Advanced time-division transition-edge sensor readout development for CMB-S4

CPAD Workshop 2023

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08 November 2023

SLAC NATIONAL ACCELERATOR LABORATORY

CMB-S4

NSF

U.S. DEPARTMENT OF ENERGY Office of Science

CMB-S4

9 small and large aperture telescopes planned for the South Pole and Atacama Desert

Next generation ground-based Cosmic Microwave Background experiment.

- Joint DOE/NSF.

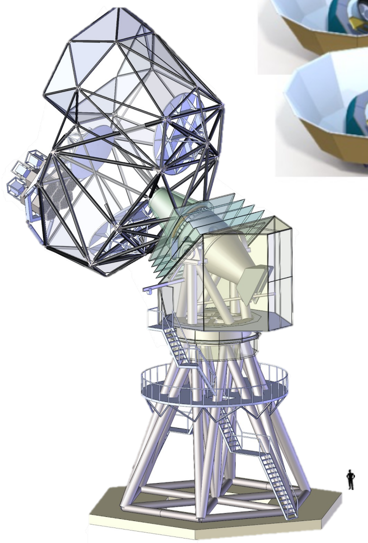
Over 500,000 superconducting sensors observing over 20-270 GHz.

- Order of magnitude more sensors on sky than all existing efforts combined!

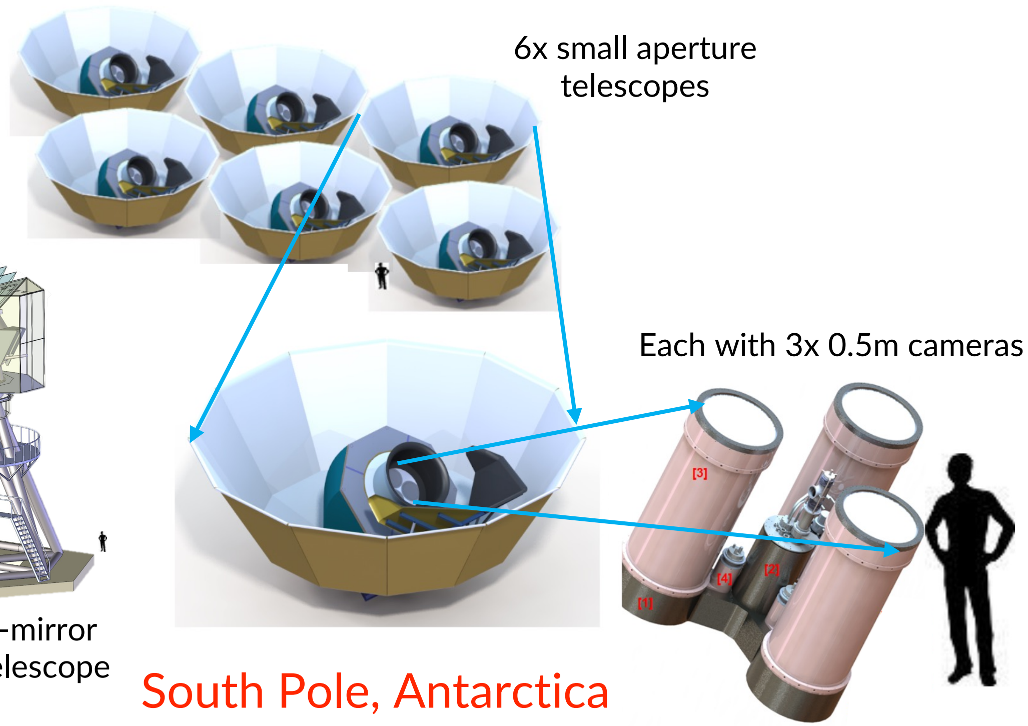
Transformative science impact

- Primordial gravitational waves
- Dark matter & exotic relics
- Dark energy & the neutrino mass scale
- Galaxy evolution, the IGM, and transients

[CMB-S4 Science book, arXiv:1610.02743](https://arxiv.org/abs/1610.02743)

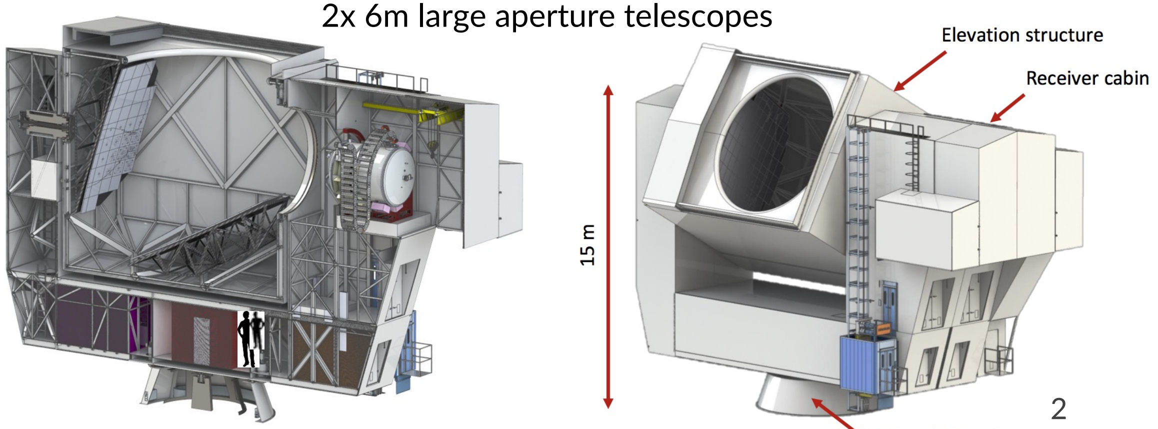


1x 5m three-mirror anastigmat telescope



South Pole, Antarctica

2x 6m large aperture telescopes



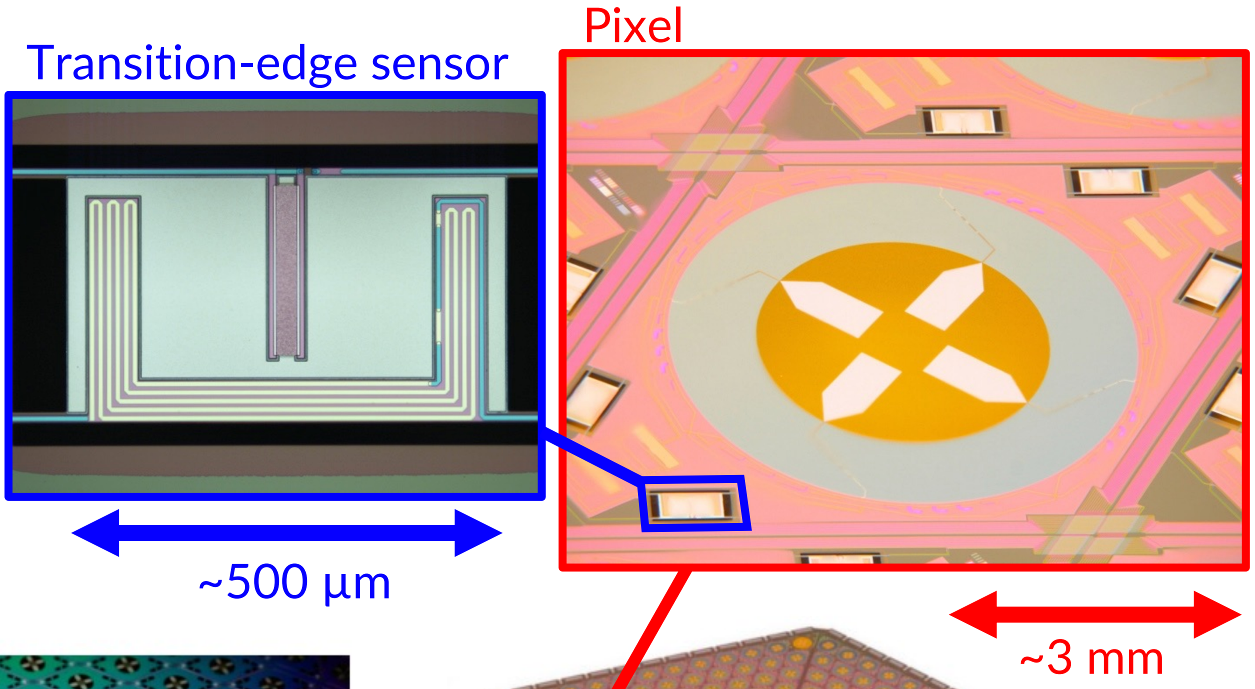
Atacama Desert, Chile

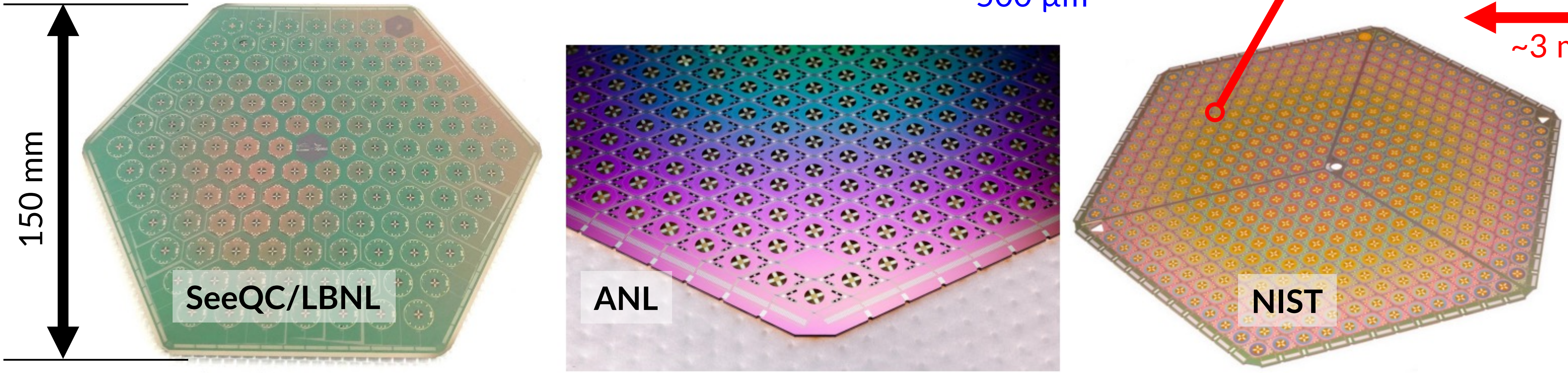
TES arrays for CMB-S4

State-of the-art arrays of polarization-sensitive, dichroic pixels fabricated on 150-mm wafers.

- Observed sky signal transduced into current using transition-edge sensors (TESs). Over 500,000!

Low noise TES readout at this density and scale presents a formidable technical challenge.





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TES readout / time division multiplexing (TDM)

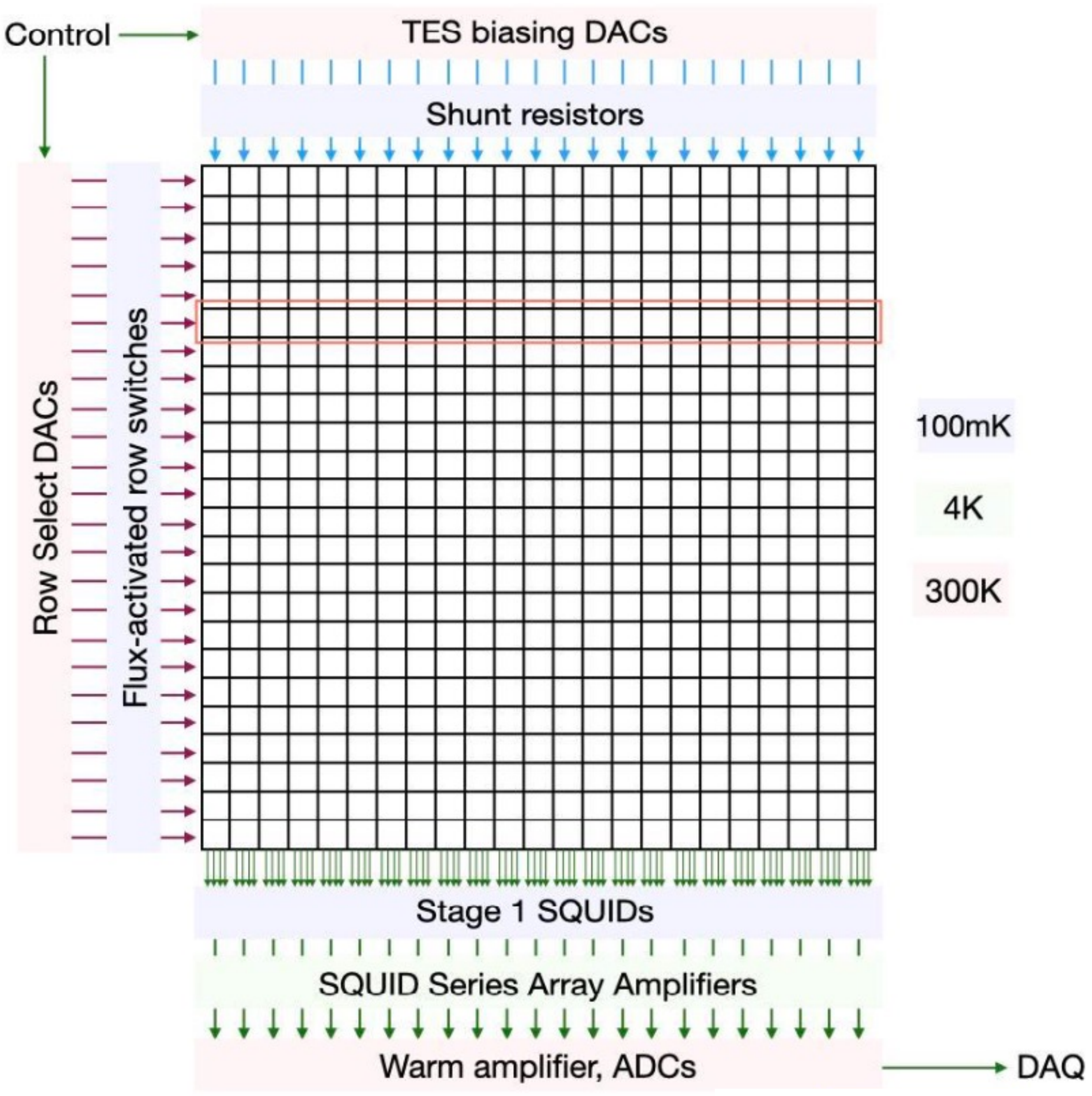
TESs read out cyclically in a 2D grid of *rows* and *columns* – time division multiplexing (TDM).

- Readout and TES bias along *columns*.
- One *row* at a time drives amplifiers, switched cyclically in rapid sequence.
- Cold amplifiers and switching implemented using Superconducting Quantum Interference Devices.

10+ years of deployment heritage on CMB experiments, but at much smaller scale.

Challenges for CMB-S4

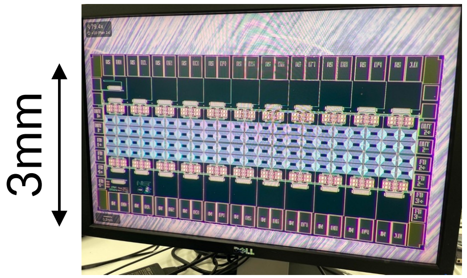
- High wire count / scales with number of channels.
- Higher channel counts requires more bandwidth.
- Existing cold and warm electronics too large, obsolete.



CMB-S4 TDM readout architecture

Baselining two-level SQUID TDM readout architecture.

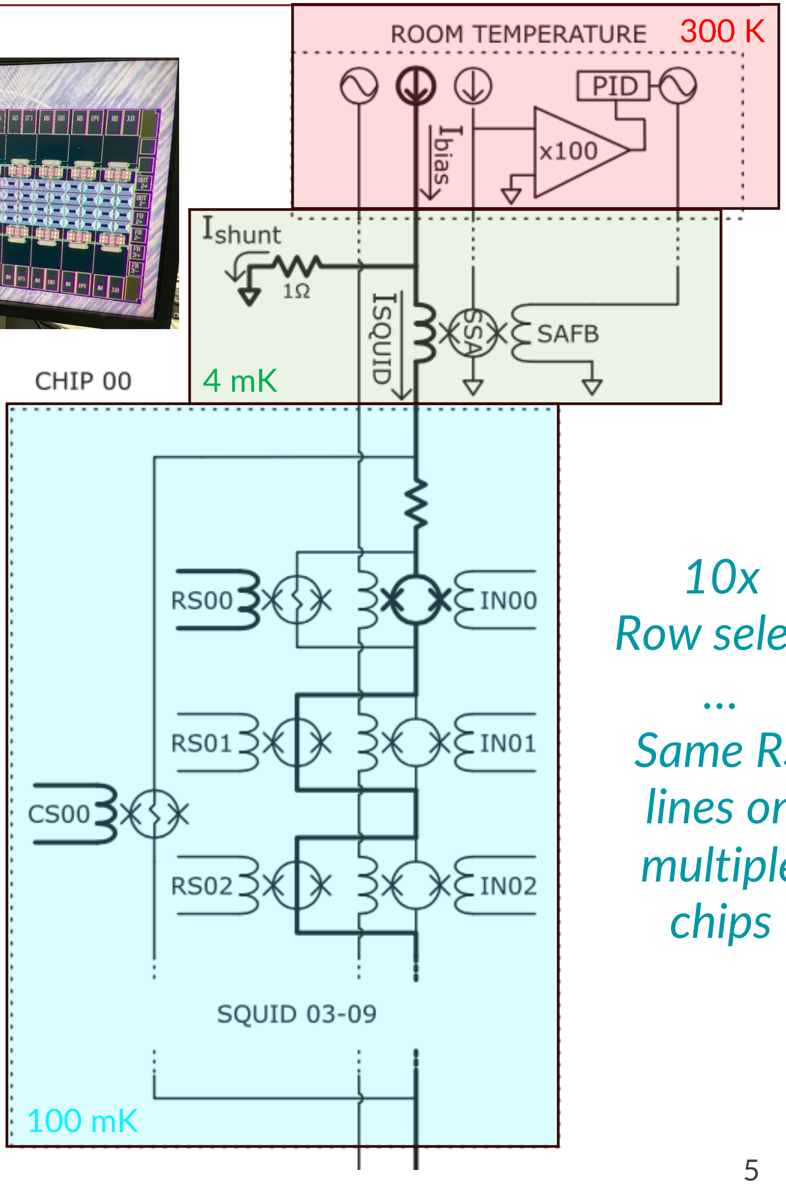
- Dedicated 100mK SQ1 amplifies each TESs' current.
- Superconducting flux-activated row-select (RS) switches rapidly switch which row's SQ1 is active on a column.
- All SQ1s on a column drive a common SQUID series array.



Incorporating recent advancements developed by NIST for the Athena X-ray mission. C.S. Dawson+, IEEE Trans. App. Supercon. 29 (5), 2019
M. Durkin+, IEEE Trans. Appl. Supercon. 33 (5), 2023

- Hierarchical switching – 2^{nd} level chip select (CS) to reduce row-select wire count (>4x reduction in row switching wires).
- Higher bandwidth / faster row switching – 160 ns demonstrated.
- Higher gain, lower impedance SQ1s and SQUID series arrays.
- Symmetrized designs to reduce EMI pickup.

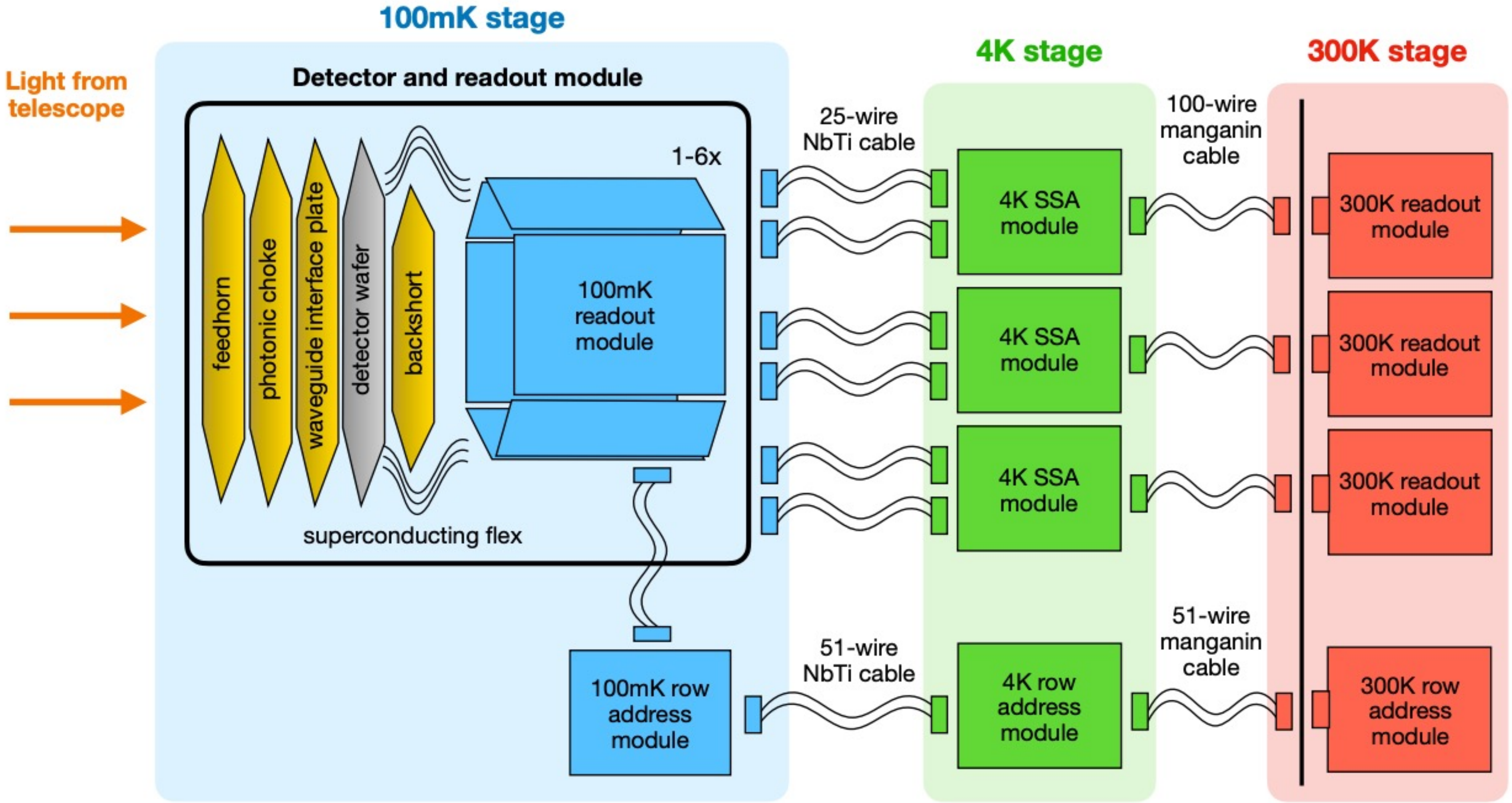
Chip select



10x Row select
...
Same RS lines on multiple chips

Further chips below

CMB-S4 readout – System level design



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CMB-S4 readout – 100 mK electronics

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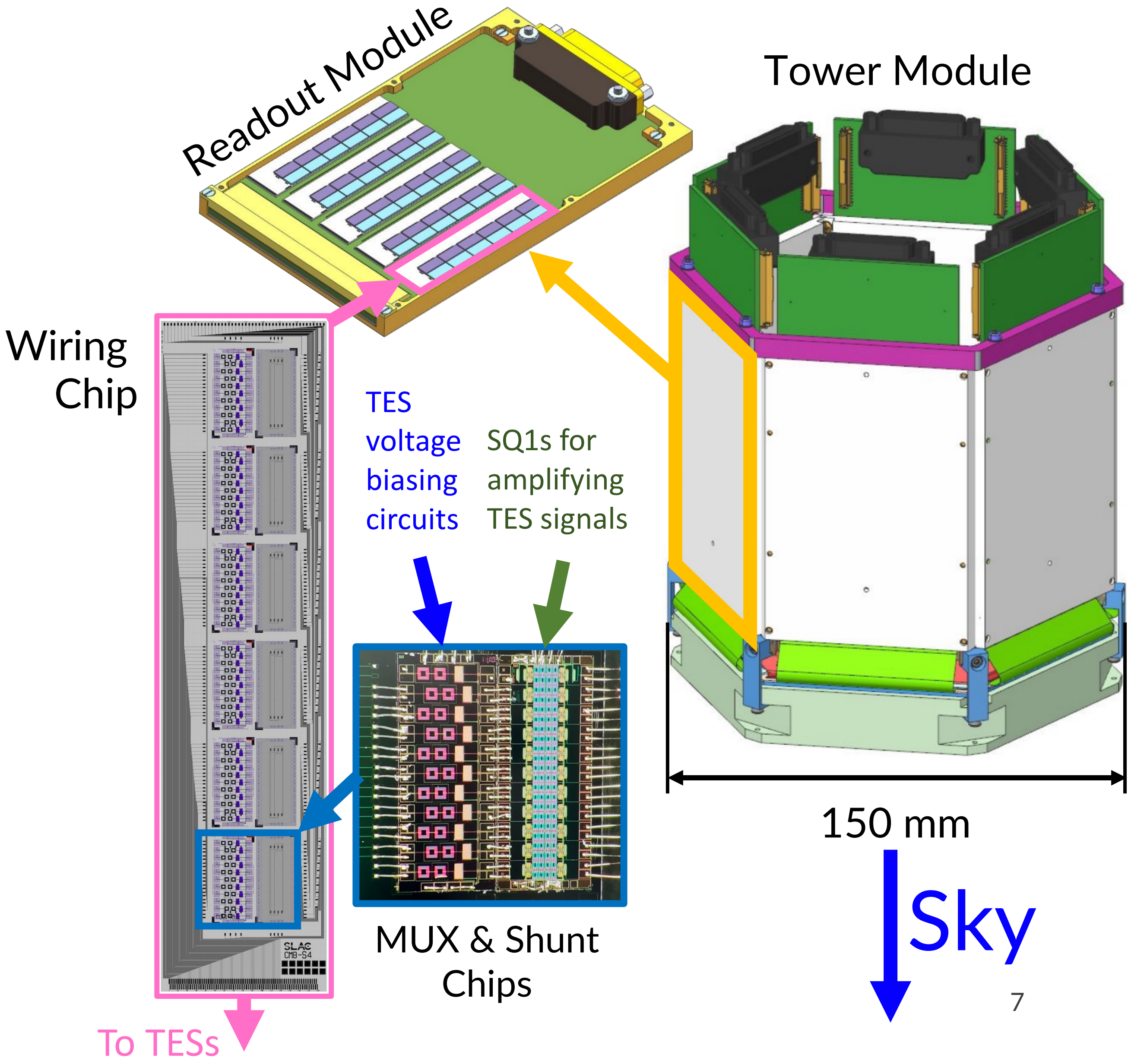
100 mK readout (TES bias + MUX circuits) packaged in modules behind wafer.

- Modular approach eases production & screening and allows for independent optimization of readout and array packaging.
- Requires superconducting flexible cables.

Key challenges / design drivers :

- Low impedance TESs require superconducting, low inductance connection to readout.
- Highest channel count arrays require dense trace pitch (70 m) at array interface.
- 100mK modules must fit within array footprint.
- Superconducting flex production at scale.
- SQ1s must be shielded from magnetic fields/RFI.



CMB-S4 readout – 4K electronics

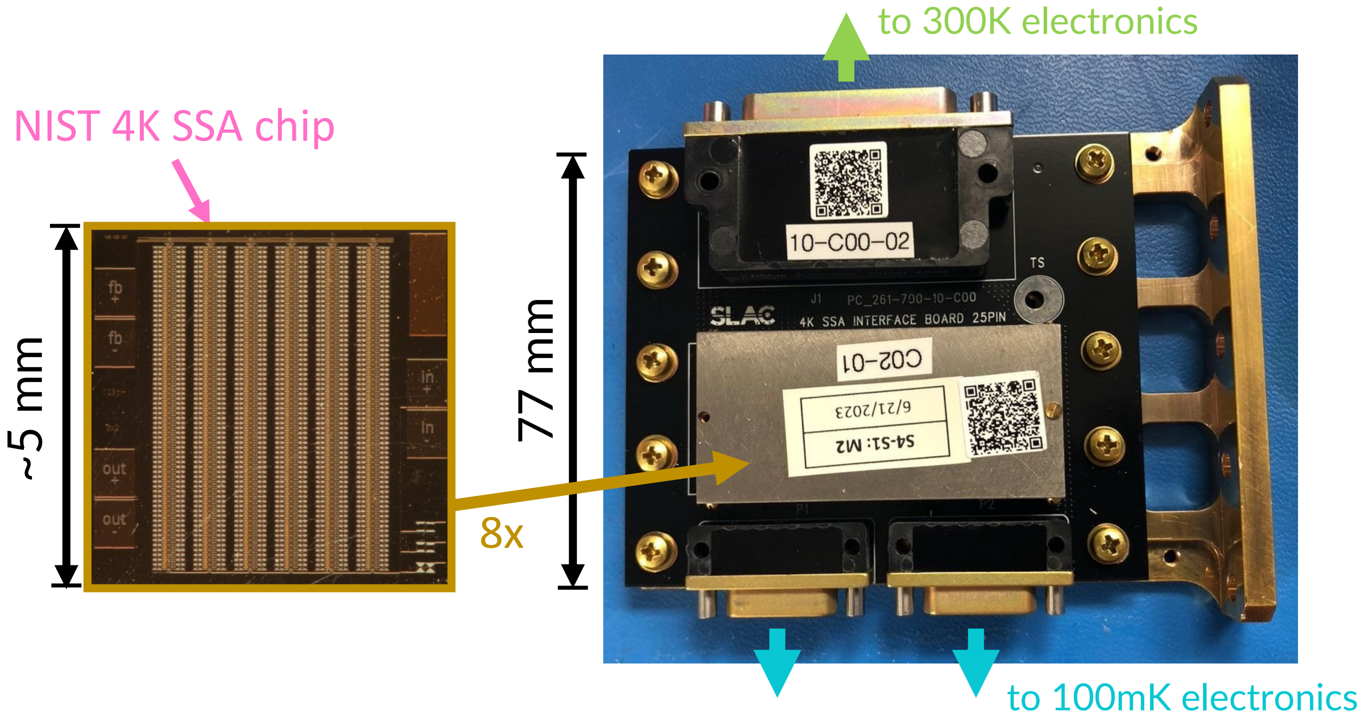
Dedicated SQUID series array (SSA) at 4K amplifies SQ1 signals for each column.

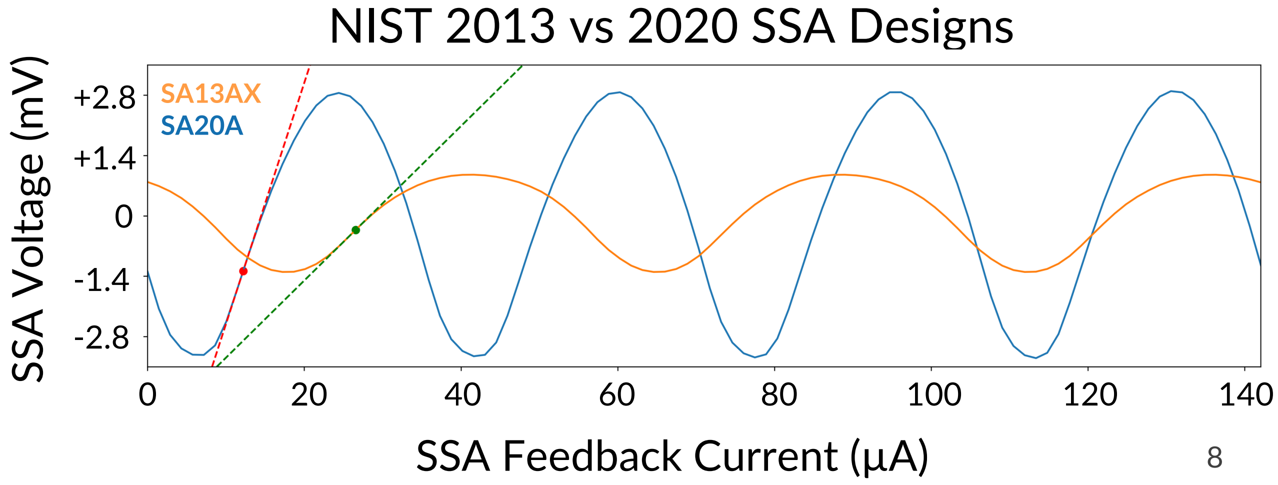
- Connects to 100mK (warm) electronics via superconducting (resistive) twisted pair.

Baselining new NIST designs (2020) with the potential for significantly more bandwidth and gain. [M. Durkin+, IEEE Trans. Appl. Supercon. 33 (5), 2023]

Key challenges / design drivers :

- SSA must be well shielded from magnetic fields and RFI.
- SSA ↔ warm electronics interface must have sufficient bandwidth to support multiplexing.





CMB-S4 readout – warm readout

Warm readout must control cold SQUID and TES bias electronics and read back TES signals without contributing appreciable noise.

- Firmware must provide PID SQUID controller, data transmission, and reliable control interface.

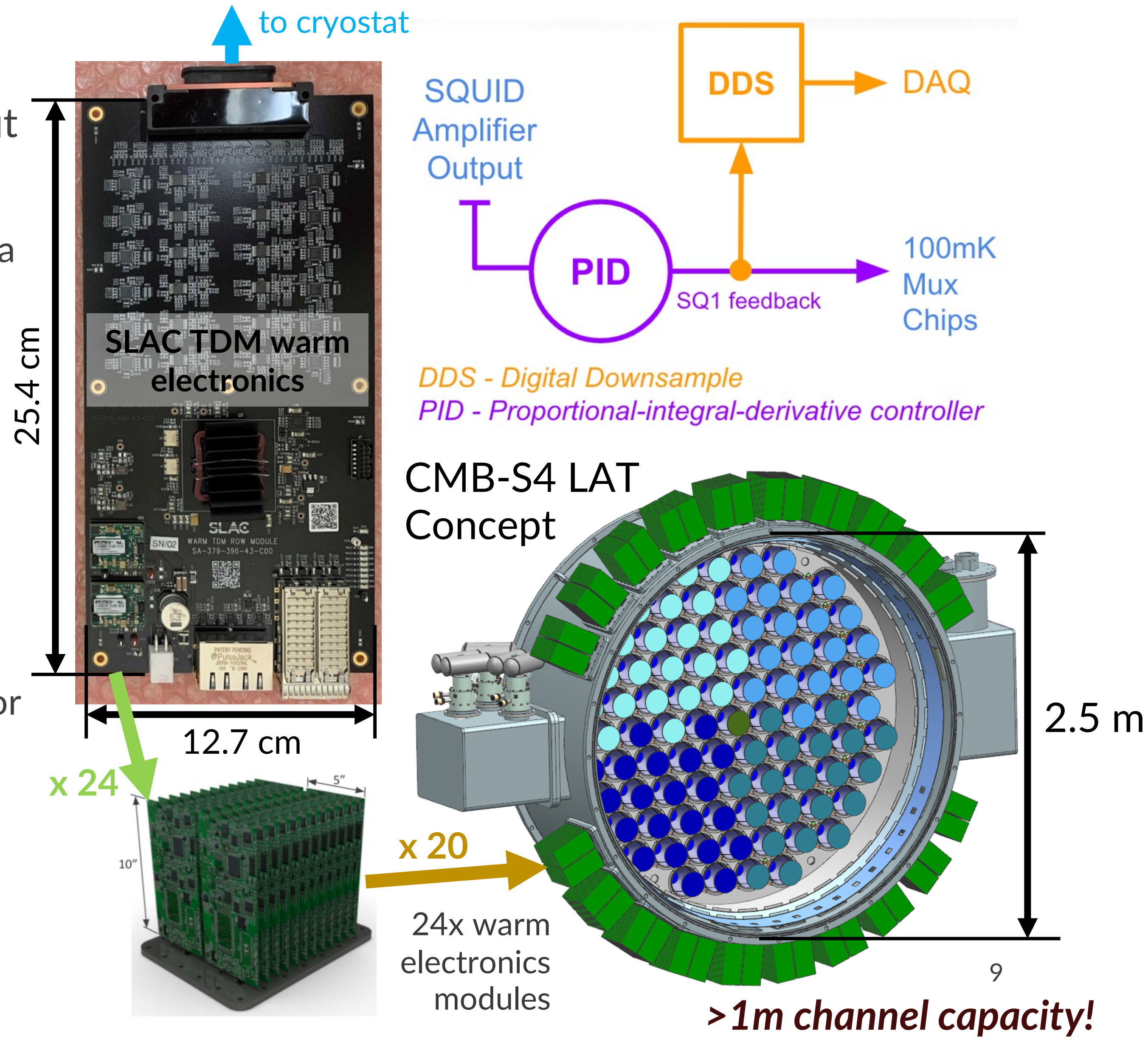
SLAC developing new TDM warm electronics

- Compact, modular, flexible approach.

[See poster at CPAD by Benjamin Reese & David Goldfinger]

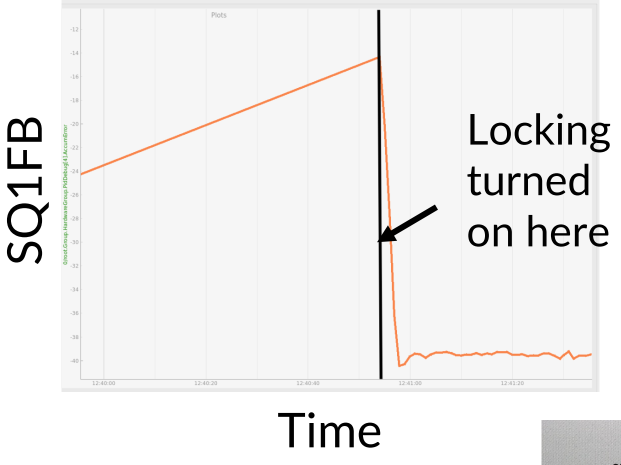
Key challenges / design drivers :

- Low frequency performance critical, particularly for small aperture receivers.
- Form factor must be kept small to fit on receivers.
- Need more bandwidth than legacy systems.

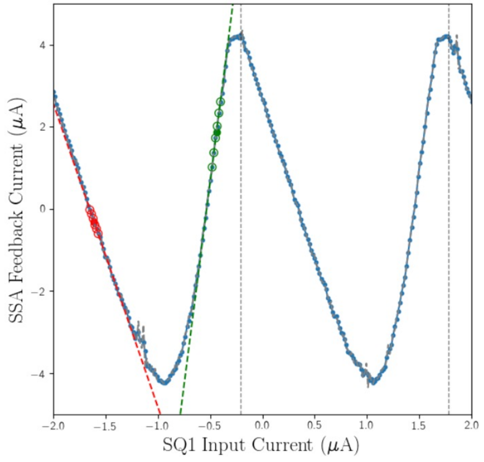


CMB-S4 readout string testing

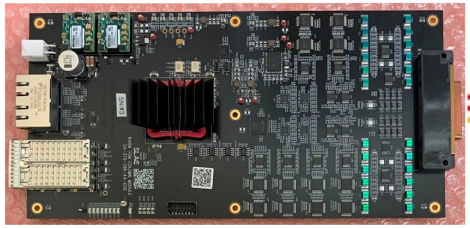
First two-stage SQUID locking with SLAC warm electronics!



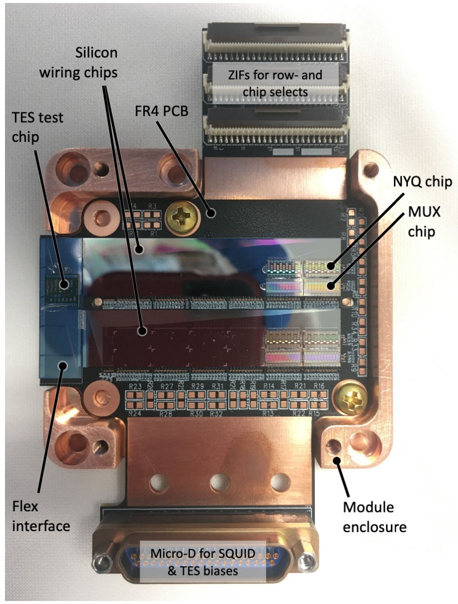
First 2-level 100mK MUX designed for CMB

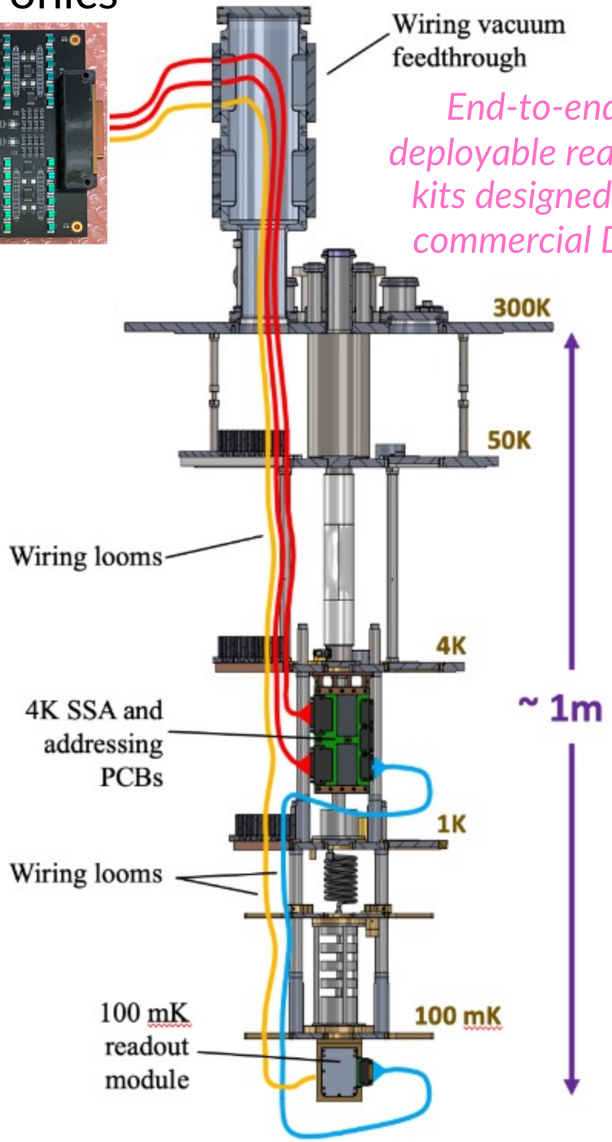


SLAC warm electronics



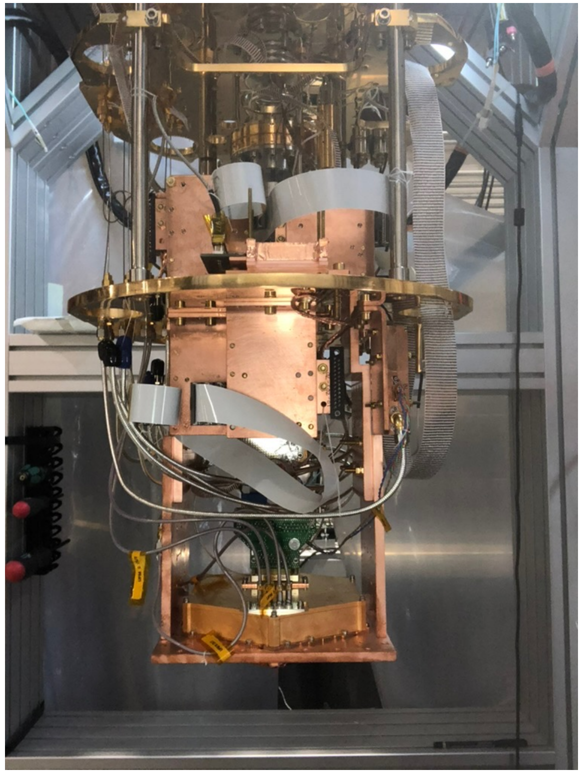
Prototype 100mK readout modules





End-to-end, deployable readout kits designed for commercial DRs

CMB-S4 readout developing at a fast pace on cryostats at SLAC, FNAL, UIUC, and UNM.



CMB-S4 near term readout focus

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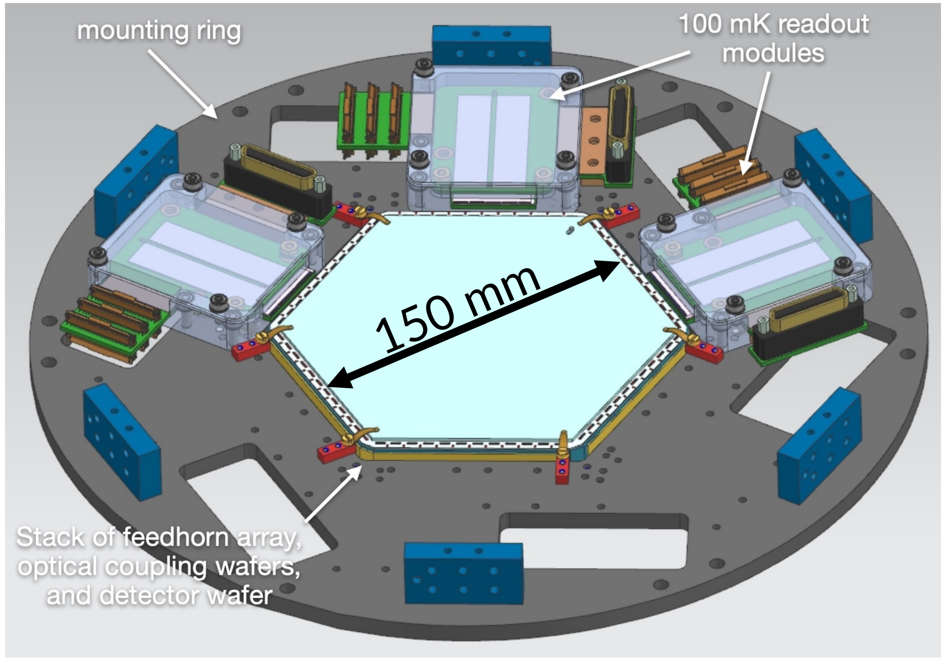
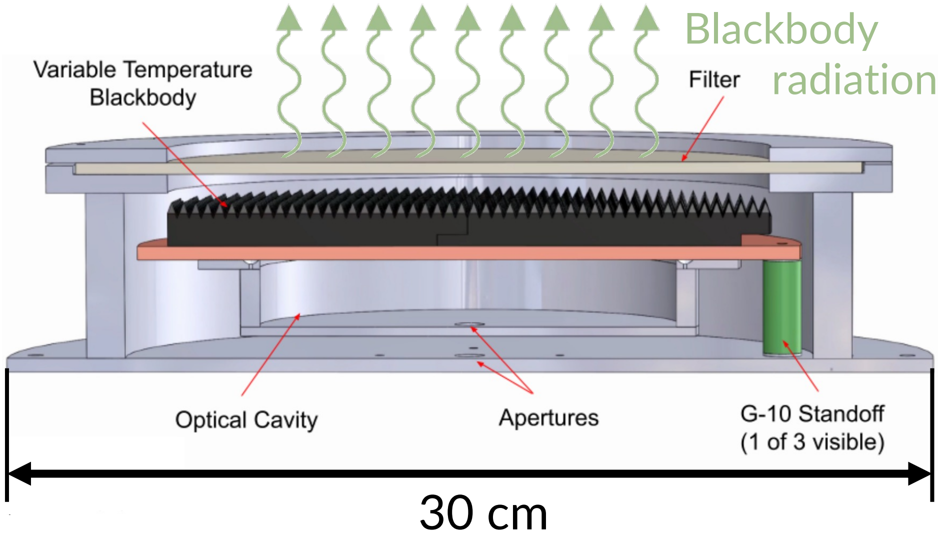
In progress: an end-to-end demonstration with full CMB-S4 detector wafers using prototype wafers and readout.

- "Flat module" pre-prototype allows wafer testing without high density superconducting flex.
- Enables early optical characterization of prototype wafers using variable temperature blackbody sources.



Next priorities for CMB-S4 readout:

- Characterize and build end-to-end model of baseline readout design using existing prototypes – critical for vetting design & setting requirements.
- Focus on deployable warm readout electronics and high density superconducting flexible cables.



Thank you!

CMB-S4 Collaboration

- >400 members
- 116 institutions
- 19 countries
- … and counting!

https://cmb-s4.org

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