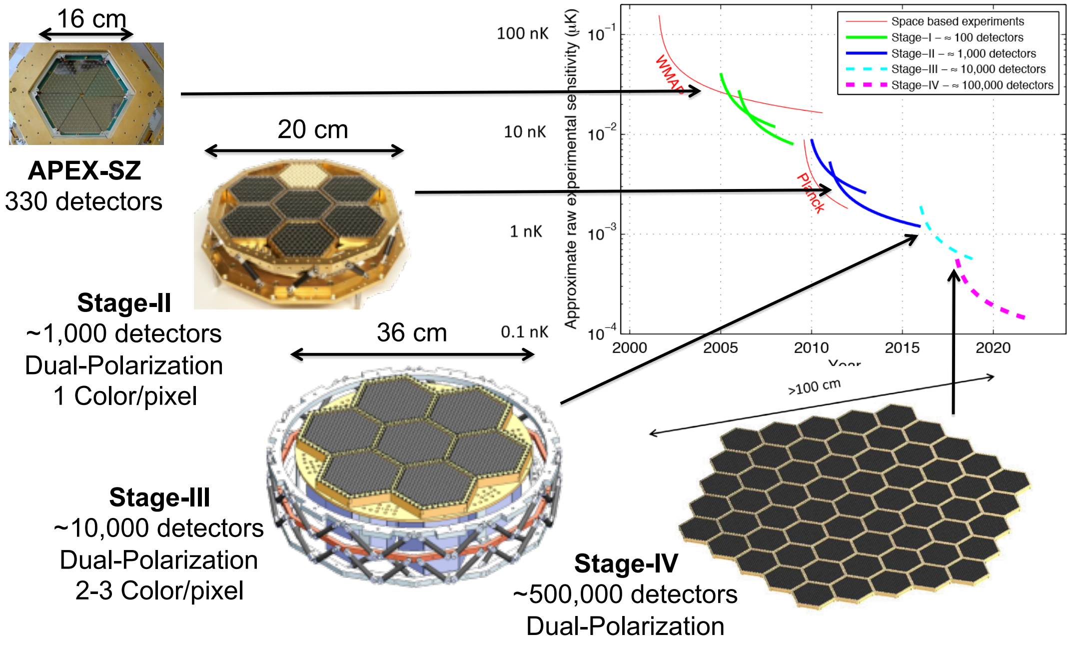
Prospects for a 10x reduction in the cost of superconducting sensors

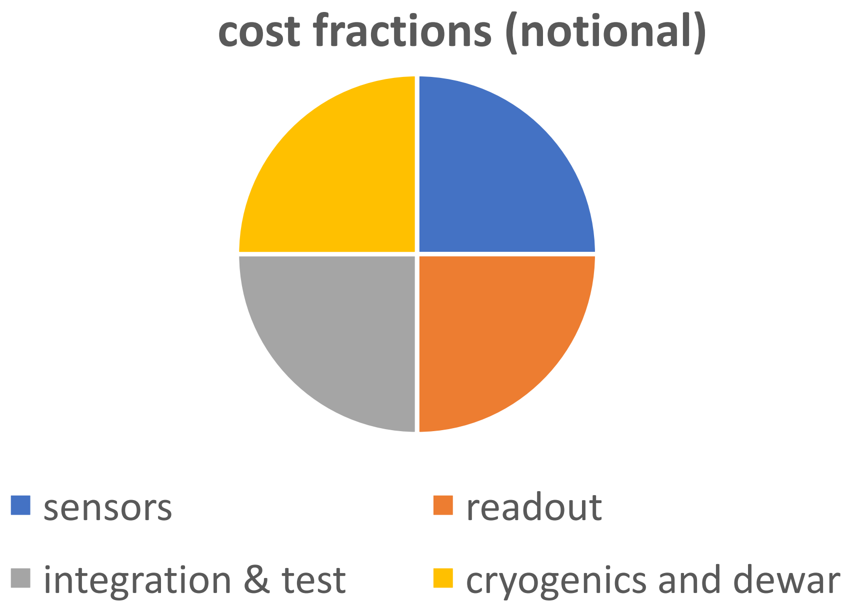
- Past & present CMB experiments use several thousand sensors
- Near term CMB experiments will use 10^4 (SPT3G) to 5×10^4 sensors (Simons)
- Future CMB experiments (S4) may use 5×10^5 sensors = 300 wafers

H. Hubmayr: present NIST production rate ~ 3 wafers/month. x3 years, x3 institutes = 300 wafers

- **This is not overwhelming**, but still desirable to reduce cost and production time
- **Important caution:** sensors are not the dominant cost of an instrument
- **Large improvements in sensor production rate possible,** but instrument costs harder to bring down



Adrian T. Lee CMB-S4 Workshop at LBNL (March 2016)



Ideas for improving costs and production rates

Sensors

- Good part yields reduce this cost
- Work underway on commercial sensor fabrication. Certain to increase production rates, uncertain to reduce costs
- Several institutes make CMB detectors (ANL, UCB, NIST, Goddard, JPL, …). Some steps underway to coordinate fabrication (UCB-NIST). But, process flows still separate. Is any specialization useful? Example: TES films from common source.

Readout

- Microwave readout for TESs and MKIDs promises much higher multiplexing factors: $O(10^3)$
- But costs of new electronics (SLAC, FNL, Abaco) need to be understood. SBIRs?
- Packaging and cabling technologies strongly affect yield and ease of integration. Often overlooked and under-resourced. Many efforts: >5 institutes making superconducting flex

Cryogenics & Dewar

- Already commercial items
- Use SBIR program to fund development of "economical dilution refrigerator"? Dilution fridge for CMB different than fridge for quantum computing. One manufacturer has already shown that fridges for sensors can be less expensive
- Traditionally purchased individually for each project and different each time. Can projects converge on some common components and purchase together?

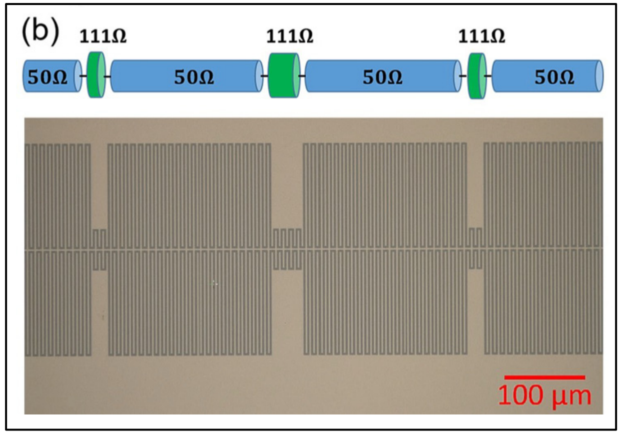
Integration & Test

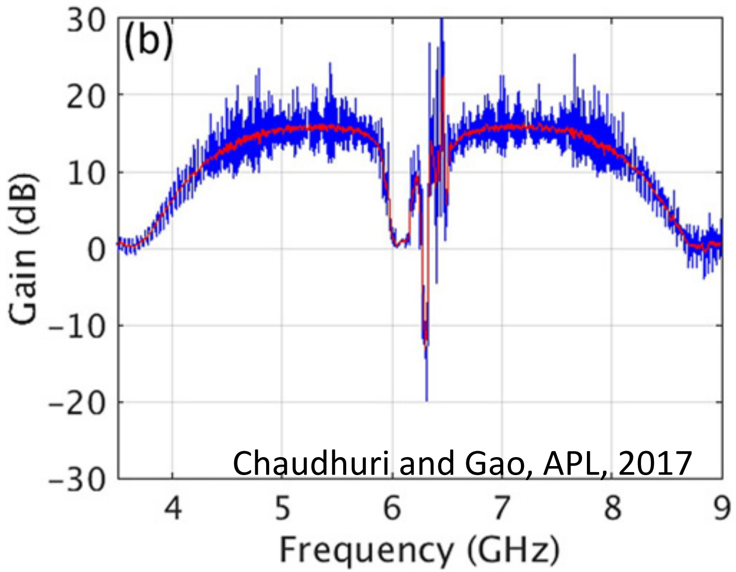
- Good part yields best way to reduce this cost
- Modern tooling useful: automatic wirebonders, automatic 300K probe stations, automatic 4K probe stations, …
- MKID integration easier than TES (but production costs similar)

Costing is complicated: not all $ are the same, large tool sets already exist, institutes make their own equipment and R&D investments, physicists aren't economists … .

Prospects for bringing superconducting sensors to a scale comparable to semiconductor devices

- CCDs and active pixel sensors routinely achieve pixels counts of O(10^6) or more
- Largest instruments with superconducting sensors have ~10^4 pixels: SCUBA2, SPT3G, optical MKIDs, …
- At CMB wavelengths, semiconductor sensors aren't ideal predictor of technological direction: pixel size ~ 1 mm^2 so 10^6 pixels occupy ~1 m^2. Poses unique challenges
- Nonetheless, some approaches from semiconductor instruments worth considering such as hybridization using solder or indium bumps to mate sensors and readout. Good for scalability, but in tension with desire for low cost and high production rates.
- Good reasons to be optimistic about scalability of readout technologies for superconducting sensors:
  - microwave readout for TESs and MKIDs
  - multiple stages of multiplexing to use bandwidth most efficiently
  - other useful devices: parametric amplifiers …





Chaudhuri and Gao, APL, 2017

Conclusions

1. Fabricating 300 wafers of sensors for CMB S4 is a large challenge, but not an overwhelming one. Existing production rates X 3 years X 3 institutes can meet demand.

2. Cost and difficulty for integration & test, readout, and cryogenics & dewars are comparable to sensor production. For example, sensor testing may take longer than sensor production. These project elements should not be ignored.

3. There are numerous ways to increase production rates, lower costs, and add technical capability (but none are truly blue sky).