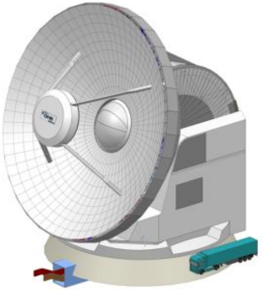
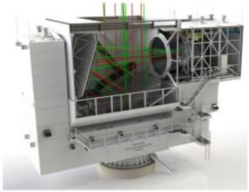
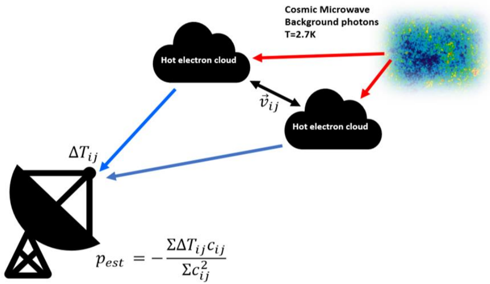


Towards the next generation of large aperture telescopes, and probing the motions of the LSS.

Patricio Gallardo - U. Chicago





Presenter Introduction

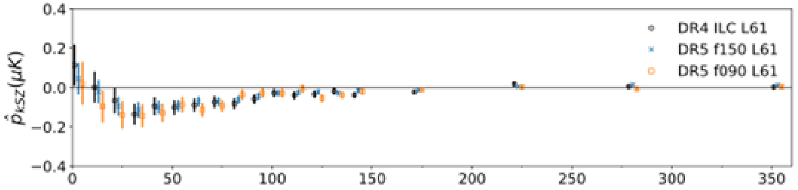
Patricio Gallardo

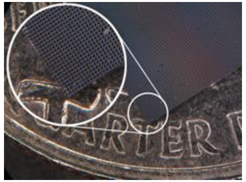
Fellow at Kavli Institute for Cosmological Physics at the University of Chicago

THE UNIVERSITY OF CHICAGO KICP

Previous experience:

- Ph.D. in Physics at Cornell University: https://github.com/patogallardo/Thesis/
- Simons Observatory optical evaluation
  Gallardo, et al. SPIE proc. (2018)
- ACT optical modeling and characterization
  Gallardo et al. SPIE proc, (2018)
- Detector array development arXiv:1912.02902
  Gallardo, Niemack et al. JLTP (2019)
- Data analysis: Detection of the pairwise kSZ effect with ACT
  Calafut, **Gallardo**, Vavagiakis et al Phys. Rev. D (2021)
- Development of an Anti-Reflection coating for THz waves
  Gallardo, Koopman, Cothard, et al App. Opt. (2016)
- Three-mirror Anastigmat development
  Gallardo et al. Appl. Opt. (2024)
- Optics Designs for AtLAST
  Gallardo et al. SPIE proc. (2024)
- Testing Gravity With the kSZ. (in prep.)

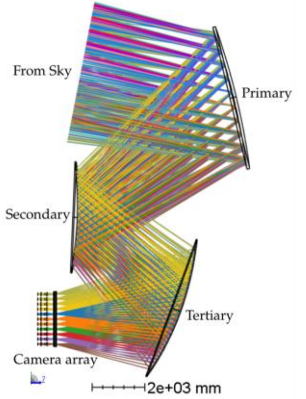





Research Article | Applied Optic

Freeform three-mirror anastigmatic large-aperture telescope and receiver optics for CMB-S4

Patricio A. Gallardo[a], Roberto Puddu[b], Kathleen Harrington[c,d], Bradford Benson
John Carlstrom[a,c,d,f,g], Simon R. Dicker[h], Nick Emerson[i], Jon E. Gudmundsson[j,k], Mic
Limon[h], Jeff McMahon[a,d,e,f,g], Johanna M. Nagy[l], Tyler Natoli[a,d], Michael D. Niemack
Stephen Padin[o], John Ruhl[l], Sara M. Simon[e], and the CMB-S4 collaboration [p]



CMB-S4 Science Goals

Fore more details, see:
CMB-S4 Decadal White Paper
CMB-S4 Science Case, Reference Design, and Project Plan

Goal 1: Test models of inflation by measuring or putting upper limits on r, the ratio of tensor fluctuations to scalar fluctuations.

Goal 2: Determine the role of light relic particles in fundamental physics, and in the structure and evolution of the Universe.

Goal 3: Measure the emergence of galaxy clusters as we know them today. Quantify the formation and evolution of the clusters and the intracluster medium during this crucial period in galaxy formation.

Goal 4: Explore the millimeter-wave transient sky. Measure the rate of mm-transients for the first time. Use the rate of mm-wave GRBs to constrain GRB mechanisms. Provide mm-wave variability and polarization measurements for stars and active galactic nuclei.

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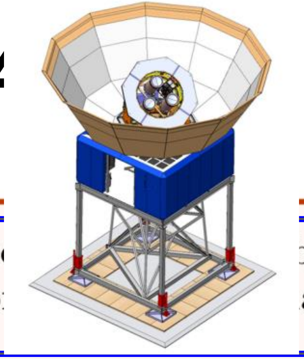
Inflationary science goals

Non-Inflationary science goals

CMB-S4 ce s



Fore more details, see:
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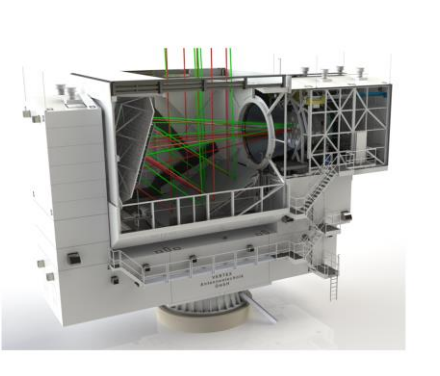
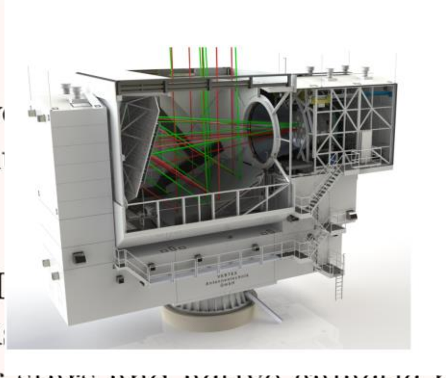
Inflationary science goals

Goal 2: Determine the role of light relic particles in fundamental physics, and in the structure and evol



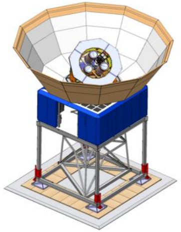


Goal 3: Measure lusters as w ify the formation and ev the intracl crucial period in galaxy f

Goal 4: Explore ient sky. M nsients for the first time. RBs to con rovide mm-wave variabili rements for stars and active galactic nuclei.

Non-Inflationar science goals

Surveys of CMB-S4



The science goals motivate two surveys:

- A deep survey (3% of sky) for the inflationary science goal
  - Small aperture telescopes for B-mode searches
  - Large aperture (5-m class) for delensing
- A wide survey (70%) for the non-inflationary science goals
  - Large aperture telescopes

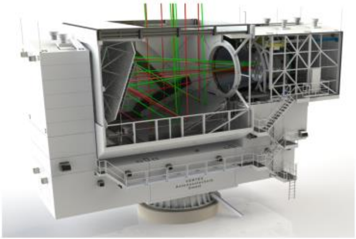
CMB-S4 Science Case, Reference Design, and Project Plan

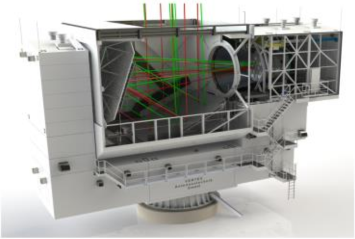
CMB-S4 Collaboration

July 9, 2019

The science goals lead to the following measurement requirements.

- Low-resolution ultra-deep measurements (noise levels $< 1\,\mu$K-arcmin) over an exceptionally low-foreground region covering 3% of the sky are required to meet the primordial gravitational wave goals. These measurements must have high fidelity and low contamination over a wide range of angular scales and frequencies. Large-angular-scale measurements with resolution of around 30 arcminutes and well-determined beam properties and excellent control of systematic contamination are needed to image the B-mode polarization signature of the primordial gravitational waves. Small-angular-scale measurements with resolution of order 1.5 arcminutes are needed for removing the contamination of the degree-scale B modes caused by gravitational lensing of the much stronger CMB E-mode polarization, a process referred to as "delensing."
- High-resolution ($\leq$ 1.5 arcminutes) deep and wide measurements at a noise level of $1\,\mu$K-arcmin over approximately 70% of the sky (60% of the sky after applying a Galactic cut) are required to meet the light relic and legacy data goals.





Large Aperture Telescope concept

These science goals are met with two surveys.

Two surveys -> Two telescopes.

1) Deep-wide survey (2xCD)
    a) Non-inflationary science goals
    b) ~70% of sky, wide patch of sky
    c) High angular resolution (arcmin)
    d) 6m diameter, made of panels
2) Ultra-deep survey (TMA)
    a) Inflationary science
    b) Delensing: removal of contamination of the degree-scale B-modes caused by gravitational lensing.
    c) Small patch, 3% of sky coverage.
    d) Clean beams, gap-less mirrors
    e) Uniform camera coverage across bands
    f) 5m diameter.

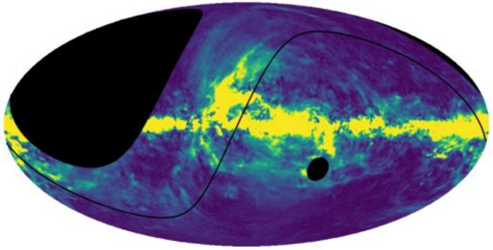
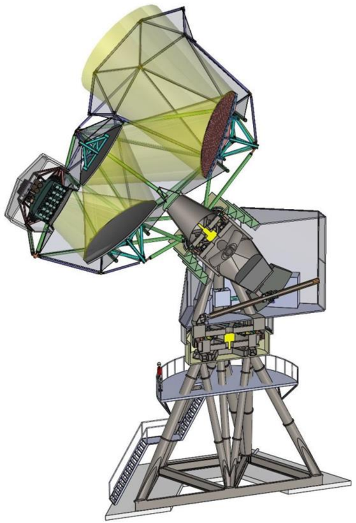
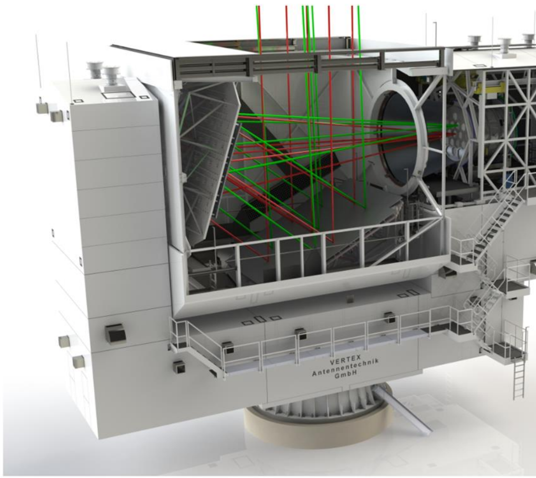


Figure 4. CMB-S4 survey area, in Galactic co





The Crossed Dragone Telescope

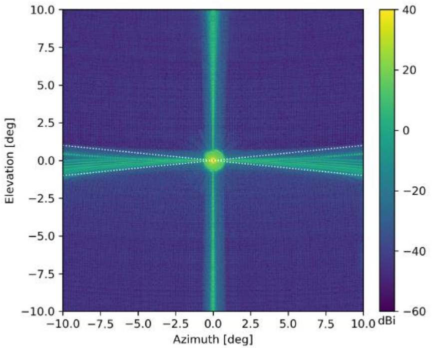
6-meter diameter aperture

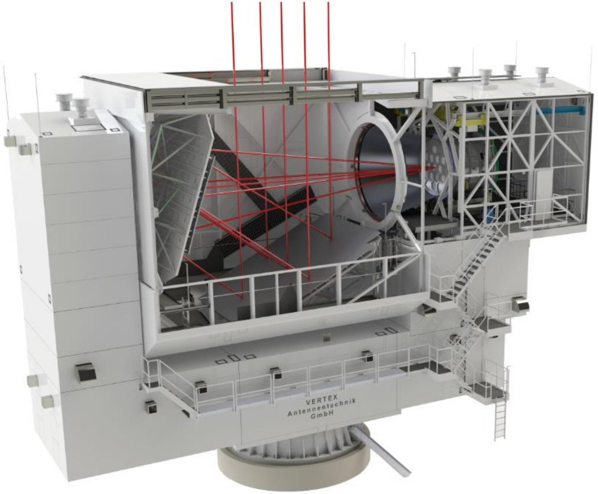
Made of paneled mirrors

Freeform mirrors

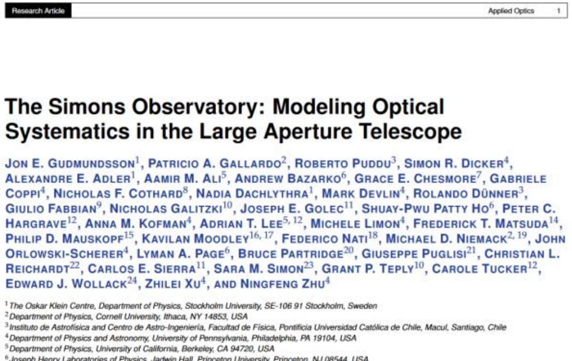
f/2.6

Design in construction for the Simons Observatory LAT and CCAT





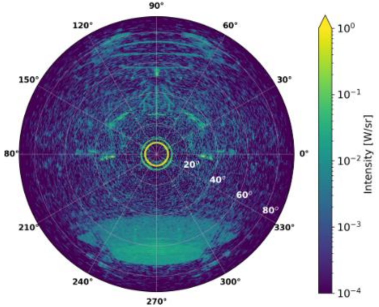
Gumundsson et al. 2020

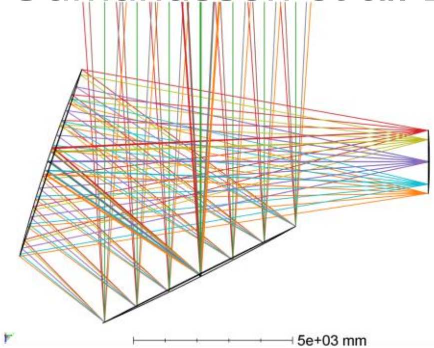

Research Article Applied Optics 1

The Simons Observatory: Modeling Optical Systematics in the Large Aperture Telescope

Jon E. Gudmundsson[1], Patricio A. Gallardo[2], Roberto Puddu[3], Simon R. Dicker[4], Alexandre E. Adler[1], Aamir M. Ali[5], Andrew Bazarko[6], Grace E. Chesmore[7], Gabriele Coppi[4], Nicholas F. Cothard[8], Nadia Dachlythra[1], Mark Devlin[4], Rolando Dünner[3], Giulio Fabbian[9], Nicholas Galitzki[10], Joseph E. Golec[11], Shuay-Pwu Patty Ho[6], Peter C. Hargrave[12], Anna M. Kofman[4], Adrian T. Lee[5, 12], Michele Limon[4], Frederick T. Matsuda[14], Philip D. Mauskopf[15], Kavilan Moodley[16, 17], Federico Nati[18], Michael D. Niemack[2, 19], John Orlowski-Scherer[4], Lyman A. Page[6], Bruce Partridge[20], Giuseppe Puglisi[21], Christian L. Reichardt[22], Carlos E. Sierra[11], Sara M. Simon[23], Grant P. Teply[10], Carole Tucker[12], Edward J. Wollack[24], Zhilei Xu[4], and Ningfeng Zhu[4]

[1] The Oskar Klein Centre, Department of Physics, Stockholm University, SE-106 91 Stockholm, Sweden
[2] Department of Physics, Cornell University, Ithaca, NY 14853, USA
[3] Instituto de Astrofísica and Centro de Astro-Ingeniería, Facultad de Física, Pontificia Universidad Católica de Chile, Macul, Santiago, Chile
[4] Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA
[5] Department of Physics, University of California, Berkeley, CA 94720, USA
[6] Joseph Henry Laboratories of Physics, Jadwin Hall, Princeton University, Princeton, NJ 08544, USA





The Three Mirror Anastigmatic Telescope

Three mirrors to correct for astigmatism, 9 deg fov at 1mm

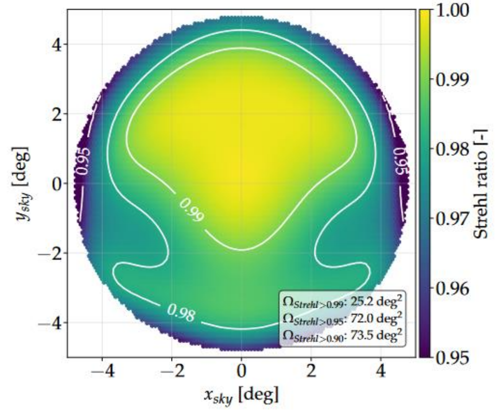
Freeform, polynomially defined mirrors

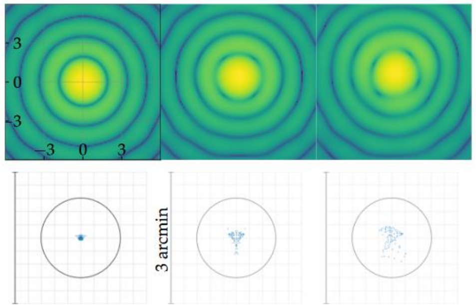
$$z(x,y) = \sum_{i,j}^{i,j \in 0..5} A_{i,j} (x/R)^i (y/R)^j,$$

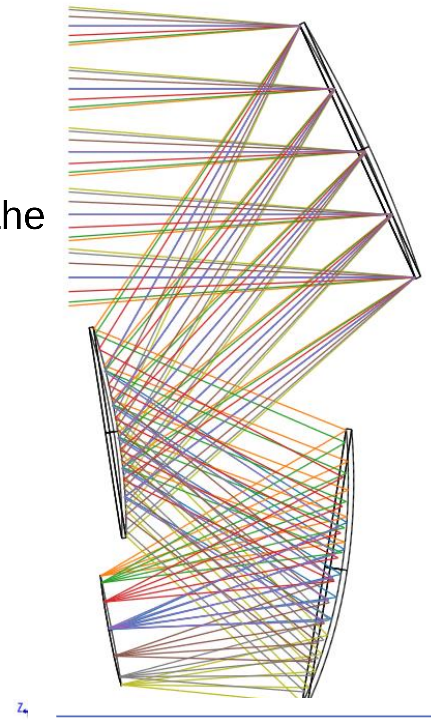
Lower f/# than previous designs (Padin 2018) to match the Crossed Dragone Chile LAT.

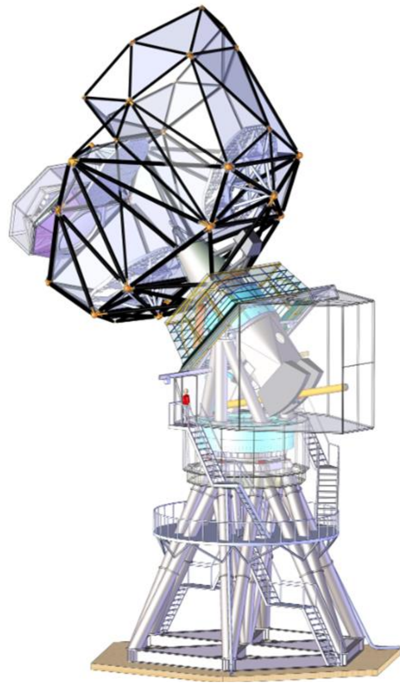
Gap-less mirrors.

Excellent image quality up to 280 GHz, 1.1mm









	$A_{0,1}$	$A_{2,0}$	$A_{0,2}$	$A_{2,1}$	$A_{0,3}$	$A_{4,0}$	$A_{2,2}$	$A_{0,4}$	$A_{4,1}$	$A_{2,3}$	$A_{0,5}$
M1	-4.9656	-140.8171	-116.1019	5.6312	4.1057	0.2358	0.0935	-0.1069	-	-	-
M2	-17.6056	-403.0607	-230.5055	61.6645	25.4229	11.6971	-2.4272	-3.5109	-	-	-
M3	-22.1905	-330.6599	-280.4026	28.1685	17.4860	-2.1208	-10.8356	-5.7779	0.8436	1.9139	0.6830

Telescope performance

Gallardo 2022 SPIE proc.

Crossed Dragone:

- **6m diameter**
- **FoV: 4.5 deg at 1mm, 7.8 deg at 3mm**

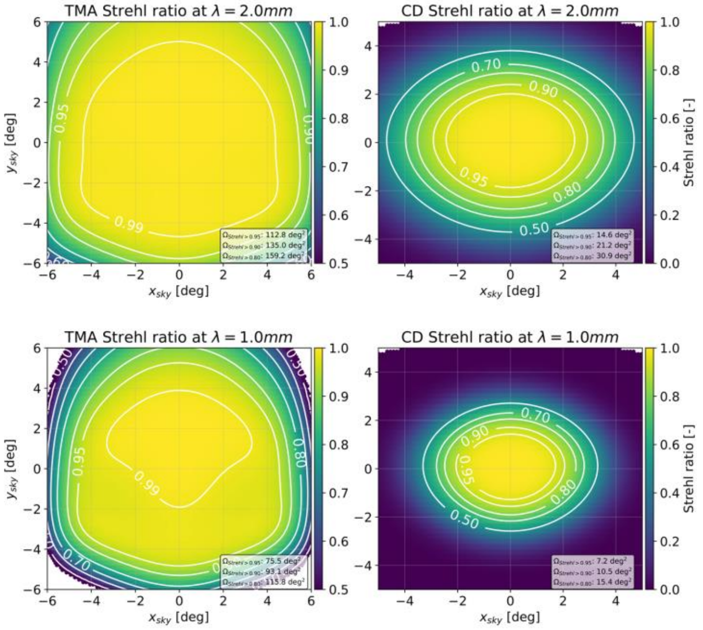
  Parshley et al. Arxiv:1807.06678
- **f/2.6**

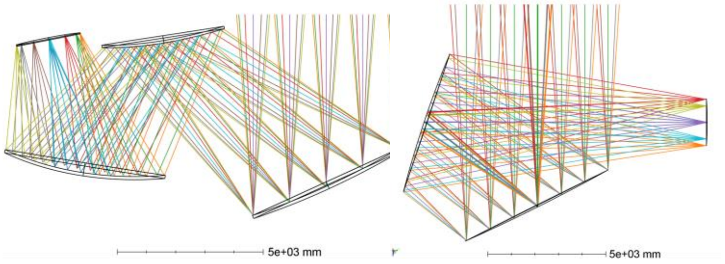
Three Mirror Anastigmat (TMA):

- **5m diameter**
- **FoV: 9.4 deg at 1.1 mm**
- **f/2.6**

$\lambda = 2\,\mathrm{mm}$

$\lambda = 1\,\mathrm{mm}$





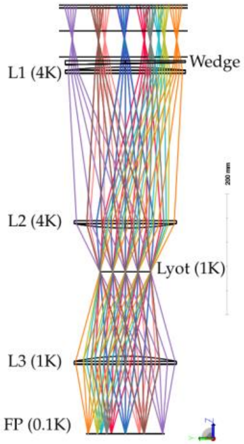
TMA Cameras

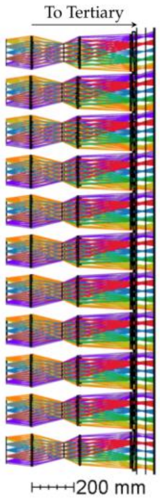
Gallardo 2024 Appl. Opt.

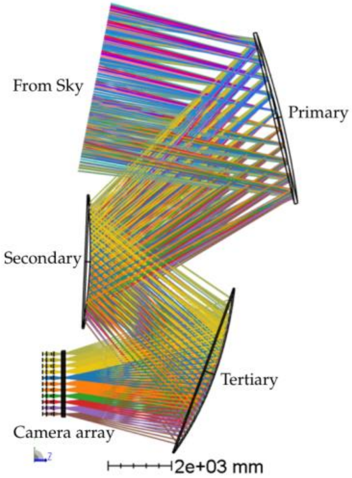
- 3 silicon lenses per camera
  - TMA: standard radially symmetric lenses

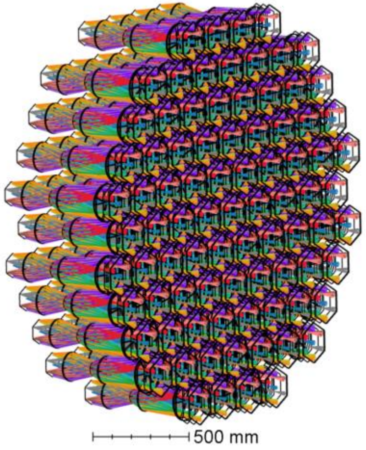
$$z(r) = \frac{(r/R)^2}{1+\sqrt{1-(1+k)(r/R)^2}},$$

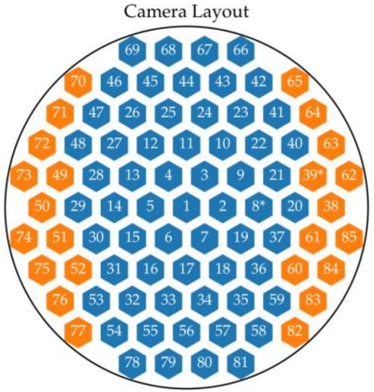
- 85 cameras arranged in a hexagonal pattern
- Lyot stop
- Alumina wedge, to correct telescope field curvature
- Accommodates ~100k detectors
- Performance:
  - 81/85 cameras at 1 mm
  - 85/85 cameras at 2 mm

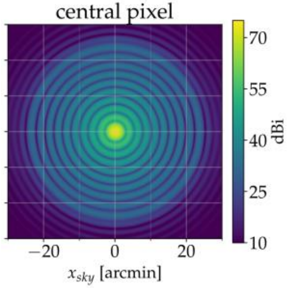


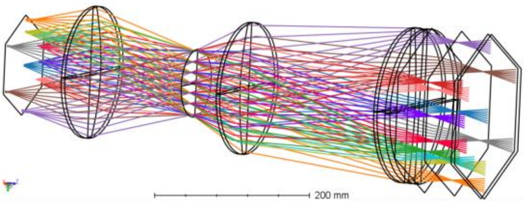












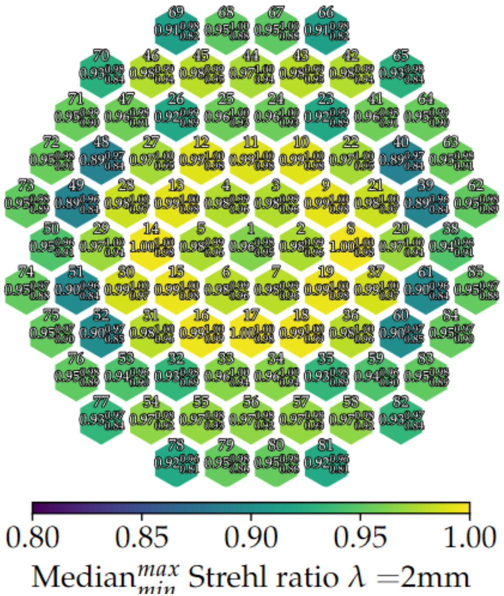
Crossed Dragone Cameras

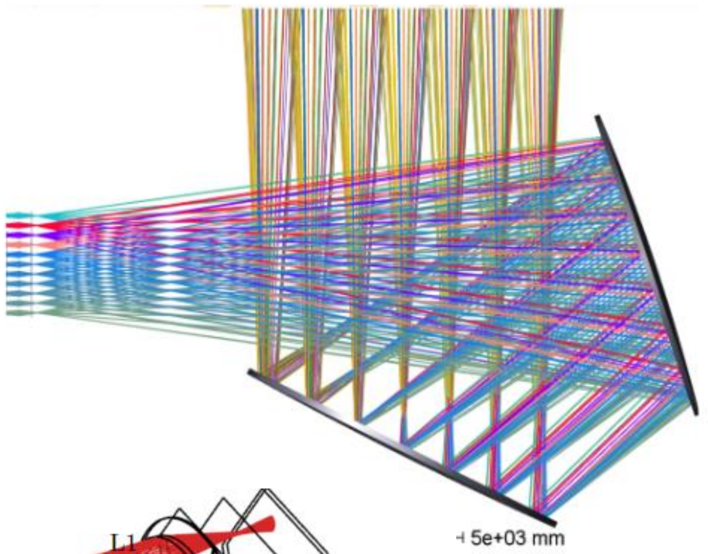
Gallardo 2024 SPIE Proc.

85 cameras

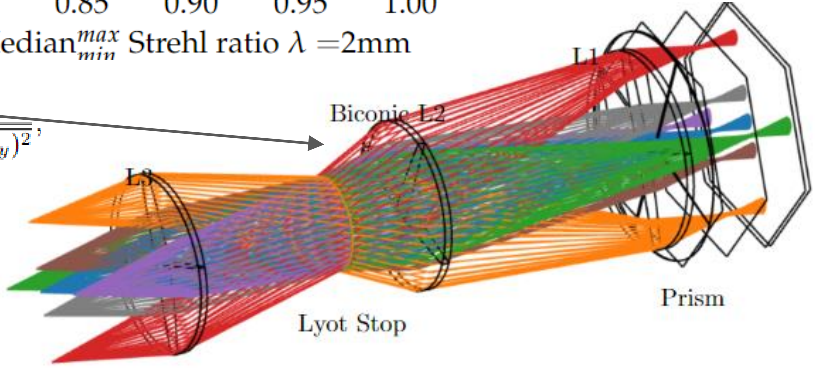
Biconic L2

Good image quality at 2mm



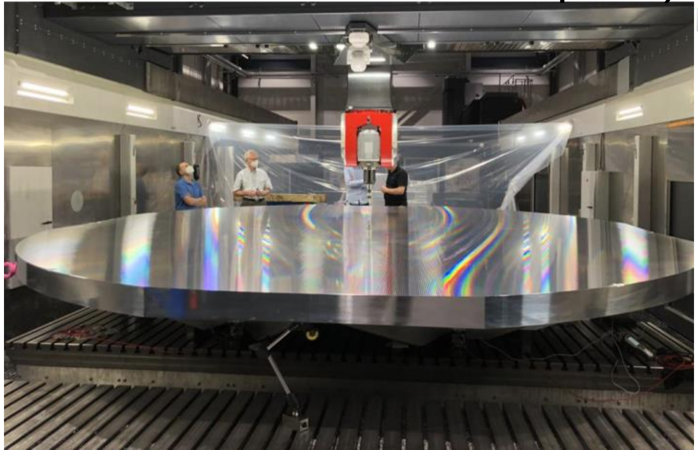


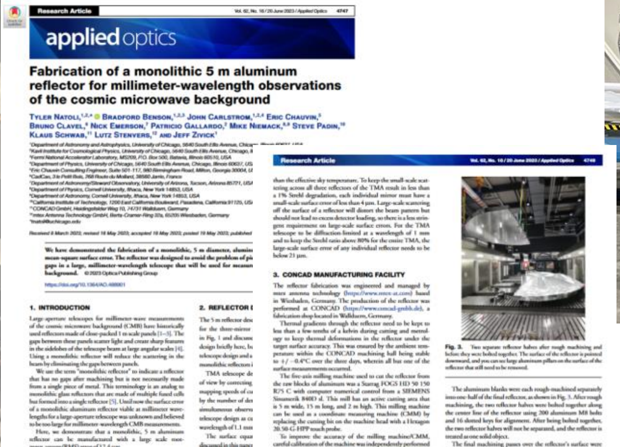
$$z(x,y) = \frac{x^2/R_x + y^2/R_y}{1+\sqrt{1-(1+k_x)(x/R_x)^2-(1+k_y)(y/R_y)^2}},$$



Status

- We have developed optical solutions for the array of cameras for the TMA and CD for CMB-S4
- TMA Primary mirror prototype has been built
- Primary mirror metrology results looks great. Natoli et al. Applied Optics.
- TMA optics: Gallardo 2024 Appl. Opt.
- CHLAT optics designs converging quickly (see Gallardo 2024 SPIE proc.) and working on prototyping




Research Article   Vol. 62, No. 16 / 20 June 2023 / Applied Optics 4747

applied optics

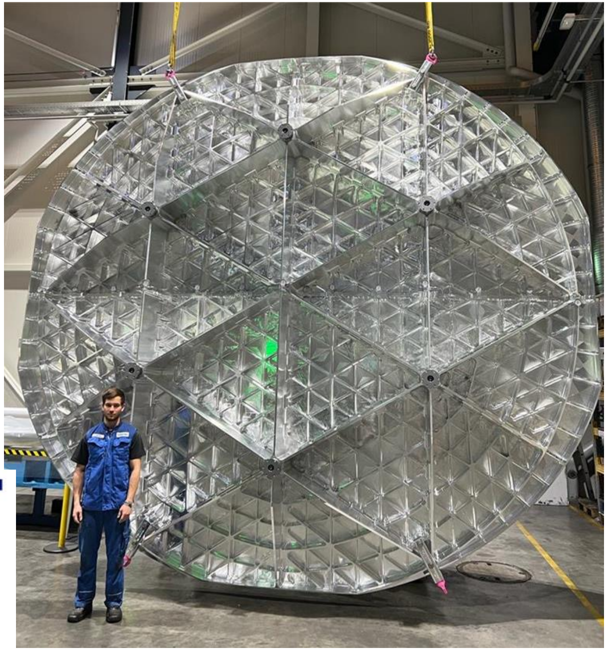
Fabrication of a monolithic 5 m aluminum reflector for millimeter-wavelength observations of the cosmic microwave background

Tyler Natoli, Bradford Benson, John Carlstrom, Eric Chauvin, Bruno Clavel, Nick Emerson, Patricio Gallardo, Mike Niemack, Steve Padin, Klaus Schwab, Lutz Stenvers, and Jeff Zivick

1. INTRODUCTION

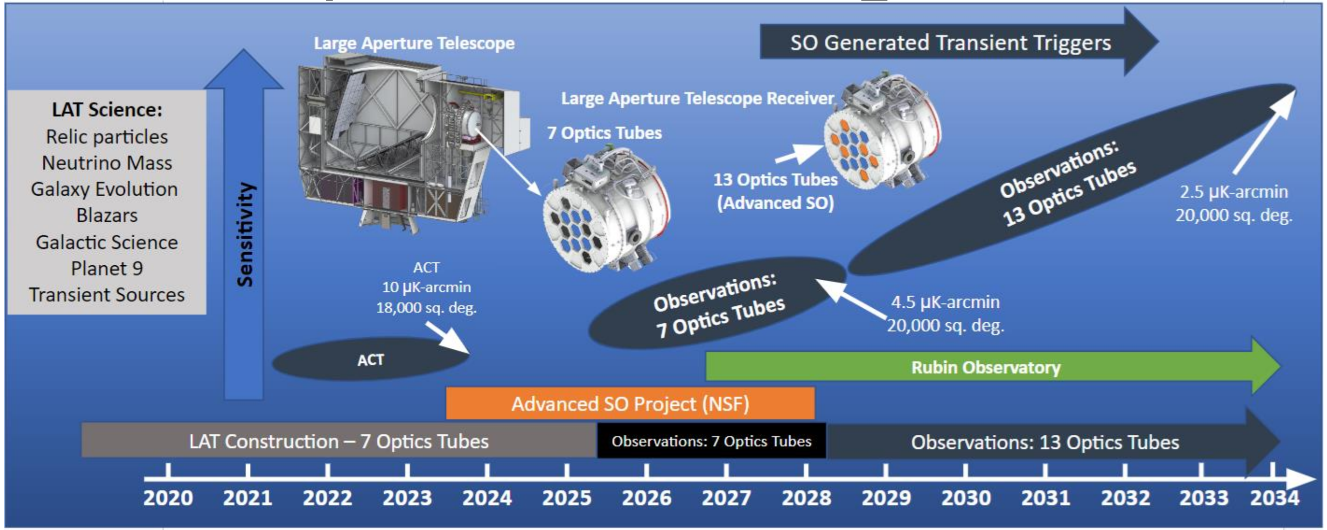
2. REFLECTOR

3. CONCAD MANUFACTURING FACILITY



Life outside S4

ASO: 13 optics tubes using biconics (see KH's talk yesterday)



60,000 detectors into the LATR

2.5 uK-arcmin over 20,000 sq. deg. in 2034

White paper with forecasts is currently in internal review.

SO Nominal: LAT map noise

Frequency (GHz)	FWHM (arcmin)	Baseline (μK-arcmin)	Goal (μK-arcmin)	Frequency Bands	Detector Number	Optics Tubes
27	7.4	71	52	LF	222	1
39	5.1	36	27		222	
93	2.2	8.0	5.8	MF	10,320	4
145	1.4	10	6.3		10,320	
225	1.0	22	15	UHF	5,160	2
280	0.9	54	37		5,160	

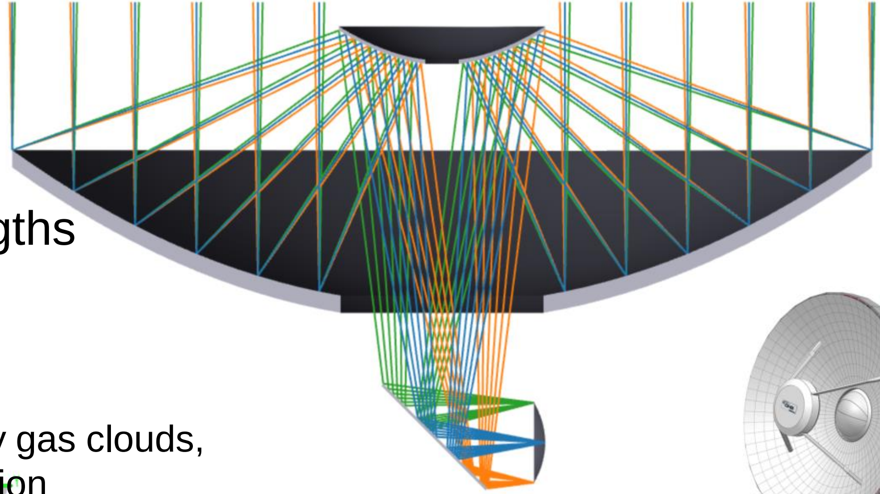
ASO: LAT map noise

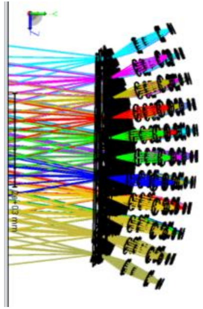
Baseline (μK-arcmin)	Goal (μK-arcmin)	Frequency Bands	Detector Number	Optics Tubes
58	39	LF	222	1
30	20		222	
5.25	3.5	MF	20,640	8
5.7	3.8		20,640	
14	9	UHF	10,320	4
33	22		10.320	

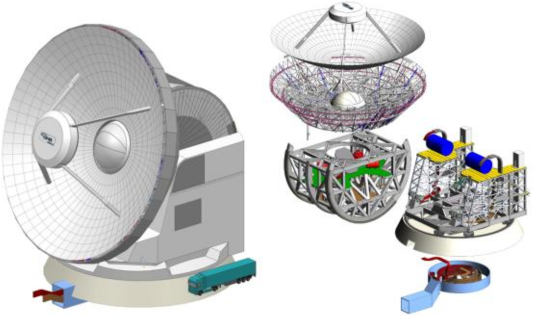
AtLAST

Design study

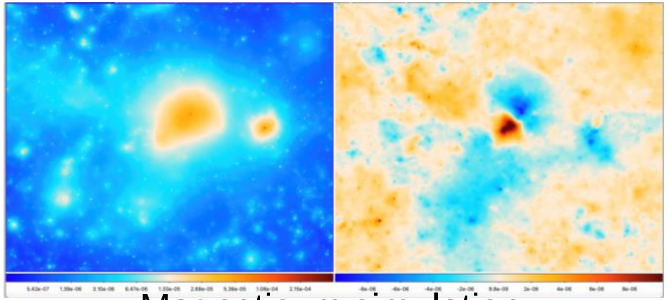
- 50-meter telescope
- Mm-submm wavelengths
- 2-degree field of view
- Science:
  - ■Solar physics
  - ■Survey our galaxy to study gas clouds, dust, star and planet formation
  - ■Survey galaxies at high redshift
  - ■Study nearby galaxies
  - ■SZ effect down to galaxy scales



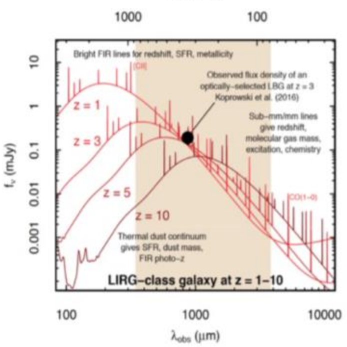


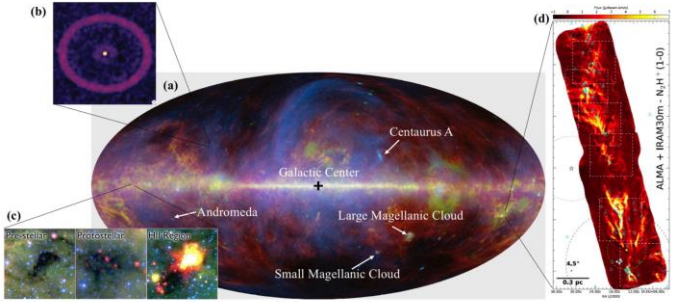


Design: AtLAST Mroczkowski et al. ArXiv:2402.18645
Optics: Gallardo et al. ArXiv:2406.11502



Magneticum simulation





The Pairwise kSZ

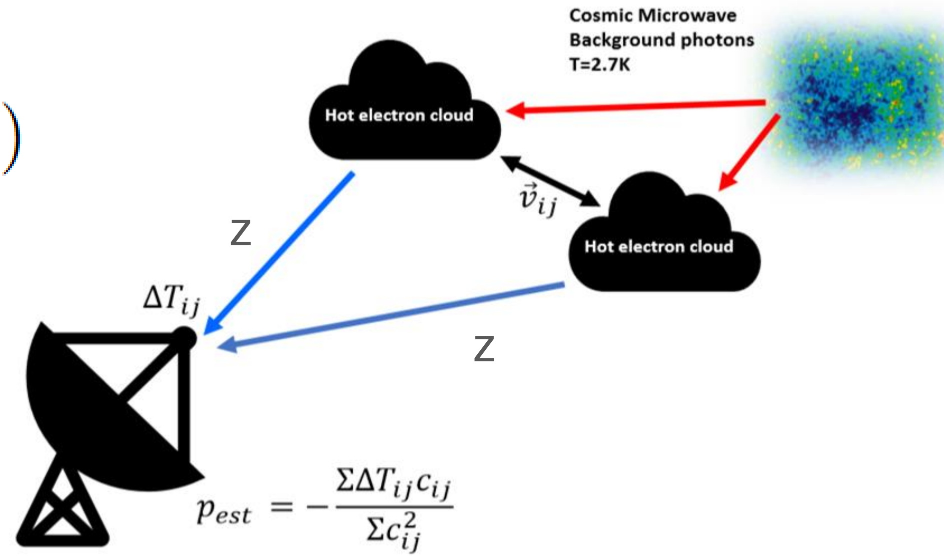
The kSZ is a distortion due to the doppler shifted SZ effect.

$$\hat{p}(r,z) = -\frac{T_{\text{CMB}}}{c}\bar{\tau}V(r,z)$$

The kSZ can be extracted from the data if one knows the 3D positions of galaxy clusters, or a tracer of it.

$$\tilde{p}_{\text{pair}}(r) = \frac{\sum_{i<j}(\mathbf{p}_i \cdot \hat{\mathbf{r}}_i - \mathbf{p}_j \cdot \hat{\mathbf{r}}_j)c_{ij}}{\sum_{i<j} c_{ij}^2}$$

$$c_{ij} \equiv \hat{\mathbf{r}}_{ij} \cdot \frac{\hat{\mathbf{r}}_i + \hat{\mathbf{r}}_j}{2} = \frac{(r_i - r_j)(1+\cos\theta)}{2\sqrt{r_i^2 + r_j^2 - 2r_i r_j \cos\theta}},$$



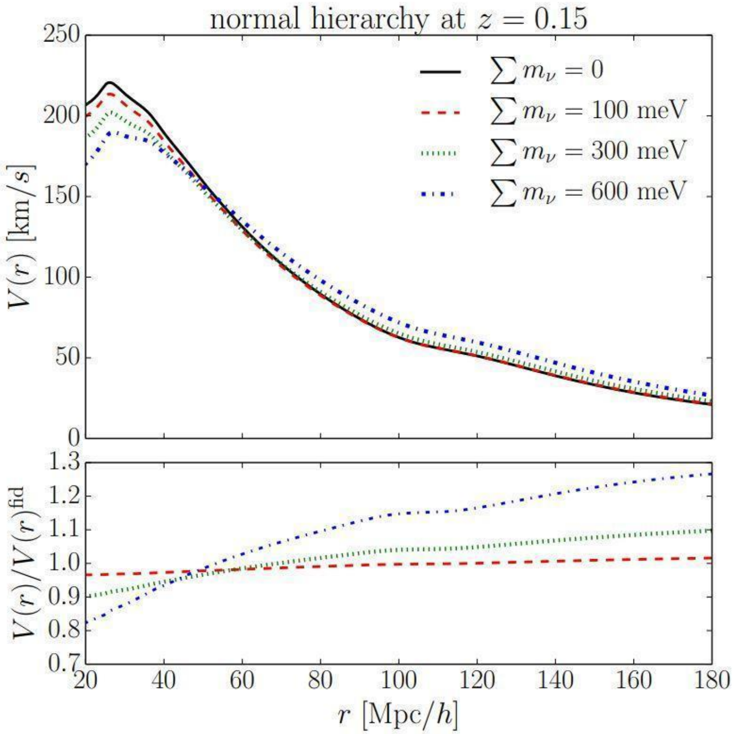
The Pairwise kSZ

In linear theory, the pairwise kSZ is proportional to a moment of the correlation function. It is sensitive to changes in the clumping of matter.

$$V(r,z) = -\frac{2}{3}\frac{f(z)H(z)r}{1+z}\frac{\bar{\xi}_h(r,z)}{1+\xi_h(r,z)}$$

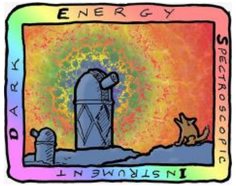
It can be used to constrain:

- The sum of the neutrino mass
- σ_8
- The growth factor f
- Dark energy
- Gravity
- The baryon content

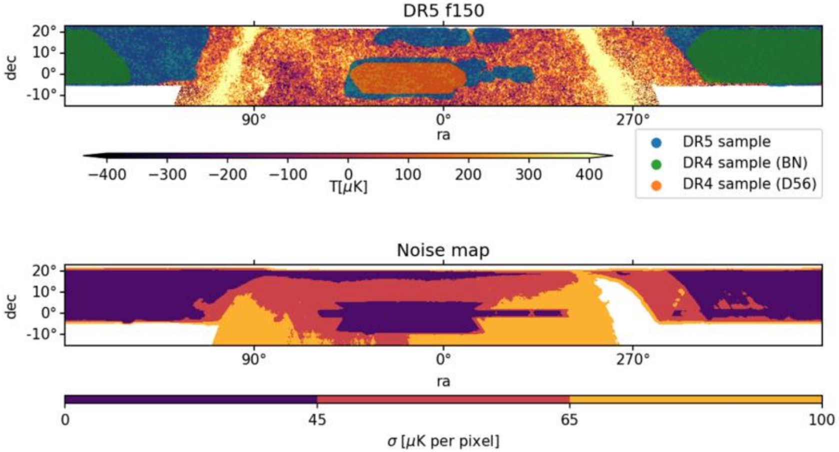


E. M. Mueller, F. de Bernardis, R. Bean, M. D. Niemack (2014), 1412.0592

The Pairwise kSZ



- Single frequency and component separated CMB maps + galaxy group and cluster catalogs (i.e. DESI, SDSS)
- Code evolving from ACTxSDSS projects; ACTxDESI



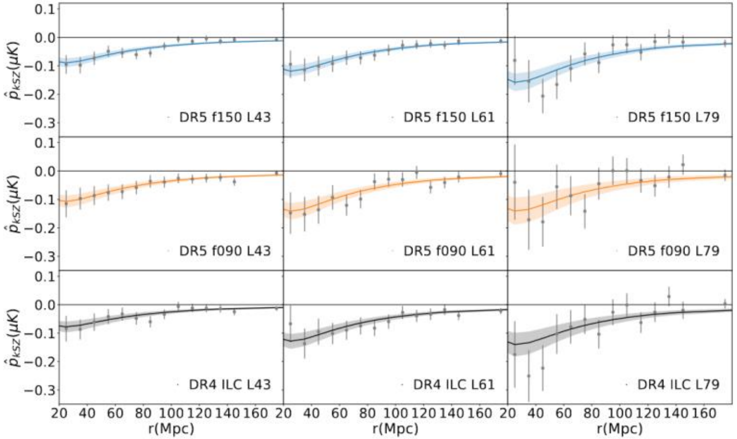
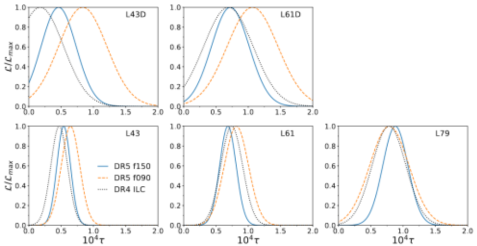
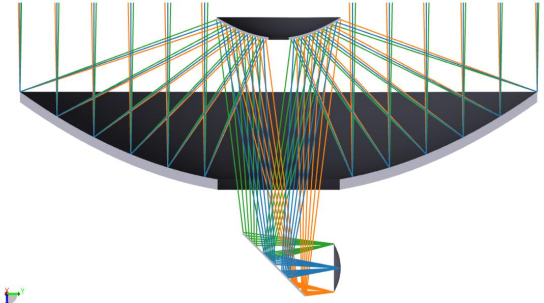


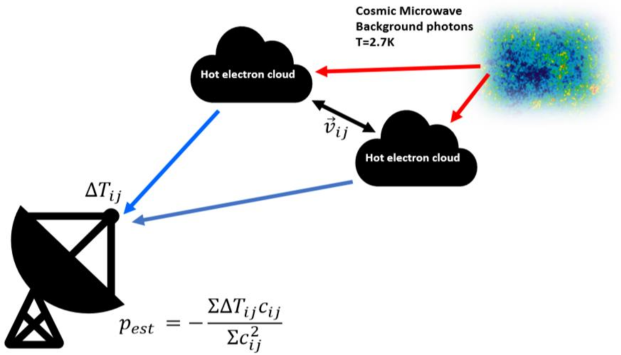
FIG. 4: The extracted pairwise signal for the DR4 ILC [black, lower] and DR5 f090 [orange, middle] and DR5 f150 [blue, upper] maps for the three cumulative luminosity-selected galaxy tracer samples, $L43$ [left], $L61$ [center], $L79$ [right], overlaid with the theoretical pairwise velocity model using the *Planck* best-fit cosmology corresponding to the best-fit $\bar{\tau}$ value and 1σ boostrap-derived uncertainties.

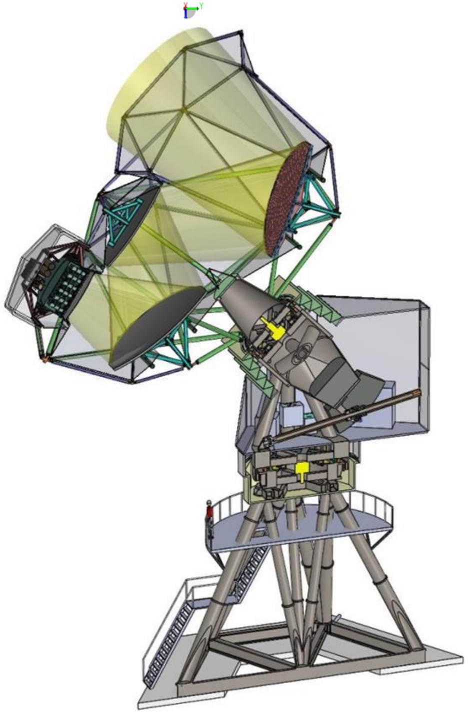


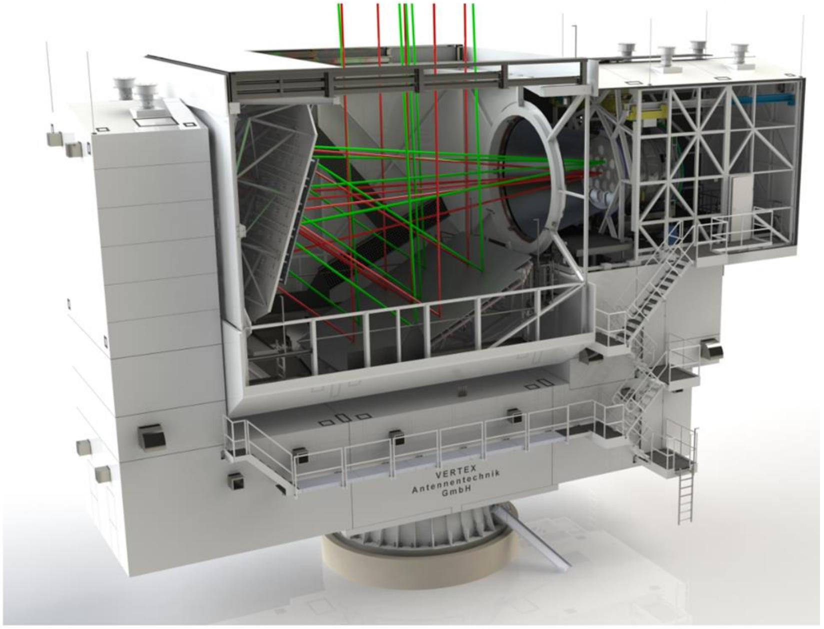
Calafut, **Gallardo**, Vavagiakis et al 2021.

Thanks!




Cosmic Microwave Background photons T=2.7K
Hot electron cloud
$\vec{v}_{ij}$
Hot electron cloud
ΔT_{ij}
$p_{est} = -\frac{\Sigma \Delta T_{ij} c_{ij}}{\Sigma c_{ij}^2}$




VERTEX
Antennentechnik
GmbH

Backup

Camera distribution

Two kinds of cameras for the 85 tubes

Frequency distributions according to optical performance:

CD: best image quality at the center

TMA: uniformly good image quality