Long Wavelength Cameras for CSO and CCAT

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November 13, 2010

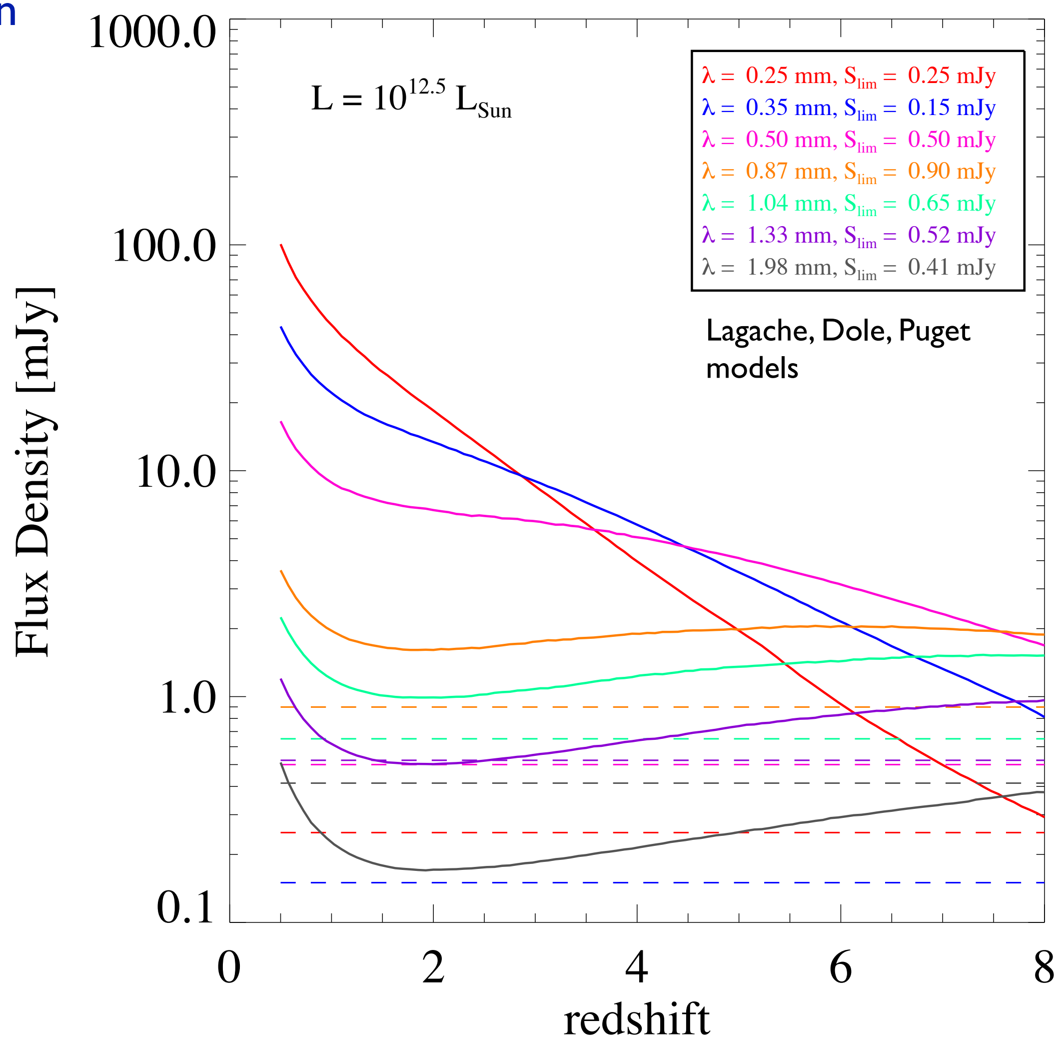
with thanks to
the MUSIC instrument and science teams

Outline

- CCAT long wavelength camera design considerations
- Enabling technologies
- MUSIC: a pathfinder on the CSO

Instrument Design Criteria

- Science drivers
  - Push the luminosity limit down from 10^{13} L_{Sun} to $10^{12.5}$ L_{Sun}
    - upcoming cameras will reach confusion limit on ~few deg^2 in lifetime; starting to get to representative volumes, but would like few times larger
    - confusion limit at CCAT decreases by 2-3x relative to 15 m, 5x relative to 10 m → need x10 in mapping speed to get same area to new confusion limit, x100 to get 10s to 100s of deg^2 to confusion
  - Go out to much higher z
  - Obtain as much redshift information from photometry as possible
  - Cross-correlations rely on large area



Instrument Design Criteria

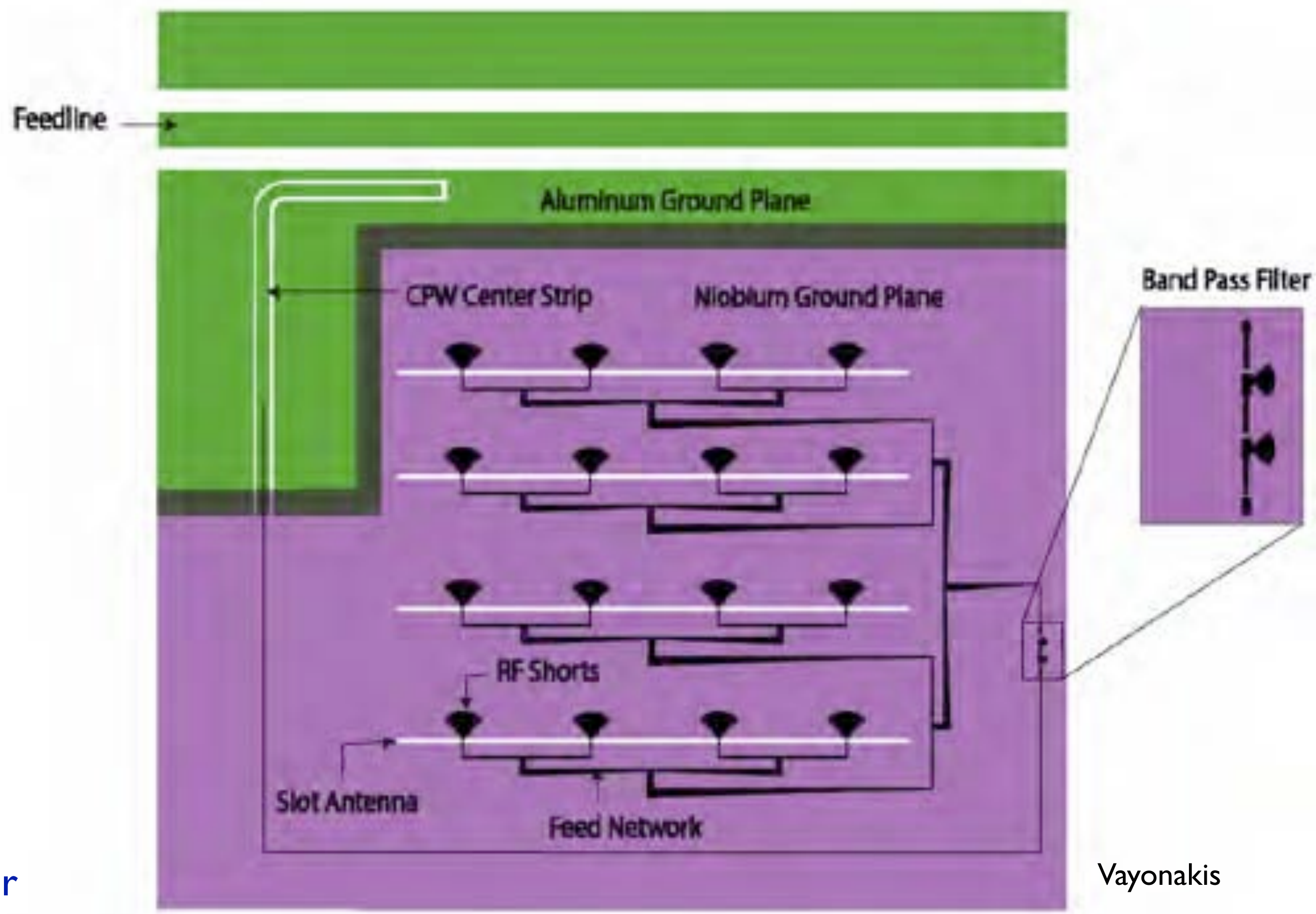
- Instrument requirements
  - "Reasonable" increase in mapping speed to obtain the above:
    - SCUBA-2, MUSIC: AΩ ~3 m^2 → CCAT gives AΩ ~40 m^2 at 20' FoV, ~400 m^2 at 1 deg
    - Gain ~2-3 in NEP from site, telescope
    - → x100 to x1000 in mapping speed
  - Simultaneous multiband coverage
    - obtain as much photometric information as possible on galaxies
    - Galaxy clusters: separate submm galaxy and cluster signals, detect kinetic SZ effect
    - multiple colors can separate sky noise and astronomical sources
    - Observatory efficiency! Appreciable amount of time unsuitable for short-submm observing.

Instrument Design Choices

- 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)
    - Requires many dichroics or bandpass filters to get multiple colors
  - Single-pol antenna-coupled design offers "simple" way to cover multiple bands with varying pixel sizes simultaneously (but lose x2 in integration time)
  - Uses Nb slot antenna and microstrip: naturally limits shortest wavelength to 740 μm (405 GHz) or 620 μm (485 GHz).
- Longest wavelength set by pixel size, complementarity to other facilities; 2 mm or 3 mm (150 or 100 GHz)

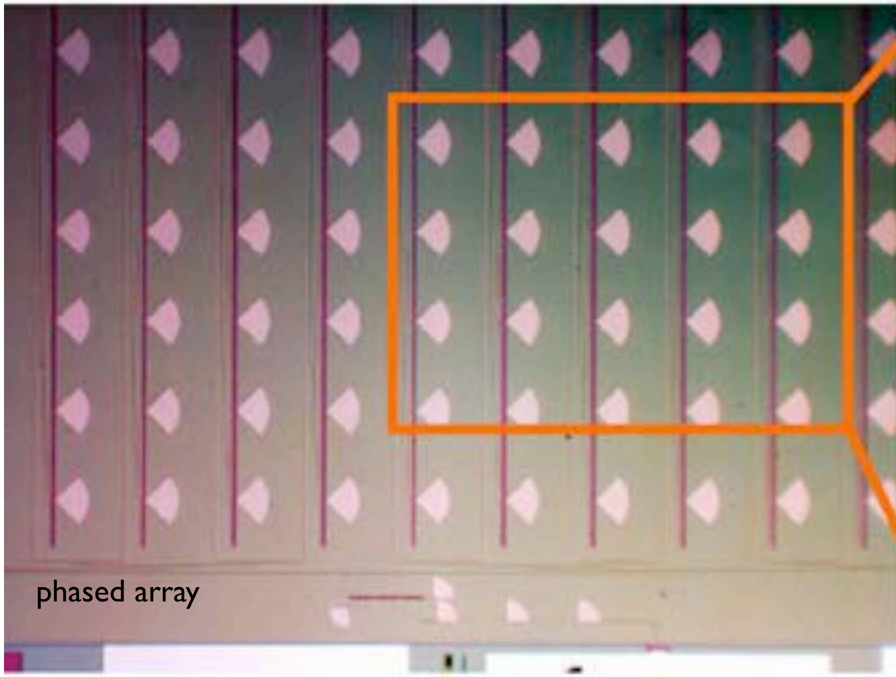
Antenna Coupling and Inline Bandpass Filters

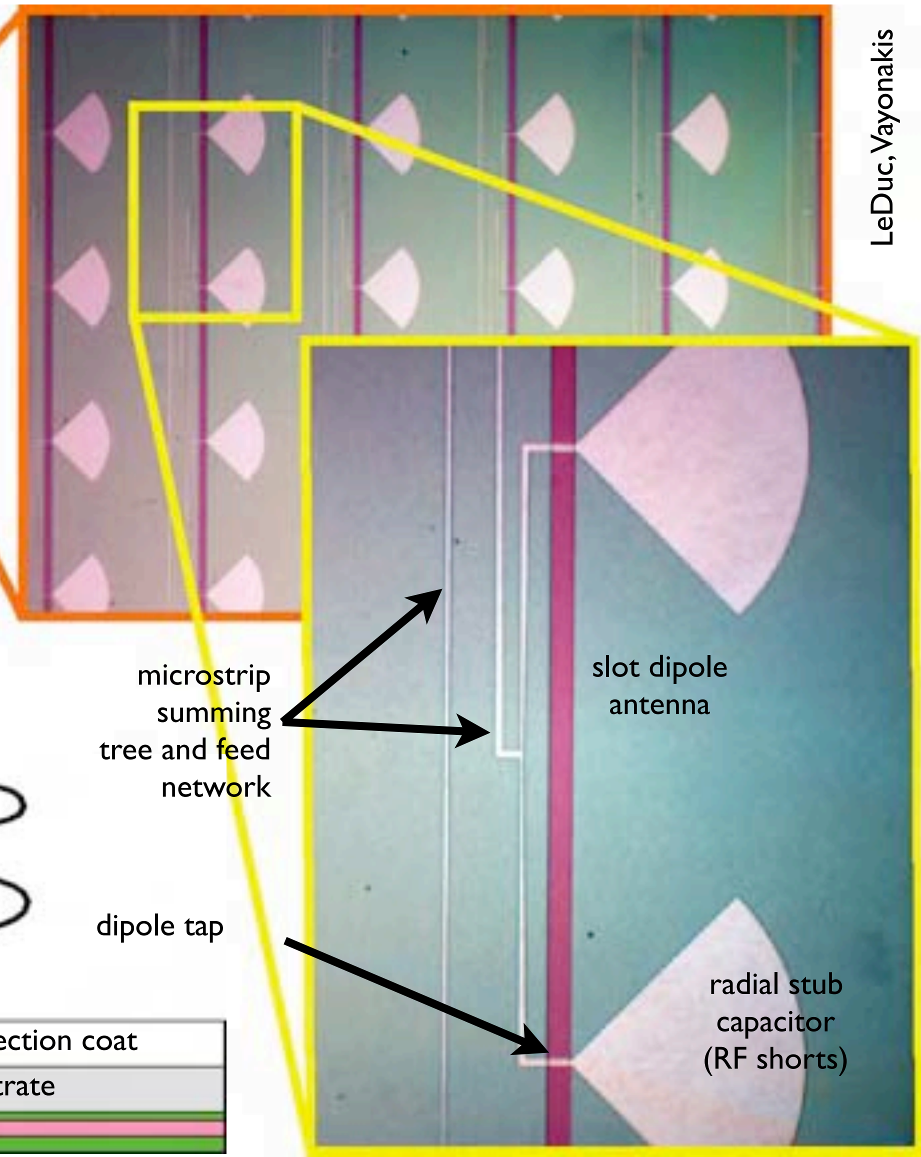
- Feedhorns are bulky, low fill-factor, and monochromatic
- Perform the beam definition with a phased-array antenna (Bock, Day, Zmuidzinas)
  - planar geometry, photolithographic fabrication
  - ~octave bandwidth
  - power exits on microstrip transmission line
  - bandpass filters may be inserted
  - separates optical absorption from power detection (decouples detector size)
  - power absorbed in MKID resonator



Vayonakis

Antenna Coupling

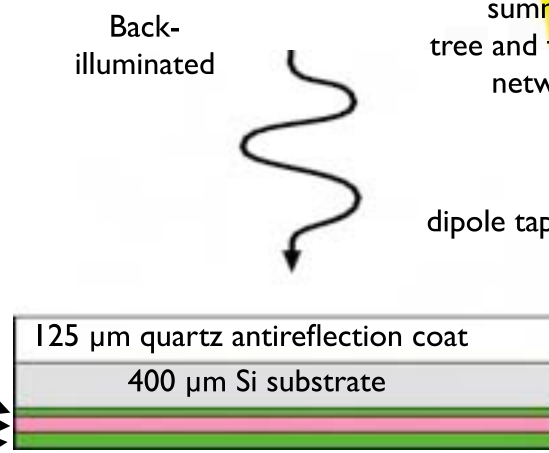




3 mm slot length, 3 mm array width
16 slots, 16 feeds per slot
188 μm feed and slot spacing
20 micron slot width

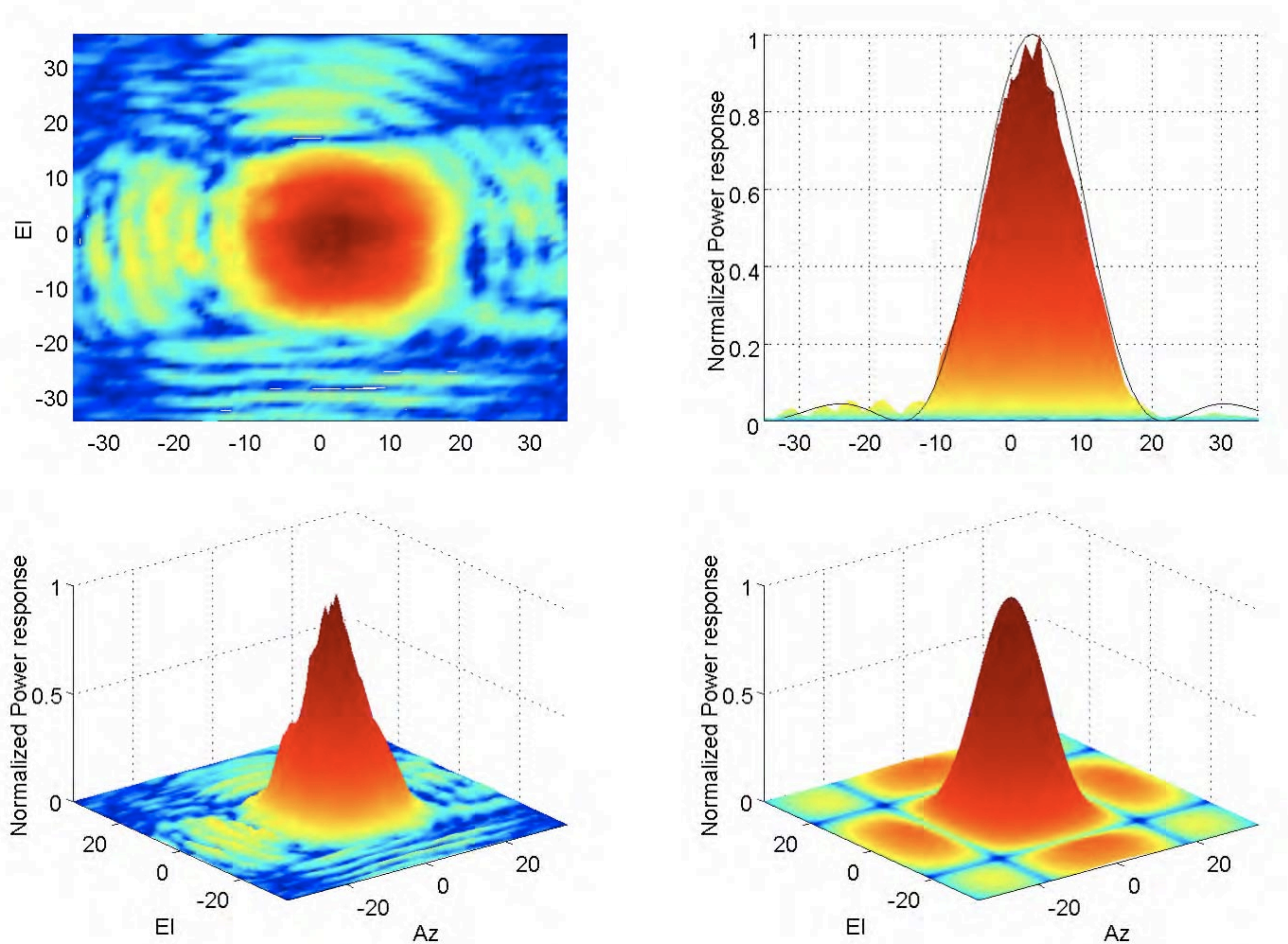
40 nm Al MKID

200 nm Nb ground plane
400 nm SiO_2 microstrip dielectric
400 nm Nb wiring layer



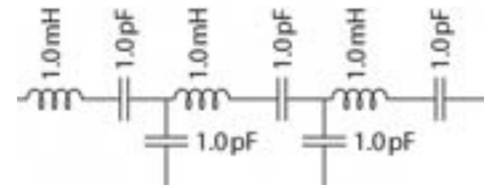
Antenna-Coupled Pixels

- 100 GHz beam maps (SIS detector)

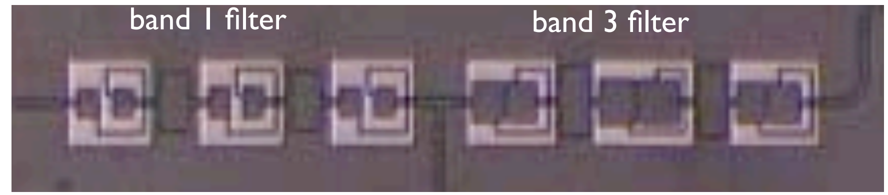


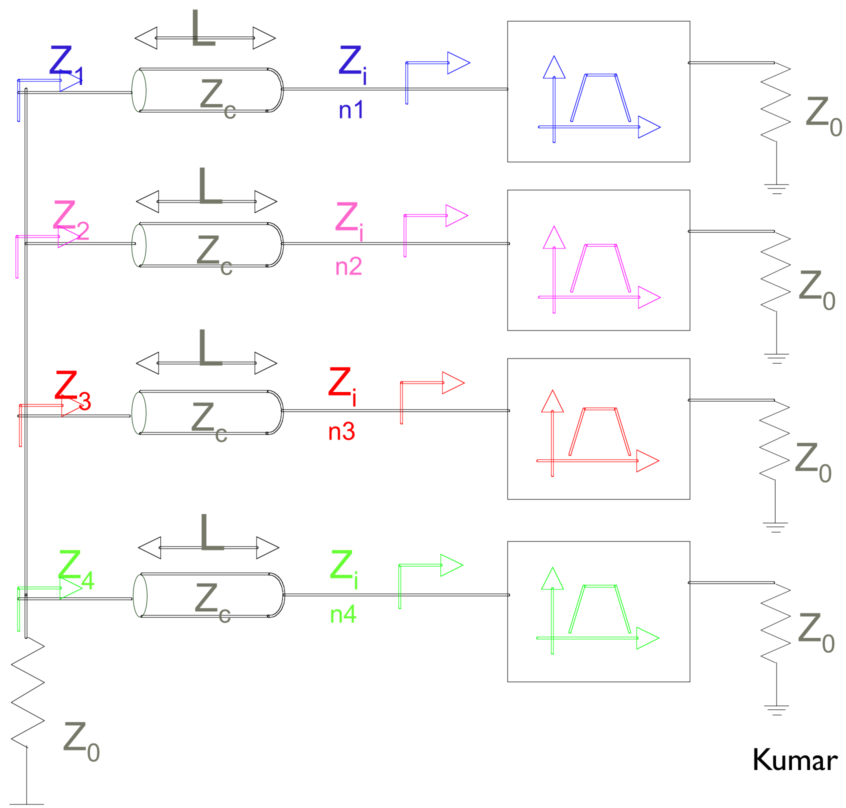
Tasos Vayonakis, Alexey Goldin

Antenna Coupling

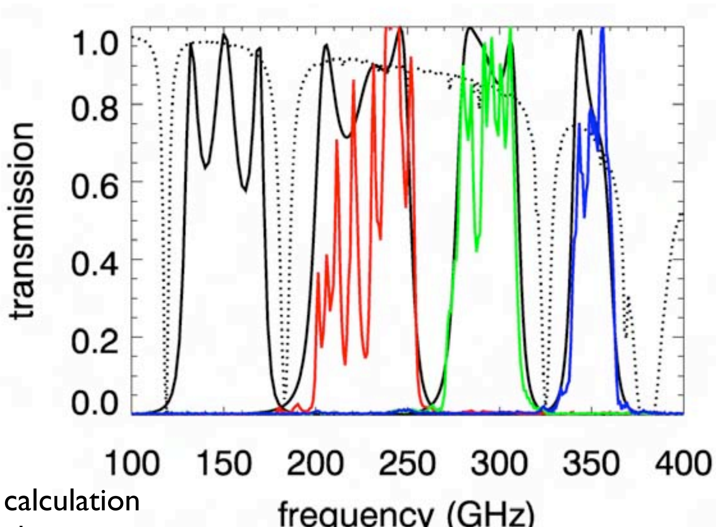


- Colors defined by in-line bandpass filters
  - lumped-element LC filters
  - High out-of-band impedance allows many filters in parallel
  - Maximally efficient use of all photons received
  - Good match to SZ and thermal emission from dusty submm galaxies





Kumar

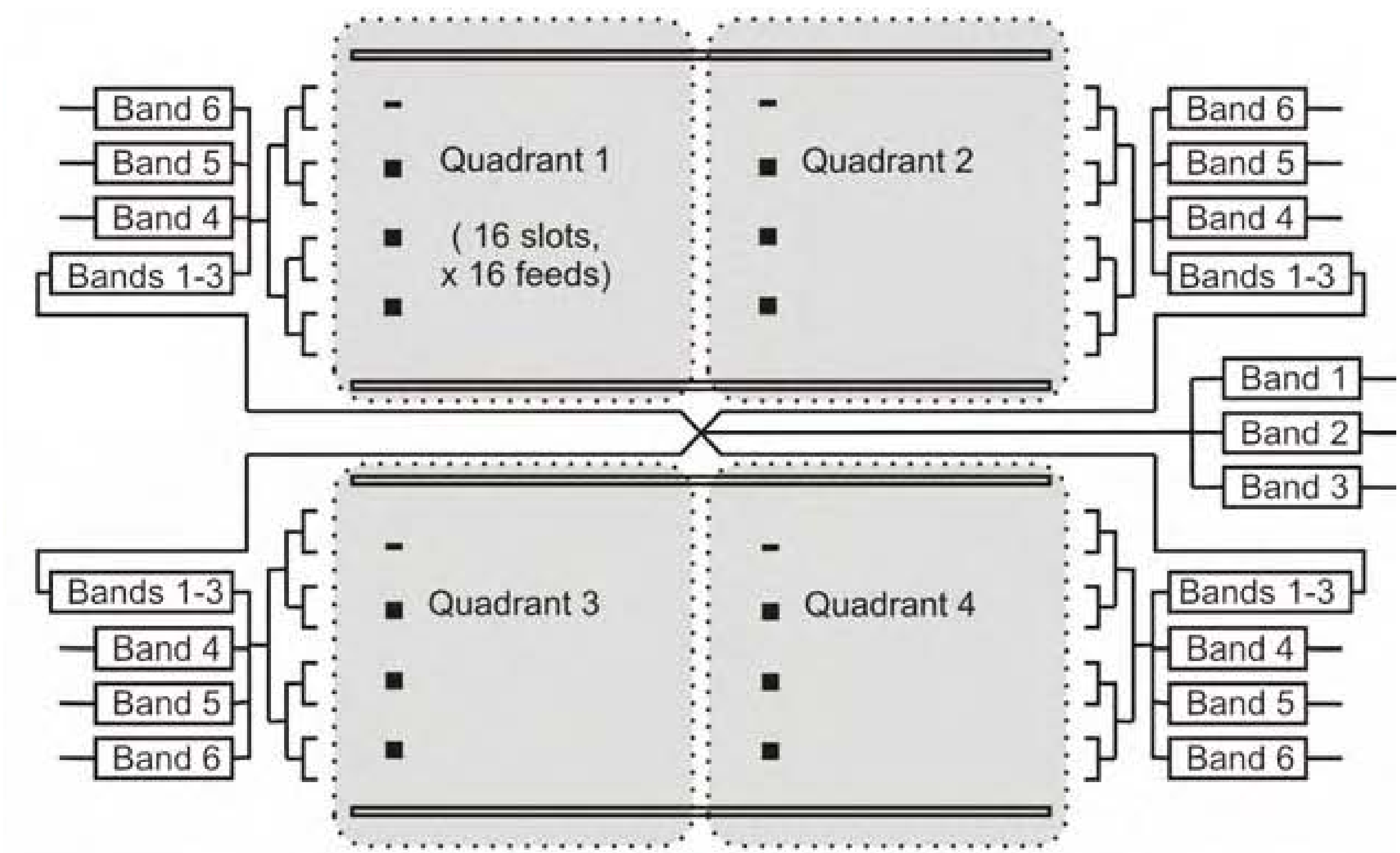


black: calculation
color: data

Duan/Sayers/Czakon/Hollister

Multiscale Pixellization

- Single pixel size can only be ~optimal for 2-3 bands
- Change pixel size in binary manner with wavelength



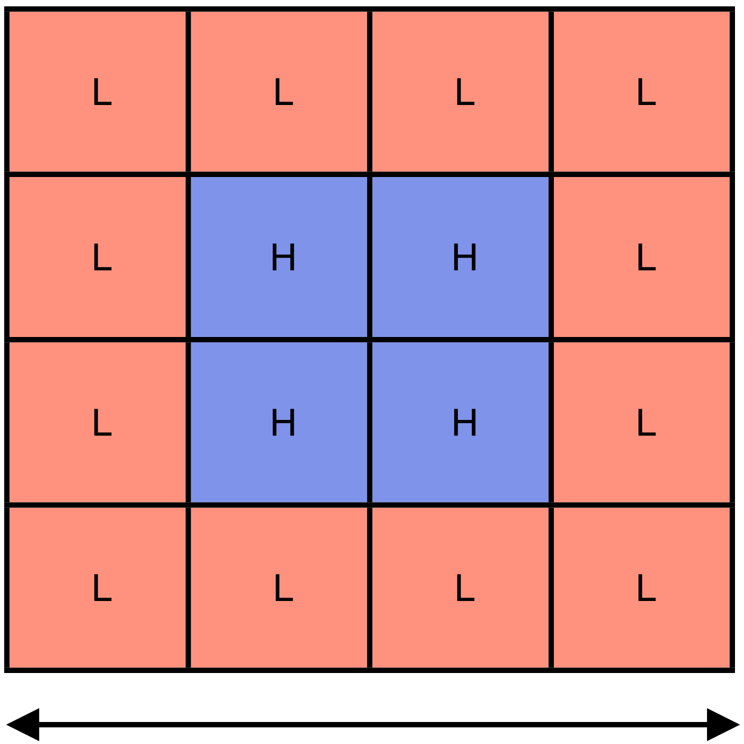
Peter Day

Detector Options

- Two reasonable options:
  - Superconducting transition-edge sensors (TESs)
  - Microwave kinetic inductance detectors (MKIDs)
- Pros and Cons
  - Sensitivity: TESs are background-limited, MKIDs not quite yet but should get there soon
  - Degradation under optical loading: slight advantage to MKIDs
  - Fabrication: Not a strong driver
  - Multiplexing: MKIDs easier in principle, TESs more advanced in practice
  - Cold electronics power dissipation: Advantage TESs
  - Microphonics Susceptibility: Advantage MKIDs
  - Magnetic Field Susceptibility: Advantage MKIDs
- Should use experience in field to judge at appropriate time
  - Many TES-based arrays out in field and working well, including antenna-coupled.
  - MKID arrays to be first deployed with MUSIC, NIKA, ATACamera

Pixel Numerology

- Design driven by desire to keep detector counts reasonable, yet gain substantially in mapping speed over SCUBA-2/MUSIC generation.
- Could increase 740 μm, 870 μm pixel counts by ~x4 more if readouts capable



20 arcmin

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

Band GHz (μm)	$\Delta\nu$ (GHz)	Pixel Size $f \cdot \lambda$	Number of Spatial Pixels
150 (2000)	30	1.15	16 tiles × 256 = 4096
220 (1400)	40	1.6	16 tiles × 256 = 4096
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			51,200 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.

Imaging Spectroscopy

- CCAT long wavelength cameras should reach confusion very quickly
- Multi-object spectrometer is necessary, but will rely substantially on pre-selection
- Imaging spectroscopy could provide useful intermediate capability
- FTS?
  - Can provide enough resolution to see CO ladder and other important lines; esp. useful if lines contribute substantially to flux
  - Frequency resolution can be varied on the fly by setting mirror travel
    - fast, coarse mode for higher-resolution continuum measurements
    - slower, fine mode for line searches
  - Sensitivity penalty ok given speed to confusion
  - Works in all bands at same time
  - Not clear how to get it into the optical train...

MUSIC: A Multi-Color Camera for the CSO

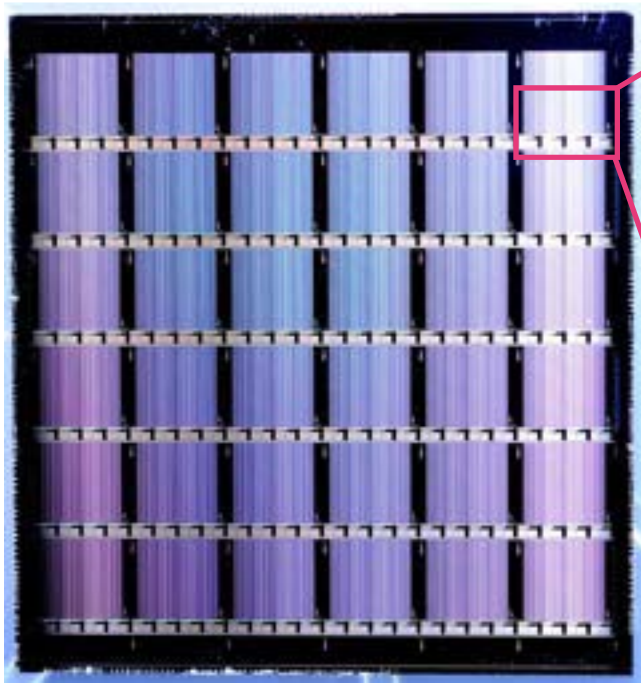
- MUlticolor Sub/millimeter Inductance Camera
- New technologies enable ~background-limited, multi-color camera (850 μm - 2 mm) with wide FOV (14', 600 spatial pixels)
  - Planar photolithographic phased-array antennas: large-format arrays on a single wafer, ~octave instantaneous bandwidth
  - Planar photolithographic bandpass filters: many colors from a single antenna
  - Microwave Kinetic Inductance Detectors (MKIDs): a new, highly multiplexable detector
- Science goals
  - Submillimeter Galaxies (SMGs)
    - Wide-area surveys with multicolor information: find the high-z objects
    - Follow-up of Herschel SMGs: measure spectral energy distributions, select high-z
    - Study SMGs in lensed galaxy cluster fields
  - Galaxy clusters
    - Multicolor Sunyaev-Zeldovich effect observations of known clusters to study ICM, measure cosmological parameters in coordination with X-ray, optical/IR
    - e.g., followup of Planck catalog, HST CLASH program, etc.
- Open international access via CSO

The MUSIC Team

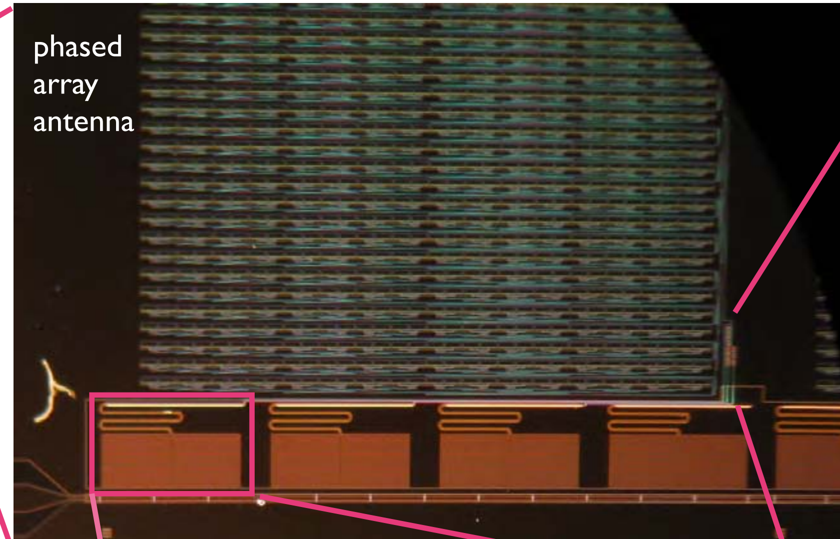
- Instrument Team
  - CU: Jason Glenn, Phil Maloney, James Schlaerth
  - JPL: Peter Day, Rick LeDuc, Hien Nguyen
  - Caltech: Nicole Czakon, Tom Downes, Ran Duan, Sunil Golwala, Matt Hollister, Dave Miller, Omid Noroozian, Jack Sayers, Seth Siegel, Jonas Zmuidzinas
  - UCSB: Ben Mazin, Sean McHugh
- Survey Team
  - Arizona: Dan Marrone
  - Caltech: Ranga-Ram Chary
  - CU: Alex Conley
  - Rutgers: Andrew Bake
- Science Team
  - Caltech: Andrew Benson
  - CU: Nils Halverson
  - JPL/IPAC/Caltech: Colin Borys, Darren Dowell, Olivier Dore
  - USC: Elena Pierpaoli

Multicolor Antenna-Coupled MKIDs

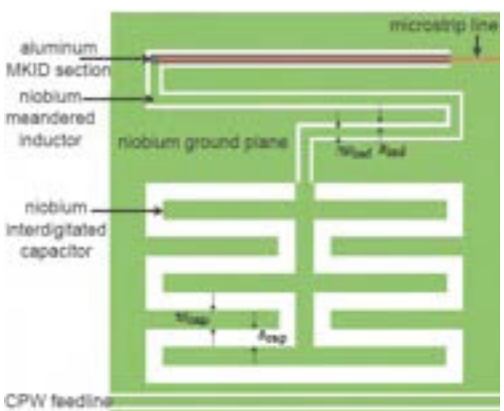
6 x 6 spatial pixel array
x16 to make full focal plane



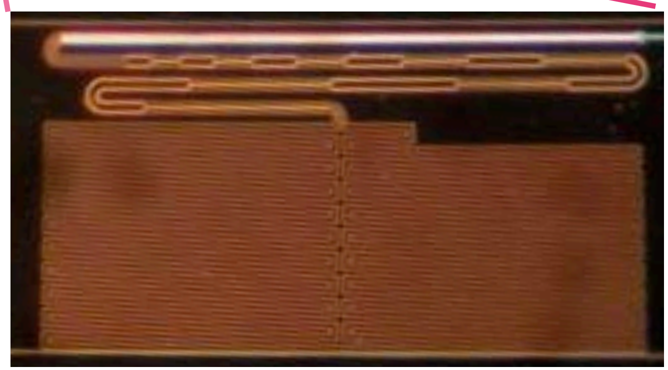
single pixel



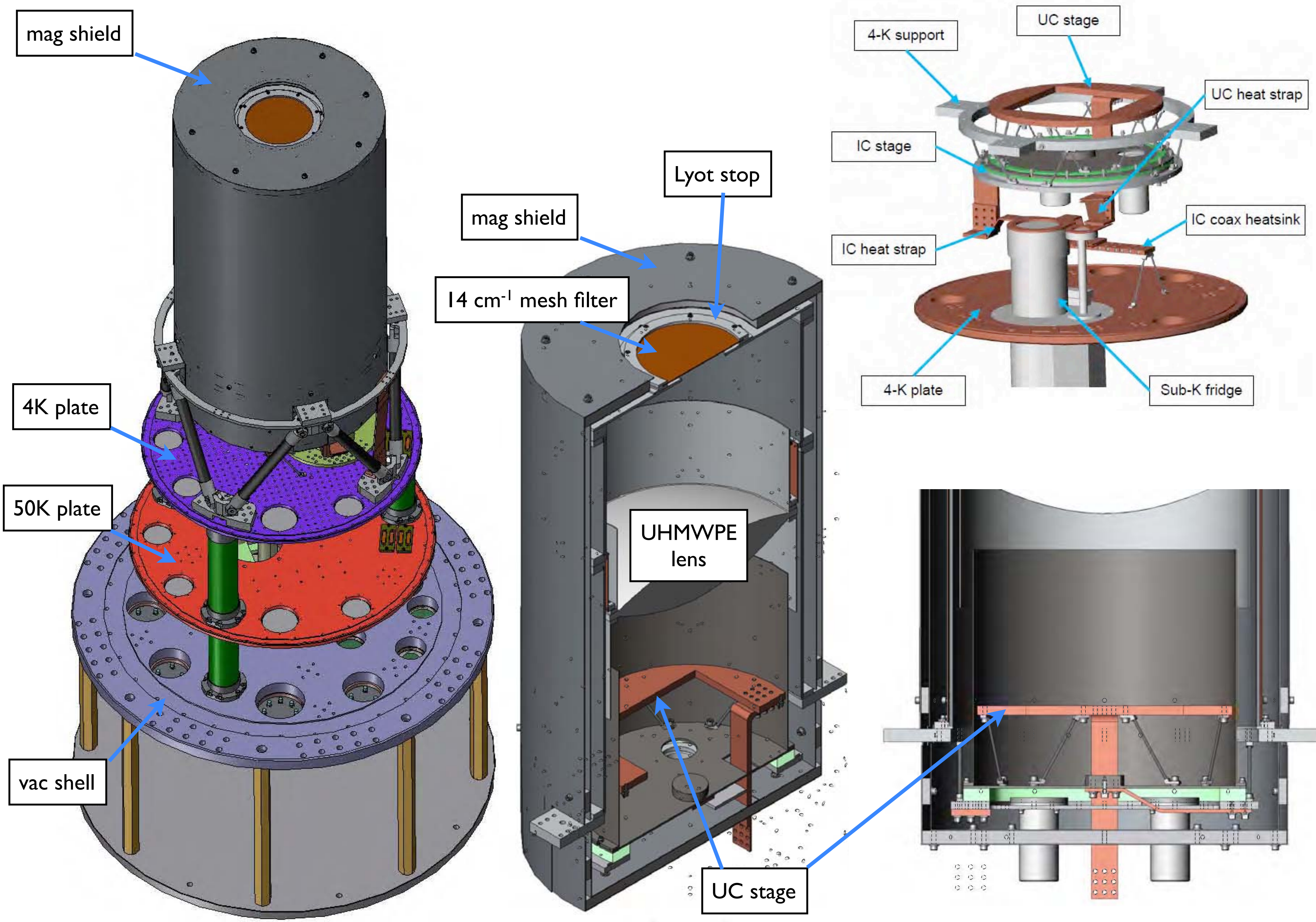
bandpass filters
(2 colors)



MKIDs
(four,
one per color)



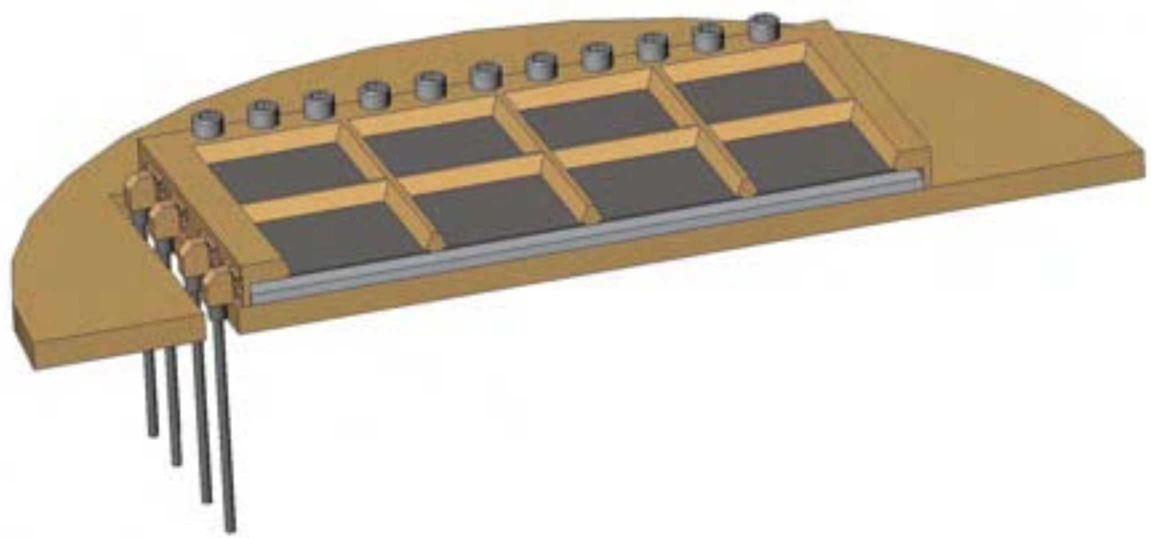
Detector development funded by JPL RTD,
NASA APRA, Moore Foundation


mag shield
4K plate
50K plate
vac shell
mag shield
Lyot stop
14 cm^{-1} mesh filter
UHMWPE lens
UC stage
4-K support
UC stage
UC heat strap
IC stage
IC coax heatsink
IC heat strap
4-K plate
Sub-K fridge

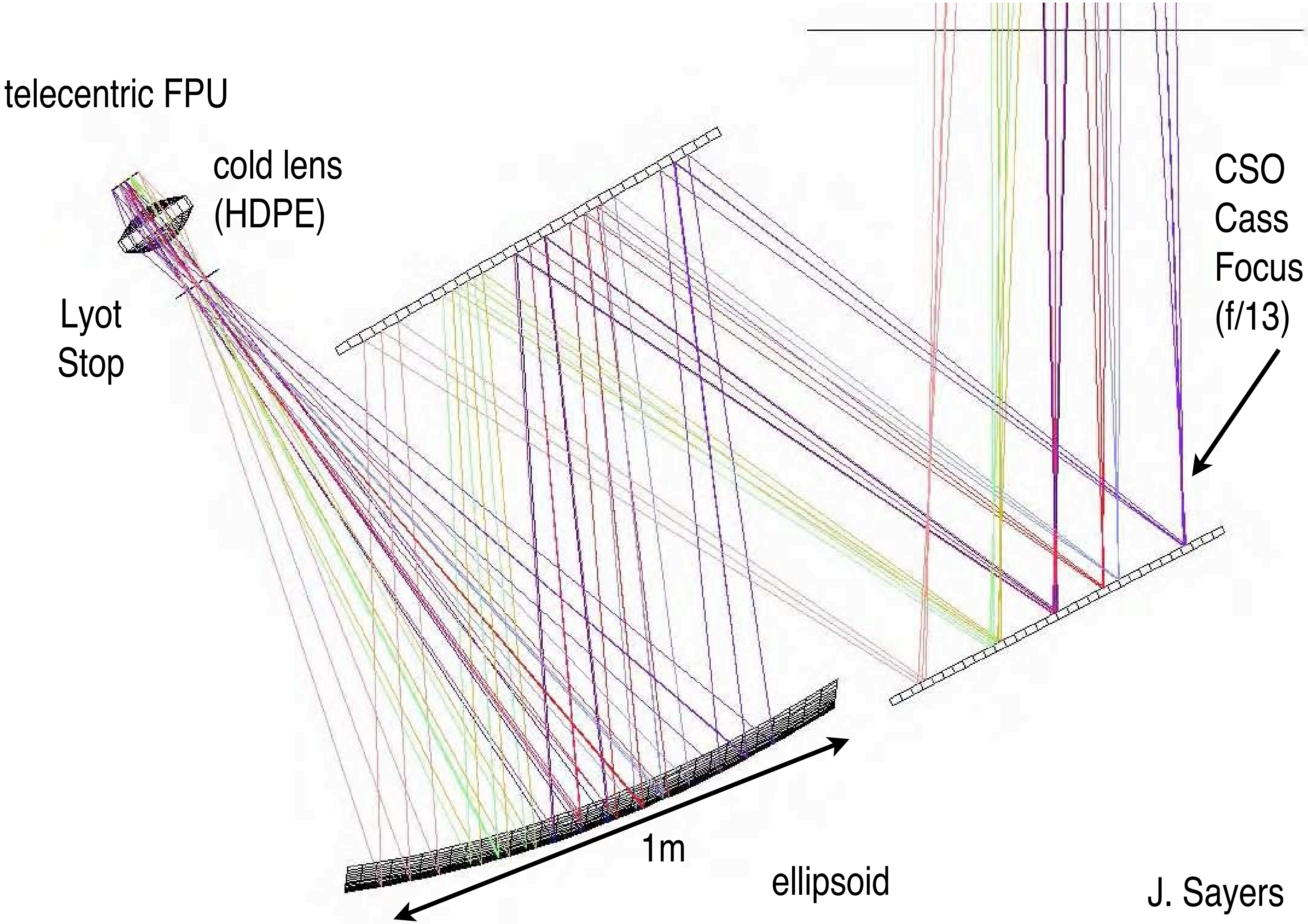
M. Hollister

Focal Plane Design

- FPU will be assembled from 16 subarrays on 8 wafers
- Must accomodate AR tiles
- 16 coaxes
- Blind mate design to simplify installation
- Only 16 signal connections!

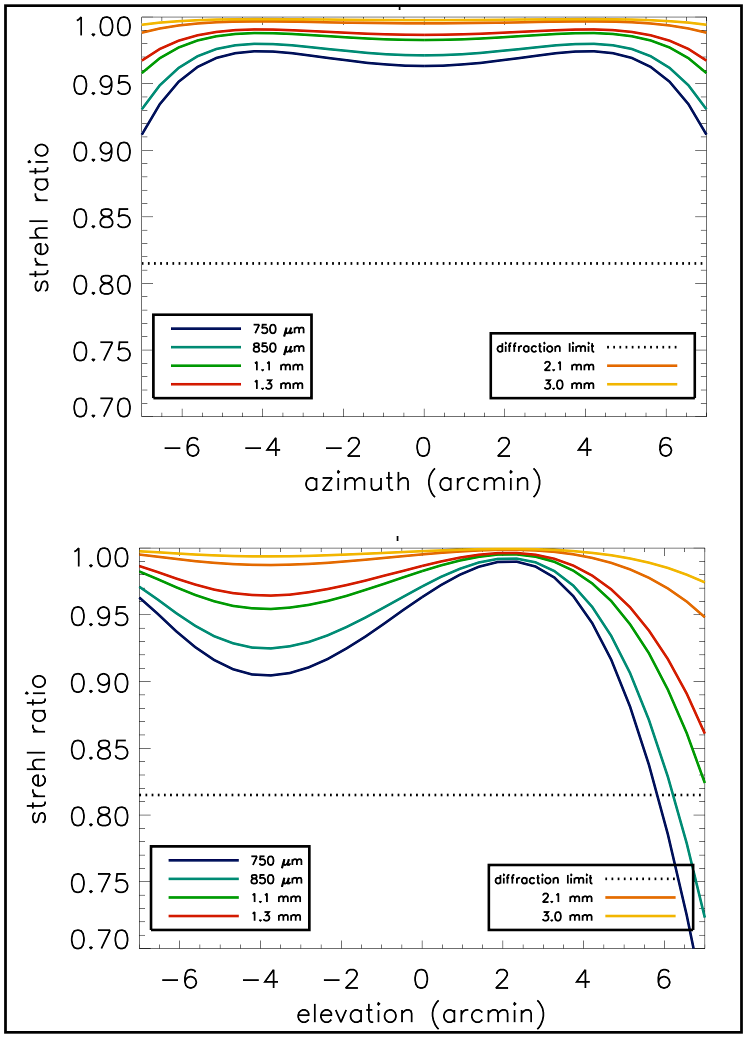


Optics Design

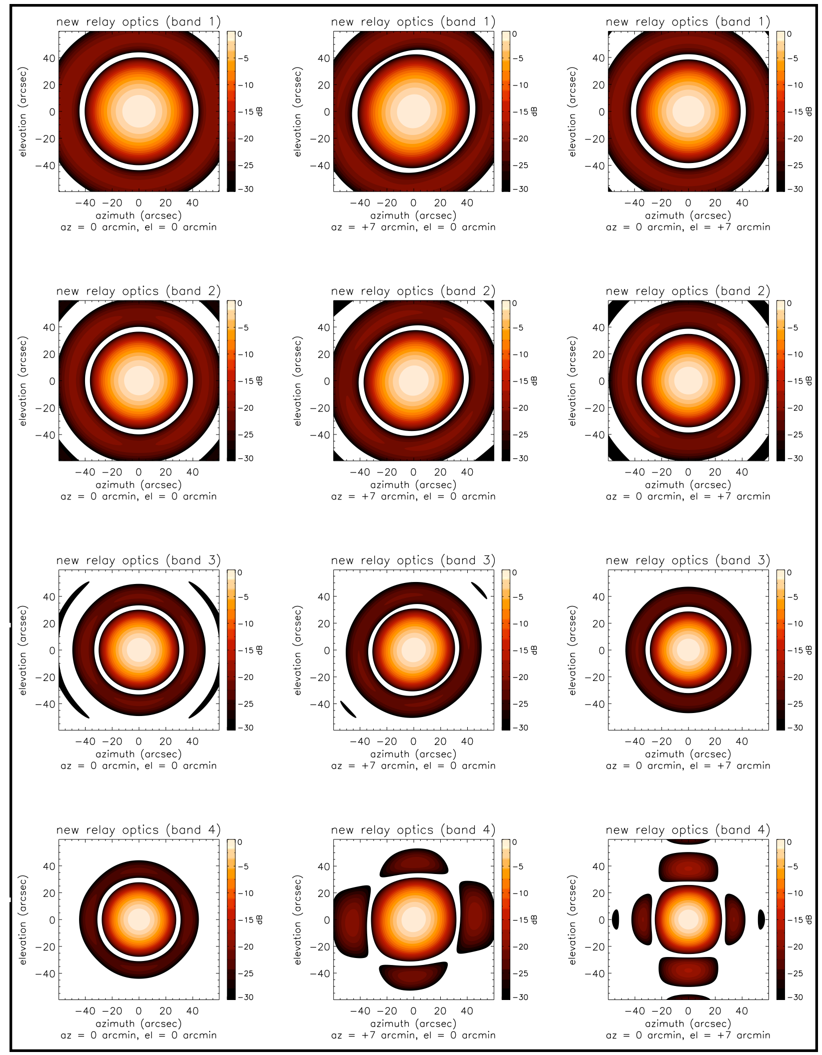


Optical Design

Strehl Ratio



far-field beams



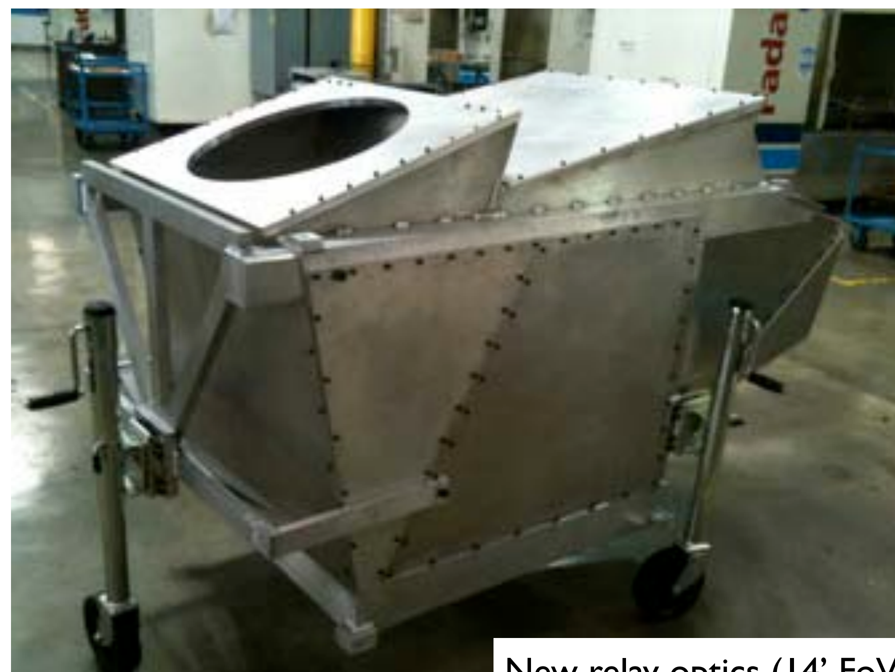
J. Sayers

Dewar/Optics Status

- Cryostat + sub-K fridge have been verified with optical loads
- Mag shield + optics tube + sub-Kelvin hardware have been bench-assembled and will go into dewar soon
- Warm optics done and ready for fit check and optical test

2-layer A4K mag shield
< 1 mJy/degree mag signal

Dewar under test at JPL

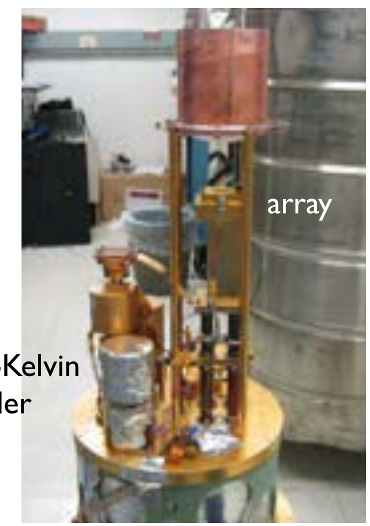


New relay optics (14’ FoV)

Submm/mm MKID Demonstration Camera

- 18-pixel/3-color DemoCam2 fielded in May/June, 2010, at CSO
- *Close-to-final versions of antenna, bandpass filters, MKIDs*
- All components functional, observed planets and bright sources
- Sensitivity ~250-500 mJy $\sqrt{\text{sec}}$, problems understood and in process of fixing

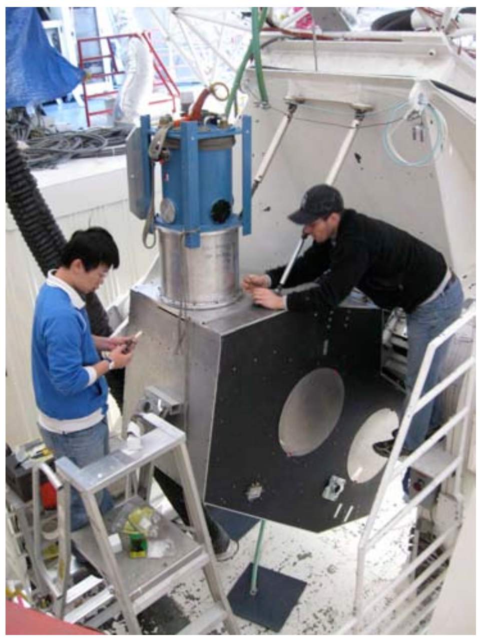
Lyot stop and lens

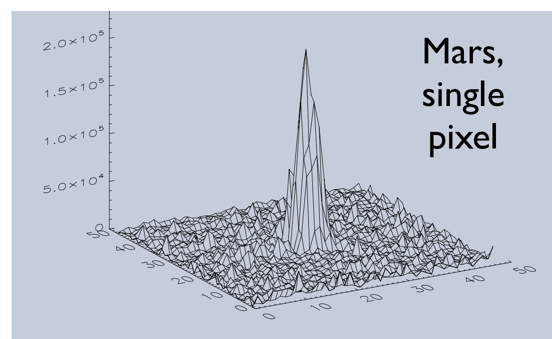


sub-Kelvin cooler

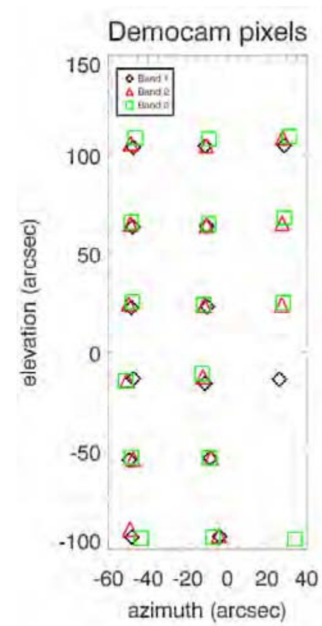
LHe/LN dewar

On the telescope



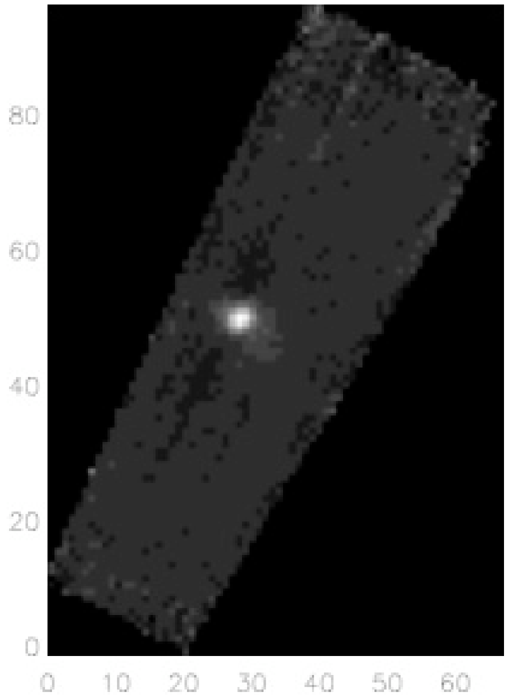


18 pixels and 3 colors

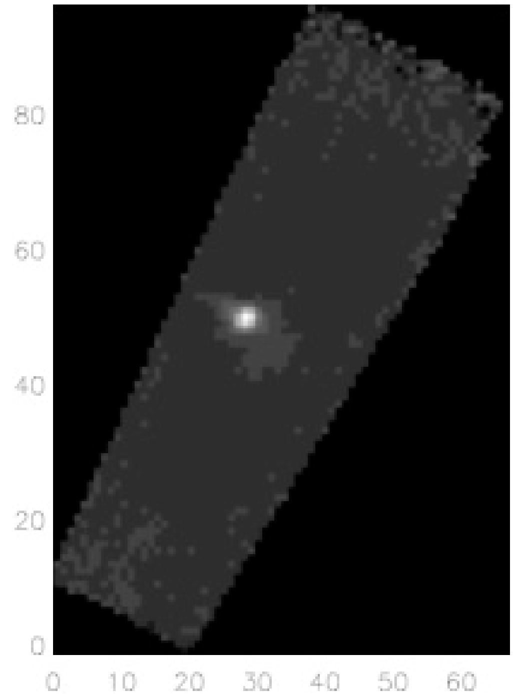


Submm/mm MKID Demonstration Camera

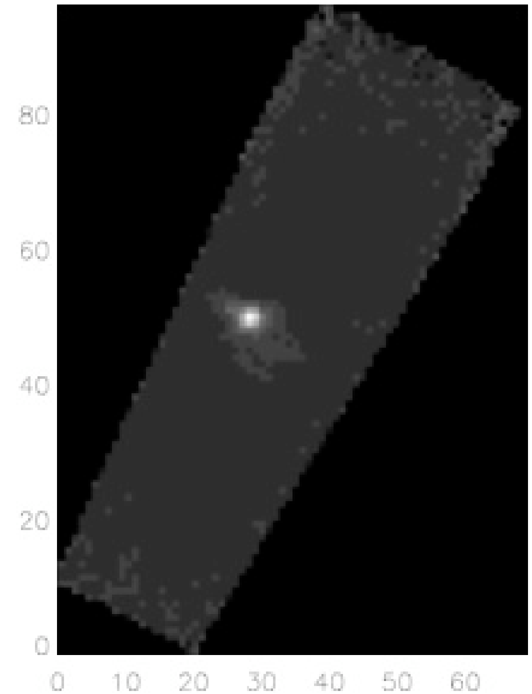
Coadds of G34.3 from May 26, 2010 simultaneous observation in 3 bands



Band 1-
230 GHz



Band 2-
290 GHz



Band 3-
350 GHz

MUSIC Status

- System-level pieces coming together well
  - Dewar/cryogenics working well
  - New relay optics done
  - Iterating on RF readout electronics
  - Beams and bandpasses look good
- Challenges: sensitivity being limited by:
  - Low optical efficiency: 6-12% for device, expect ~50-60%.
    - Attacking with new antenna design, change of dielectric, diagnostic tests
    - Excellent efficiency demonstrated in similar BICEP2/Keck/SPIDER CMB arrays
  - Tile heating
    - Replace crystal quartz AR coat with etched silicon
  - 1/f in electronics
    - New iteration with more careful thermal design
    - Studying RF amplifier 1/f; promising results obtained
  - Expect to solve these soon and go into production on science arrays!
- Instrument integration spring/summer 2011
- Commissioning in fall, 2011

Conclusions

- Technologies being developed for powerful long-wavelength camera for CCAT
- Should think about an imaging spectroscopy option
- Will learn much from SCUBA-2 and MUSIC to inform the design
- MUSIC commissioning next year and doing science soon after!