SQUIDs for FDM
in Satellite CMB Experiments

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B-modes From Space
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SQUIDs for FDM
in Satellite CMB Experiments

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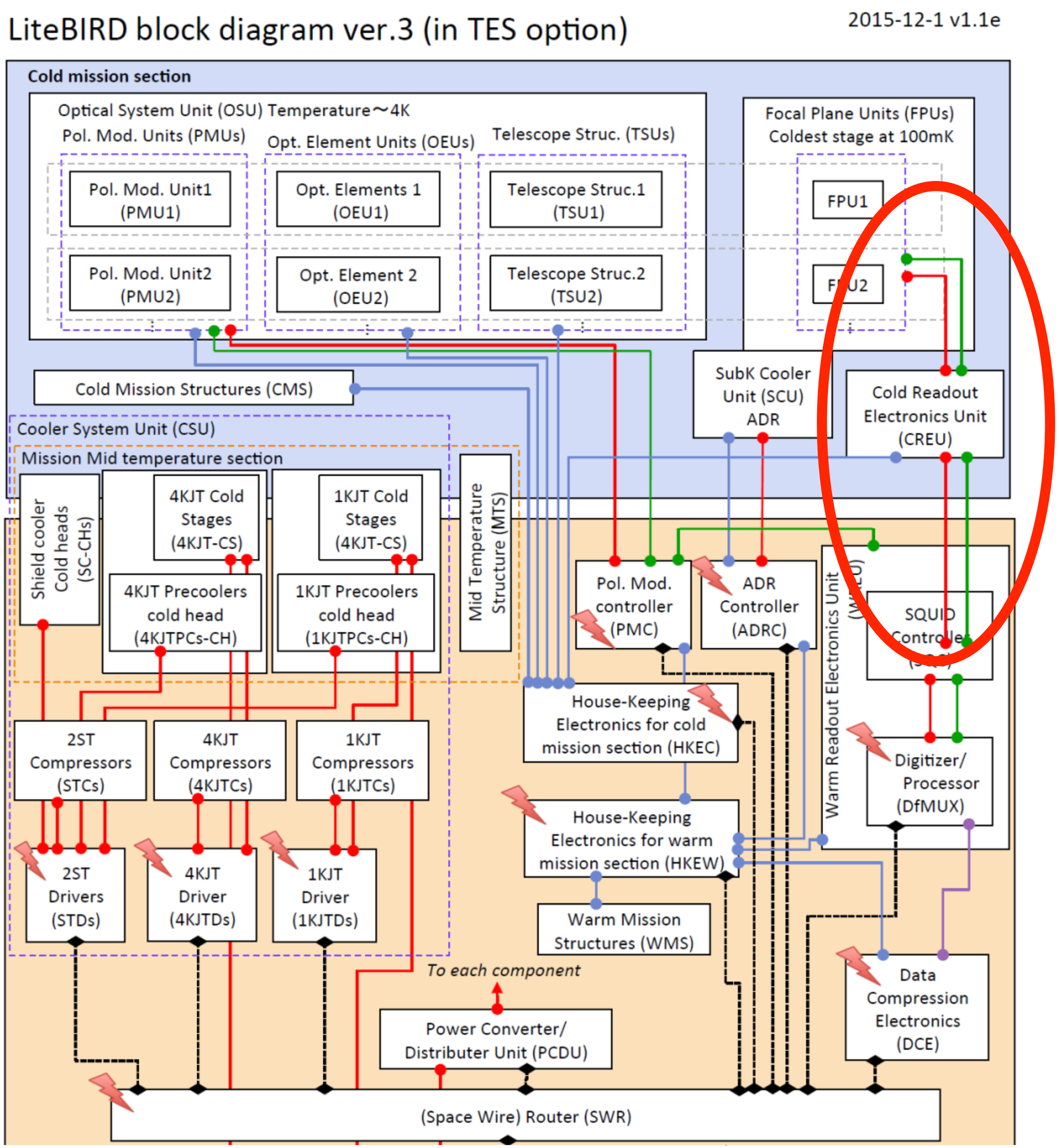
SQUIDs for FDM
in Satellite CMB Experiments

Outline

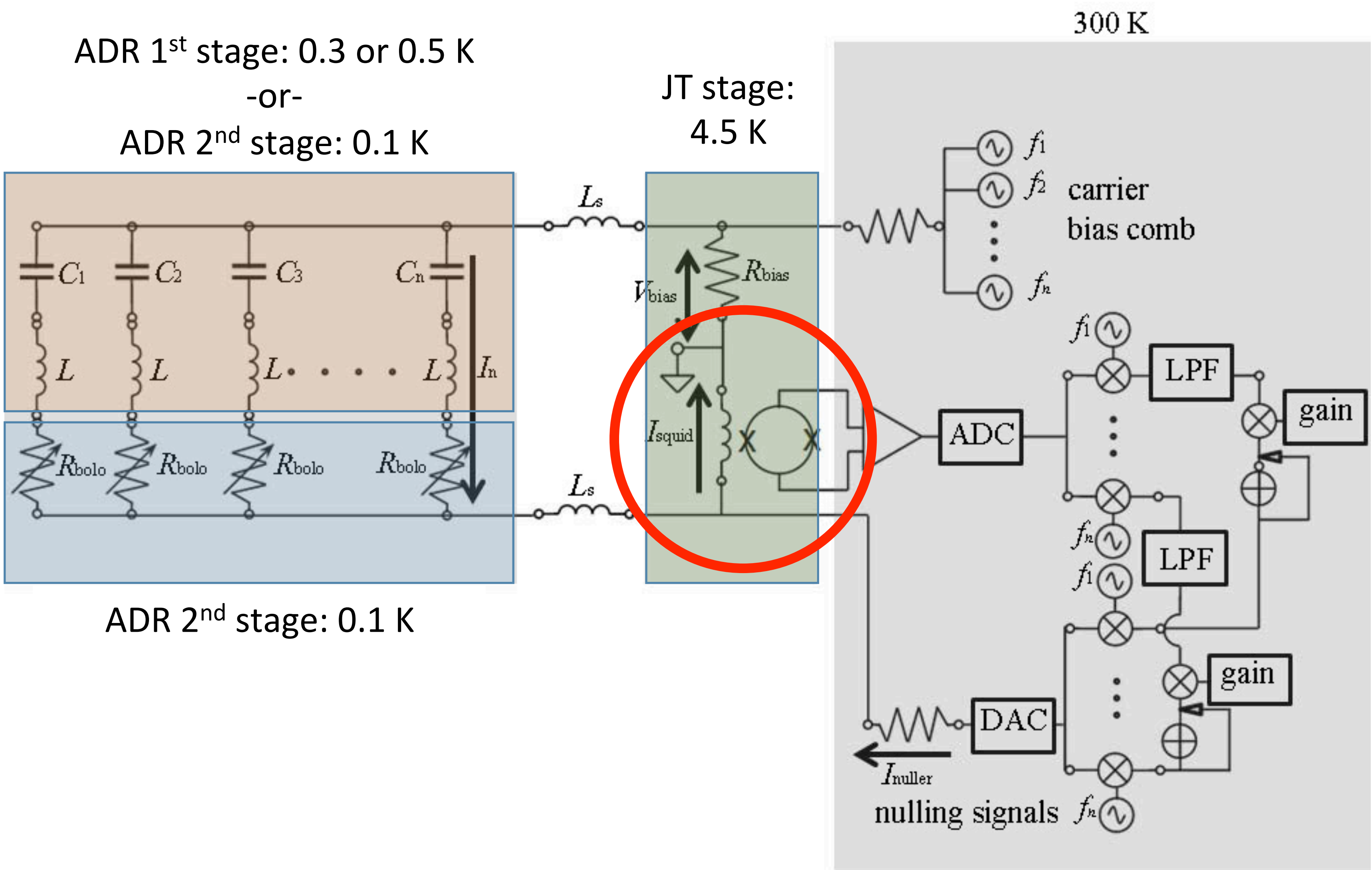
- Scope of talk
- Context in the field (History)
- Optimizing for LiteBIRD
- Designs for optimization
- Conclusions



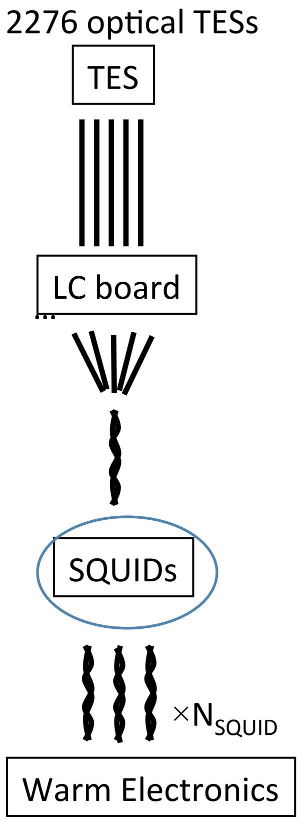
This talk is about optimizing this bit:

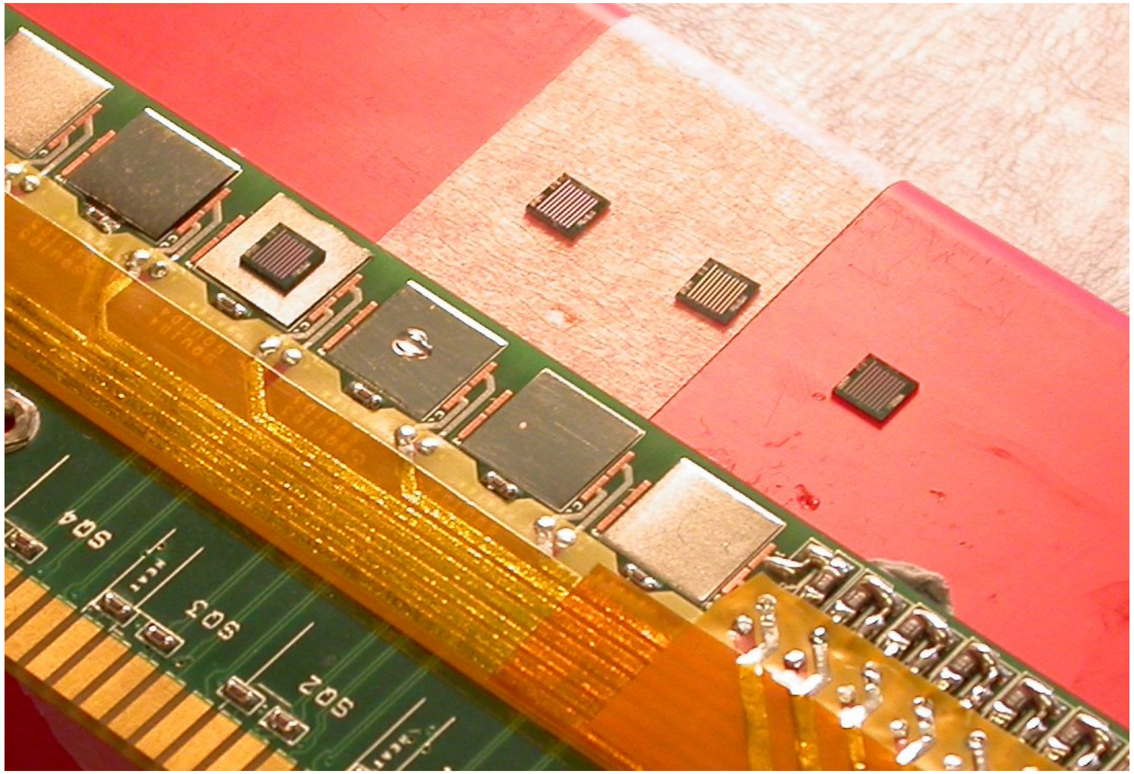
The cold SQUIDs and their interaction with wiring

Readout circuit



SQUIDs


2276 optical TESs
TES
LC board
…
SQUIDs
$\times N_{SQUID}$
Warm Electronics



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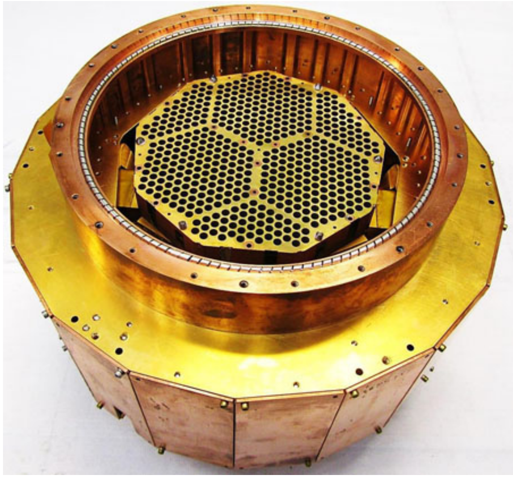
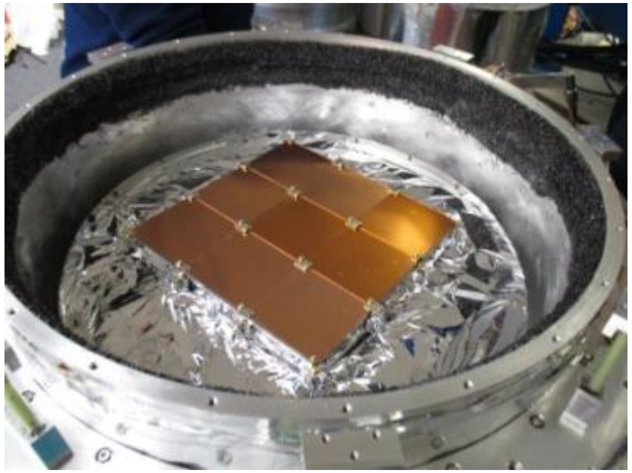
Some SQUIDs used in CMB polarimeters in the field

ACTpol

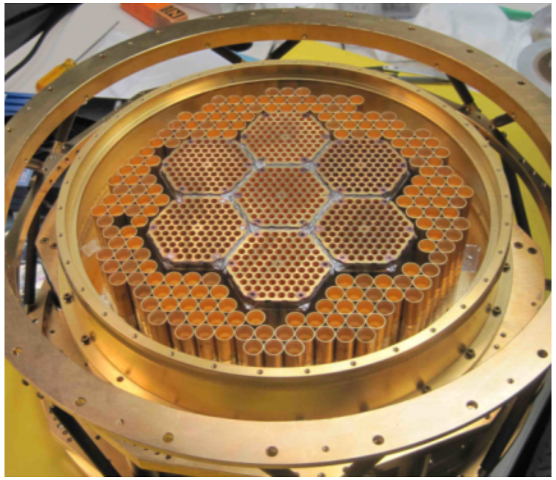


BICEP-3, SPIDER

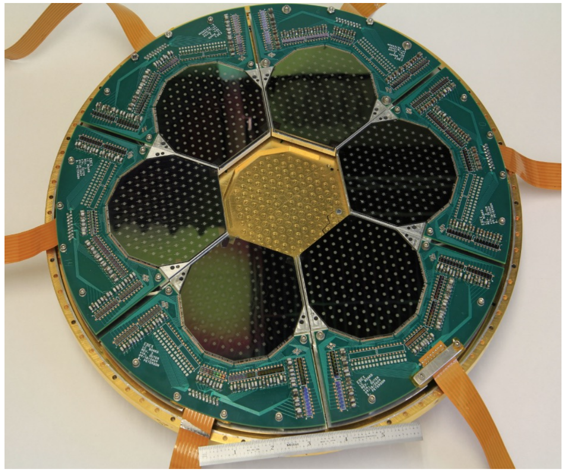


Keck Array

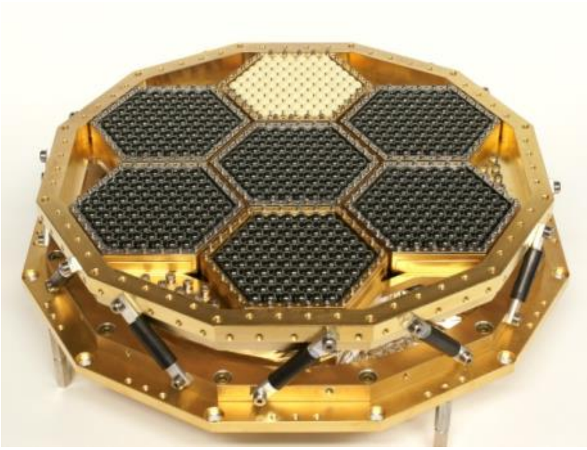
SPTpol



EBEX



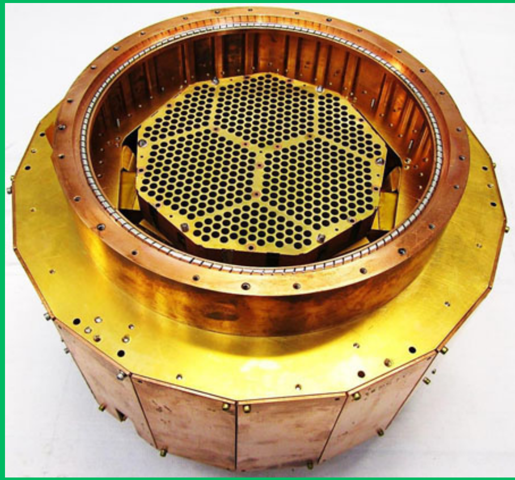
POLARBEAR, Simons



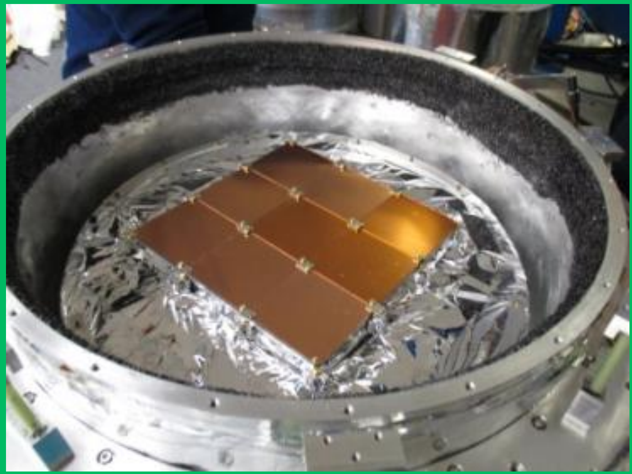
Some SQUIDs used in CMB polarimeters in the field

TDM

ACTpol



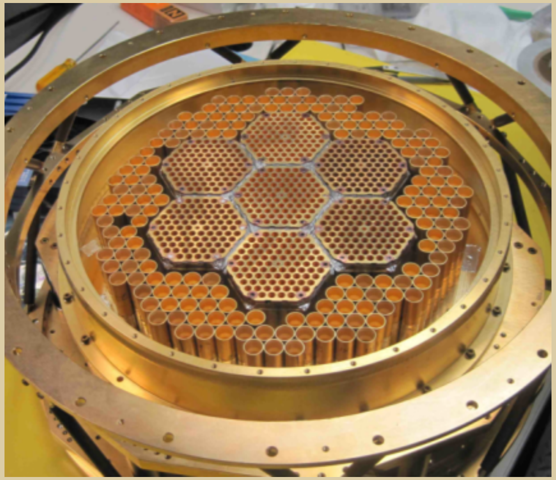
BICEP-3, SPIDER



Keck Array

FDM

SPTpol



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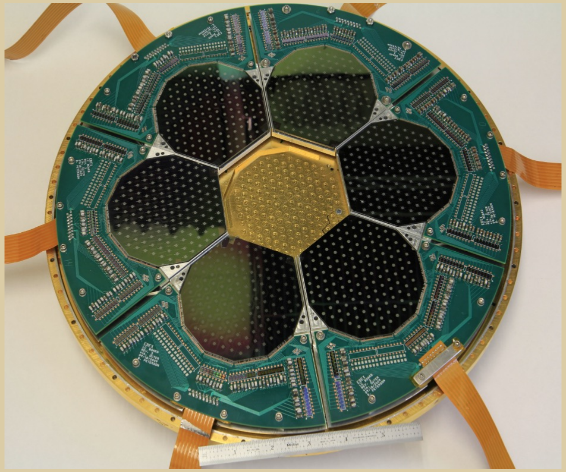
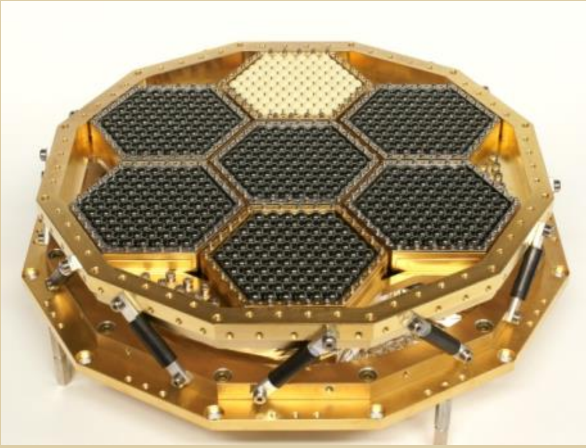


POLARBEAR, Simons



Some SQUIDs used in CMB polarimeters in the field

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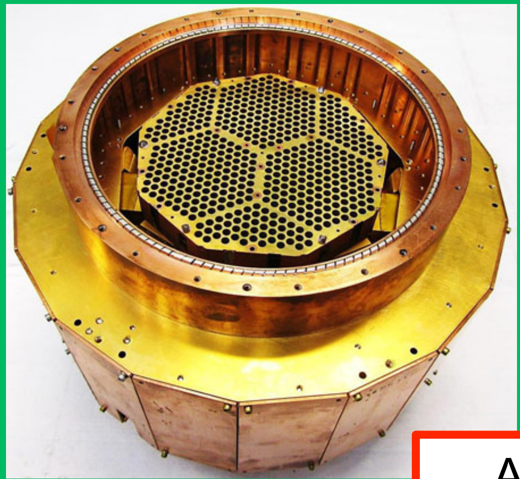
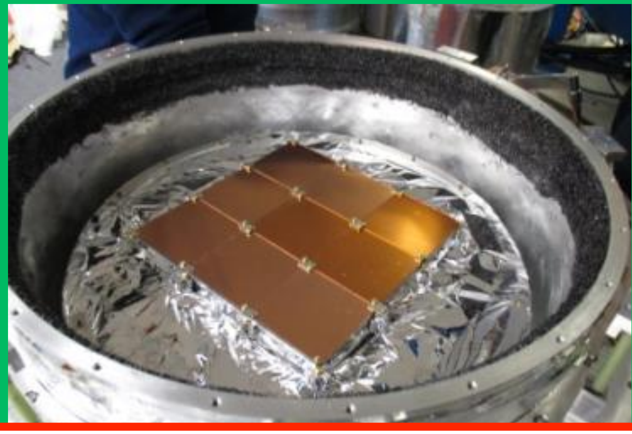


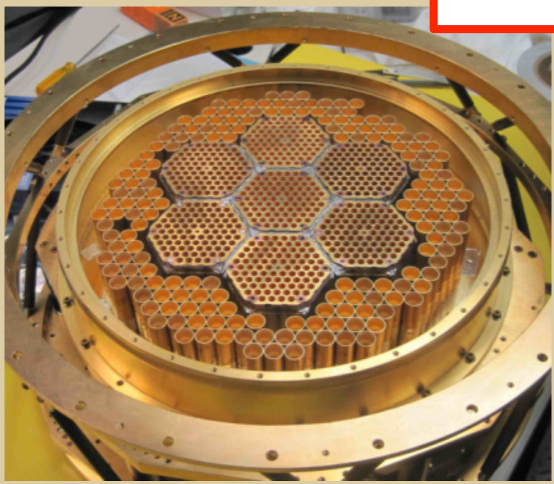
BICEP-3, SPIDER

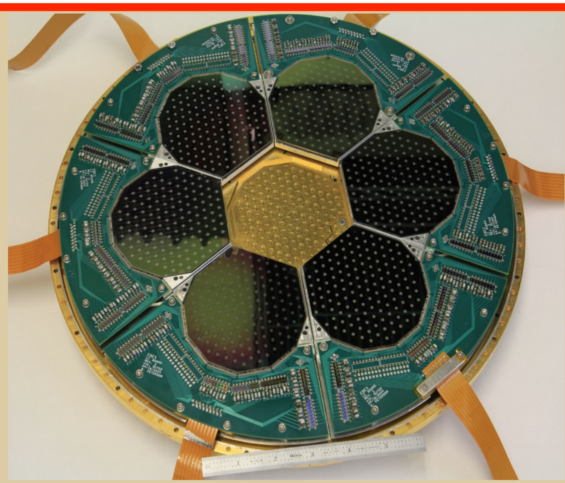


Keck Array

All the SQUIDs used in these experiments were designed and fabricated by members of the LiteBIRD team

SPTpol





EAR, Simons

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SQUID optimization for LiteBIRD

Design SQUIDs to use the resources available in the satellite platform, with realistic wiring harnesses in the EMI and radiation exposure from the spacecraft and L2 environment

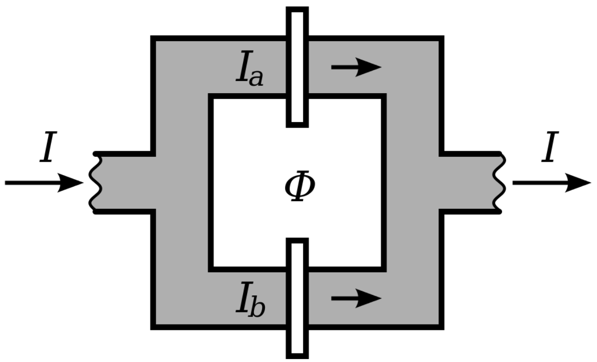
- Power dissipation at each temperature stage
- Dynamic range / noise
- Electromagnetic interference (EMI) sensitivity
- Magnetic field sensitivity
  a) AC magnetic field pickup in operation
  b) Flux-trapping sensitivity in initial cooldown (magnet off)
  c) Flux-trapping sensitivity in mag cycle (magnet on)
  d) Requirements for flux-expulsion through heating?
- Output impedance / dynamic resistance matched to wiring
  Determined by wiring harness length, characteristic impedance, normal resistance, and characteristics of room-temperature preamplifier
- Operational temperature of SQUID amplifiers
  a) 4K
  b) Intermediate temperature
  c) Base temperature
  d) Two-stage

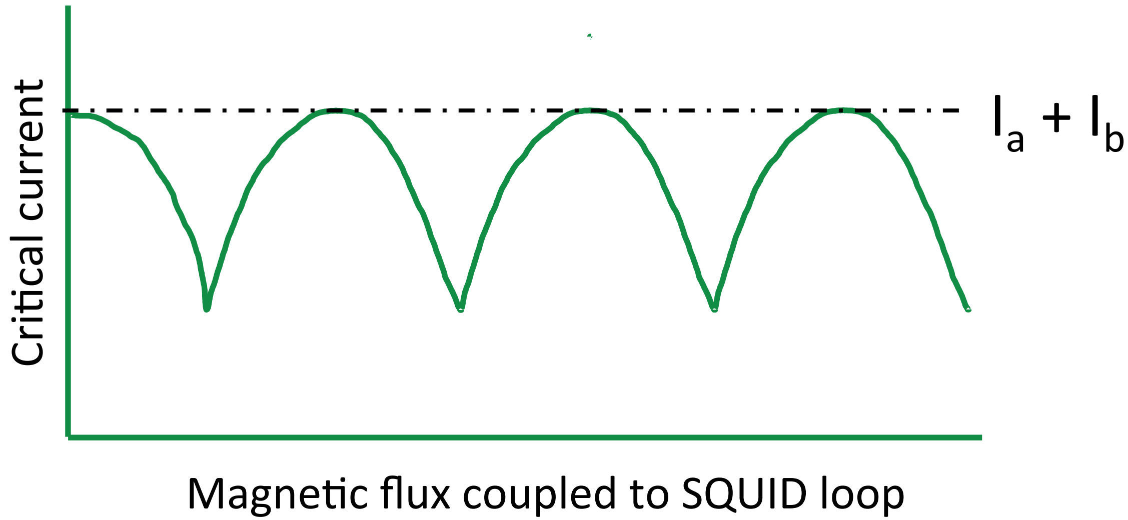
Tools for SQUID optimization

- Single SQUID design optimization
- Asymmetric SQUIDs (internal self-feedback)
- Gradiometric SQUIDs (series and / or parallel)
- Series-array SQUIDs (for large output voltage)
- Series / Parallel SQUIDs
- Two-stage SQUIDs (one cold single SQUID followed by a series / parallel SQUID at higher temperature
- SQUIDs with differential output for rejection of common-mode pickup in wiring harness

dc SQUIDs

- Superconducting Quantum Interference Device (SQUID)
- Invented by Arnold Silver, Ford
- Quantum interference pattern analogous to a two-slit interferometer





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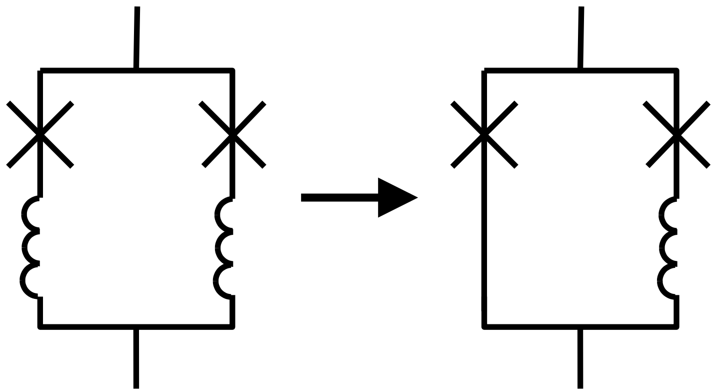
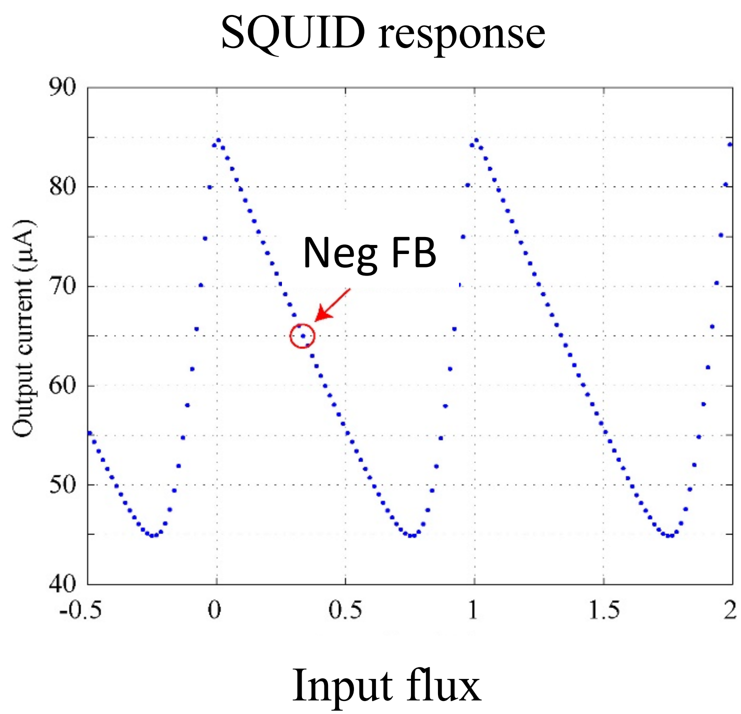
Asymmetric SQUIDs (Self-feedback)

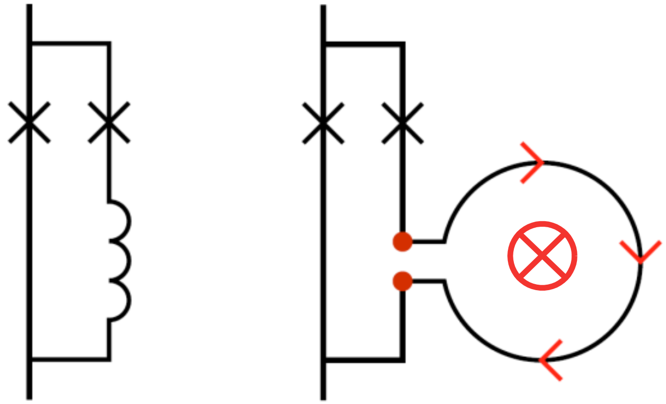




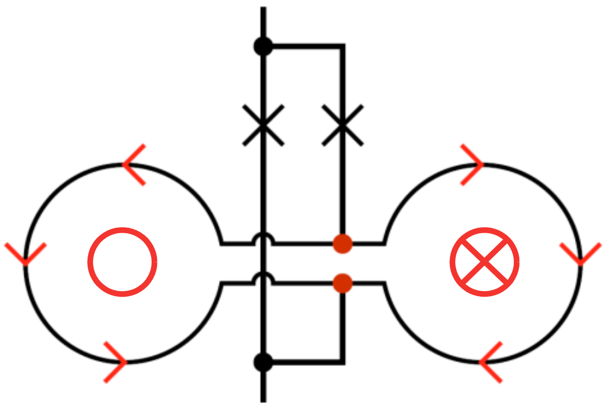
- Put most of the inductance on one side of SQUID loop
- Circulating current in SQUID either enhances (positive feeback) or reduces (negative feedback) the coupled flux.
- Positive feedback: increases output voltage, reduces dynamic range
- Negative feedback: reduced output voltage, increased dynamic range, improved linearity

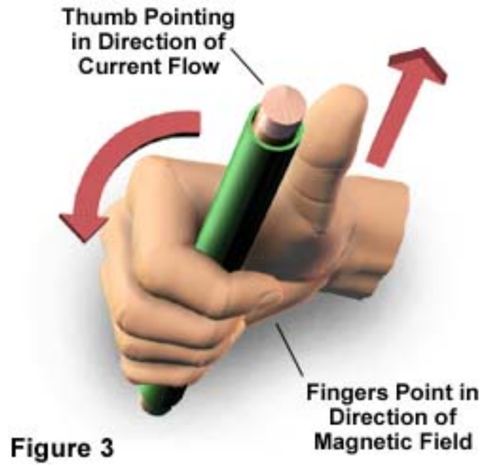
Gradiometer SQUIDs for B field insensitivity

Non-gradiometric SQUID



First-order parallel gradiometer

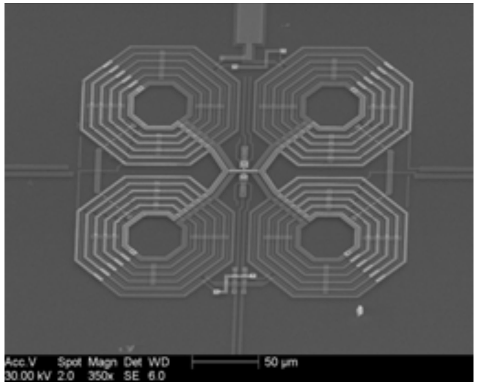




- **Insensitive to uniform B fields**
- Sensitive to first-order B gradients
- **Allows efficient input coils**
- Trapping flux-quantum in coil leads to 180 degree dephasing: only for single SQUIDs

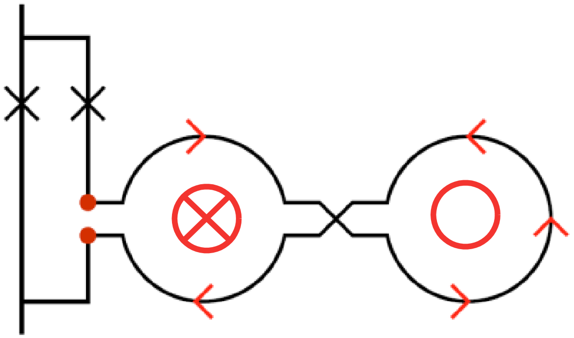
Gradiometer SQUIDs for B field insensitivity

Second-order parallel gradiometer



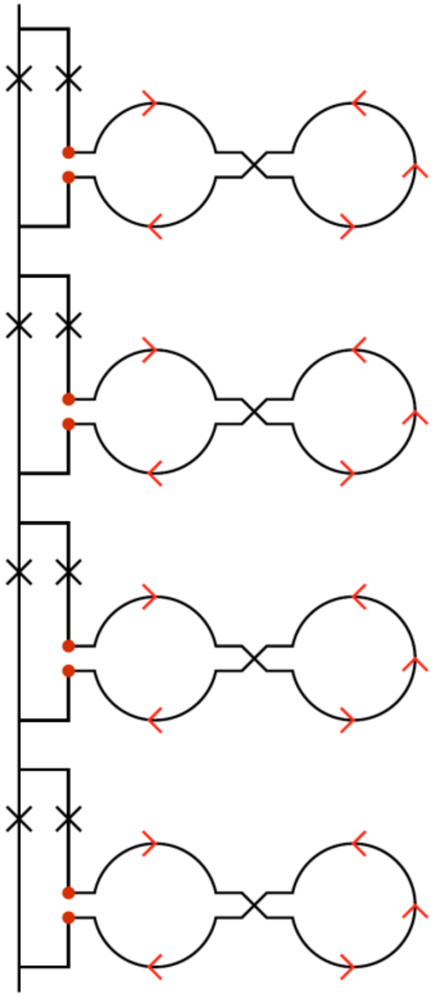
- **Insensitive to uniform B fields**
- **Insensitive to first-order B gradients !!!**
- **Allows efficient input coils**
- Trapping flux-quantum in coil leads to 180 degree dephasing: only for single SQUIDs

First-order serial gradiometer



- **Insensitive to uniform B fields**
- Sensitive to first-order B gradients
- Limited input coil efficiency
- **Doesn't dephase: great for series-array SQUIDs (next)**

Series-array SQUIDs



With proper engineering, response curve looks like that of a single SQUID

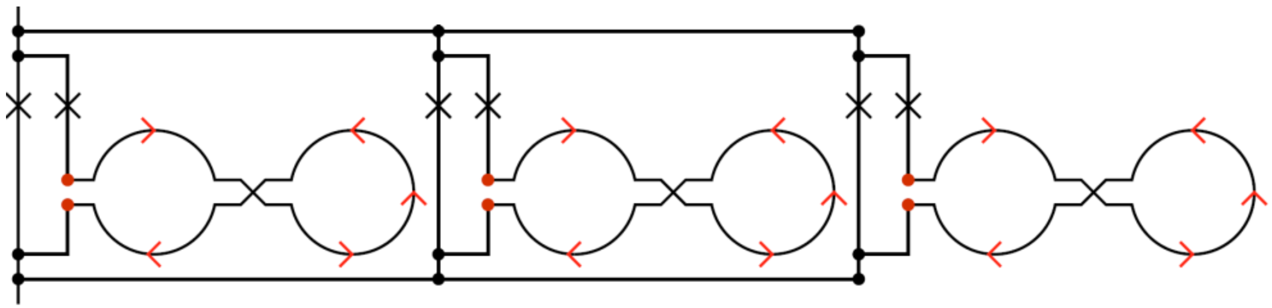
N SQUIDs in series

- **N times higher output voltage**
- **sqrt(N) times higher signal-to-noise ratio**
- N times higher dynamic resistance
- N times higher power dissipation

Must use serial gradiometer to prevent dephasing

Increases output voltage swing

Parallel-array SQUIDs



With proper engineering, response curve looks like that of a single SQUID

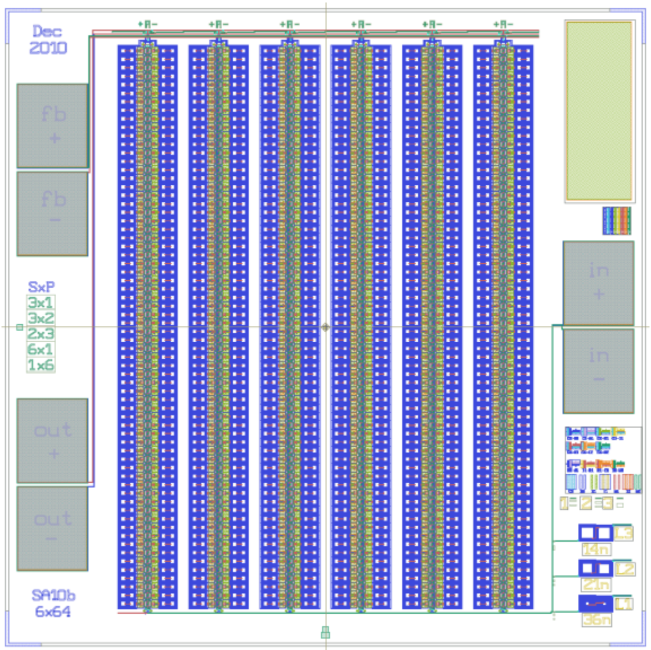
M SQUIDs in parallel

- **sqrt(M) times higher signal-to-noise ratio**
- **M times lower dynamic resistance**
- M times higher power dissipation

Must use serial gradiometer to prevent dephasing

Reduces output dynamic resistance

Parallel / Series array SQUIDs



2 x 192 (parallel x series) SQUID array design deployed on BICEP-3

Increases output voltage and reduces output dynamic resistance

Conclusion

- Further optimization possible:
    1. Two-stage SQUID (first stage at base temperature, SA SQUID at 4K)
    2. Differential output from SA and differential preamp: insensitive to common-mode pickup in wiring harness
- Requirements for SQUIDs are being established
- SQUID specifications can be optimized for LiteBIRD requirements and resources