Technology R&D* for CMB-S4

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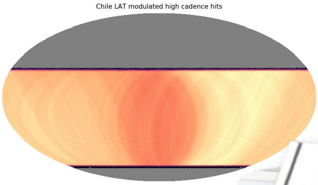
CMB-S4 Science Goals (informal edition):

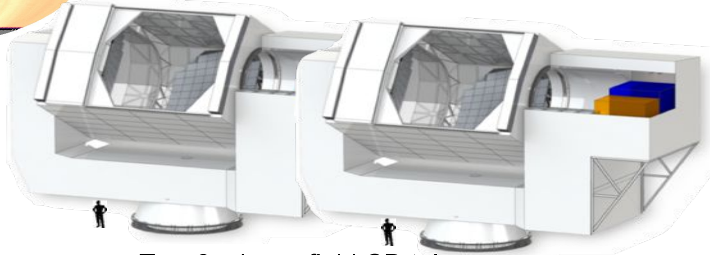
- Search for the CMB polarization signal from Cosmic Inflation
- Search for the signatures of light relic particles in the CMB angular power spectra
- Take a census of growth, via SZ galaxy clusters, to much lower mass and higher redshift.
- Bust open the window on millimeter-wave transient sources.

"Snowmass" CF5 Instrumentation Workshop, May 6, 2022

CMB-S4 Project In A Nutshell

A deep-wide N_{eff} and Legacy Survey targeting 60% of sky from Chile, using 2 x 6m telescopes, with ~270K detectors in 6 bands.

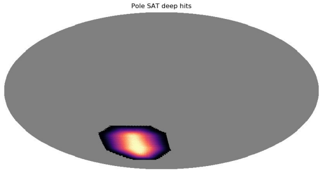




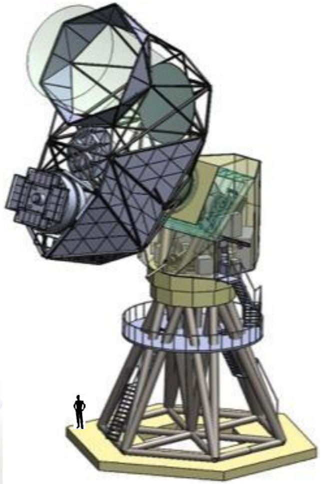
Two 6m large-field CD telescopes

Chile

An ultra-deep “r” survey targeting ~3% of the sky from the South Pole, using 18 x 0.5m small refractor telescopes with ~150K detectors in 8 bands and a dedicated de-lensing 5m telescope with ~130K detectors in 7 bands.



18 x 0.5m small telescopes (3 per cryostat)

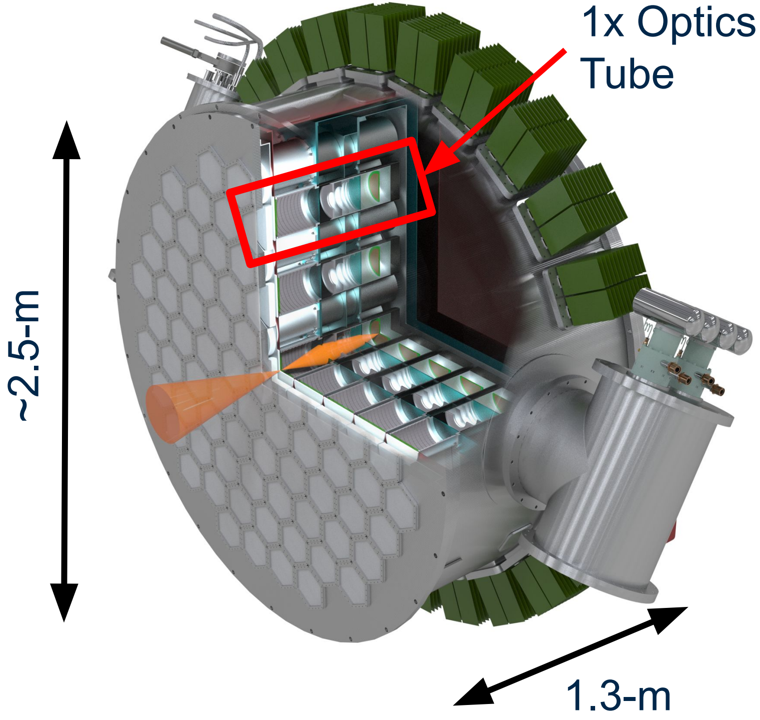


5m TMA

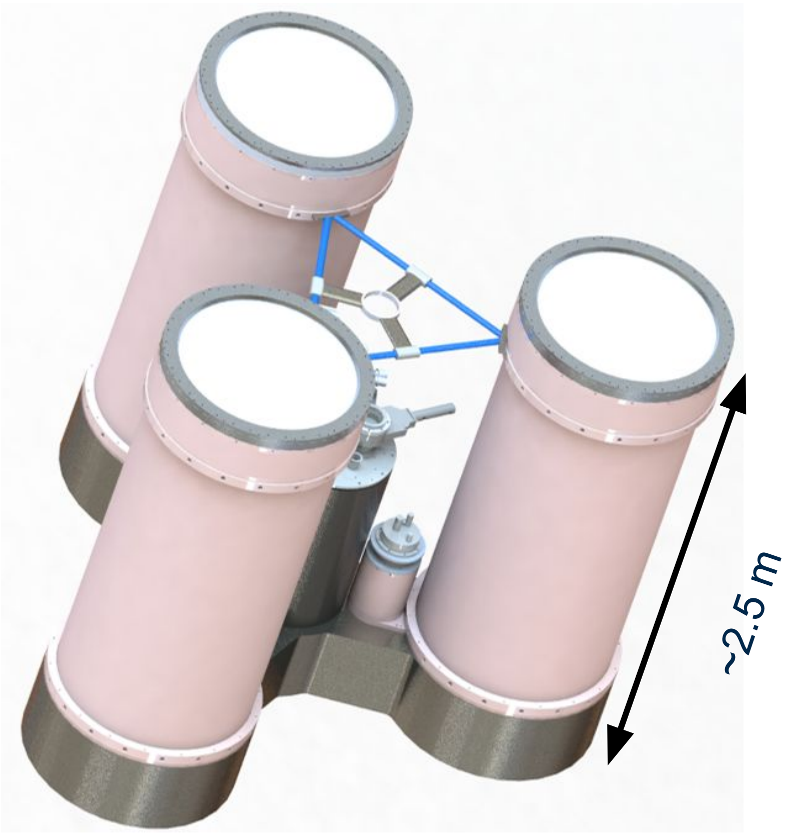
South Pole

For comparison:
AdvACT (9K det, 3 wafers),
SPT3g (16K det, 10 wafers)

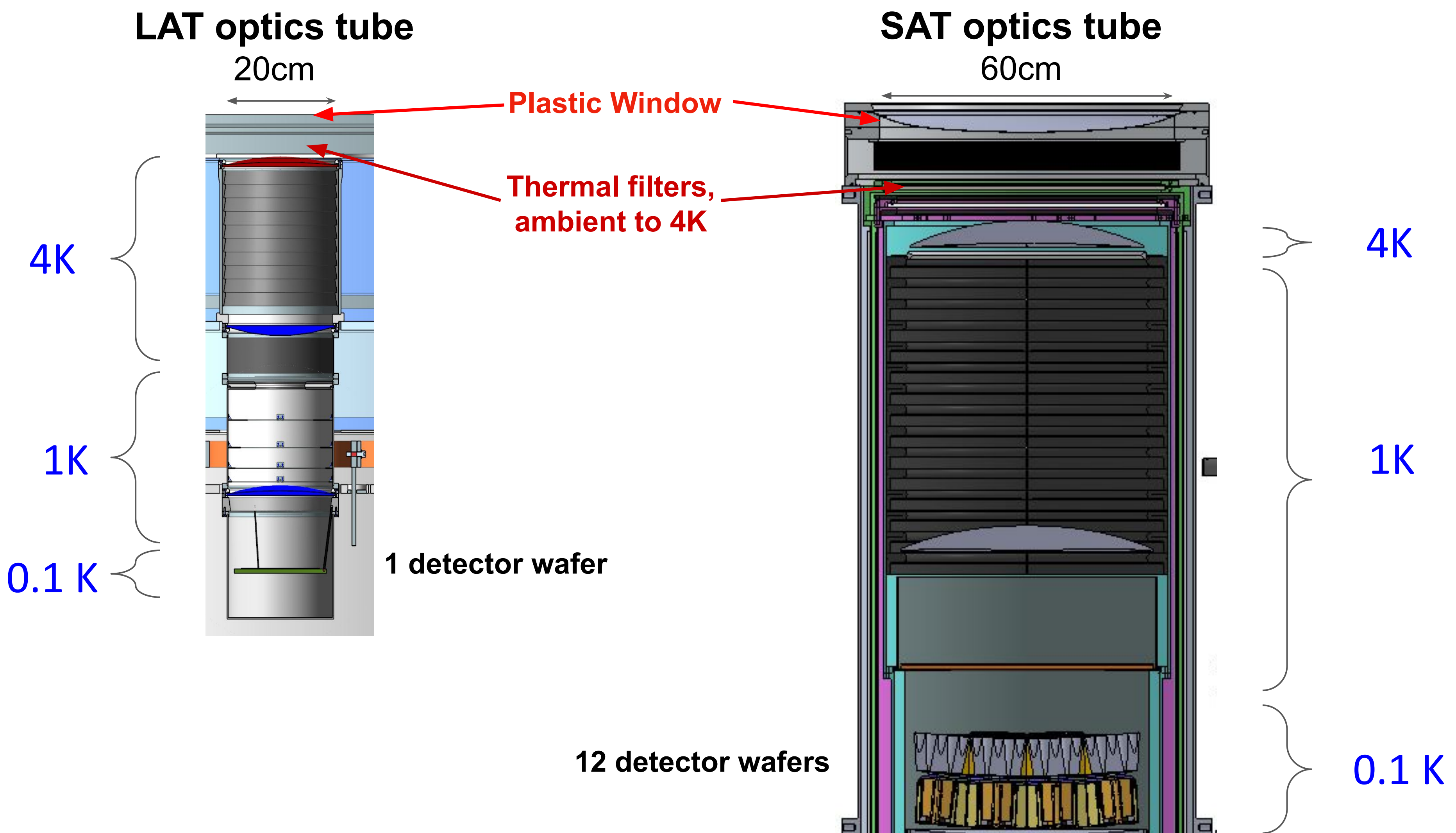
Large Cryogenic Cameras



LAT Receiver - 85 tubes



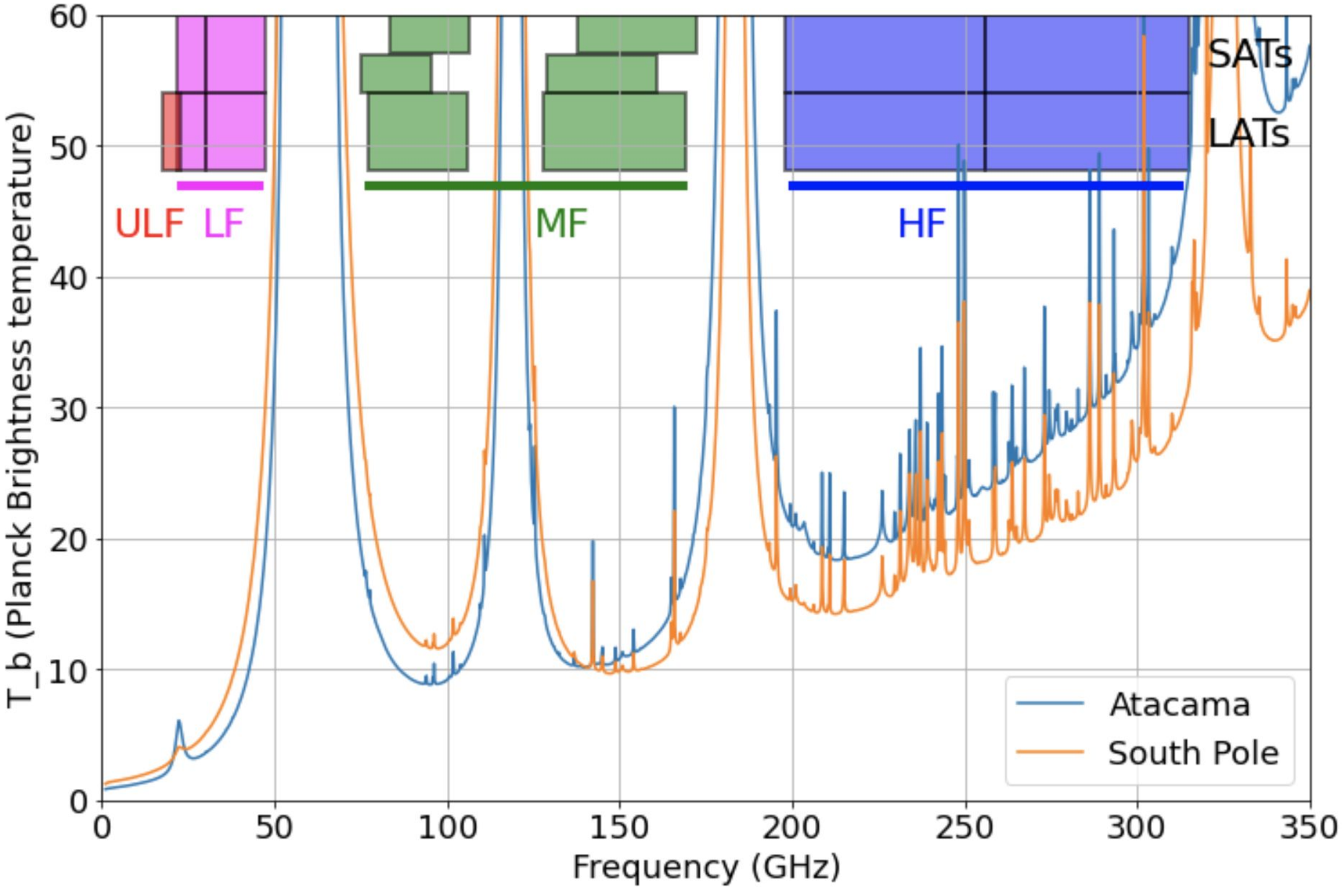
SAT Receiver - 3 tubes



LAT optics tube
20cm
SAT optics tube
60cm
Plastic Window
Thermal filters,
ambient to 4K
4K
1K
0.1 K
1 detector wafer
12 detector wafers
4K
1K
0.1 K

Detector wafer count per band: **Total wafer count = 471**

4 ULF 49 LF 306 MF 112 HF



For comparison: AdvACT (3 wafers), SPT3g (10 wafers)

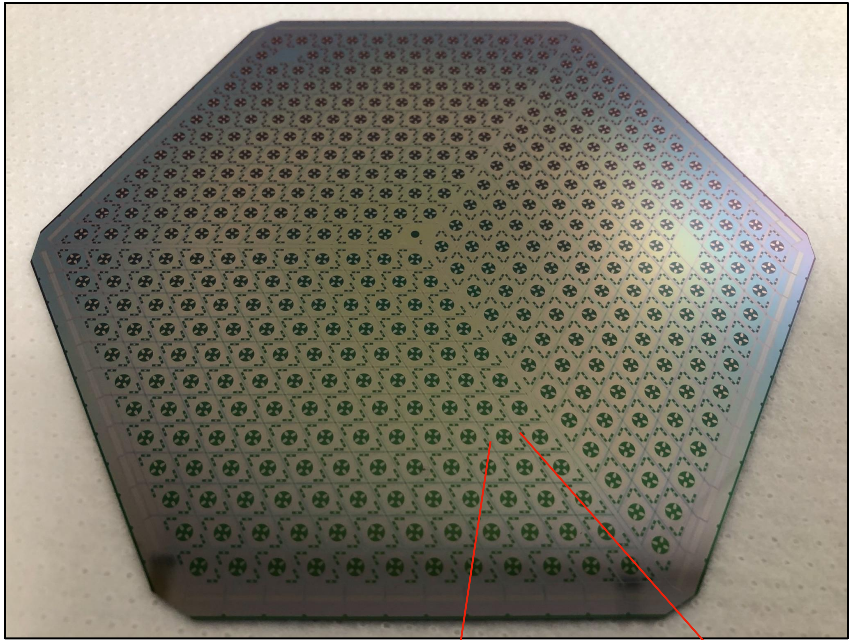
CMB-S4's "enabling, niche technologies":

- Superconducting TES bolometers, in bulk.
- Dichroic, dual-polarization pixels.
- Time-domain mux cryogenic SQUID-based readout, in bulk.
- High-throughput millimeter-wave receivers with
  - low loss
  - effective thermal infrared heat-load management
  - low added photon loading
- Reliable 100mK cryogenics
- High-throughput millimeter-wave telescopes, especially with "gapless mirrors"

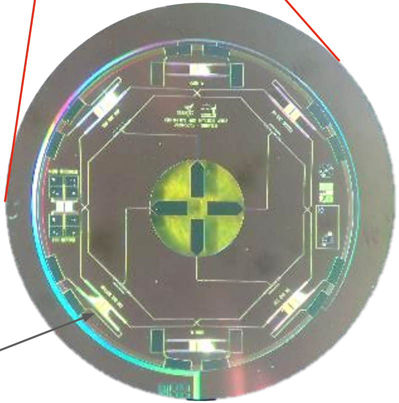
Superconducting TES Detectors

Key enabling features:

- Quantity, =>
  - mechanical/electrical yield,
  - ability to repeatedly hit required specs (efficiency, noise, saturation power, bands…)
  - at multiple fab facilities
- Uniformity across large wafers
- On-silicon bandpass filters and splitters
- "Calibration" TES with 2nd, higher transition temperature.



150mm Si wafer



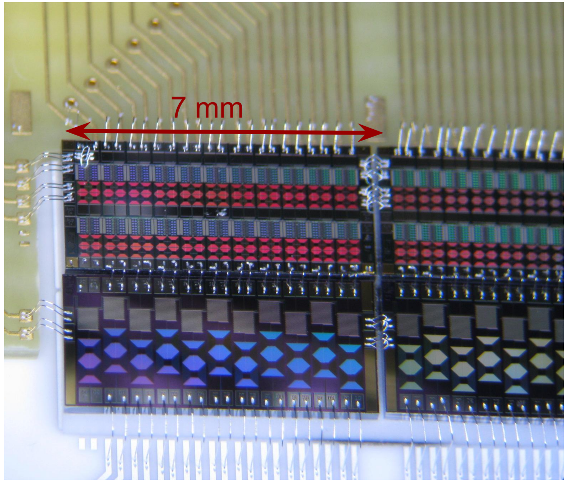
2 color,
2 polarization
pixel

TES

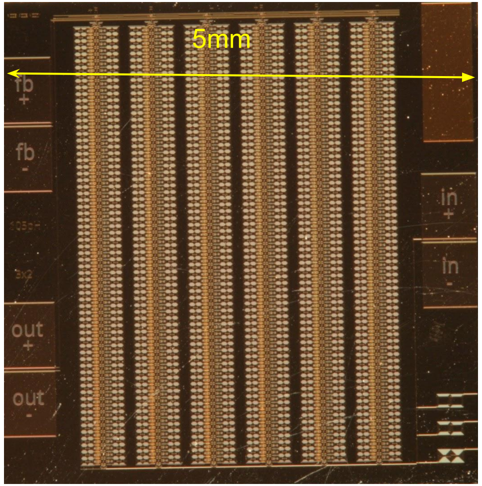
Time-division SQUID MUX Readout:

Chosen from three alternatives because it was the most mature option.

Challenges: SQUID quantity, reliable high-density superconducting flex cables.



100mK SQUIDs,
1 per detector
~60K boards needed



4K SQUID arrays,
1 per ~60 detectors
~8000 arrays needed

100mK superconducting flex cables, 2mil pitch

Millimeter-wave cryo-optics:

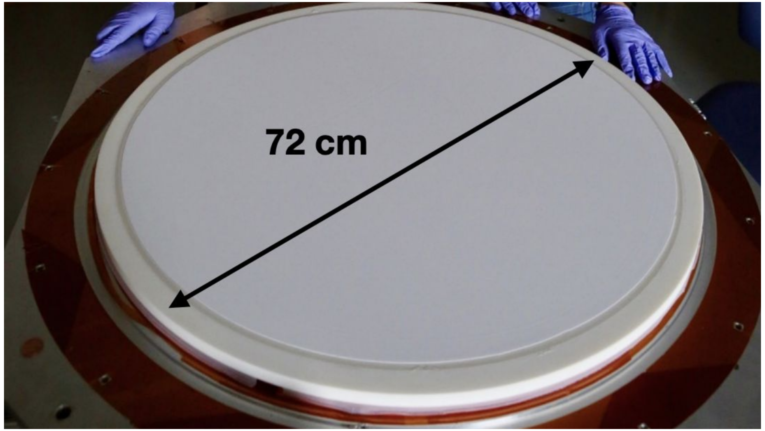
We want high efficiency in all the optics to avoid losing CMB photons (signal).

We especially want low loss in the T > 10K optics to avoid the additional penalty of adding photons, which adds noise.

Current baseline: 35% to 65% of the optical power is from the instrument, rather than the sky (= atmosphere + CMB).

=> R&D for better low-loss millimeter-wave windows and thermal IR filters (which are at T>10 K), is well motivated.

(Mirror gaps are also a significant emitter for the CHLAT low frequency bands.)



AR-coated Alumina IR filter
(SPT, U. Illinois)

"Enabling" Cryogenic systems:

- Pulse-tube coolers to 4K *(20 years ago this was LHe!)*
- Commercial dilution refrigerators to 100mK
  - Colder => better sensitivity at low frequencies where photon noise is low.
  - No "recycling" time lost, as with many current 300mK 3He sorption systems)

- Remote sites => Electrical Power is supplied by diesel generators.
  Fuel = $$$

~50% of entire electrical power budget is for cryogenics

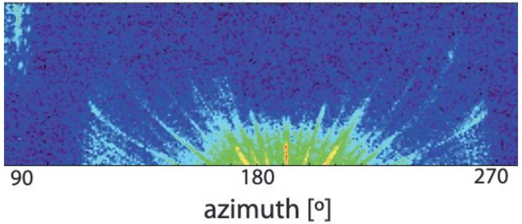
=> lower power cryogenics is very desirable.

Large monolithic mirrors

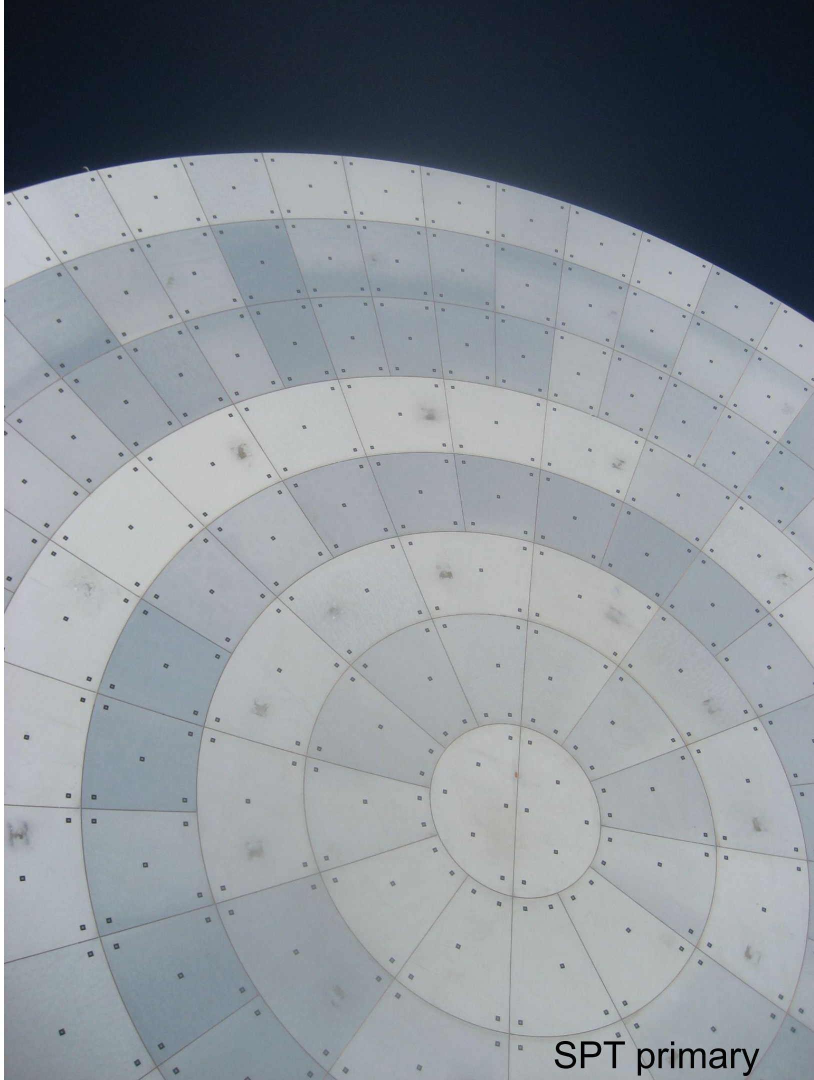
All CMB telescopes > 3m in size so far have been constructed from discrete panels, with ~1mm gaps, because machining large mirrors to the required precision is… hard.

Those gaps are **emissive** (photon loading!), and cause large-angle **"diffraction sidelobes"** by virtue of the grid of narrow line features they impose on the primary reflected E-field.

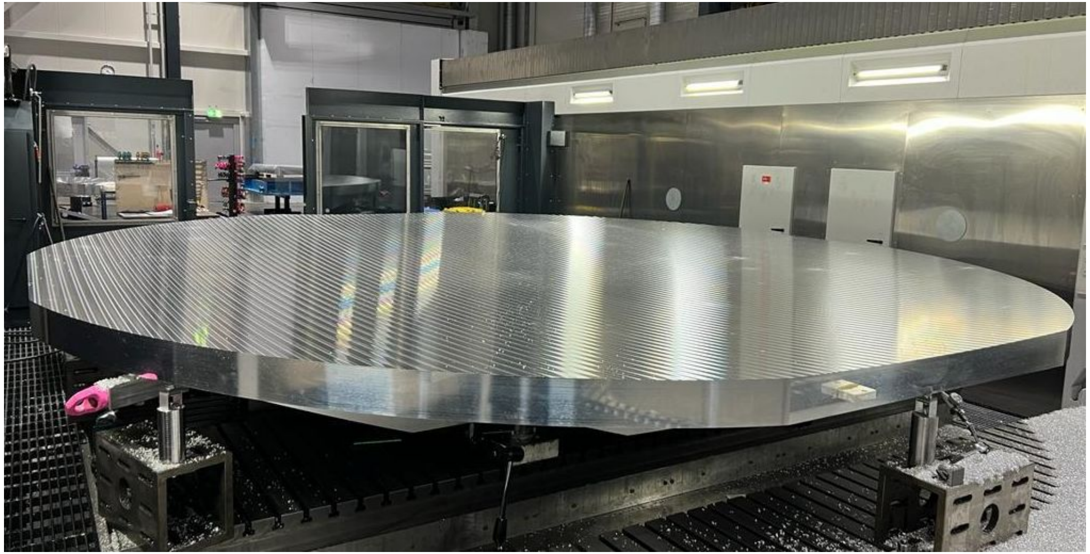
Eliminating those gaps by using a large monolithic ("gapless") mirror solves both of these problems. **The elimination of those wide-angle sidelobes is a critical step in using the TMA for the large angle "r" science.**



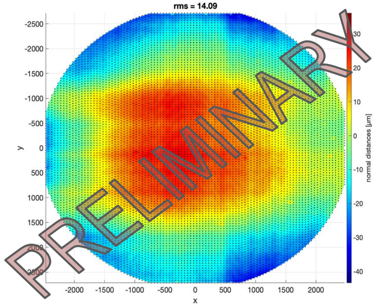
SPT "gap" sidelobe pattern, McMahon & Mehl



The TMA working group has designed and had a contractor machine a 5m "monolithic" primary mirror! *(Machined from two halves, bolted together before final machining pass)*



Preliminary rms, on machine by contractor, is 14 microns, well below spec. *(Still to be verified by team)*



Summary

- CMB-S4 is enabled by a variety of important technologies that we are working to produce in larger quantitities than before.
  - Our baseline model only requires performance similar to previous-generation experiments.

- Some areas for performance improvements:
  - Improved optical efficiency, especially of the warm components, will improve sensitivity.
  - Gapless mirrors will help large-aperture telescopes to contribute to low-ell (cosmic inflation) science.
  - Cryo-systems power consumption improvements would reduce operations costs.

End