Recent developments of commercially fabricated horn antenna-coupled Transition Edge Sensor bolometer detectors for next generation Cosmic Microwave Background polarimetry experiments

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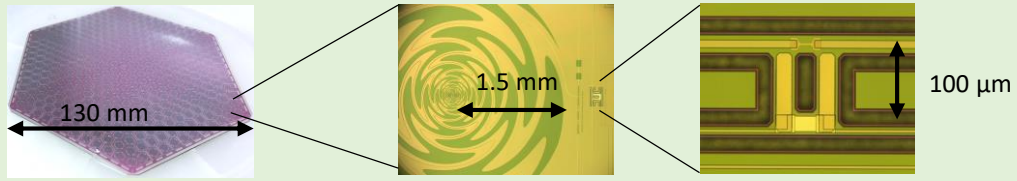
Motivation

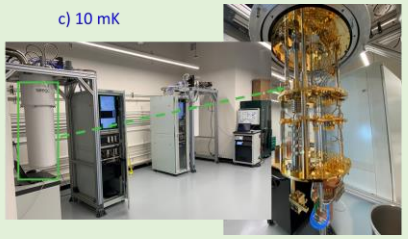
- Next generation Stage-IV ground based CMB experiment, CMB-S4, will make a definitive measurement of CMB polarization with O(500,000) detectors
- **Commercial micro-fabrication foundry's high fabrication throughput enables this order of magnitude increase in detector count**
- CMB-S4 recently **selected horn antenna-coupled TES bolometer detector** for the base line detector technology
- Seeqc have successfully fabricated sinuous antenna coupled TES detector arrays previously. We adapted most of the fabrication processes to fabricate horn coupled detector arrays



Sinuous antenna detector array | **Pixel details** | **XeF2 released TES bolometer**

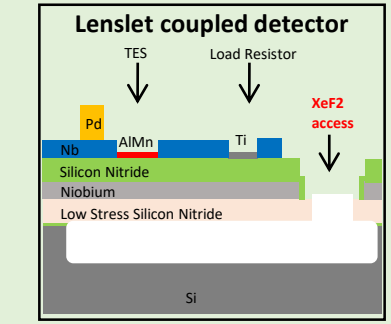
Commercial TES bolometer detector fabrication

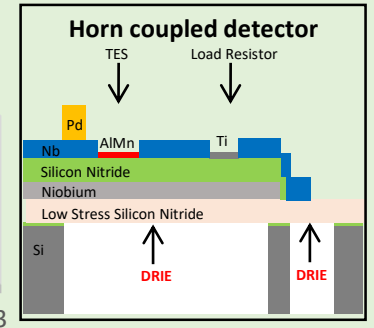
- Seeqc Inc. (https://seeqc.com/) is a company based in New York state that specializes in development and fabrication of superconductor electronics
- Engineers at Seeqc have extensive expertise and experience in superconducting microfabrication
- Seeqc Inc. recently procured DRIE etcher for through wafer fabrication process
- Every fabrication steps was done at Seeqc Inc.
- Seeqc also has multiple dilution refrigerators for cryogenic characterization of devices
- Seeqc uses industrial-scale fabrication method to increase throughput and reduce cost per wafer
- Commercial techniques for stringent quality assurance improve uniformity, repeatability, and yield by using high throughput fabrication and metrology equipment

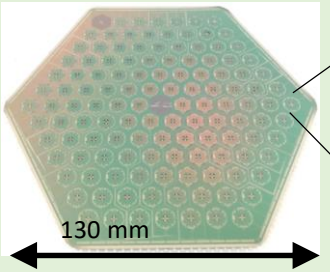


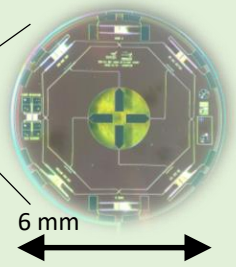
Horn couple detector fabrication

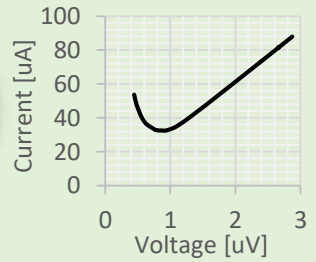
- Fabrication steps for lenslet+sinuous antenna coupled detector and horn coupled detector are identical except for how silicon substrate is etched to release TES bolometer
  - Lenslet coupled detector: XeF2 etch
  - Horn coupled detector: DRIE etch
- We made two changes to the fabrication process:
  - Thicker low stress silicon nitride to survive DRIE process
  - Back side lithography for DRIE process
- We used stealth laser dicing technique offered by GDSI to dice large hexagonal arrays without breaking released membranes
- TES bolometers successfully operated
- **We fabricated prototype detector arrays for the CMB-S4 project**





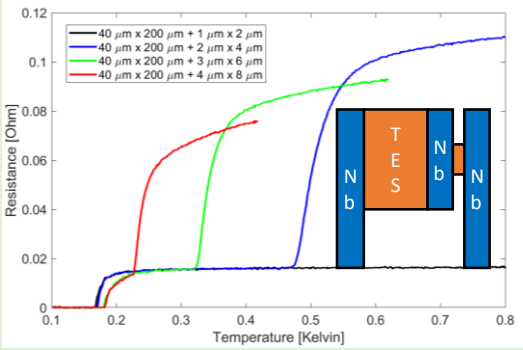






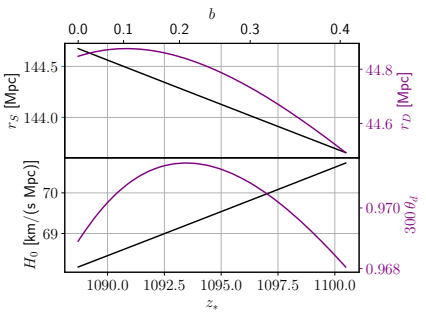
Dual Tc TES bolometer

- We have also developed a design to achieve TES sensors with two different superconducting temperatures (Tc) without changing the fabrication process.
- We modified Tc using a superconducting proximity effect between Nb and AlMn alloy. TES material, AlMn alloy, sandwiched between Nb gaps (1 um ~ 4 um) to raise its Tc.
- Dual-Tc TES sensors are useful when same the detectors are required to operate under different incoming power.

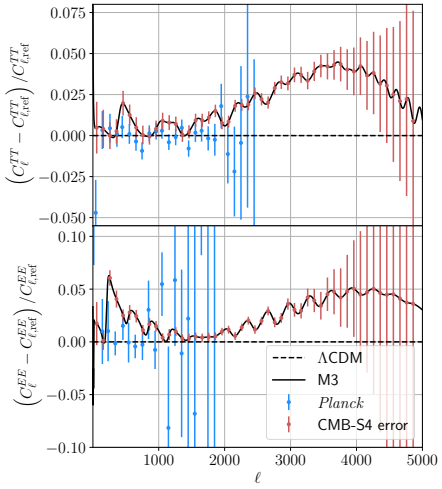


Small-scale Clumping at Recombination and the Hubble Tension

Earlier recombination ($\langle n^2 \rangle > \langle n \rangle^2$) $\Rightarrow$ smaller sound horizon $r_S \Rightarrow$ higher H_0 at $\theta_s = \text{const}$.



But different damping scale: comov. r_D and angular $\theta_d = r_D/r_*$, clearly detected with CMB-S4 precision.



Recent Progress on Frequency Domain Multiplexed Readout of TES Bolometers

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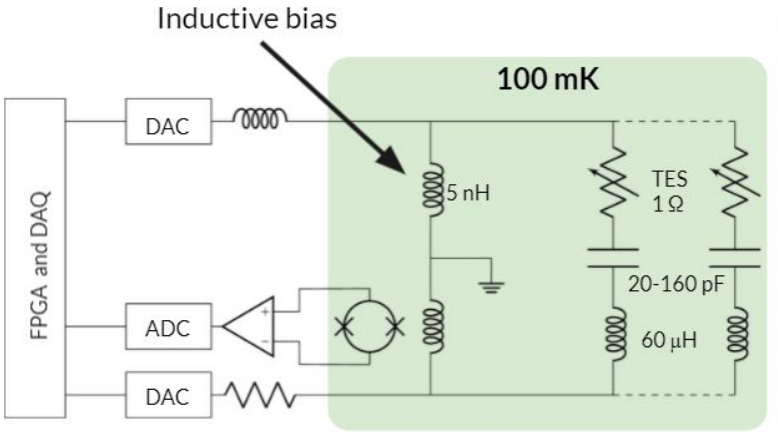
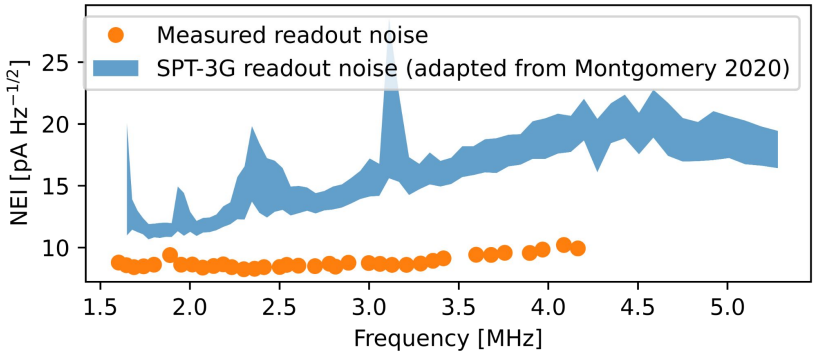
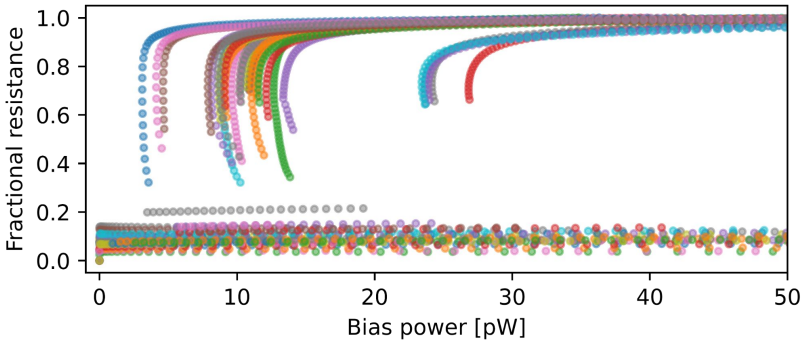
[6] National Institute of Standards and Technology
[7] High Energy Accelerator Research Organization
[8] McGill University

- Demonstration of lowest readout noise to date with DfMux
- ~5x reduction in residual superconducting resistance
- TES operation with inductive bias element







Millimeter-Selected High-z Proto-Clusters in the South Pole Telescope Survey

Scott Chapman, SPT-SMG Collaboration

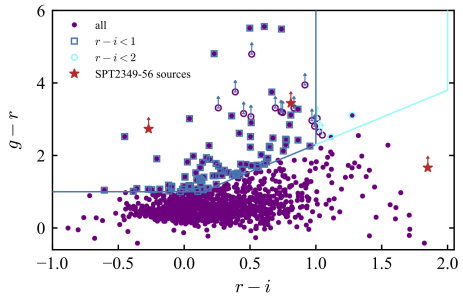
Rotermund et al. 2021, MNRAS, 502, 2, 1797 Hill et al. 2020, MNRAS, 495, 3, 3124

The South Pole Telescope

- 1.4, 2, & 3mm 2500 deg^2 SPT survey
  - discovery of rare, yet bright millimetre-selected sources
  - ~ 90% are gravitationally lensed
  - **~ 10% break-up into several individual galaxies**
- Proto-clusters (PC)
  - high-z progenitors to clusters - most massive virialized structures in the universe
  - high mass densities, high merger rates, expected to host massive galaxies observed as luminous starbursts
  - excellent laboratory to study star formation and

Lyman-Break Galaxies (LBGs)

- UV-bright (rest-frame) galaxies presenting a strong Lyman break in their SED
  - various colour-selections can be adopted to search for LBGs within a narrow redshift window
    - very effective at identifying optically-selected proto-clusters
  - colour-criteria for $z \sim 4$ proto-clusters
    $g - r > 1$; $-1 < r - i < 1$; $1.5(r - i) < g - r - 0.8$

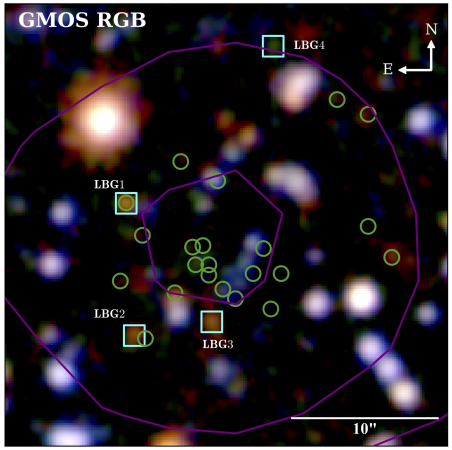


Do millimetre-selected proto-clusters display a LBG overdensity?

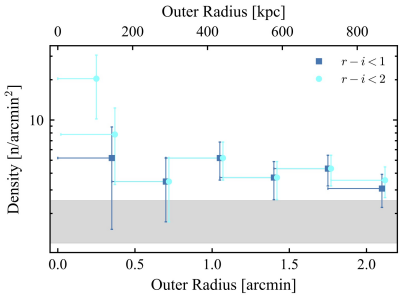
SPT2349-56 at z = 4.3

See talk 021 in cosmology session by Ryley Hill

- Brightest proto-cluster of the SPT-PC sample
  - 23 SMGs within its core - no larger than the Milky Way dark matter halo!
    - GMOS g,r,i-band image
    - LABOCA: purple contours
    - ALMA SMGs: green circles
    - LBGs: cyan squares



- Optical follow-up in Gemini-GMOS g,r,i-bands
  - SMGs are faint/undetected in optical/near-IR bands
  - revealed a strong overdensity of LBGs within the inner core, and a subsequent modest overdensity out to 3-arcmin-radius
  - barely a 3σ significance following the Toshikawa et al. (2018) detection criteria



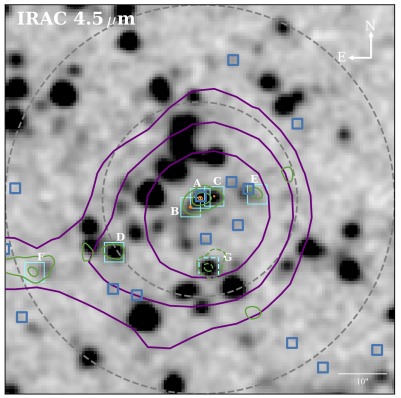
Conclusions from SPT2349-56

Exceedingly difficult to identify SPT2349-56-like, millimetre bright proto-clusters in large-field surveys through optical overdensity techniques

Important to search for early formative structures at millimetre wavelengths

Further SPT-PCs

- Will the findings of SPT2349-56 hold for other sub-millimetre selected proto-clusters?
- 9 proto-cluster candidates in the SPT-PC sample
- SPT0457-49 may be a close analog to SPT2349-56
  - 6 SMGs identified in shallow ALMA data, z = 4
  - early evidence of a LBG overdensity within the core larger than that of SPT2349-56
    - IRAC 4.5 μm image
    - LABOCA: purple contours
    - ALMA SMGs: green contours
    - LBGs: blue squares



Searches for LBGs in further SPT-PC candidates is ongoing, with the goal of putting these systems in context of early structure formation and how they may differ from optically-selected proto-clusters