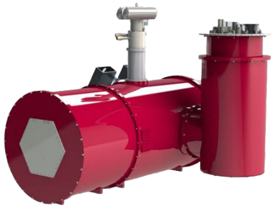
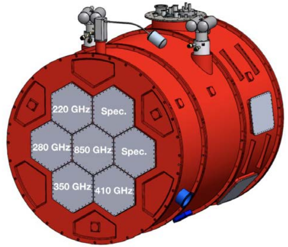
CCAT-prime
Status of Prime-Cam and related Instrumentation



Prime-Cam team

(authors at https://arxiv.org/abs/1908.10451 plus others)



Topics:

CCAT-prime

Overview of Instruments

Overview of Prime-Cam and instrument modules - Mike Niemack
Prime-Cam instrument performance overview - Steve Choi
Mod-Cam single module tester and first light module - Eve Vavagiakis

Broadband Technologies

Broadband optical module design and performance - Patricio Gallardo
Detector heritage and BLAST performance - Jordan Wheeler/NIST
First light detector array and readout development - Cody Duell

Spectrometer Technologies

Spectrometer module overview - Nick Cothard
Spectrometer module optical design performance - Zach Huber
Prototype Fabry Perot Interferometer (FPI) etalons - Bugao Zou
FPI optimization for observations - Mahiro Abe and Thomas Nikola

350 um Module Updates - Doug Henke and Scott Chapman

Next steps for Prime-Cam - Mike Niemack

Overview of Prime-Cam (Mike Niemack)

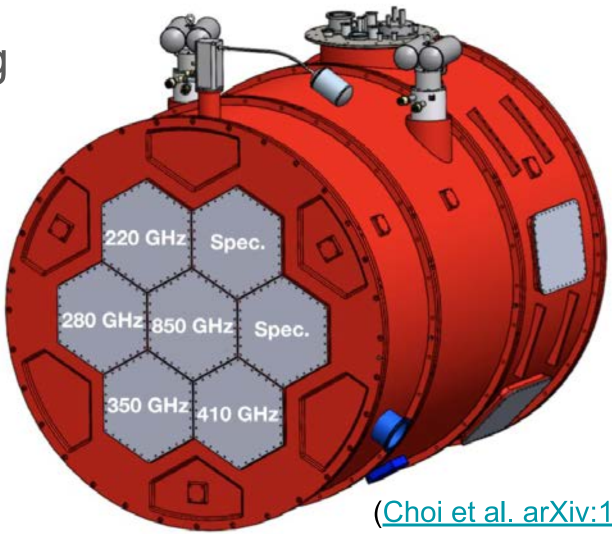
A unique feature of the CCAT-prime optics design is the large field of view

Prime-Cam is a high-throughput instrument that fills ~½ the diameter of the FOV

Prime-Cam has 7 “instrument modules” enabling simultaneous observations

Design evolved from Simons Observatory 13 module (aka. optics tube) cryostat

Cryostat delivery expected in Summer 2020



(Choi et al. arXiv:1908.10451)

Fig. 1: A model of the Prime-Cam cryostat (1.8 m diameter) is shown with a possible configuration of broadband and spectrometer instrument module positions.

Overview of Prime-Cam

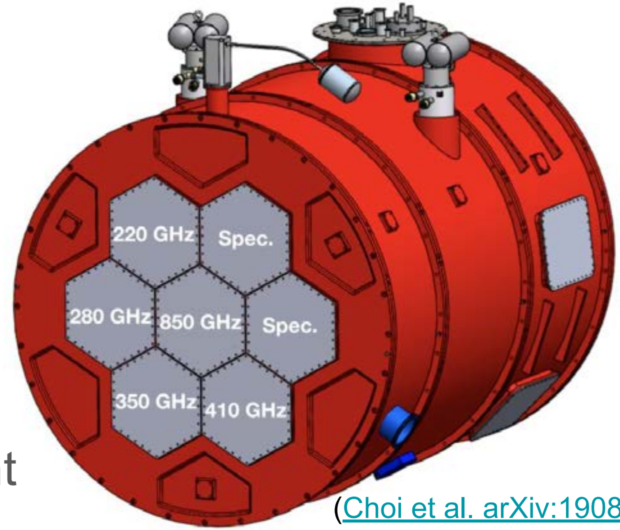
Many science cases to be discussed later

Science prioritization should continue driving instrument module distribution

Current module priorities:

- Broadband polarimeters:
  280 GHz at first light, then 350 GHz
- Spectrometer (210 - 420 GHz)
- 850 GHz (350 um) polarimeter

Need to test modules after Prime-Cam deployment
=> Mod-Cam

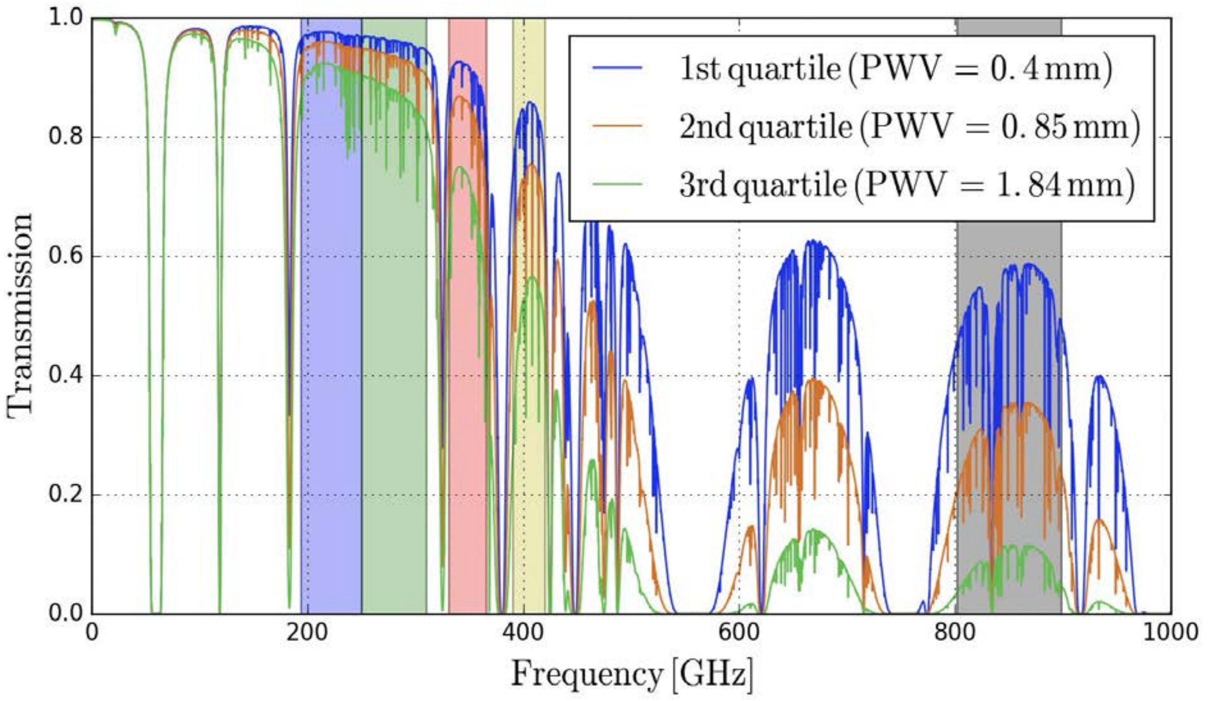


(Choi et al. arXiv:1908.10451)

Fig. 1: A model of the Prime-Cam cryostat (1.8 m diameter) is shown with a possible configuration of broadband and spectrometer instrument module positions.

Instrument performance overview (Steve Choi) – detector passbands

- Reference detector passbands selected upon further inspection of the atmosphere with the am code.
- Passbands moved to remove overlaps and avoid strong atmospheric lines.
- Transmission up to 6% higher than before (up to ~30% better sensitivity).
- PWV values in the legend account for observing elevation of 45 deg.

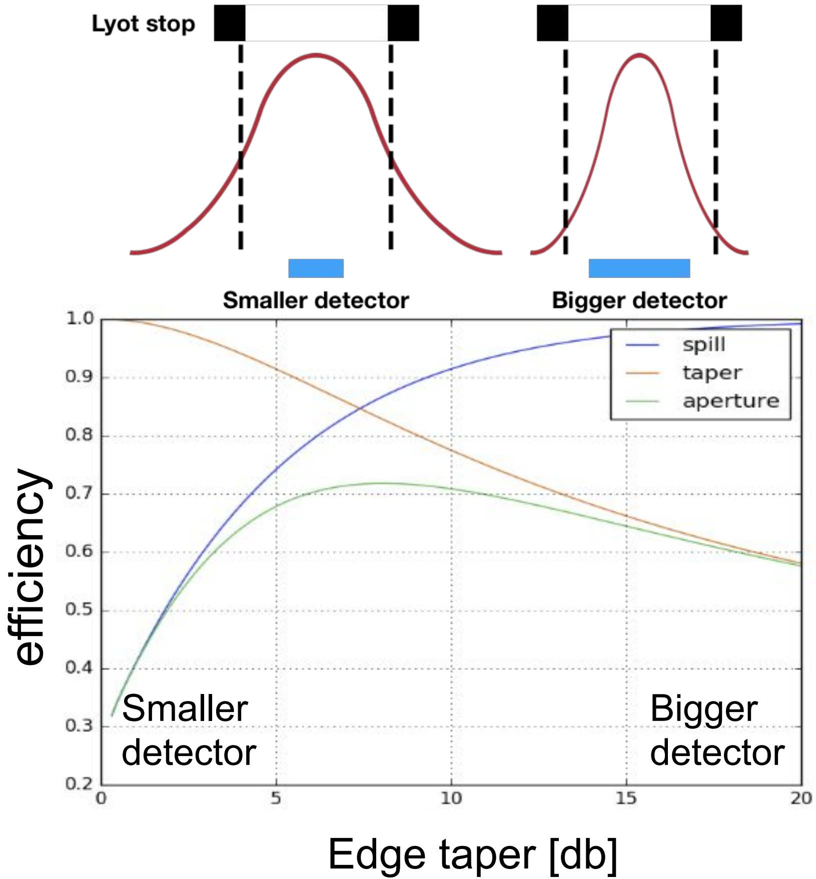


(Choi et al. arXiv:1908.10451)

Instrument performance overview (Steve Choi) – detector size & technology choice

CCAT-prime

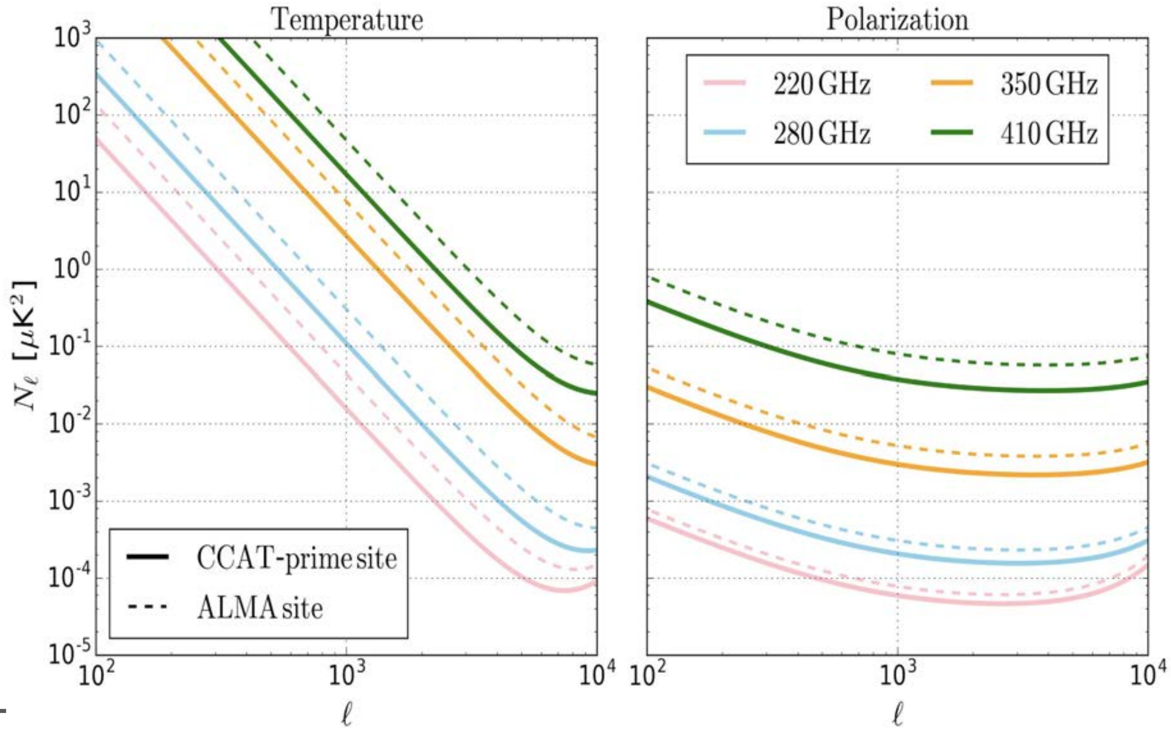
- Bigger detectors:
  - More light in the beam -- higher spill efficiency
  - Smaller illumination (bigger beam size) -- lower taper efficiency
  - Smaller number of total pixels
- Smaller detectors:
  - Less light in the beam -- lower spill efficiency
  - Bigger illumination (smaller beam size) -- higher taper efficiency
  - Bigger number of total pixels
- **Reference detector choice: TES → KID based on sensitivity calculations.**



Instrument performance overview (Steve Choi) – noise curves

CCAT-prime

- Noise curves calculated for baseline design with KIDs.
- White noise from instantaneous sensitivities from Gordon's spreadsheet with updated input (transmission, efficiency, etc.)
- SO atmosphere (fluctuation) noise model included for 1/f noise.
- In use by some science forecast teams (by both CCAT and SO).



(Choi et al. arXiv:1908.10451)

Instrument performance overview (Steve Choi) – sensitivity summary

CCAT-prime

- Instantaneous and integrated sensitivity given for:
  - 15,000 deg^2 wide survey
  - 410 deg^2 deep survey
  - 8 deg^2 spectrometer survey

- $$N_\ell = N_{red}\left(\frac{\ell}{\ell_{knee}}\right)^{\alpha_{knee}} + N_{white}$$
  - ℓ_{knee} = 1000, α = –3.5 for Temp.
  - ℓ_{knee} = 700, α = –1.4 for Pol.

(atmospheric noise model: SO Collaboration arXiv: 1808:07455)

Broadband channels wide survey (15,000 deg^2; 4,000 hours)

ν GHz	$\Delta\nu$ GHz	Resolution arcsec	NEI Jy $sr^{-1}\sqrt{s}$	Sensitivity μK-arcmin	NET $\mu K\sqrt{s}$	N_{white} μK^2	N_{red} μK^2
220	56	57	3,700	15	7.6	1.8×10^{-5}	1.6×10^{-2}
280	60	45	6,100	27	14	6.4×10^{-5}	1.1×10^{-1}
350	35	35	16,500	105	54	9.3×10^{-4}	2.7×10^{0}
410	30	30	39,400	372	192	1.2×10^{-2}	1.7×10^{1}
850	97	14	6.0×10^{7}†	5.7×10^{5}	3.0×10^{5}	2.8×10^{4}	6.1×10^{6}

Broadband channels star formation survey in 1st quartile PWV (410 deg^2; 680 hours)

ν GHz	$\Delta\nu$ GHz	Resolution arcsec	NEI Jy $sr^{-1}\sqrt{s}$	Sensitivity μK-arcmin	NET $\mu K\sqrt{s}$	N_{white} μK^2	N_{red} μK^2
220	56	57	3,000	6	6.3	2.9×10^{-6}	2.5×10^{-3}
280	60	45	4,900	11	11	1.0×10^{-5}	1.7×10^{-2}
350	35	35	12,300	42	40	1.5×10^{-4}	4.3×10^{-1}
410	30	30	27,400	149	134	1.9×10^{-3}	2.7×10^{0}
850	97	14	3.8×10^{7}†	2.3×10^{5}	1.9×10^{5}	4.5×10^{3}	9.8×10^{5}

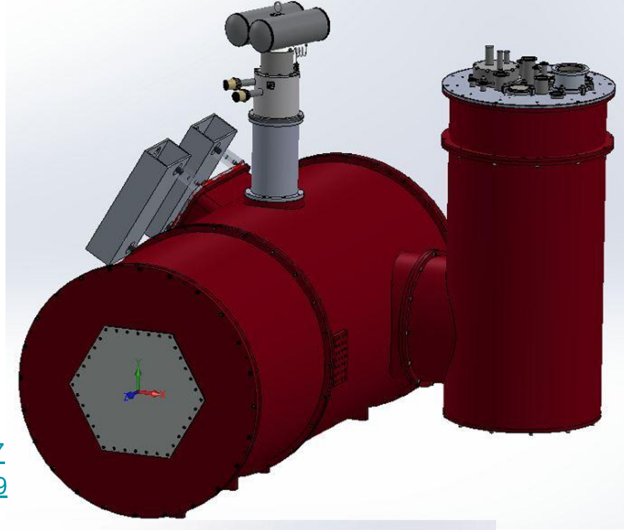
Selected spectrometer channels targeted survey (8 deg^2; 4,000 hours)

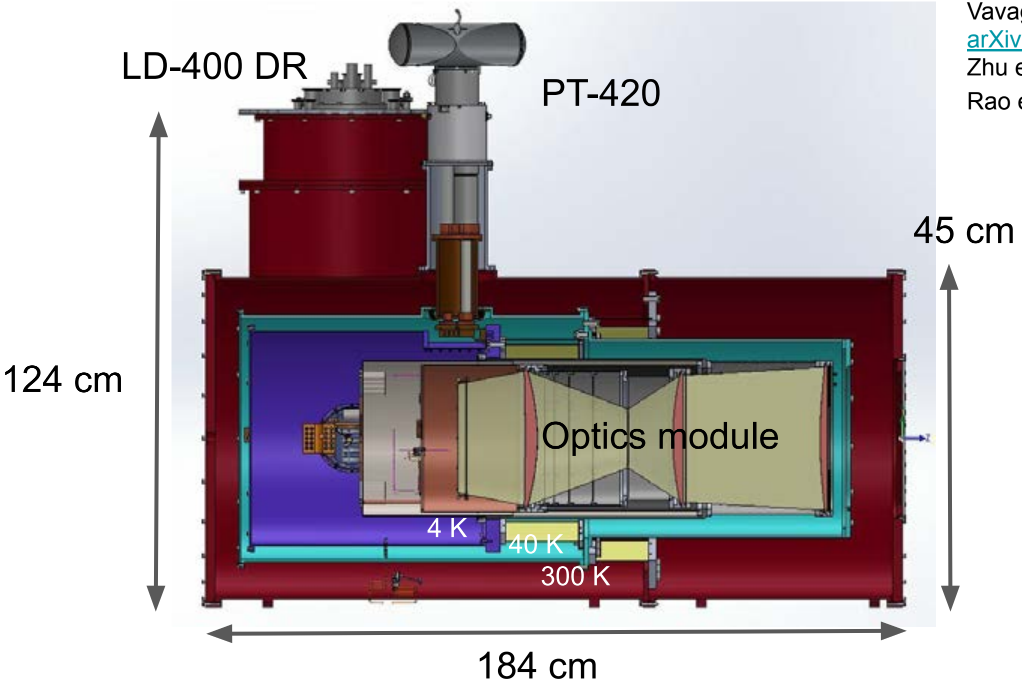
ν GHz	$\Delta\nu^*$ GHz	Resolution arcsec	[CII] redshift	NEI Jy $sr^{-1}\sqrt{s}$	N_{white} $Mpc^3\ Jy^2\ sr^{-2}$
220	2.2	57	7.5	12,900	1.2×10^{9}
280	2.8	45	5.8	16,600	2.0×10^{9}
350	3.5	35	4.4	30,600	6.3×10^{9}
410	4.1	30	3.7	61,500	2.3×10^{10}

(Choi et al. arXiv:1908.10451)

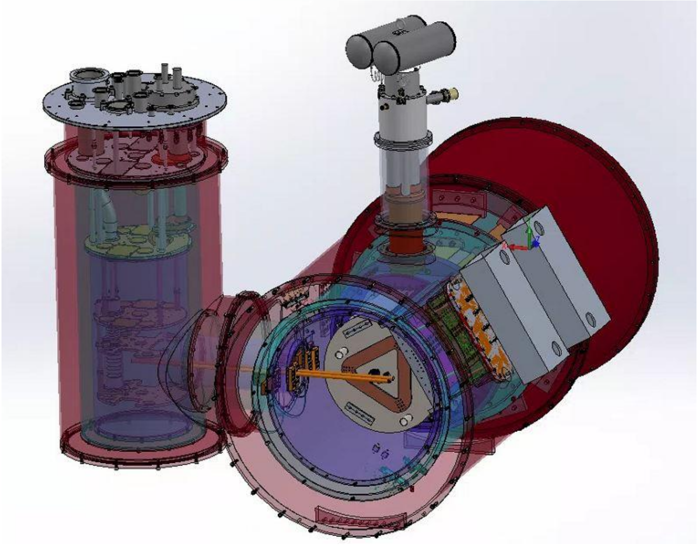
Mod-Cam (Eve Vavagiakis, Cornell)

- Single optics module for first light and testbed for Prime-Cam
- Side-car DR design enables easy rear swapping of modules
- Optics tubes can be SO size or smaller
- Flexible readout options, compatible with SO readout design



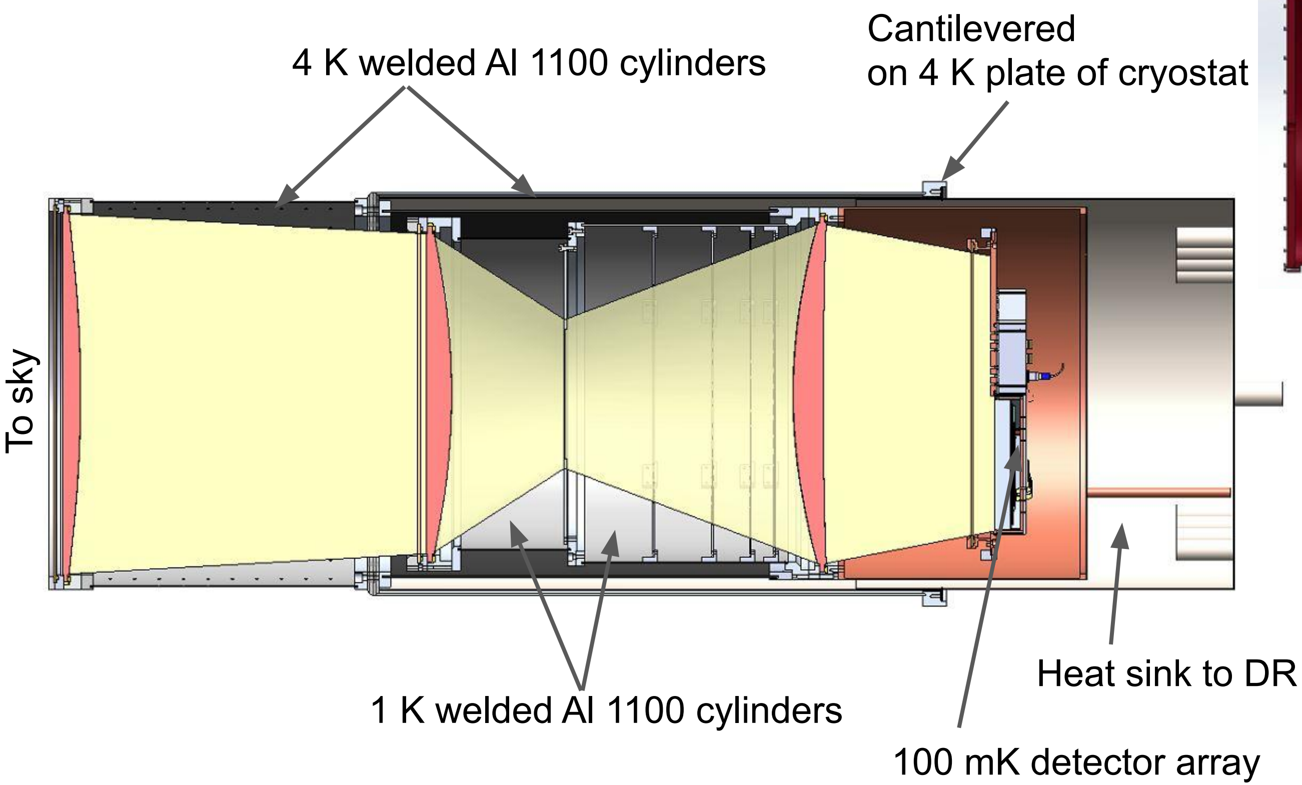


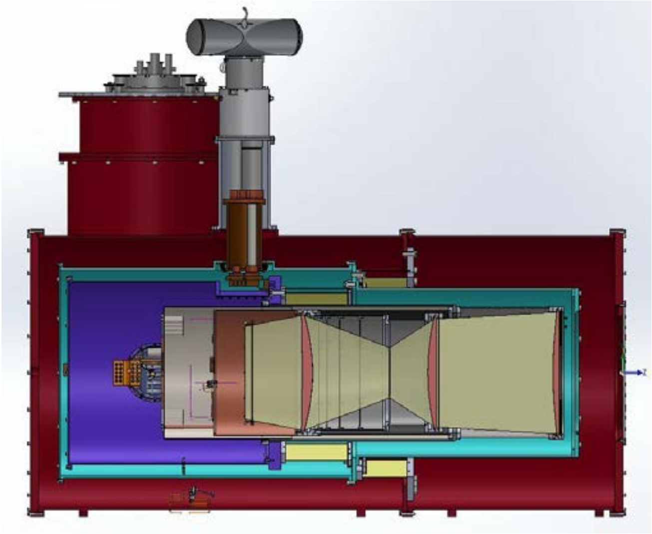
Vavagiakis et al. arXiv:1807.00058
Zhu et al. arXiv:1808.10037
Rao et al. arXiv:2003.08949

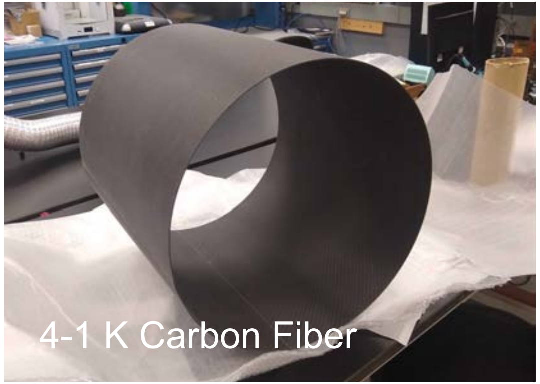


Mod-Cam (Eve Vavagiakis, Cornell)

- First optics module in construction

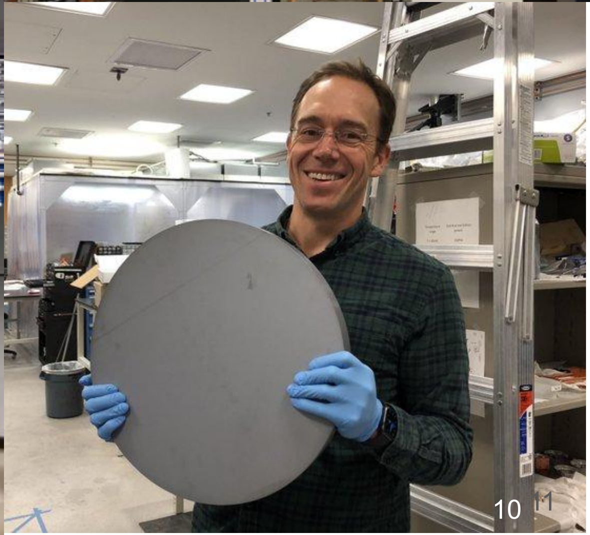




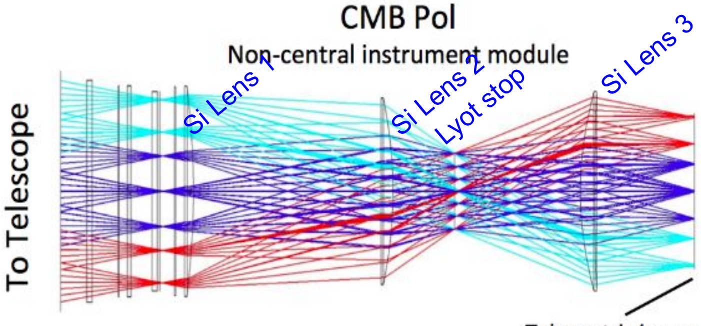


Mod-Cam (Eve Vavagiakis, Cornell)

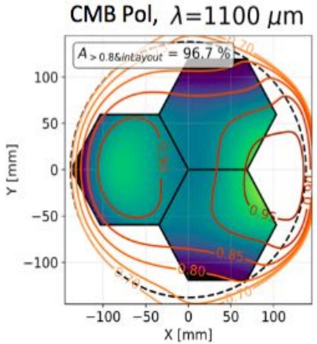
- Fabrication underway, expect delivery before Cornell labs open
- First fit checks begun
- Laboratory space prepped
- Silicon lens material ready

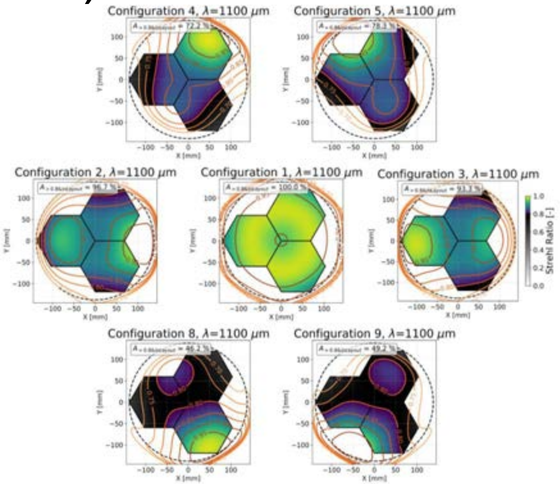


Broadband module optics (Patricio Gallardo)



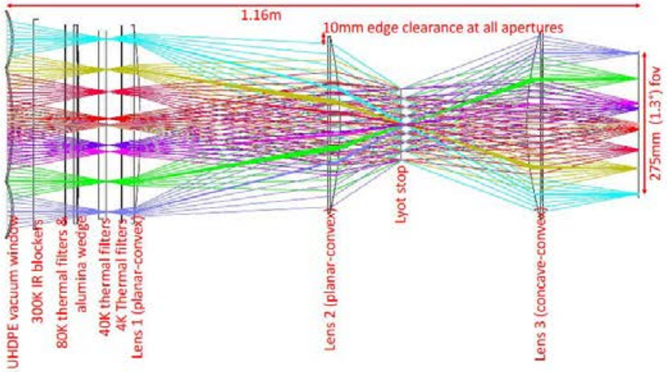
[Arxiv1707.00058](https://arxiv.org/abs/1707.00058)

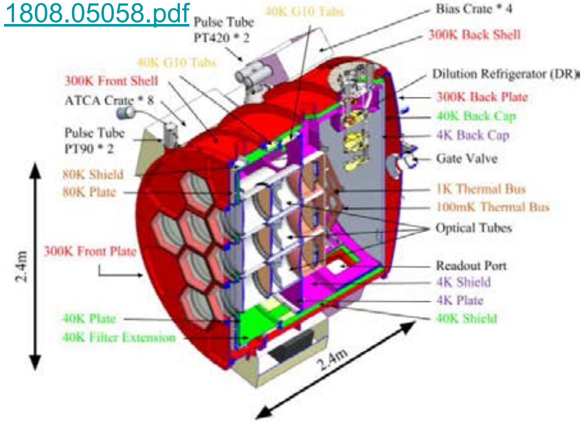


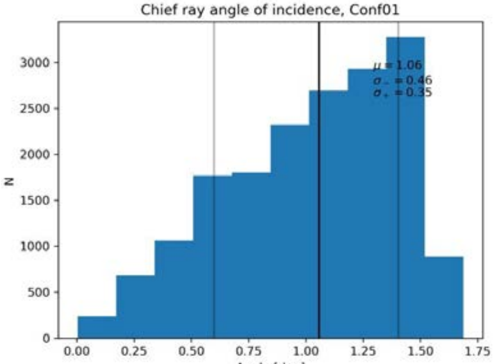


[arXiv:1808.05152](https://arxiv.org/abs/1808.05152)

Design inspired in the SO cold optics Arxiv: [1808.05058.pdf](https://arxiv.org/pdf/1808.05058.pdf)







Detector Heritage (Jordan Wheeler/NIST)
Large Format MKID Detector Arrays

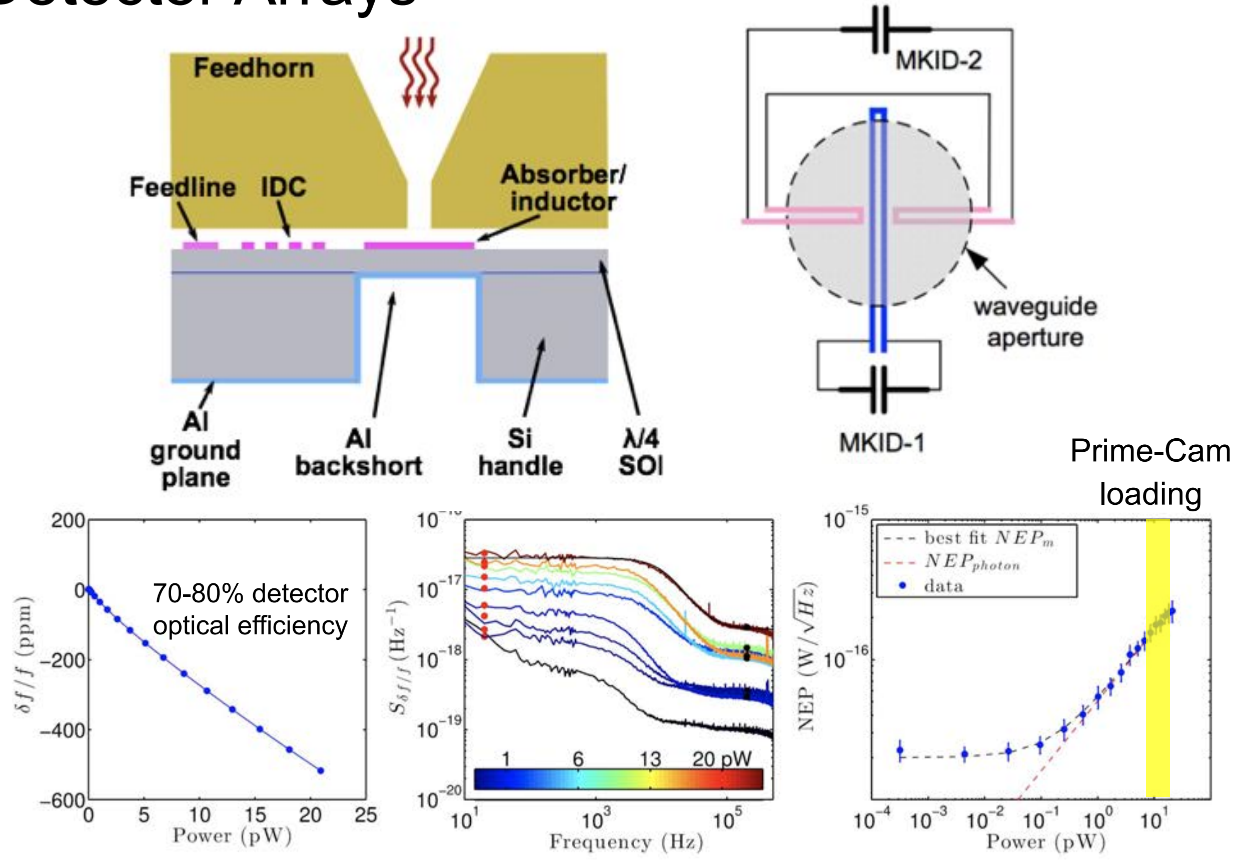
CCAT-prime

BLAST-TNG:

Balloon-borne mission recently launched

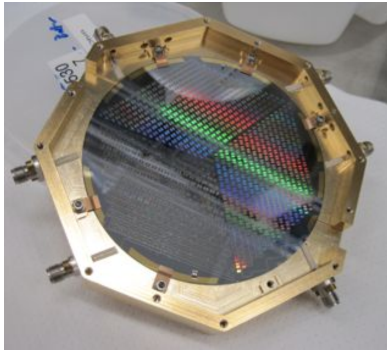
TolTEC:

3 detector wafers all delivered and now integrated into instrument cryostat



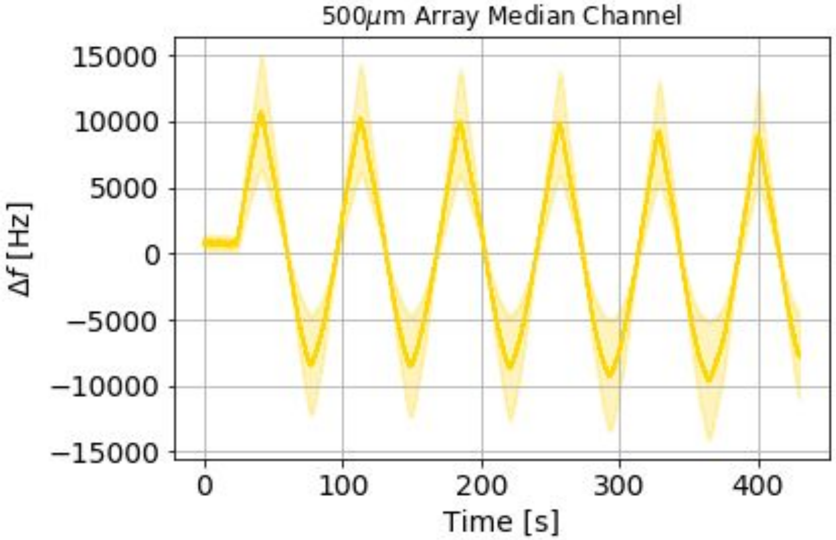
Hubmayr et al. 2015

Detector Heritage BLAST-TNG (Jordan Wheeler/NIST)

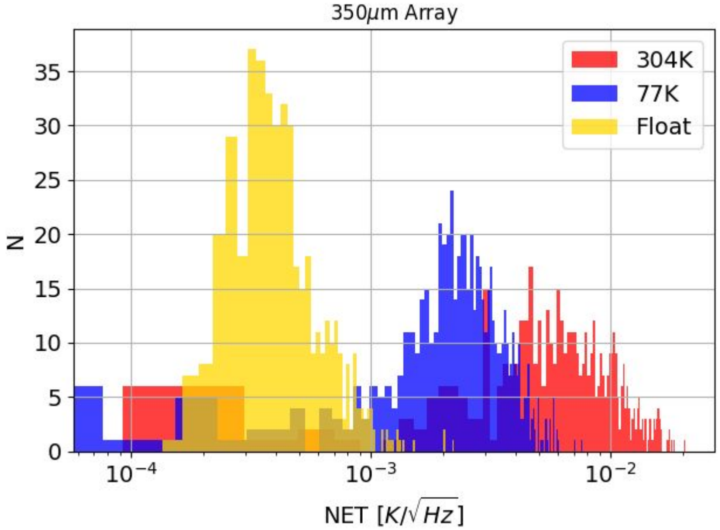


Preliminary Flight Data
Credit: Adrian Sinclair ASU

Sky dip +/- 5 degrees

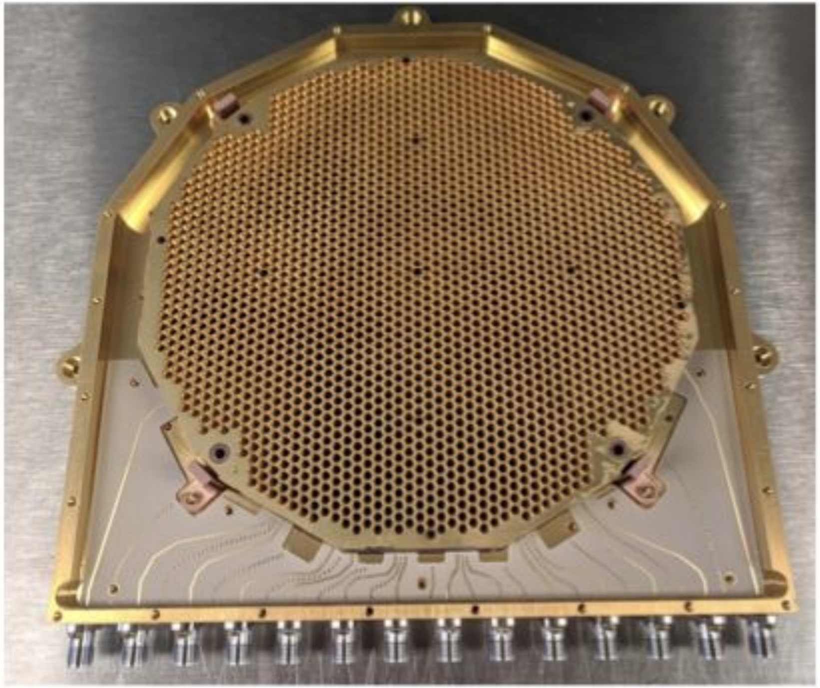


350um ~ ~~300uK/rtHz~~ ~600uK/rtHz?
Data analysis is an ongoing process



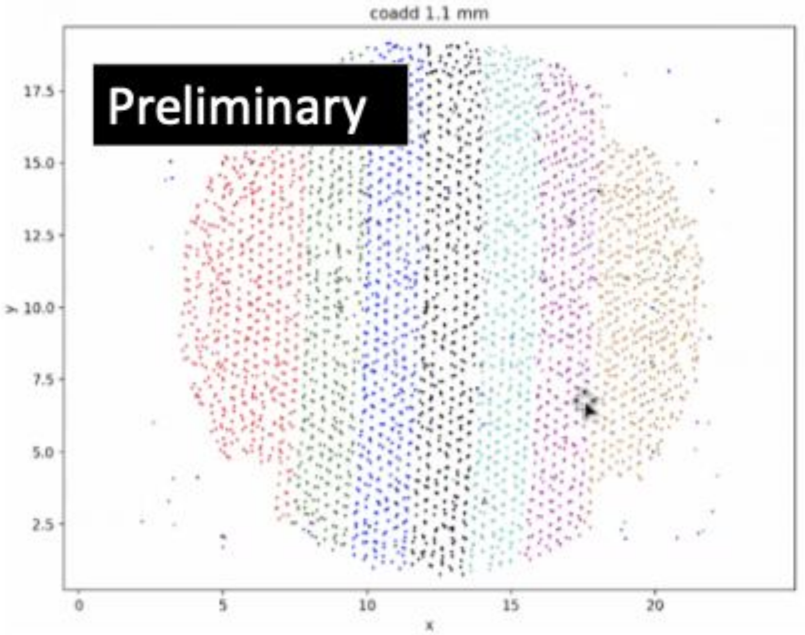
Detector Heritage TolTEC (Jordan Wheeler/NIST)

1.1mm Toltec array mounted behind silicon feedhorn stacks. RF shield removed.



4012 resonators (inc. darks) split onto 7 networks (color coded on right)

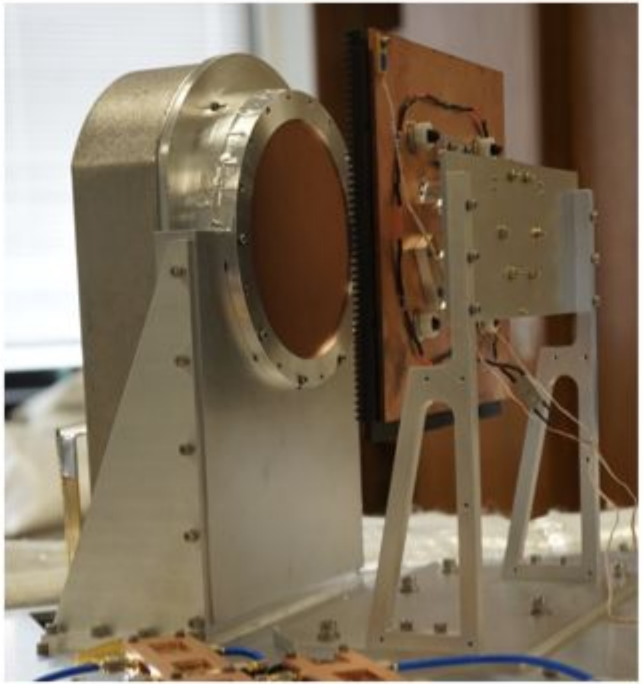
Beam map centroids found for 3748/3984 optical resonators



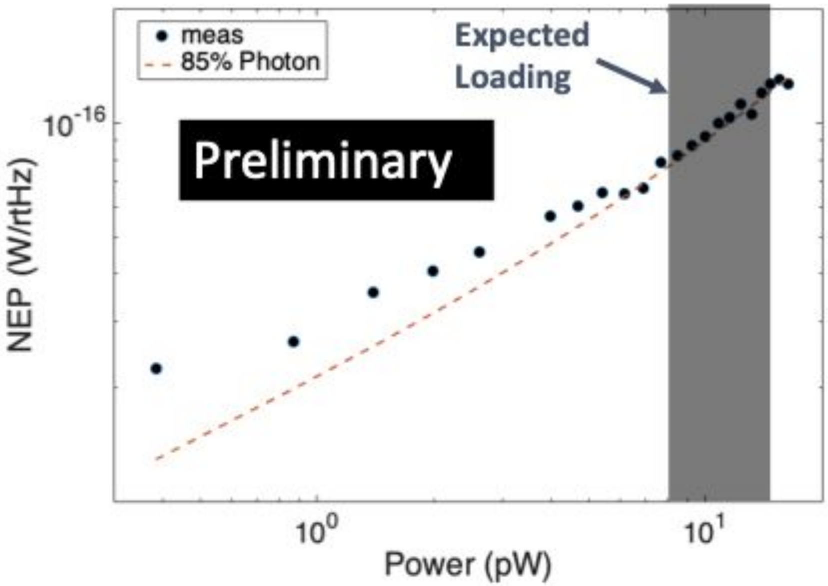
Detector Heritage TolTEC (Jordan Wheeler/NIST)

CCAT-prime

1.1mm Toltec array inside magnetic shielding and behind low-pass filter. Looking at UMASS cold load



Photon-limited noise performance (NIST cold load tests, not from setup to left)

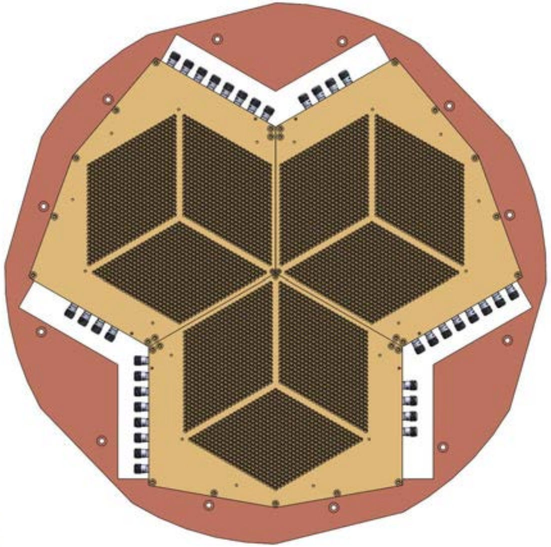


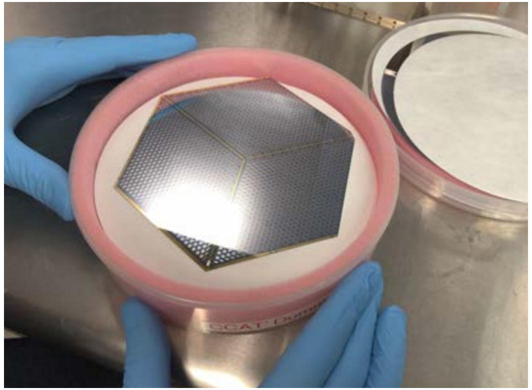
~ 85% optical efficiency
Consistent w/ expectations from simulation

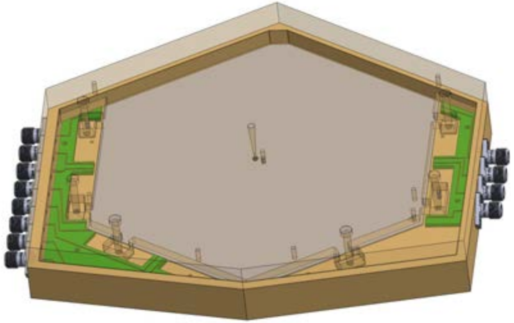
Excited to deliver the best MKIDs yet for CCAT-prime!

First light detector array and readout (Cody Duell)

- First detector array will have ~3500 polarization-sensitive kinetic inductance detectors (KIDs) for observing at 280 GHz (1.1 mm)
- Wafer layout and detector designs complete
  - Received first dummy mechanical wafer!
  - Final arrays are ready for fab pending mechanical tests
- Mechanical designs (array mount + feedhorns) complete; currently being fabricated at ASU (Phil Mauskopf, Chris Groppi et. al.) for mechanical tests and integration this year



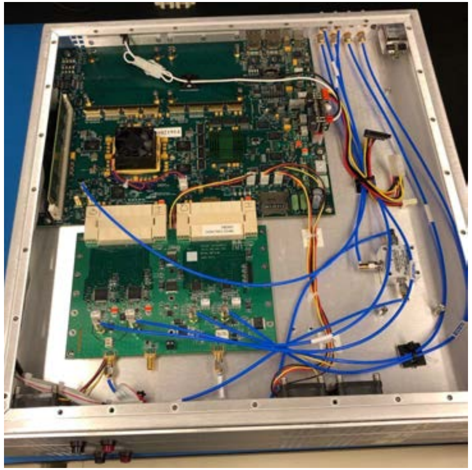


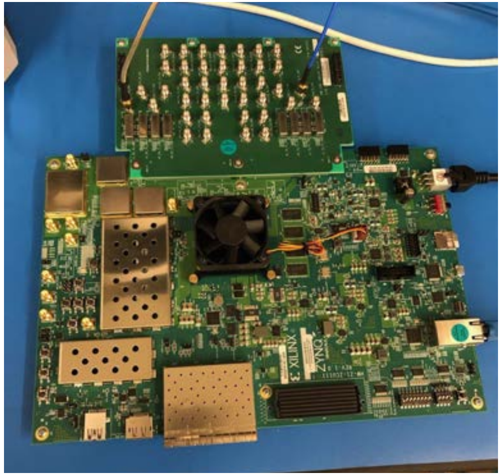


Above: Focal plane layout of a single instr. module with 3 arrays
Right: Mechanical designs of a single array mount
Middle: Mechanical test dummy wafer
Far left: sample spline profile feedhorn cut (design from Sara Simon)

First light detector array and readout (Cody Duell)

- For readout, able to borrow heavily from BLAST-TNG & TolTEC readout using ROACH-2 systems at first light (not feasible for fully-populated Prime-Cam) (arXiv:1611.05400)
  - 500-1000 detectors per ROACH-2 system
- Looking forward: intend to use Xilinx RFSoC-based readout to reduce power consumption and get ~5-10x readout bandwidth
- Biweekly calls for several RFSoC-based readout projects led by Gustavo Cancelo at Fermilab





Above: RF/IF components for interfacing with ROACH-2

Left: ROACH-2 system

Far left: Xilinx RFSoC

First light detector array and readout (Cody Duell)

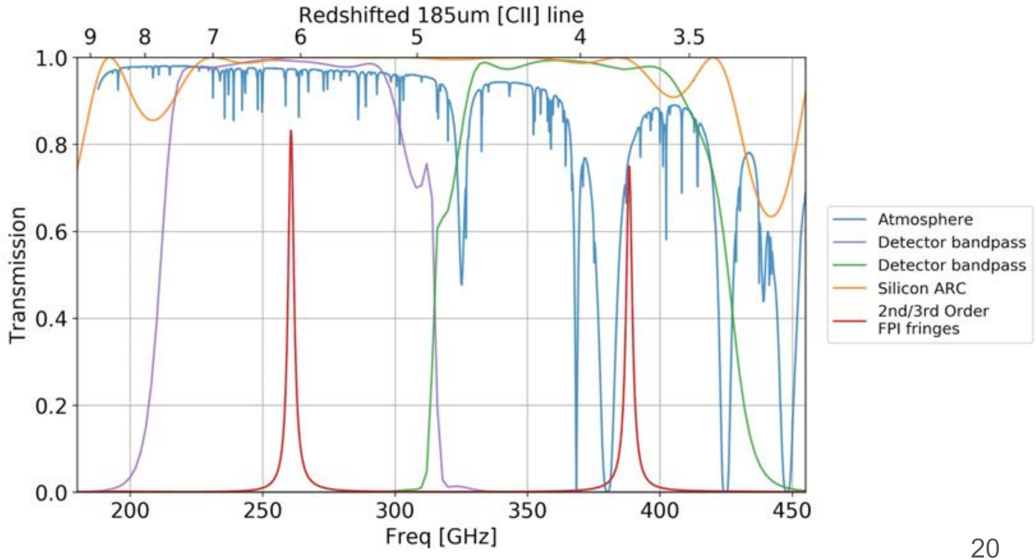
CCAT-prime

The current readout testbed (my guest room)...

EoR-Spectrometer module overview (Nick Cothard)

- [CII] line intensity mapping between redshifts 3.5-8
  - Measure aggregate emission from star forming galaxies, hence process of re-ionization
  - Trace evolution of structure during early galaxy formation
- Much more on EoR LIM tomorrow (Weds at 10am EST)

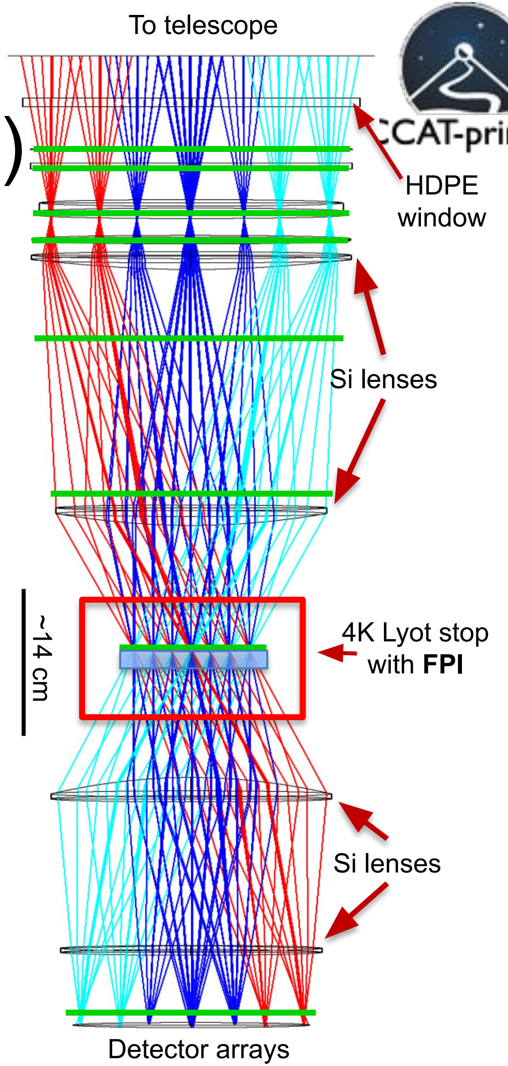
- Scanning Fabry-Perot Interferometer (FPI)
  - Spectral resolution $R \approx 100$
  - 210 - 420 GHz
  - Second and third orders in-band
- Focal plane detector arrays
  - Low and high band KID arrays
  - Spectrally multiplex observations



(Cothard et al. 2019 arXiv:1911.11687)

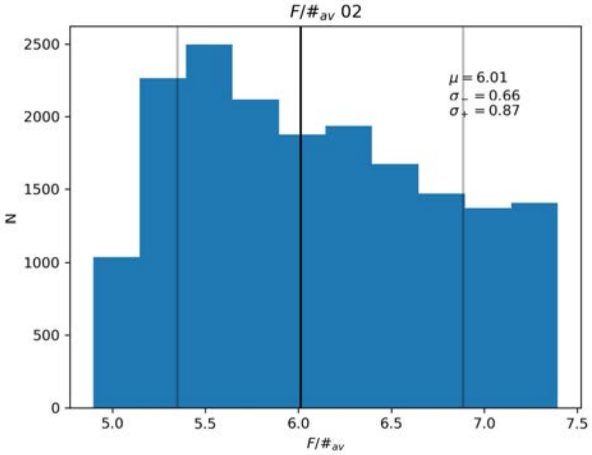
EoR-Spec module design (Nick Cothard)

- Silicon lenses
  - Optimized for well collimated beams at the cryogenic FPI
- Scanning, cryogenic, silicon-substrate FPI
  - ~14 cm silicon substrate mirrors: RP and λ shift
  - Low-loss, high thermal and mechanical performance
  - Metamaterial ARCs and reflective meshes
  - 2nd and 3rd order fringes imaged simultaneously
- Superconducting detector arrays
  - Baseline technology: KIDs
  - Two low-band, one high-band arrays
  - Band-defining filters from Cardiff used on each array

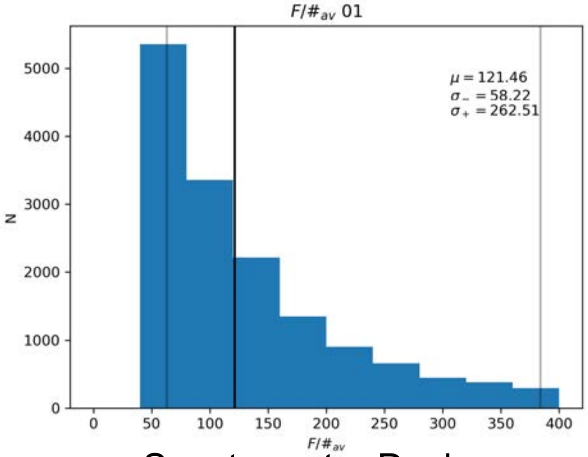


Spectrometer module optics (Zach Huber)

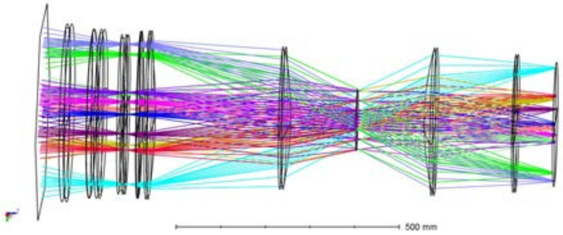
- Broadband Design - highly concentrated F/# at Lyot stop leads to telecentric beam at focal plane
- Spectrometer optics - much higher F/#s indicate highly collimated beam at Lyot stop - this is necessary to achieve resolving powers of > 100



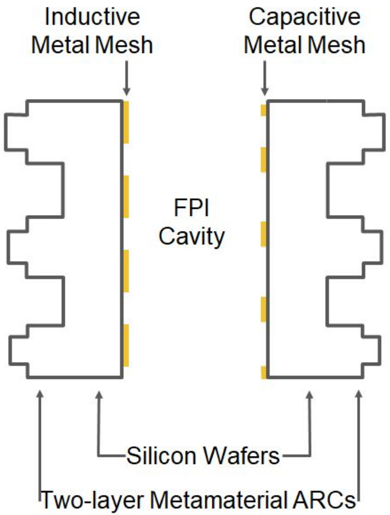
280 GHz Broadband Design
Dicker, et. al. arxiv:1808.05058



Spectrometer Design
Vavagiakis, et. al. arxiv:1807.00058



Prototype FPI etalons (Bugao Zou)



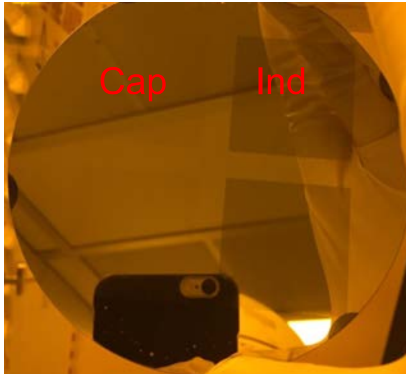
Silicon substrate based mirrors instead of free-standing metal meshes

Metal mesh reflectors

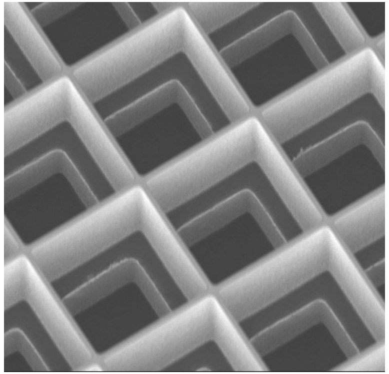
- Evaporation and lift-off lithography techniques
- Combination of inductive and capacitive meshes
- Resolving power ~100 at 2nd and 3rd order

Metamaterial anti-reflective coatings

- Micromachined with deep reactive ion etching
- Mitigate strong Fresnel reflections of silicon
- Multiple layers → wider bandwidth



Metal meshes

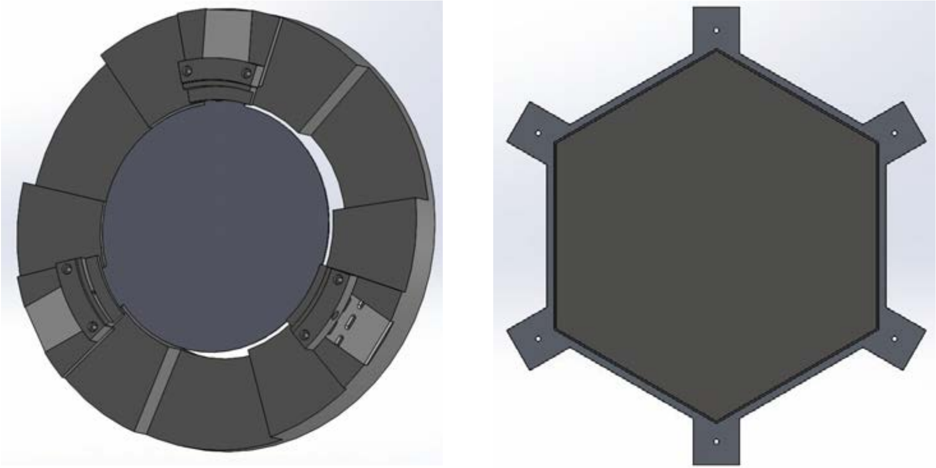


AR Coatings

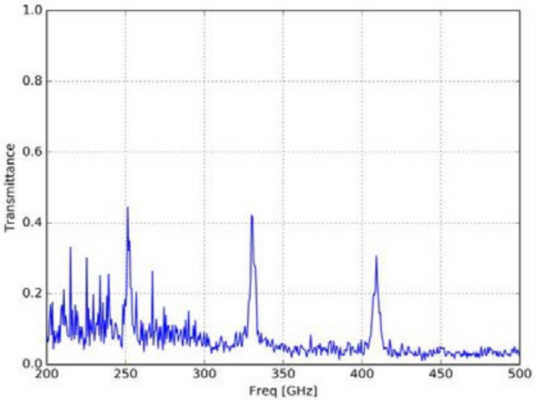
(Cothard et al. 2018 arXiv:1807.06019)
(Gallardo et al. 2016 arXiv:1610.07655)

Prototype FPI etalons (Bugao Zou)

- Fourier Transform Spectrometry (FTS) measurements and FPI mechanicals ongoing
- Capacitive metrology



Different FPI mounting designs

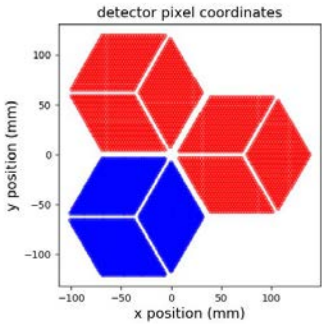


FTS measurements for fixed FPI

FPI optimization for observations (Mahiro Abe)

Three detector arrays assigned to cover 2nd and 3rd order FPI modes (spectral multiplexing)

Off-axis beams blue-shifted from FPI resonant frequency (spatial multiplexing)

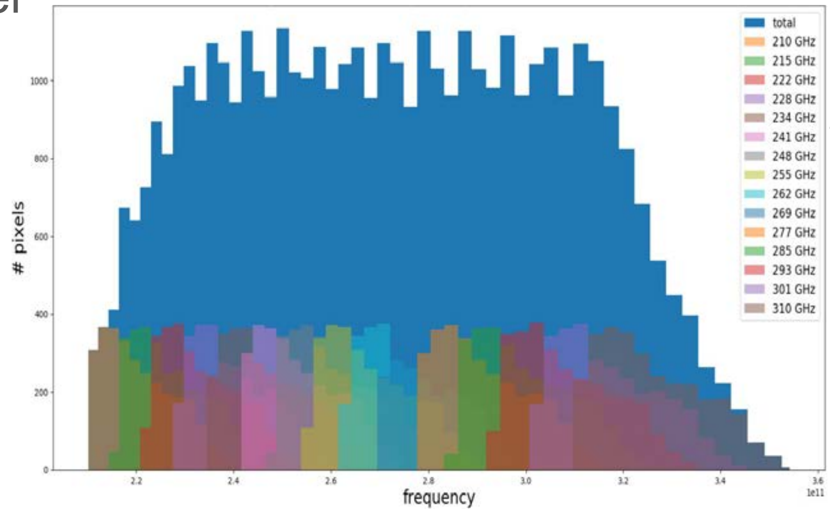


Optimization for uniform sensitivity over 210-420 GHz band

- FPI diameter
- FPI scan steps
- map sensitivity ∝ sqrt(# pixels)

Next optimization steps:

- collimation distortion, beam walk-off, FPI transmission and resolving power
- sky scan strategy



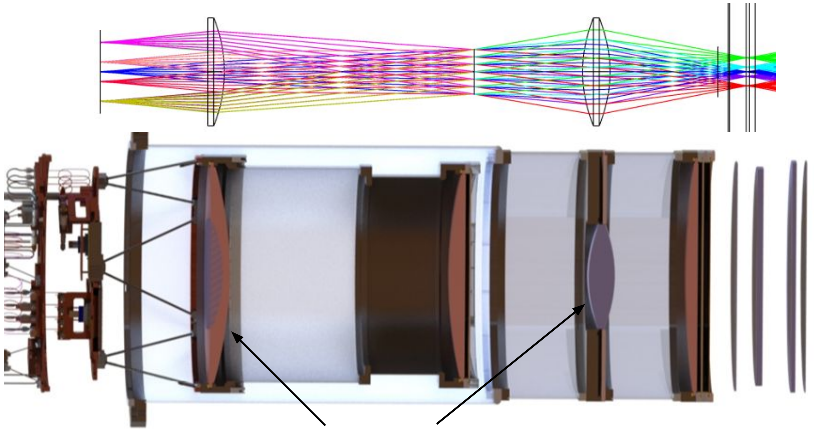
Pixel histogram for the 210-315 GHz band detector (14cm diameter FPI, 15 scanning steps)

350 μm module development (NRC-Herzberg)

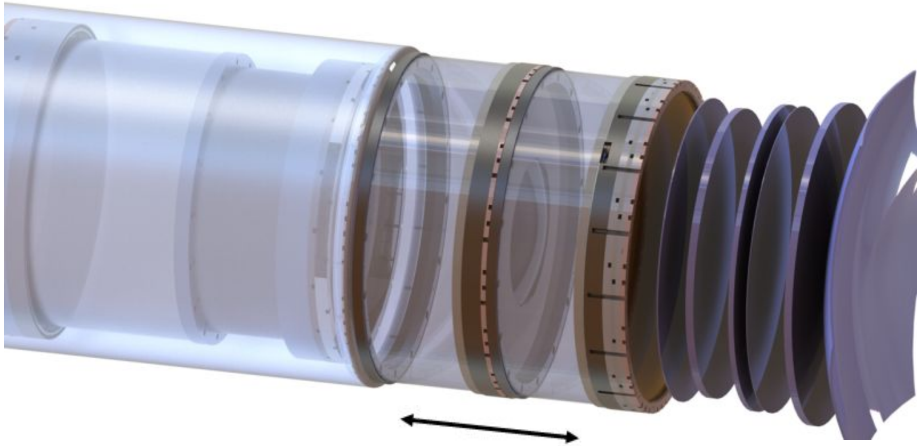
Doug Henke, Doug Johnstone, Lewis Knee (NRC); Colin Ross, Scott Chapman (Dalhousie)

- First-light/Commissioning camera optical study
- Reduced scope to lessen complexity, cost, and build time
- 10 mm thick x 180 mm diameter UHMWPE lenses
- No AR; Re-use existing instrument module design
- Later to be replaced with more powerful science module

- Small FoV ~ 0.25° in diameter
- f/5.556, image size of 140 mm
  - 1.80 F-λ for MKID BLAST-TNG horns (3.5 mm pixels)
  - 0.54 F-λ for TES (MBAC, 1.1 mm^2 pixels)
- NEP ~ 4×10^{-16} W·Hz$^{-1/2}$



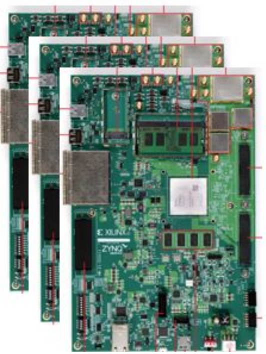
2 lenses inserted within existing module

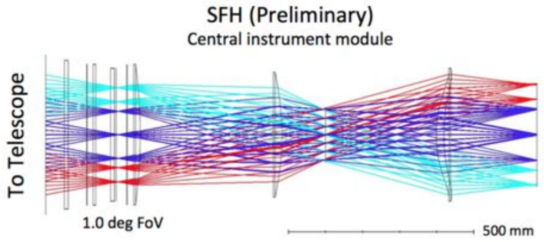


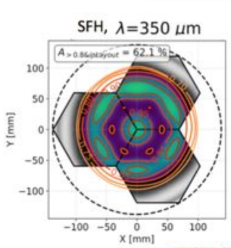
Coupling section for lens

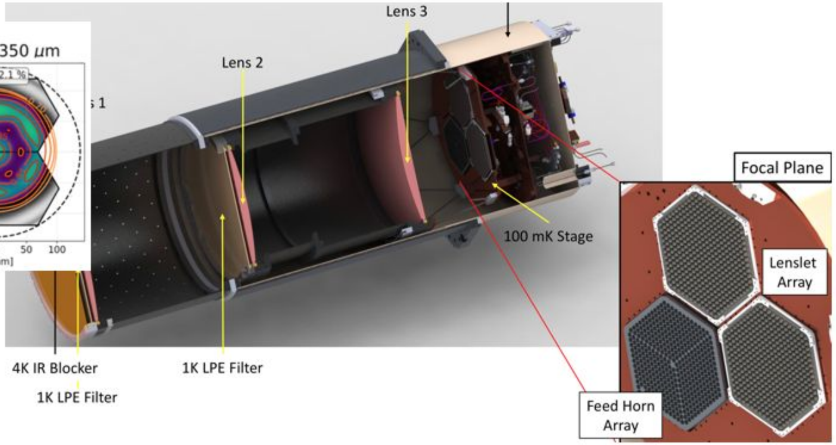
350μm module development (RTI/CFI, Scott Chapman)

- ~$3M (CAD) CFI budget for Prime-Cam-350μm ; UBC experience with sub-K instrumentation and readout development ; project management experience from other big projects (GIRMOS, CHIME): ~2023 integration with Prime-Cam ; *NRC-HAA in-kind contributions are likely possible.*
- Readout development plan; current ROACH2 systems (e.g., BLAST-TNG) 500-1000 detectors readout per coax pair (~512MHz for BLAST-TNG, detectors from 500MHz to 1.12GHz) ; *would require ~30 ROACH2 to readout 18,000 detectors (solution below)*
- Baseline of 3x 15cm KID arrays (total ~18,000 detectors) from NIST ; Similar KIDs with metal feedhorns flown on the BLAST-TNG ; 1deg FoV achieves 1.4 F-λ spacing (Vavagiakis et al. 2018).









Xilinx Zynq UltraScale+ RFSoC ZCU111 system being developed for KID readout ; ***expect to replace 5-10 ROACH2 systems = 1 board / array!***

Next steps for Prime-Cam (Mike Niemack)

CCAT-prime

- Integrate and test Mod-Cam and Prime-Cam at Cornell
- Build first light 280 GHz module
    - Internally funded and proceeding in Cody's house
    - Aim to add 350 GHz array to this module
- Waiting to hear on proposals for:
    - 350 GHz capability
    - Spectrometer modules
    - 850 GHz (350 um) module (Canadian)
- *We welcome input on frequencies/capabilities to prioritize in new proposals*
- **6 more modules to go … would YOU like to help?**