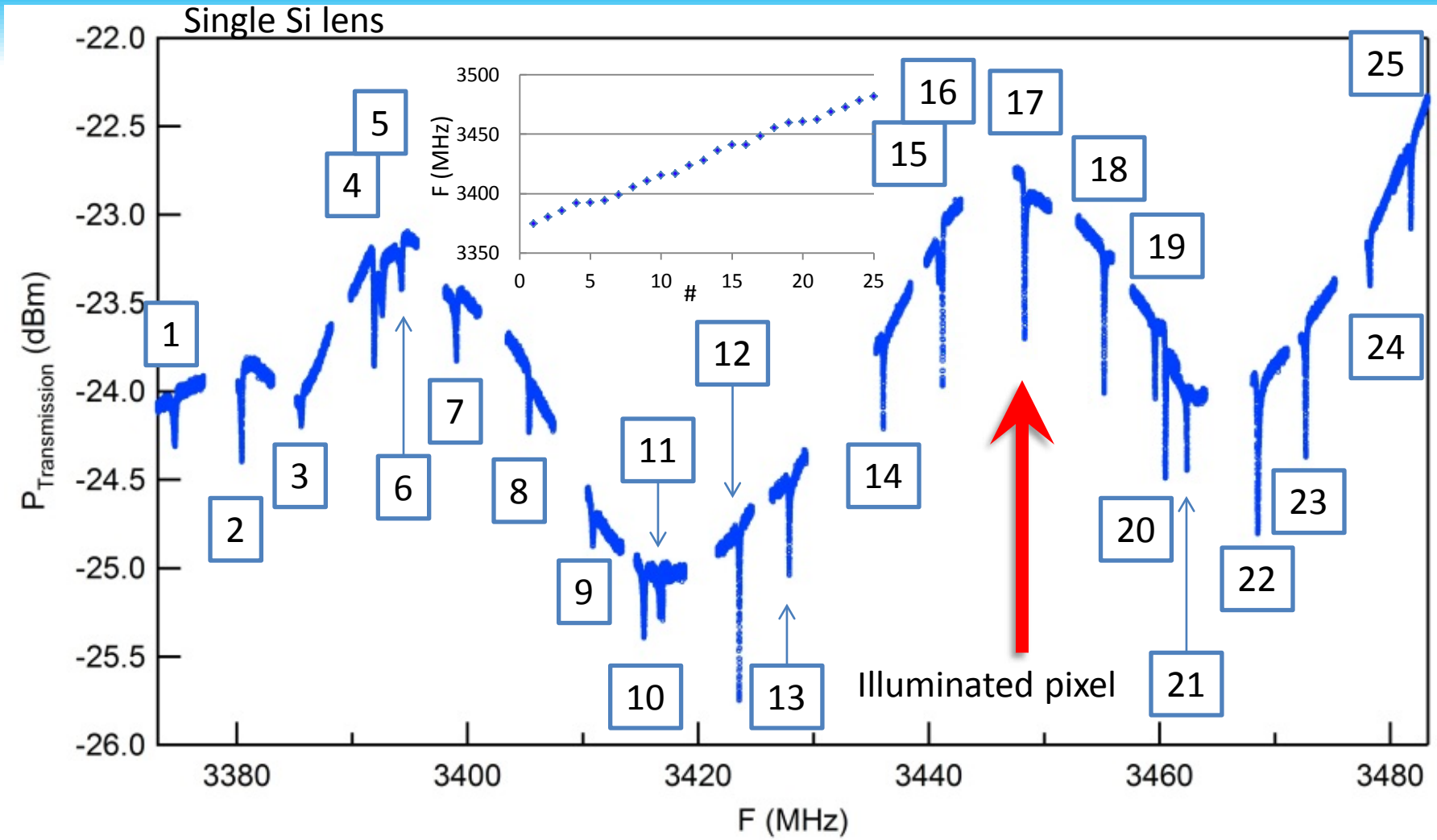
QCD 5x5 Array



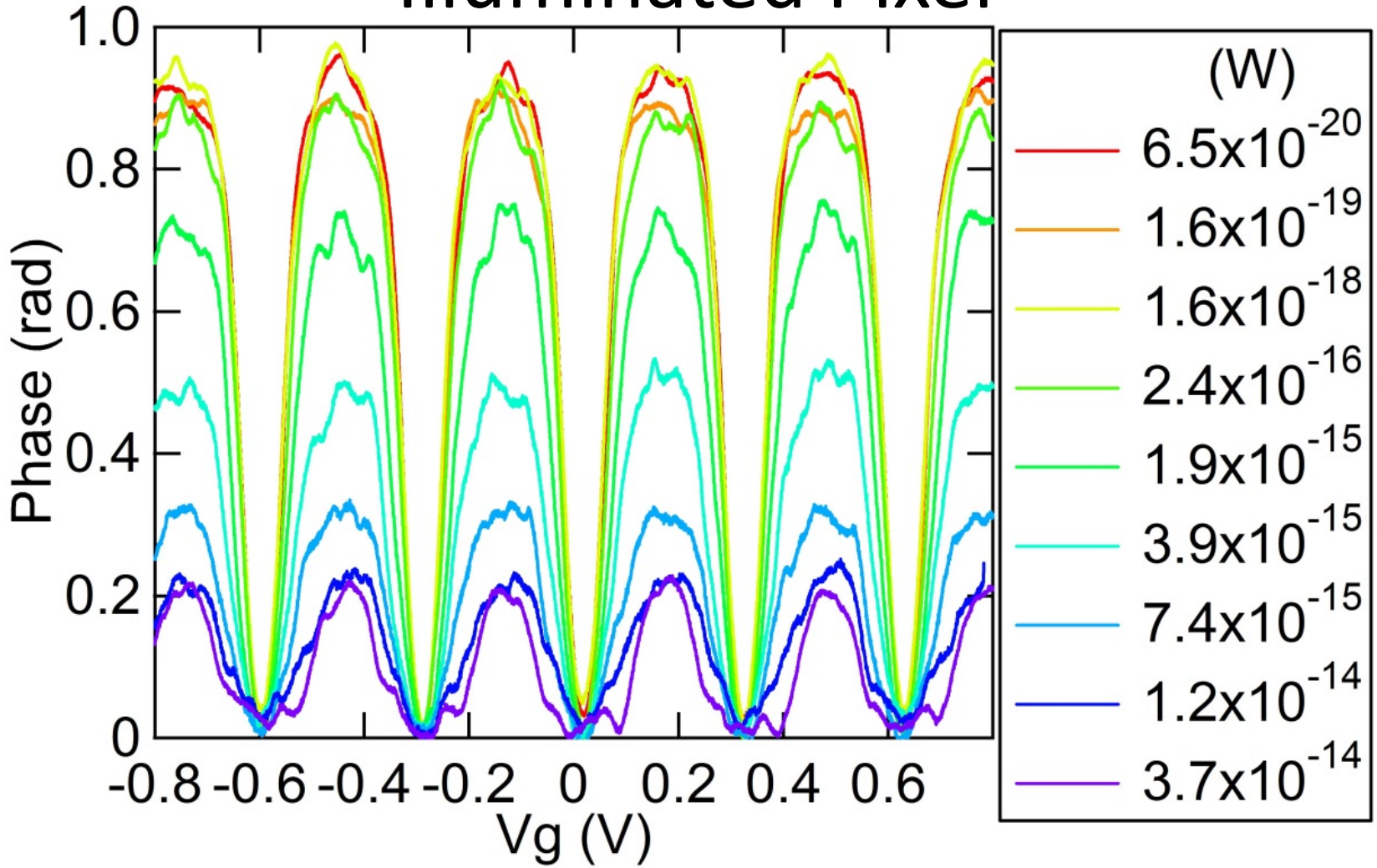
- Detector density limited by λ/2 resonator length

Resonances



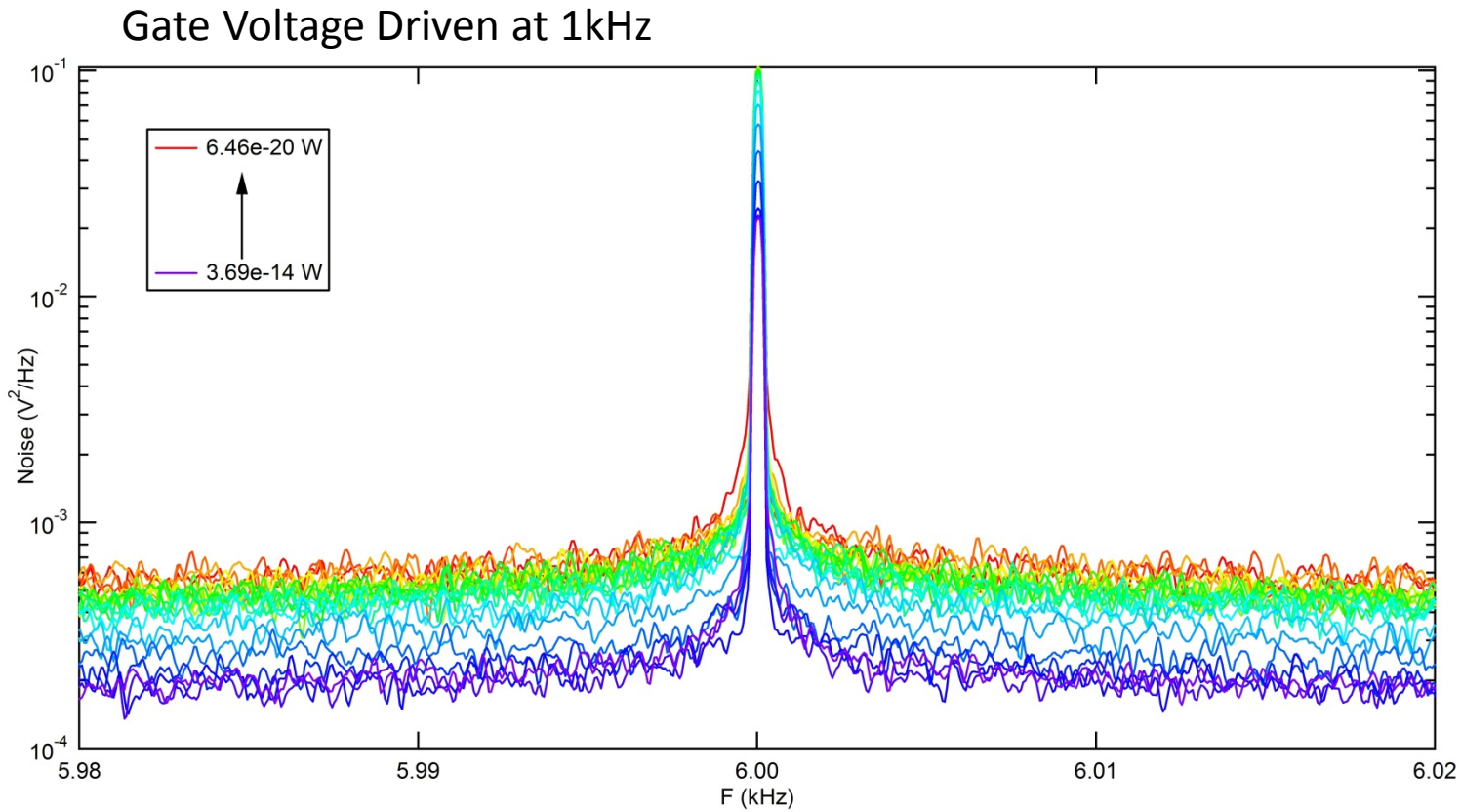
Plot of all 25 resonances, variable spacing and depth due to various coupling capacitor sizes.

Results – QCD phase response Illuminated Pixel



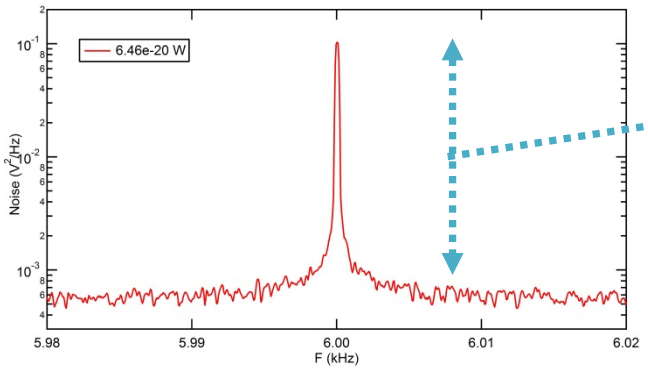
- 2e periodic QCD phase signal vs. gate voltage for various black body powers. More photons, smaller signal.

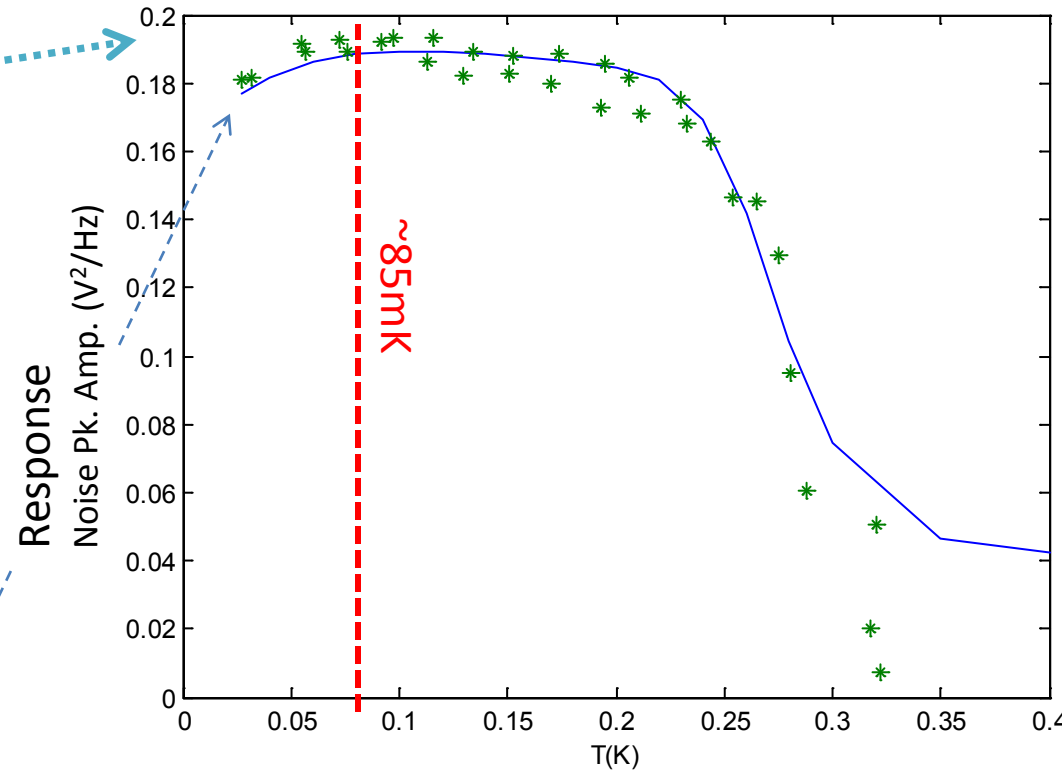
Results – Noise (85mK)



- Noise spectrum from 6th harmonic QCD signal where V_g is tuned to sweep through 6 QCD peaks.

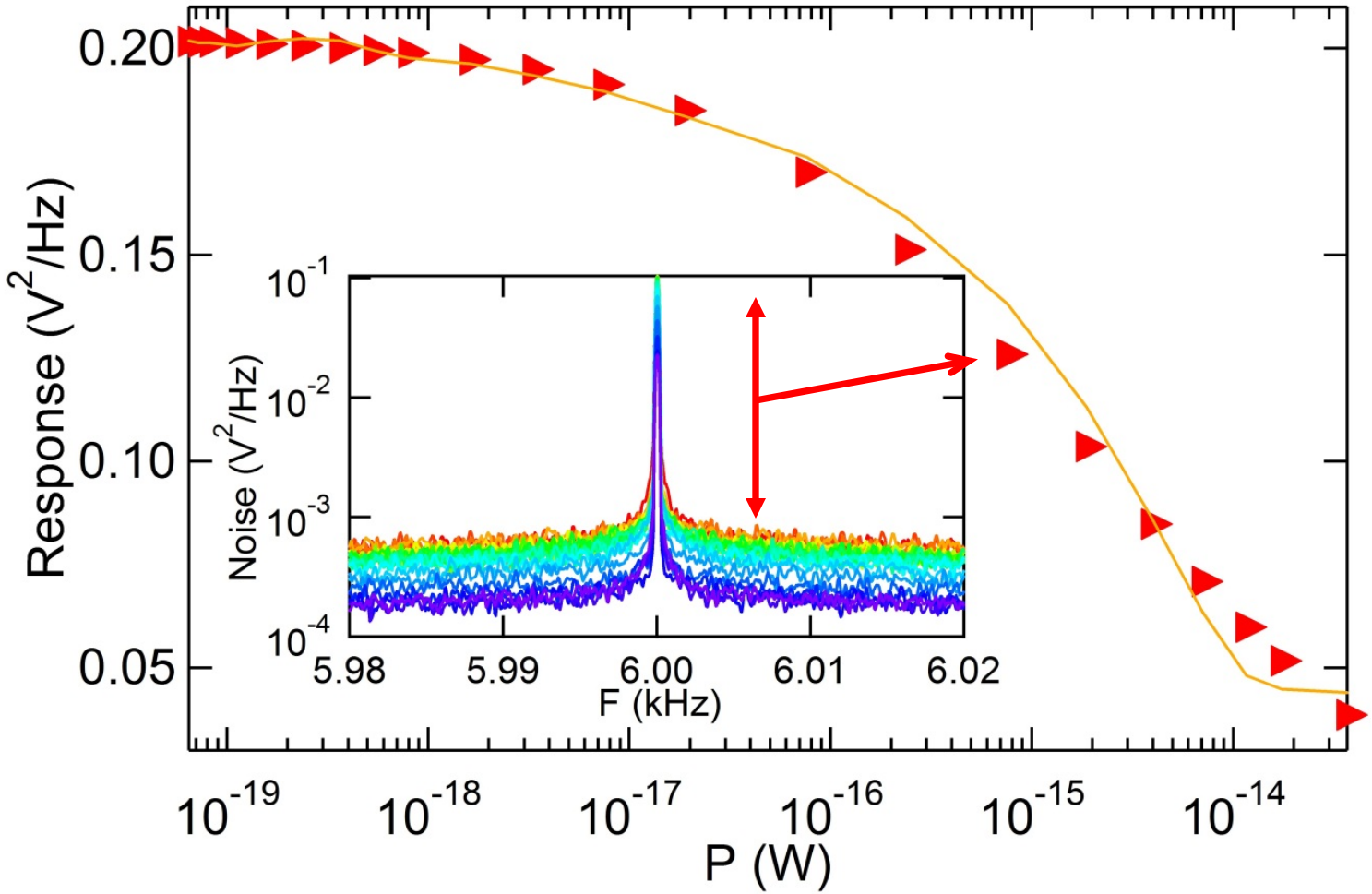
Results - Sample Temp. Dep.





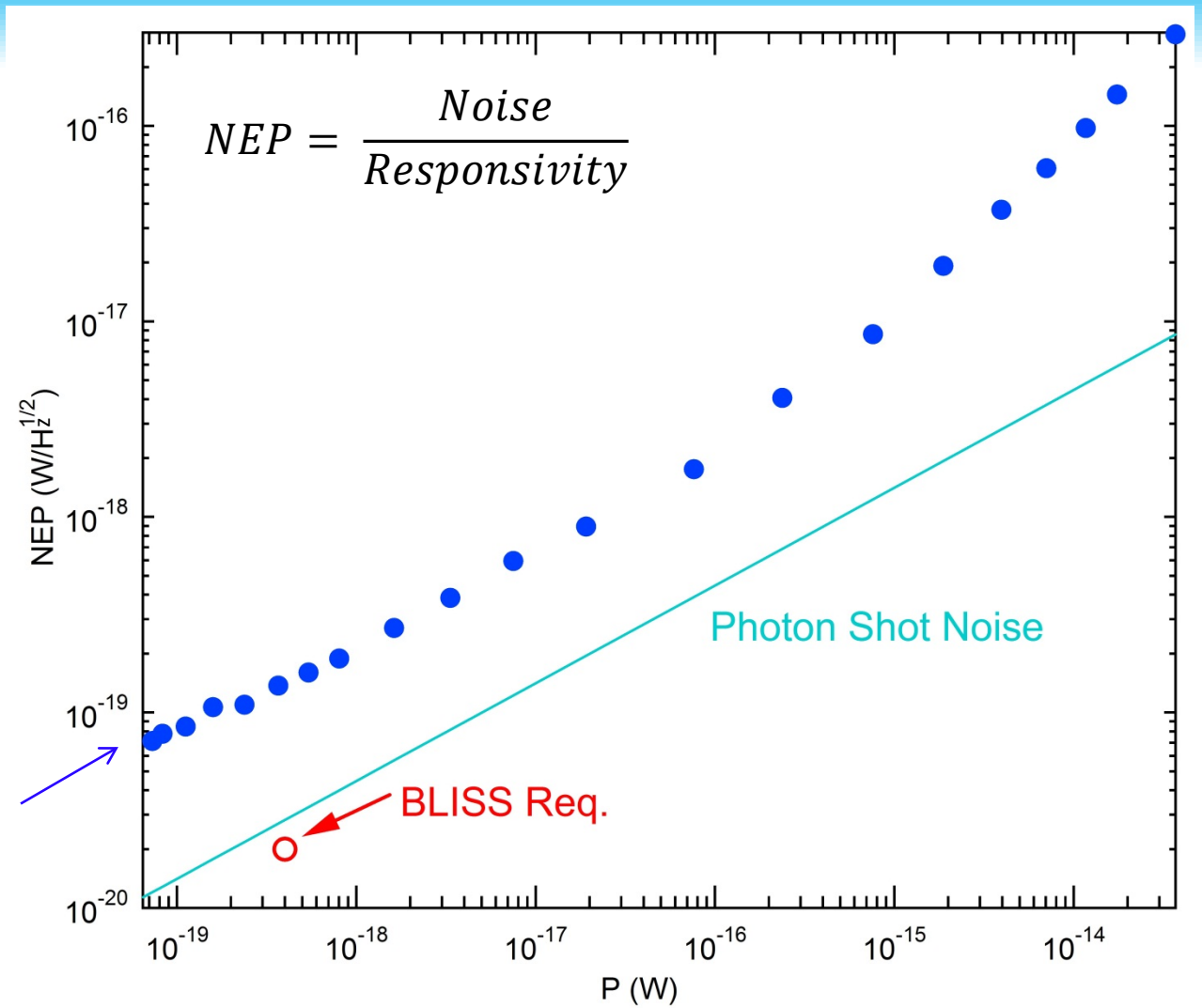
- QCD signal peaks at ~85mK
- Low T
  - Backflow of quasiparticles from Au/Nb/Al
- Calibration check

Results – Response (85mK)



$$Responsivity = \frac{\partial(\boldsymbol{Response})}{\partial P}$$

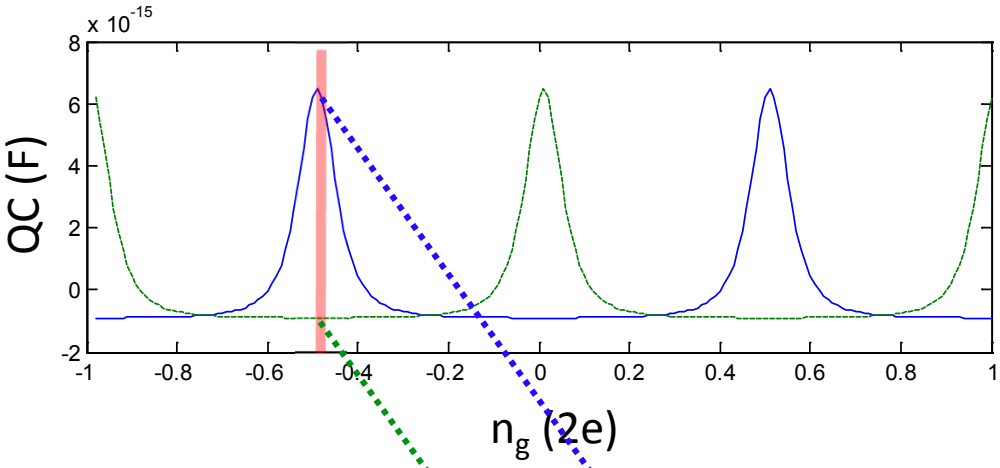
NEP Calculation (85mK)

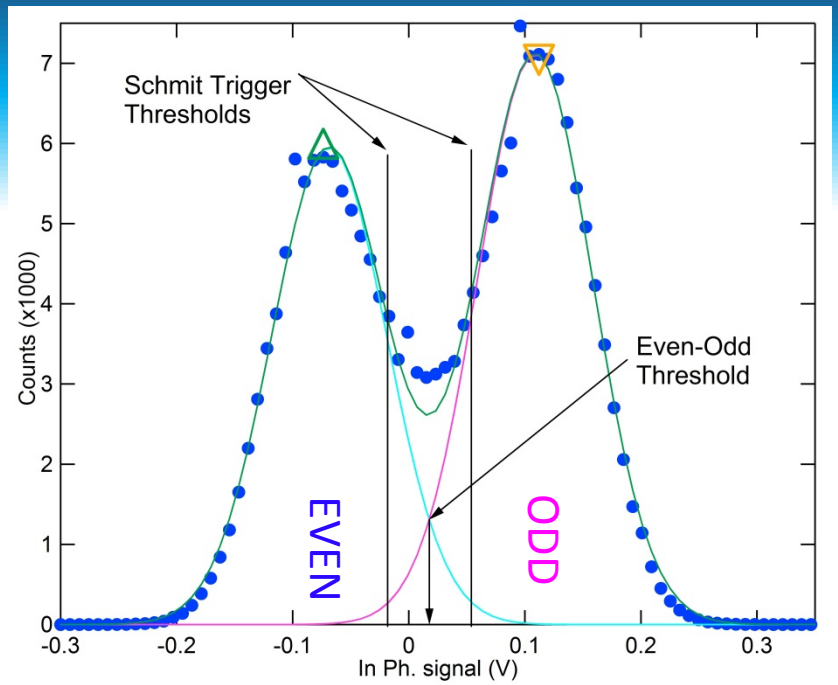


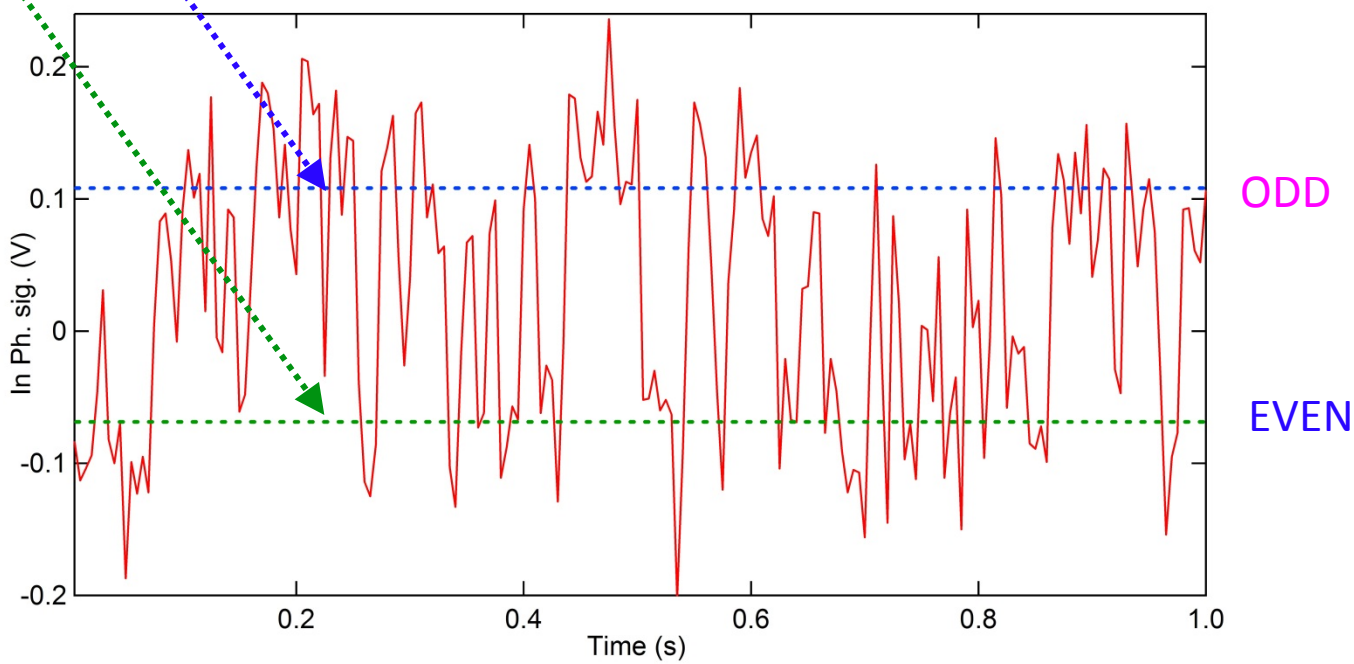
7×10^{-20} W/Hz$^{1/2}$

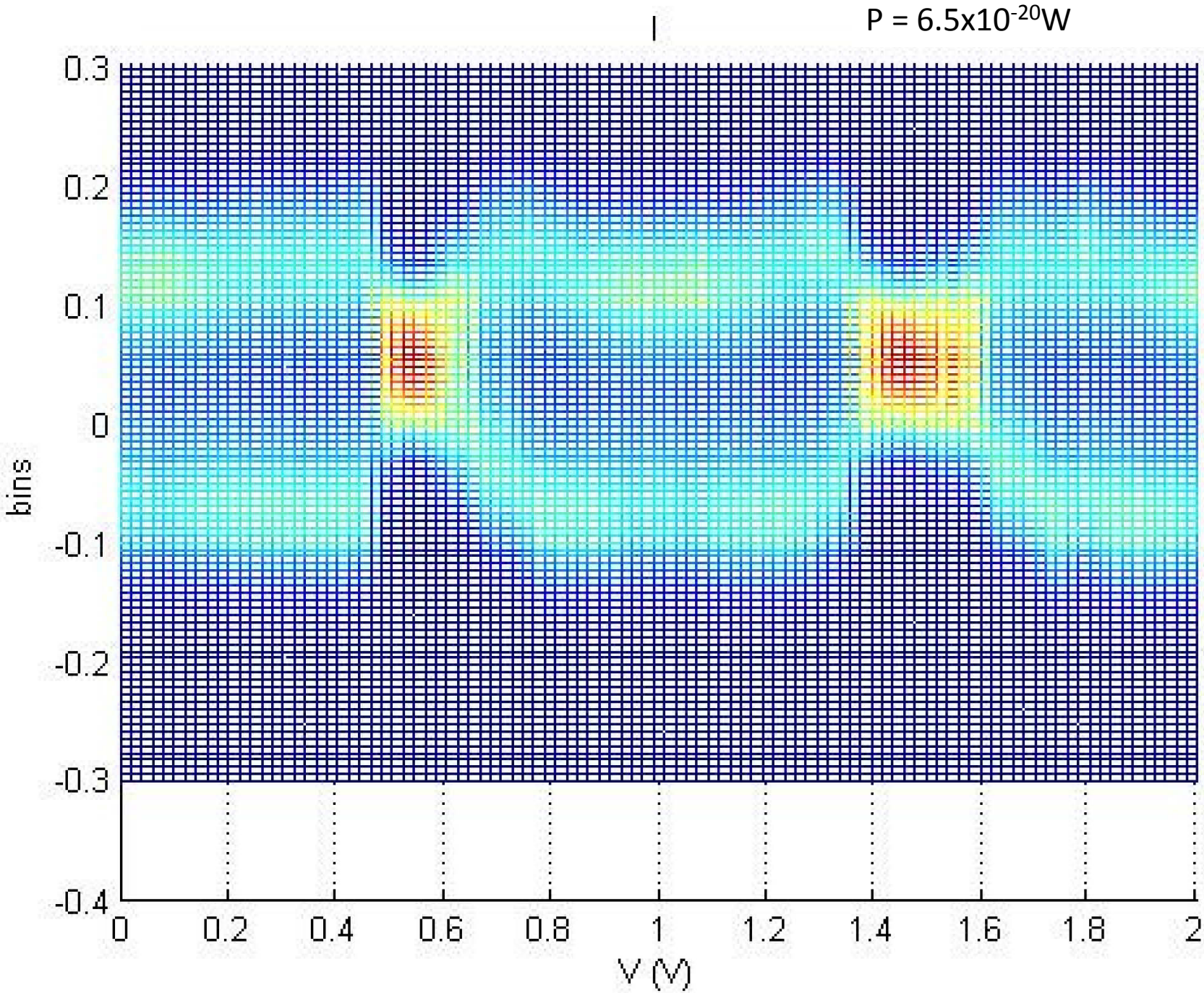
- Calculated NEP from response and noise.

Telegraph Signal

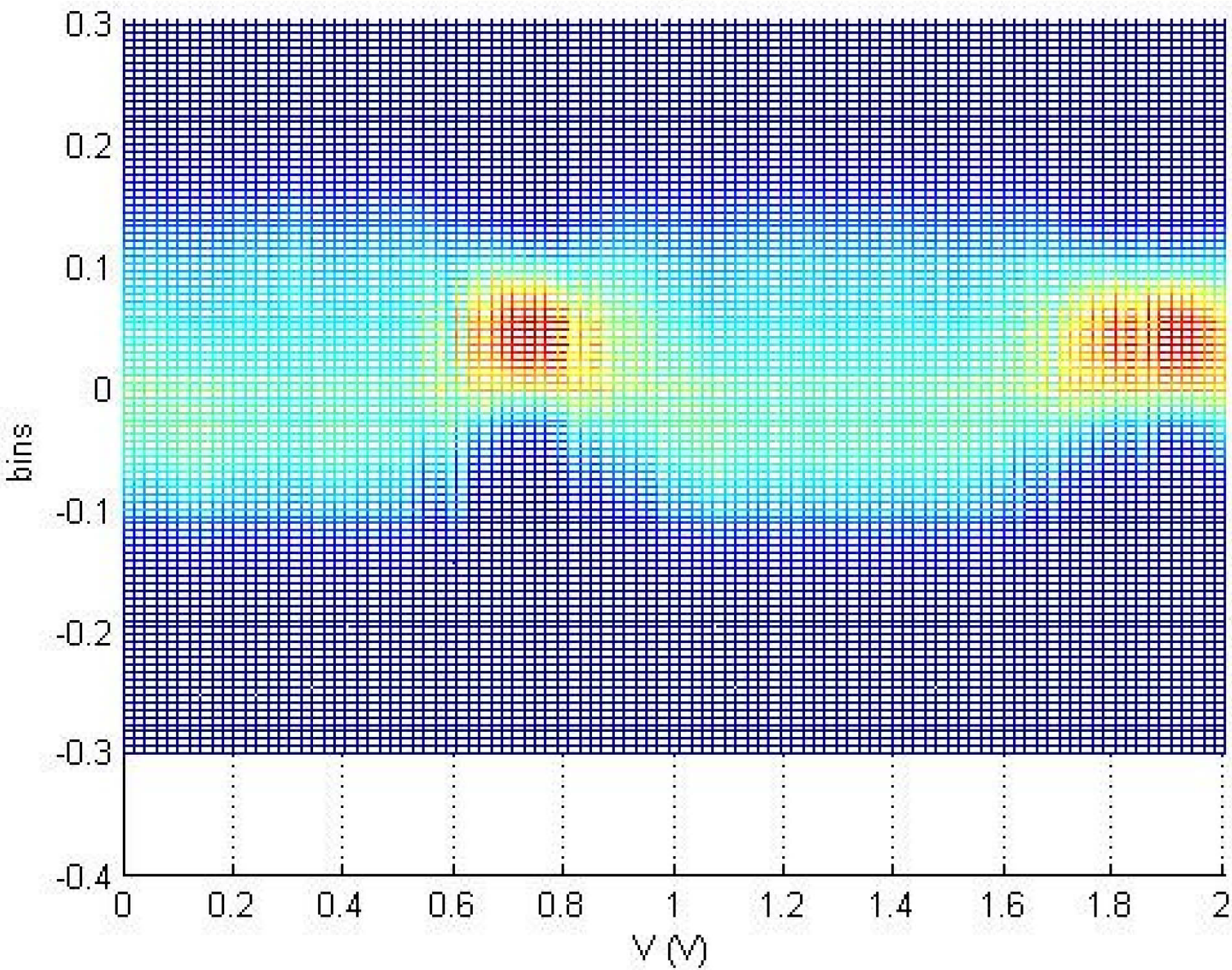


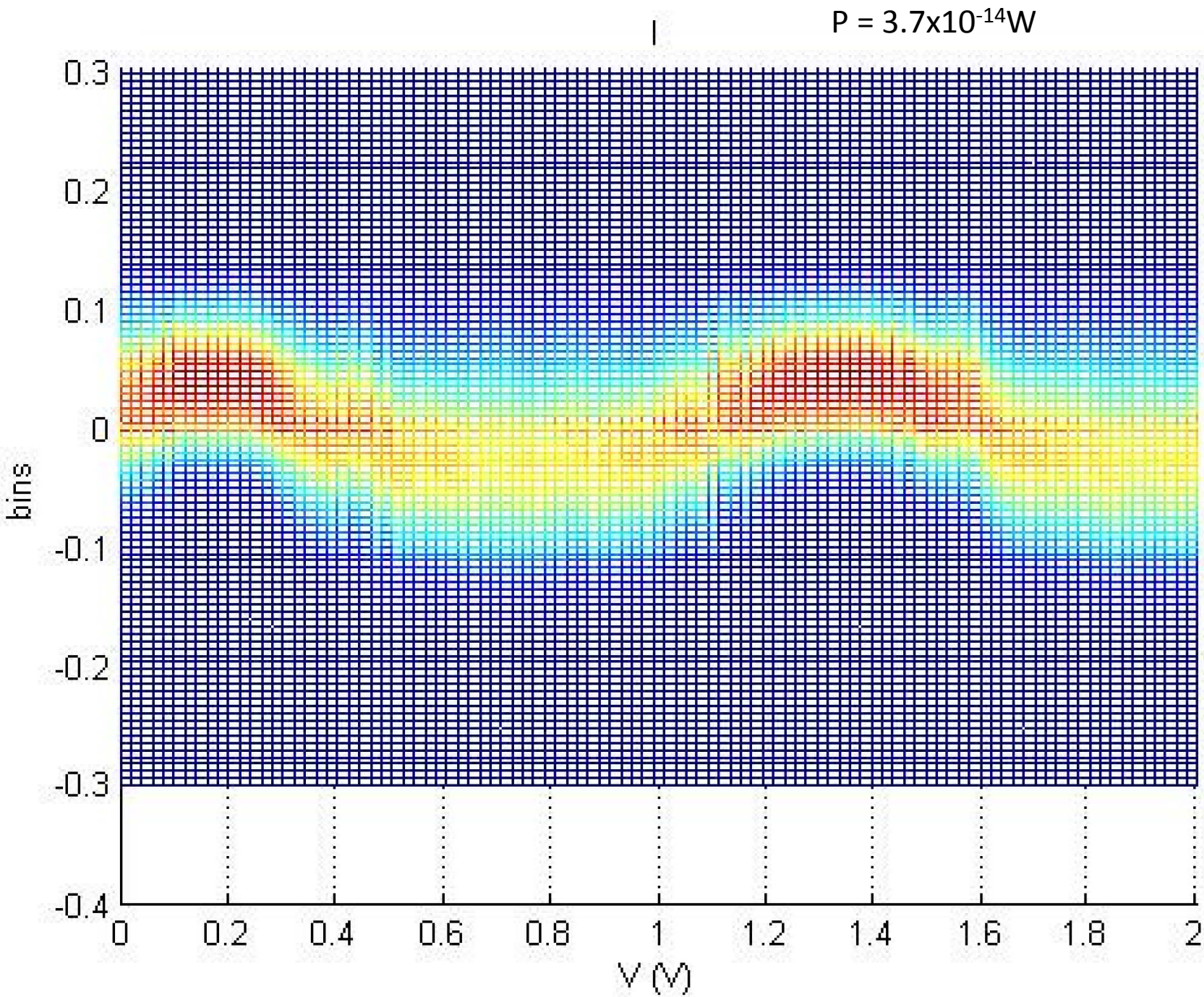





P = 6.5x10-20W
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
bins
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
V (V)

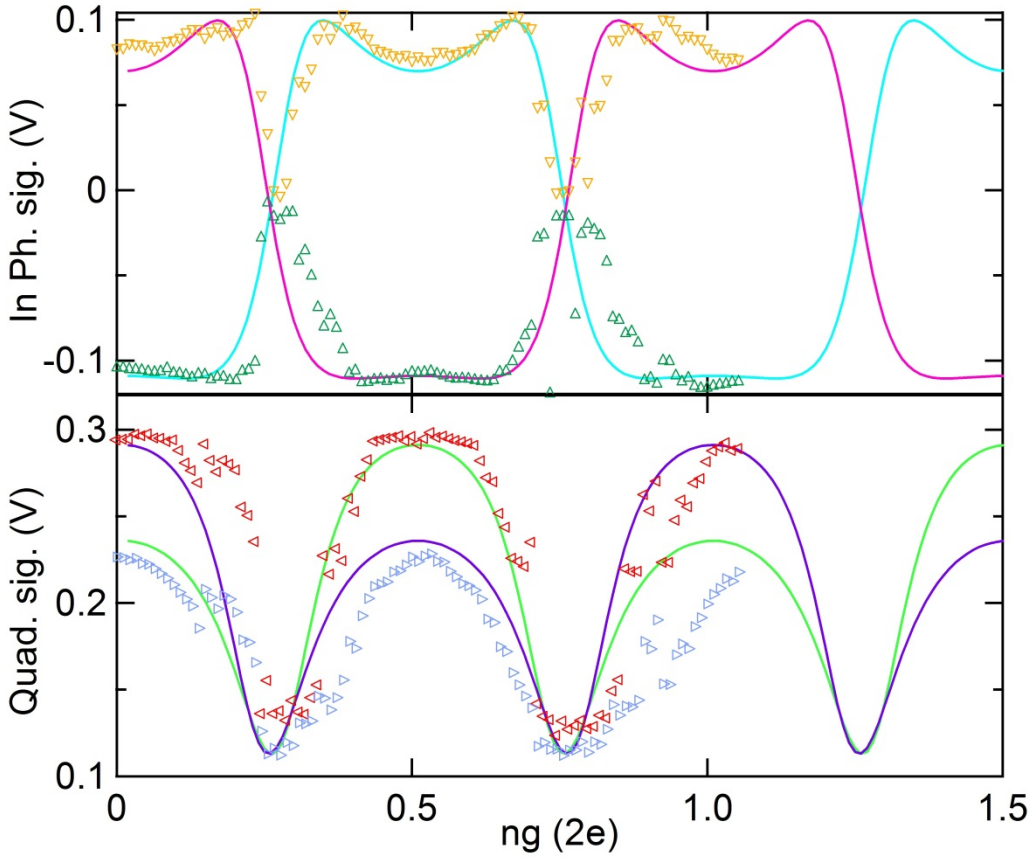
P = 9.7x10^{-15}W

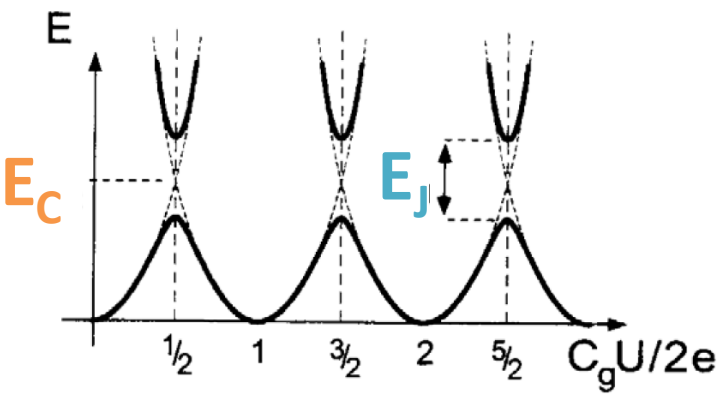



P = 3.7x10-14W
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
bins
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
V (V)

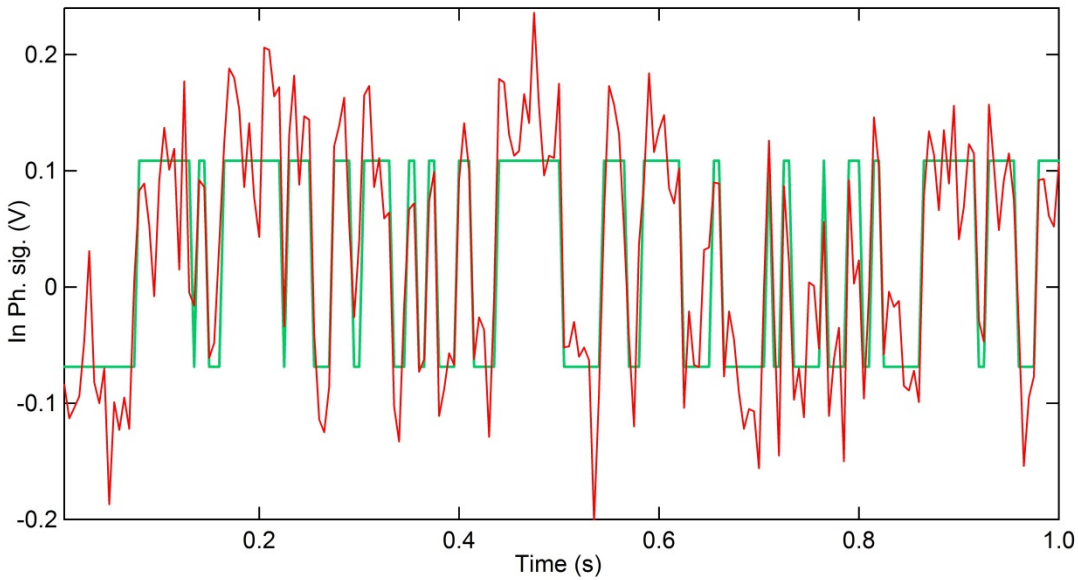
Telegraph Noise - Histogram Peaks

- Fit yields:
  - Charging Energy
    - $E_C = 0.51$ K
  - Josephson energy
    - $E_J = 1.4$ K
  - Junction capacitance
    - $C_J = 0.55$ fF
  - Gate capacitance
    - $C_g = 1.26$ fF





Telegraph Signal – Dwell Time

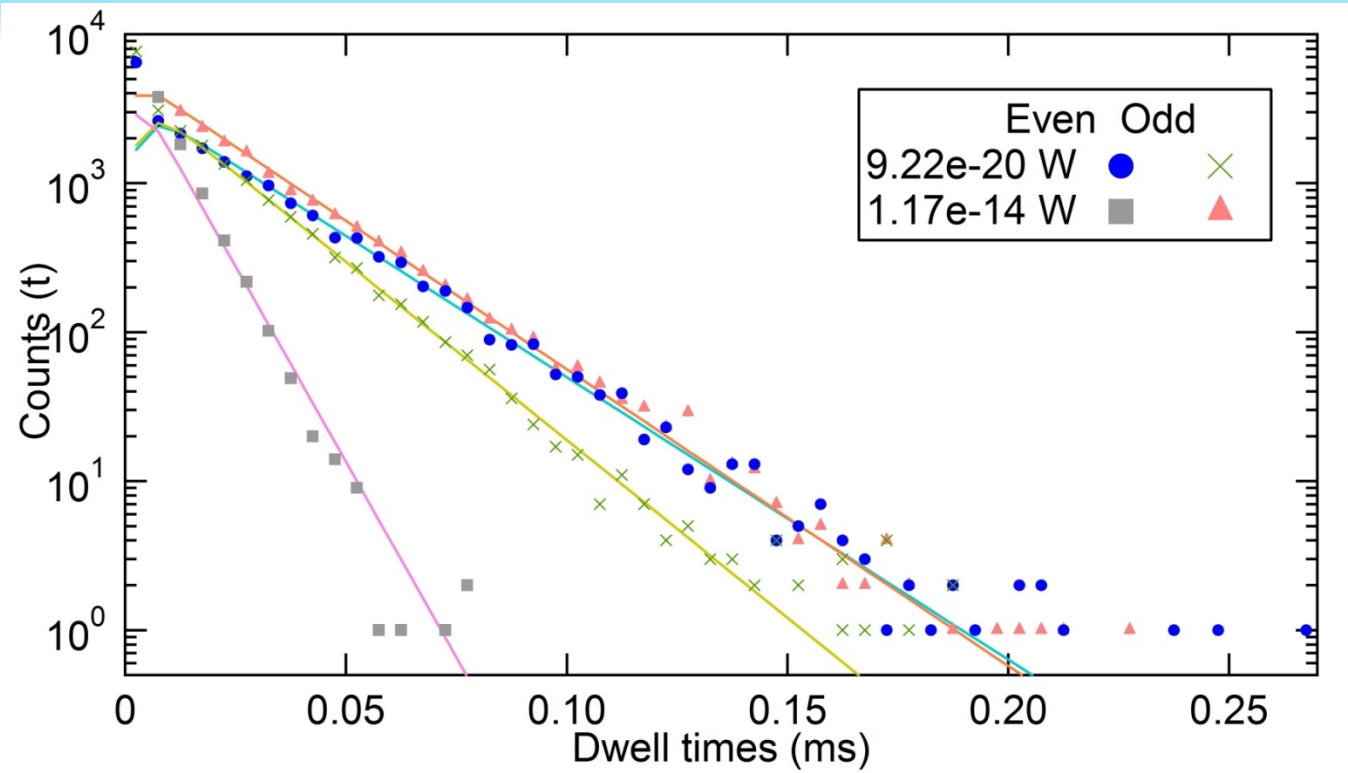


ODD

EVEN

- Apply Schmitt trigger algorithm
- Measure dwell time distribution in even and odd state

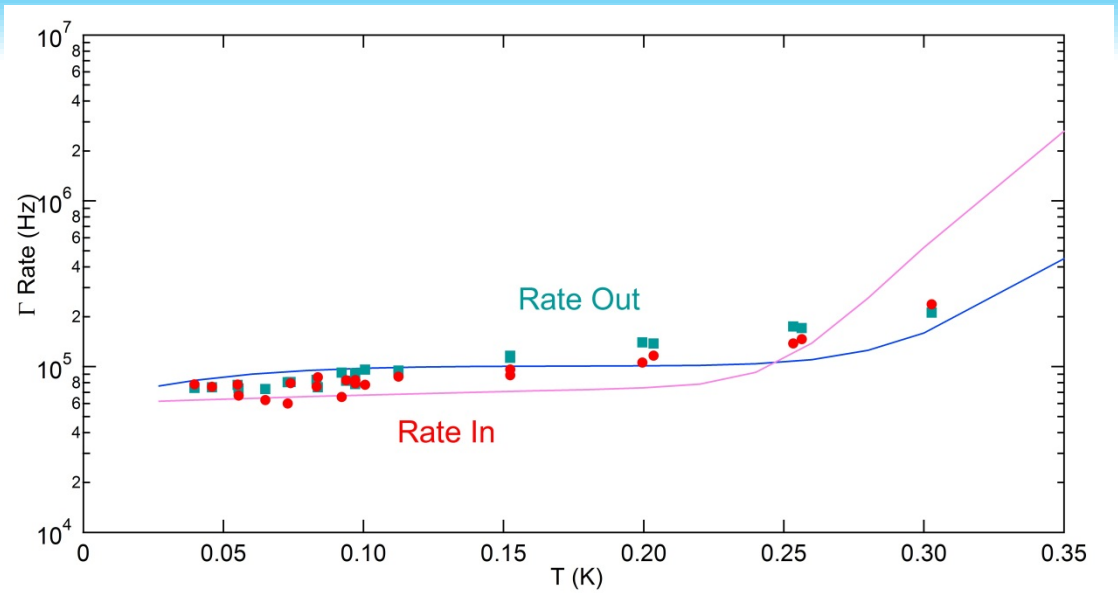
Dwell Time Histogram



- Tunneling rates comparable to measurement time $1/\Gamma_{DET}$
  - Apply procedure by Naaman and Aumentado -PRL **96**, 100201 (2006)
- Fit curves to:

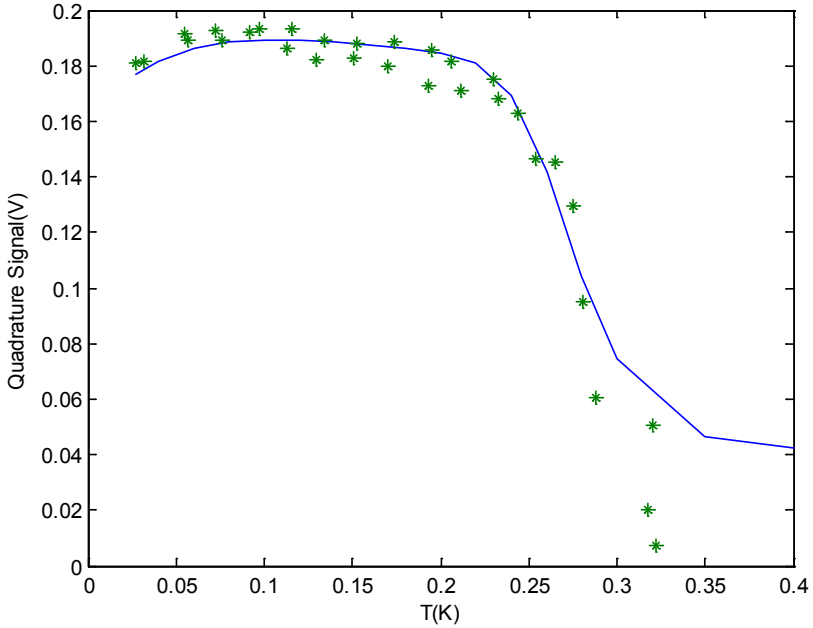
$$h \propto e^{-\frac{1}{2}\lambda t}\sinh\left(\frac{\theta t}{2}\right) \qquad \theta = \sqrt{\lambda^2 - 4\Gamma_{IN}\Gamma_{DET}} \qquad \lambda = \Gamma_{DET} + \Gamma_{IN} + \Gamma_{OUT}$$

Tunneling Rates – Sample Temp. Dep.

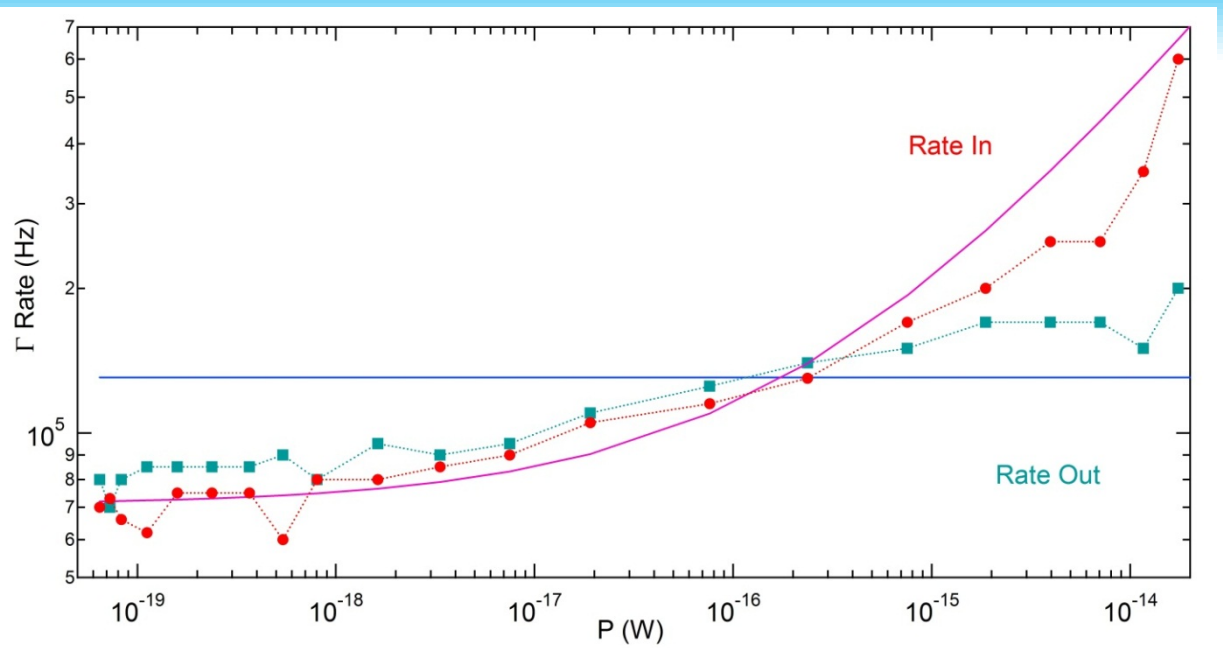


Fit:
Shaw et al. PRB **79** , 144511 (2009)

Γ_{in} yields this fit →



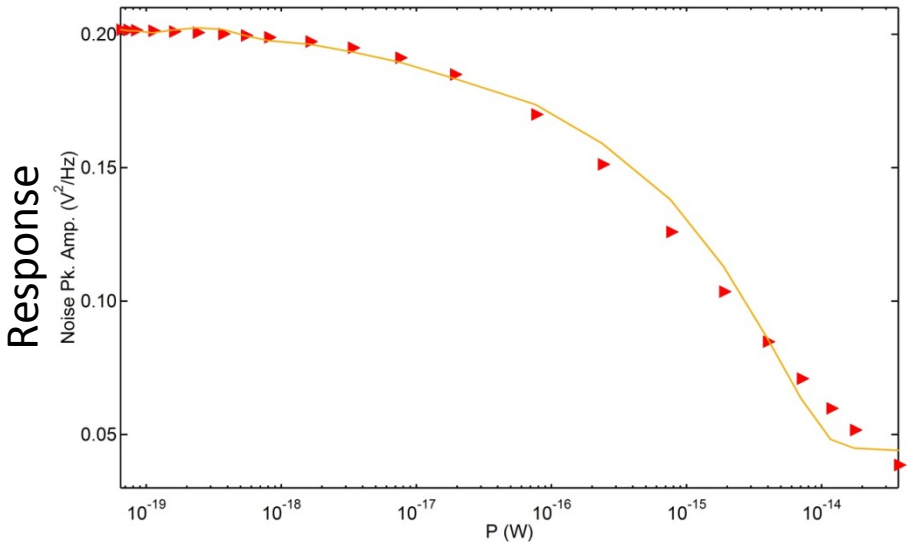
Tunneling Rates – Power Dep.



Fit:
Shaw et al. PRB **79** , 144511 (2009)

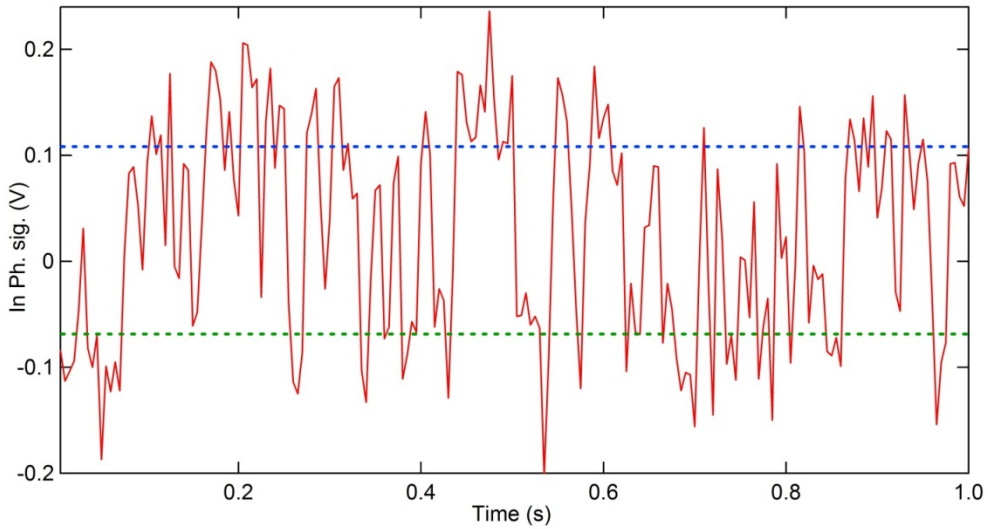
Γ_{in} yields this fit →

$$Response = \frac{\Gamma_{in}}{\Gamma_{in} + \Gamma_{out}} Amp.$$



Telegraph Noise

- Shows extent of quasiparticle poisoning
- Can be used to find Tunneling Rates
  - Double check and fit Response
- Physical understanding of detector

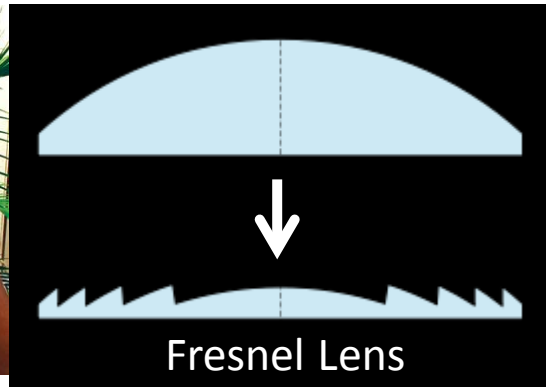


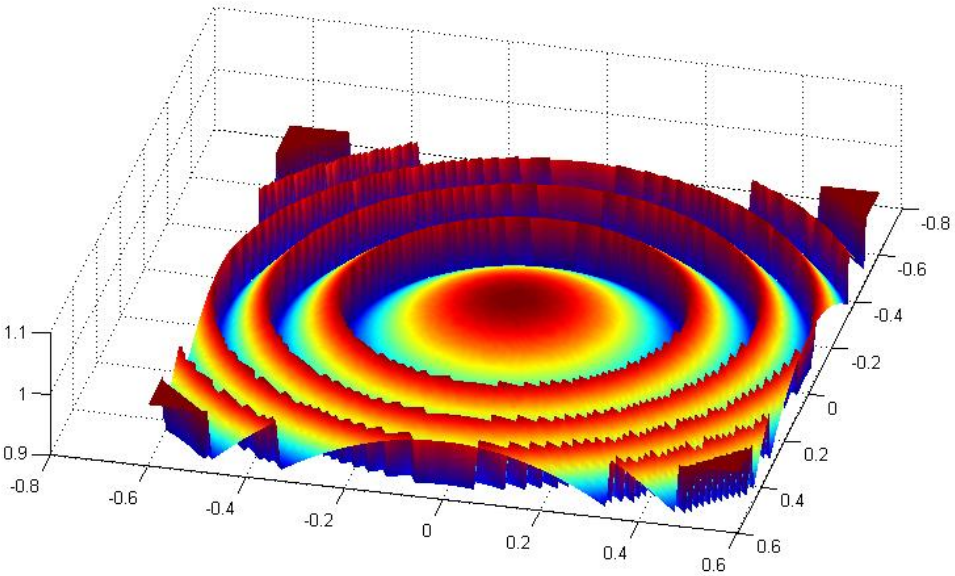
Outline

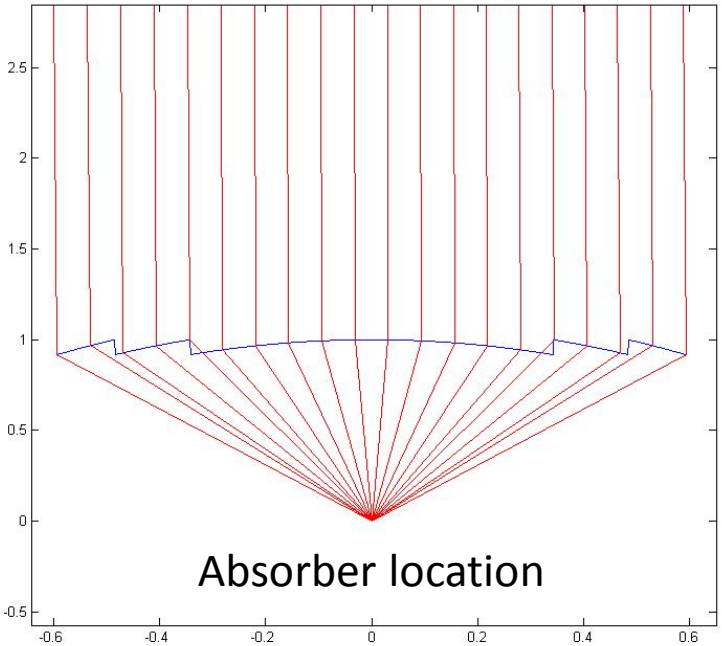
- Project Objectives
- Detector Concept
- Experimental Setup
- Noise
- Quantum Capacitance Results
- Current Work

Si Fresnel Lens

- Si Fresnel Lens
  - Compact way to make a lens
  - Fabricated at JPL
    - By ebeam lithography

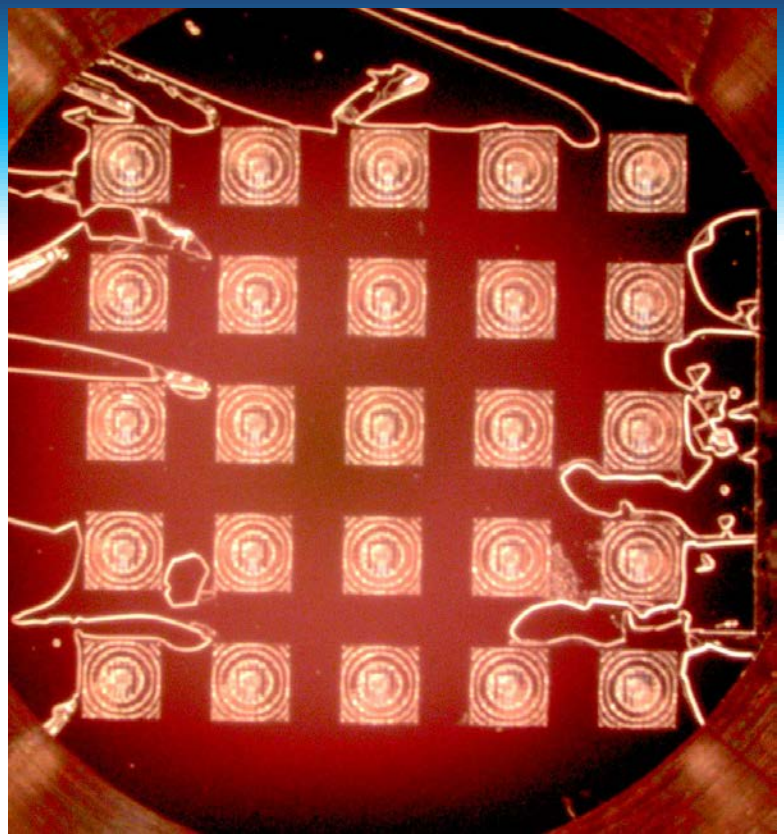


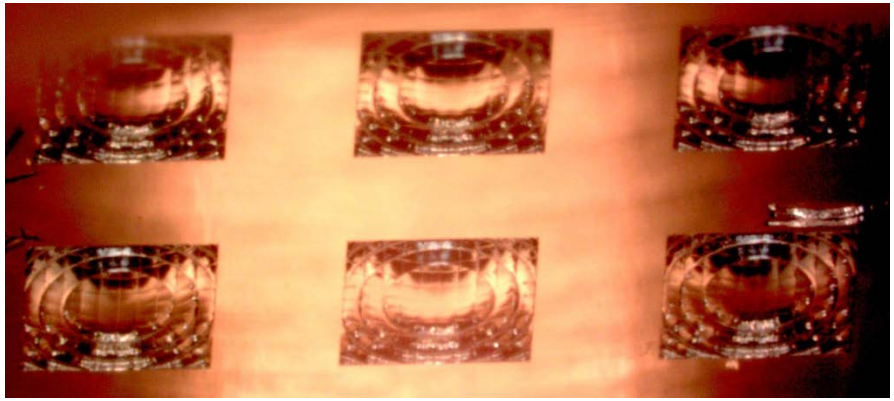


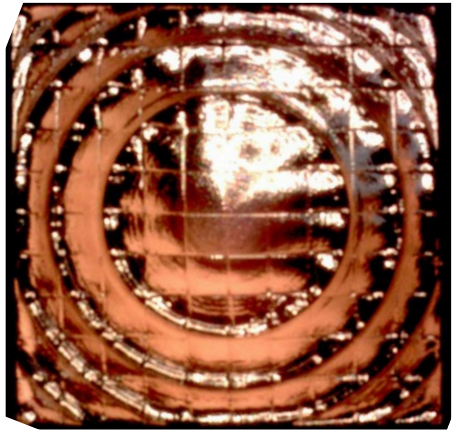


Scale-up: Fresnel Lens Array

- QCD array is aligned/mounted to Fresnel Lens array
  - Each lens is focused onto each QCD antenna
  - Illuminates all pixels
  - Can scale with QCD Array
    - Limited by resonator size

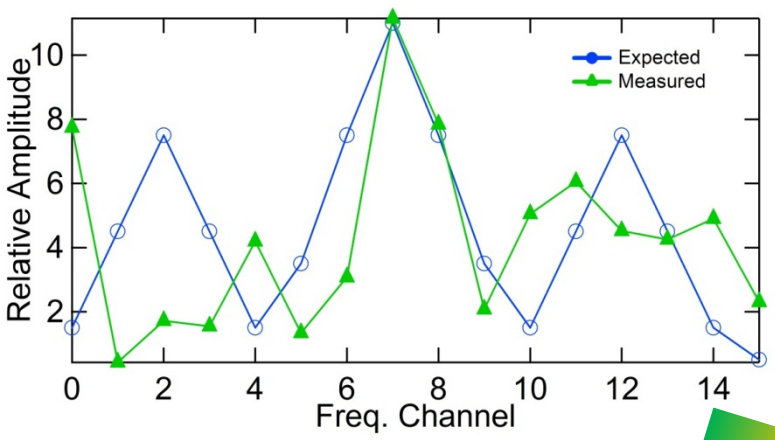


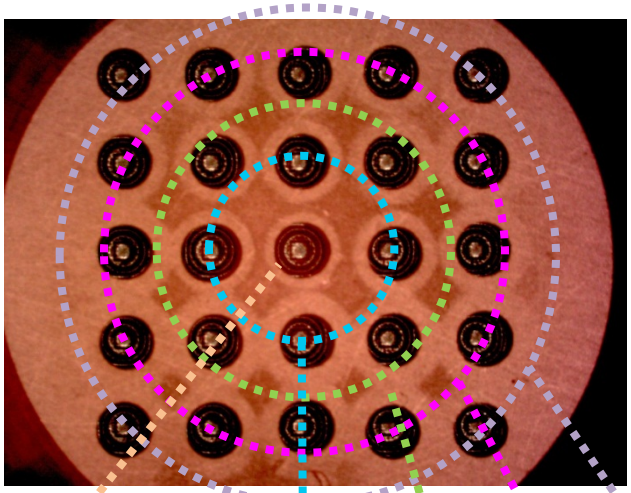


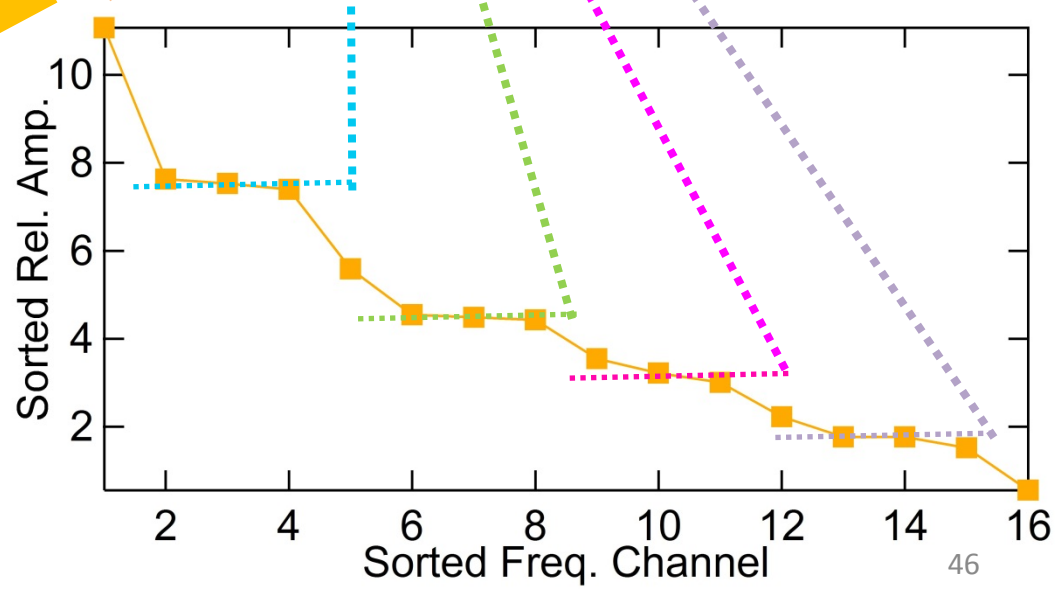


1.2mm

Signal Amplitude Distribution

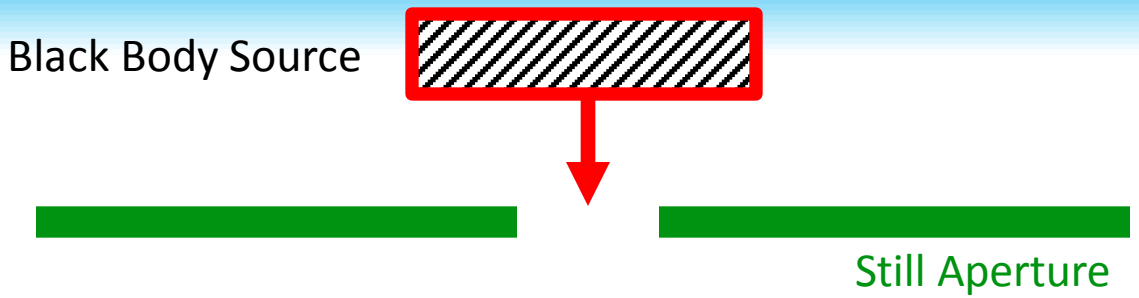






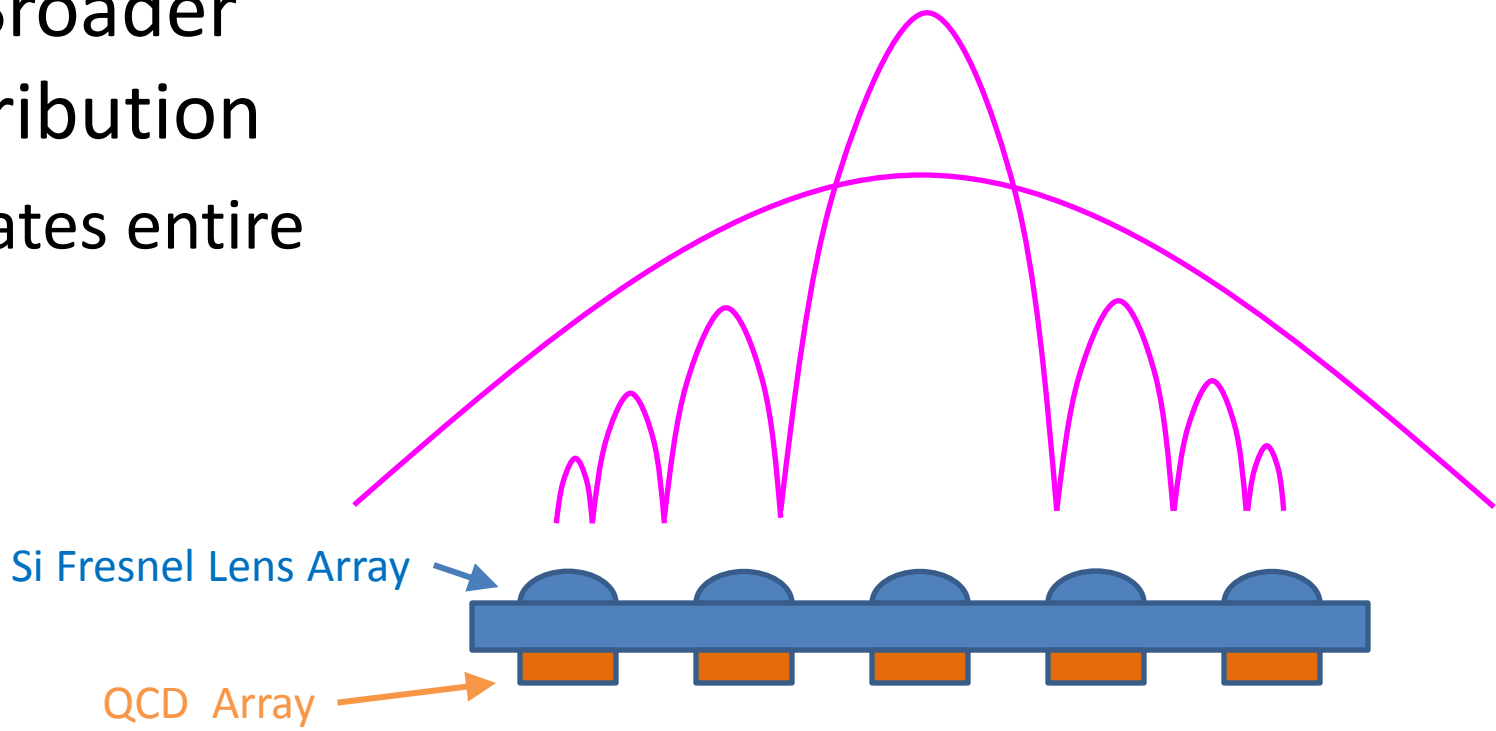
- Steps in the relative amplitude from 2mm still aperture.

Aperture Adjustments



Smaller Aperture/Broader power distribution

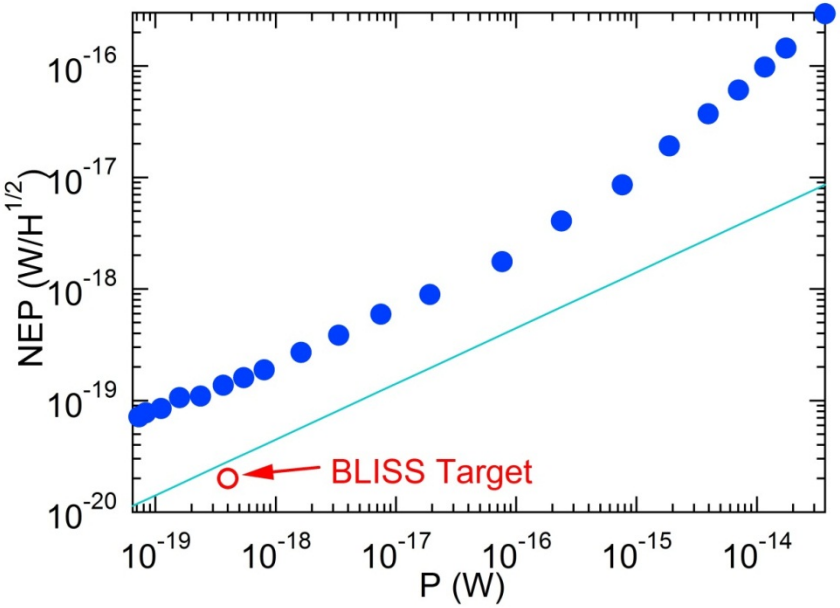
- Illuminates entire array



Conclusion

Quantum Capacitance Detector

- Optimal operating temperature ≈ 85-90mK
- Current Cutting Edge
  - NEP ≈ 7×10^{-20} W/Hz$^{1/2}$ at 9×10^{-20} W (200μm)
- Telegraph Signal
  - Can find power dependence of Γ_{in} and Γ_{out}
    - Fits to Response data very well
- Current work
  - Fresnel lens array
  - Optimizing detector design



Applied Physics Letters 100, 263509 (2012)

Acknowledgements

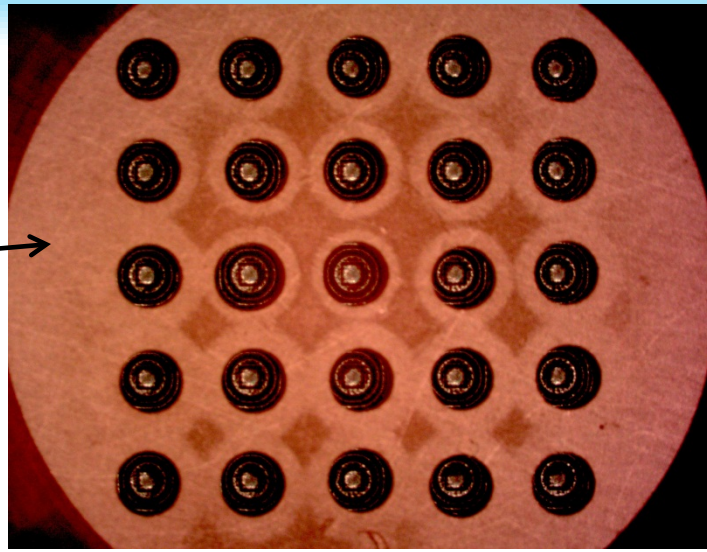
- Dr. Pierre Echternach
- Richard Muller
- Dr. Jon Kawamura
- Dr. Andrew Beyer
- Mike Lee
- Dr. Matt Shaw
- Dr. Chris McKenney
- Dr. Morgan Cable
- Dr. Amanda Stockton

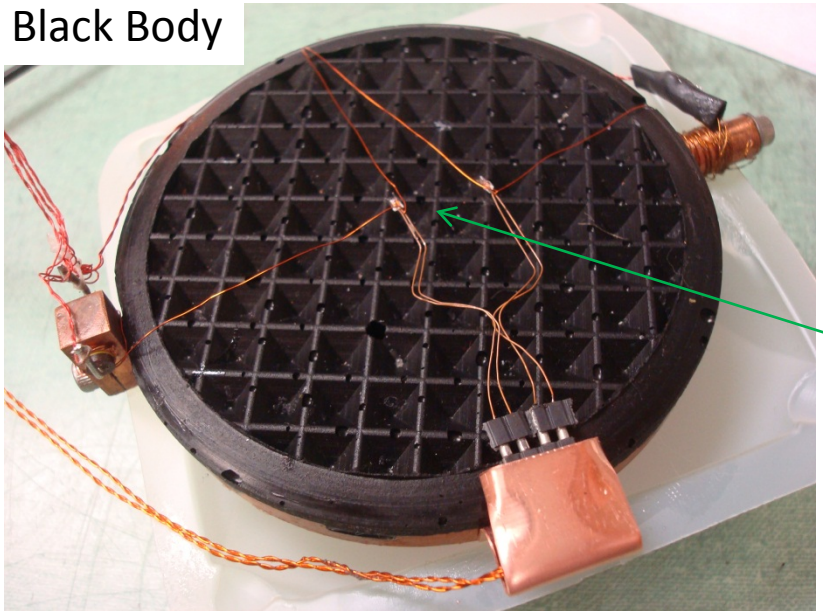
- Everyone in the Superconducting group in MDL
- University Research Affairs and the JPL Postdoc Office

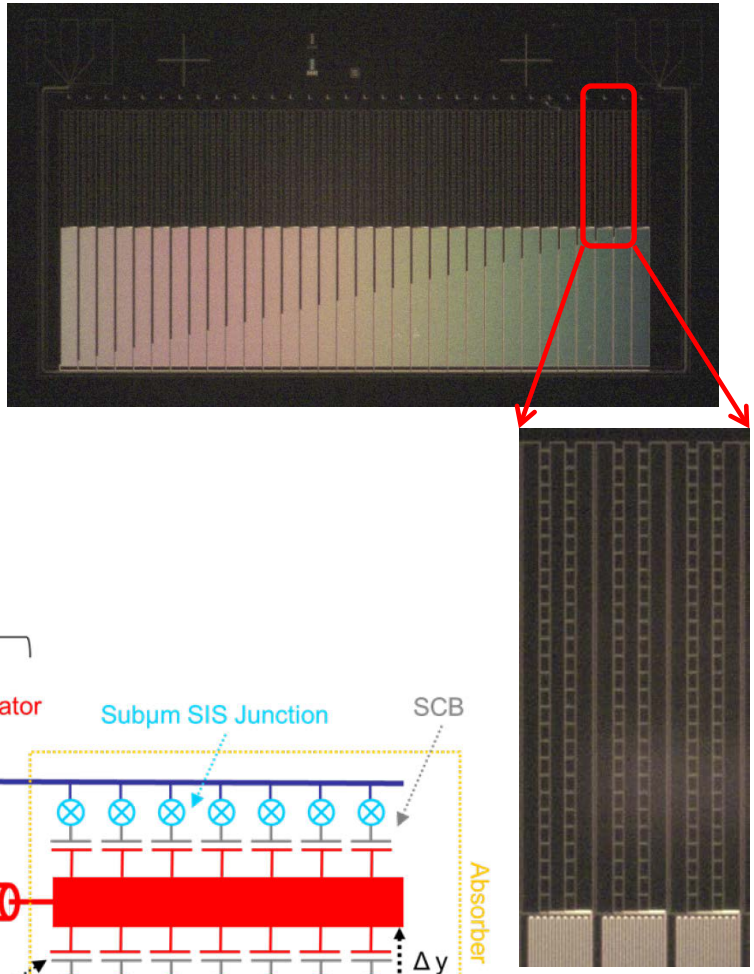
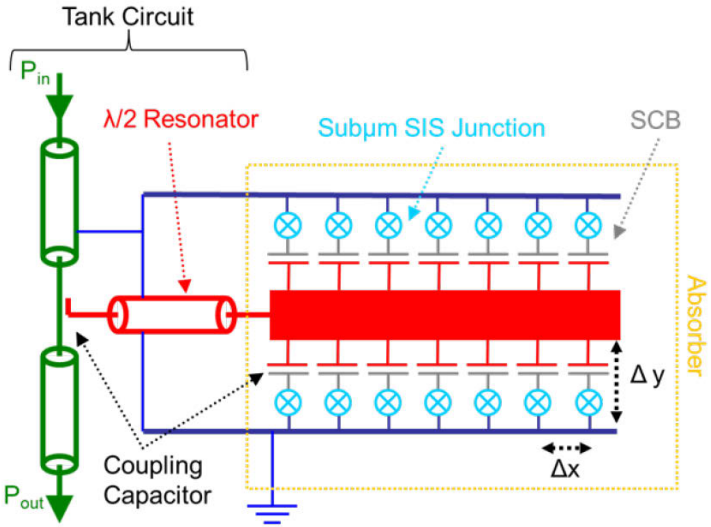
Thank you

Future Steps

- Test new geometries
  - Copper aperture array
  - Large BB and Still Aperture
- Pulsed Single Filament Black Body Source
  - Quicker response





Future Steps - Spectroscopy

- New design - Spectroscopy
  - Detector density will maximize detector absorption by approximating an index of refraction-matched thin film.
  - Similar advantages to current QCD design
    - Frequency multiplexing
    - Sensitivity
  - Added advantage
    - Higher absorption rate
    - SCB/SIS redundancy
- Able to close the gap in the long-wavelength bandwidth of current detectors.