SQUATs* for single THz photon sensing with BREAD and other activities at SLAC

*Superconducting Quasiparticle-Amplifying Transmons

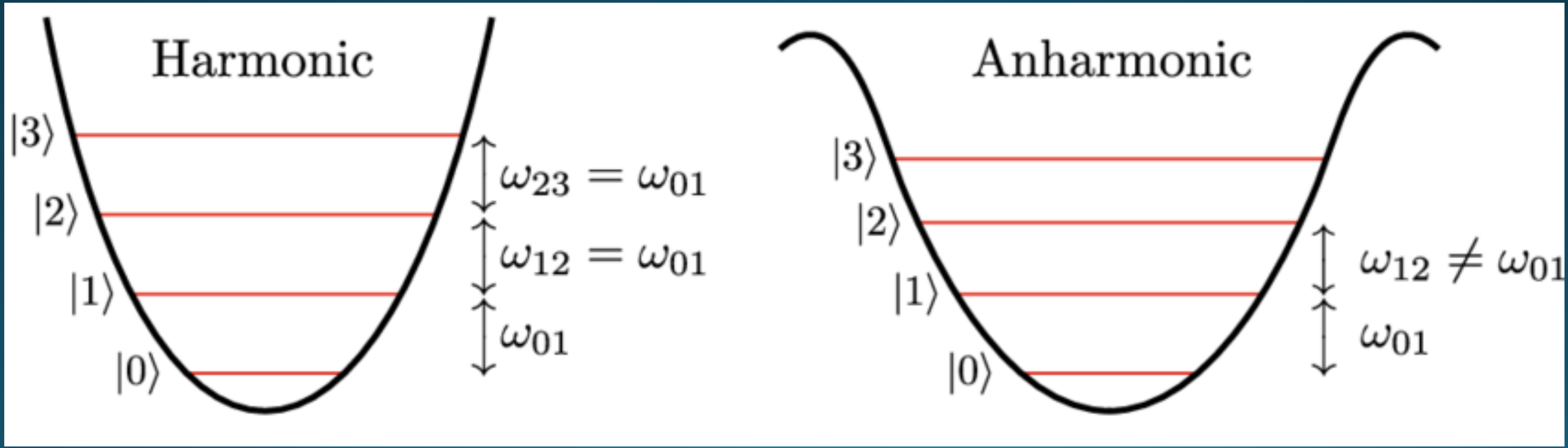
Chiara P. Salemi
Stanford University and SLAC
BREAD Collaboration Meeting, October 2023

Agenda

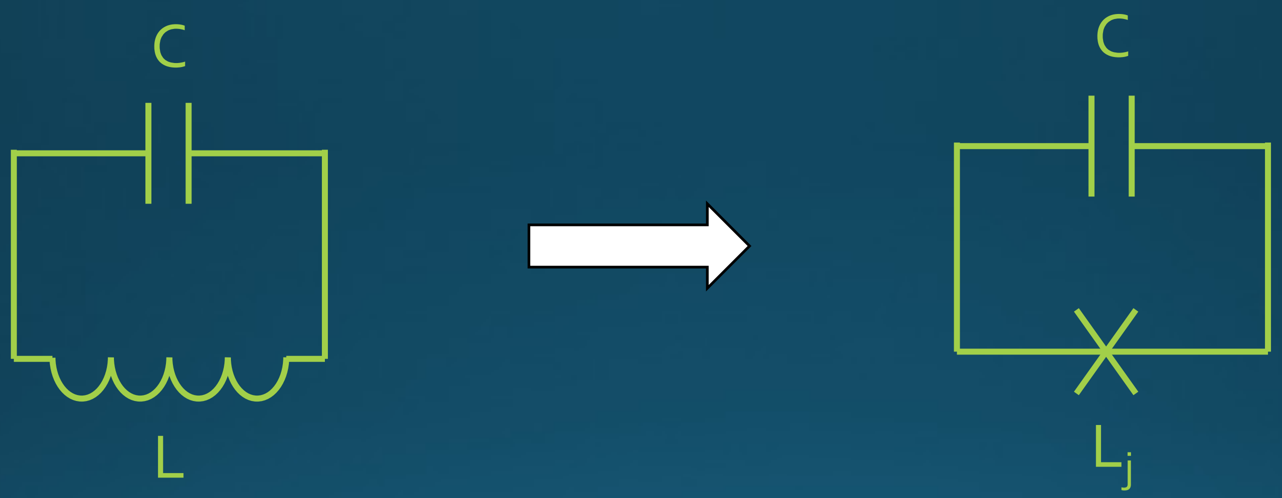
- What is a SQUAT?
  - Qubits
  - Qubits for photon sensing
  - Use in TeraBREAD
- Activities at SLAC (current status + future)
  - SQUATs, EM simulations, calibration

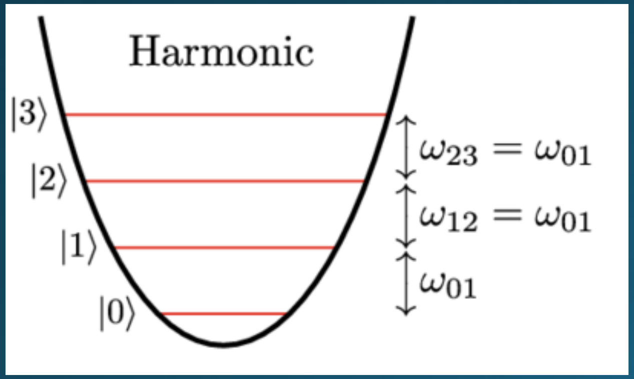
What is a qubit? (theory)

- Anharmonic oscillator
  - Unequal level spacings
  - Ignore everything above the first excited state
  - Treat as a two-level system:
    - |0> and |1>

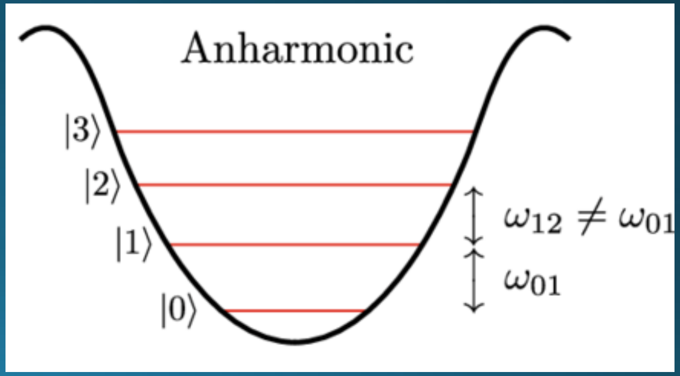


What does a superconducting qubit look like?





*Properties determined by charging energy (E_c) and Josephson energy (E_j)



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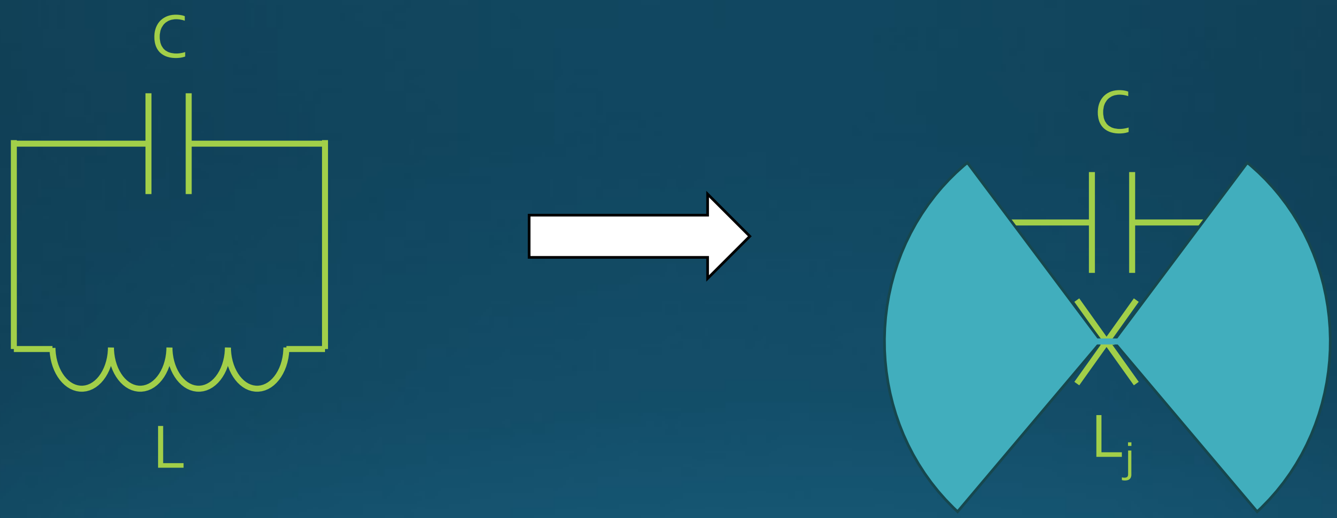

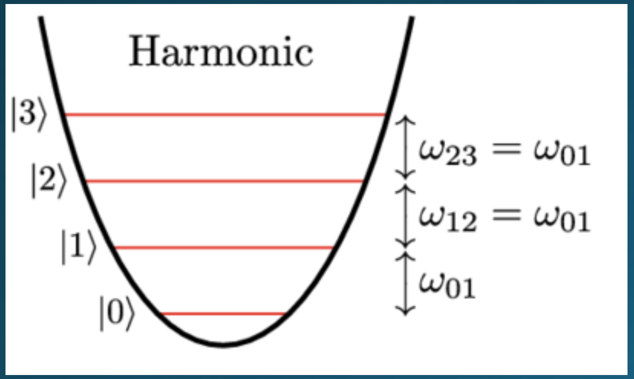

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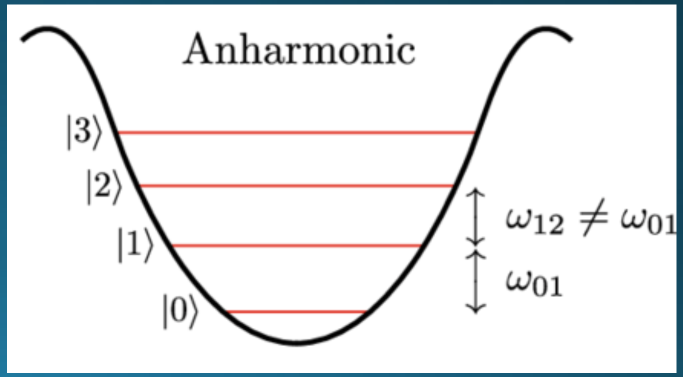
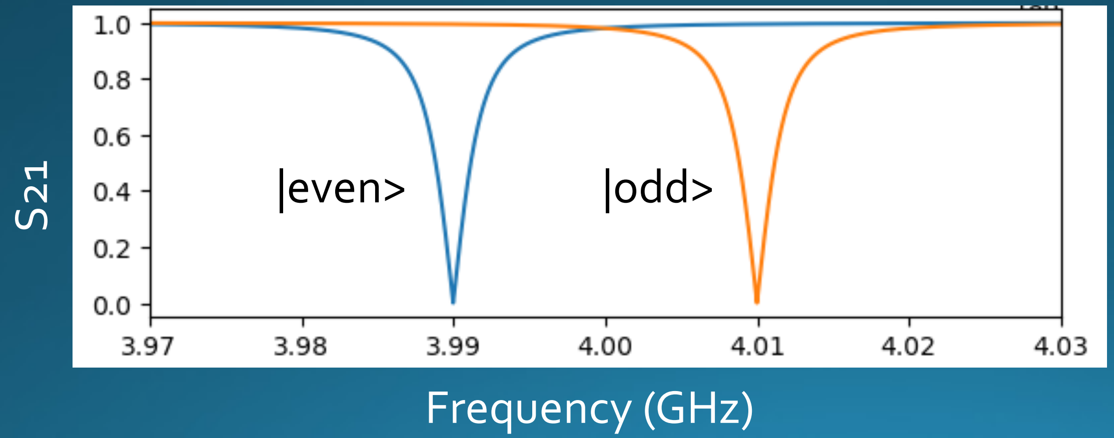


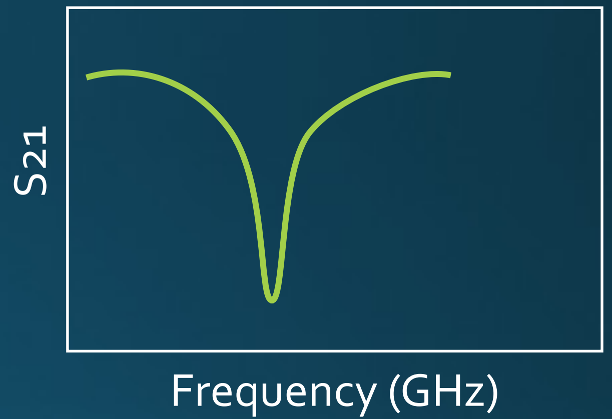
Qubits for computing vs. for particle detection

- For computing, need coherence – the state needs to stay put long enough to do a calculation!
- Quasiparticles tunneling across junction moves the energy levels and destroys coherence
- Energy depositions create quasiparticles
- Use qubits to detect energy depositions!



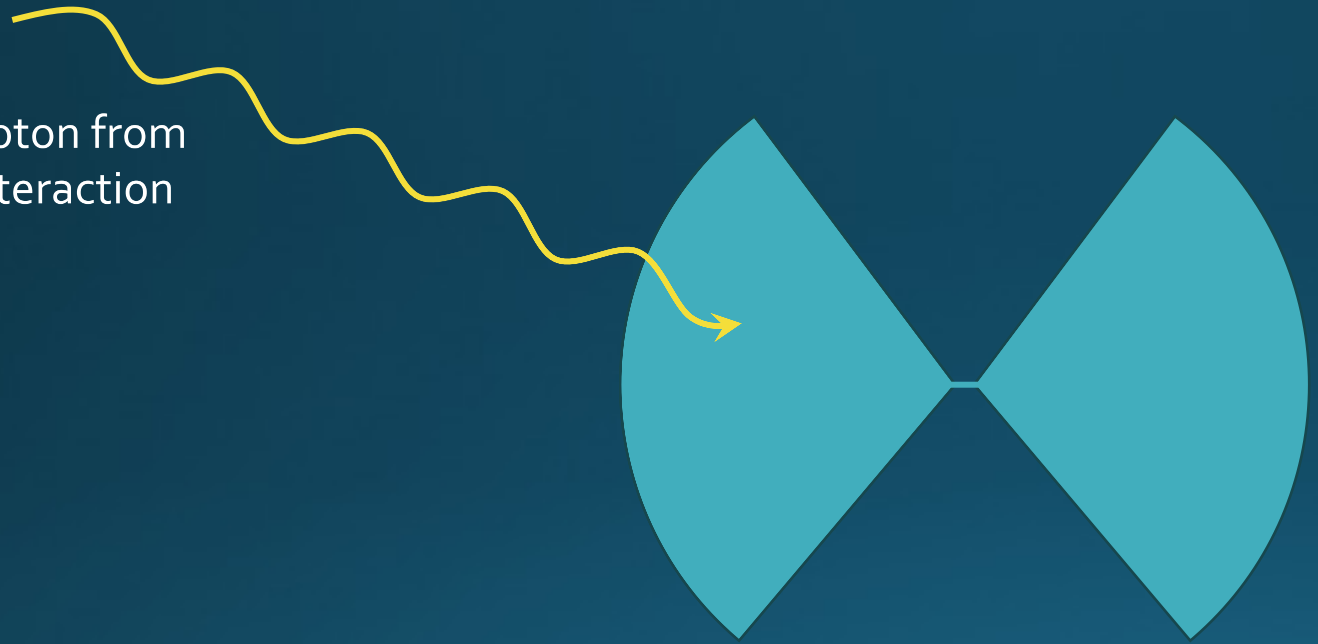
Signal pathway

(0) observe qubit resonance by injecting signals down a feedline that is coupled to the qubit



Signal pathway

(1) photon from
DM interaction



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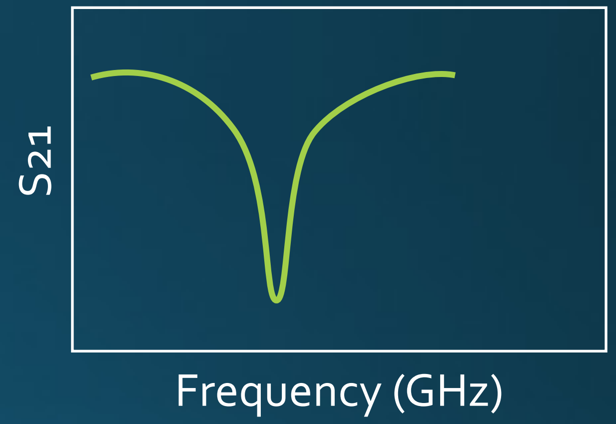

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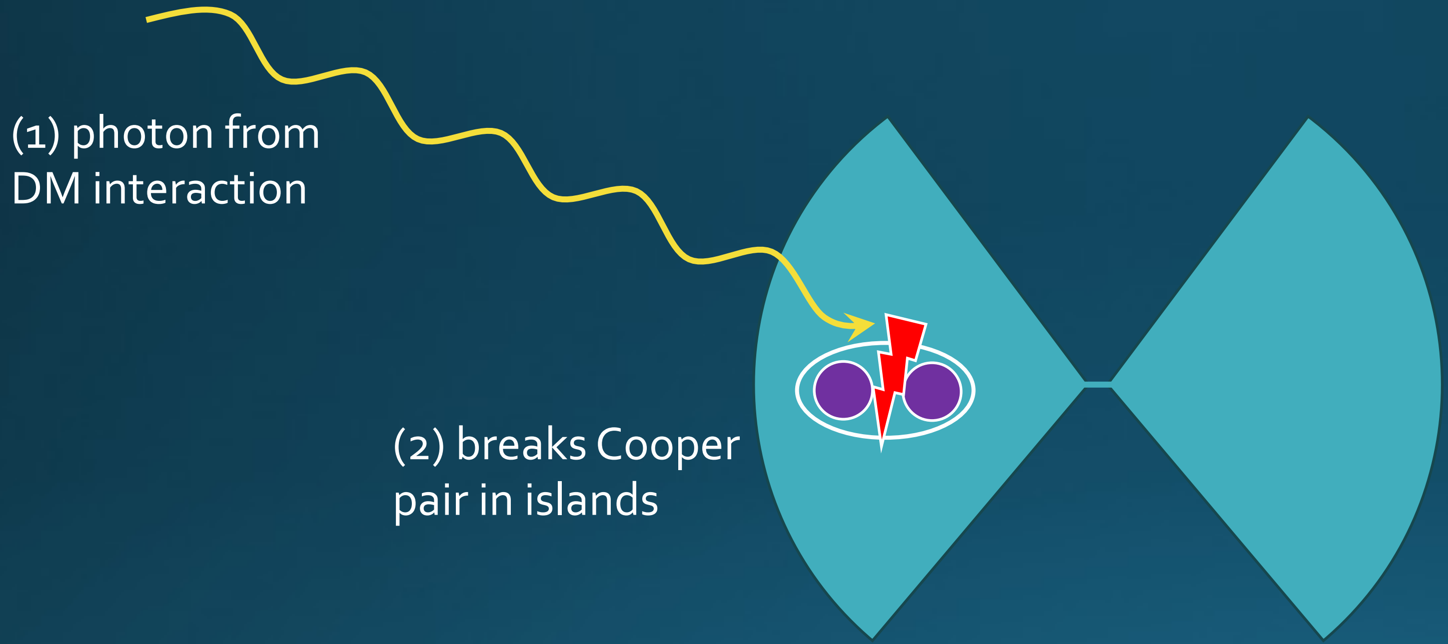

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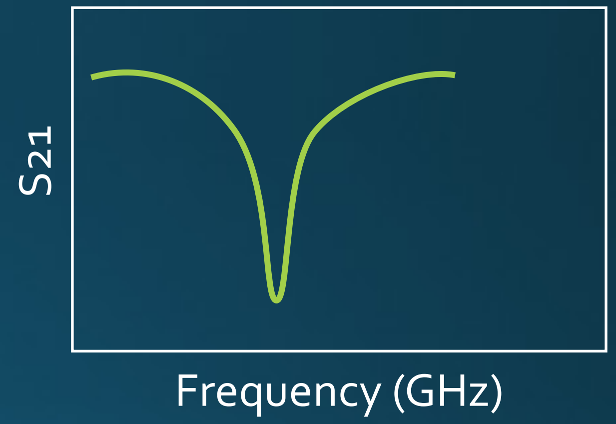
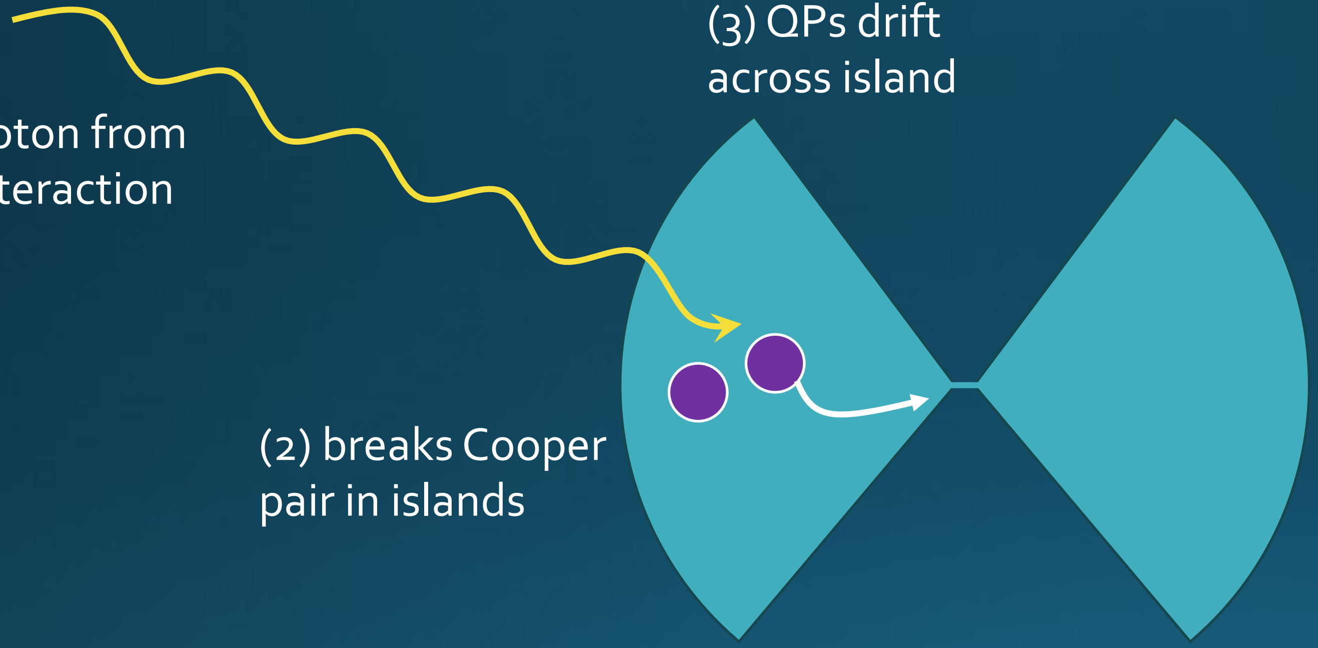


Signal pathway

(1) photon from DM interaction

(3) QPs drift across island



(2) breaks Cooper pair in islands

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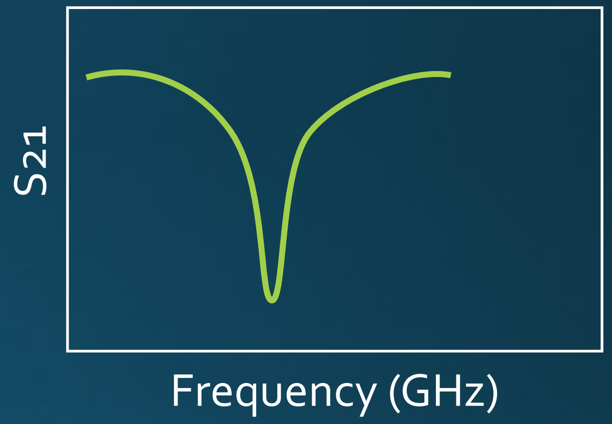

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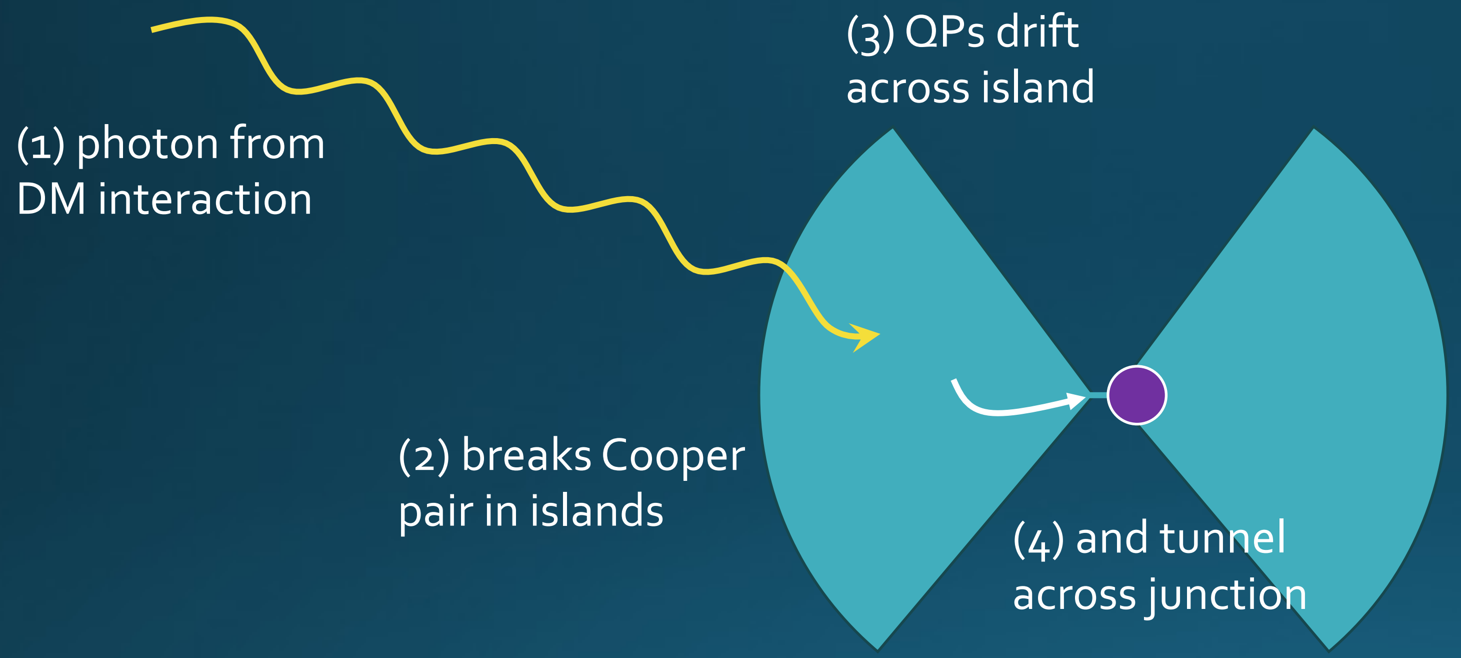
Signal pathway



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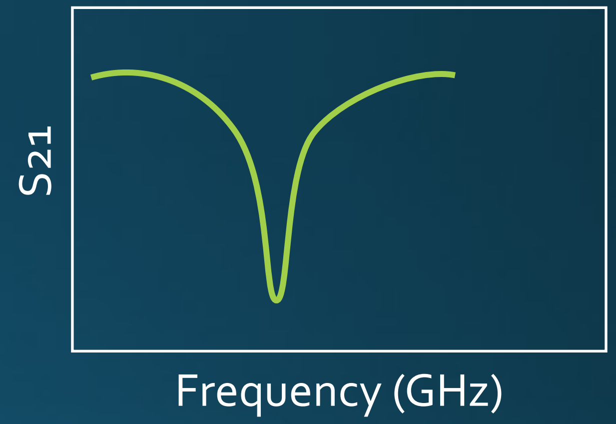

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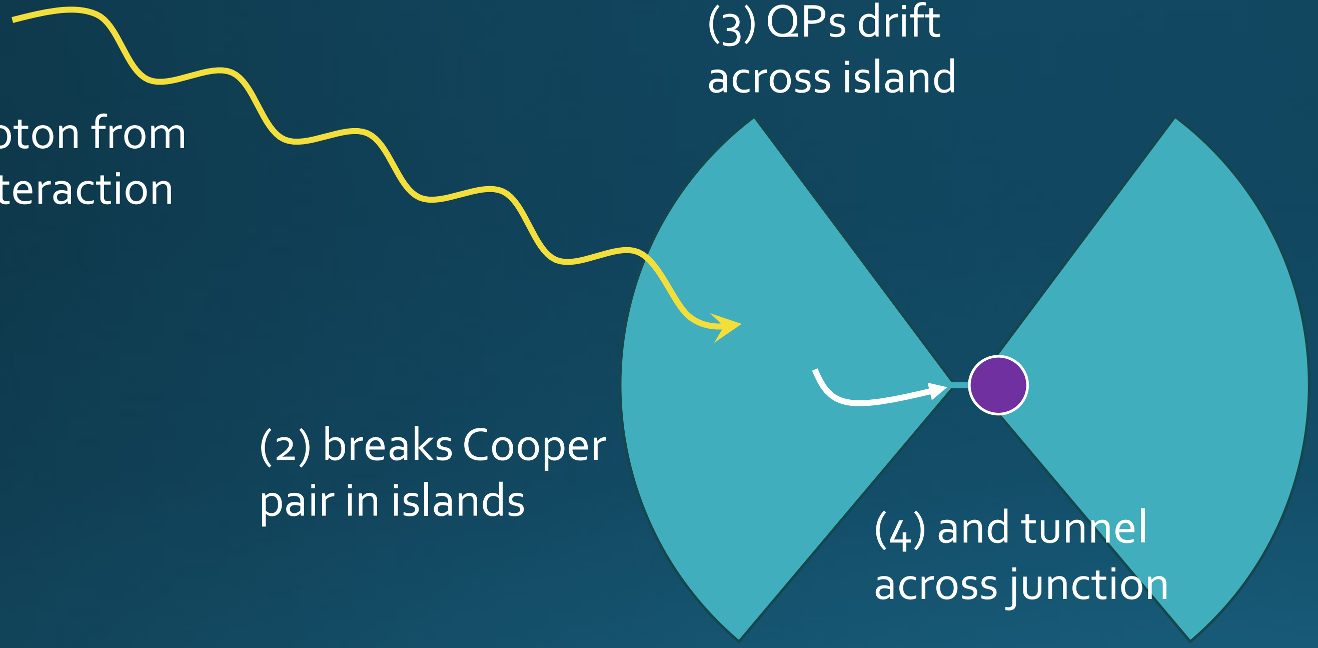

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(5) resonance shifts as qubit parity swaps

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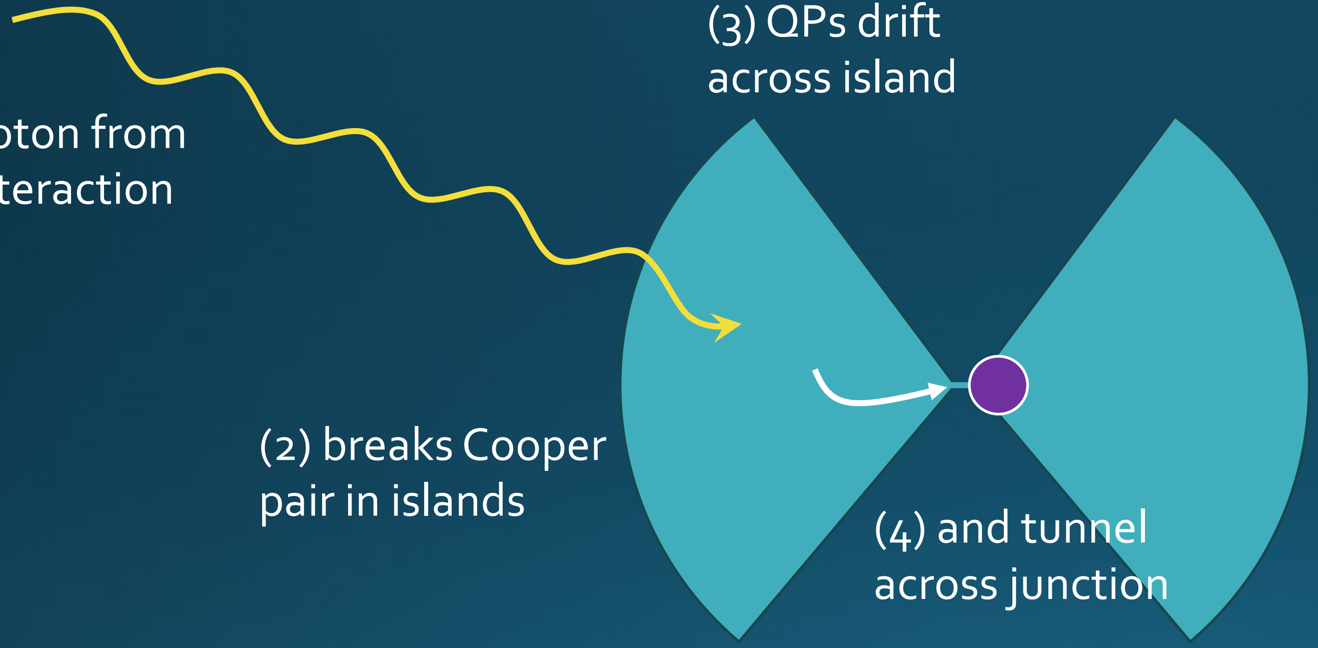

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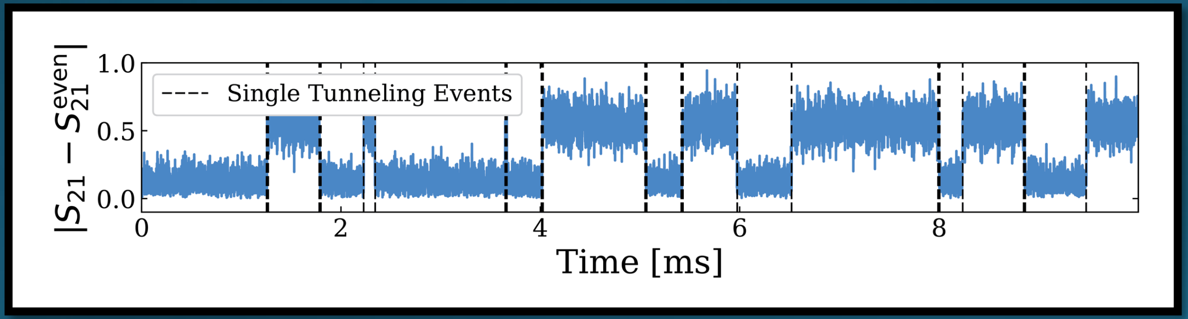

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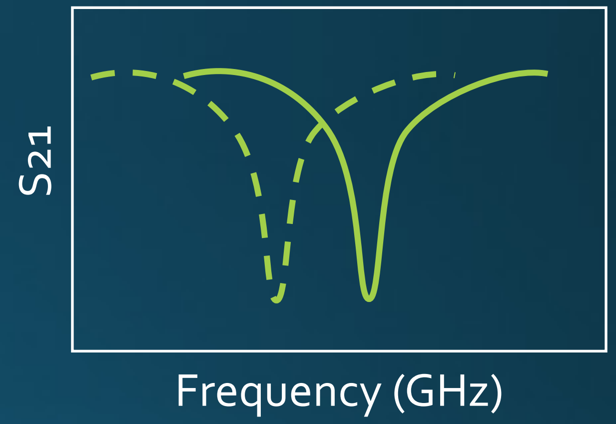

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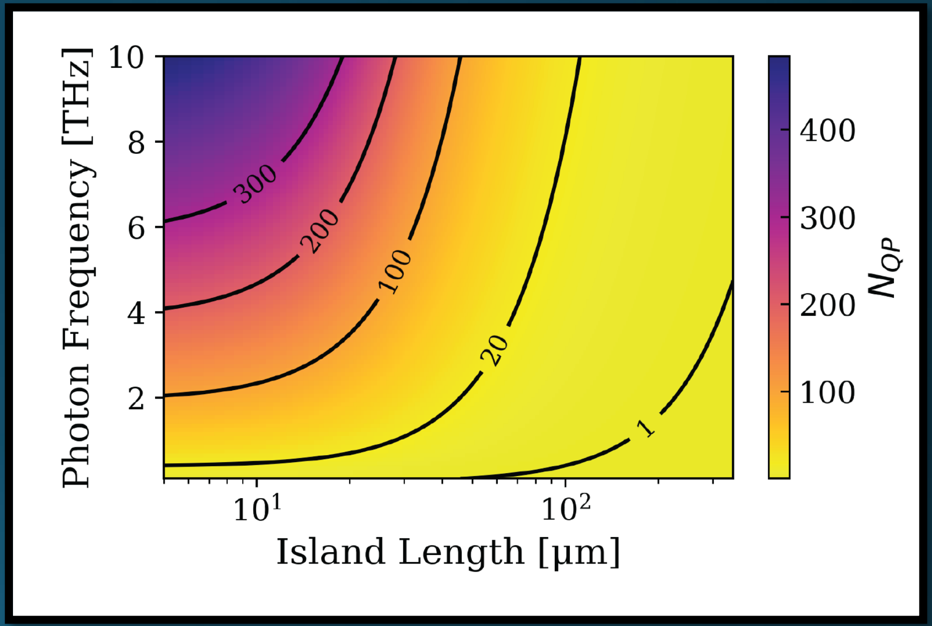
Advantages for BREAD

- Excellent energy sensitivity
  - (Sub-)THz photons
  - meV phonons



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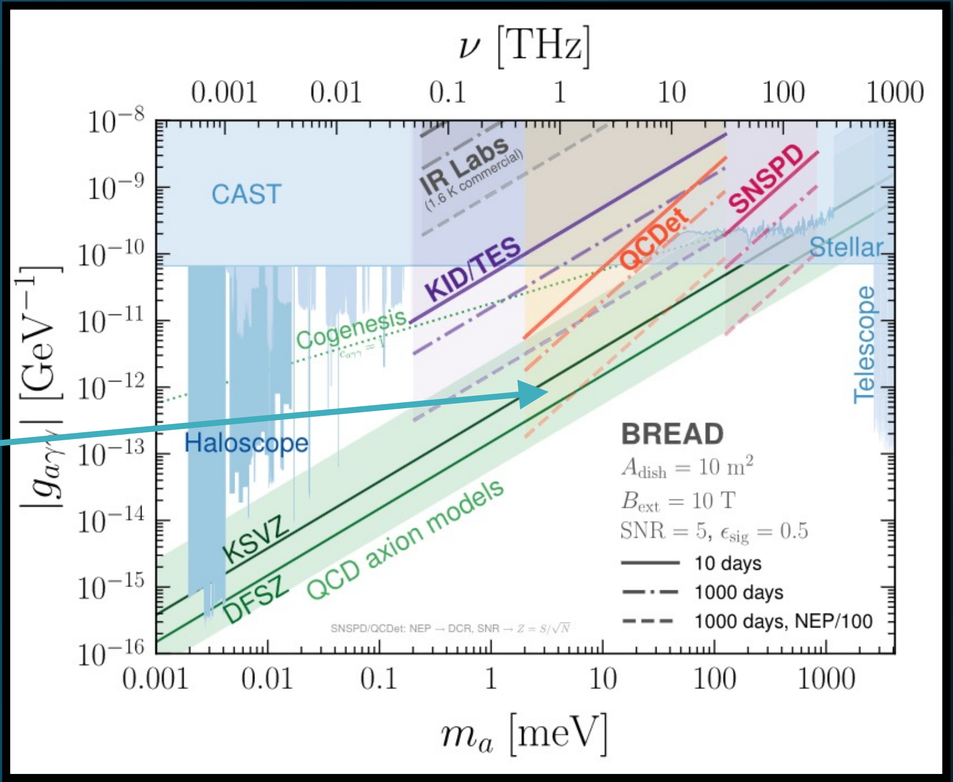

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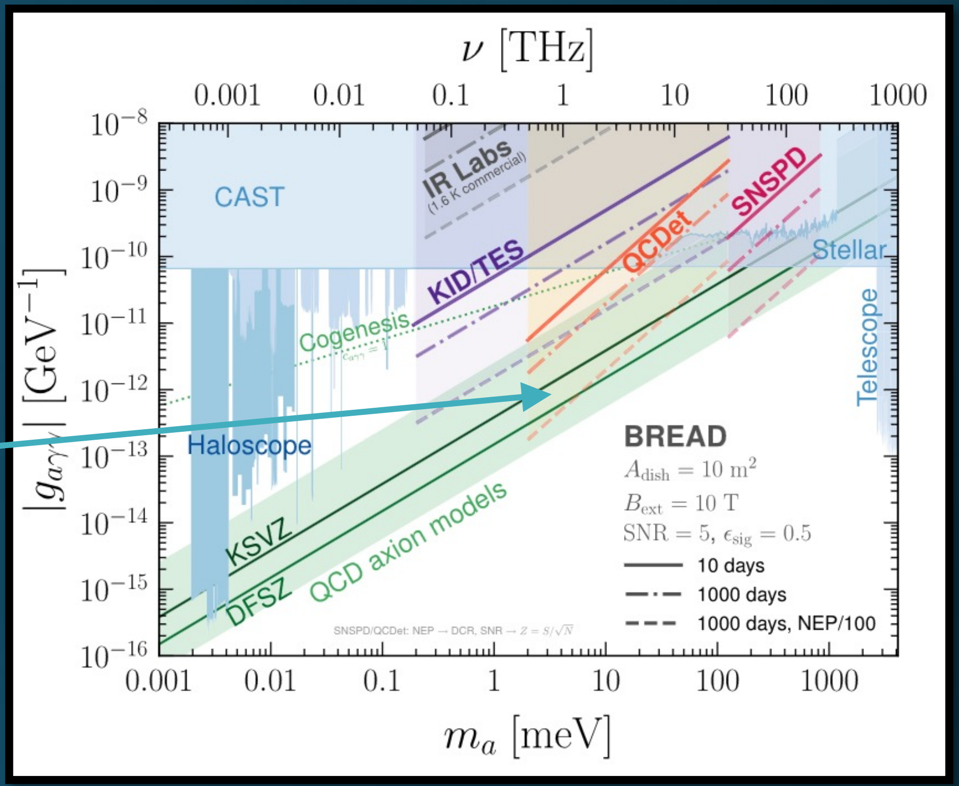

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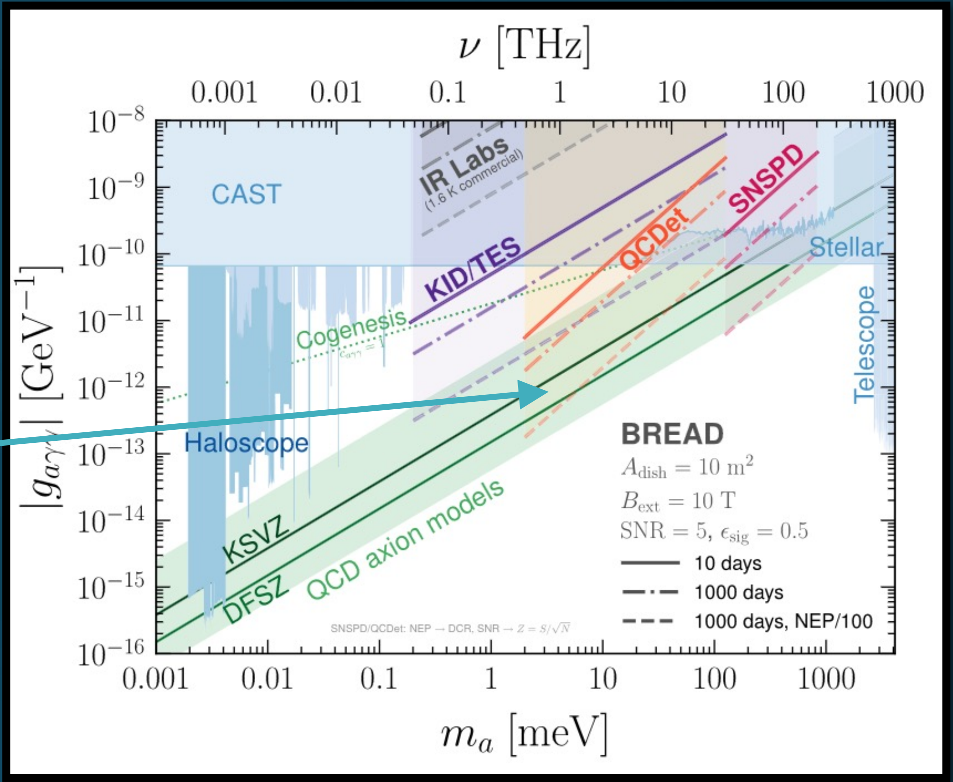

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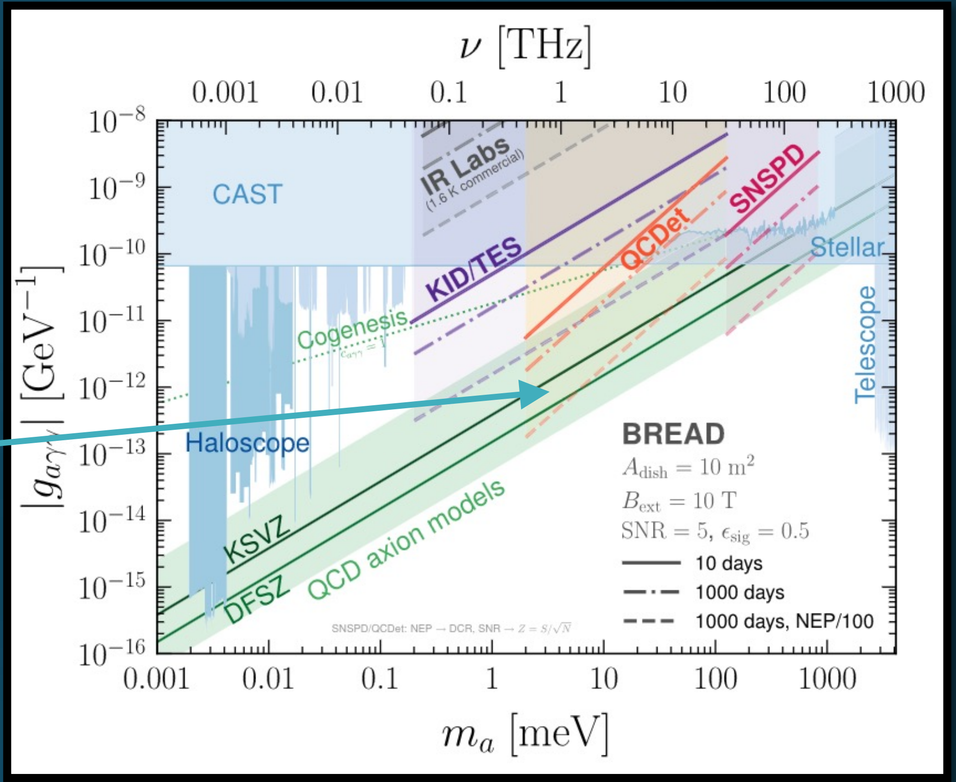

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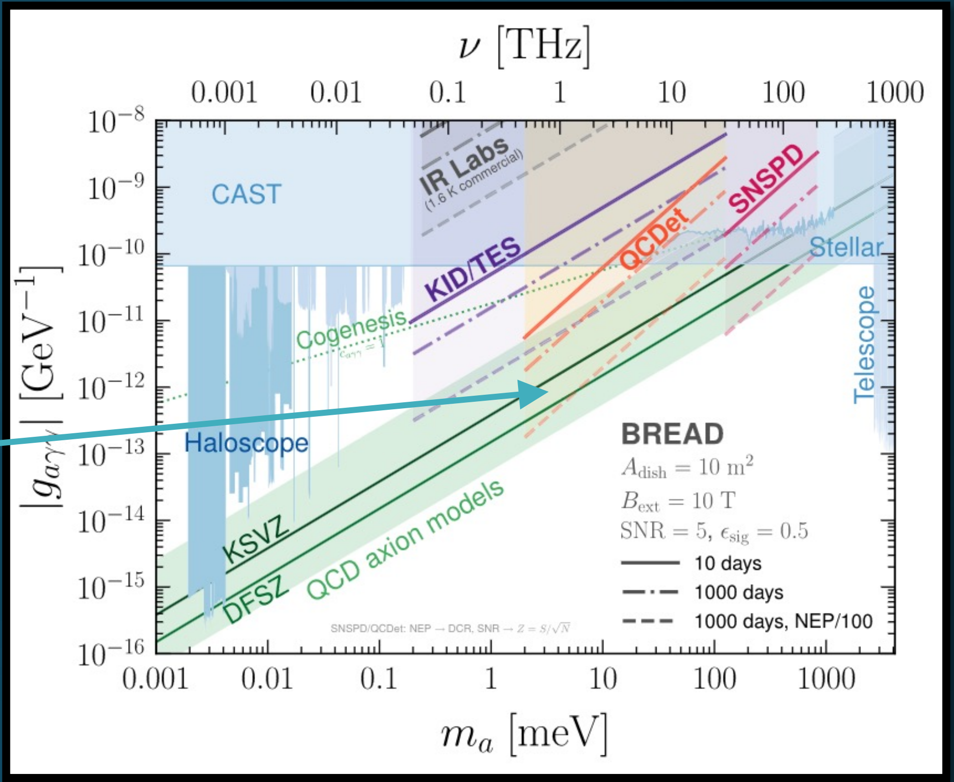

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- Design paper out on the arxiv as of Monday! First devices fabbed at Stanford and being packaged this week → arxiv: 2310.01345

Activities at SLAC

SQUATs

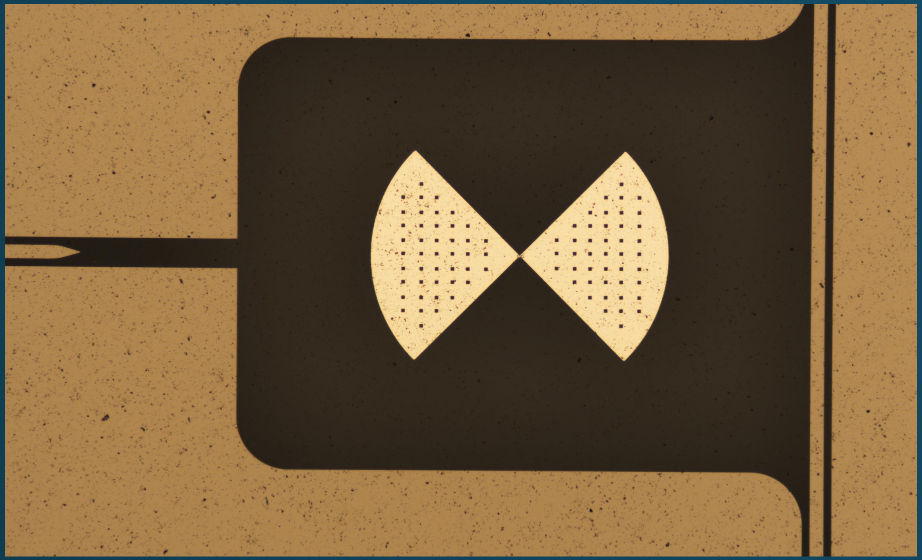
- Fabrication and testing of initial devices (ongoing)
- Understanding our readout
- Iteration on design
- Noise mitigation

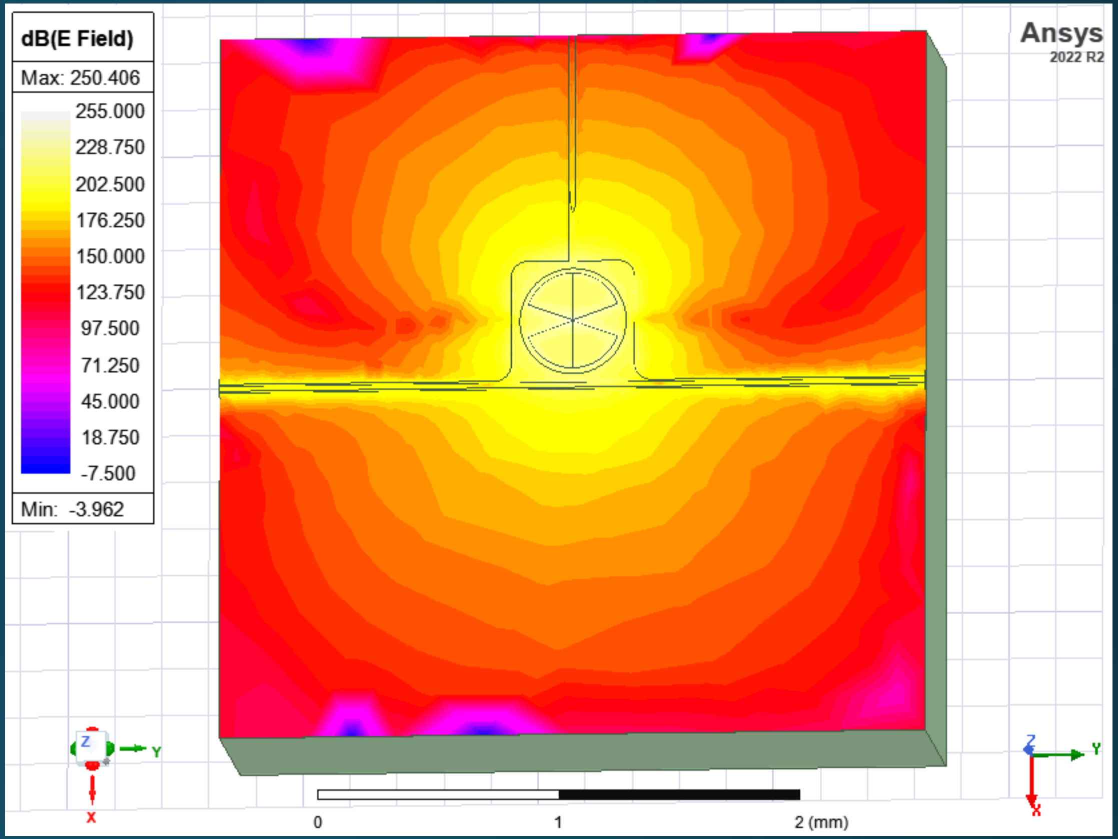
Team @ SLAC:

- PIs:
  - Noah Kurinsky
  - Dave Schuster
- Postdoc:
  - Chiara Salemi (device design, testing)
- Grad students:
  - Jadyn Anczarski (fabrication)
  - Aviv Simchony (housing design, testing)
  - Zoe Smith (housing design, testing, fabrication)
  - Taj Dyson (readout chain)
  - Hannah Magoon (rotation fall/winter 2023) (readout chain, testing)
- Post-bac:
  - Noshin Tabassum (fabrication, testing)

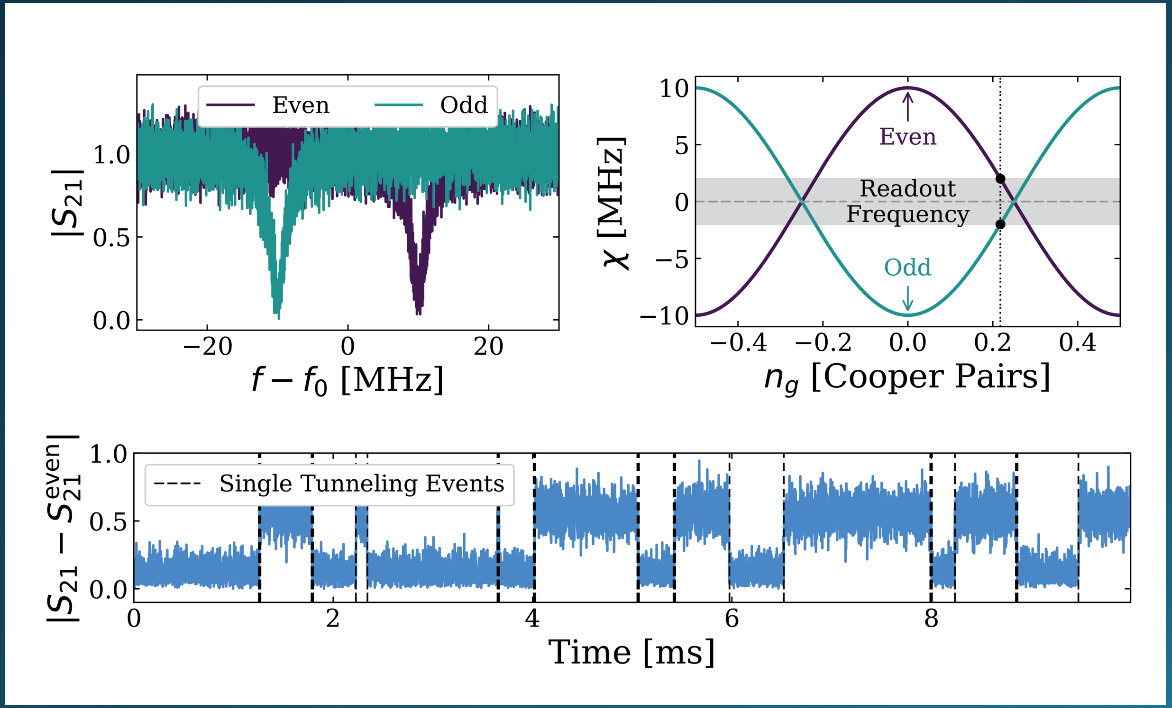
+ Caleb Fink, postdoc @ LANL

Microscope photo of recently fabbed SQUAT (Anczarski)





HFSS simulation of qubit resonance used to tune device parameters (Salemi)



Simulated events in SQUAT for optimizing readout parameters (Kurinsky)

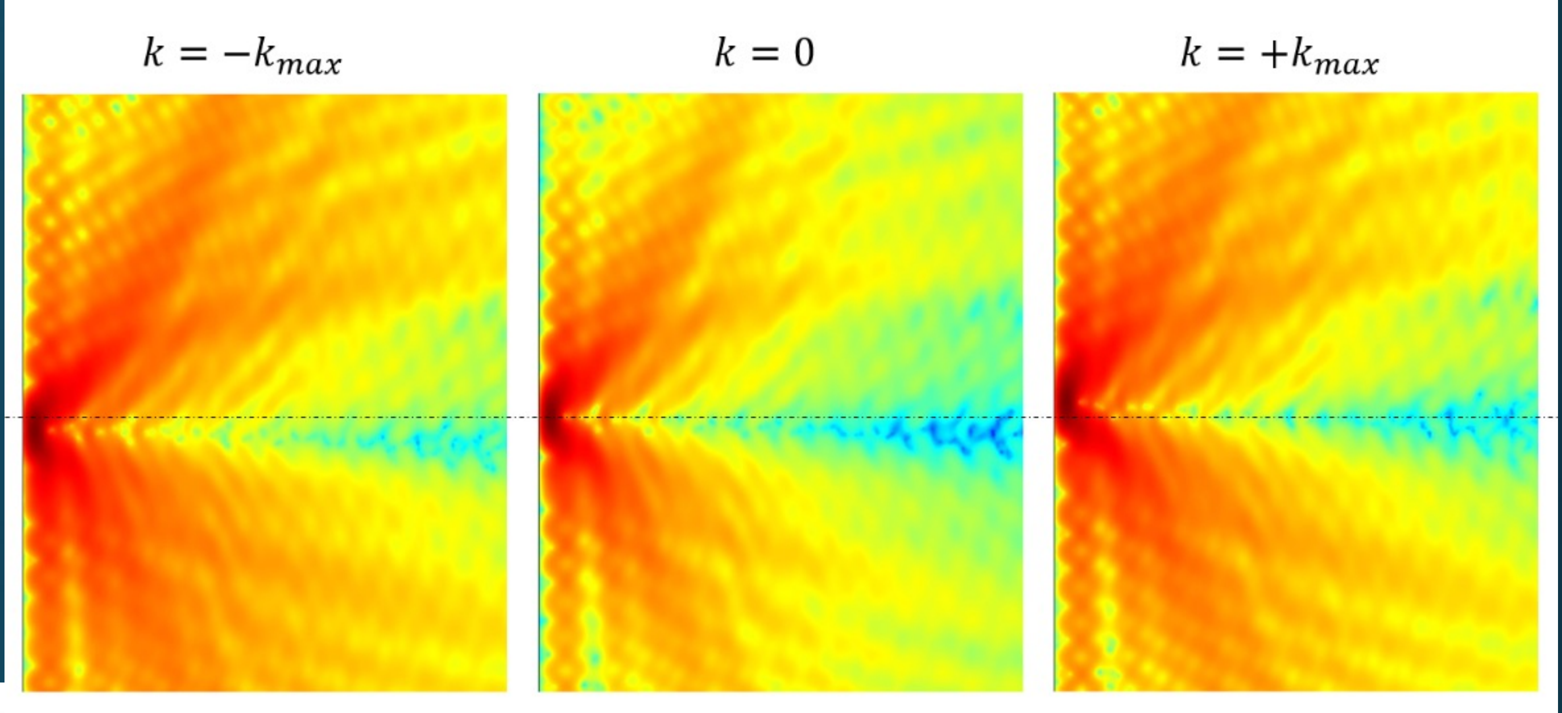
TeraBREAD EM simulations and design

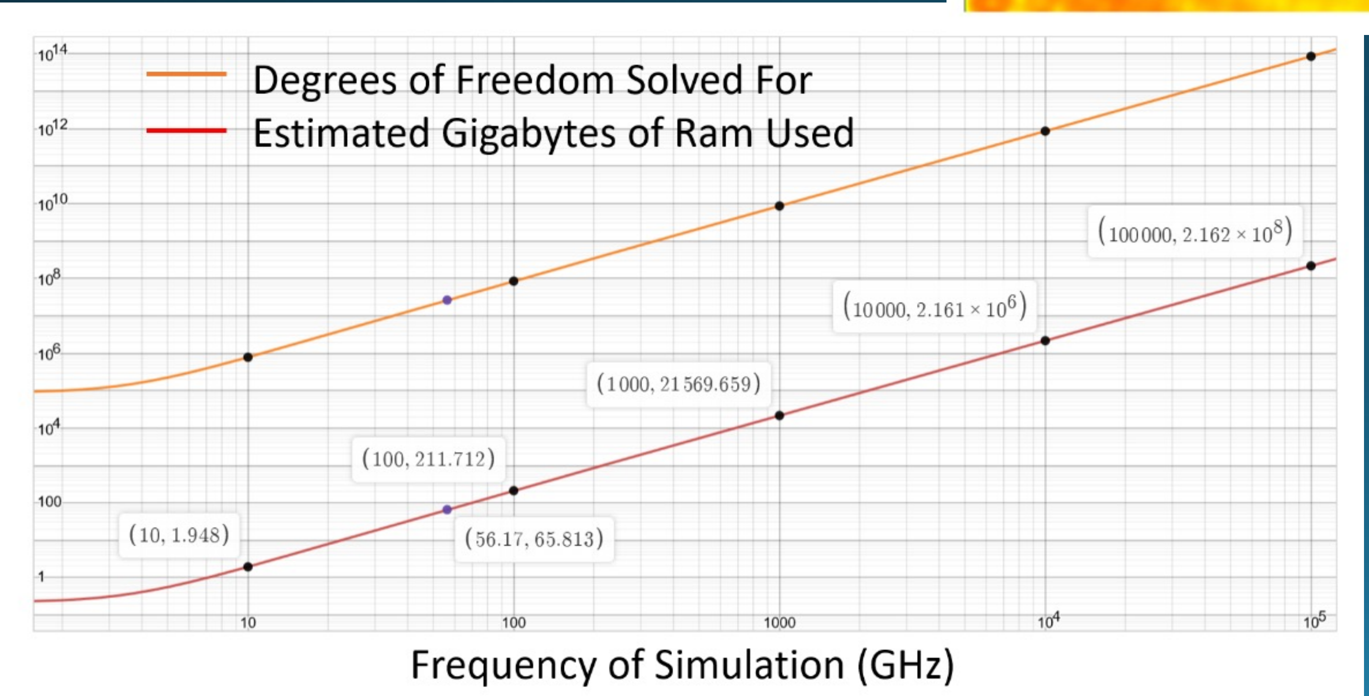
- COMSOL simulations for frequencies approaching intermediate THz regime (ongoing)
- Simulations and design of TeraBREAD optics

Team @ SLAC:

- PI:
  - Noah Kurinsky
- Postdoc:
  - Chiara Salemi
- Grad student (rotation fall 2023):
  - Dhruv Tandon
- SULI undergrad (summer 2023):
  - Lionel Whitehead

Motion of focal spot with changing axion velocity for λ_{deB}~10d (Whitehead)





Estimated memory resources needed to simulate reflector geometry for THz regime (Whitehead)

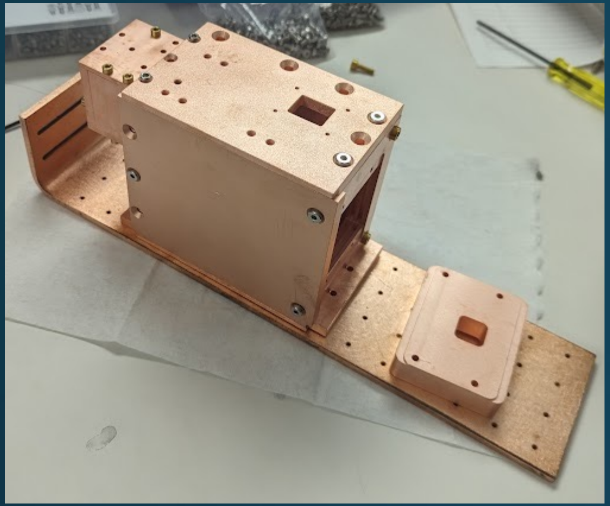
Device calibration

MEMS-based steerable system for cryogenic device characterization (BYO light source)

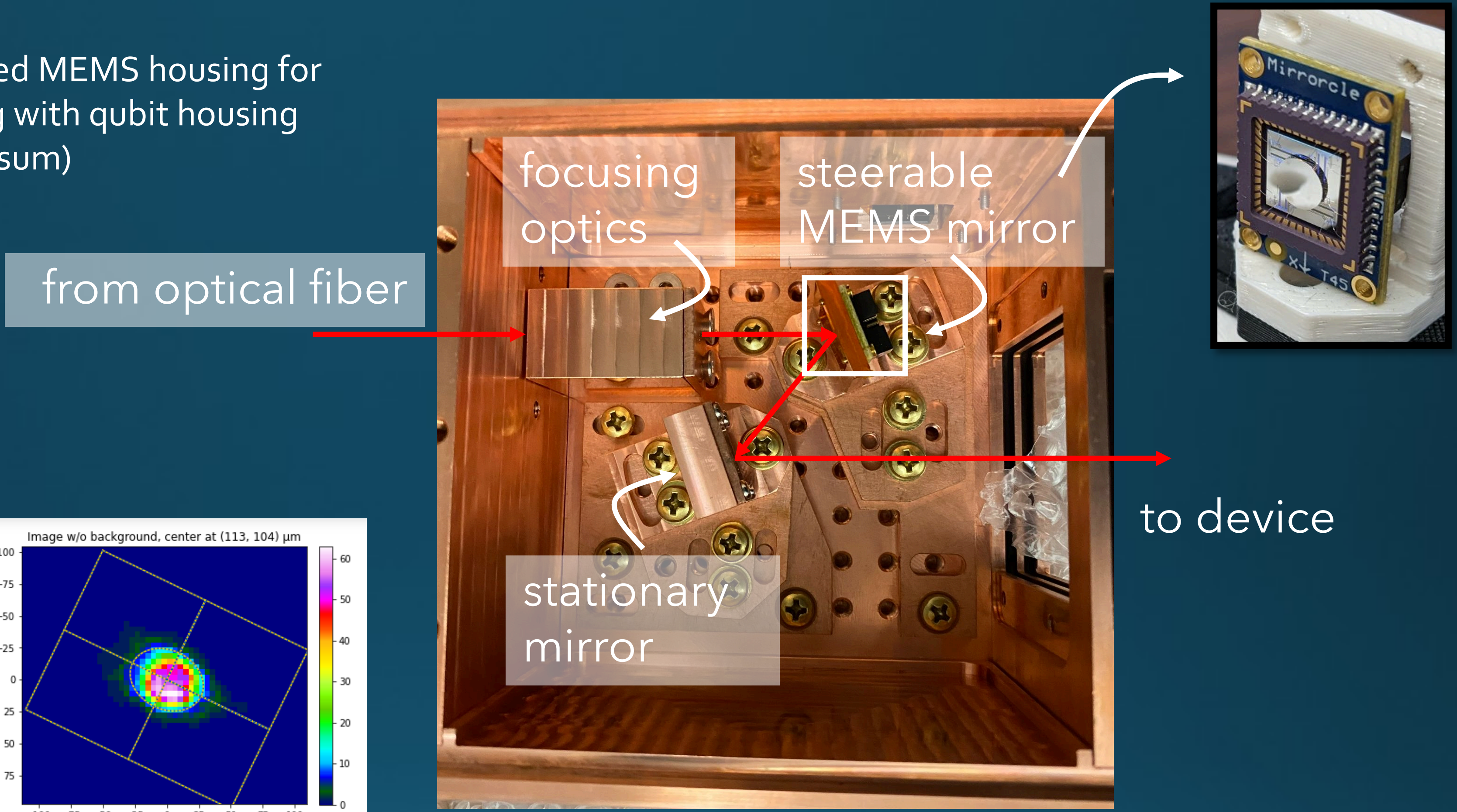
- Warm optical path building and testing (ongoing)
- Fridge integration (starting now)
- Cold device testing
- Integration with THz sources

Team @ SLAC:

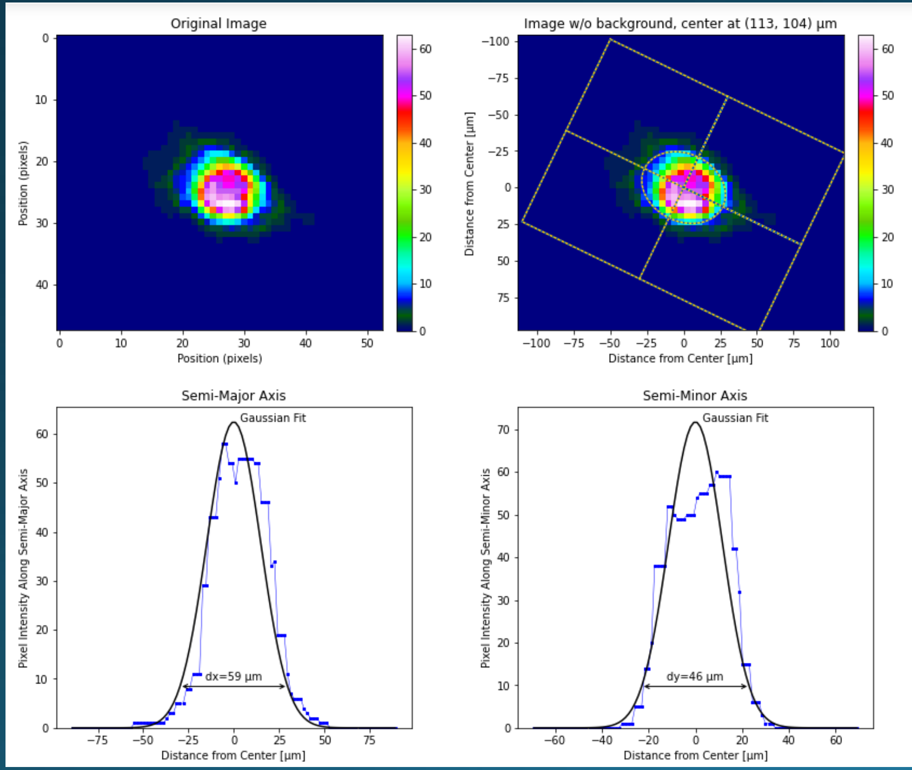
- PIs:
  - Kelly Stifter
  - Noah Kurinsky
- Postdoc:
  - We are hiring!
- Post-bac:
  - Noshin Tabassum



Updated MEMS housing for mating with qubit housing (Tabassum)



Focusing and steering optics (Stifter)



Measurement of calibration spot. Most recent spot size is 61 um with pulse time of 10 us (Tabassum)

Take-aways

SLAC has a rich program of TeraBREAD-related efforts

- SQUAT single THz photon sensors in development
- Simulation and design work underway toward understanding and building BREAD in the THz frequencies
- MEMS-based steerable calibration system deployed and being improved for better cryogenic device characterization

SLAC is hiring postdocs!

BREAD-adjacent work on calibration for SQUATs and other sensors

Fellowship position:

https://academicjobsonline.org/ajo/jobs/25538

DMQIS group specifically:

https://academicjobsonline.org/ajo/jobs/25563

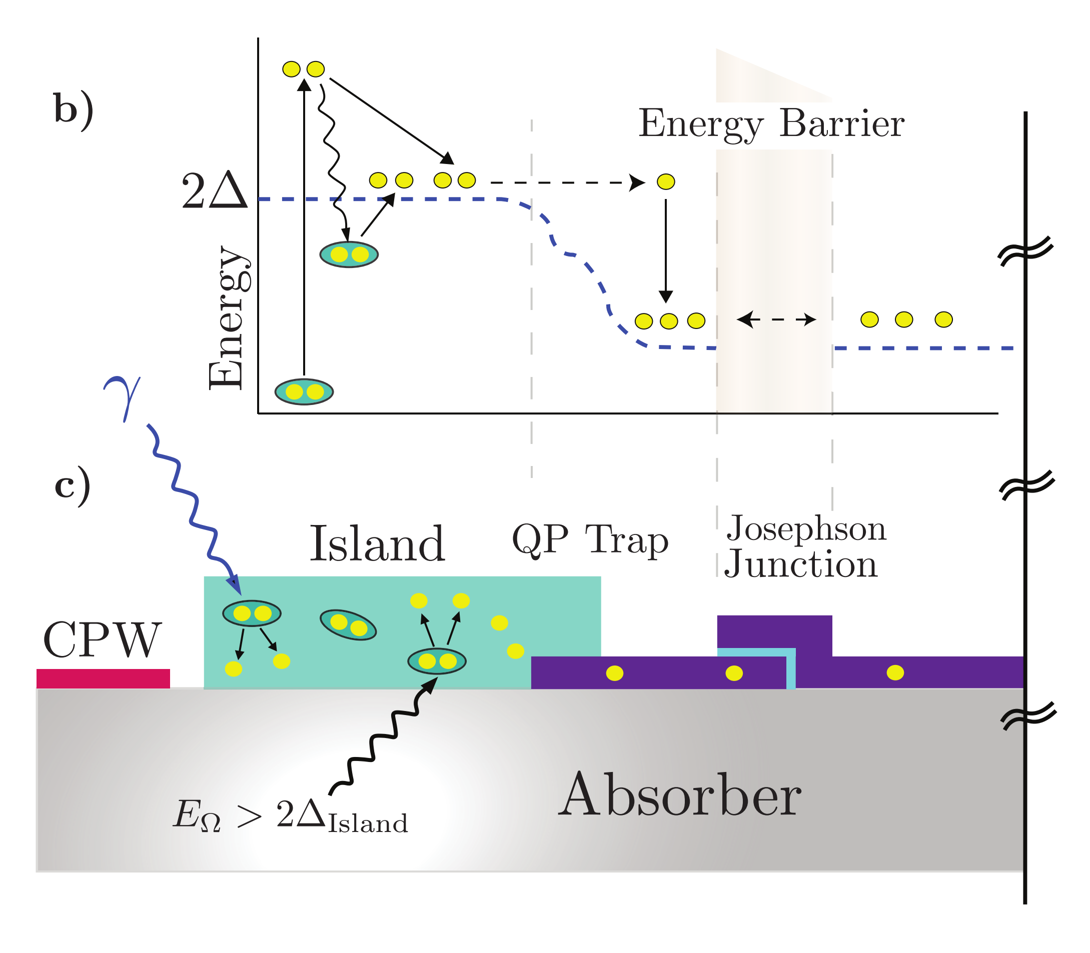
Apply to both!

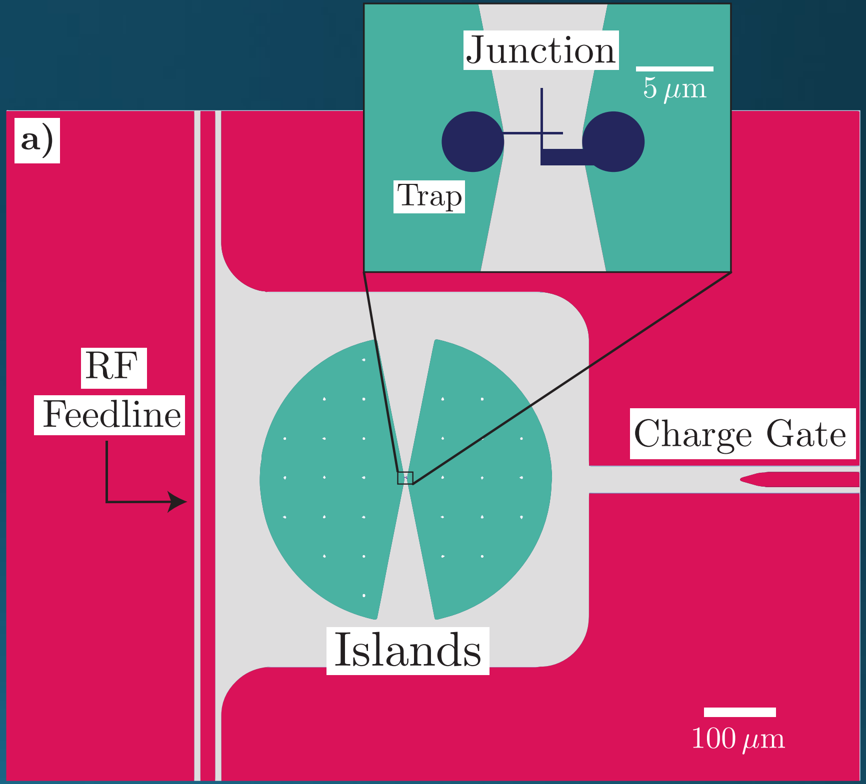
Backup

Designing for optimal sensitivity

1. Maximize photon coupling
   - Increase island size, tile many sensors over chip, coat bottom of chip, optimize broadband antenna, etc.
2. Optimize QP transport
   - Decrease island size, thicken island
3. Maximize QP tunneling
   - Trap QPs near junction with materials and/or layer thicknesses
4. Improve readout sensitivity
   - Optimize E_j/E_c and Q for readout sensitivity, charge bias at optimal sensitivity point

Energetics of quasiparticle transport



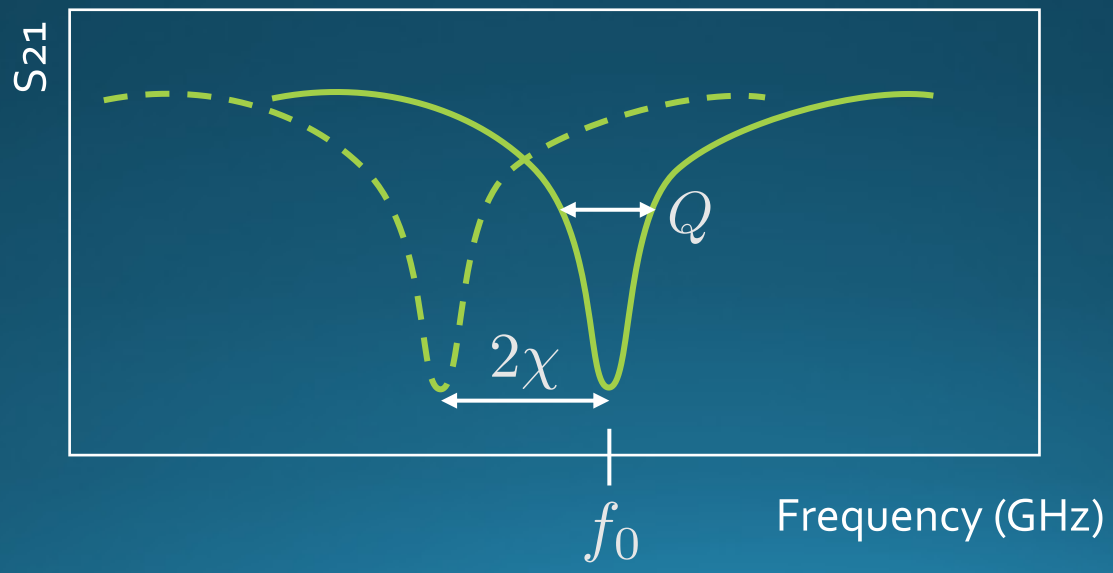


Readout principle

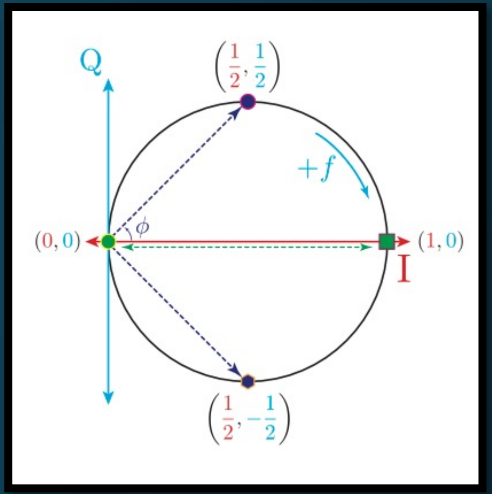
- Transmission measurement (S21)

$$V_s = S_{21} V_r$$

- Optimize SQUAT parameters (geometry, junction) and readout tone frequency for either amplitude or phase readout



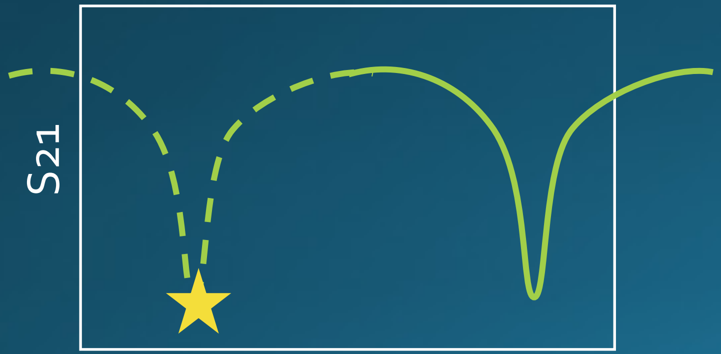
Readout optimization



Amplitude signal

$$2\chi \gg f_0/Q$$

- Signal is appearance/ disappearance of readout tone
- Readout tone must be precisely at resonance frequency



Phase signal

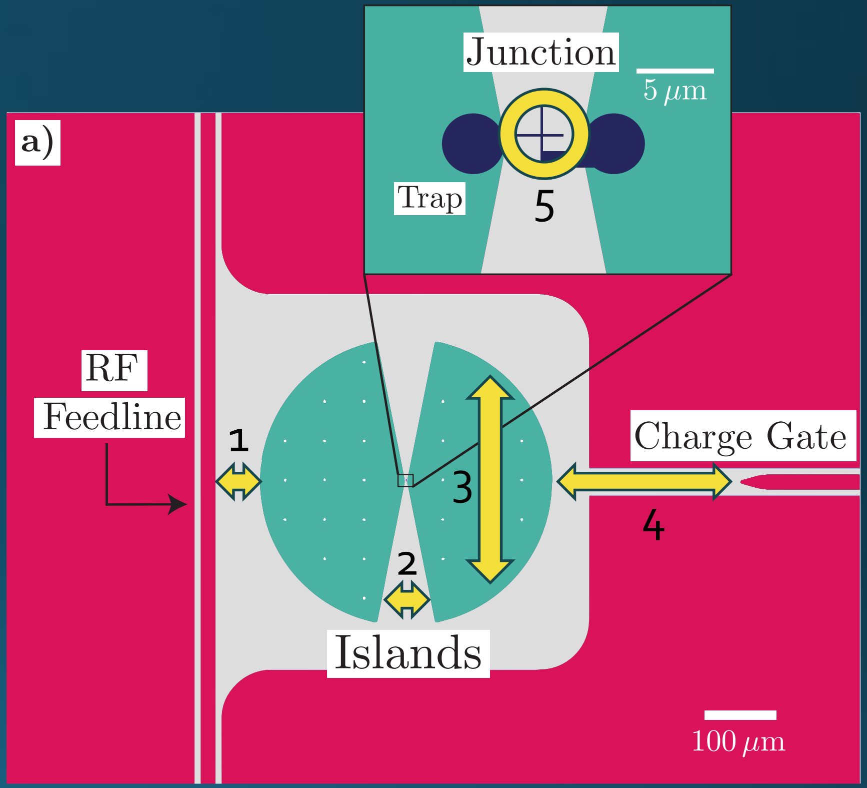
$$2\chi \approx f_0/Q$$

- Signal is change in tone phase
- Insensitive to precise resonance and readout tone frequency

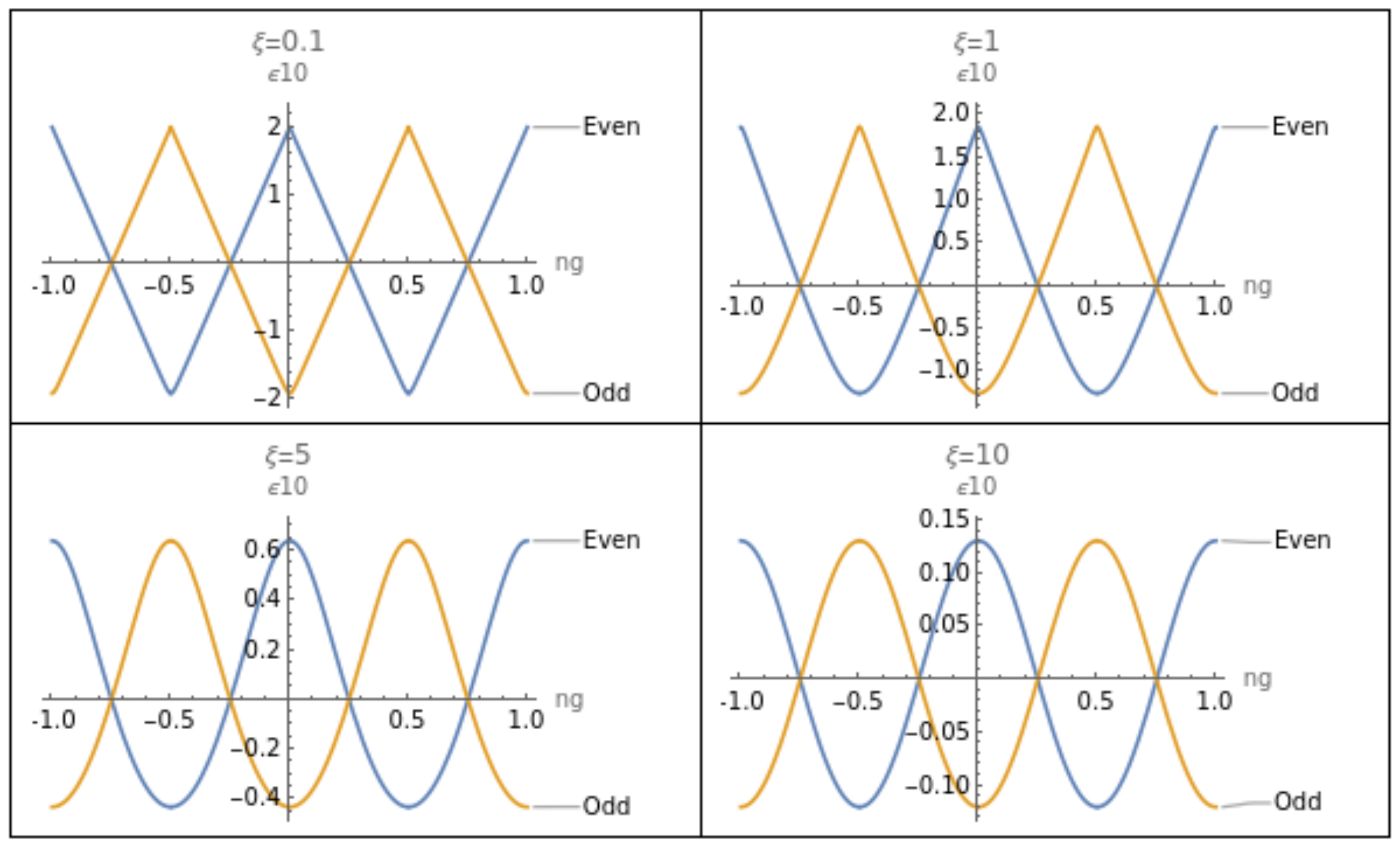
How to tune what

In practice, device design is tuned iteratively

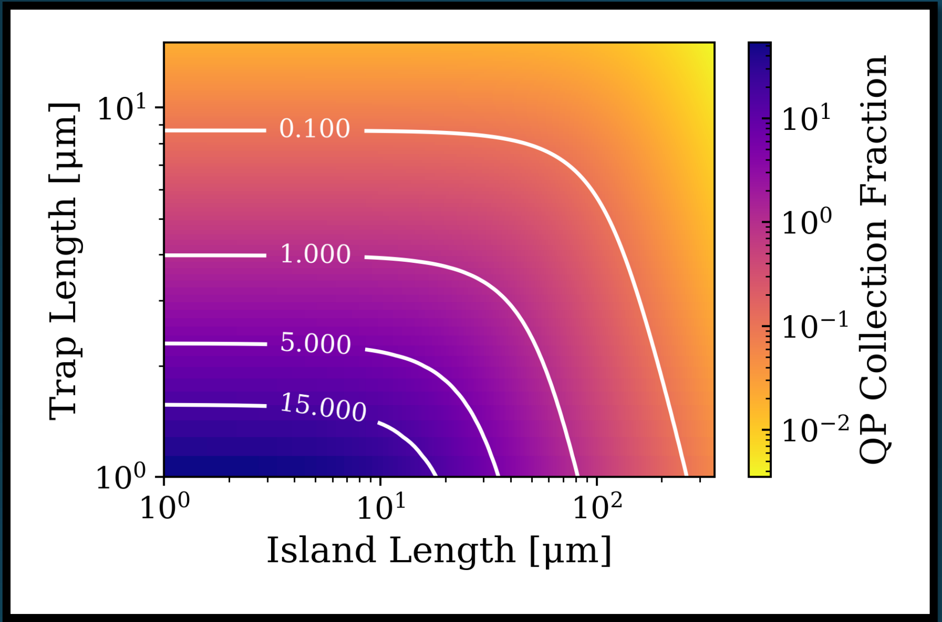
- $2\chi(E_J/E_C)$
- $f_0(L, C)$ aka $f_0(E_J, E_C)$
- $Q \sim Q_{coupling}$: 1
- E_J: 5
- E_C: 1, 2, 3, 5
- Charge gate coupling: 4



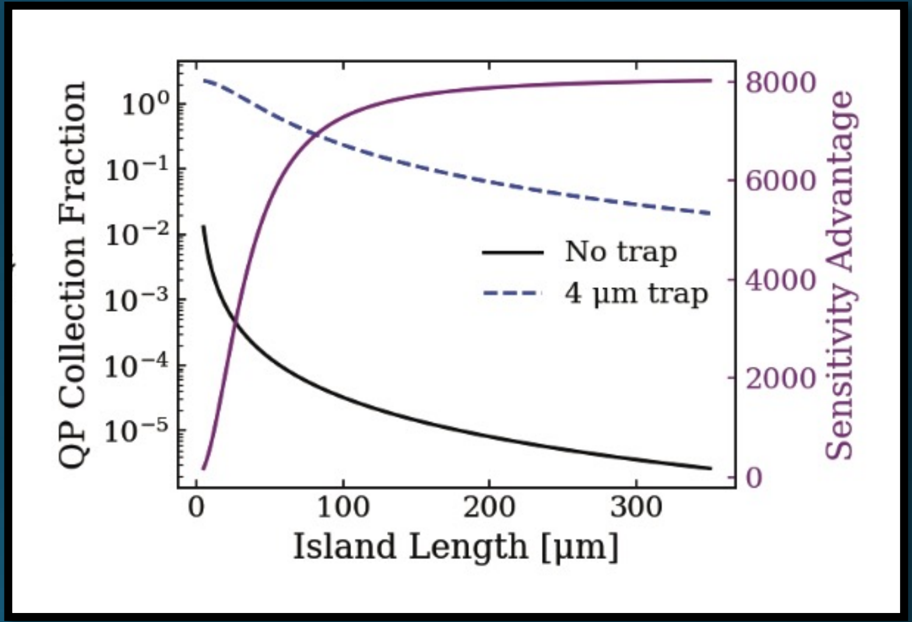
$\xi = E_j / E_c$ affects the charge sensitivity



Quasiparticle collection



By tuning the trap and island size, we can increase the number of tunneling events that we see



There is a huge increase in tunneling events when using a trap near the junction. The effect is especially important with large unit cell size (large qubit islands)