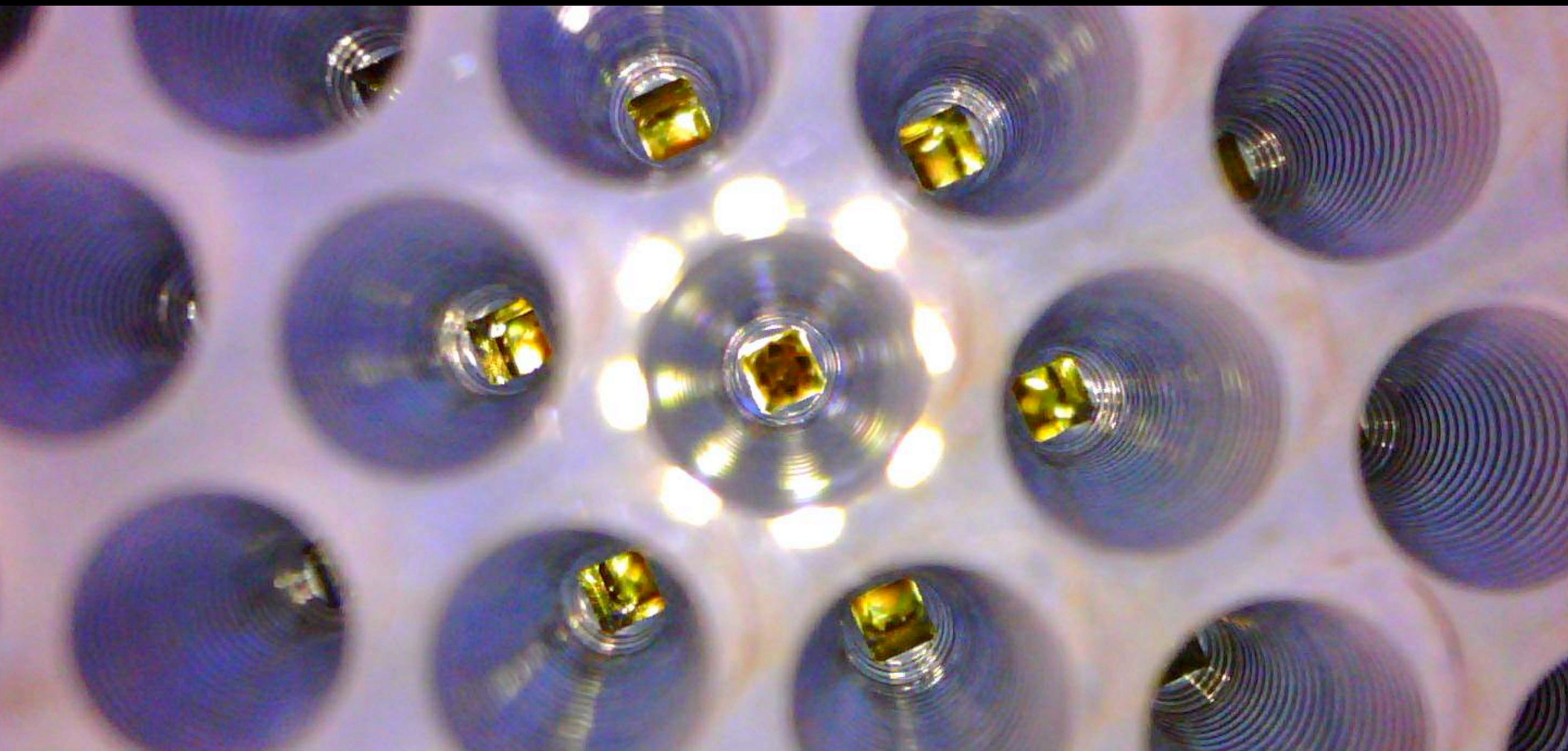
Superconducting Detector Arrays for Cosmic Microwave Background Measurements

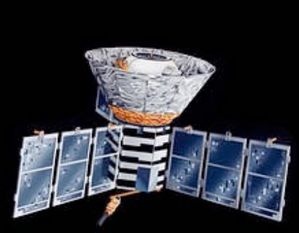
Michael Niemack, Cornell University Physics and Astronomy Departments

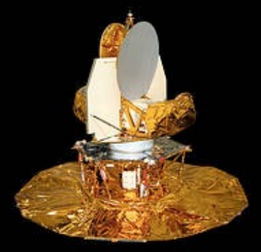
15th Pisa Meeting on Advanced Detectors – May 26, 2022

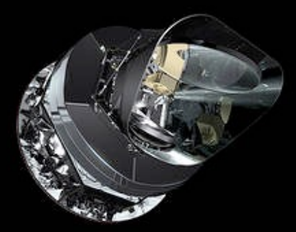


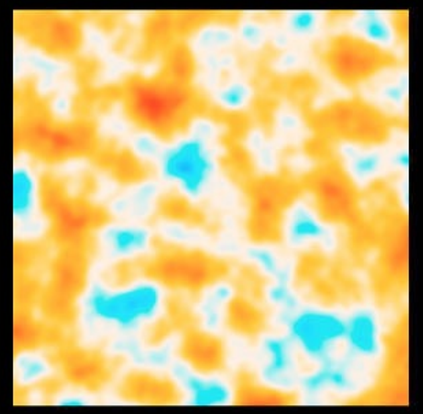
Primary CMB Anisotropies

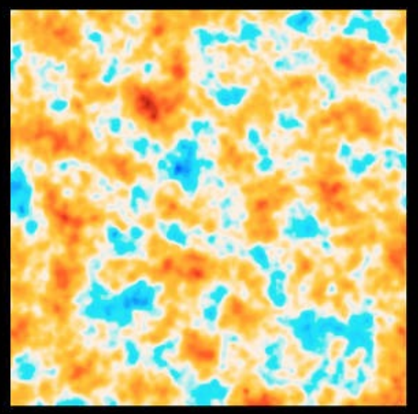
- Primary CMB anisotropies contain signatures of early universe physics











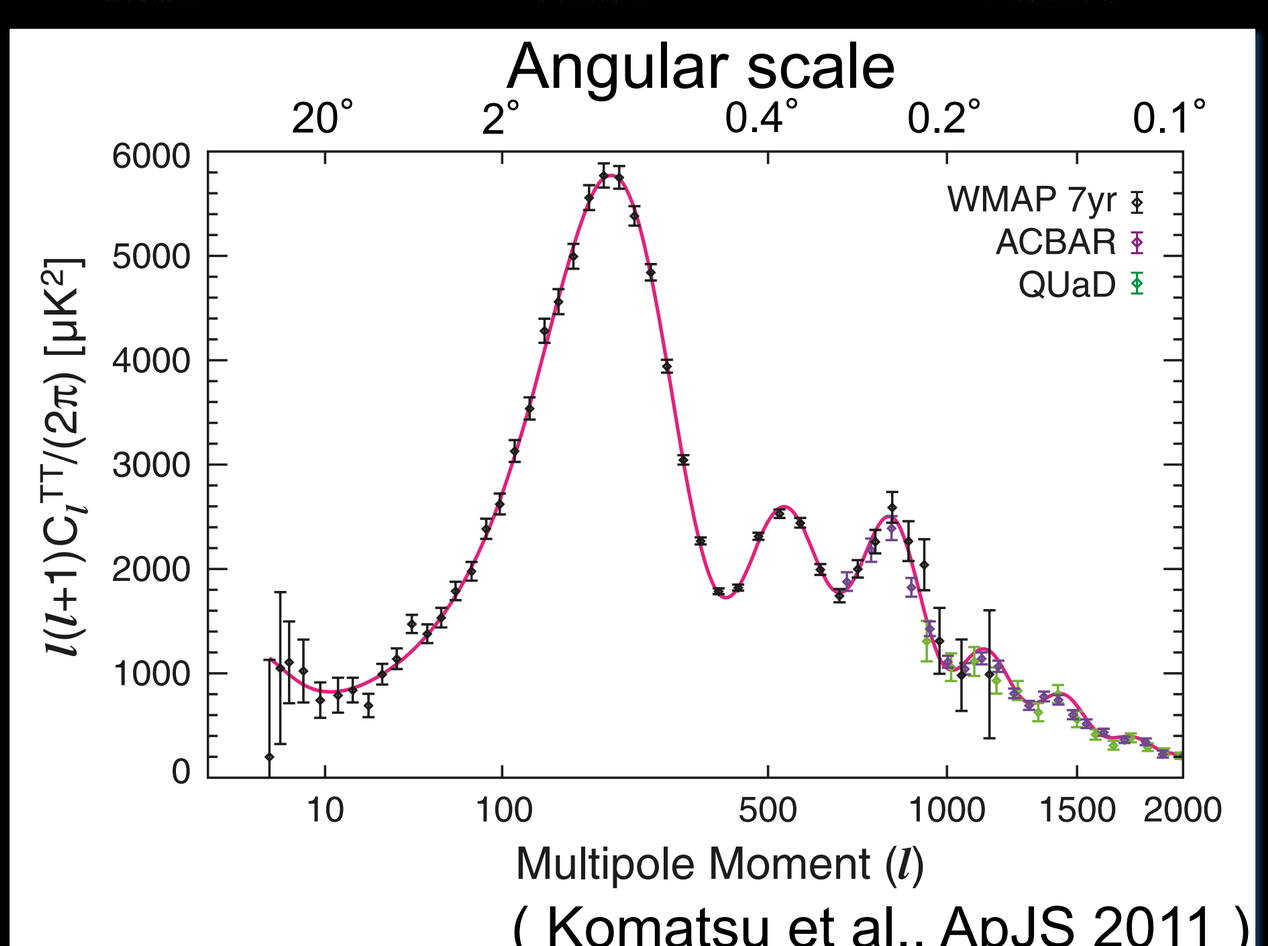
COBE WMAP Planck

- Power spectrum

$$\delta T(\theta,\varphi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi)$$

$$C_l = \frac{1}{2l+1} \sum_m |a_{lm}|^2$$

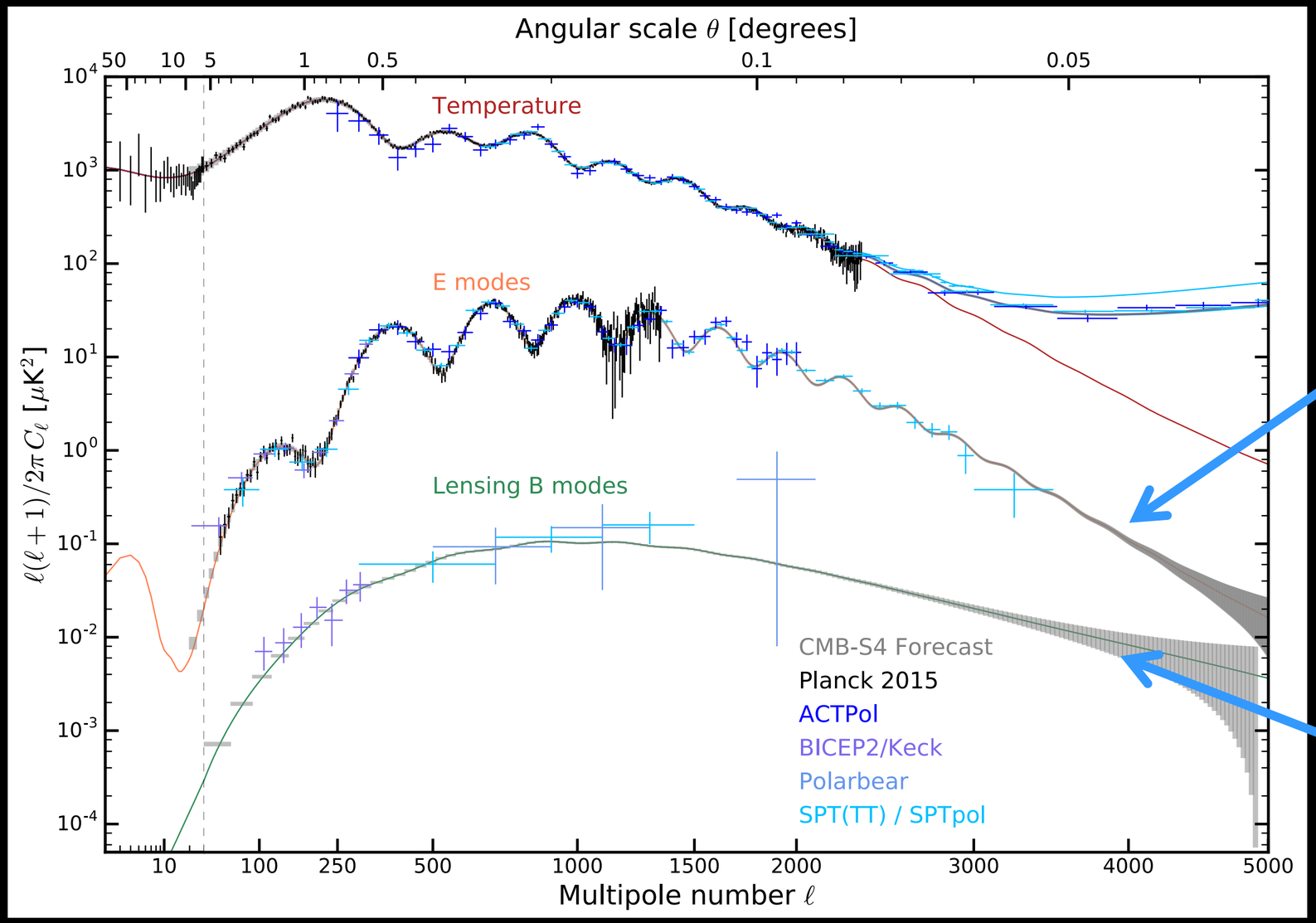
- ΛCDM 6 parameter model
  - $\Omega_m h^2$, $\Omega_b h^2$, Ω_Λ, τ, n_s, Δ_R^2



(Komatsu et al., ApJS 2011)

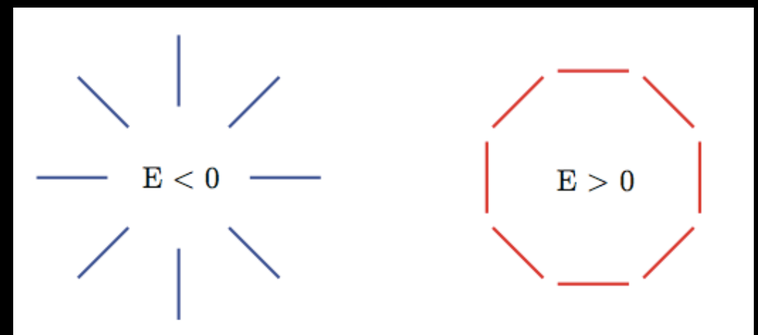
Current CMB Survey Research

Temperature & Polarization Power Spectra

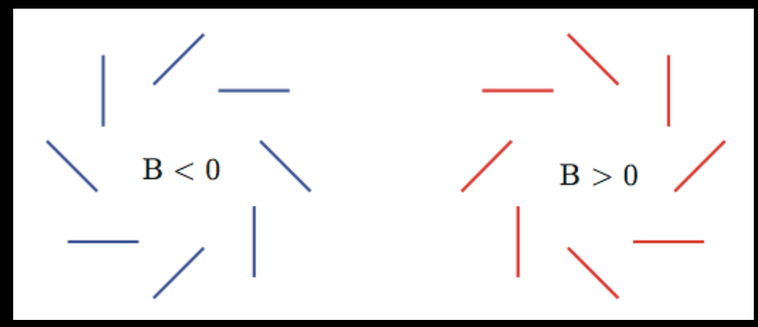


Polarization Anistotropies

Curl free ‘E-modes’

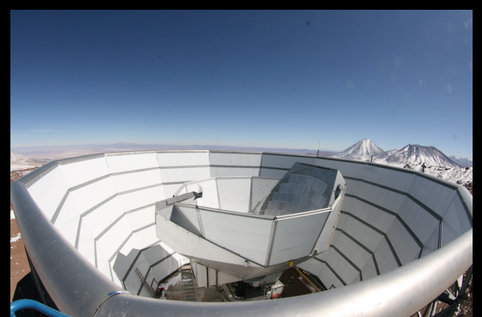


Divergence free ‘B-modes’



Atacama:

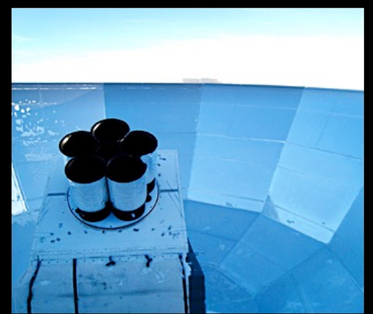
ACT – 6m



SA – 2.5m

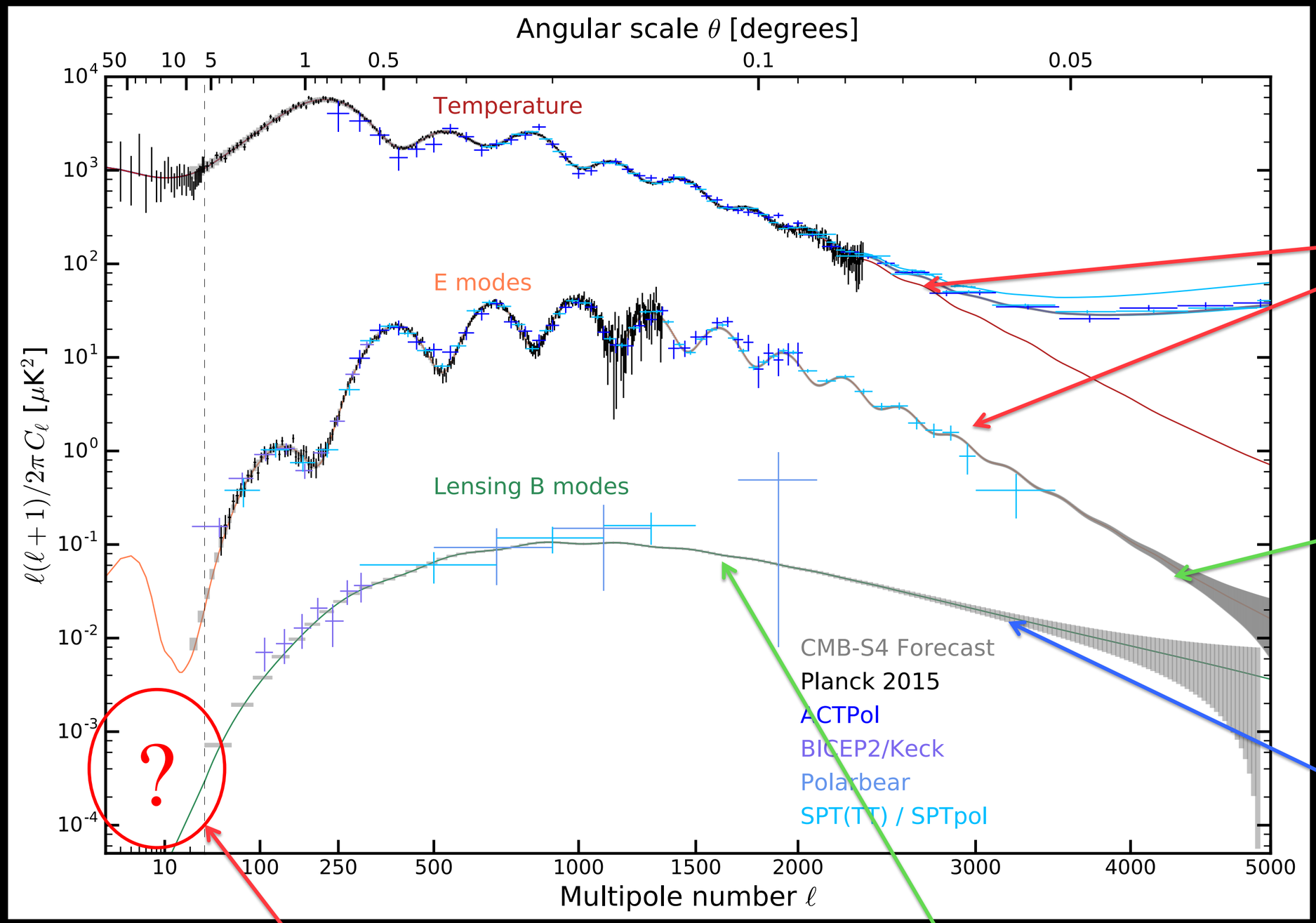
South Pole:

Keck – 0.5m



SPT – 10m

Current & Future CMB Survey Research



Hubble Constant
H_0

Light relics (ν, DM)

Early
Dark Energy

Cosmic Structure

Smoking gun of inflation?
r

(CMB-S4 Science Book, arXiv:1610.02743)

~ 10^1 meters

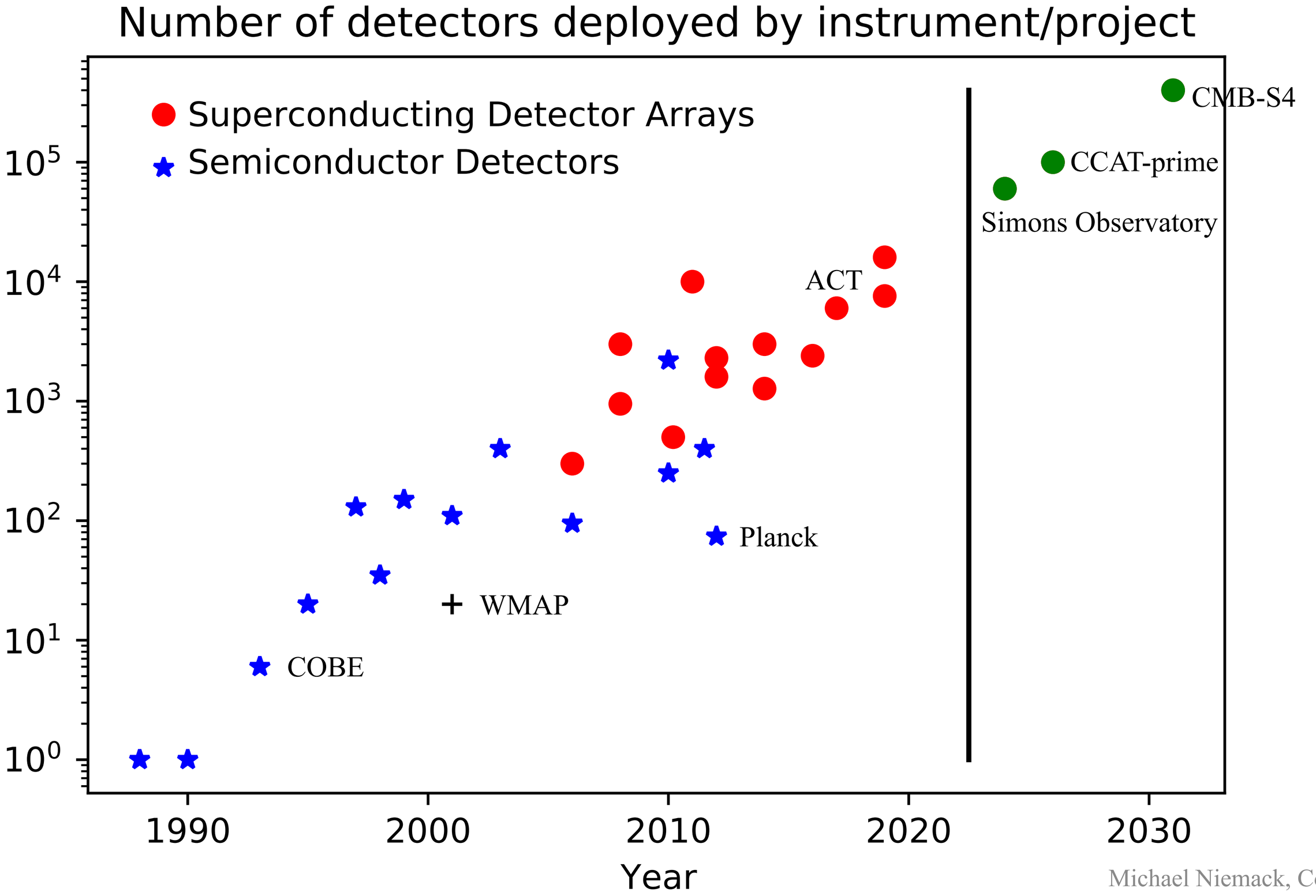
Atacama Cosmology Telescope (ACT)

~ 1 meter

Feedhorn array

~ 10^{-1} meters

Detectors versus Time



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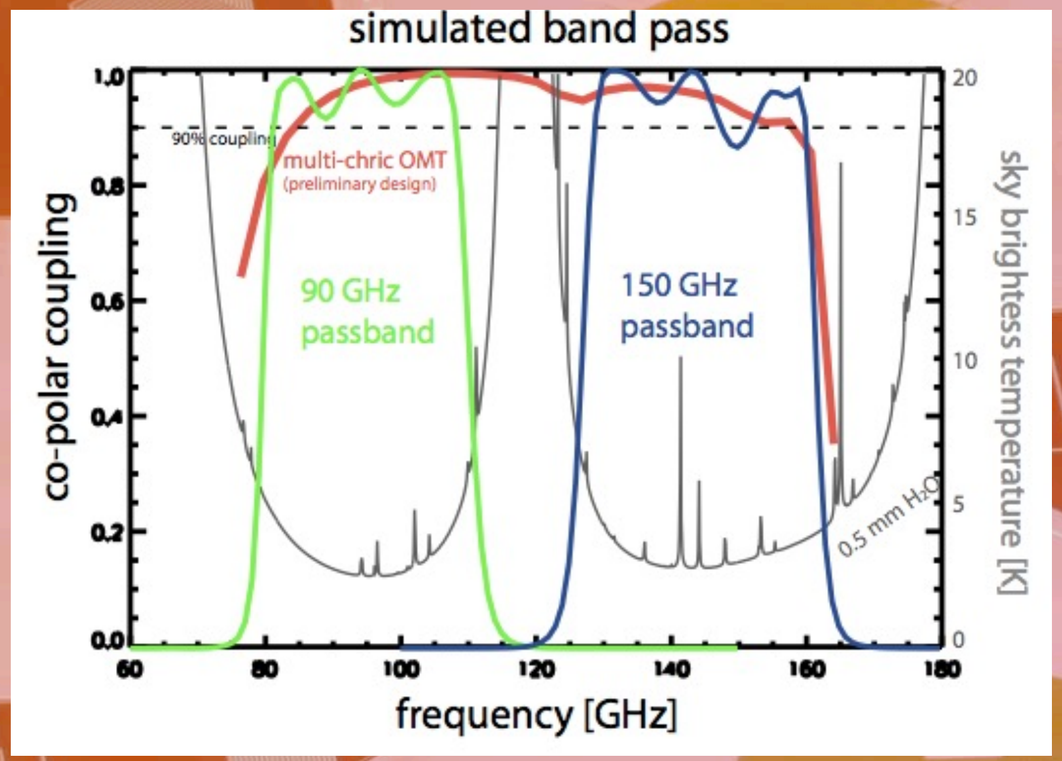
~ 10^{-2} meters

5mm

Background-limited superconducting detectors

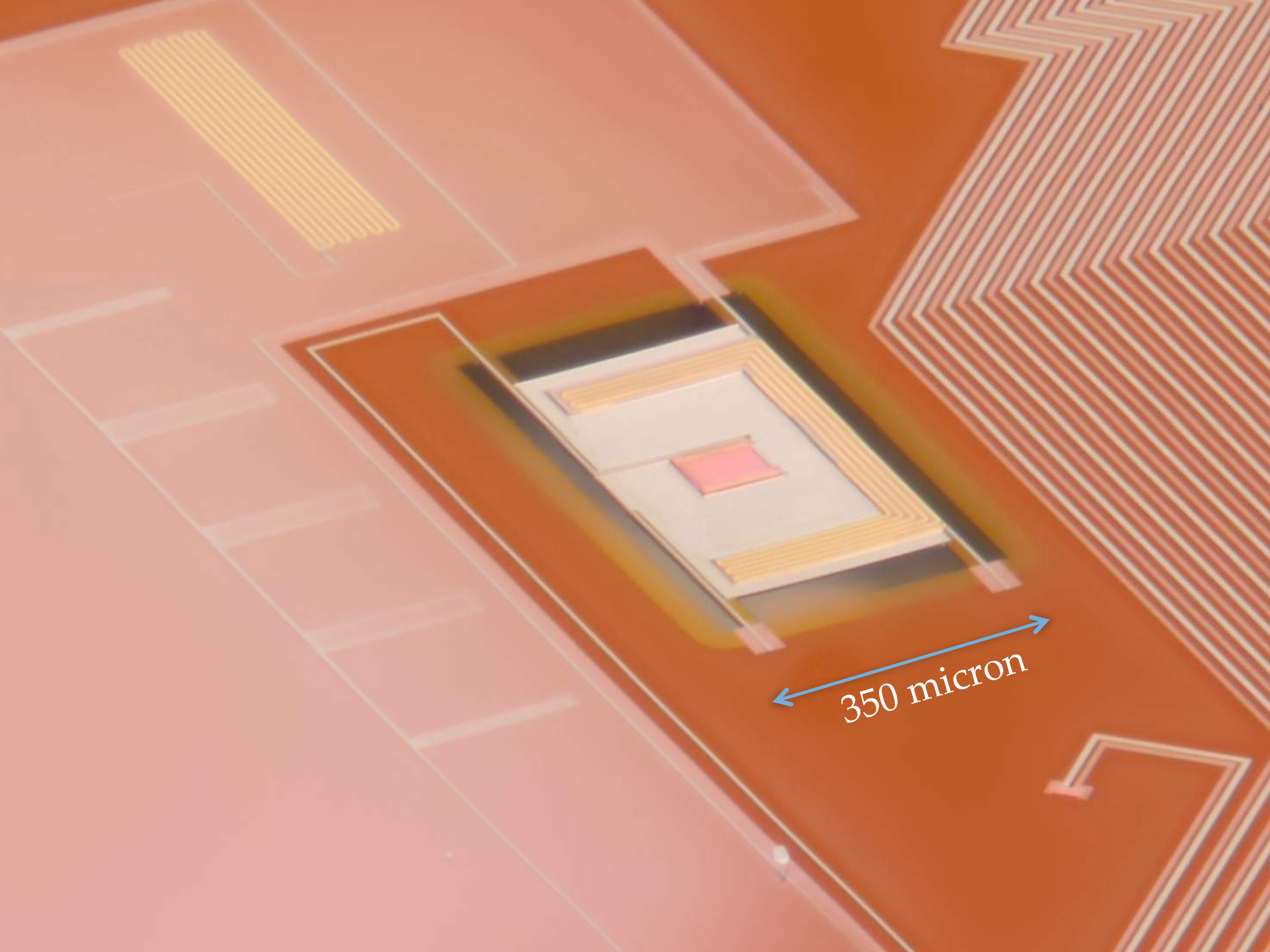
~ 10^{-2} meters



ACTPOL NIST

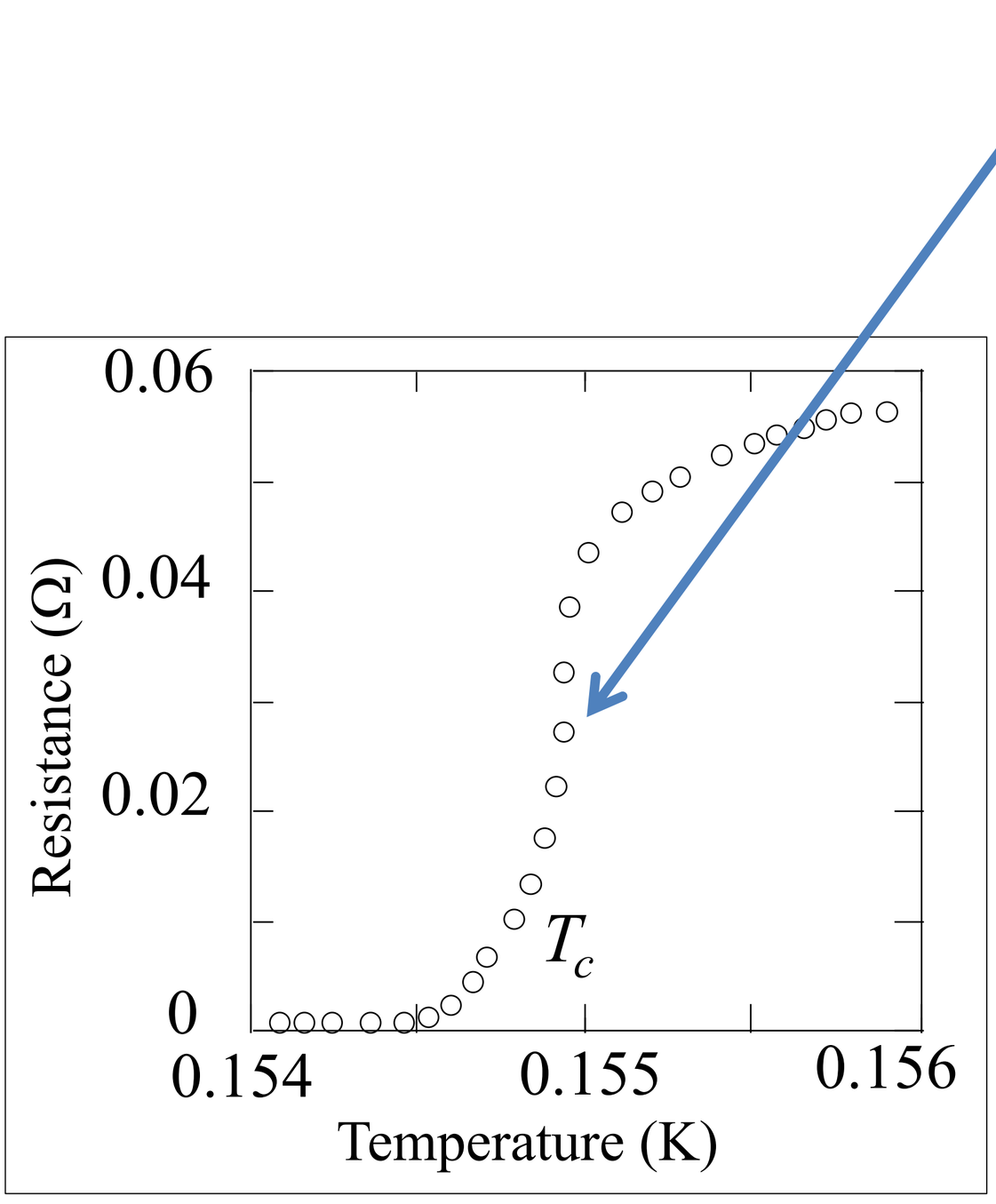
~ 10^{-3} meters

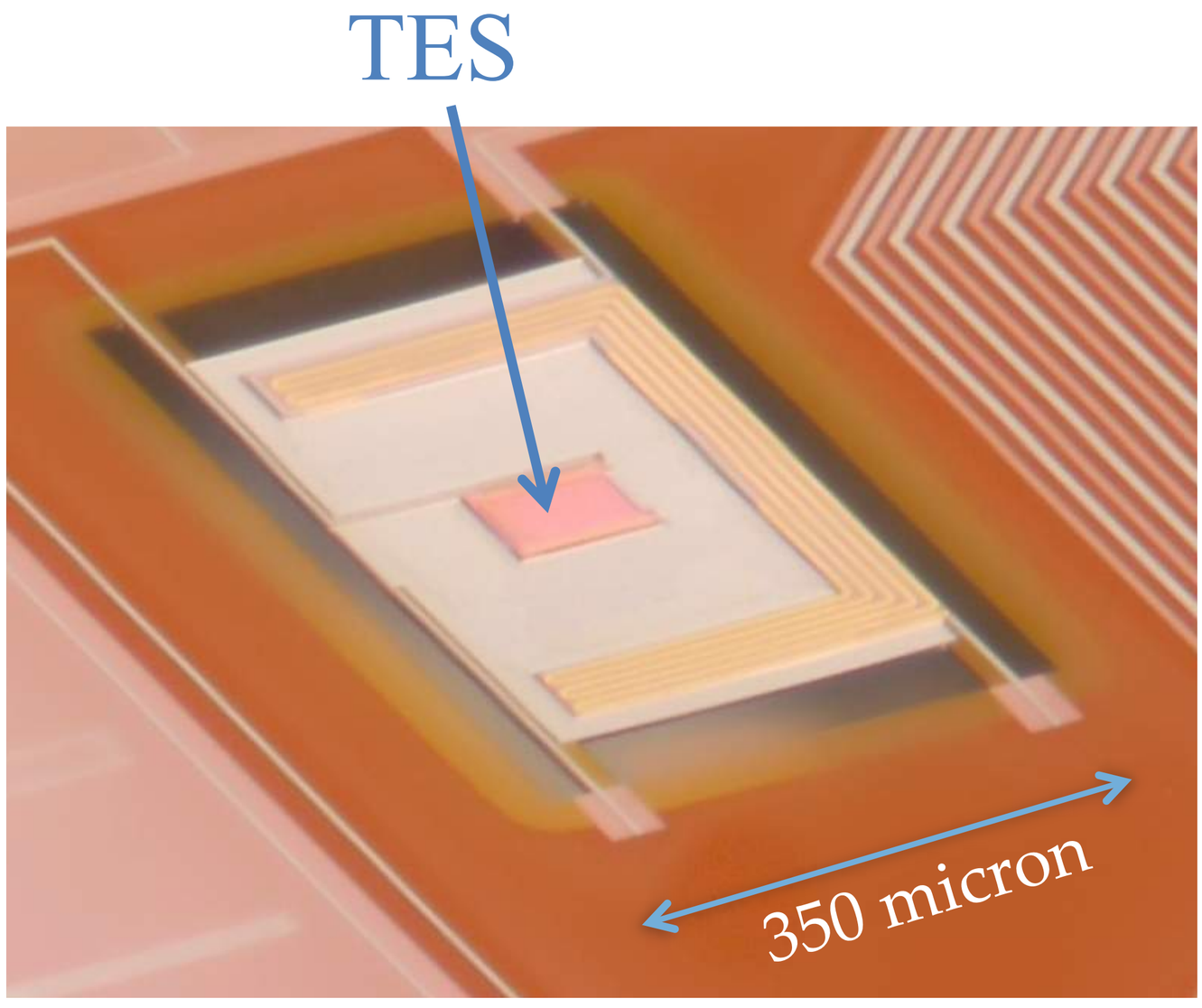
ACTPol PA3


350 micron

Superconducting Transition Edge Sensors (TES)

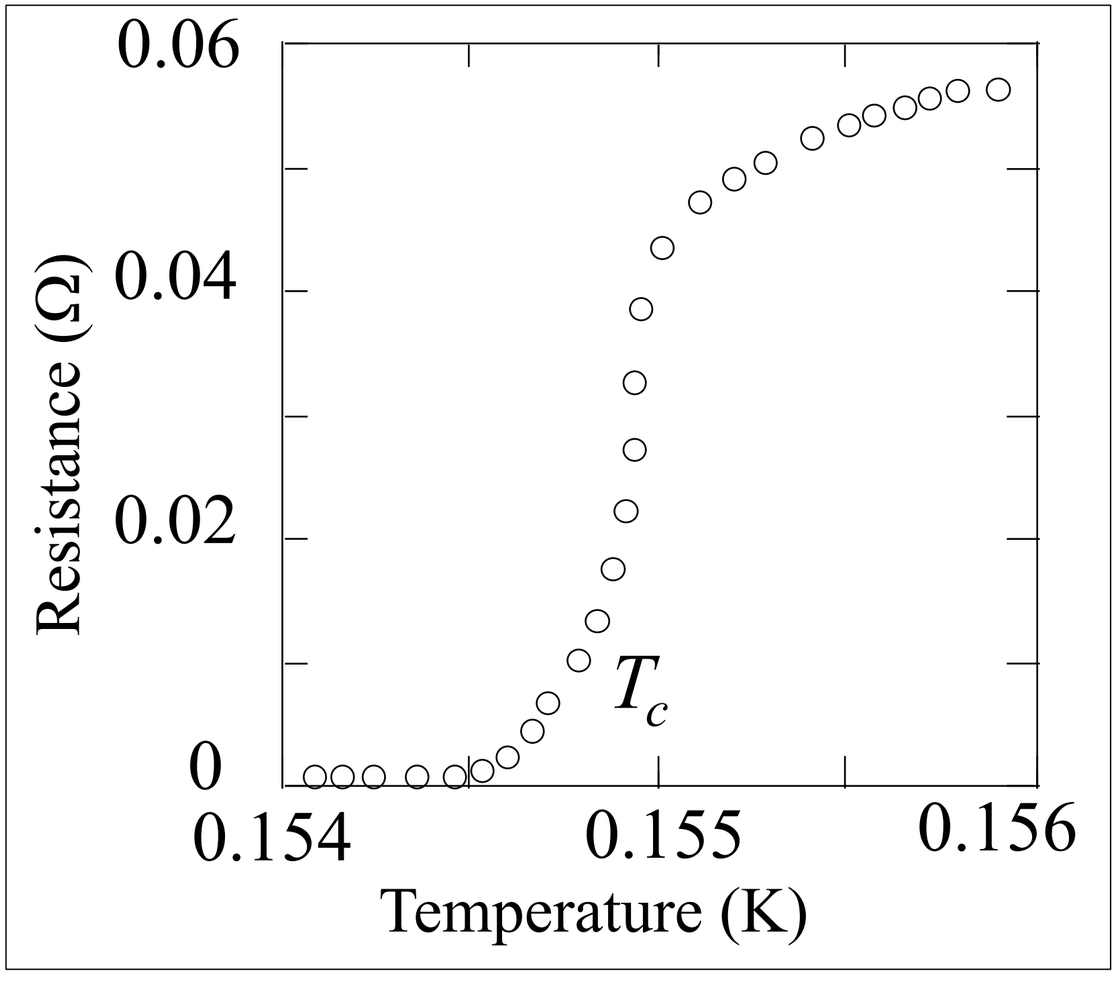
- Sub-Kelvin operation
- Voltage biased at superconducting transition, T_c



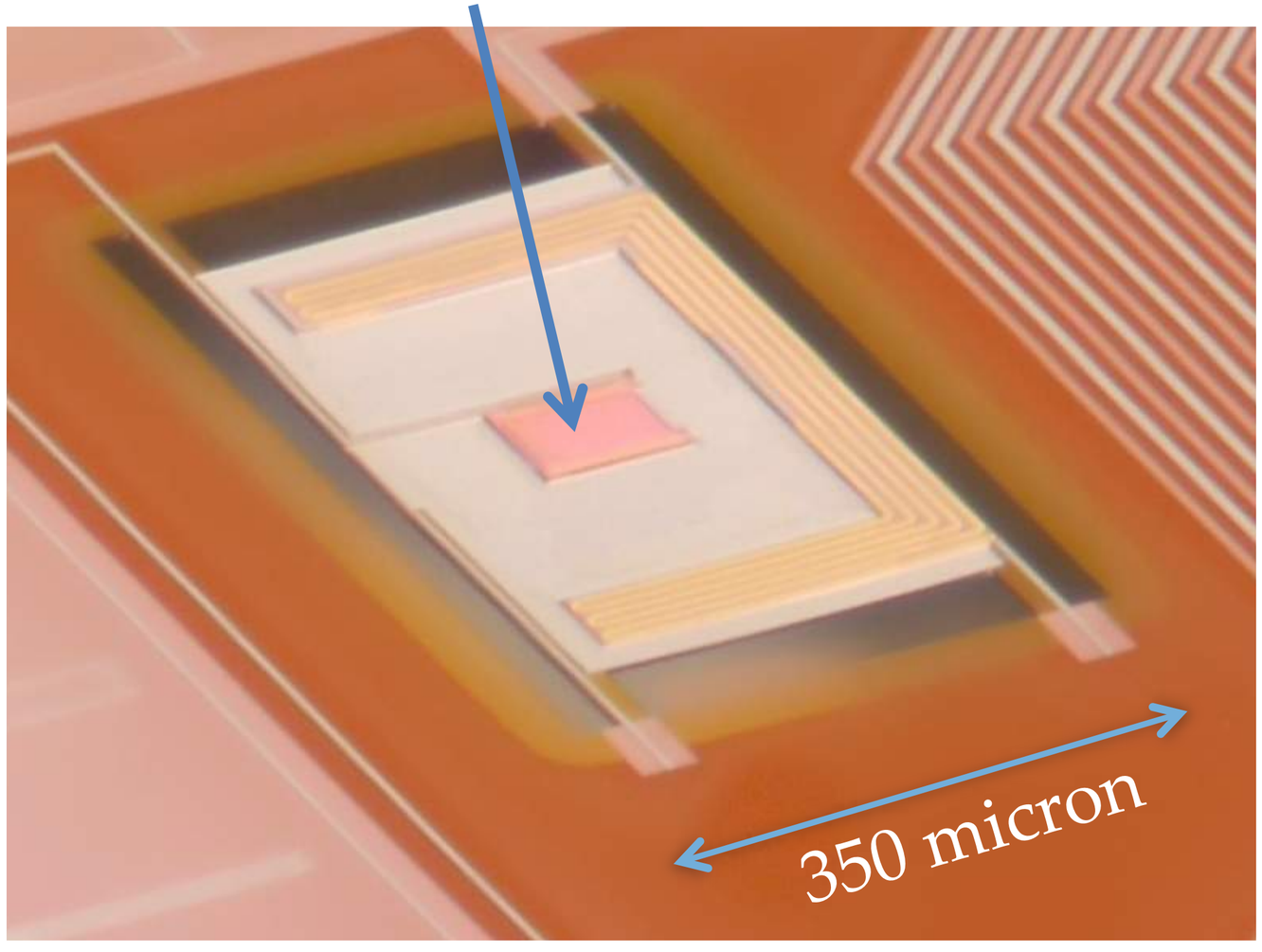


Superconducting Transition Edge Sensors (TES)

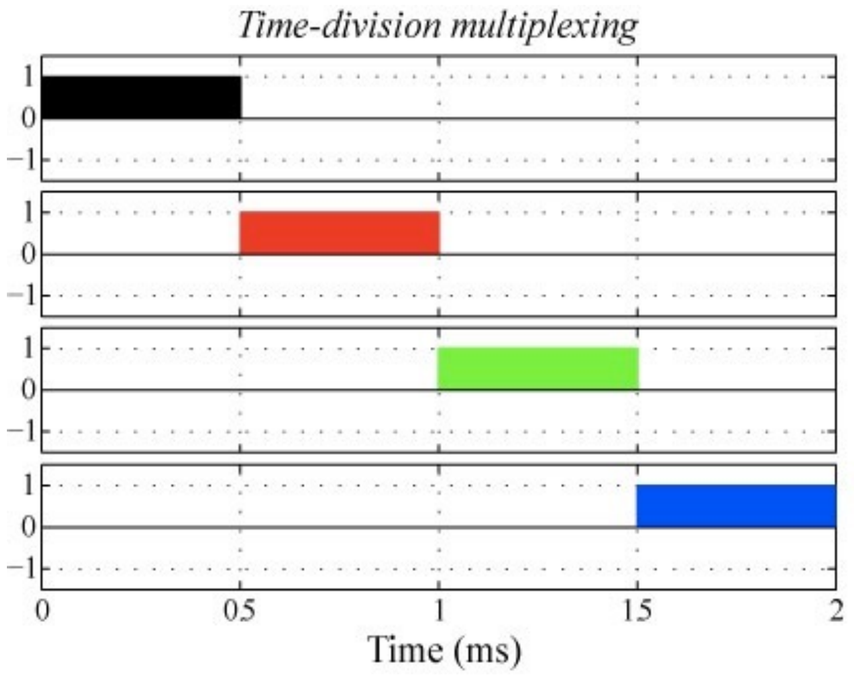
- Sub-Kelvin operation
- Voltage biased at superconducting transition, T_c
- Low-T current readout => SQUIDs

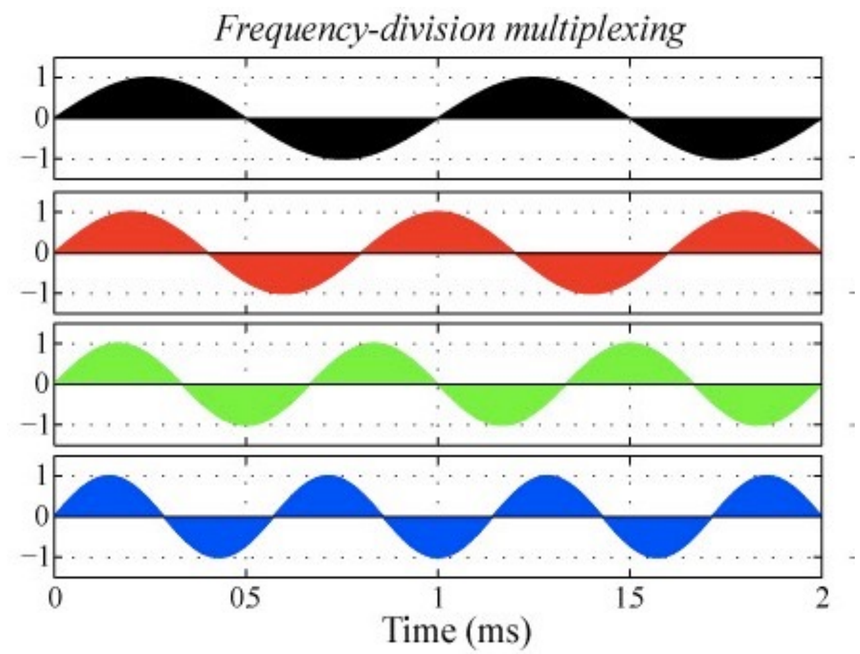


TES



SQUID Multiplexing for large TES Arrays





Different signal modulation techniques

- Time-division multiplexing (Chervenak et al., APL 1999)

  Current Advanced ACT arrays ~6000 detectors

  (Henderson et al., SPIE 2016)

  Mature approach

  => Adopted for CMB-S4 >500,000 detectors observations starting ~2030

CMB-S4
Next Generation CMB Experiment

- GHz Frequency-division multiplexing

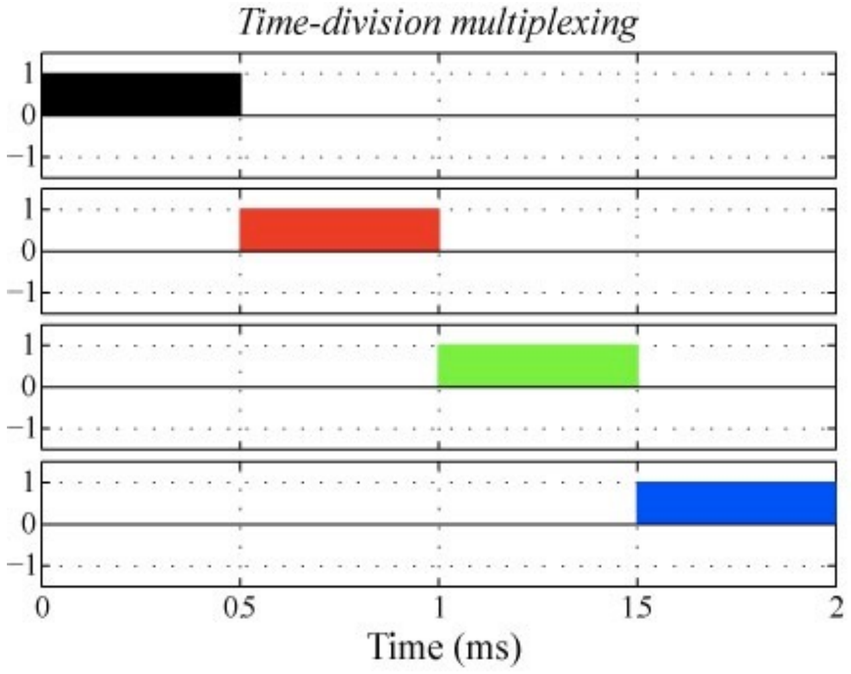
  Simons Observatory arrays ~60,000 detectors

  observations starting 2023!

  (McCarrick et al. ApJ 2021)

SIMONS OBSERVATORY

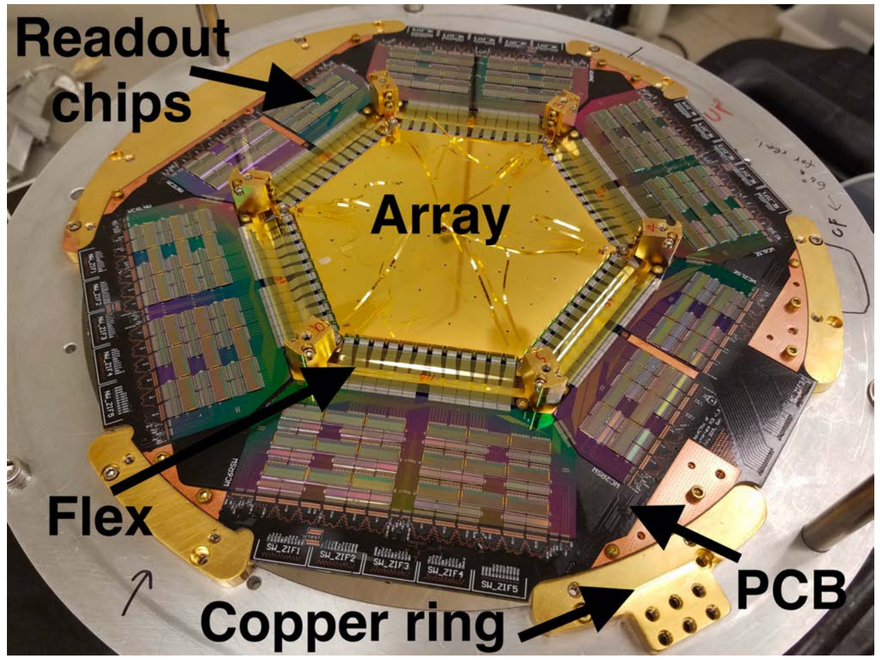
SQUID Multiplexing for large TES Arrays



Different signal modulation techniques

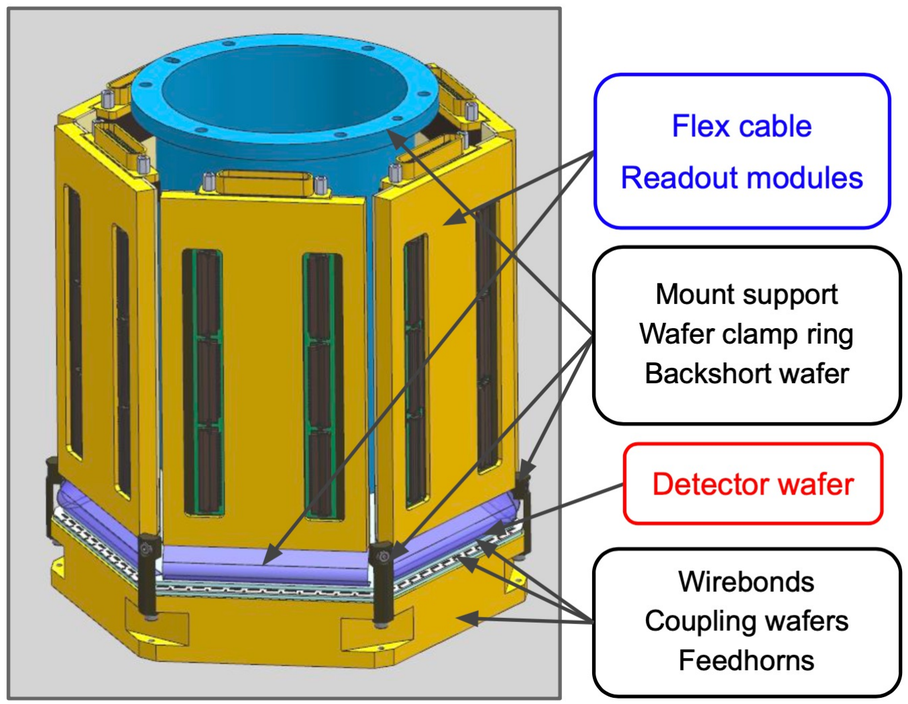
- Time-division multiplexing (Chervenak et al., APL 1999)

  Advanced ACT array with 64x multiplexing



(Henderson et al., SPIE 2016
Choi et al., JLTP 2018)

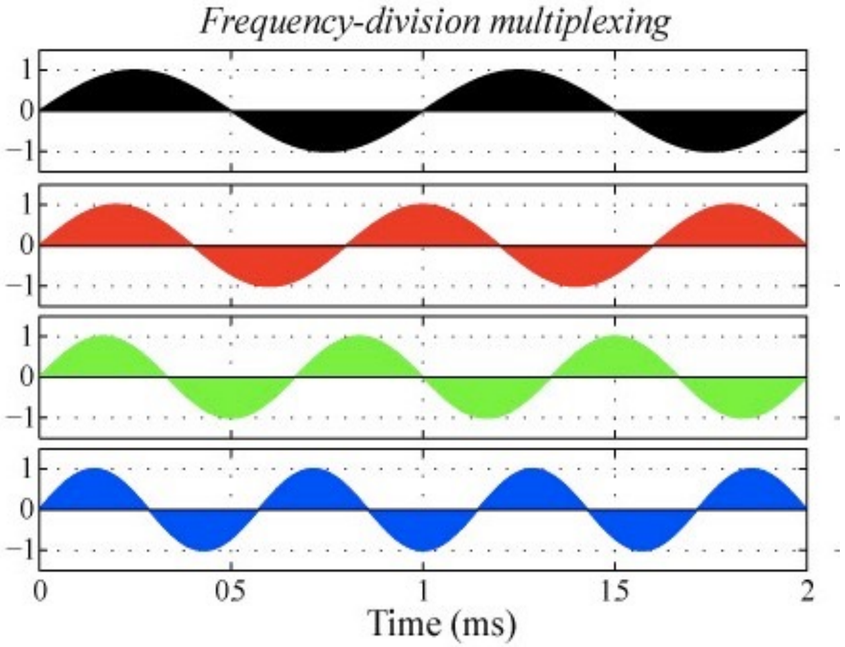
CMB-S4 arrays – need to fold readout behind array to fit many arrays side-by side



CMB-S4 Collaboration – cmb-s4.org

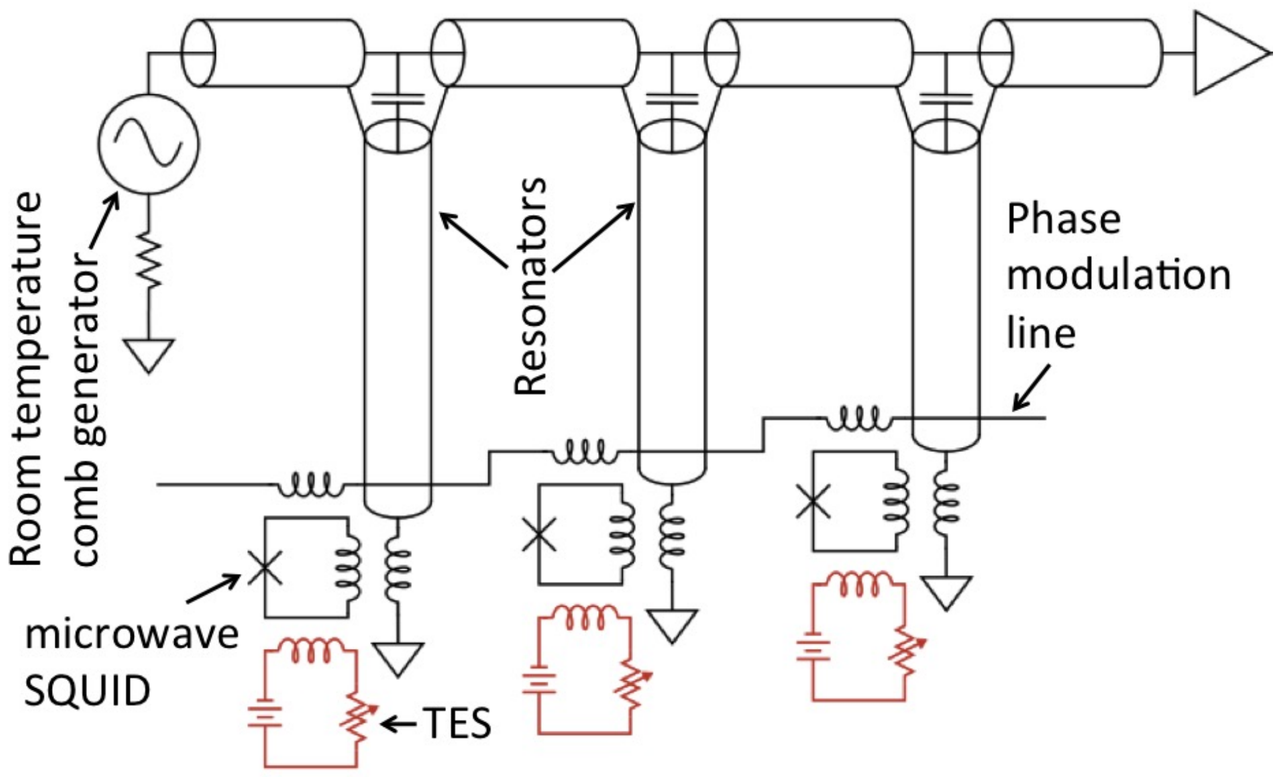
CMB-S4
Next Generation CMB Experiment

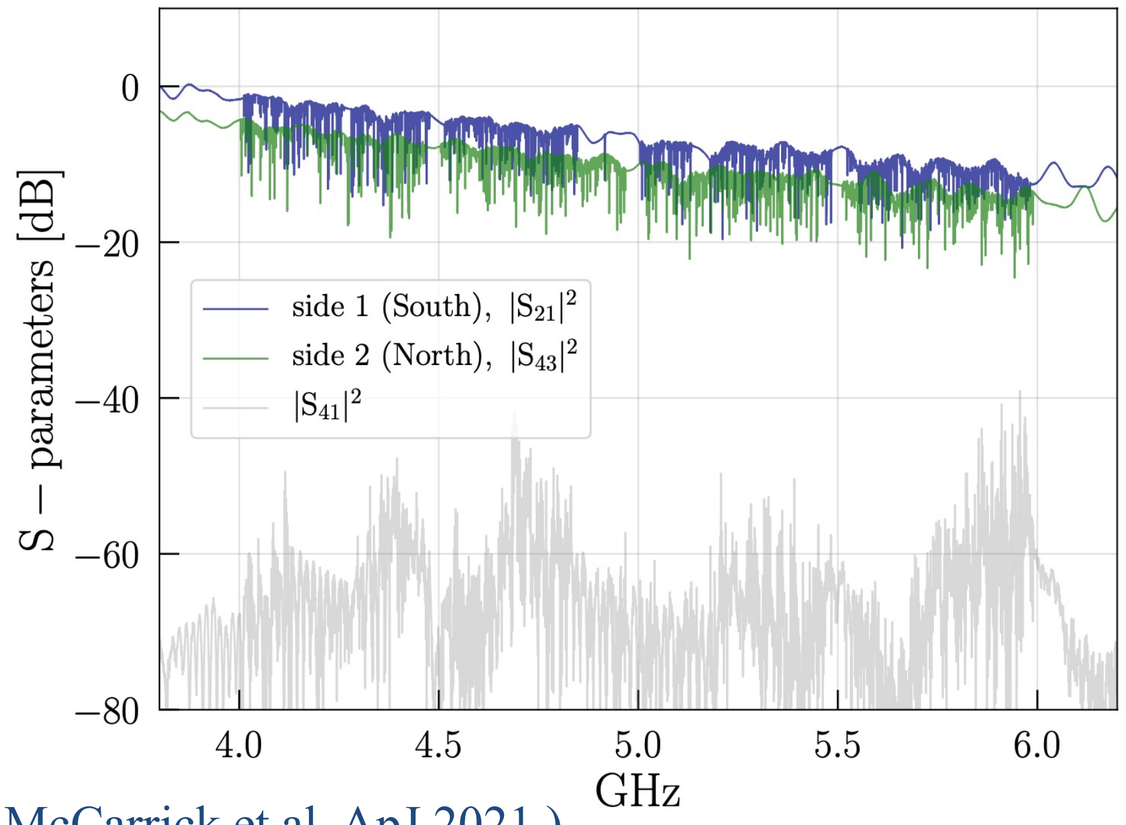
SQUID Multiplexing for large TES Arrays



GHz frequency-division multiplexing

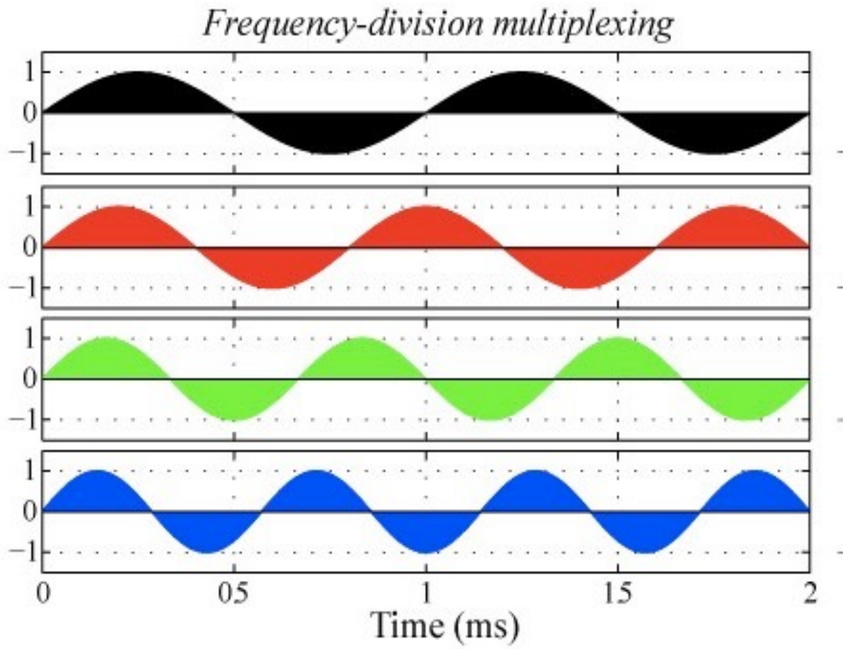
- Difference frequency for each TES
- 2 coax + 2 twisted pair
- 910x multiplexing factor
- Fewer wires than time-division, though focal plane integration with TESes is still a challenge





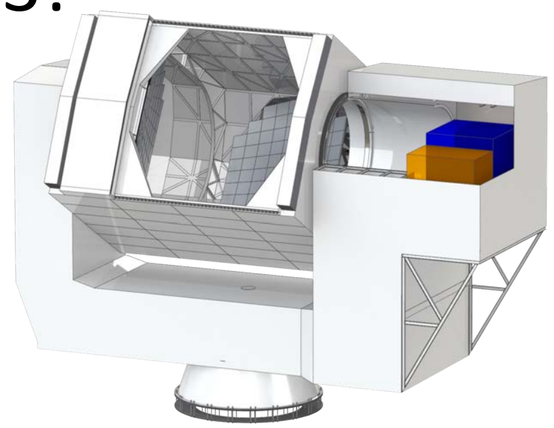
(McCarrick et al. ApJ 2021)

SQUID Multiplexing for larger TES Arrays

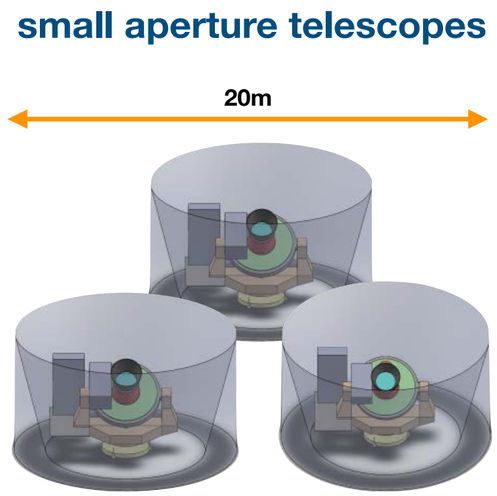


GHz frequency-division multiplexing

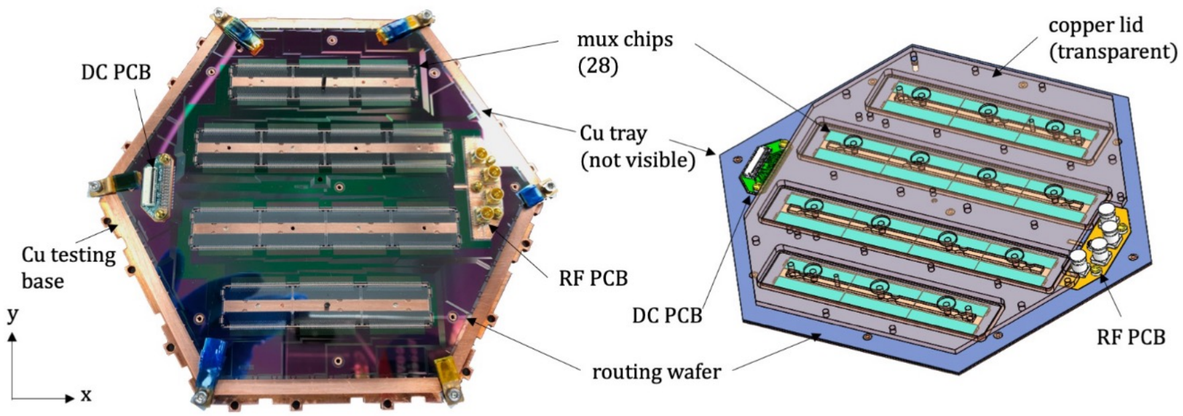
- **Simons Observatory (simonsobservatory.org)** project is using this and it will be deployed in Chile in 2023!

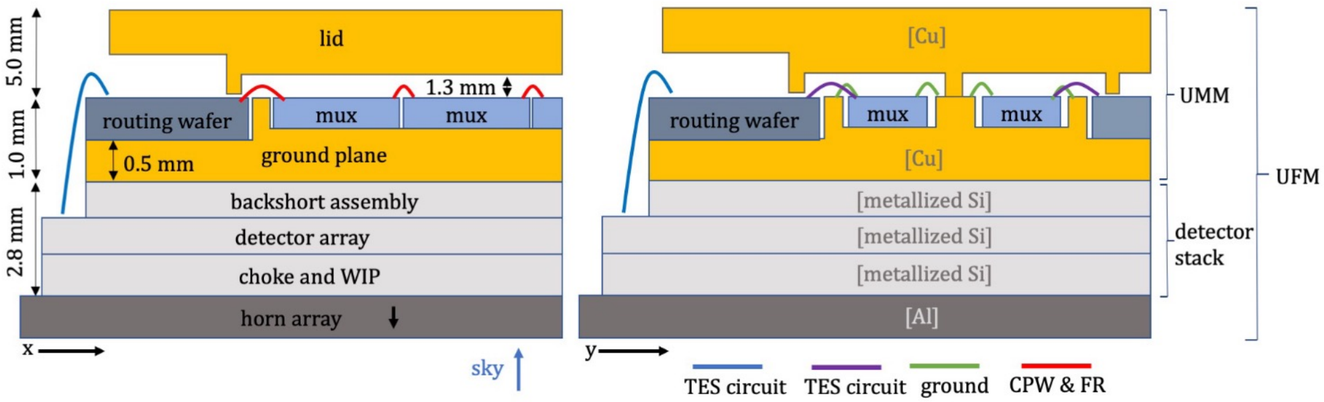


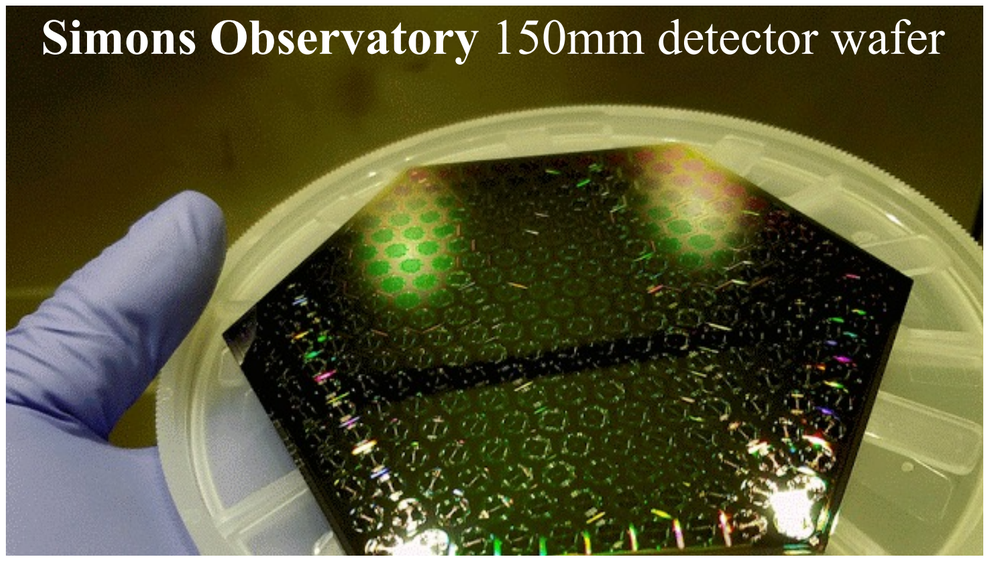
Large aperture telescope



(McCarrick et al. 2021 – readout for 1820 TES channels)







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Kinetic Inductance Detectors for larger arrays

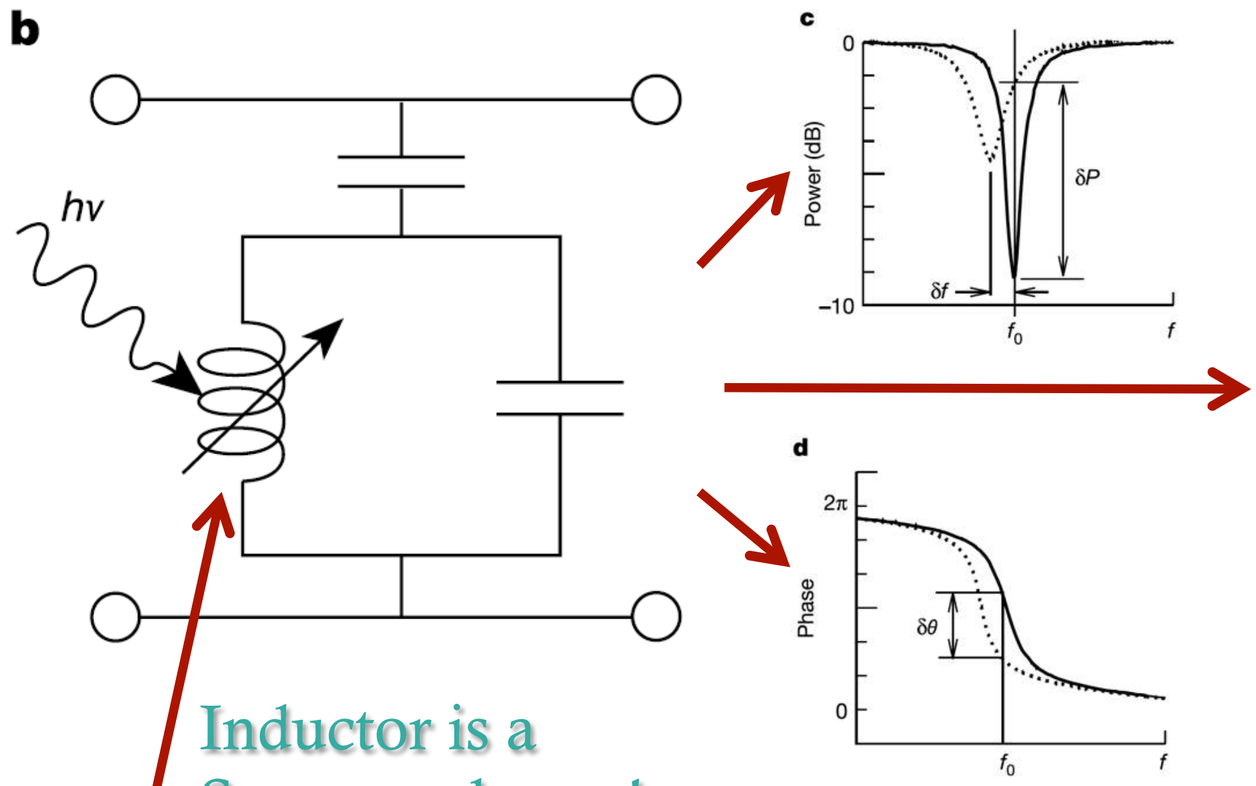
- Newer detection approach
  - Use kinetic inductance of superconductor
  - Circuit resonance changes due to pair breaking

(Day et al. Nature 2003)

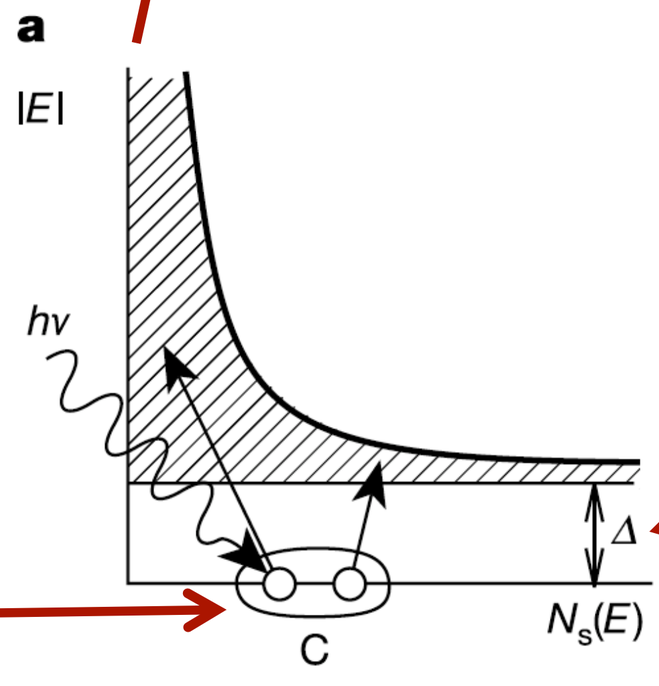
- Naturally multiplexable
  - Frequency comb like microwave SQUIDs

- ***More detectors at shorter (< 1 mm) wavelengths due to ~100x fewer wirebonds!***

MKID Equivalent Circuit



Inductor is a Superconductor!



Cooper Pair

From Ben Mazin

Energy Gap

Silicon – 1.10000 eV

Aluminum – 0.00018 eV

Energy resolution:

$$R = \frac{1}{2.355}\sqrt{\frac{\eta h\nu}{F\Delta}}$$

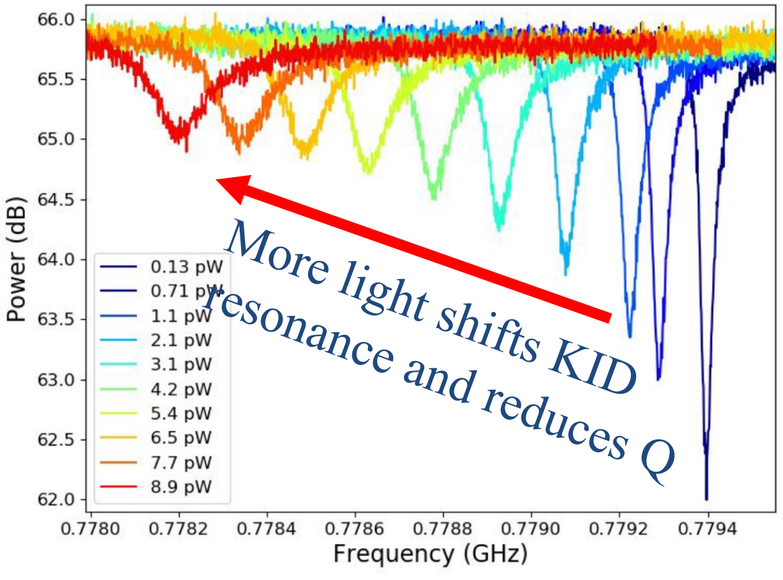
Kinetic Inductance Detectors for larger arrays

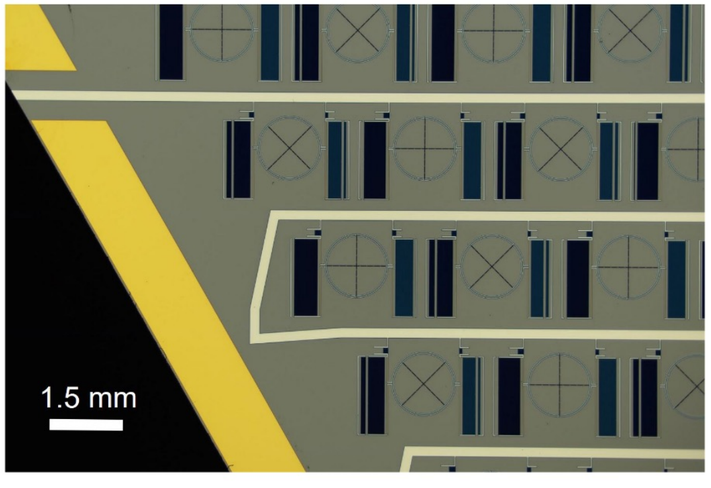
CCAT-prime (ccatobservatory.org)

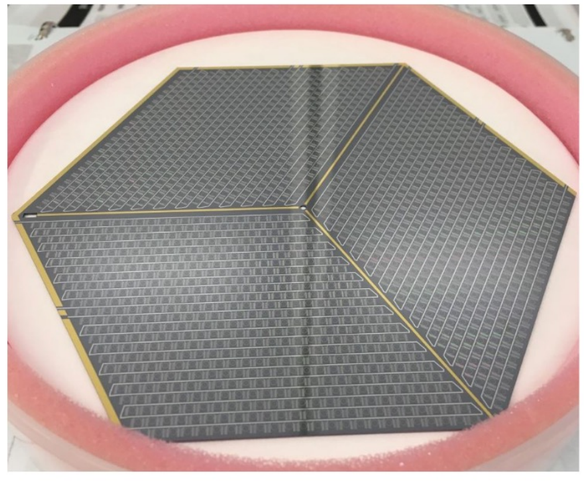
adopted KIDs to be deployed in 2024!

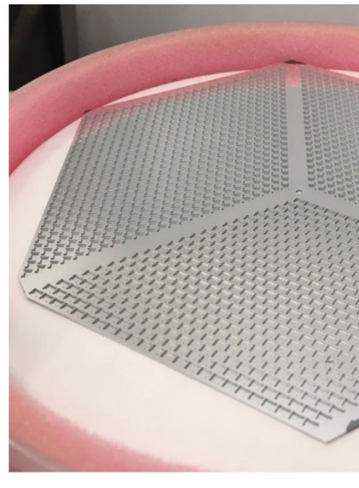
Planning for > 100,000 KIDs

(Duell et al. SPIE 2020 – First CCAT-prime array with 3456 KIDs!)









Telescopes for CCAT-prime and Simons Observatory

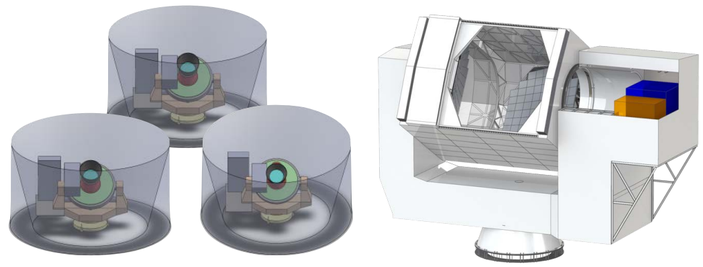
… to illuminate ~10x more detectors are being built in Germany!

(Niemack 2016 Applied Optics, Parshley et al. 2018 SPIE)

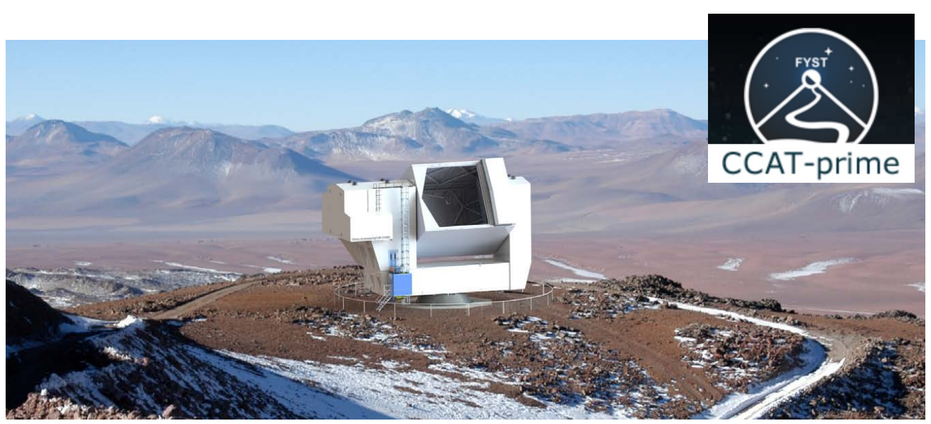
Telescope base 3 weeks ago in Duisburg, Germany

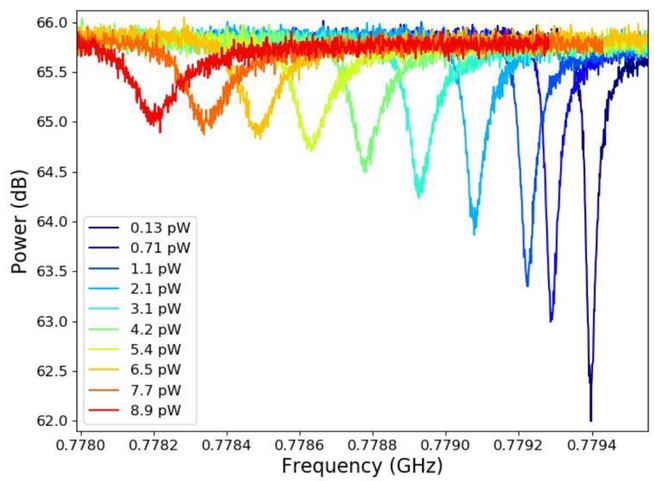
Wrap up

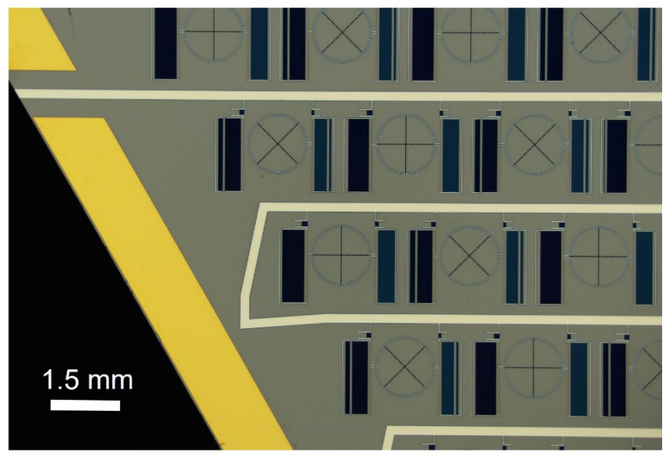
- Feedhorn coupled Transition Edge Sensor (TES) detectors are achieving background-limited performance on **ACT** and others
- ***Need more detectors to improve CMB measurements***
- TESes will be used in **Simons Observatory** **and** **CMB-S4**
  - **Simons Observatory** using frequency-division readout **in 2023**
  - **CMB-S4** using time-division readout in ~2030



- Kinetic Inductance Detectors (KIDs) enable more detectors per wafer at wavelengths less than ~1mm and will be used in **CCAT-prime**
  - **CCAT-prime** using KID arrays **in 2024**







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