Transition Edge Sensor Bolometers for CMB Polarimetry

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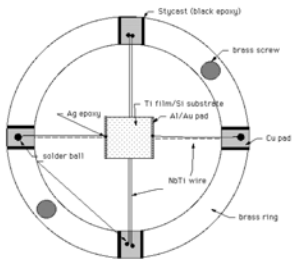
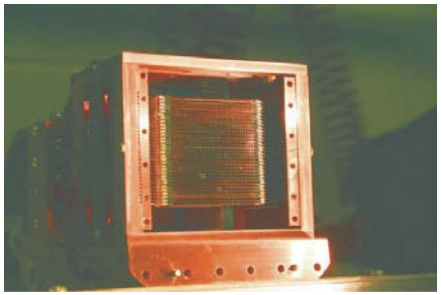
Thanks To: Jamie Bock, William Duncan, Gene Hilton, Kent Irwin, Nikhil Jethava, Adrian Lee, Harvey Moseley, Lyman Page, Bob Silverberg, Giorgio Siringo,

Status Summary

- Technology has made rapid progress in the last decade; TRL is high and trajectory is goo



Lee, c.1996



ACT – Zhao 2008

- Astronomical instruments are penetrating
- Near-term balloons will mature amply
- TES bolometers represent a robust candidate technology for CMB polarimetry

TES Bolometer Theory

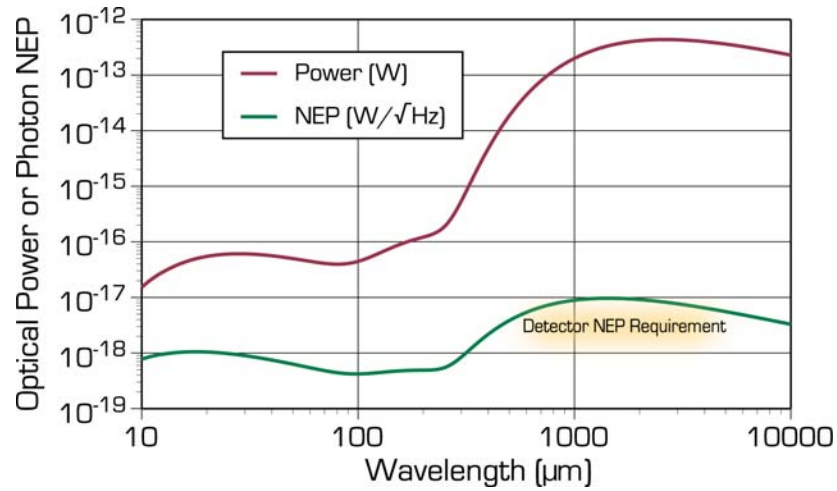
- Solved up to nonequilibrium, nonlinear (second order) model (see, e.g. Irwin & Hilton 2005)
  - Predictive, testable, complete

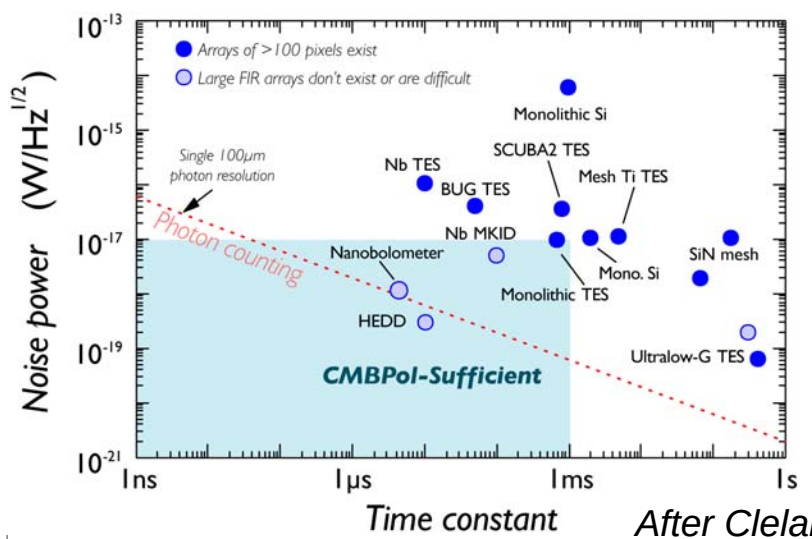
$$S_{total}(\omega) = 4k_B T_0^2 G F_{thermal} + 4k_B T_0 R_0 I_0^2 \left(1 + 2\beta_I\right) \frac{1 + \omega^2 \tau^2}{\mathcal{L}_I^2} + 4k_B T_0 R_L I_0^2 \frac{\left(\mathcal{L}_I - 1\right)^2}{\mathcal{L}_I^2} \left(1 + \omega^2 \tau_I^2\right) + \frac{S_{Iamp}(\omega)}{\left|s_I(\omega)\right|^2} + S_{Excess}(\omega)$$

  - Mostly well established
- Much work on “excess noise” theories
  - Some not very physically-motivated
  - All have both experimental verification and refutation.

TES Bolometer Requirements

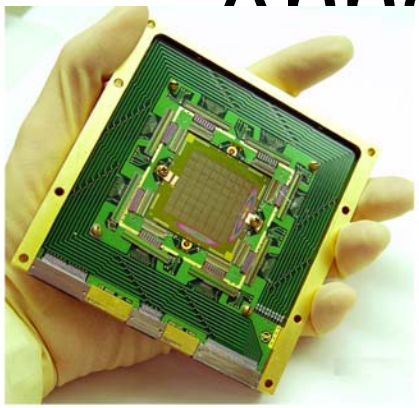
- NEP, P_{sat} known
  - Achieved!
- Speed varies, but ≈1ms satisfies most.
  - Achieved!
- Formats of ≈10^3 pixels
  - Achieved! (mostly…)

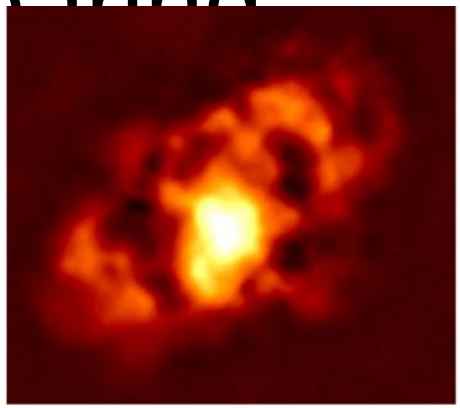


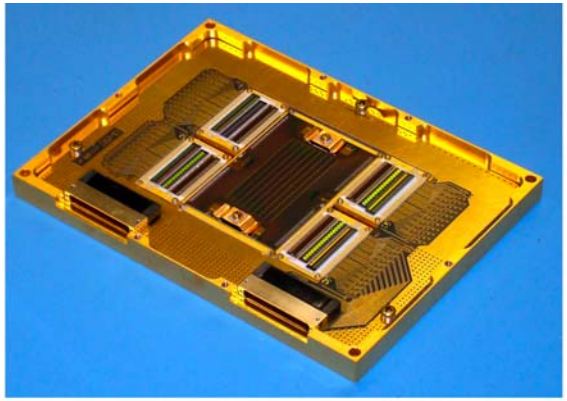


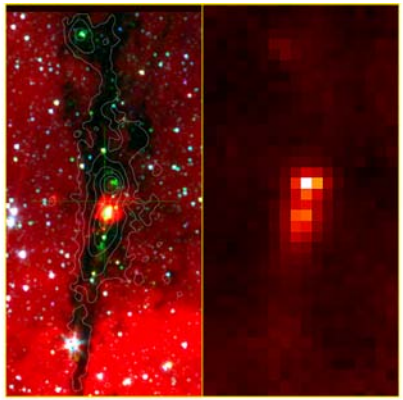
After Cleland

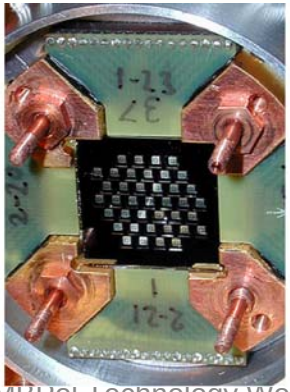
Astronomical Applications Appearing

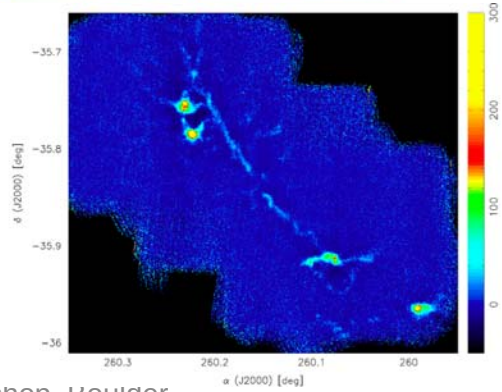












Positive Aspects of Progress

- Several TES-based instruments exist
  - APEX-SZ, ACT, SPT, MUSTANG, GISMO, SETA have all achieved first light in mm wavelengths
- Multiplexers work; large formats (kilopixel) have been fielded
  - NIST TDM - ACT
  - Berkeley FDM - SPT
- Sensitivity requirement achieved (sort of)
  - Record? MUSTANG, GISMO, ACT all $\approx 4 \cdot 10^{-17} W/\sqrt{Hz}$

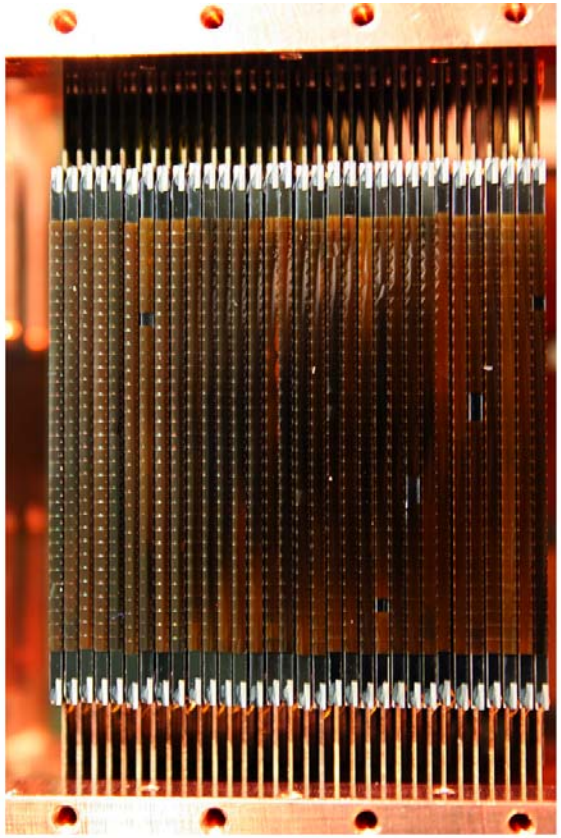
Much Yet To Be Done…

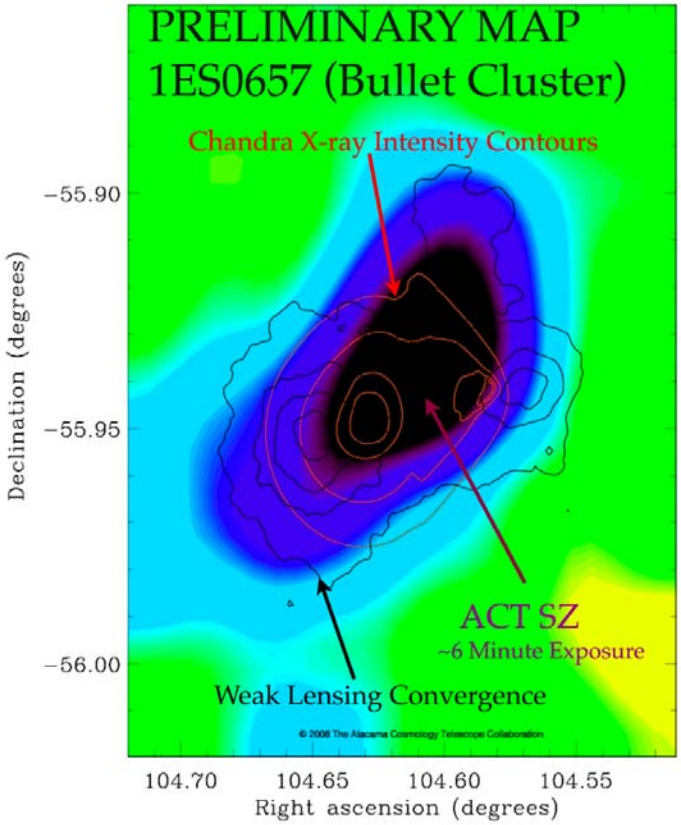
- “Excess Noise” not understood.
  - Theory not quite there
  - Experiments disagree
- Polarimetry and TES bolometers.
  - Optical? Should be straightforward.
  - On-chip? Not even close.
- Suborbital operation; “relevant environment”
  - EBEX and Spider or something similar!

Technology Readiness Level

- My estimate: TRL=4.8
- “The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications… can be tested in a ‘simulated’ or somewhat realistic environment.”
- Why not 6? “At this level, if the only ‘relevant environment’ is the environment of space, then the model/prototype must be demonstrated in space.”

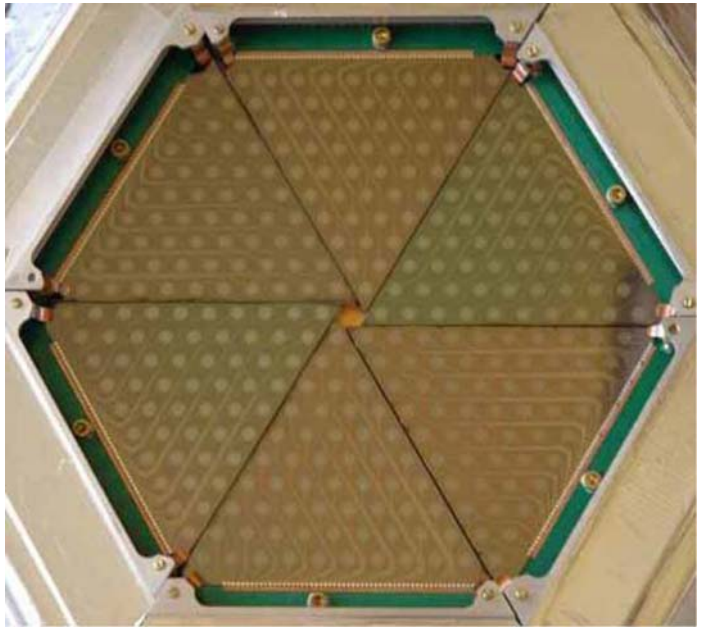
TES State-of-the-Art for CMB (1)

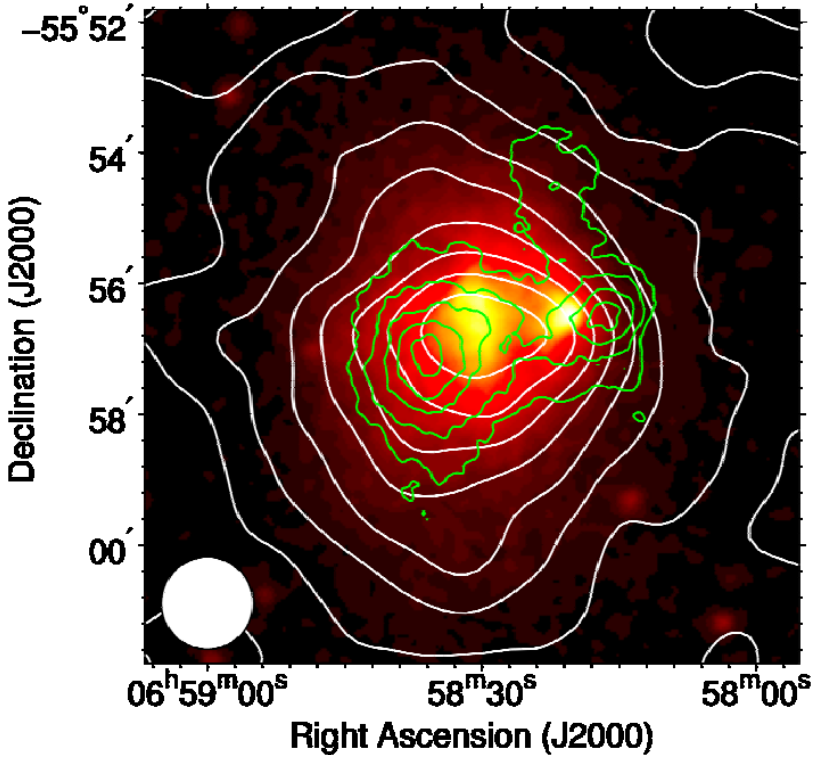




Figures courtesy of the ACT Collaboration

TES State-of-the-Art for CMB (2)

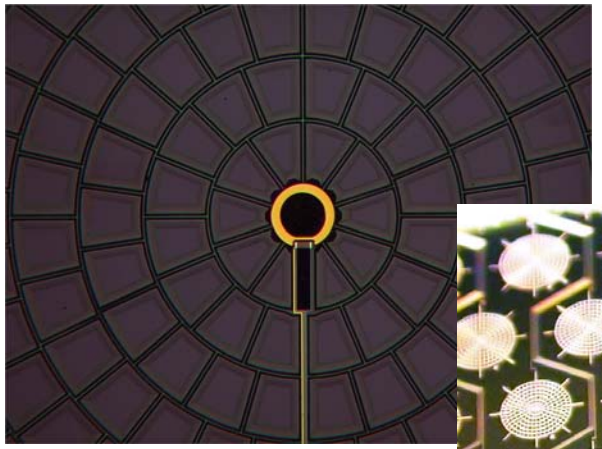




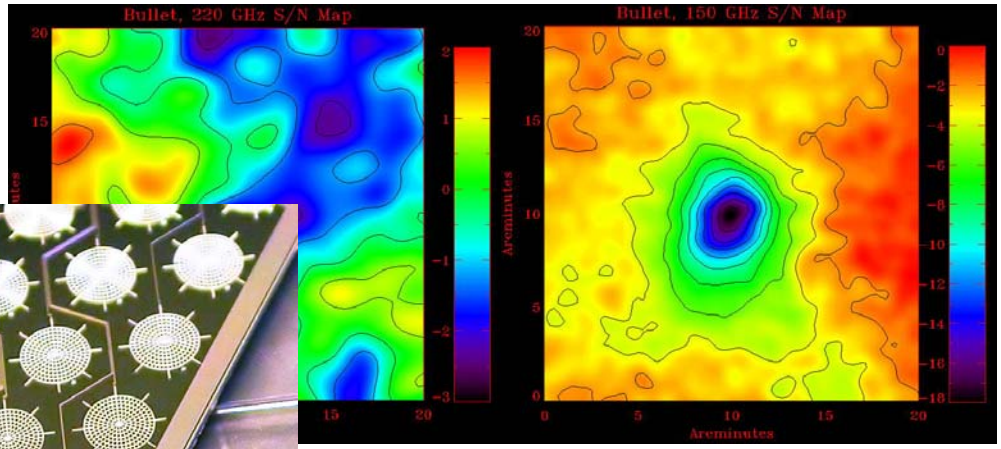
Images from Mehl et al. 2008; Adrian Lee

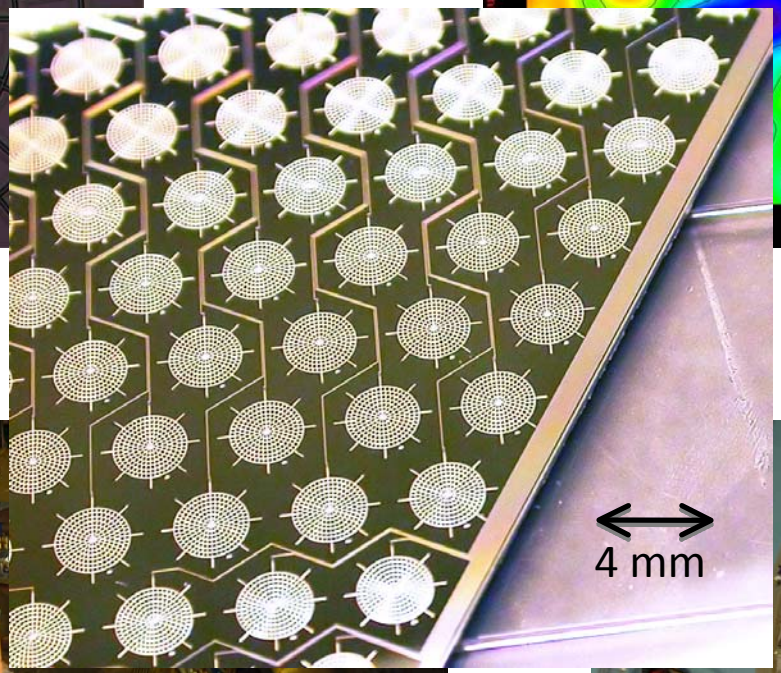
TES State-of-the-Art for CMB (3)

2 mm



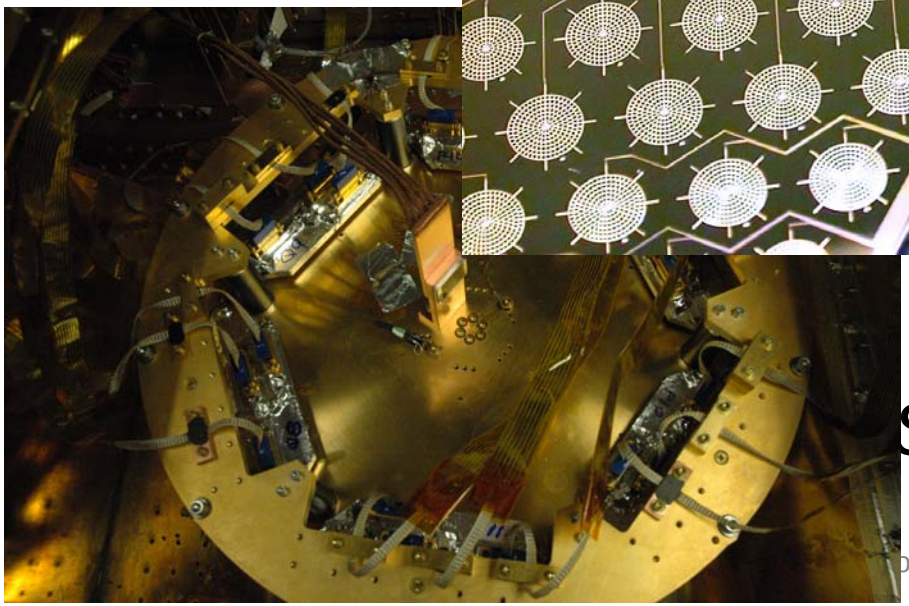
220 GHz Bullet Cluster 150 GHz





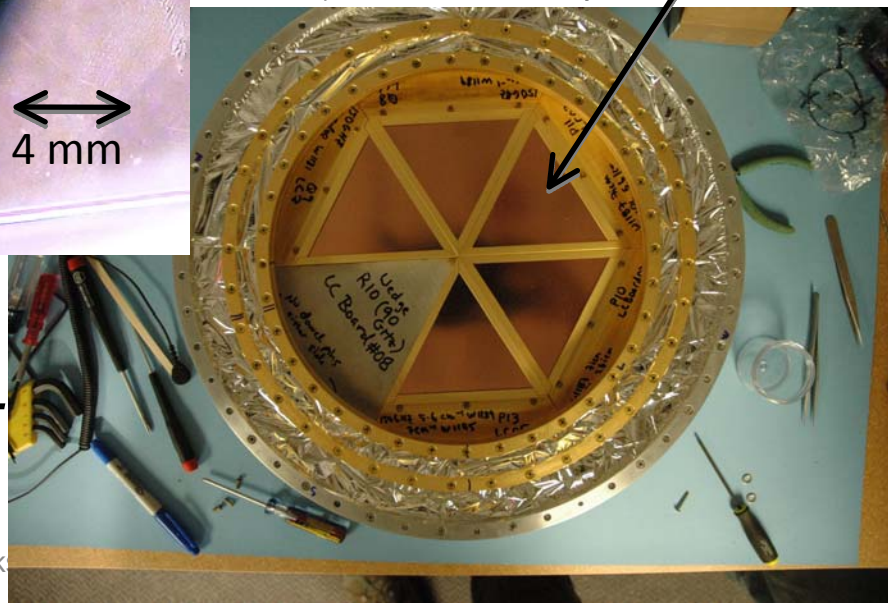
4 mm

960 Pixel fMUX wiring



20 cm

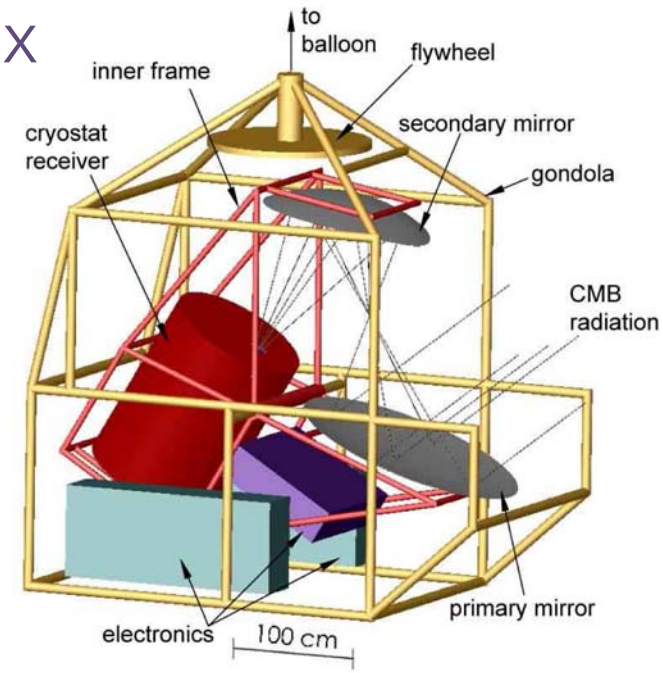
Mesh filters

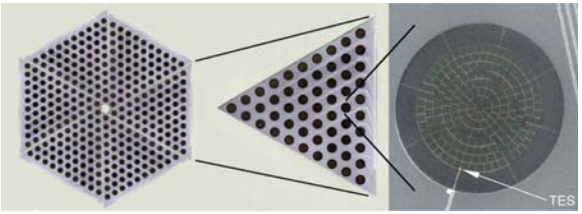


SPT

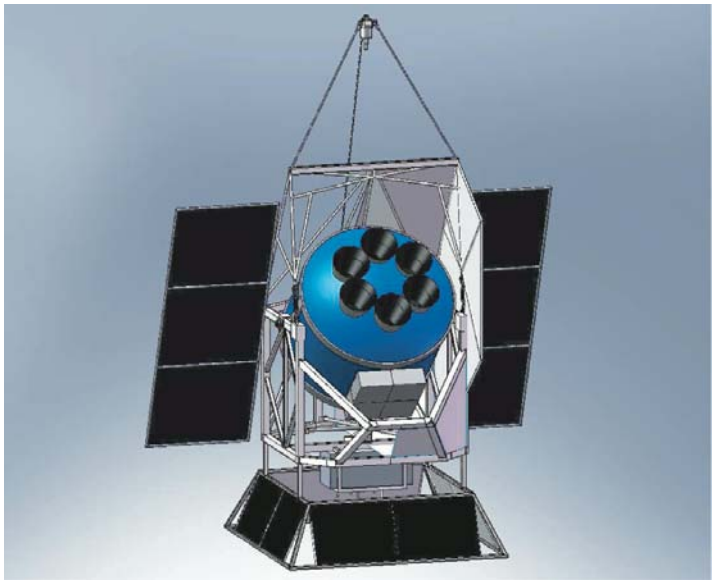
A Big Leap Forward in TRL

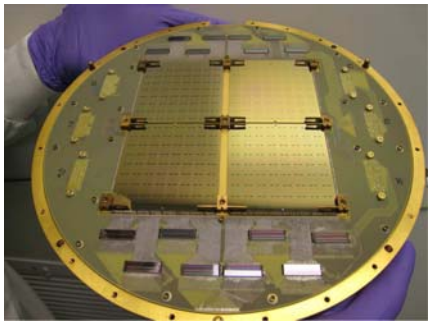
EBEX:





Spider:





"…somebody needs to operate successfully a suborbital *TES-based instrument"*

Advantages of TES Bolometers

- Sensitivity allows background-limited operation
- Large format arrays yield excellent mapping speed
- Response time permits many viable scan patterns and polarization modulation schemes
- Technology has matured to an acceptable level to begin directed investment in earnest

TFCMBR Technology Recommendation T1

"We recommend technology development leading to receivers that contain a thousand or more polarization sensitive detectors, and adequate support for the facilities that produce these detectors."

"…highest priority needs to be given to the development of bolometer-based polarization sensitive receivers."

Some Possible TES Downsides

- Dynamic range: sufficient, would like better
- Stability: adequate ($\approx$0.1Hz), would like better
- Magnetic fields: solved by design
- Microphonics: not a challenge
- Multiplexing electronics: mature
- Foundries: several exist

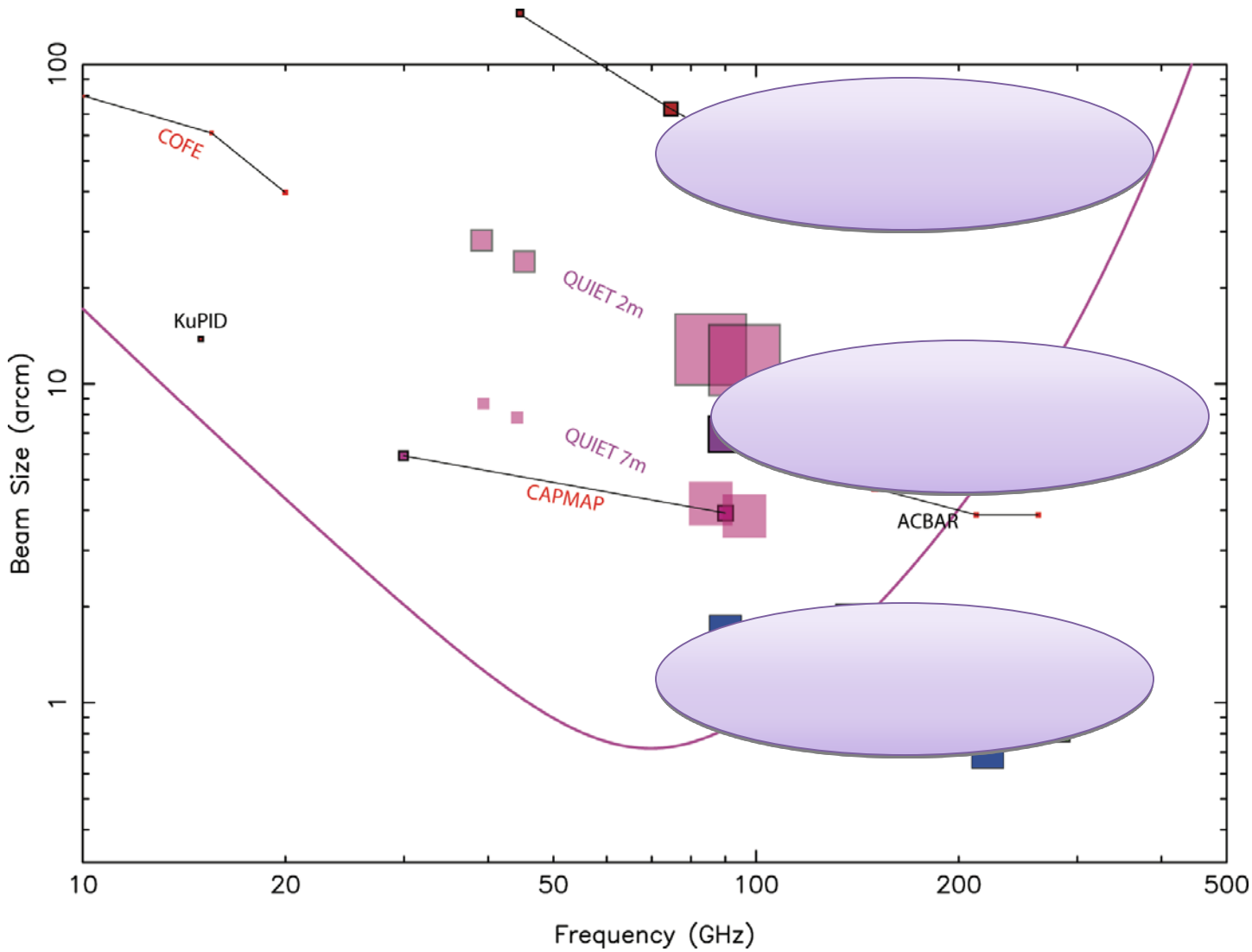
TES Bolometers vs. Coherent

- Sensitivity is (probably) better in real application – at ν >100GHz
- Large arrays more feasible; multiplexing helps! HEMT multiplexing?
- Cryogenics for 0.1K system might be better
  - Kilopixel HEMT array takes ≈10mW·1000=10W @ 20K
  - Kilopixel TES array takes ≈300nW@0.1K
  - Scaling law for coolers: if P.E.$\propto T^2$, this gives 10mW @ 20K!
  - Admittedly, with significant increase in complexity!
- HEMT IF ←→TES RF

TES vs. Semiconductor and KID

- TES is less mature than SC, more than KID
- Multiplexing much easier than SC, ≈same as KID
- Sensitivity same as SC, slightly better than MKID
- Readout more complex but simpler than SC; KID readout simpler (?) but not mature
- *Nil nisi bonum*, KID might be competitive

TES Bolometer Instruments Common?



Conclusions

- TES bolometers are well-established.
- Several independent and interrelated groups are pushing this technology forward rapidly.
- For CMB polarimetry, will likely offer the highest performance in terms of combined sensitivity, array format, and availability.
- Directed investment could achieve TRL=6 in a few years on the entire system.

Carpe Diem!