Technology Challenges for the next decade of CMB

Clarence Chang
Argonne National Lab
and the University of Chicago

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Goals:

- Provide a framework for putting future CMB work in context
- Articulate where we are technically and to show the momentum in the field
- Will use TES bolometer arrays with single-moded optics as a concrete example for assessing generic challenges
- Though other approaches (e.g. MMICs, muti-moded bolometers, mKIDs, bolometric interferometry) won't be presented in detail, they should be included in our discussions

Similar language to DETF

- Stage II: (>1K detector elements)
  - e.g: EBEX, SPTpol, BICEP2/Keck, Polarbear, ACTpol...
  - already observing (or about to)
- Stage III: (>10K detector elements)
  - 10x mapping speed over Stage II
- Stage IV: (>100K detector elements)
  - 100x mapping speed over Stage II
  - This is what would come next (deploy ~2020, observe for 5 years?)
  - What challenges do we need to overcome?

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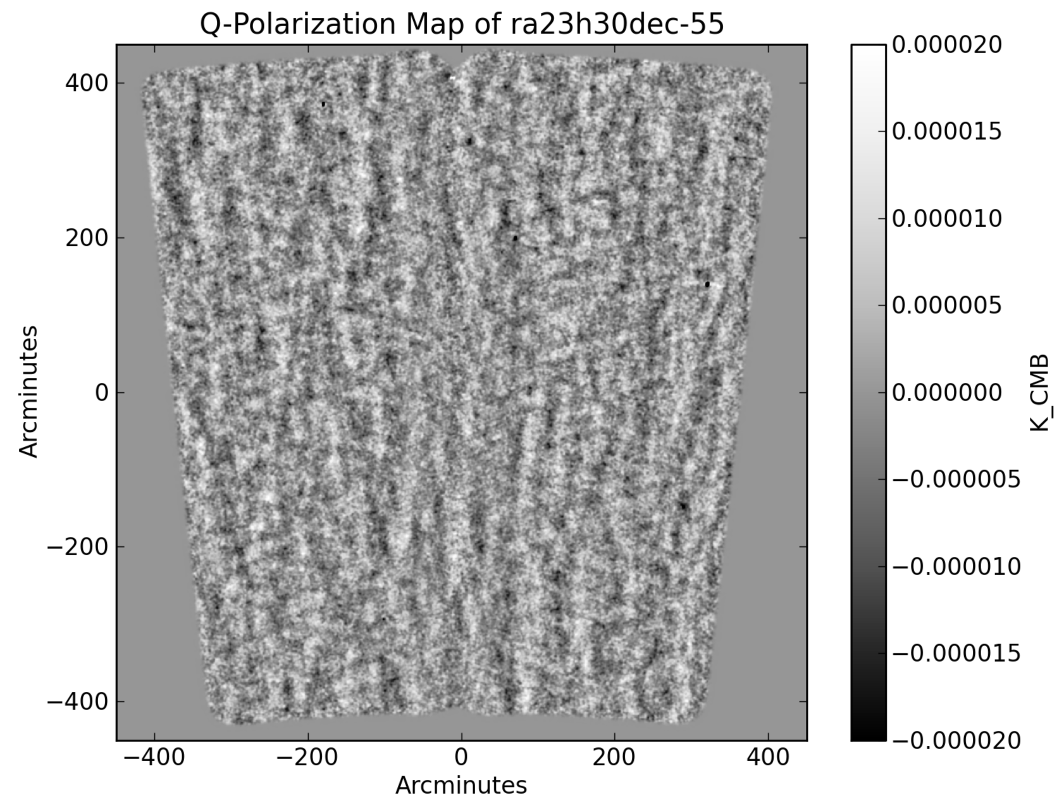
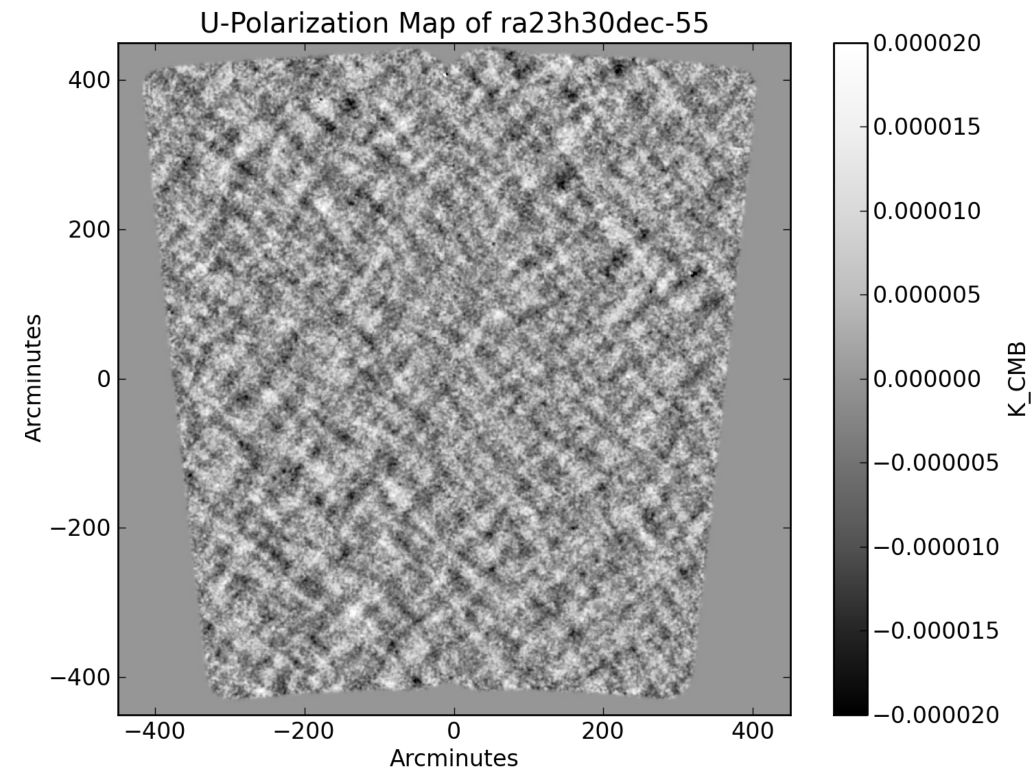
1. Brief intro to (TES bolo) technology for Stage II
2. How this is evolving for Stage III
3. Thoughts for Stage IV

NB: 1 & 2 mostly background to provide framework for understanding 3

Stage II: where we are now

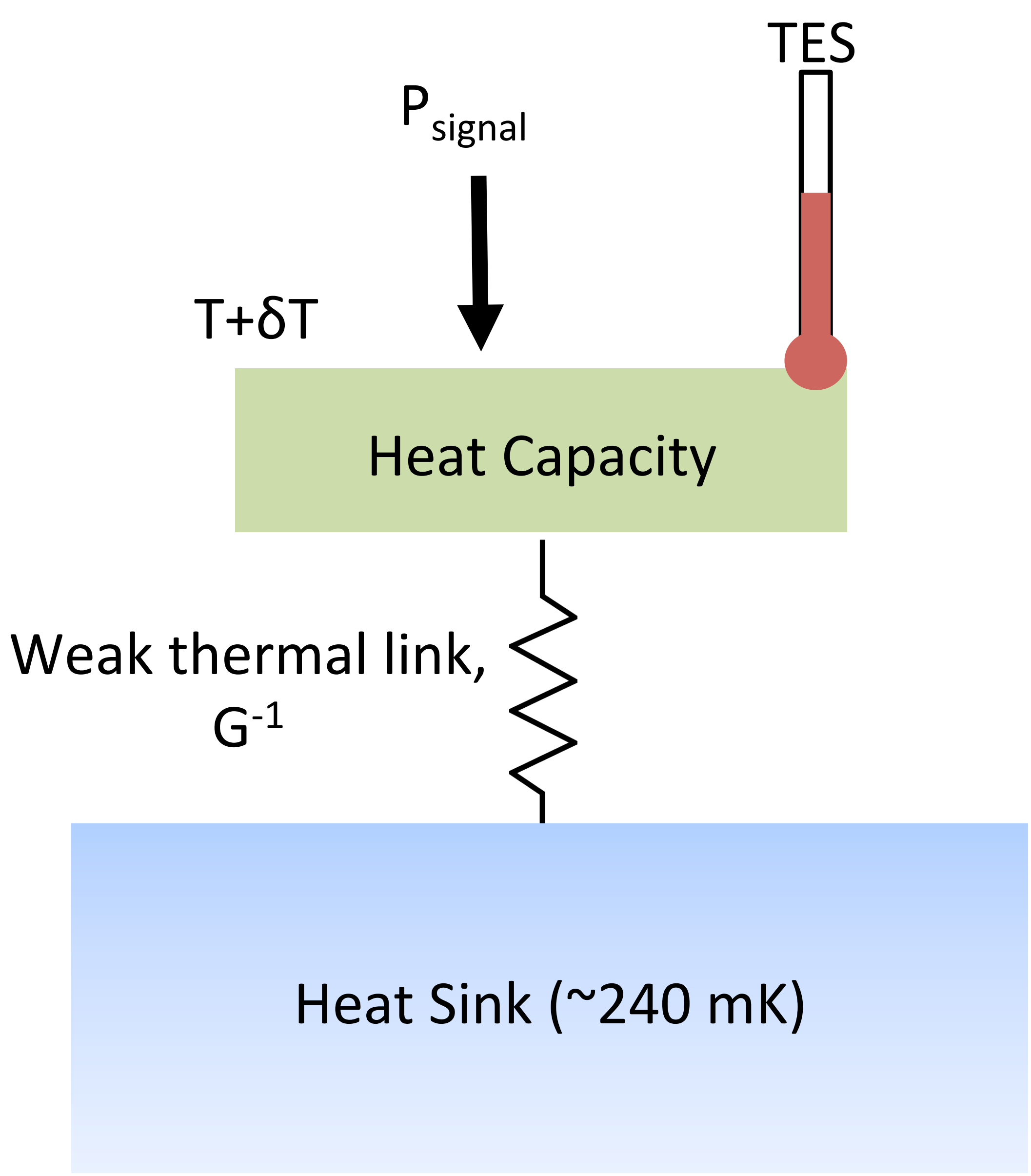
100 deg2 6 months with SPTpol
~10 uK rms





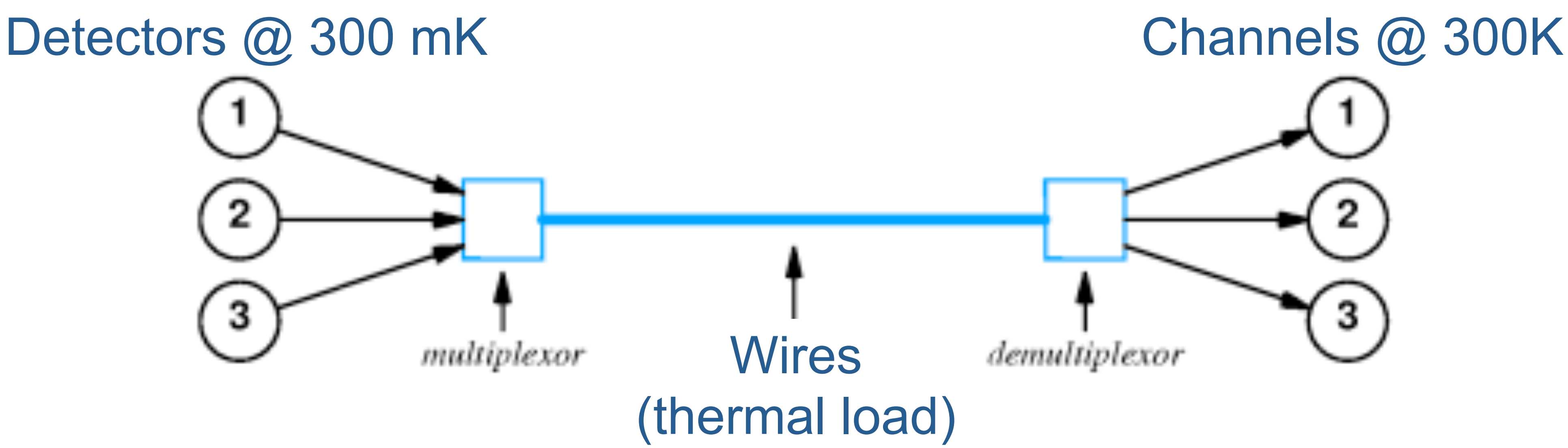
- Multiple Stage II experiments are already taking data with 1-3 years in the can
- Mapping speeds are not far off from where we expect them to be (pretty much right on the nail)
- Demonstration that these technologies are mature
  - can build forefront experiments with some reliability

Bolo basics



- Changing optical power on detector changes temperature
  - Look at hot spot, T_{bolo} increases
  - Look at cold spot, T_{bolo} decreases
- Measure T_{bolo} to get T_{sky}
- Fundamental noise terms (detector sensitivity)
  - Thermal carrier “G” noise from weak thermal link
  - Photon shot noise
- Background limited. Gain in sensitivity only through larger focal planes (more optical modes)

Multiplexing



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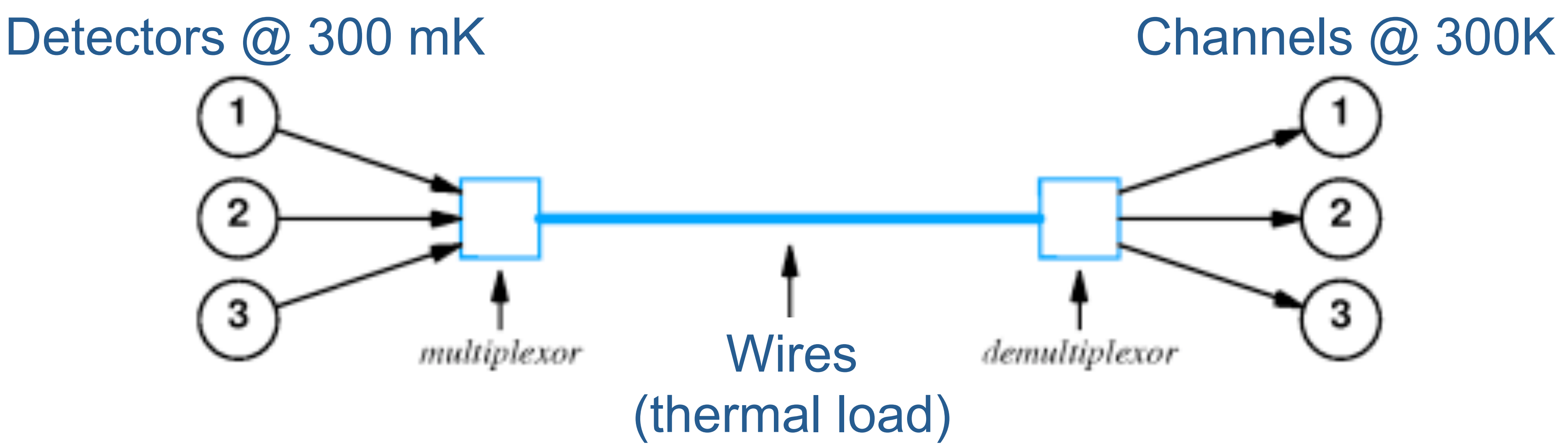
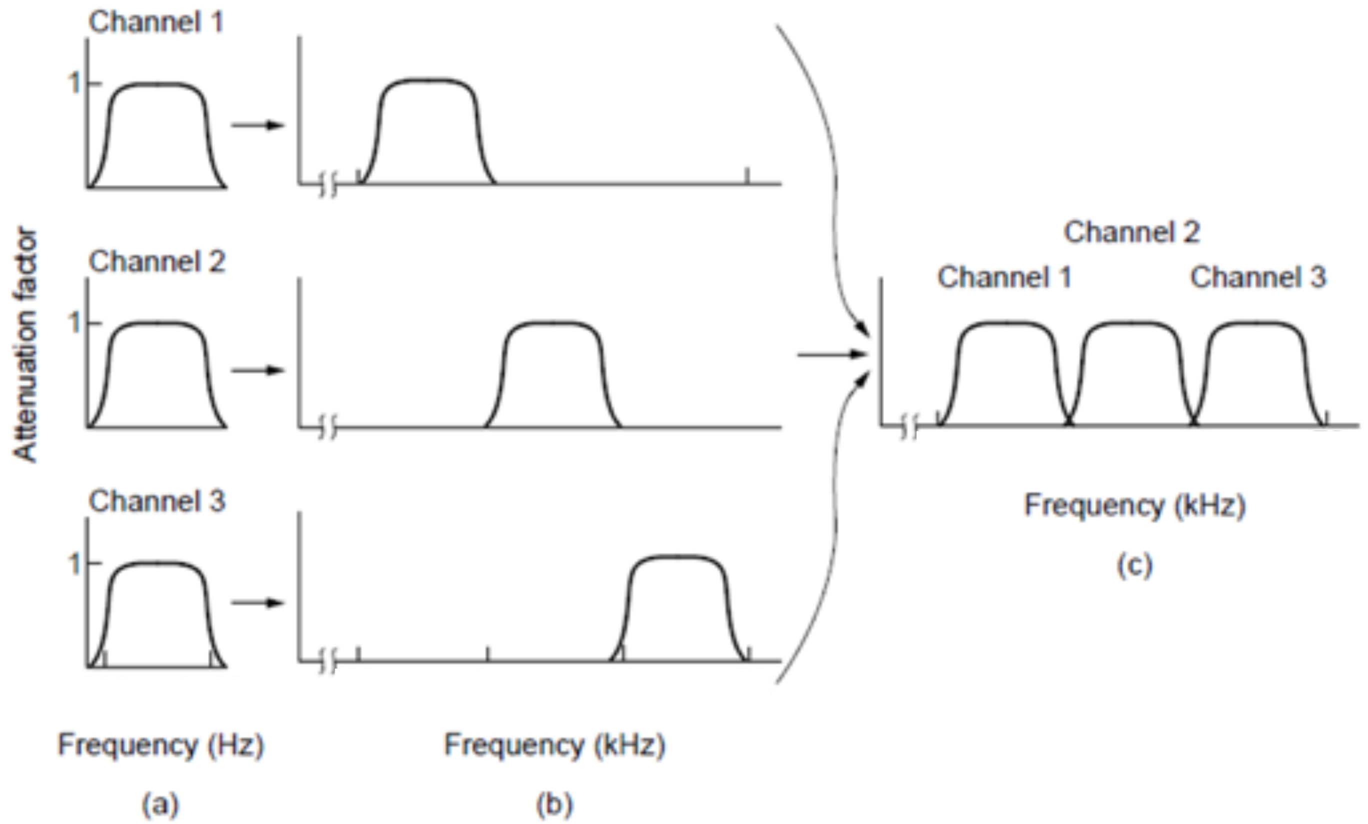


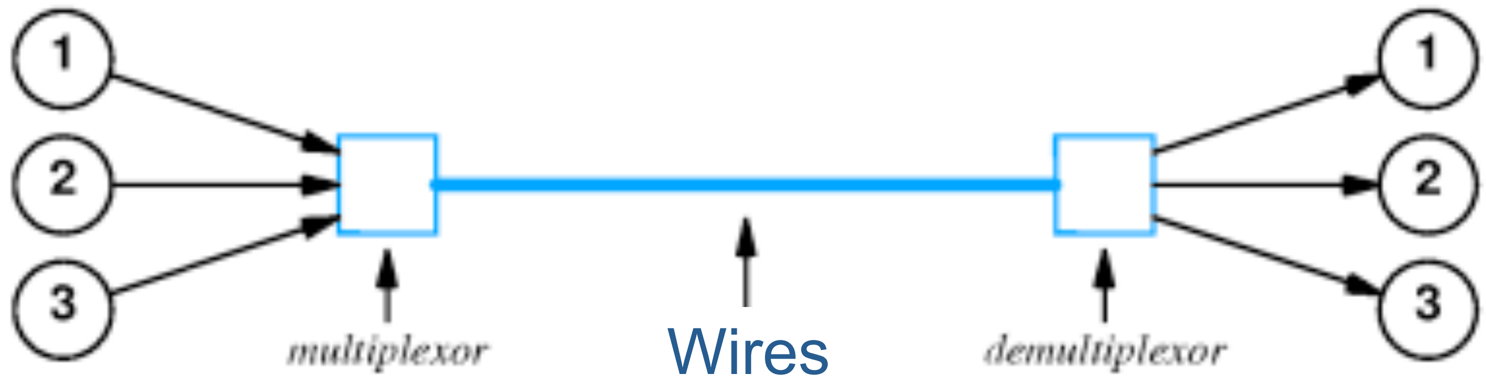


Frequency

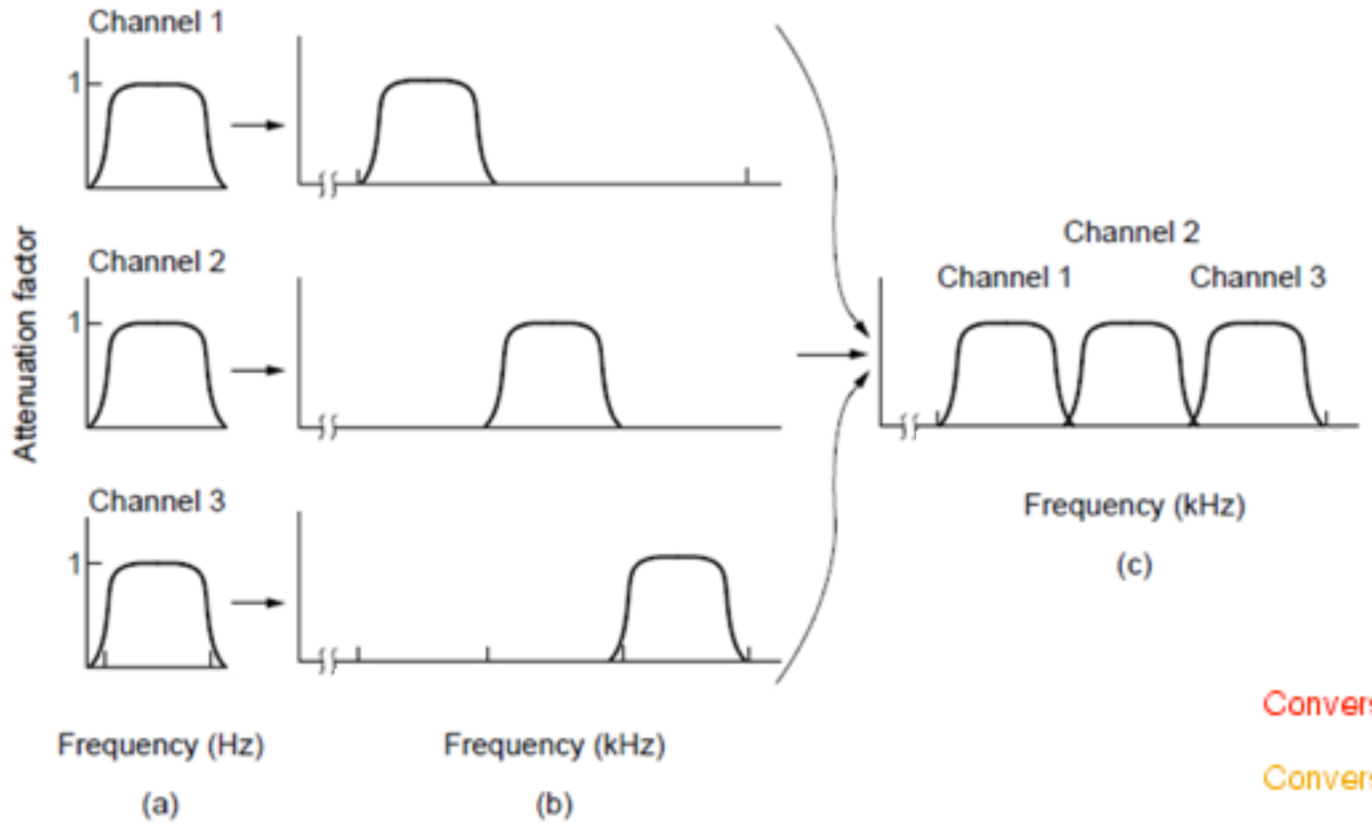
Multiplexing

Detectors @ 300 mK

Channels @ 300K

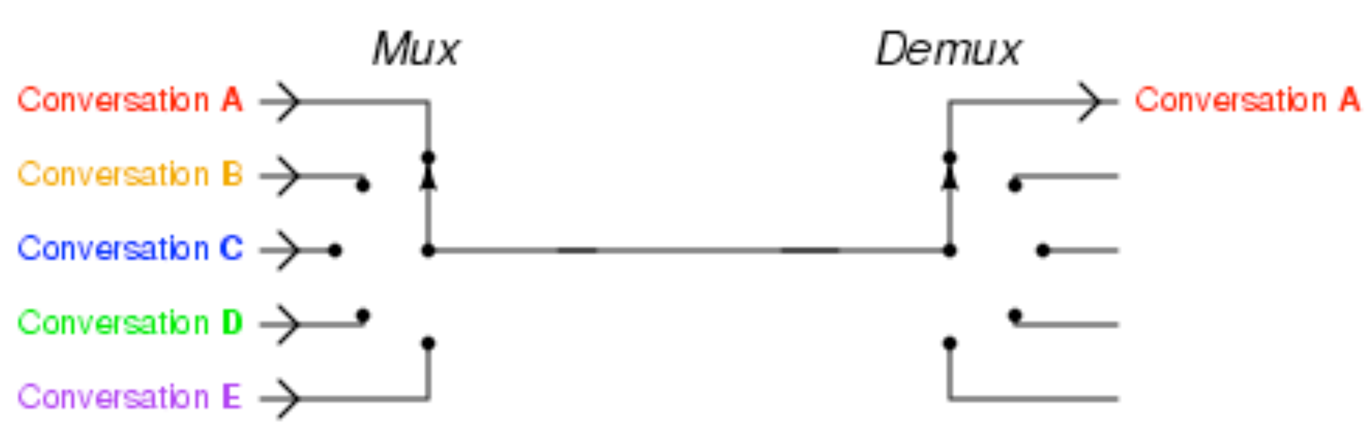


Wires
(thermal load)



Frequency

Time



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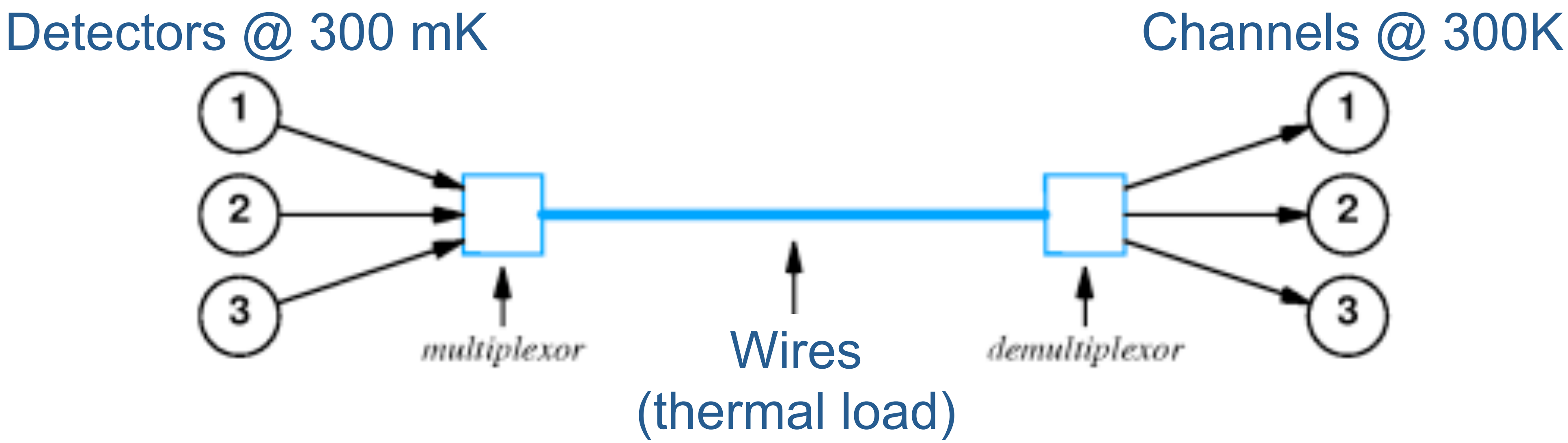
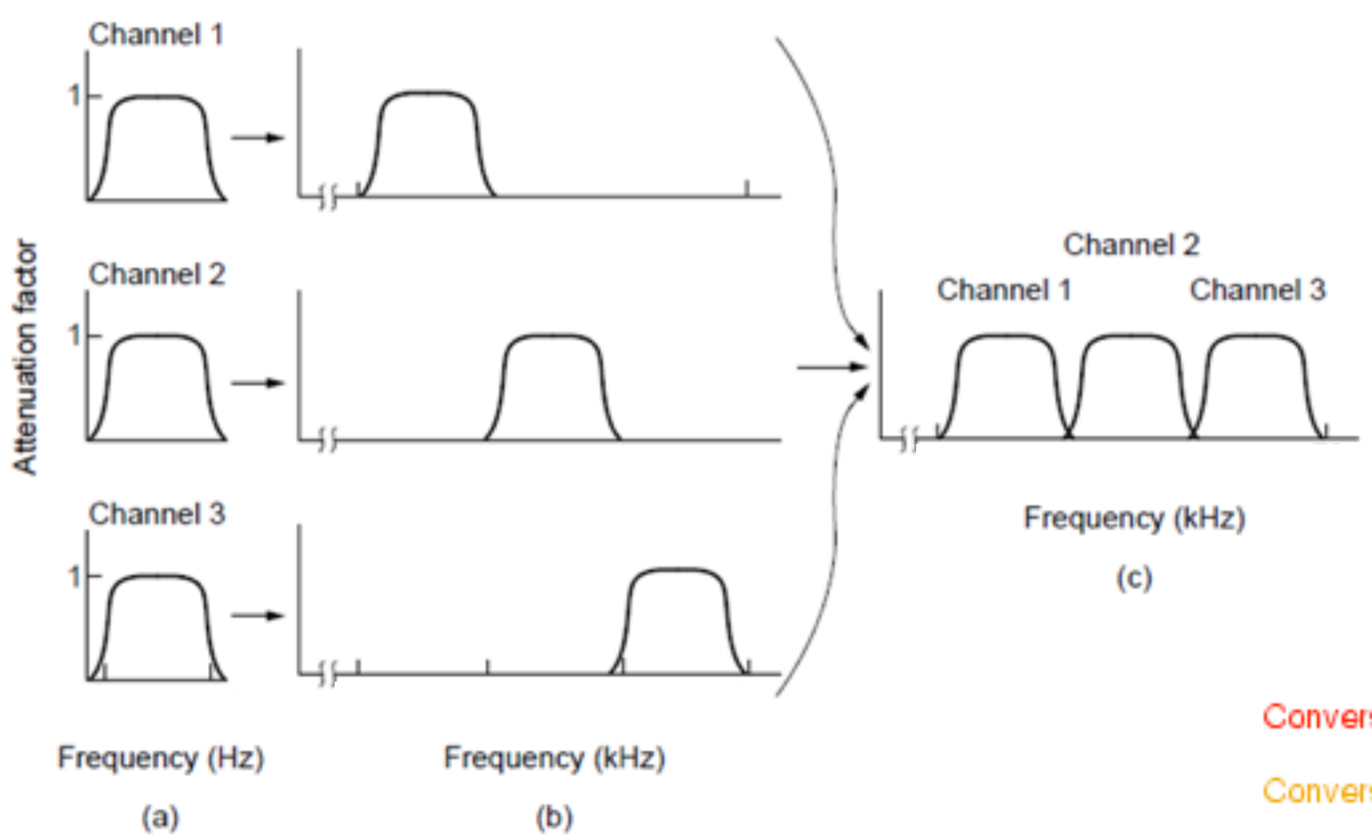
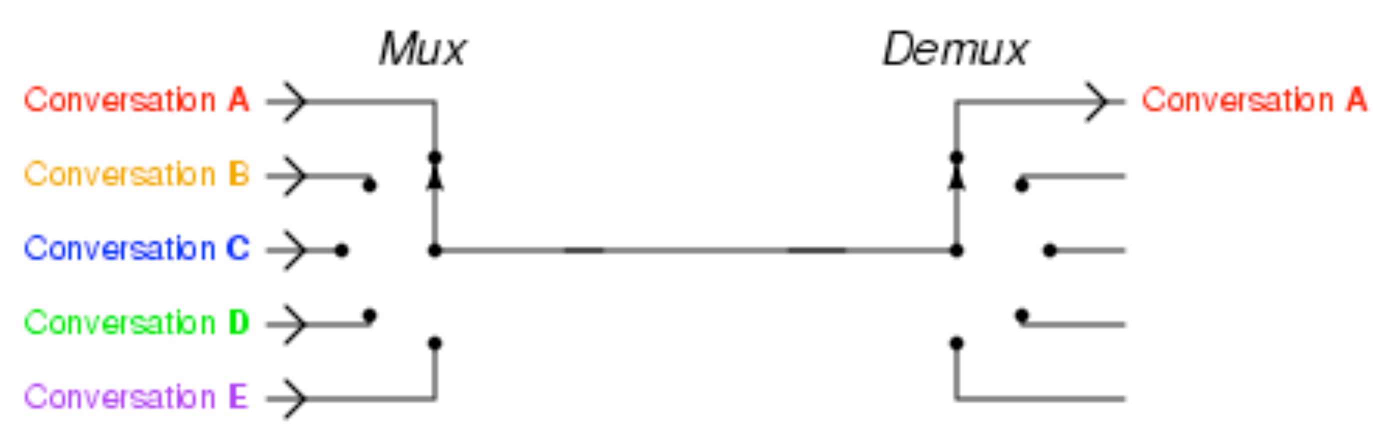




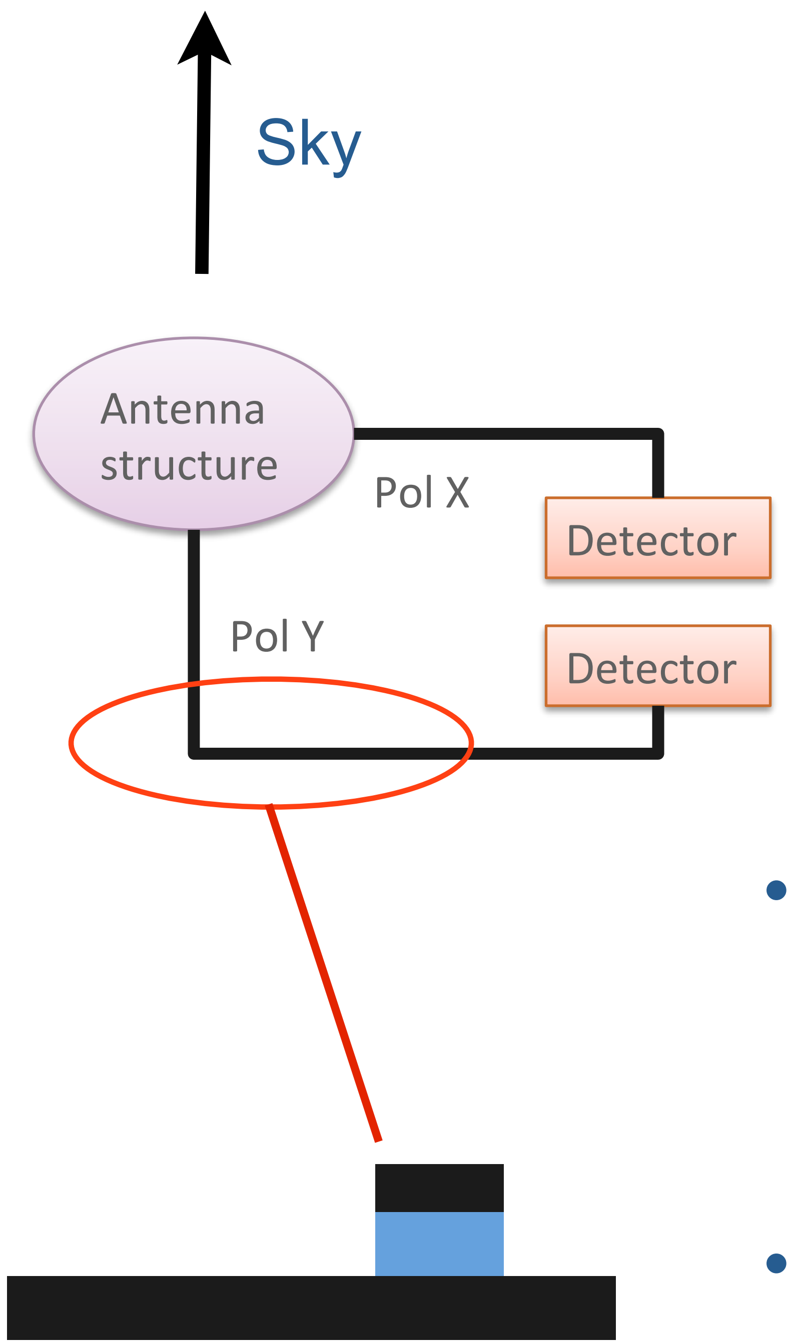
Frequency

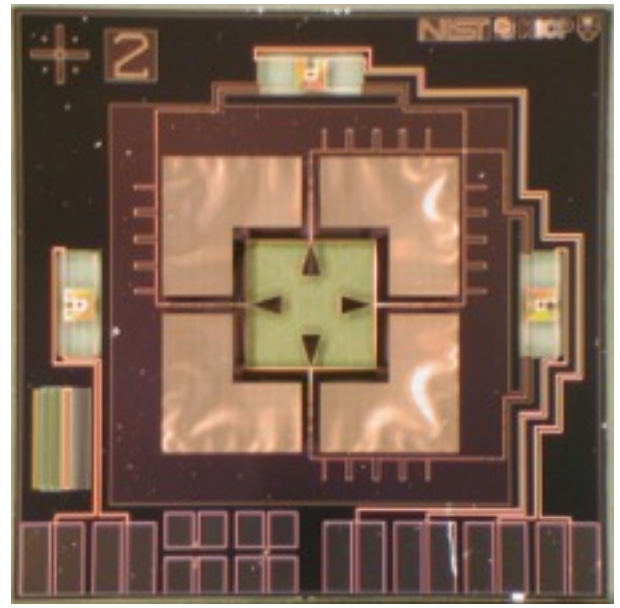
O(10) MUX for Stage II
O(50) MUX for Stage III
Sufficient for Stage IV

Time

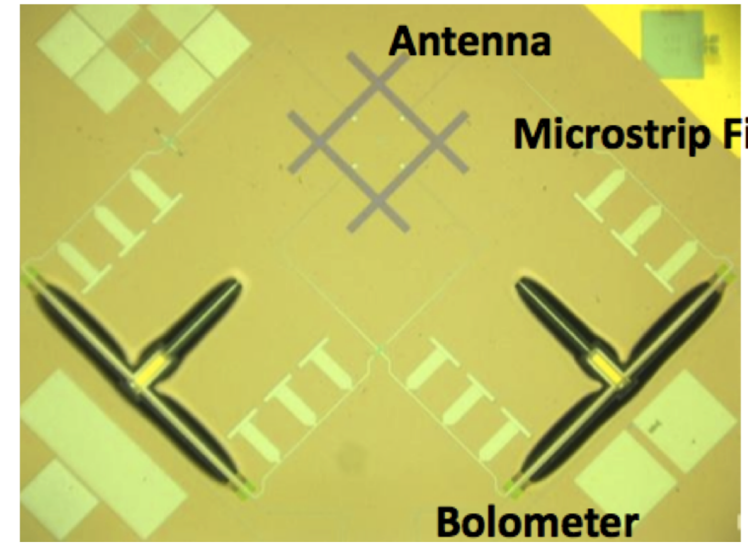


"Optics" and Superconducting Microstrip



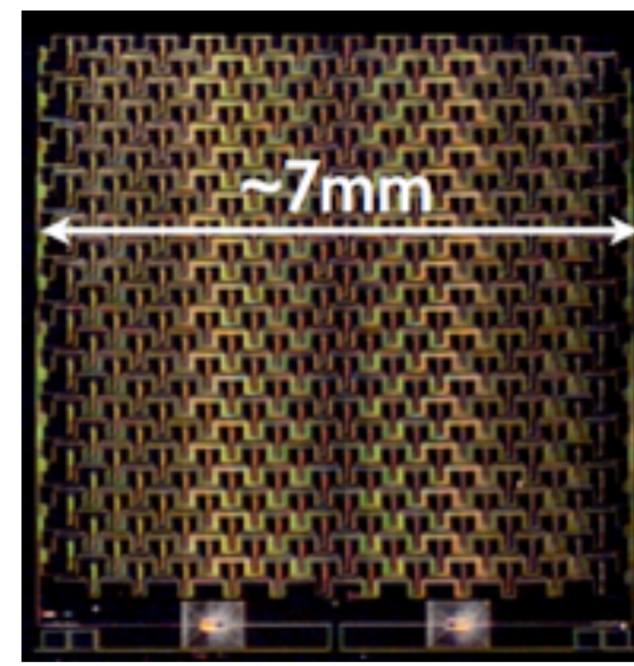


SPTpol (& ACTpol)

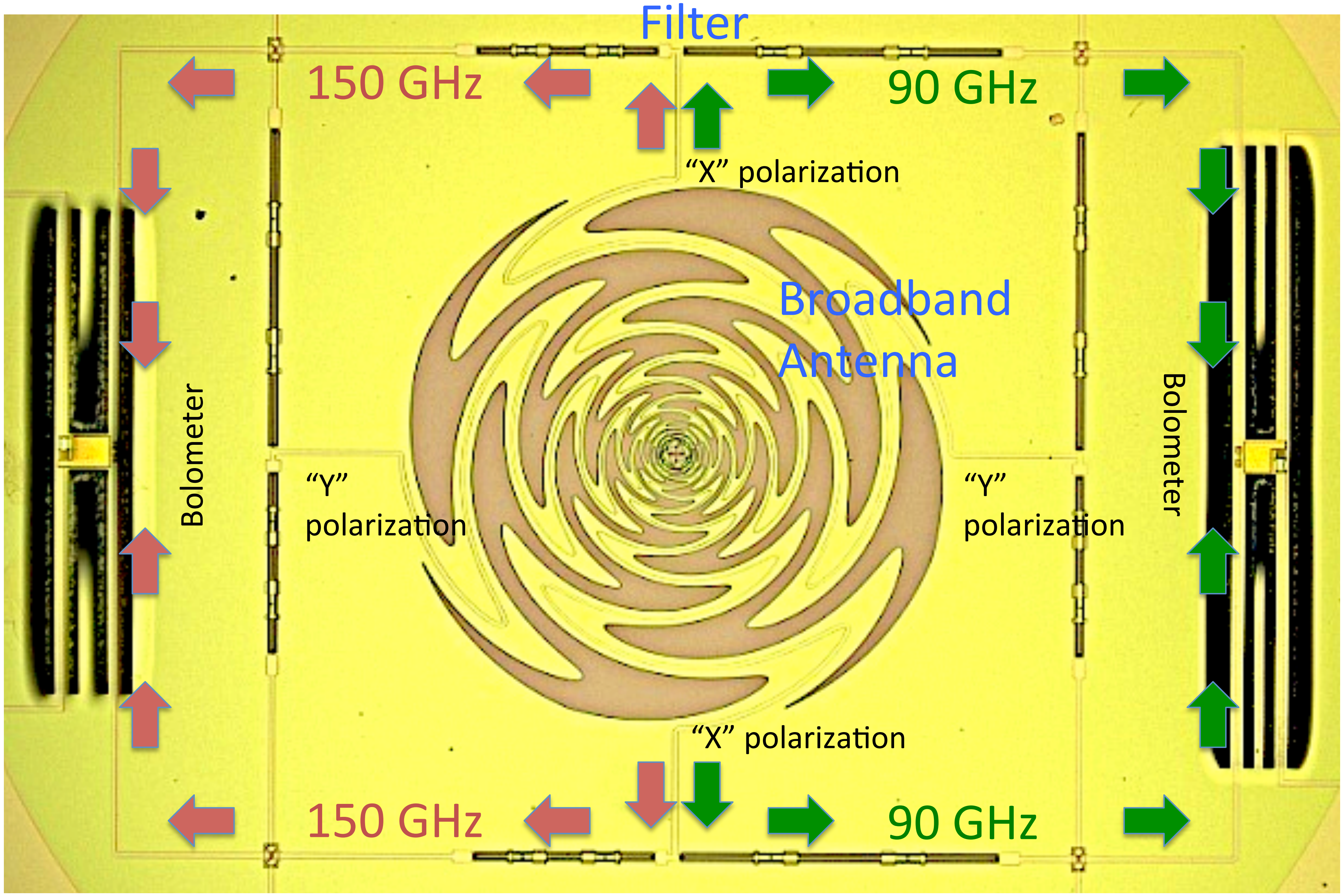


Polarbear

- Manipulate field with planar structures e.g.:
  - band pass filters
  - beam synthesis
  - polarization separation
- Elements fabricated as part of the focal plane
- Implemented in existing Stage II experiments as single band detectors (2 bolos per pixel)



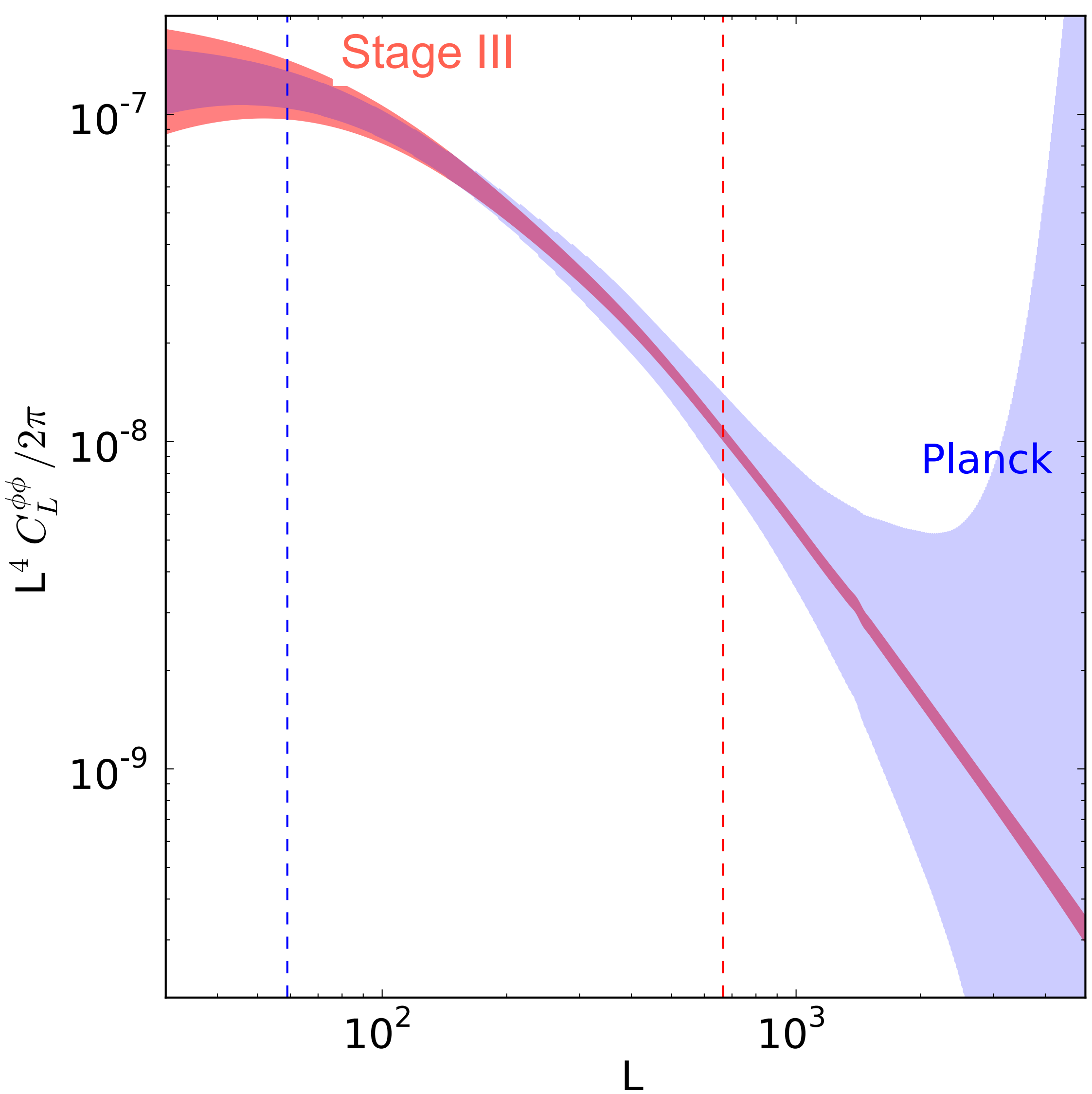
BICEP2/Keck

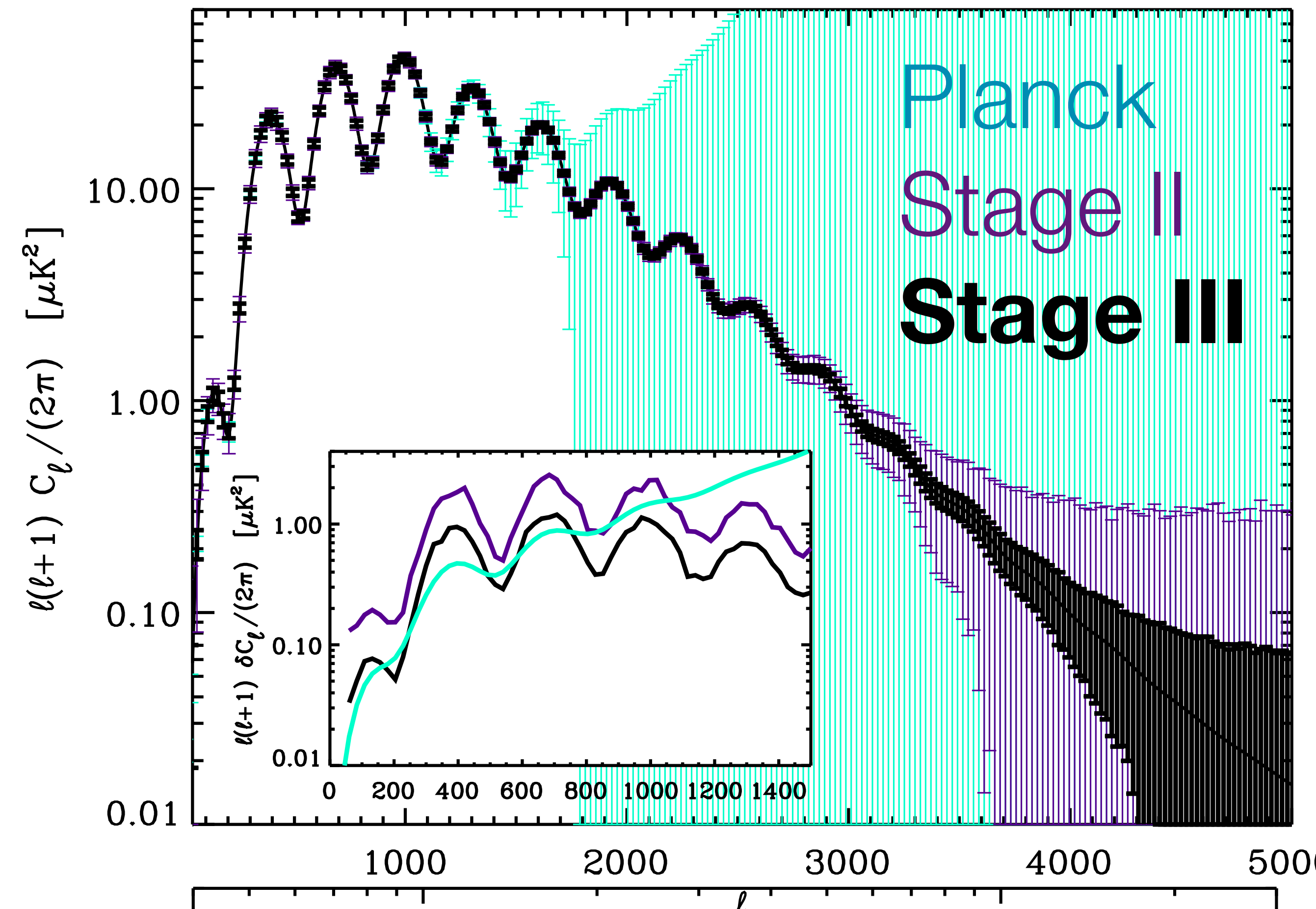


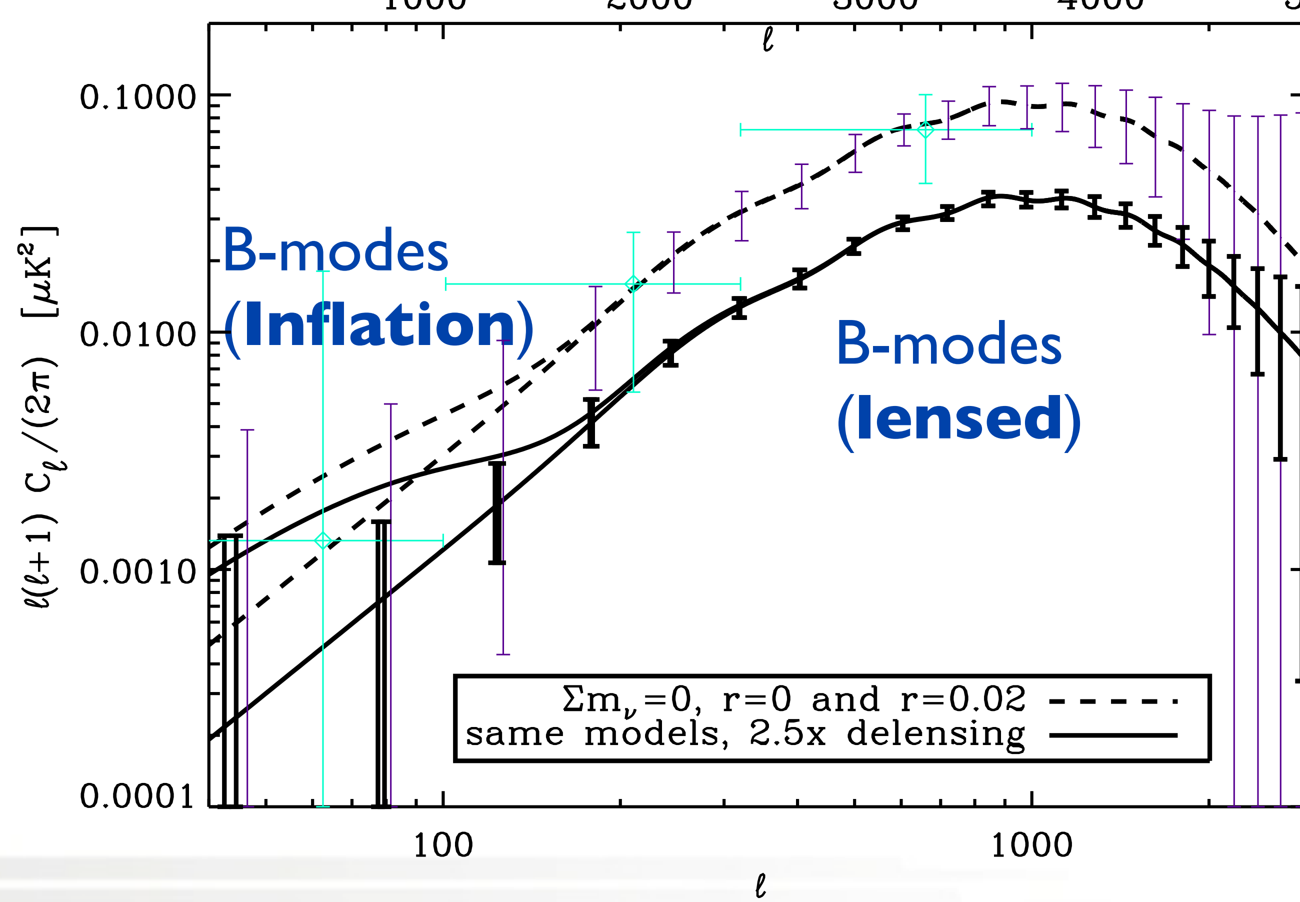
- Development by Berkeley over past few years
- Analogs for Feedhorn coupled (NIST) and phased array (JPL)
- Focus of ANL-UCB-NIST joint collaboration for SPT-3G focal plane (6 bolos per pixel, 16,000 bolos focal plane)
- Together with larger apertures (e.g. BICEP3) will yield 10x over Stage II

Where we will be scientifically post Stage III?

- Stage III
  - σ(r) = 0.01
  - σ(Σm_ν) = 60 meV
- Stage IV
  - 10x mapping speed over Stage III to map 10x the area to ~1 uK arcmin







Production Challenges

- Stage IV likely to be multi-platform experiment
  - background limited detectors. 10x increase in mapping speed over Stage III requires ~100k detector elements
  - Stage III will use up most of the usable focal plane area for a given cryostat
  - BICEP2/Keck demonstrates this can work. Future collab. w/ SPTpol
- Idealistic “extrapolation” to Stage III production only (excl. development)
  - Larger arrays, more modes per pixel (multi-chroic)
  - Want 10 arrays
  - Assume reasonable yield (~70%)
  - Assume reasonable (realistic?) hours
  - Optimistic est. ~6 months for production of a Stage III focal plane
- Idealistic “projection” for Stage IV (10x bigger)
  - ~60 months (5 years) for <u>production only</u>
  - Need to increase production throughput
  - Upgrade fabrication facilities. Collaborate/parallelize between multiple fabs.
    - e.g.: ANL/NIST/UCB-LBNL collaboration for SPT-3G & PBII

Testing challenges

- Real time feedback
  - Testing time comparable to fab cycle. A little better if everything is right. A lot longer if there are issues
  - Role typically filled by university groups for Stage II.
  - This continues to be the plan for Stage III.
  - Increased university and national lab involvement for Stage IV

- MUX development
  - 4x-10x increase in MUX factor is achievable
  - For a multi-platformed Stage IV, no gain from additional MUX improvement beyond this.
  - Probably makes sense to connect electronics production and QC with a National lab.

Addressing systematics & cost with additional technology?

Test Particle

- TES bolometer arrays with single-moded optics are a mature technology for CMB polarimetry.
- There is momentum and potential to achieve 10-100x improvement in experiment mapping speed
  - after Stage III, challenges deal with realizing large scale production & delivery
  - required gains in MUX readout and cryogenics are modest and achievable

- Questions:
  - What systematics are important for Stage IV?
  - What technical aspects of TES bolo arrays are driving costs/time?
- Do other technologies address some of these issues? Trade-offs?
  - e.g.: MMICs for lower frequency channels & foregrounds. Different development & testing resources vs TES bolometers
  - e.g.: Multi-moded detectors for large angular scales without MUXing. Save on detector fab and readout cost. Forfeit small angular scale science (e.g. neutrino mass)
  - **Homework: assess what are the trade-offs and gains**

Strong Overlap with Instrumentation Frontier

- Charge of Instrumentation Frontier (Snowmass)
  - Provides evaluation of HEP technology R&D
  - Identifies and advocates new promising technologies
- Coordinating Panel for Advanced Detectors (CPAD)
  - Standing panel over the next decade
- Technical challenges for Stage IV are well matched to program
  - non-commercially available technology
  - large scale
  - critical for enabling science
  - broadly applicable (e.g.: X-ray for A&A and synchrotron, optical for DE, DM, neutrinos)
- Joint CPAD & Community Instrumentation Frontier Workshop at Boulder April 17-19 (https://indico.fnal.gov/conferenceDisplay.py?confId=6280)

Final thoughts

- Stage II is already here and very impressive. Technical achievements from past decade are yielding high-quality CMB data. Bar is set very high...

- Well defined plan for some Stage II technologies to move to Stage III. Stage III will utilize the entire available focal plane area for a single platform. Will even include multi-moded/chroic pixels.

- Stage IV CMB project is not an incremental improvement over Stage III.
  - Probably multi-platformed.
  - Scale of production is challenging for our existing framework.

- Homework: assess role/impact of a broader suite of technologies

- Stage IV CMB has a healthy case to be made with regards to Instrumentation R&D.
  - Encourage participation in the Instrumentation Frontier discussions in addition to CF discussions.
  - Encourage increased engagement with CPAD