Large Aperture Telescopes Update

Michael Niemack

LAT Working Group regular members: Amy Bender, Brad Benson, John Carlstrom, Eric Chauvin, Simon Dicker, Nick Emerson, Patricio Gallardo, Ian Gullett, Richard Hills, Matt Hollister, Sherese Humphrey, Michele Limon, Jeff McMahon, Don Mitchell, Johanna Nagy, Tyler Natoli, Erik Nichols, Steve Parshley, John Ruhl, Zhilei Xu, Jeff Zivick

CMB-S4 Collaboration Meeting
May 9-13, 2022

Thanks to many other LAT collaborators!

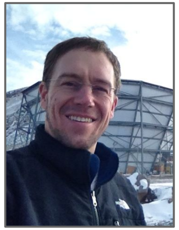
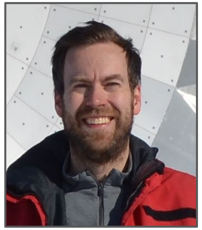
CMB-S4

LAT Team

1.06
LARGE APERTURE TELESCOPES
Mike Niemack (Cornell)
Nick Emerson (U. Arizona)

1.06.01	1.06.02	1.06.03	1.06.04	1.06.05	1.06.06
LAT Management	**South Pole Large Aperture Telescopes**	**Chilean Large Aperture Telescopes**	**Large Aperture Telescope Receivers**	**Large Aperture Telescope Commissioning Receiver**	**Large Aperture Telescope Calibration Hardware**
Nick Emerson (U. Arizona)	Eric Chauvin (U. Chicago)	Mike Niemack (Cornell U.)	Brad Benson (U. Chicago)	Jeff McMahon (U. Chicago)	Johanna Nagy (Washington U. St. Louis)



LAT Regular Contributors:
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Tyler Natoli (Chicago)
Erik Nichols (Chicago)
Steve Parshley (Cornell)
Michael Niemack (Cornell)
John Ruhl (Case Western)
Zhilei Xu (MIT)
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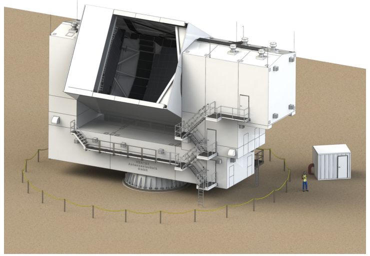
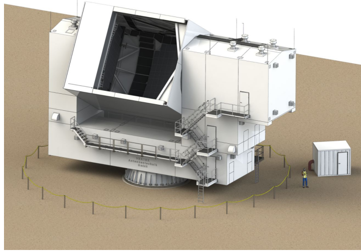
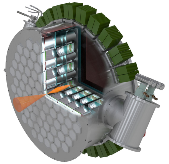
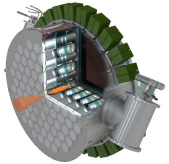
LAT Design Overview - Why 2 Designs?

- Chile - Legacy Survey (> 50% sky)
  - Two 6m aperture telescopes in Chile (CHLAT) to achieve **1.4’ resolution at 150 GHz at required sensitivity**
  - Two receivers to illuminate detectors on those telescopes
  - **Based on mature design for CCAT-prime project and Simons Observatory LATs being built in Chile**

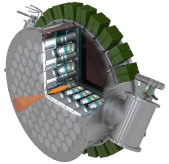


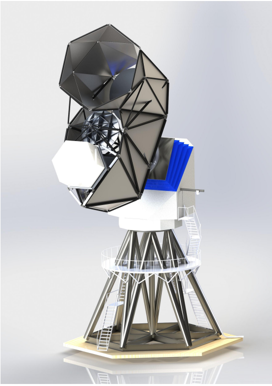






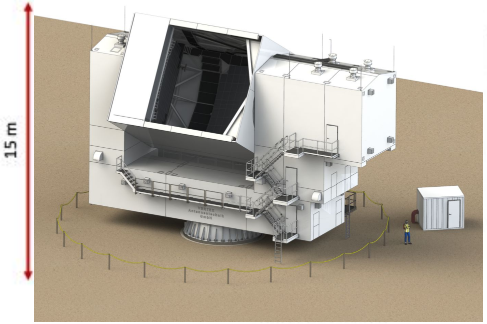
- South Pole - Delensing B-mode Survey (~3% sky)
  - 5m aperture telescope at South Pole (SPLAT or SPTMA) to achieve **1.6’ resolution at 150 GHz**
  - Receiver to illuminate detectors on that telescope
  - **Critical Delensing B-mode Survey features:**
    - **Survey uniformity enabled by TMA optics**
    - **Gapless mirrors to prevent B-mode contamination**
    - **Boresight rotation to verify polarization systematics**

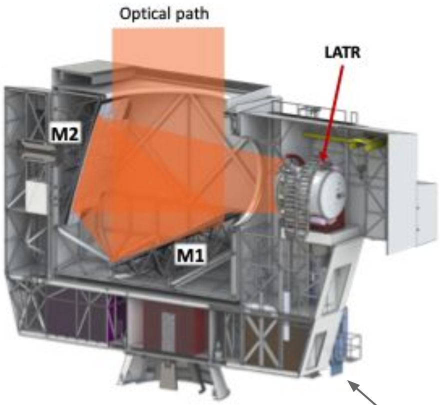




- Commissioning Receivers
- Calibration Hardware

Preliminary Baseline CHLAT Design





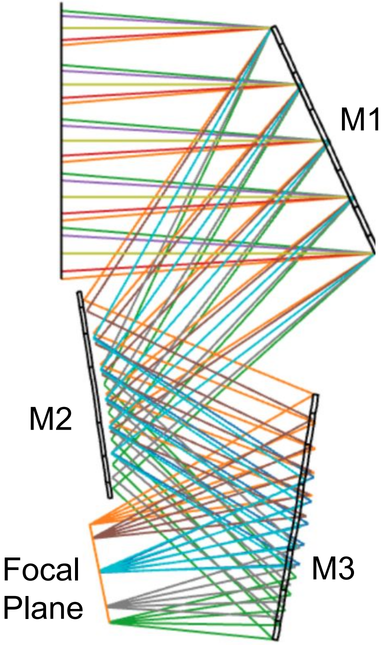
CHLAT Design: CCAT/FYST & SO LAT
6m Crossed Dragone (CD)

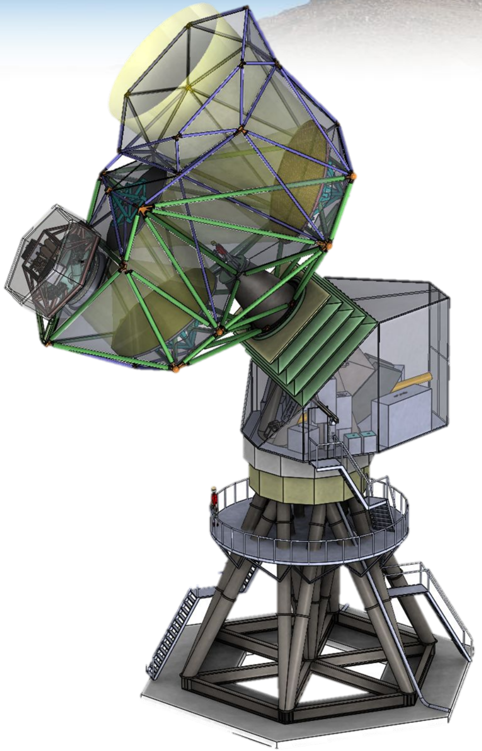
Parshley et al. arXiv:1807.06678
Parshley et al. arXiv:1807.06675
Galitzki et al. arXiv:1808.04493
Gudmundsson et al. arXiv:2009.10138

- Chilean survey depth requires two high throughput telescopes
- Two 6m Crossed Dragone (CD) telescope satisfy requirements
- Lowest cost and risk option is to replicate the CCAT/FYST and SO LAT design, which is currently under construction
- **Baseline: build 2 new CD LATs based on this design**

Preliminary Baseline SPLAT Design

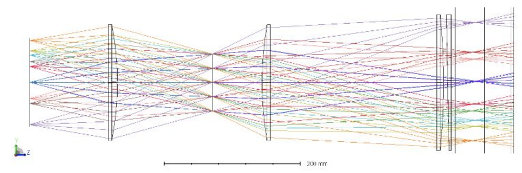
- 5 meter aperture meets requirements for South Pole LAT Survey
- 5 meter aperture with Three Mirror Anastigmat (TMA) design provides sufficient throughput and allows monolithic (gapless) mirrors
- Additional features achieve survey uniformity and mitigate systematics for Level 1 B-mode measurement science goals
  - **TMA design** provides better image quality, which is critical for uniform frequency coverage of smaller field from South Pole
  - **Monolithic mirrors** eliminate panel gap sidelobes to prevent B-mode contamination
  - **Boresight rotation** to mitigate B-mode systematics by rotating polarization (Q ⟷ U)



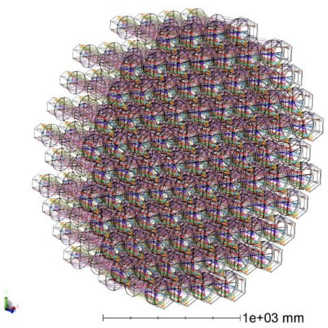


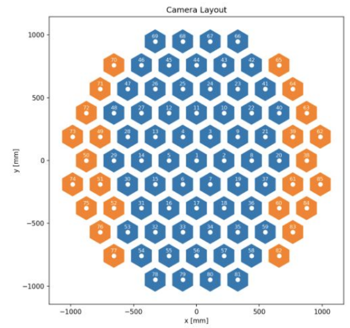
South Pole Design:
5m Three Mirror Anastigmat (TMA)
Padin Applied Optics 2018, 57(9), SPTMA Wiki
Gallardo et al. 2022 in prep.

SPLAT Status and Receiver Optics



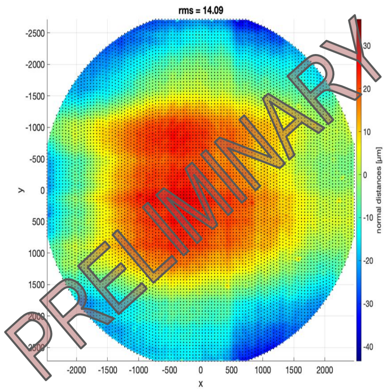
SPLAT and SPLATR optics optimization has nearly converged, and design will soon be published (Gallardo et al. 2022, in prep)

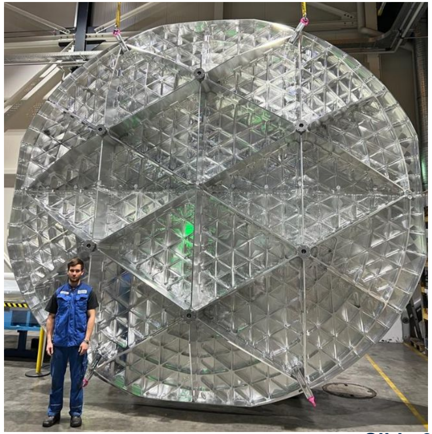




Mechanical design is rapidly maturing, including analyses of deformations (gravitational, thermal, wind)

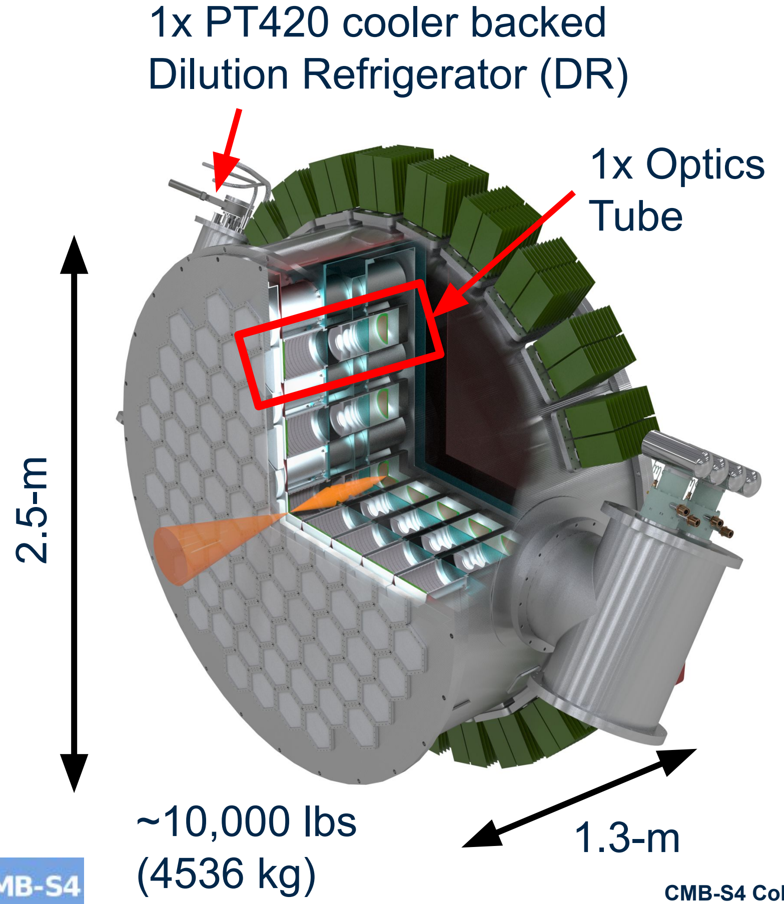
Prototype gapless mirror fabrication of full scale 5m primary mirror is nearly complete!
Ships to Chicago for characterization soon.





SPLAT baffling analyses are converging as well and will also soon be published
(Gullett et al. 2022, in prep)

LAT Receiver (LATR): Preliminary Baseline Design



85 Optics Tube Cryostat Design:

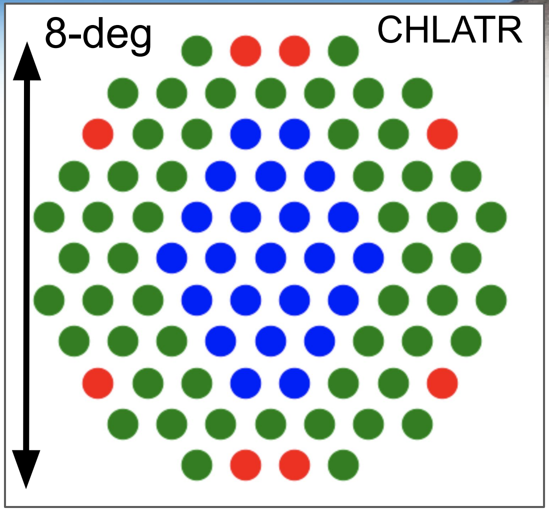
- Each of the 85x optics tubes consist of a 3-lens (18-cm aperture diameter) design that couples to a single (13-cm diameter) detector wafer.
- LATR cryostat design compatible with SPLAT (f/2.5) and CHLAT (f/2.4) telescopes, with some slight modifications:
    - Science goals require slightly different frequency distribution of optics tubes.
    - Different telescope optics designs will require different camera lens designs.
    - Different mounts (hexapod vs. rotator)
    - Note: Similar dimensions to SO-LATR, e.g., S4-LATR is a 0.05-m larger diameter but ~1.0-m shorter.

Example trade study: Survey Uniformity and CD versus TMA optics design

- Survey comparisons
  - South Pole Survey covers ~3% of sky
  - Chilean Survey covers > 50% of sky
- FOVs of both LATs are ~8 deg diameter
- For a small survey uniform frequency distribution across the FOV is critical to achieve full overlap between frequencies
- CHLAT two mirror optics have best image quality in middle, so all high frequency optics tubes must be in middle
- **SPLAT three mirror optics correct astigmatism, such that high frequency tubes can be distributed uniformly across FOV to achieve required survey uniformity**

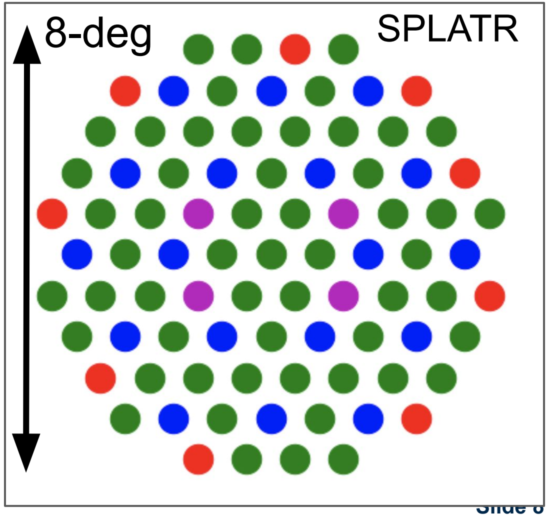
CHLATR Frequency Band Layout by Tube

- 8 LF
- 54 MF
- 23 HF



SPLATR Frequency Band Layout by Tube

- 4 ULF
- 9 LF
- 54 MF
- 18 HF



LAT Commissioning Receivers

Three LAT Commissioning Receivers (LATCRs) will be constructed, and will be used to characterize the following:

1. Telescope performance, beam size, and pointing using point source measurements in all frequency bands
2. On-sky detector performance, including noise and system efficiency
3. Optics tube performance, including the above and excess loading

First LATCR will be shared for the CHLATs, the second will be used for the SPLAT, and the third will be used as a Testing Receiver during US LATR integration

The LATCRs will include a telescope interface flange and dummy mass, to mimic the full LATR weight, for acceptance tests of telescope servo performance.

Left: Preliminary LATCR design

Right: Example CCAT-prime commissioning receiver is similar size and design (<1m diam.)

LAT Calibration Hardware -

See Johanna Nagy's talk during systematics session for more details

Includes both pre-deployment and on-site validation and calibration equipment

Bandpasses: *FTS measurements* required for instrument performance verification and component separation

Beams: Pre-deployment measurements of LATCR and LATR beams with *chopped artificial sources* and on-site as well as measurements of planets/sources with receivers on telescopes and far-sidelobe measurements of the moon and *artificial sources*

Gain: Astronomical sources, artificial sources, and bias steps will be used

Mirrors: *Tower holography* will be used to characterize mirror alignment as well as *photogrammetry and/or laser trackers*

Optical efficiency: Pre-deployment measurements of *LATR beam filling blackbody sources*

Optical time constants: Bias step measurements and possibly a *chopped thermal source*

Pointing: Measurements of astronomical sources and *optical star cameras*

Polarization angle efficiency: Pre-deployment measurements of *chopped polarized sources* and on site measurements of astronomical sources and possibly *artificial sources on a tower or drone*

LAT Opportunities

Baseline is to build two new Chilean LATs

LAT Opportunities

- Reuse Simons Observatory LAT
- Reuse Simons Observatory LATR with Simons Observatory LAT
- Reuse CCAT-prime/FYST
- MOUs to explore these opportunities are in place with Simons Observatory and CCAT-prime

LAT Summary

The preliminary baseline design that meets all requirements is well-developed

The LAT and LATR designs include input from many members of the collaboration with different backgrounds and experience

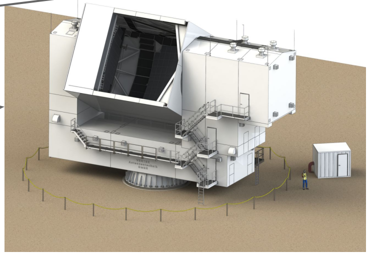
Detailed analyses and trade studies conducted to optimize performance, facilitate production, and meet requirements for CHLAT, SPLAT, and LATRs

Making excellent progress toward readiness for PDR/CD-1

Backup

LAT PBDR Scope

6	**Large Aperture Telescope (LAT) and Receivers**	
6.01	**Large Aperture Telescopes and Receivers Management**	
06.01.01		LAT Management
6.02	**South Pole Large Aperture Telescope (SPLAT)**	
06.02.01		SPLAT Engineering
06.02.02		SPLAT Telescope
6.03	**Chilean Large Aperture Telescopes (CHLAT)**	
06.03.01		CHLAT Engineering
06.03.02		Chile LAT1 Telescope
06.03.03		Chile LAT2 Telescope
6.04	**Large Aperture Telescope Receivers (LATR)**	
06.04.01		LATR Engineering
06.04.02		LATR Test Equipment
06.04.03		South Pole LATR (SP-LATR)
06.04.04		Chile LATR1 (CH-LATR1)
06.04.05		Chile LATR2 (CH-LATR2)
6.05	**Large Aperture Telescope Commissioning Receiver (LAT-CR)**	
06.05.01		LAT-CR Engineering
06.05.02		LAT-CR Fabrication
06.05.02.01		LAT Commissioning Receiver - US (US-CR)
06.05.02.02		LAT Commissioning Receiver South Pole (SPLAT-CR)
06.05.02.03		LAT Commissioning Receiver Chile (CHLAT-CR)
6.06	**Large Aperture Telescope Calibration Hardware (LAT-CALHW)**	



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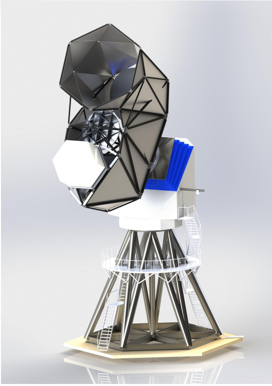

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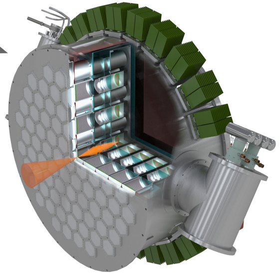


x3

x3

CHLAT Status And Receiver Optics

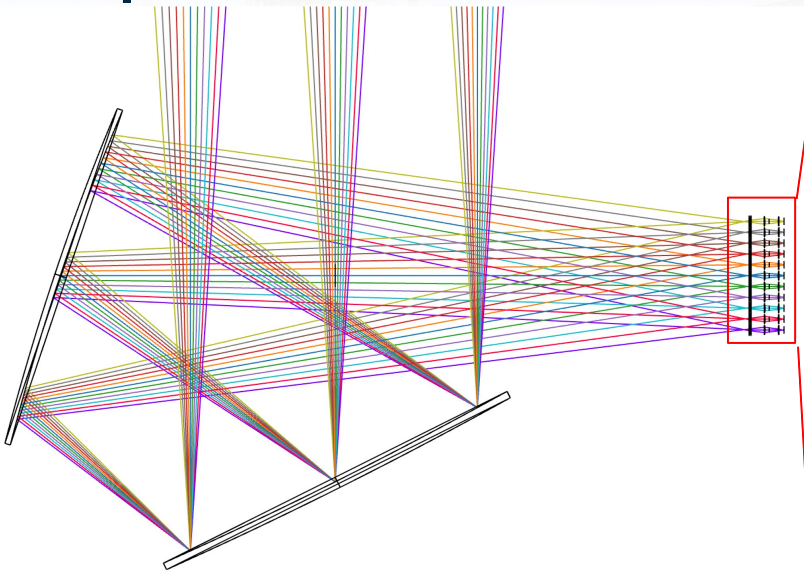
Substantial progress on CCAT/FYST and Simons Observatory LAT fabrication is retiring risk for the CMB-S4 CHLAT design

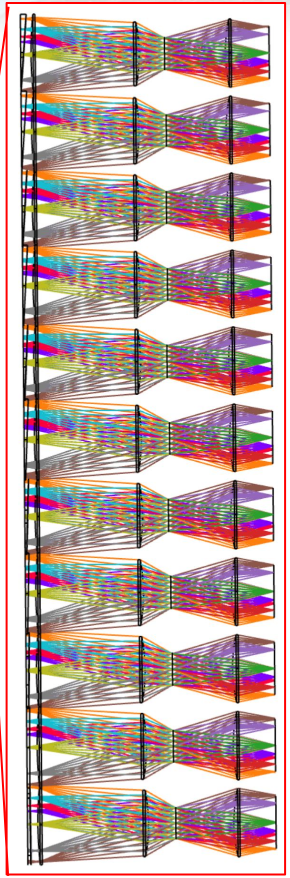
New receiver optical designs and analyses for 85-tube LATR using biconic lenses

Optical systematics studies published by Simons Observatory (Gudmundsson, Gallardo, Puddu, Dicker et al. arXiv:2009.10138)

Ground screen option retired

Same 85-tube LATR design for SPLAT





Tradeoffs between CHLAT and SPLAT designs

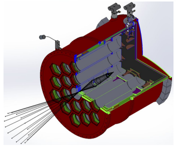
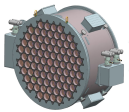
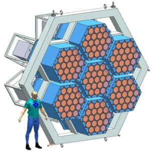
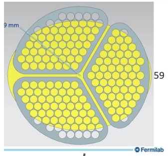
- CHLAT design selection was made after reviewing Simons Observatory selection process that compared: crossed-Dragone, Cassegrain, Gregorian, and three mirror anastigmat designs.
  - Crossed-Dragone design is most compact and lowest cost option to provide a sufficiently large field-of-view to achieve the science goals.
  - Alternative options would require more LATs in Chile and/or greater cost.
  - The CCAT-prime/SOLAT design is lowest risk, since it is already being built.
  - 1.4’ resolution enabled by the 6m aperture is required to achieve the galaxy cluster L1 science goals for the Chilean Survey. (1.6’ resolution from 5m aperture TMA design would not achieve L1 science goals.)

- SPLAT design selection was driven by mitigating systematics (symmetric beams, no panel gap sidelobes, boresight rotations) and South Pole survey strategy efficiency that are critical to achieve L1 science goals.
  - TMA design provides the most symmetric beams (Strehl > 0.95 at 1mm) by a significant margin, because the third mirror corrects astigmatism.
  - Gapless mirrors reduce systematics, and the smaller 5m aperture is needed to enable gapless mirrors.
  - Boresight rotation to rotate Q into U is needed for South Pole survey systematic studies, and engineering of design with boresight rotation is well underway largely funded externally.
  - The combination of symmetric beams, gapless mirrors and boresight rotation enable important systematic checks on *r* measurement.

Summary of LATR trade studies

- LATR alternatives summarized at right

- Selection of 85 tube cryostat was made after careful comparisons with several other designs.
    - Mapping speed of 85 tube cryostat is required for L1 Legacy Survey requirements
    - Lower cost than having multiple cryostats, because one $0.5M dilution refrigerator is needed per cryostat
    - Lower cost than 19 tube cryostat, because only one detector module design is needed (instead of two) at each frequency, which significantly simplifies detector array and module production

Single wafer/tube advantage

Multiple wafers/tube advantage

Optics and Detector wafer quantities for LAT Receiver options for each LAT

Telescope design	CD	CD	TMA	TMA
# cryostats per telescope	1	1	7	3
# tubes per cryostat	19	85	19	53
total # tubes	19	85	133	159
window aperture (cm)	40	18	18	18
detector wafers per tube*	4	1	1	1
total detector wafers	**76**	**85**	**133**	**159**
detector modules per tube*	6	1	1	1
total detector modules	**114**	**85**	**133**	**159**
silicon lenses per tube	3	3	3	3
silicon lens diameter (cm)	40	20	20	20
total # silicon lenses	**57**	**255**	**399**	**477**
window material	UHMWPE	silicon/lens	siicon/lens	siicon/lens
Non-lens windows	19	0	0	0
Filters based on SO/CCAT configuration				
alumina filters per tube	1	1	1	1
IR blocking filters per tube	4	4	4	4
Low pass filters per tube	2	2	2	2
total alumina filters	19	85	133	159
total IR blocking filters	76	340	532	636
total low pass filters	38	170	266	318
mapping speed ratio estimate	**1.00**	**1.24**	**1.10**	**1.30**

* Note that the "4 wafers" in the 19 tube design are based on 3 hex modules plus 3 diamond modules