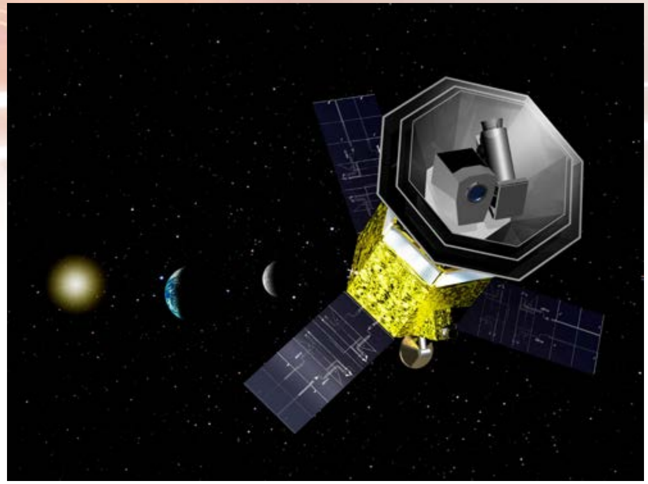


U.S. NASA Explorer Mission of Opportunity for LiteBIRD

And current NASA Technology Development Program

Kam Arnold

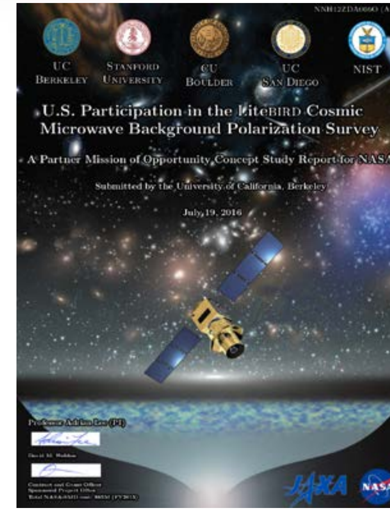
University of California San Diego

UC BERKELEY | STANFORD UNIVERSITY | CU BOULDER | UC SAN DIEGO | NIST | GODDARD

US LiteBIRD Program:
History & Upcoming Milestones

NASA LiteBIRD-Focused Program

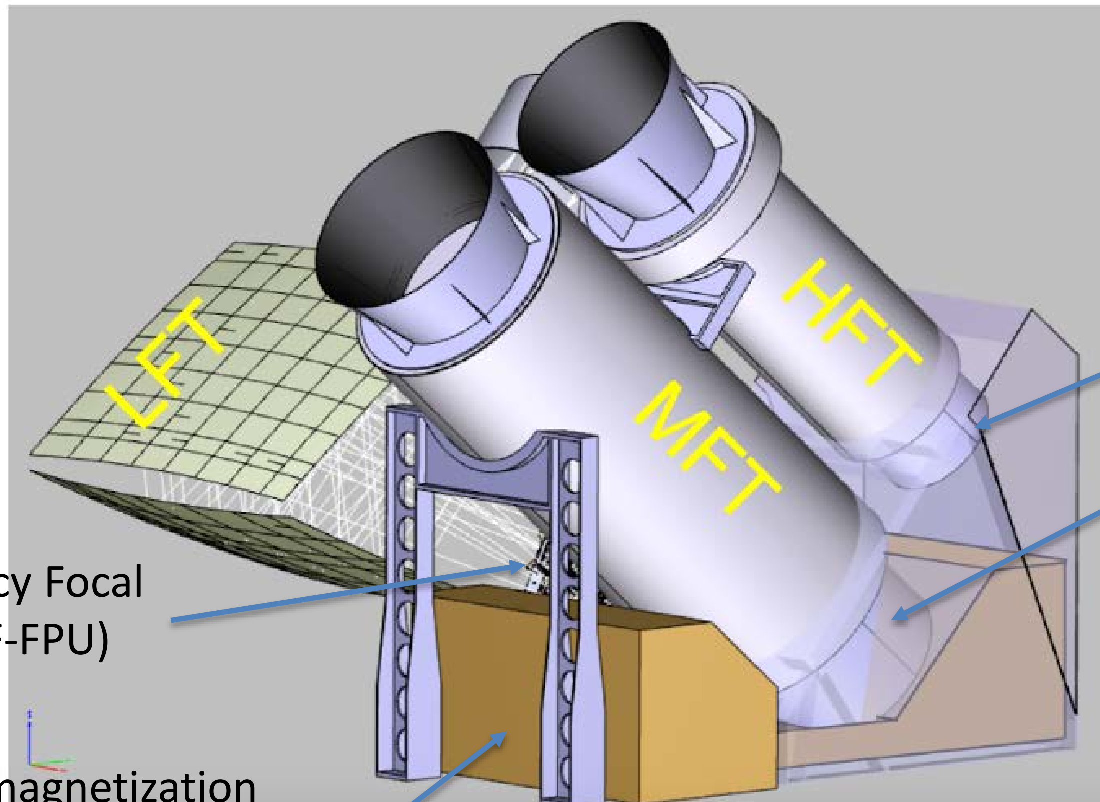
- 2015 September: Phase A #1 begins for US Participation in LiteBIRD
- 2016 July: Concept Study Report #1 (CSR) Submitted
- 2018 March: Development funds granted as part of a Strategic Astrophysics Technology program
  - US$4.7M
  - 3-year program
  - Deliverables: detector and cryogenic readout technologies to TRL 5, including mission simulations with realistic detector and instrument properties.
- 2019 August 1: NASA MO Pre-proposal #2 Due, US$75M cost cap
- 2020 May: Nominal start of Phase A
- 2021 February: projected date of NASA CSR #2 submission
- 2021 October: projected start of NASA phase B



Drafting pre-proposal for August 1st around current baseline instrument

Phase A would then be concurrent with the remaining technology development program with the deliverable of TRL-5 for all technologies.

US Scope in Context



HF-FPU

MF-FPU

Low-Frequency Focal Plane Unit (LF-FPU)

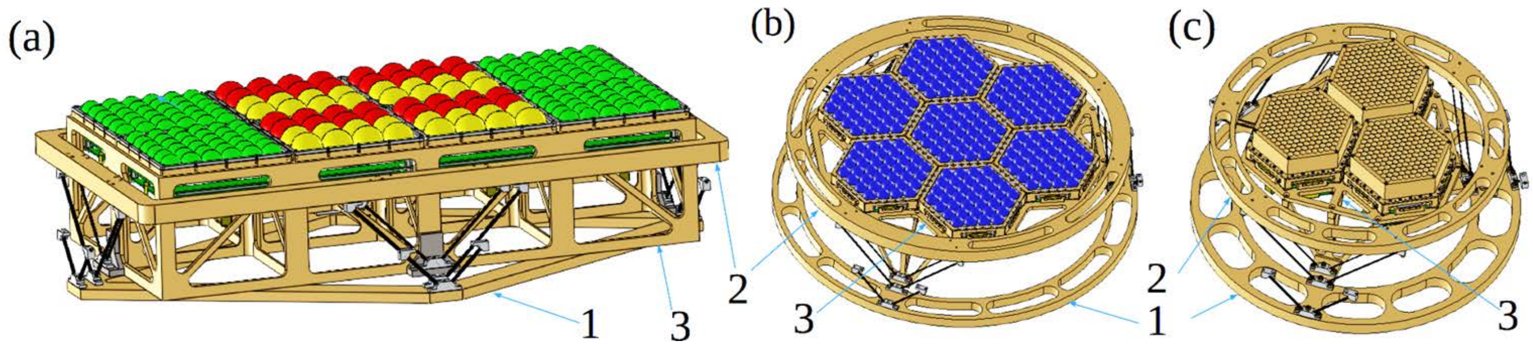
Adiabatic Demagnetization Refrigerator providing 2K stage (2K-ADR)

…and data management, including high-performance computing

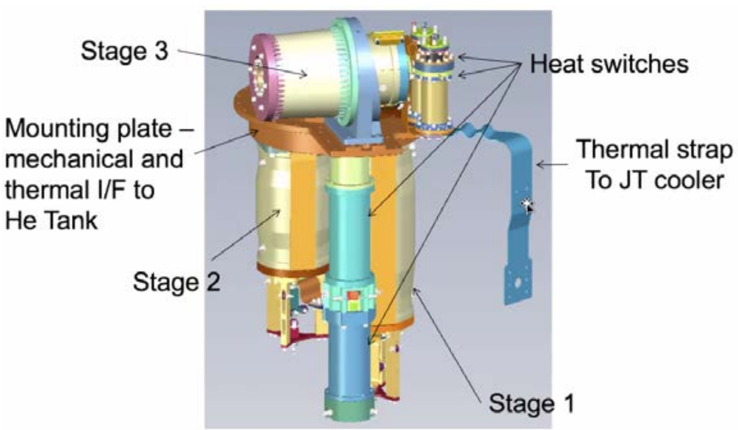
Overview of US Scope

Focal Plane Units Including Cryogenic Readout Components

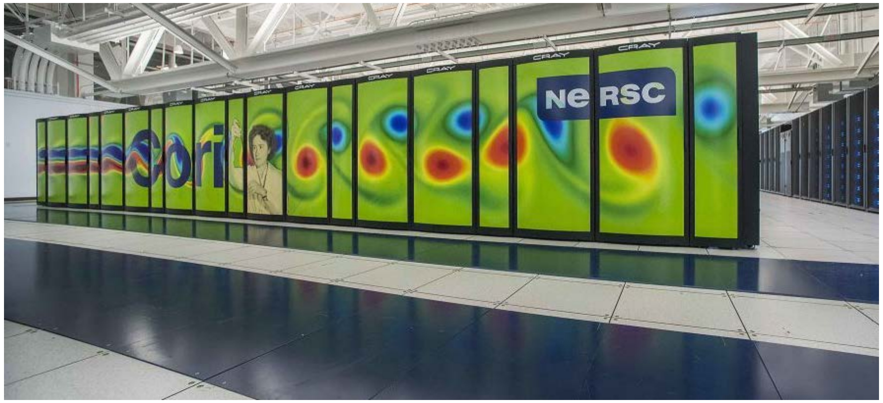
LF MF HF



2K-ADR



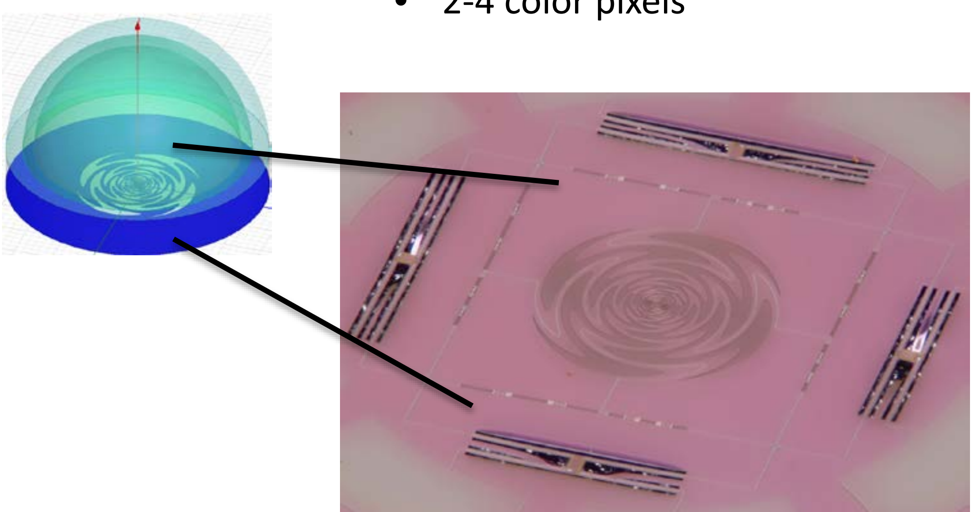
Data Management



Two detector Architectures

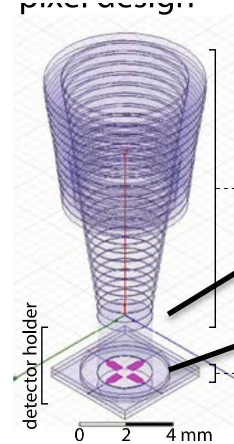
Lenslet-Coupled Sinuous Antenna

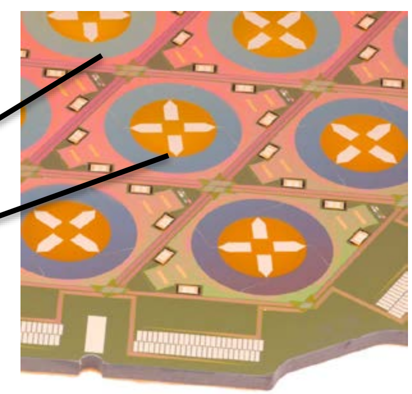
- Newer design with larger fractional bandwidth possible
    - On sky – SPT3G, POLARBEAR
- 2-4 color pixels



Horn-Coupled Ortho-Mode Transducer

- Well established design
    - Published Results from ACTpol and SPTpol
    - Lots of design analysis in the literature
- 2-color pixels
- Higher frequencies possible with current designs

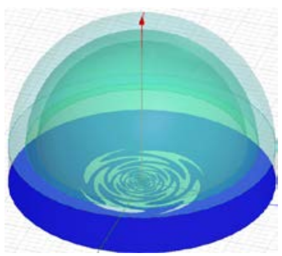




Focal planes: transition edge sensor (TES) bolometers with two different coupling architectures

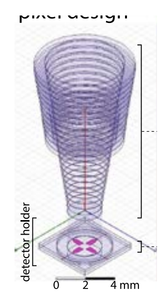
Architecture choice depends on fractional bandwidth and maximum frequency requirements

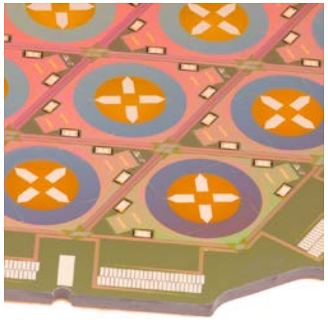
<u>LF & MF Pixels:</u>

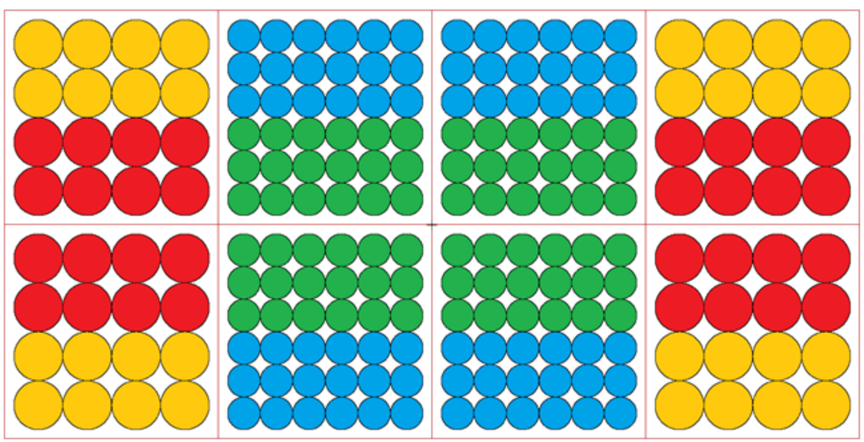


Lenslet-Coupled Sinuous Antenna for broadband trichroic pixels

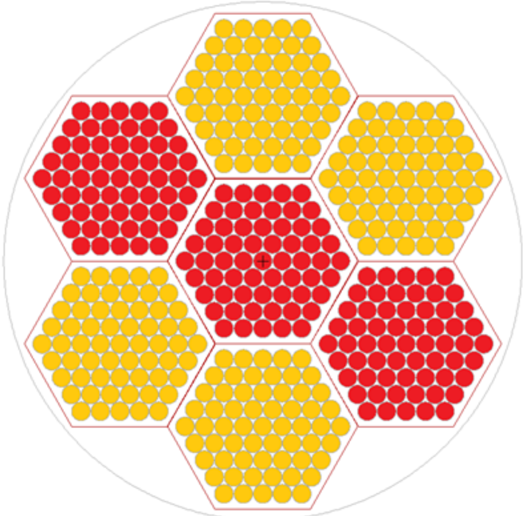
<u>HF Pixels:</u>



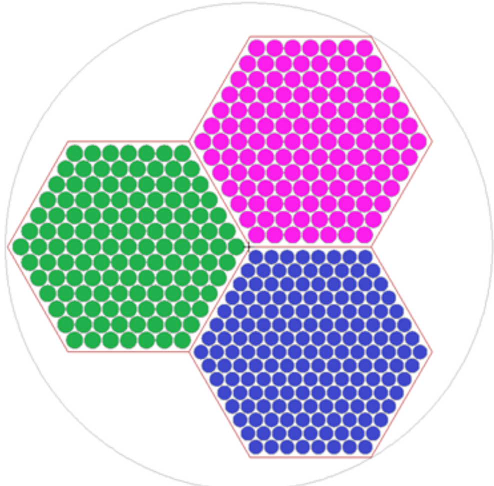




LFT: 420 mm

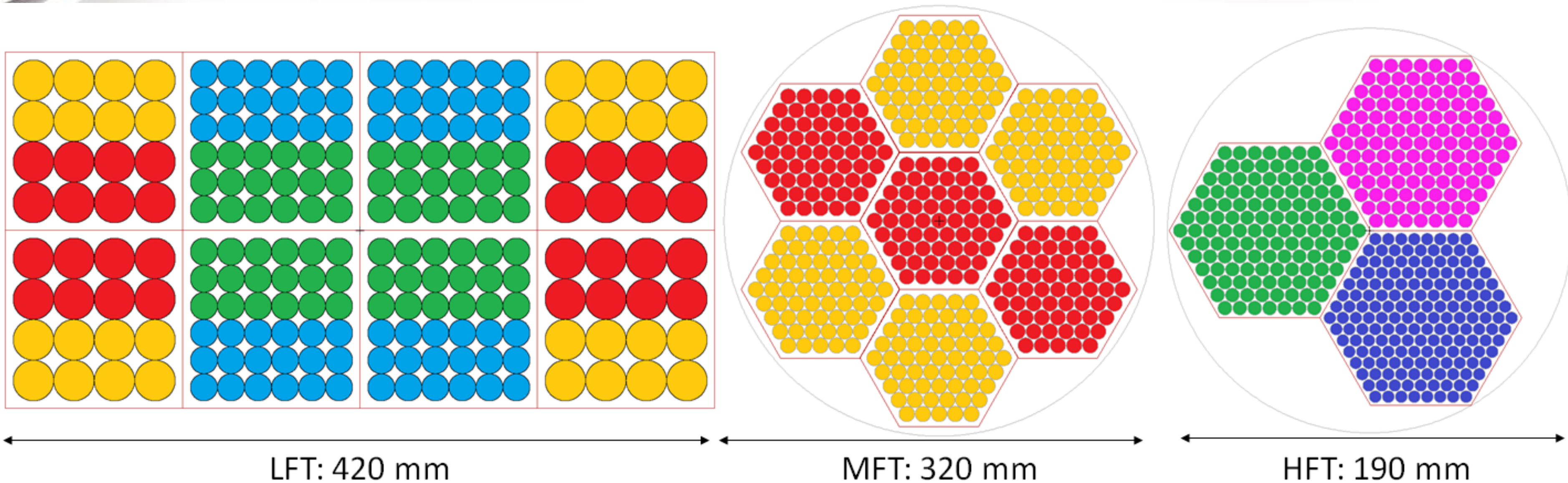


MFT: 320 mm



HFT: 190 mm

Detector Configuration & Number



Telescope	Detector Type	Frequency [GHz]	Pixel Size [mm]	Num Pixel
LFT	Lenslet/Sinuous	40/60/78	24	32
		50/68/89	24	32
		68/89/119	16	72
		78/100/140	16	72
MFT	Lenslet/Sinuous	100/140/195	12	183
		119/166	12	244
HFT	Horn/OMT	195/280	7.0	127
		235/337	7.0	127
		402	6.1	169

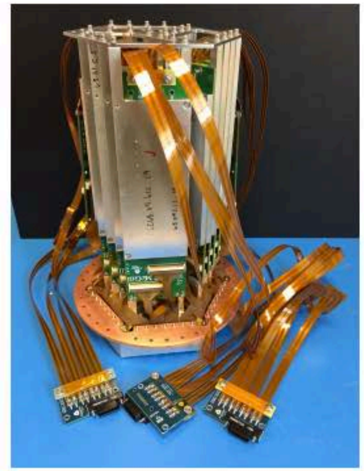
LiteBIRD Detector Fabrication Team Draws from U.S. Community

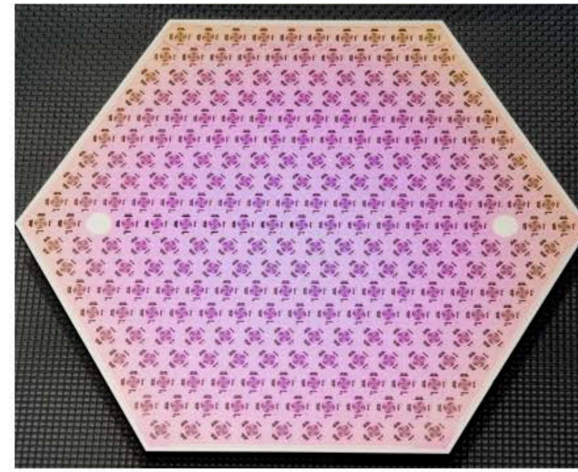
- **Berkeley**
  - Past: APEX-SZ, SPT-SZ, POLARBEAR-1, EBEX, ASTE
  - On-going: POLARBEAR-2, Simons Array, Simons Observatory
- **NIST**
  - Past: ABS, SCUBA-2, ACTPOL, AdvACT, SPT-POL, MUSTANG, SPIDER
  - On-going: AdvACT, SPIDER, Simons Observatory

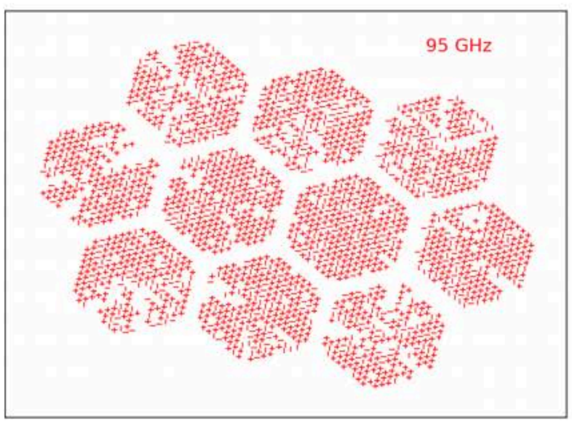
NIST

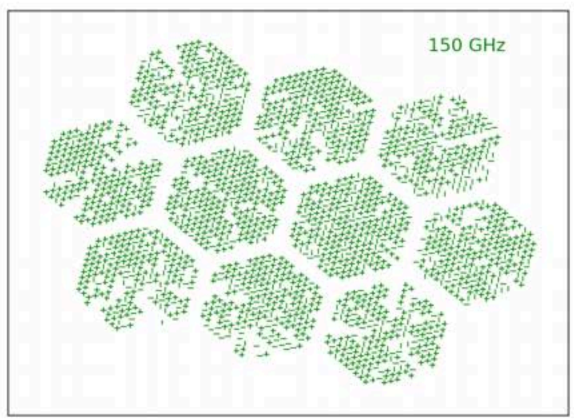
Berkeley

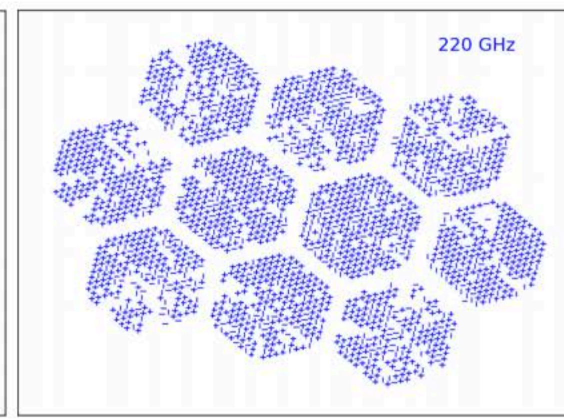
Heritage of Lenslet-Coupled Sinuous Pixels: SPT-3G Tri-Chroic Pixels





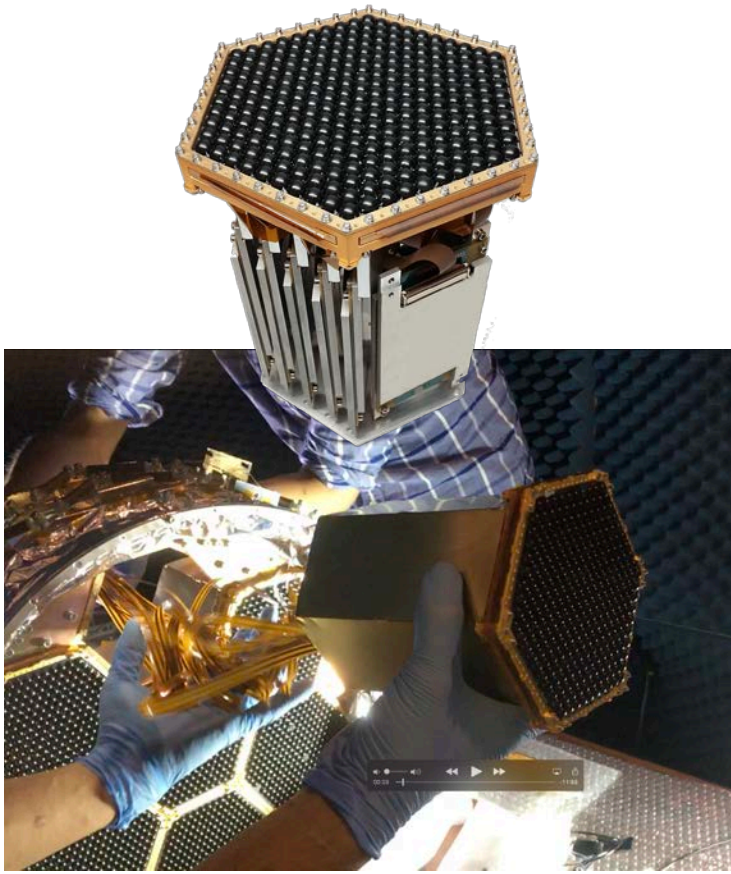


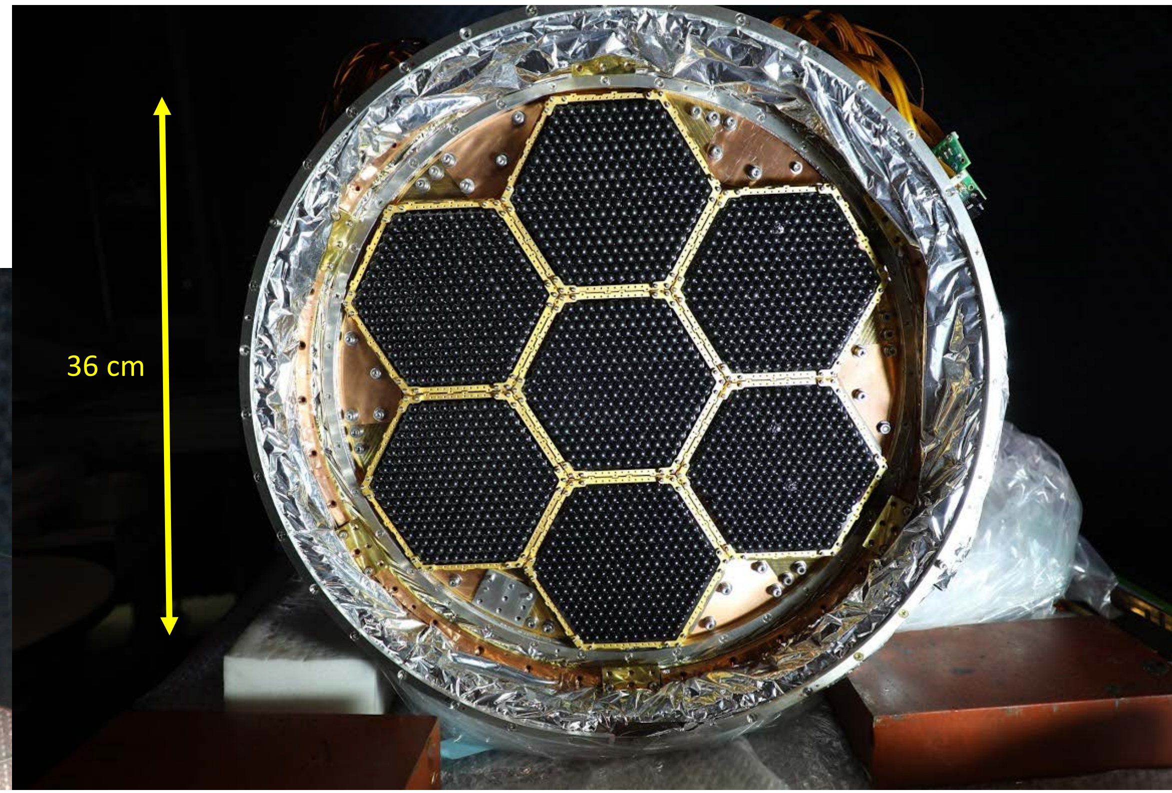




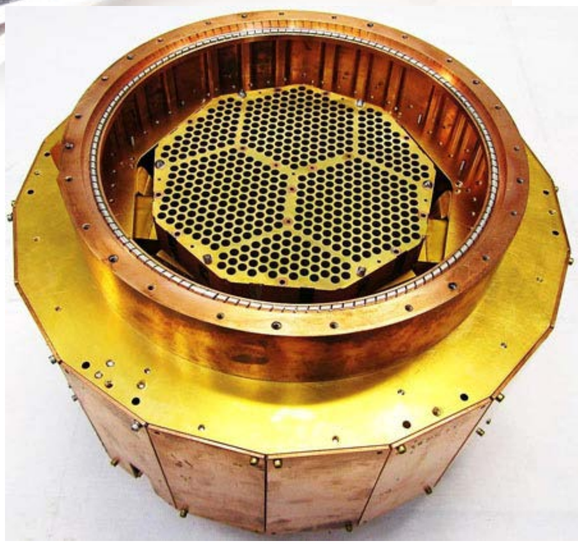
Paper on SPT-3G Instrument Performance after 2 years: https://arxiv.org/abs/1809.00036

Heritage of Lenslet-Coupled Sinuous: POLARBEAR Dichroic Pixels





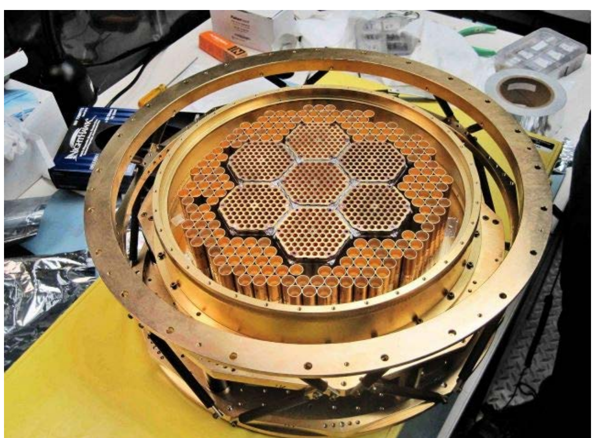
Heritage of horn-coupled OMT: ACTPol and SPTPol



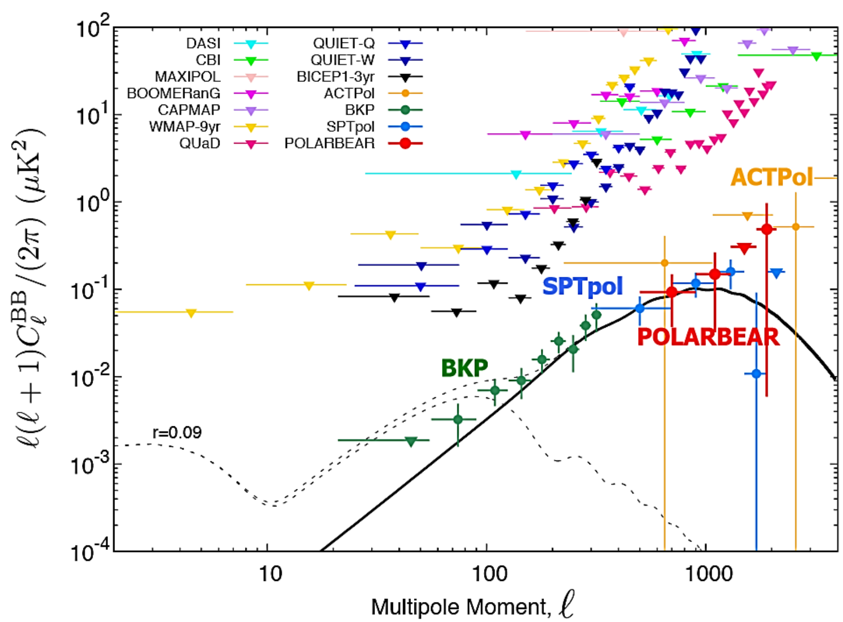
ACTPol

ACT

SPT

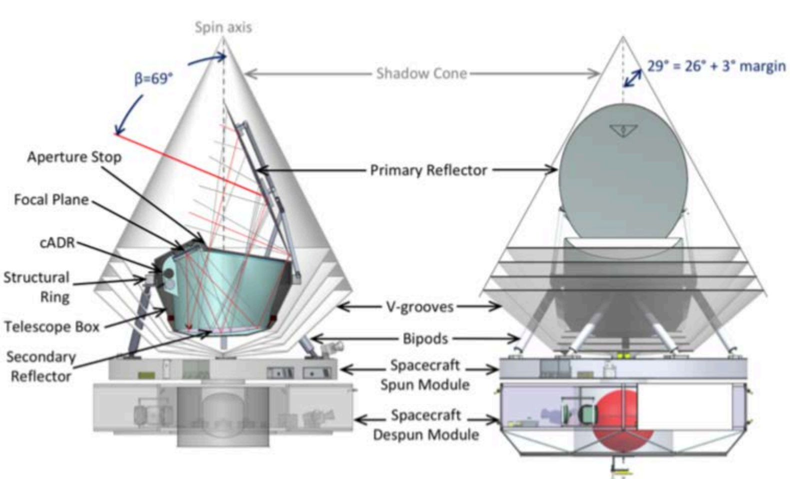


SPTPol



PICO NASA Study

- **NASA study for The Probe of Inflation and Cosmic Origins (PICO)**
  - Study for Probe class mission submitted in advance of the 2020 Decadal Survey
  - https://arxiv.org/abs/1808.01368
- **PICO chose Lenslet-Coupled Sinuous Antenna Pixels as baseline technology**



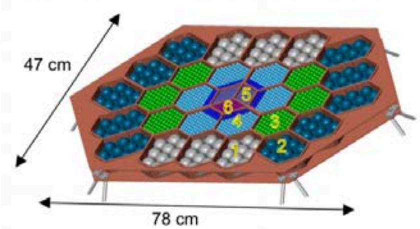


Figure 3.3: PICO focal plane. Detectors are fabricated on 6 types of tiles (shown numbered and colored to match first column in Table 3.1). The wafers are located on the focal plane such that higher frequency bands, which require better optical performance, are placed nearer to the center.

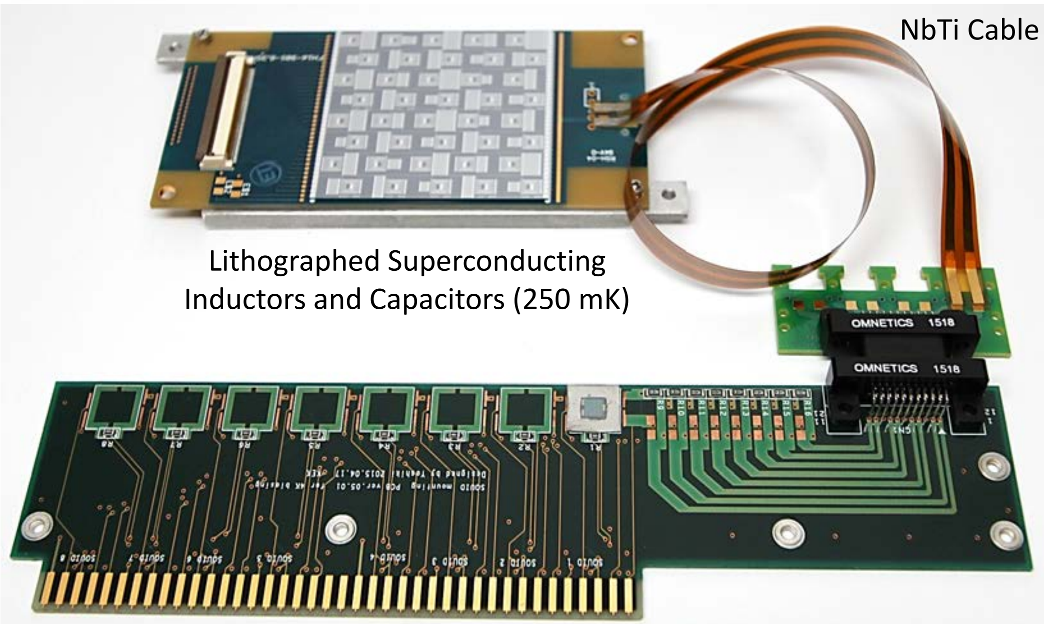
PICO's focal plane is populated by an imaging array of transition edge sensor (TES) bolometers observing in 21 overlapping 25%-wide frequency bands with band centers ranging

Tile type	N_{Tile}	Pixels / Tile	Pixel type	Bandcenters [GHz]	Sampling Rate [Hz]
[illegible]	6	10	A	21, 30, 43	45
2	10	10	B	25, 36, 52	55
3	6	61	C	62, 90, 129	136
4	6	85	D	75, 108, 155	163
		80	E	186, 268, 385	403
5	2	450	F	223, 321, 462	480
6	1	220	G	555	917
		200	H	666	
		180	I	799	

Table 3.1: PICO makes efficient use of the focal area with multichroic pixels (three bands per pixel, §3.2.1). The sampling rate is based on the smallest beam (Table 3.2), with 3 samples per FWHM at a scan speed (360°/min)sin(β=69°) = 336°/min.

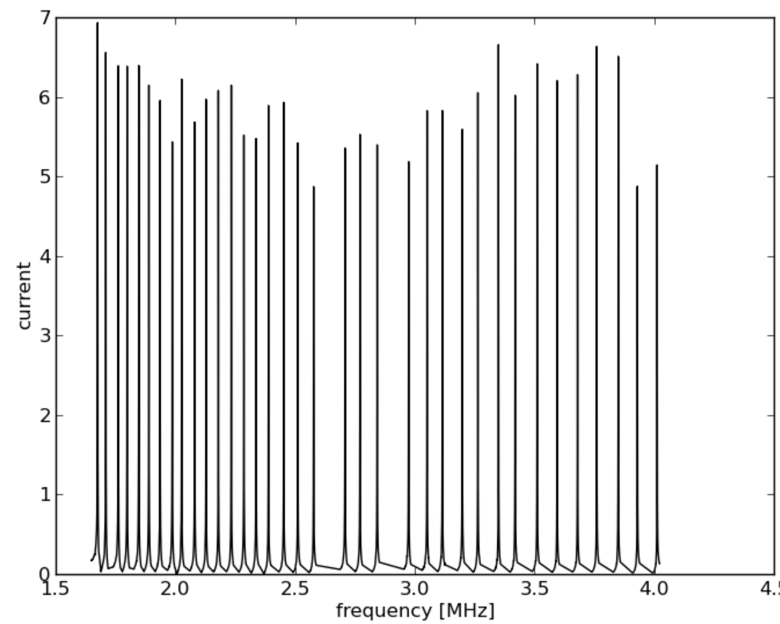
Heritage of Cryogenic Readout: SPTpol, POLARBEAR, EBEX Balloon

Cryogenic Hardware



SQUID Printed Circuit Board (4 K)

Network Analysis Demonstrating Response of System



Digital Frequency-Division Multiplexing using SQUID Array Amplifiers

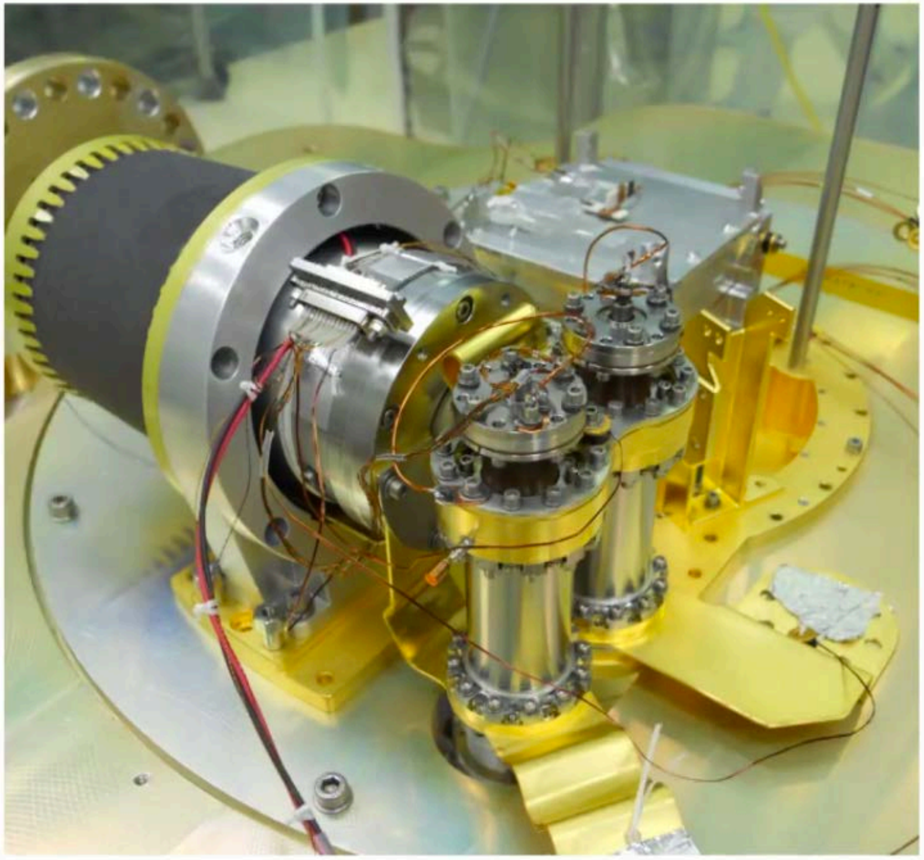
- Lithographed LC resonators fabricated at Lawrence Berkeley National Laboratory
- Two sources of SQUID Array Amplifiers
  - Commercial: StarCryo
  - R&D: National Institute of Standards & Technology (NIST)

Heritage of 2K-ADR: Hitomi/SXS

Hitomi/SXS and XRISM TRL-9 technology is directly applicable for continuous cooling of the LiteBIRD 2K Stage. These designs can be used as-is:

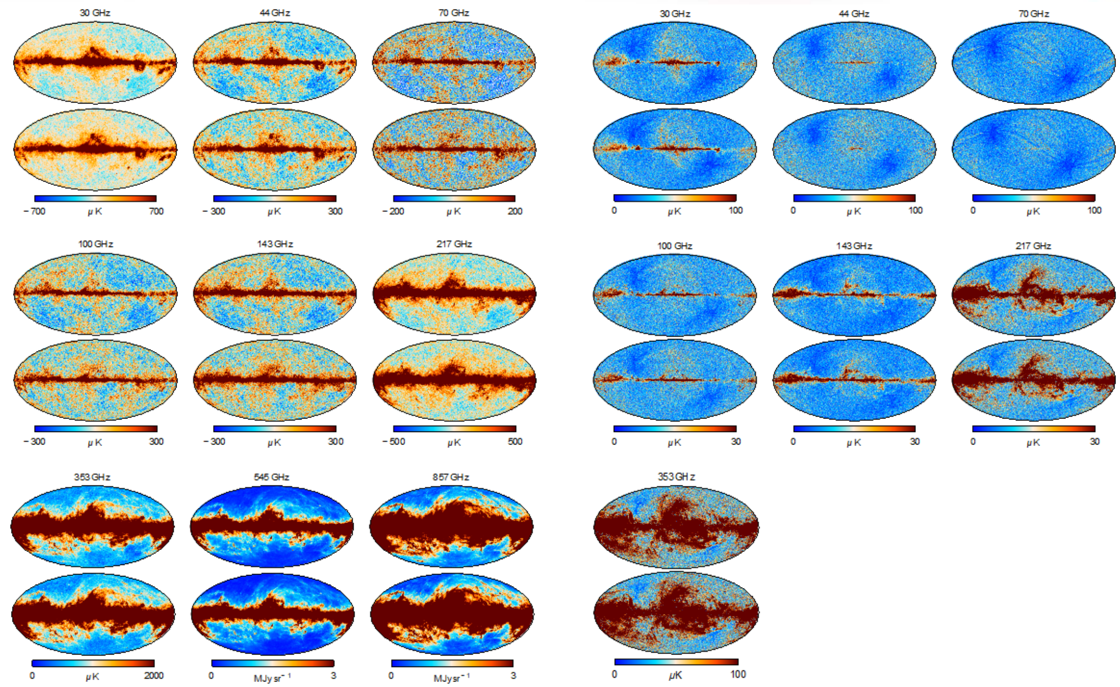
- Salt pills
- Magnets
- Magnetic Shields
- Heat switches

NASA Goddard will build these components for LiteBIRD in the US as part of the US Contribution to LiteBIRD, and will provide integrated testing support.



Experience in Data Management & Analysis

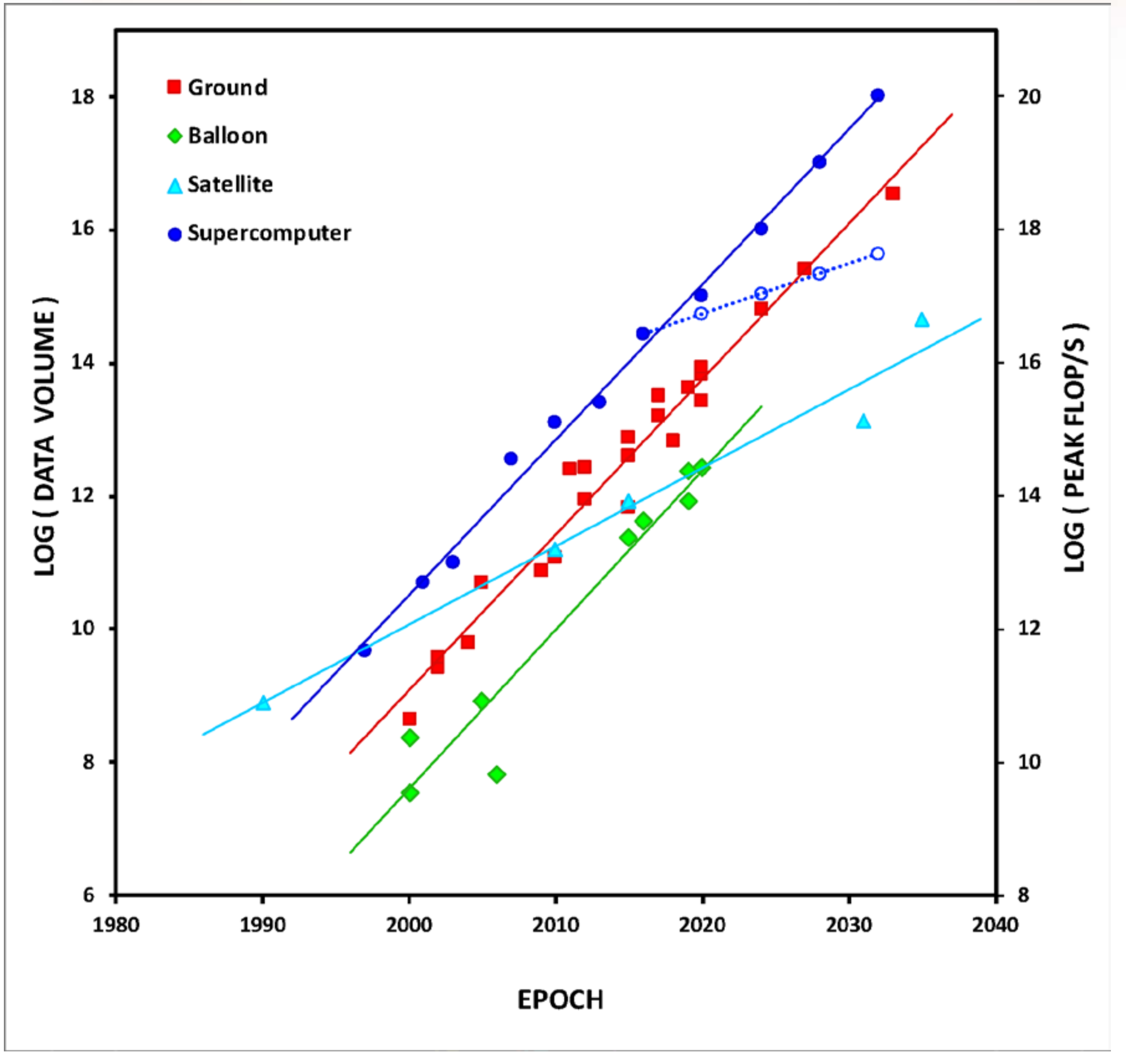
- **Leveraging Planck expertise**
  - US Planck Computational Systems Architect.
  - Lead software developers for simulation & map-making pipeline.
  - DOE/NERSC high performance computing enabling 10^4-realization Monte Carlo of full mission.



Planck real (top) and simulated (bottom) data mapped in temperature (left) and polarization (right).

Julian Borrill receiving NASA Exceptional Public Achievement Medal for his Planck role.

High-Performance Computing
Resources scaling faster than satellite data sets

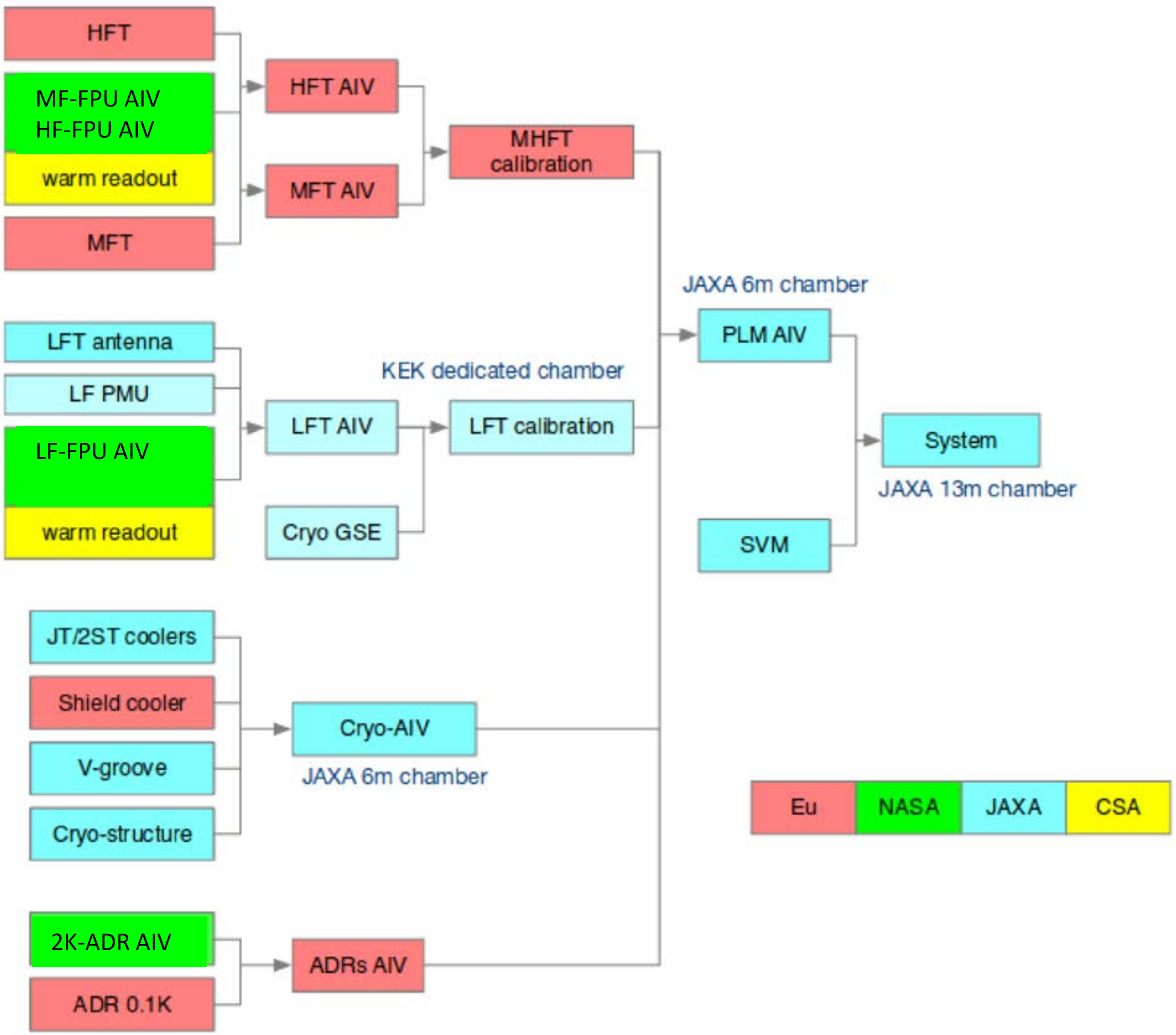


Integration Flow Diagram: US Components

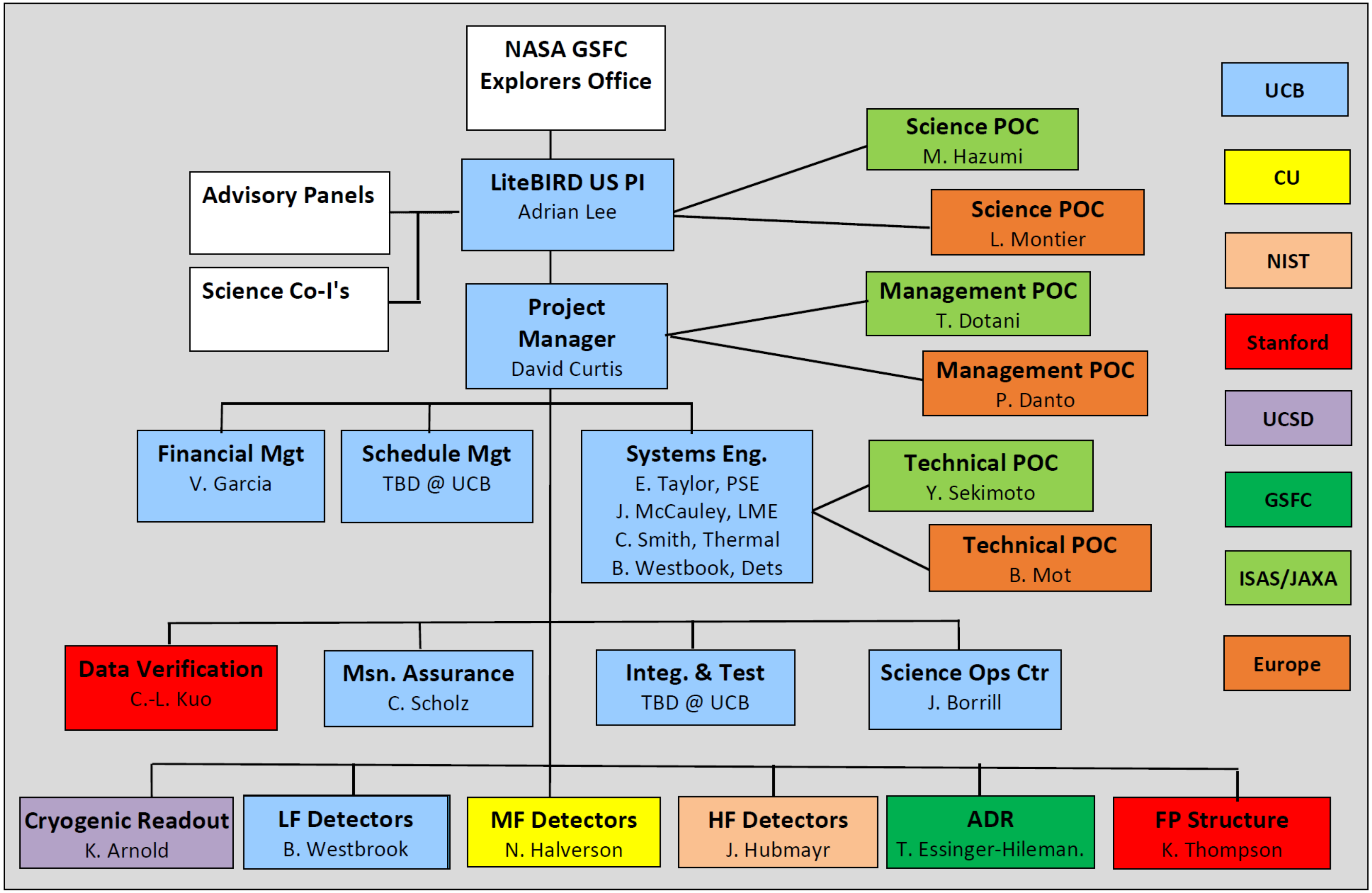
Mid-Frequency (MF) and High Frequency (HF) Focal Plane Units (FPUs)

Low-Frequency Focal Plane Unit (LF-FPU)

Adiabatic Demagnetization Refrigerator (ADR) providing temperature stage at approximately 2 K



US Org Chart


NASA GSFC Explorers Office
LiteBIRD US PI Adrian Lee
Advisory Panels
Science Co-I's
Science POC M. Hazumi
Science POC L. Montier
Project Manager David Curtis
Management POC T. Dotani
Management POC P. Danto
Financial Mgt V. Garcia
Schedule Mgt TBD @ UCB
Systems Eng. E. Taylor, PSE J. McCauley, LME C. Smith, Thermal B. Westbook, Dets
Technical POC Y. Sekimoto
Technical POC B. Mot
Data Verification C.-L. Kuo
Msn. Assurance C. Scholz
Integ. & Test TBD @ UCB
Science Ops Ctr J. Borrill
Cryogenic Readout K. Arnold
LF Detectors B. Westbrook
MF Detectors N. Halverson
HF Detectors J. Hubmayr
ADR T. Essinger-Hileman.
FP Structure K. Thompson
UCB
CU
NIST
Stanford
UCSD
GSFC
ISAS/JAXA
Europe

TRL Advancement Currently Funded by NASA

- **Currently working to advance TRL of all focal plane components, with deliverable TRLs in 2021**
- **Synchronizing technology development with requirements of LiteBIRD mission as they develop**
- **Some important technical issues currently being addressed in this LiteBIRD technology readiness development:**
  - Cosmic ray sensitivity analysis and mitigation development
  - Establishing a design for focal plane unit mechanical structures
  - Cryogenic readout development to mitigate crosstalk
  - Focal plane magnetic shielding design and requirements development
  - Building flight-specification transition edge sensor bolometers
  - Simulations of full-mission performance using instrument model including important complexities
- **Also included construction of important testing and validation infrastructure**
- **Items used for TRL advancement will be delivered as Demonstration Models (DM) focal plane components to Japanese and European partners to use in initial tests of the system.**

Technology Development Program: TRL Advancement

TRL Entering Program

Instrument	TRL	Component	TRL
ADRCP	5		
		Cryogenic	6
		Control Electronics	5
		Mechanical	9
LF-FPU	3		
		Mechanical	4
		LF Detector sub-arrays	3
		MF detector sub-arrays	3
		Readout electronics	3
HF-FPU	3		
		Mechanical	4
		HF detector sub-arrays	3
		Readout electronics	3

JAXA A1 Exit: US Component TRL Review

	Component	Description	TRL
Cryogenic Readout	Interconnects	Standard PCB and cryogenic harnesses	6-9
	LC Chips: resonators	Chips fabricated by LBNL, used in SPT-3G and POLARBEAR	5
	SQUID Array Amplifiers	first-stage amplifier	4
LF & MF Focal Plane Modules & Structures	Bolometer wafer: TES Bolometer	Mechanically & thermally released structure	5
	Bolometer wafer: Microstrip Filter	Component that provides the on-wafer spectral filtering	5
	Bolometer wafer: sinuous antenna	Planar structure that, coupled to the lenslet, couples to free space	4
	Coupling wafer: lenslets (LF & MF)	Lenslets used on SPT-3G, POLARBEAR	4
	AR Coatings	Two-layer coatings to be used on lenslets have been demonstrated in the lab	4
	Focal Plane Structure (FPS)	CFRP struts, which have been demonstrated on ground and balloon. Pending final design	4
HF Focal Plane Modules & Structure	Bolometer wafer: TES Bolometer	Mechanically & thermally released structure	5
	Bolometer wafer: microstrip filter	Component that provides the on-wafer spectral filtering	5
	Bolometer wafer: ortho-mode transducer	Used extensively in instruments on the ground and in balloons	5
	Coupling wafer: horns	Used extensively in instruments on the ground and in balloons	5
	Focal Plane Structure (FPS)	CFRP struts, which have been demonstrated on ground and balloon. Pending final design	6

Deliverable for technology development program in 2021:

Component TRLs all at 5

Notes:

FPU: Focal Plane Unit

ADRCP: Referred to the previously proposed Adiabatic Demagnetization Refrigerator Cryogenic Platform. Note we have changed the cryo system since then, and the components are at TRL7-9.

Status of some important technical issues

- **Cosmic ray sensitivity analysis and mitigation development**
  - Careful analysis of Planck lessons learned
  - Completed simulations of energy transport for our detector designs
  - Implemented hardware mitigations based on simulations
  - Testing of hardware mitigations underway
  - Designing warm electronics mitigation techniques
- **Establishing a design for focal plane unit mechanical structures**
  - Vibration testing of focal plane module demonstrated launch survival for design with acceptable heat loads
  - Mechanical Design based on Phase A1 Exit optical design underway
- **Cryogenic readout development to mitigate crosstalk**
  - Inductor-Capacitor Resonator Frequency Tuning Technique: mechanical demonstration complete, electrical testing underway
  - SQUID Array Amplifiers demonstrated at sub-Kelvin stage, now being tested for noise performance with harness of flight-like electrical properties

Status of some important technical issues

- **Focal plane magnetic shielding design and requirements development**
  - Magnetic Field Sensitivity of TES bolometers measured
  - Magnetic shield simulations show shielding factors of a few hundred
  - Developing requirements for magnetic shielding
- **Building flight-specification transition-edge sensor bolometers**
  - TESs with properties tuned for flight-like optical loading fabricated and tested
  - Detector saturation power and noise demonstrated
- **Data management & analysis: simulations of full-mission detector performance**
  - Significant expansion and optimization of software capacity and capability, including improved beam and bandpass integration and GPU kernels for the next-generation NERSC supercomputer.
    - Framework (TOAST) is also baselined for Simons Observatory & CMB-S4.
  - Ongoing development of complete instrument model (optics & electronics) down to the individual detector level.
  - First full-complexity, full-mission, simulation & reduction expected this summer.
  - TOAST training workshops planned for US and Europe in the fall.

Conclusion

- The US Team has been working on LiteBIRD continuously since 2015, either as part of a flight program or a technology development program.
- The team has substantial experience with the technology and analysis required by LiteBIRD.
- Where technology is not yet at TRL-6, funded R&D is underway to raise that TRL, and the schedule of this work is well-synchronized with the proposed NASA flight program schedule.
- We will submit our next flight program proposal in 30 days