CCAT LWCam

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with help from
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and the MKID DemoCam gang:
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CCAT

Outline

- Instrument Design Goals
- Strawman Design
- Detector Options
- Weight, power, manpower, cost

Instrument Design Criteria

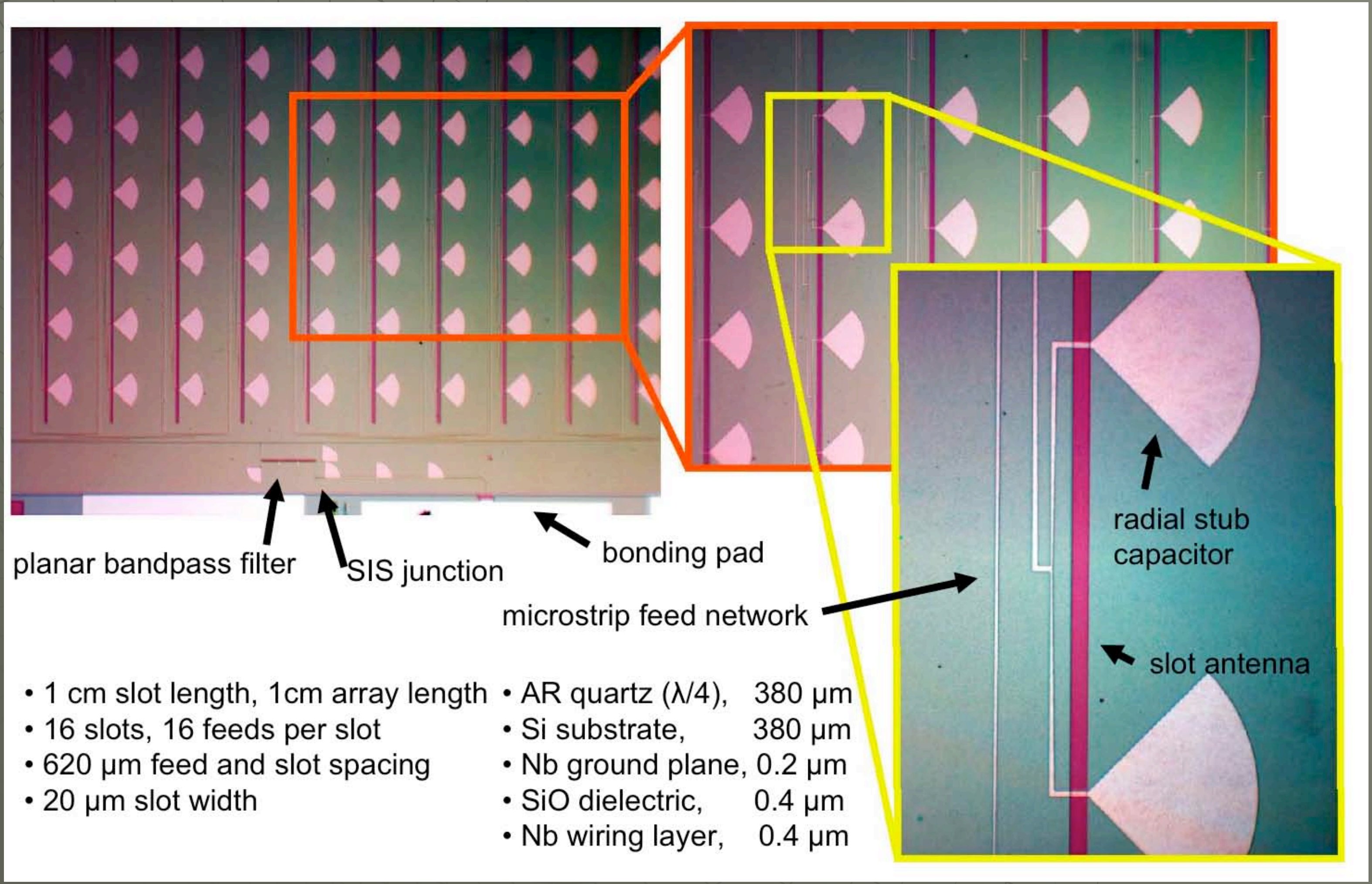
- Maximal use of FoV
  - esp.: *try* to design optics and dewar to allow it, even if we can’t fill it all right now
- Simultaneous multiband coverage
  - Most LWCam science drivers require multiband SEDs
  - For some sources, sky noise removal may be greatly enhanced (need sky ~ orthogonal to signal)
  - Observatory efficiency!
- Optical train with low optical loading
  - Atmosphere is >90% transmissive at > 1 mm under median conditions, don’t want telescope to limit us!
  - < 10% total (including telescope), < 5% desired

Instrument Design Goals

- Antenna-Coupled Architecture
  - Clearly can't do feedhorns at pixels counts we want
  - Bare absorbers are non-optimal
    - Single array doesn't work well across a wide band (pixel sizes, backshort distance)
    - No known way to cosituate multiple arrays at different colors
  - Single-pol antenna-coupled design offers "simple" way to cover multiple bands with varying pixel sizes simultaneously
- Multiplexable detectors
  - A must!

Antenna Coupled Arrays – 1

- Caltech-JPL are developing phased-array antennae



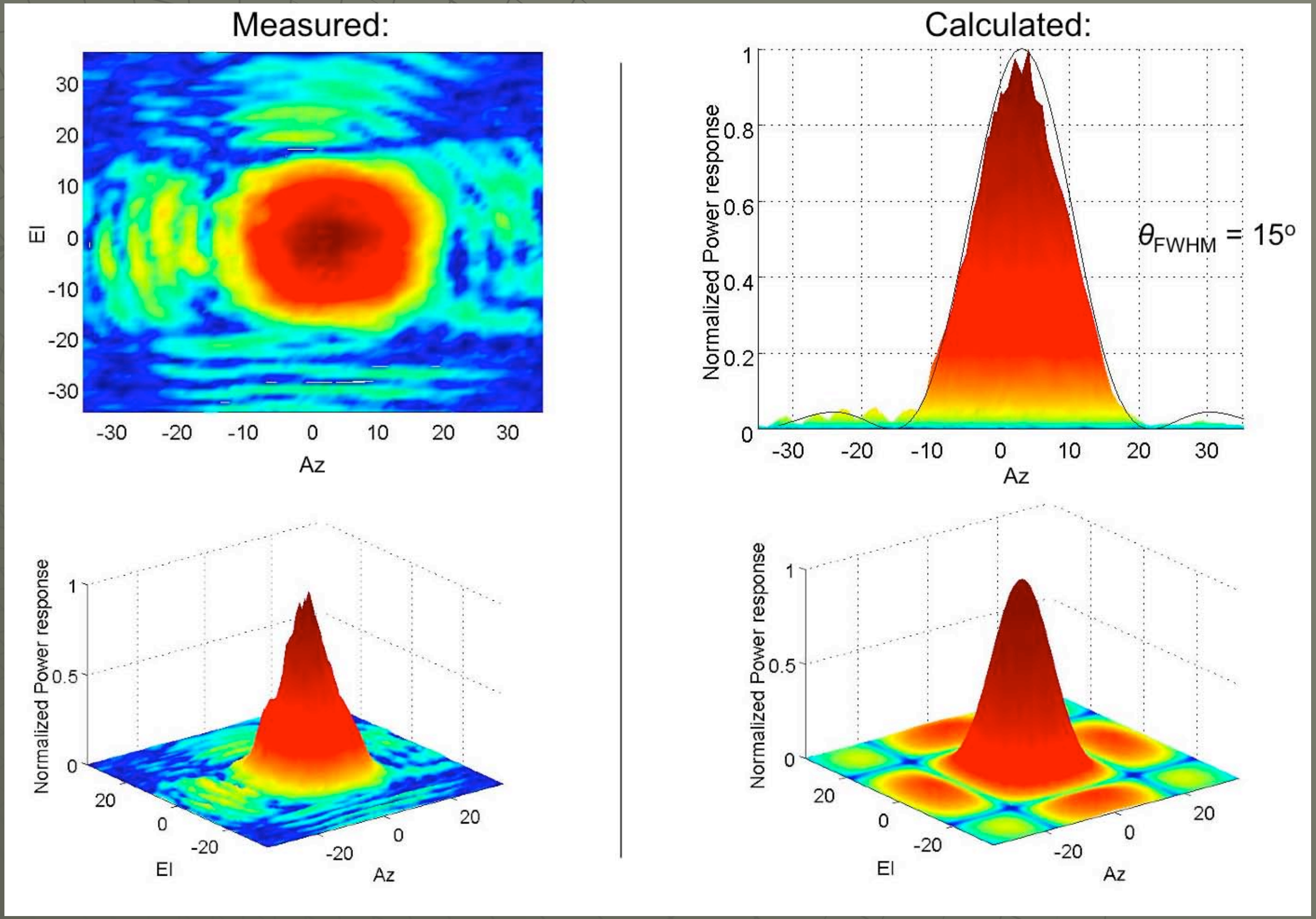
- 1 cm slot length, 1cm array length
- 16 slots, 16 feeds per slot
- 620 μm feed and slot spacing
- 20 μm slot width

- AR quartz (λ/4), 380 μm
- Si substrate, 380 μm
- Nb ground plane, 0.2 μm
- SiO dielectric, 0.4 μm
- Nb wiring layer, 0.4 μm

Tasos Vayonakis, Alexey Goldin

Antenna Coupled Arrays – 2

- 100 GHz beam maps using SIS detector; comparable maps expected soon from demo cam (initial maps had problems due to optical coupling to bare resonators)



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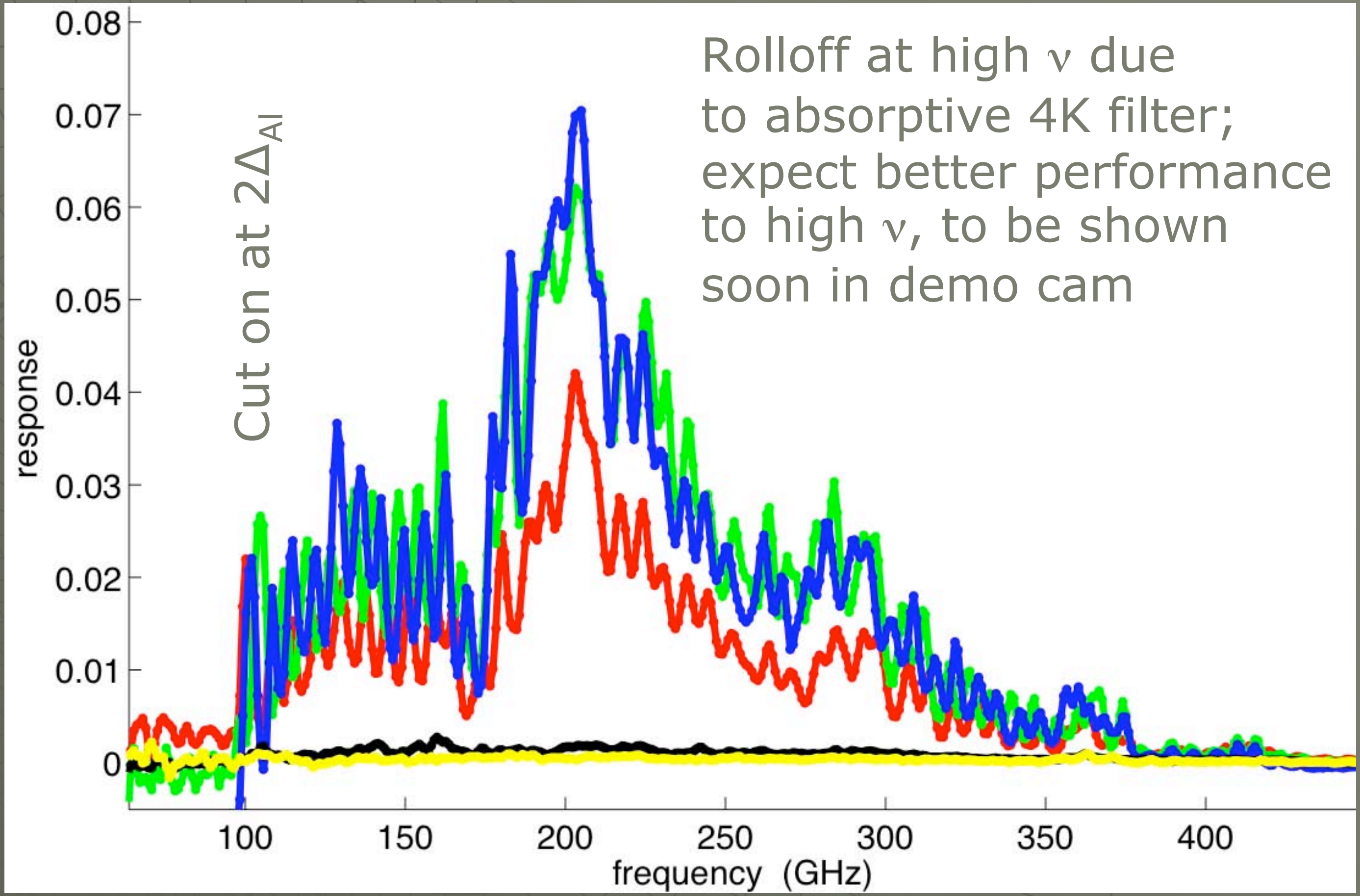
Antenna Coupled Arrays – 3

- Wide bandwidth



Cut on at $2\Delta_{Al}$

Rolloff at high ν due to absorptive 4K filter; expect better performance to high ν, to be shown soon in demo cam

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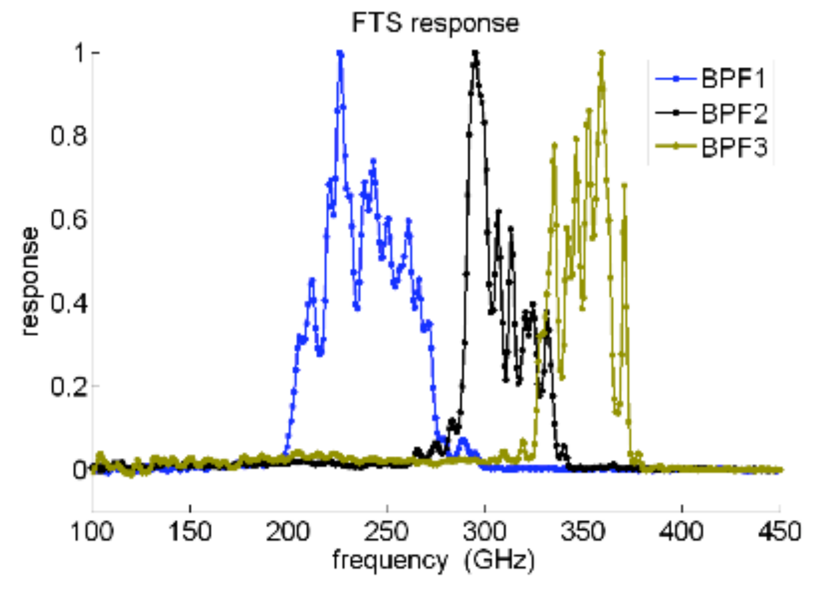
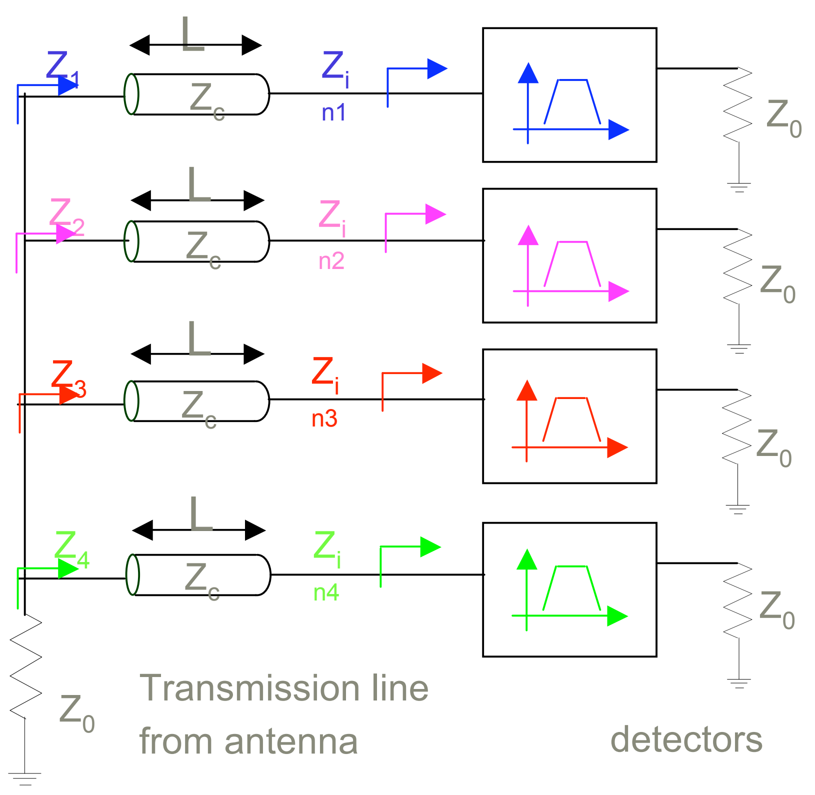
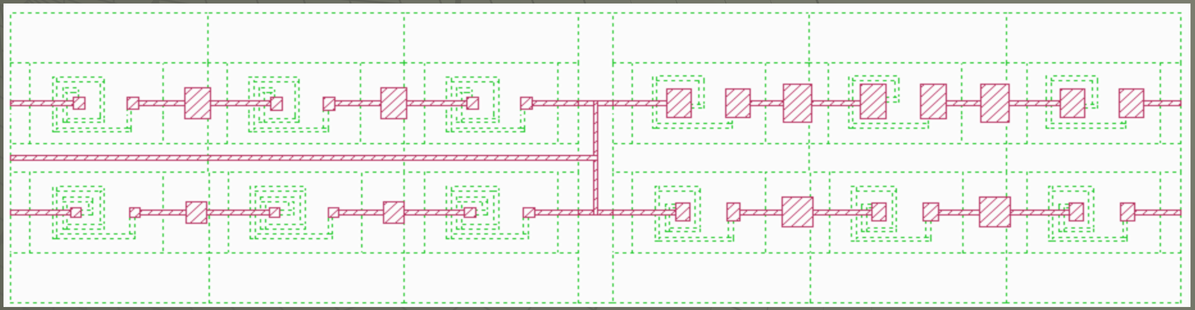
Antenna Coupled Arrays – 4

- Colors defined by in-line bandpass filters







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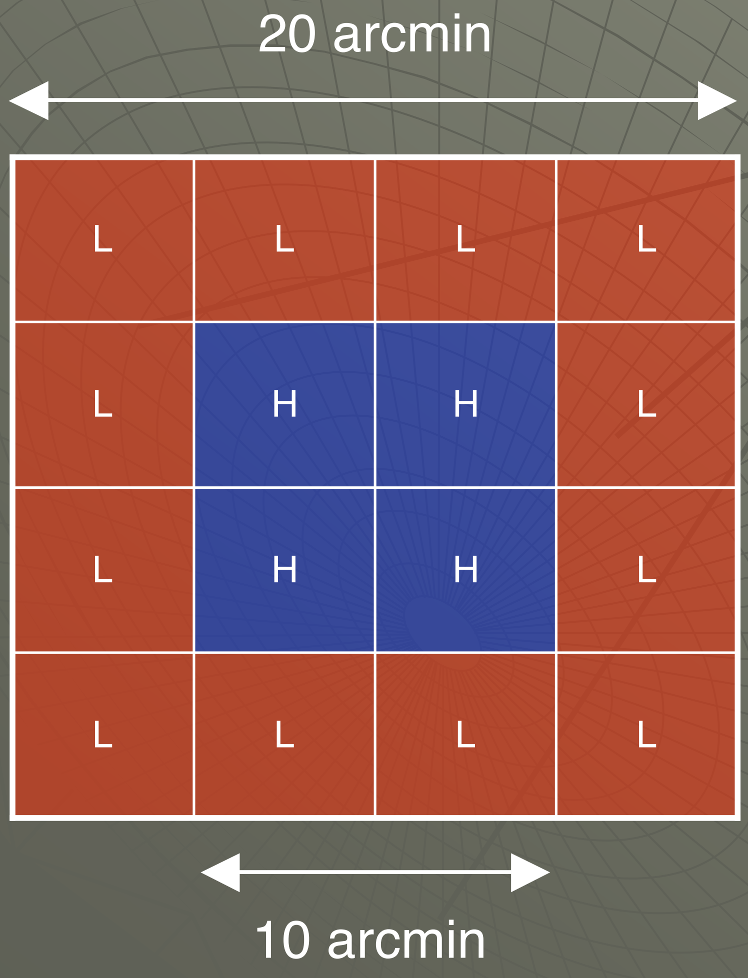
Antenna Coupled Arrays – 5

- Phased array is sensitive to a single polarization for $\sqrt{\varepsilon}\cdot(\text{tap spacing}) < \lambda < \text{slot length}$ (ε = substrate dielectric constant = 11.5 for silicon)
- Nominal design for 740 μm to 2 mm
  - Slots of length 8 mm with 64 taps (spaced at 125 μm)
  - 64 slots across a single 2 mm pixel
- Bands are separated using microstrip bandpass filters placed at the ends of a binary summing tree
- Multiscale pixellization to match pixel size to λ
  - All $64^2 = 4096$ slots summed for λ = 2 mm band: $2.3 \cdot f \cdot \lambda$ pixel
  - Subset of $8^2 = 64$ slots summed for λ = 740 μm band: $0.8 \cdot f \cdot \lambda$ pixel
  - Each 9.2 mm square is one pixel at λ = 2 mm and $8^2 = 64$ pixels at λ = 740 μm
  - $2.3 \cdot f \cdot \lambda$ at 2 mm to maximize beam control/throughput/minimize loading
  - $0.8 \cdot f \cdot \lambda$ at 740 μm to maximize sampling and angular resolution

Pixel Numerology

L = low-resolution tile
H = high-resolution tile



L	L	L	L
L	H	H	L
L	H	H	L
L	L	L	L

Band GHz (μm)	Δν (GHz)	Pixel Size f·λ	Number of Spatial Pixels
150 (2000)	30	2.3	16 tiles × 64 = 1024
220 (1400)	40	3.2	16 tiles × 64 = 1024
275 (1100)	50	2.1	16 tiles × 256 = 4096
350 (870)	40	0.7 2.8	4 tiles × 4096 = 16384 12 tiles × 256 = 3072
405 (740)	30	0.8 3.2	4 tiles × 4096 = 16384 12 tiles × 256 = 3072
Total			45,056 detectors

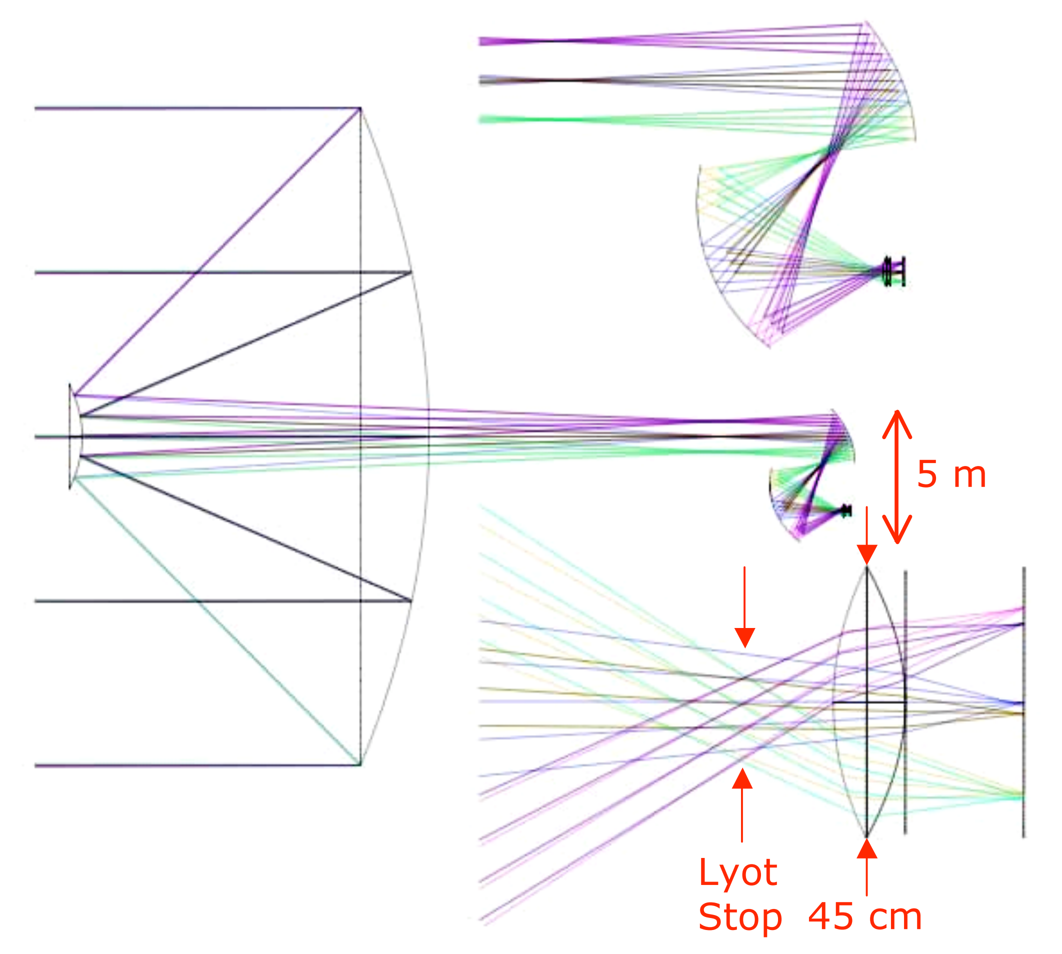
At f/2, 1 tile is approximately 74 mm across, a good fit for 4” wafer processing. Focal plane is 30 cm across, a “reasonable” size.

LWCam Optical Design

- Reimaging optics: 2 ellipsoidals + 1 cold lens to reduce telescope f/8 to f/2 for array
  - Want at least one warm focusing reimaging optic to define image of primary
  - Use two conjugate ellipsoids instead of one to partially cancel off-axis distortions
  - Cold lens provides final reduction in f/# to match array

Optical Layout

- Off-axis ellipsoids deliver Strehl ratios > 90% over the 20’ FOV excepting 2 extreme corners
- Image brought to appropriate f/2 focus by cold polyethylene lens (45 cm diameter)
- Modest 20 cm Lyot stop and 40 cm dewar entrance window
- Dewar length ~ 1 m



LWCam Optical Design

- Challenges
  - Strehl ratios still worrisome vis-a-vis beam control
  - 15% field distortion at edge of FoV
  - Big optics, 2-2.5 m! It’s a fundamental $A\,\Omega$ problem:
    - 20’ FoV and 25-m telescope -> $A\,\Omega = 13000\ \mathrm{mm}^2$
    - To keep the reimaging optics small, you end up with big off-axis angles of incidence, which screw up image quality
    - *Multiple windows and optical trains in a single camera? Would make the system more “lenslike”.*
  - Antireflection coatings
    - FP, transmissive optics must be AR coated for wide bandwidth
    - Possibilities: plastic laminates, DRIE structures in Si

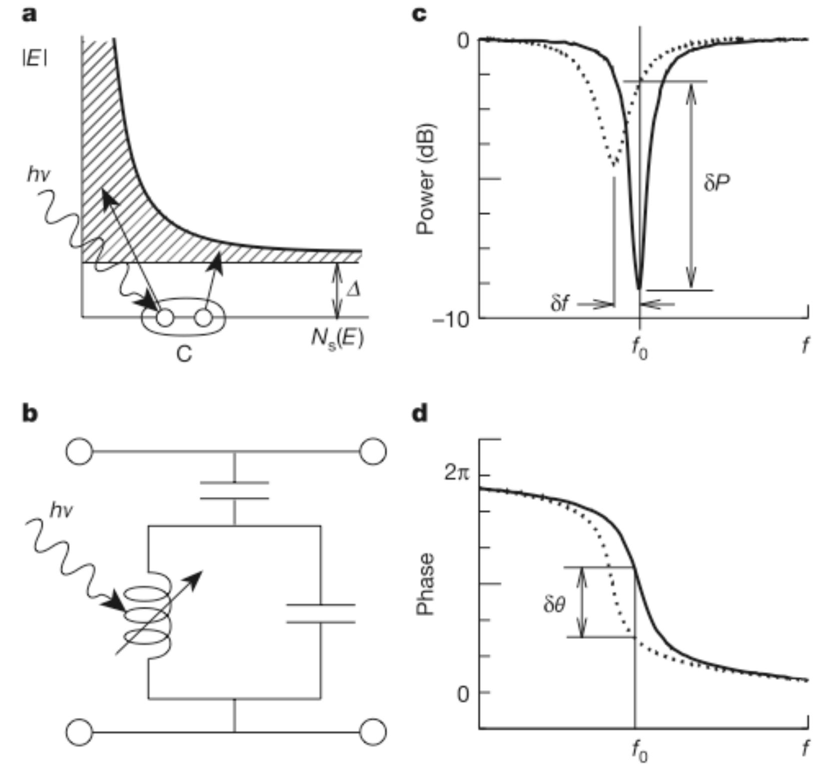
Detectors

- Only reasonable candidates are:
  - Superconducting transition-edge sensors (TESs)
  - Microwave kinetic inductance detectors (MKIDs)
- Pros and Cons
  - Sensitivity: currently TES, but MKIDs progressing
  - Degradation under optical loading: slight advantage to MKIDs
  - Fabrication: Advantage MKIDs
  - Multiplexing: Advantage MKIDs (in principle), TESs more advanced in practice to date
  - Cold electronics power dissipation: Advantage TESs
  - Microphonics Susceptibility: Advantage MKIDs
  - Magnetic Field Susceptibility: Advantage MKIDs
- Antenna-coupled TESs and MKIDs both under development at Caltech/JPL. Next year will provide lots of new information and progress.
- TESs: see Holland, Hilton, and Battistelli talks

MKIDs

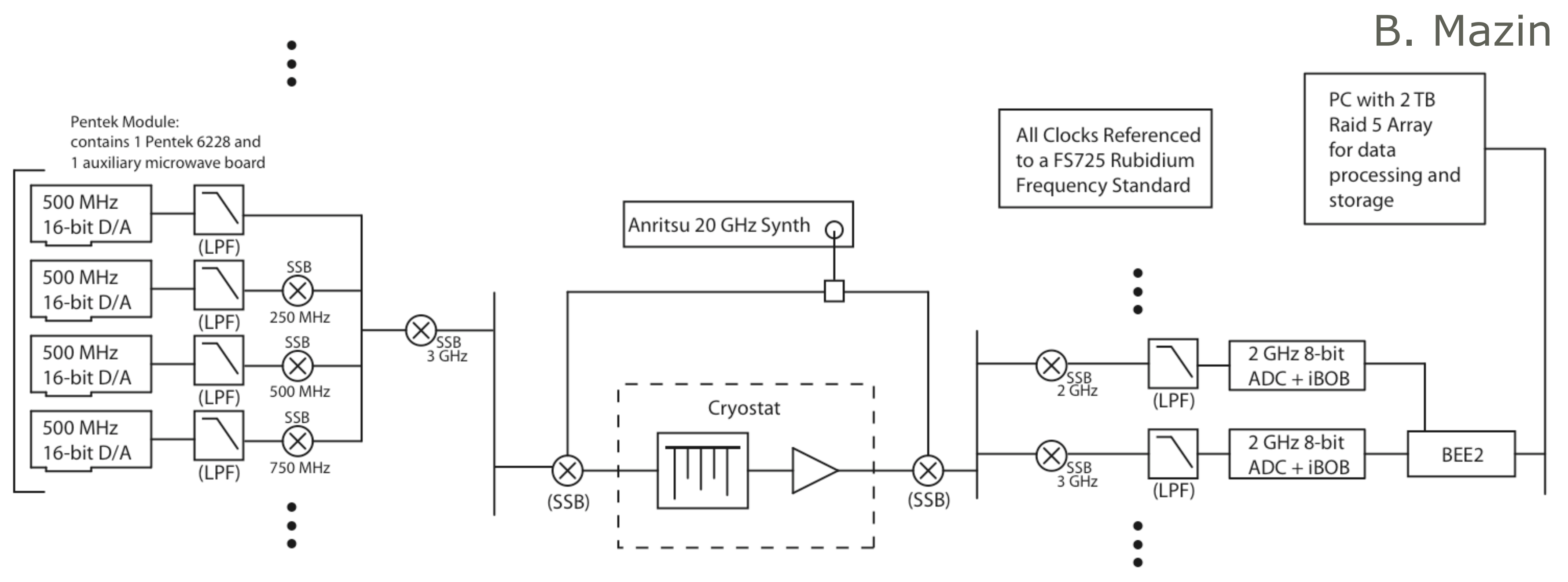
- Microwave Kinetic Inductance Detectors
  - Kinetic inductance: inertia of Cooper pair condensate in AC EM field; monitor quasiparticle density via KI. Also resistive component due to dissipation in QPs.
  - Invented and demonstrat by Day, LeDuc, Mazin, Zmuidzinas
  - Readout: monitor L (and via S_{21}.
  - Very natural frequency-domain multiplexing usi 1/4-wave resonators (LC notch circuit)

Day



MKIDs Readout

- Software-Defined Radio
  - Digitally generate frequency comb, block upconvert and sum
  - Pass into cryostat, through detector array and HEMT, and out
  - Block downconvert, digitize, and IQ mix to recover $S_{21}(t)$
  - Lots of commercial/EE-driven hardware already in existence



B. Mazin

Weight

- Comparable SPIDER/BICEP2 wet (no-LN) cryostat is ~150 kg
- Assume 10 kg/m^2 mirror mass based on primary mirror mass estimates, so 100 kg in mirrors?
- Cryocooler head: 10-20 kg
- Support structure: comparable to dewar/mirrors?
- 500 kg lower limit, 1000 kg guess at upper limit

Power Consumption

- Cryocooler: 5-10 kW
- Readout:
  - TES
    - Current SCUBA2 design: 150 W/1280 pixels. No changes ➙ 5 kW.
    - Must increase density. Would need 35 SCUBA2 style crates! (SCUBA2 uses 8).
  - MKIDs
    - 600 detectors/2 GHz BW in each BEE2 card
    - 75 BEE2 cards for 45000-detector array
    - ~300W per BEE2 card (FPGAs) + 100W for DACs, ADCs, up and downconversion ➙ 22 kW
    - Xilinx Virtex-5 vs. Virtex-II Pro: x2 lower consumption. Will improve!

Manpower

- Separable subtasks/manpower
  - Array design: 1 student
  - Optical design, window & AR coating development/fab: 1 student, 0.25 engineer
  - Readout: 1 engineer, 1 pd, 1 student
  - Cryo, dewar, system-level design:
    1 pd, 1 student, 0.75 engineer
  - Observation simulator and analysis software:
    1 pd, 1 student, 1 software engineer
  - Project manager: utter necessity to make up for distracted PIs

Array Cost

- Array fab: $2M total
  - Basis: $200k/array costed for engineering and science arrays for 2400-detector CSO MKIDCam
  - Assume JPL internal and Moore foundation funds pay for development and demo of multi-scale design
  - Assume $200k/array for two eng. arrays, $100k/array in production mode: $2M total

Cryostat and Optics Cost

- Cryostat: $400k total
  - $200k for very nice Redstone BICEP2 cryostat (wet with VCS, maybe save with dry dewar)
  - $50k for cryocooler
  - $50k for sub-K cooler
  - $100k for internal structure machining (2000 shop hrs = 1 man-year)
- Optics: $200k total
  - Reflective optics and mechanical structure: $100k
  - Transmissive optics including coatings: $100k (due to cost of Si material and DRIE)

Readout Cost

- Readout: $2M
  - For CSO MKIDCam, we costed $250k/2400 channels.
  - Correcting for items that don’t need to be duplicated gives $4M!
  - We will have to depend on Moore’s law:
    - Bulk of cost is in DAC, ADC, and digital mixer (BEE2)
    - BEE3 expected in 2007 (Virtex-5 FPGAs)
    - DACs and ADCs will also speed up and decrease in cost
  - Cost cap scheme:
    - 2/3 of channels are in the central 740/870 μm channels
    - Another 2/9 are in the outer 12 tiles
    - Begin with scaled-down system substantially below $2M, design in upgrades to be implemented when cost allows

Manpower Cost

- Manpower: $5M
  - Assumptions:
    - Fab accounts -> no overhead (benefits included)
    - 5 year build
  - 5 PI summer salary: $25k x 5 x 5 = $625k
  - 3 PD: $70k x 5 x 3 = $1M
  - 5 grad: $40k x 5 x 5 = $1M
  - 3 eng: $100k x 5 x 3 = $1.5M
  - Project manager: $150k x 5 = $750k

Budget Summary

- Summary
  - Arrays: $2M
  - Cryo: $400k
  - Optics: $200k
  - Readout: $2M
  - Manpower: $5M
  - Shipping and on-site commissioning: $100k?
- Total: $9.7M
- Worries:
  - Inflation in array cost due to fab difficulties/reliability
  - “Marching army” cost of delays: 1 year = $1M
  - What if we can’t grow out of readout cost problem
- Possible savings:
  - Shared engineering support with SWCam
  - Tail off eng. staff as project moves through build stage
  - Shared software development between SWCam and LWCam

LWCam Future Upgrades

- Upgrade paths:
  - Cover the entire FoV with Nyquist sampled pixels at 740 and 865 μm – a total of 137,216 pixels!
    - Or, more modestly, upgrade from $3f\cdot\lambda$ pixels to $1.5f\cdot\lambda$ pixels: “only” 63,488 pixels total
  - Cover the entire FoV with Nyquist sampled pixels at 620 μm resulting in 262,144 pixels in addition to the 137,216 pixels in the first upgrade
    - Or, more modestly, employ “two tier” system for an addition of 77,824 or 114,688 pixels total
    - Extension to 620 μm will be challenging due to issues with SQUID packing density (TES), and heat-loads with HEMTs (MKID)
  - There may be issues with image quality at the shorter wavelengths for the larger FoV
  - 620 μm band already covered with SWCam…