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What's next for the 50-m Atacama Large Aperture Submm Telescope?

Tony Mroczkowski

(European Southern Observatory → CSIC Institute of Space Sciences)

mm Universe 2025, 2025-06-27

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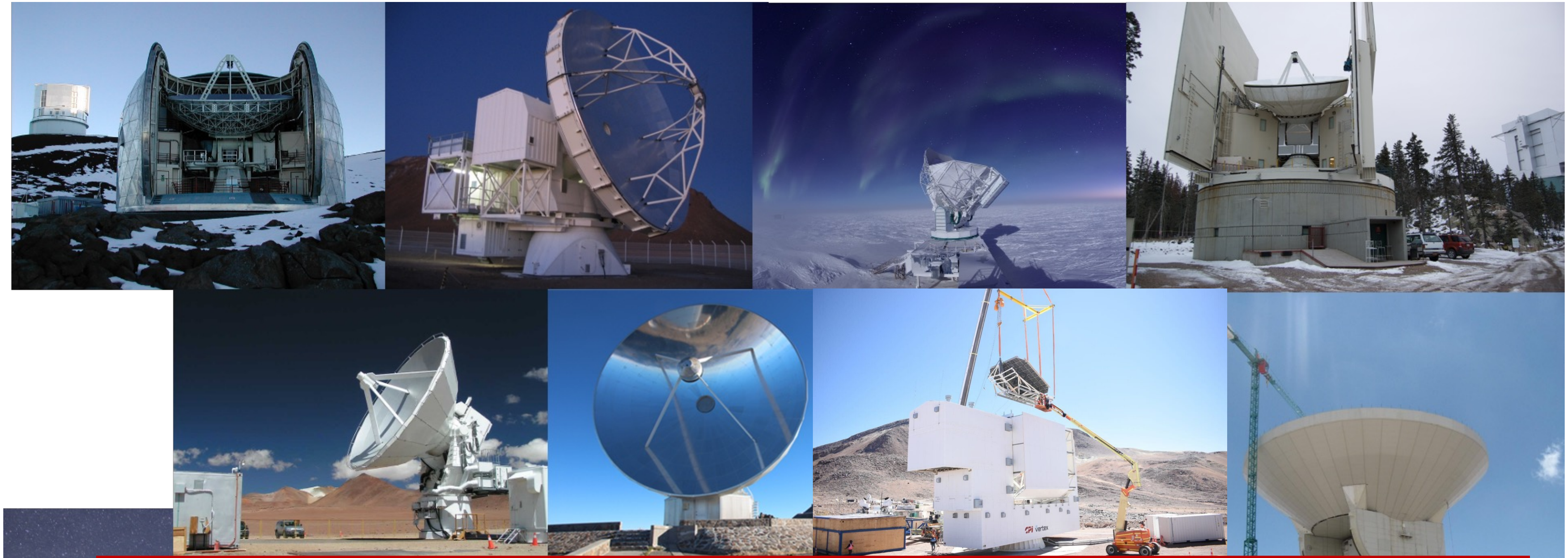
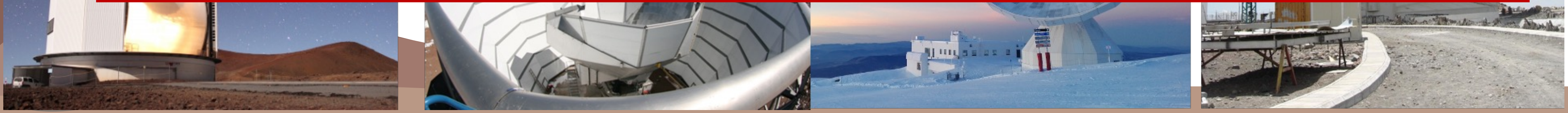
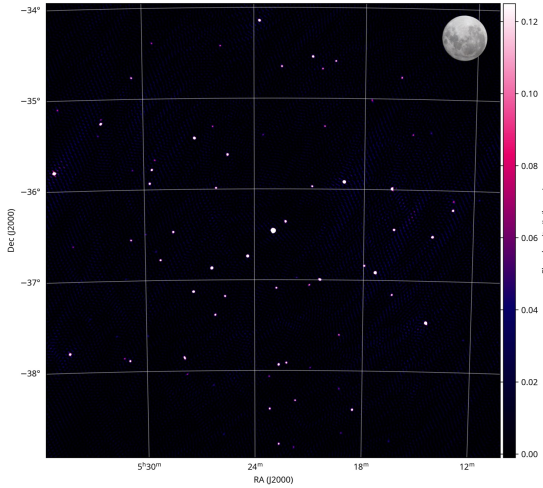
The landscape of current (sub-)mm single dish telescopes



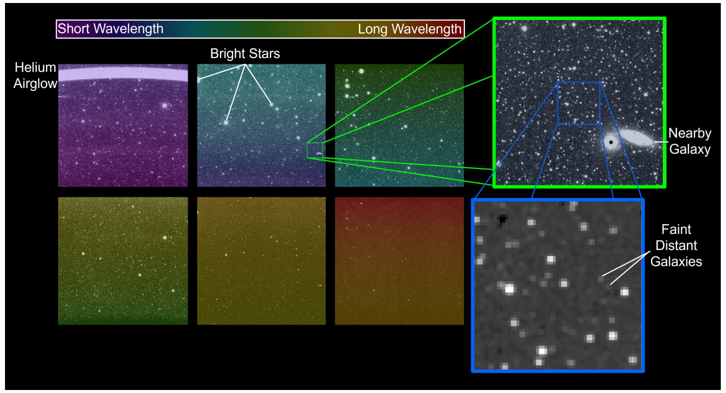
Most >10-m facilities have a FoV limited to ~ 4-20 arcmin, apart from a few dedicated small aperture (6-10 meter), ~1-2 arcmin resolution survey telescopes (SPT, CCAT/FYST, SO)
Further, no existing large (D > 15 m) aperture telescopes can observe ν_{obs} > 350 GHz



Completing our ability to map the multiwavelength sky

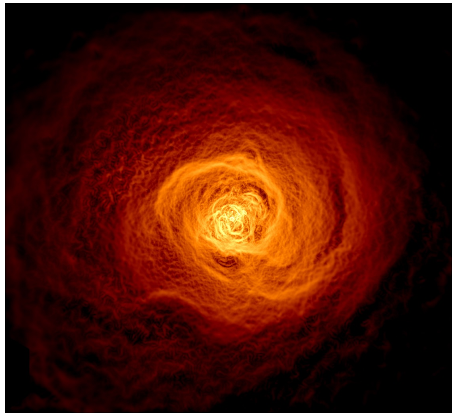


First light SKA-Low image (~25 sq. deg).
Credit: https://www.skao.int/en/news/621/ska-low-first-glimpse-universe



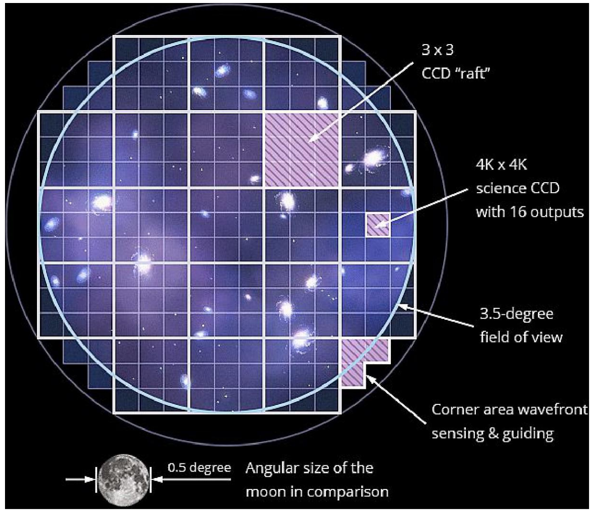
First light IR (0.75-5 micron) images from NASA's Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer (SPHEREx).
Credit: https://www.nasa.gov/missions/spherex/nasas-spherex-takes-first-images-preps-to-study-millions-of-galaxies/

Dark Energy Survey (DES) has a 2.2 deg wide instantaneous field of view.
Credit: Dark Energy Survey/DOE/FNAL/DECam/CTIO/NOIRLab/NSF/AURA
Acknowledgments: T.A. Rector (University of Alaska Anchorage/NSF NOIRLab), J. Miller, M. Zamani & D. de Martin (NSF NOIRLab)



Chandra X-ray observatory mosaic of 16'x16'pointings on the Perseus Cluster.
Credit: NASA/CXC/GSFC/ S.A.Walker, et al.
https://chandra.harvard.edu/photo/2017/perseus/

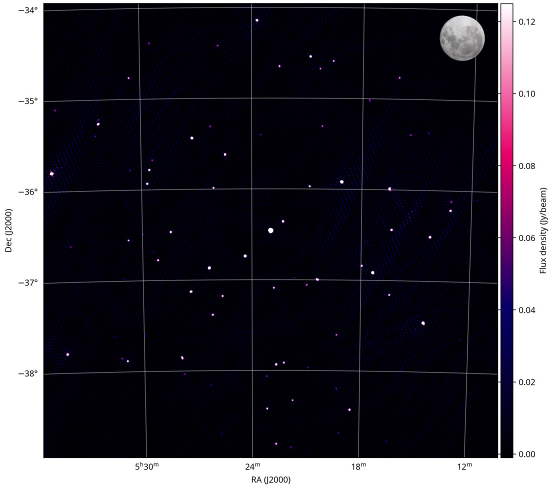
We can image (roughly) degree fields at a time across the sky with few arcsec resolution at every wavelength ***except the submm!***



Rubin Observatory will cover 9.6 deg^2 per pointing
Credit: https://directory.eoportal.org/other-space-activities/rubin-observatory#focal-plane

ALMA, < 1 arcmin field at 90 GHz, <10 arcsec field at frequencies >500 GHz.
Credit: ESO/B. Tafreshi

Completing our ability to map the multiwavelength sky



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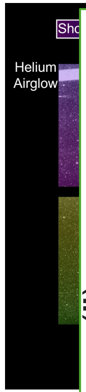

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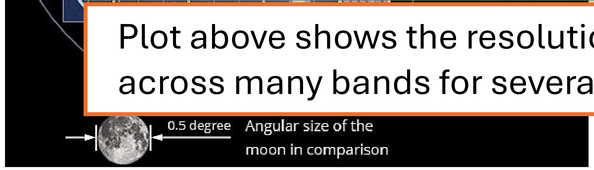

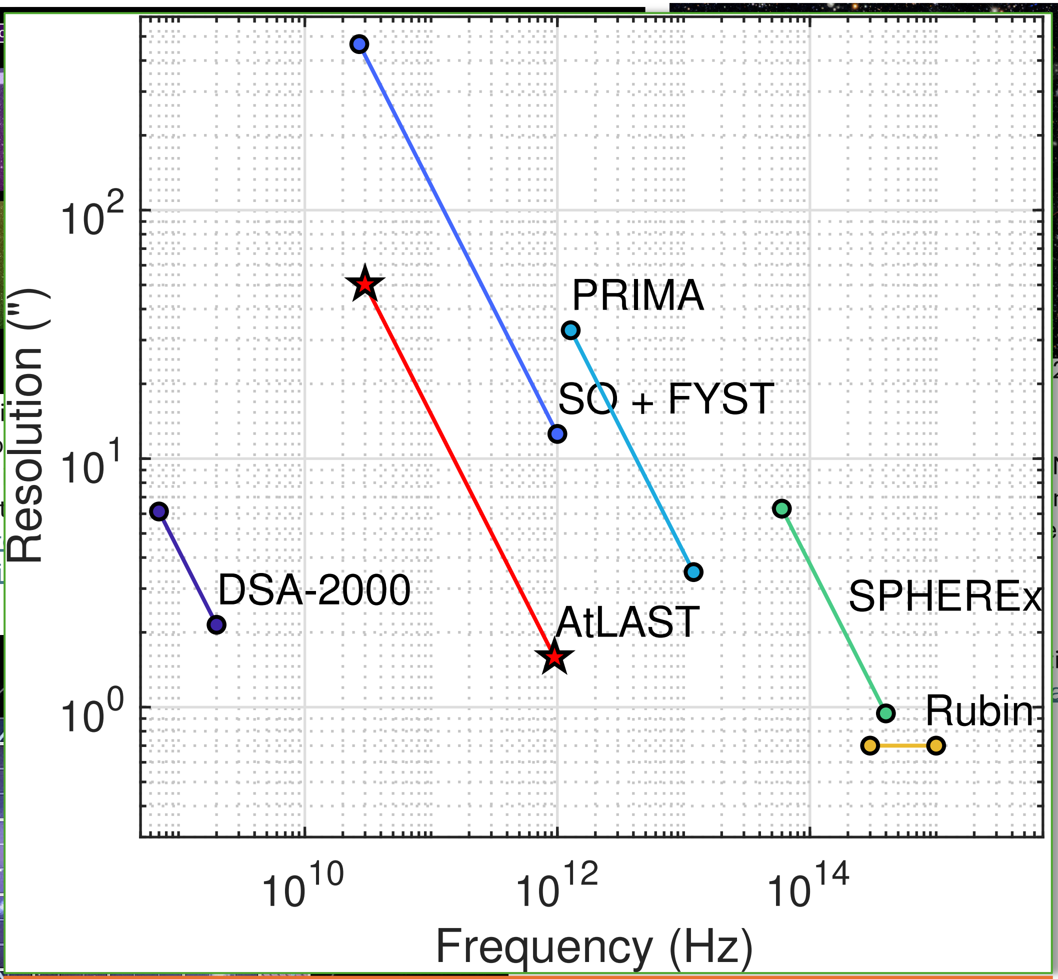

Plot above shows the resolutions and frequency coverages across many bands for several degree-scale facilities

2 deg wide

NOIRLab/NSF/AURA
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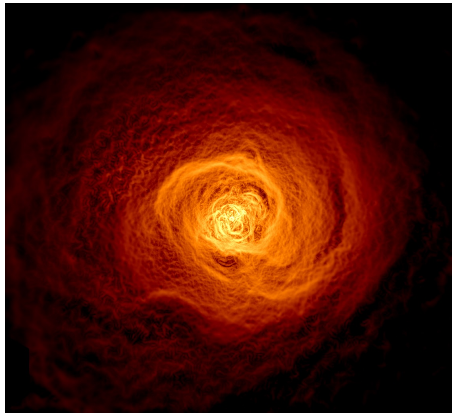

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1 arcmin field at 90 GHz, <10
ield at frequencies >500 GHz.
ESO/B. Tafreshi

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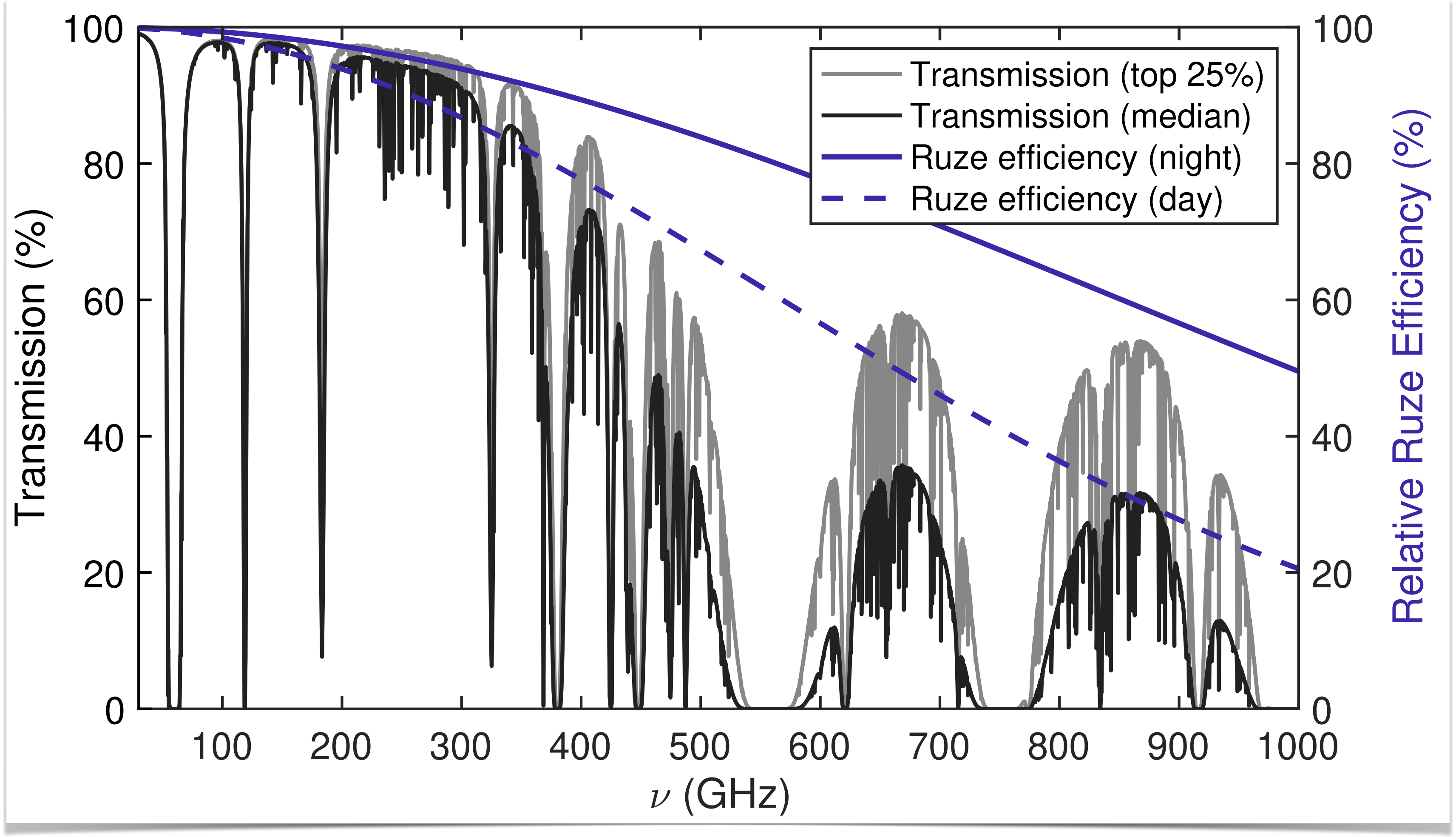
AtLAST Technical Specifications

Parameter	Value
Wavelength (λ) range	0.3 -10 mm
Primary mirror (M1) diameter	50 m
Secondary mirror (M2) diameter	12 m
Field of view (FoV)	2°(1°)
Number of instrument mount points	6
Optical design	Ritchey-Chrétien
Night(Day)-time half wavefront error	20 (30) µm
Mechanical pointing accuracy	2.5 arcsec
Astronomically-corrected pointing	< 0.5 arcsec
Solar observations	Yes
Scan speed	3°/s
Acceleration	$1°/s^2$
Elevation (EL) range	20° to 90°
Azimuthal (AZ) range	± 270°
Mount type	AZ-EL
Site location	22°58'52"S, 67°45'56"W
Site elevation	≈5000 m

AtLAST technical specifications (see Mroczkowski et al. 2025).
The 50-meter primary mirror yields a resolution of 1.5” at 350 µm and 10” at 2 mm.
Fast scanning will allow recovery of large angular scales, ensuring high fidelity imaging (see van Marrewijk et al. 2024).
Mechanical pointing accuracy is before any astronomical pointing model corrections.

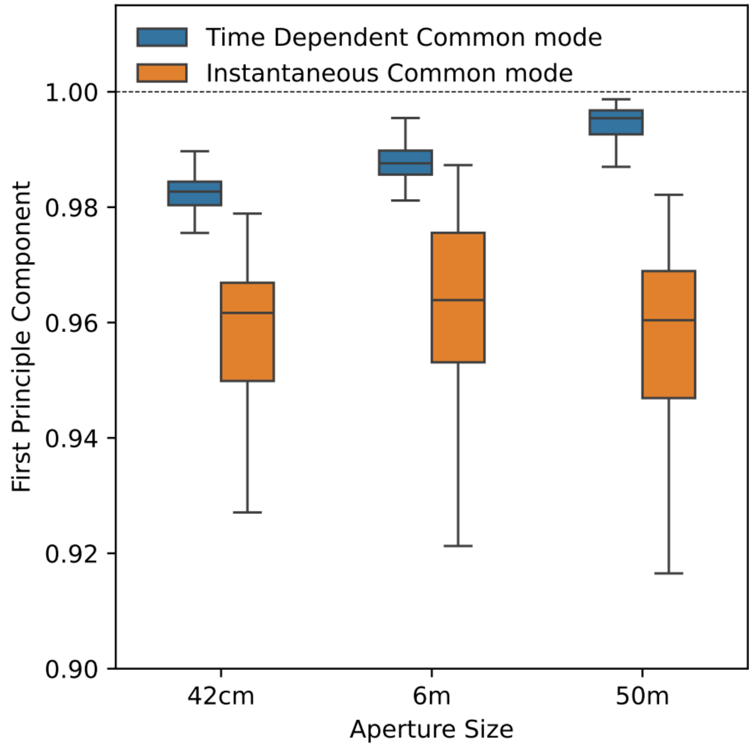
Surface accuracy vs atmospheric transmission

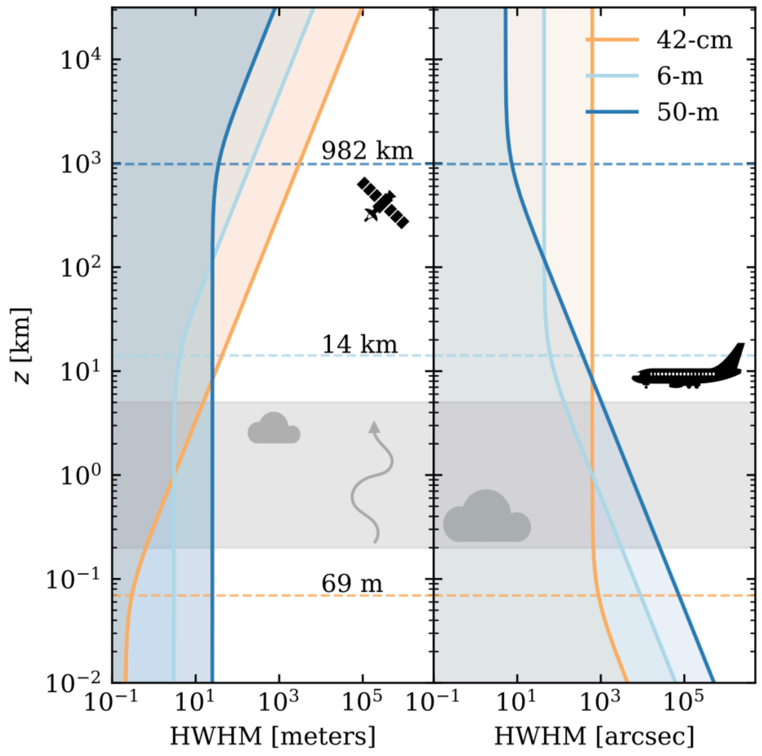
- Plotted on the right: Ruze efficiency for 20 micron (blue solid, nighttime) and 30 micron (blue dashed, daytime) RMS surface errors (from Mroczkowski et al. 2025)
- Black and grey curves show the median and top quartile transmission.
- These are well matched – *surface accuracy will not be the limiting factor for high frequency observations.*



Near vs far-field effects

- Large aperture telescopes probe a larger column of atmosphere, with smaller separation from beam to beam, leaving the atmospheric *signal* more correlated (van Marrewijk, Morris, et al. 2024).
- New results from Thomas Morris show this large beam effectively low pass filters the atmosphere and lowers the atmospheric knee, enabling lower noise on large scales!





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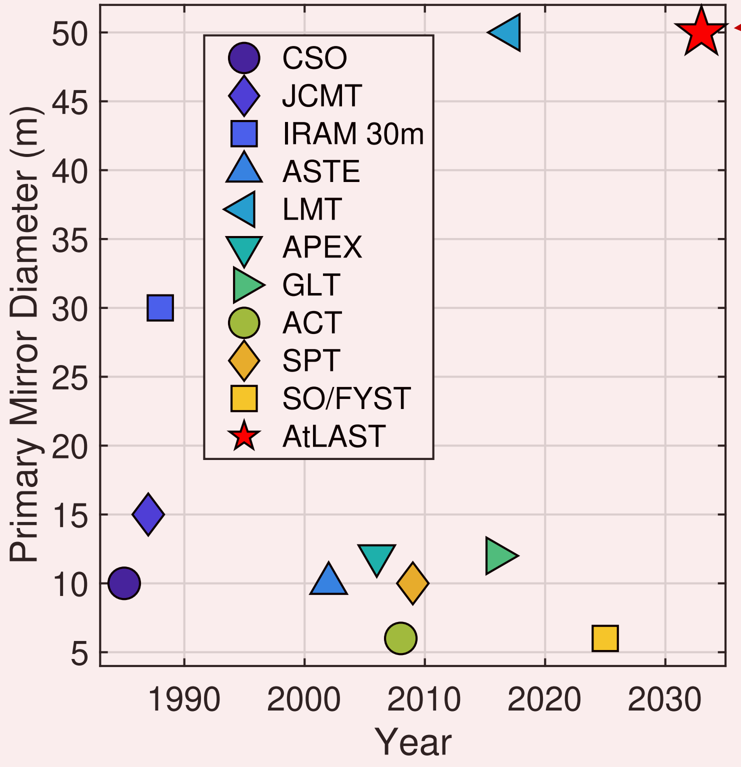
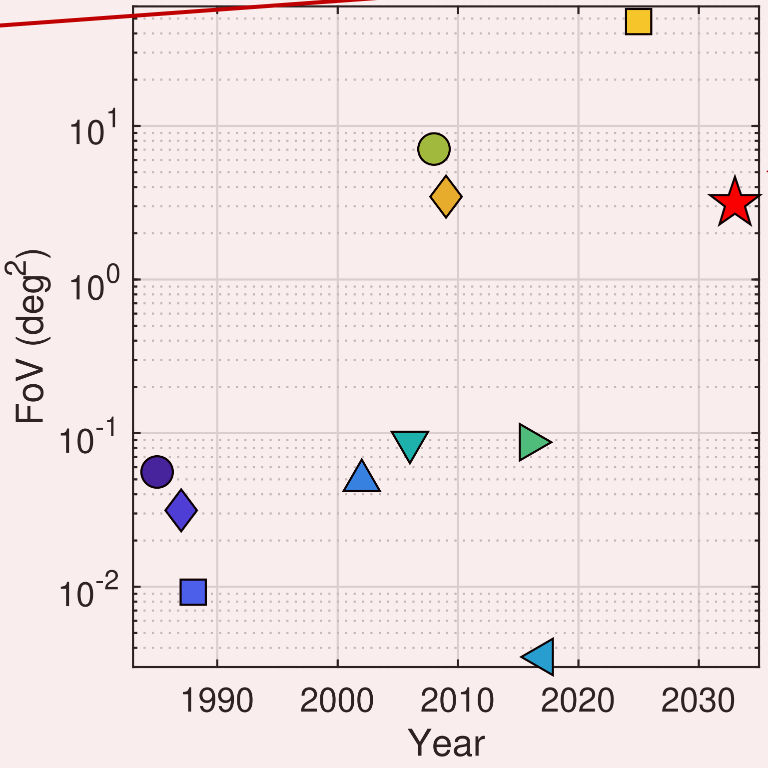
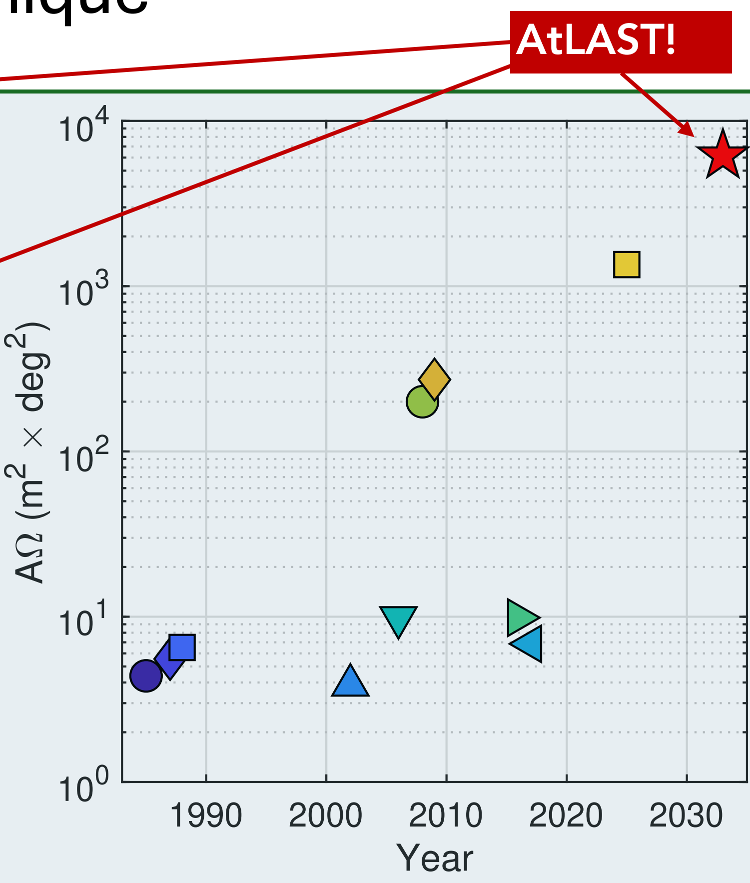
Combination of large aperture and FoV makes AtLAST unique



Primary Mirror Diameter: driven by the need for both resolution and sensitivity (collecting area)



Field of View (FoV): driven by the need for large angular scales and fast mapping

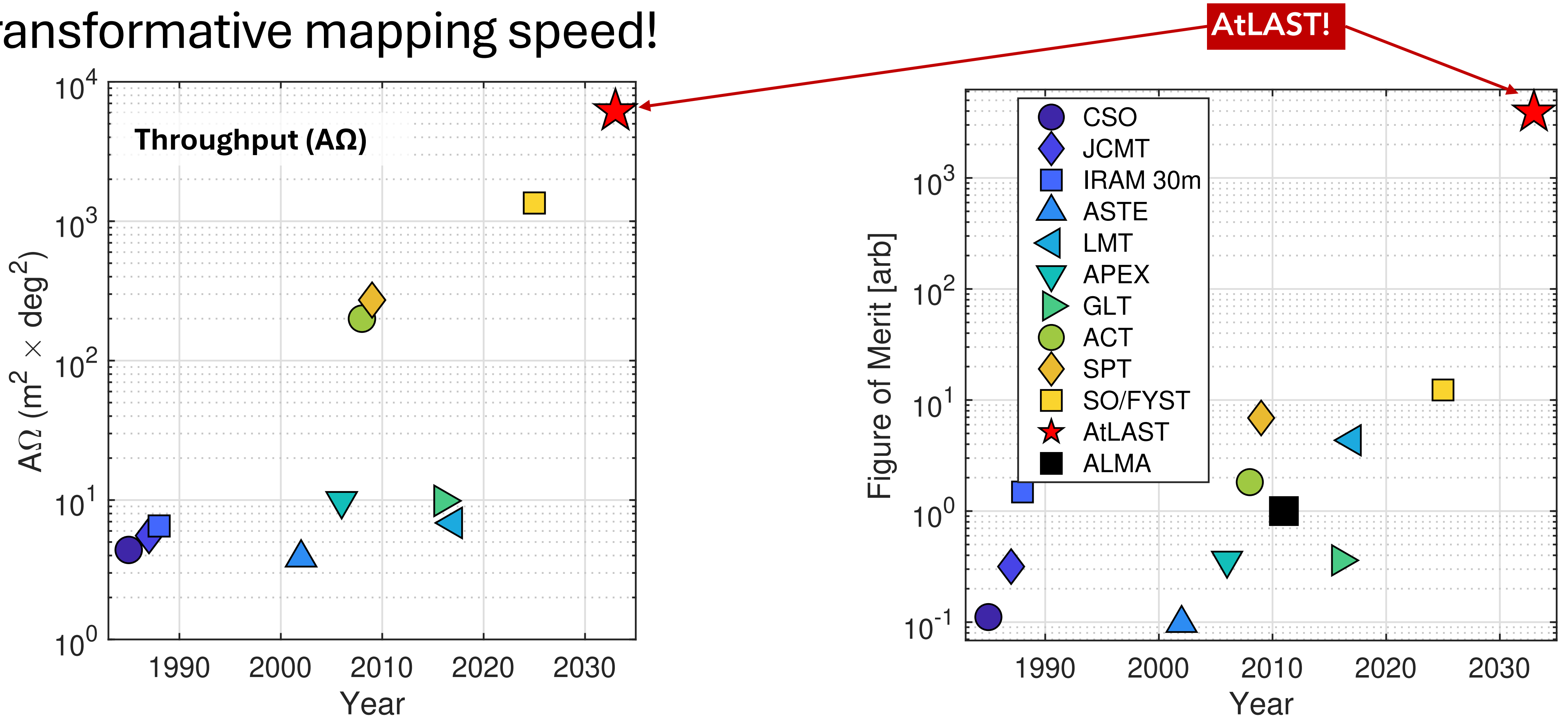


Throughput (AΩ): driven by the need for fast mapping speeds and sensitivity in wide surveys.

Need >3 million detectors at 850 μm to fill the FoV

Note: Plots include only single dish facilities that can observe at least up to 270GHz (1.1mm)

Transformative mapping speed!

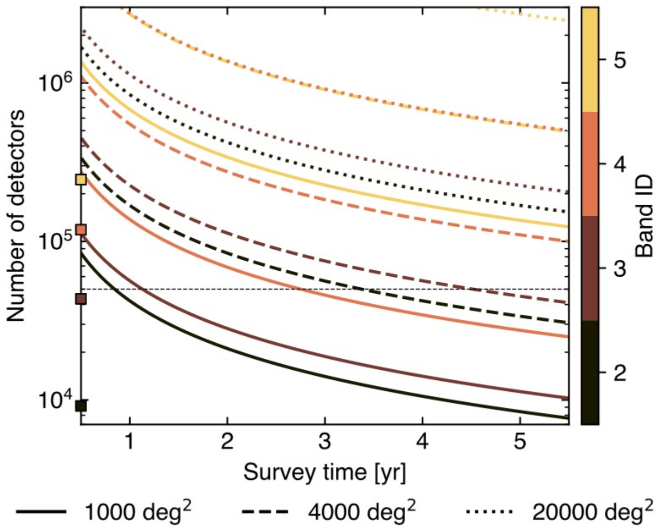


$$\mathrm{FoM} = \eta\, N_{\mathrm{FoV}}\, \Omega_{\mathrm{FoV}}\, \Delta\nu \left(\frac{A_{\mathrm{eff}}}{2k_B T_{\mathrm{sys}}}\right)^2$$

Using a figure of merit (FoM) defined in *Tools of Radio Astronomy* (Wilson, Huttemeister, Rohlfs) that is proportional to mapping speed, AtLAST is far above everything that has or will come before it.

At last, the final SZ number counts plot of the workshop!

- Cluster count forecasts from Srini Raghunathan, appearing in the AtLAST SZ science case (Di Mascolo et al. 2025).
- Requires e.g. 170k detectors for a 5 year, 4k deg^2 survey.



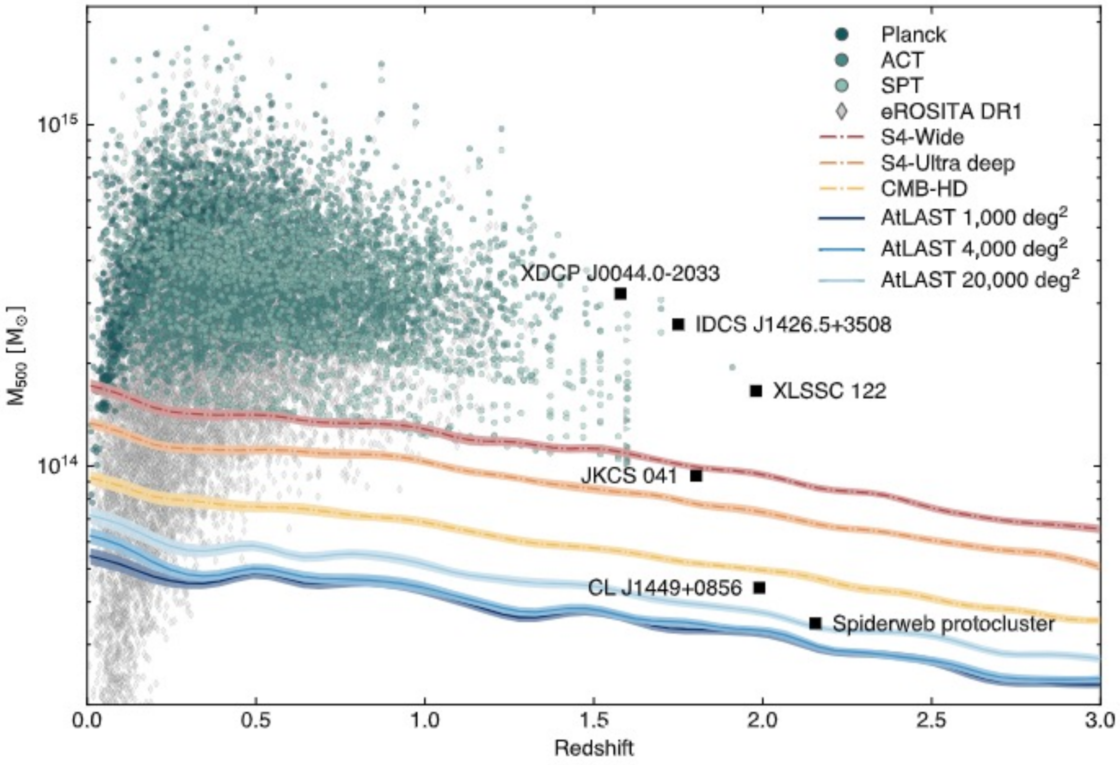


Figure 5. Mass vs. redshift detection forecast for AtLAST assuming different survey strategies (covering 1000 deg^2, 4000 deg^2, and 20000 deg^2, respectively, for a fixed survey time of 5 years) in comparison with next-generation wide-field millimeter surveys (Abazajian et al. 2016, Sehgal et al. 2019) and the eROSITA all-sky (X-ray) survey (Bulbul et al.

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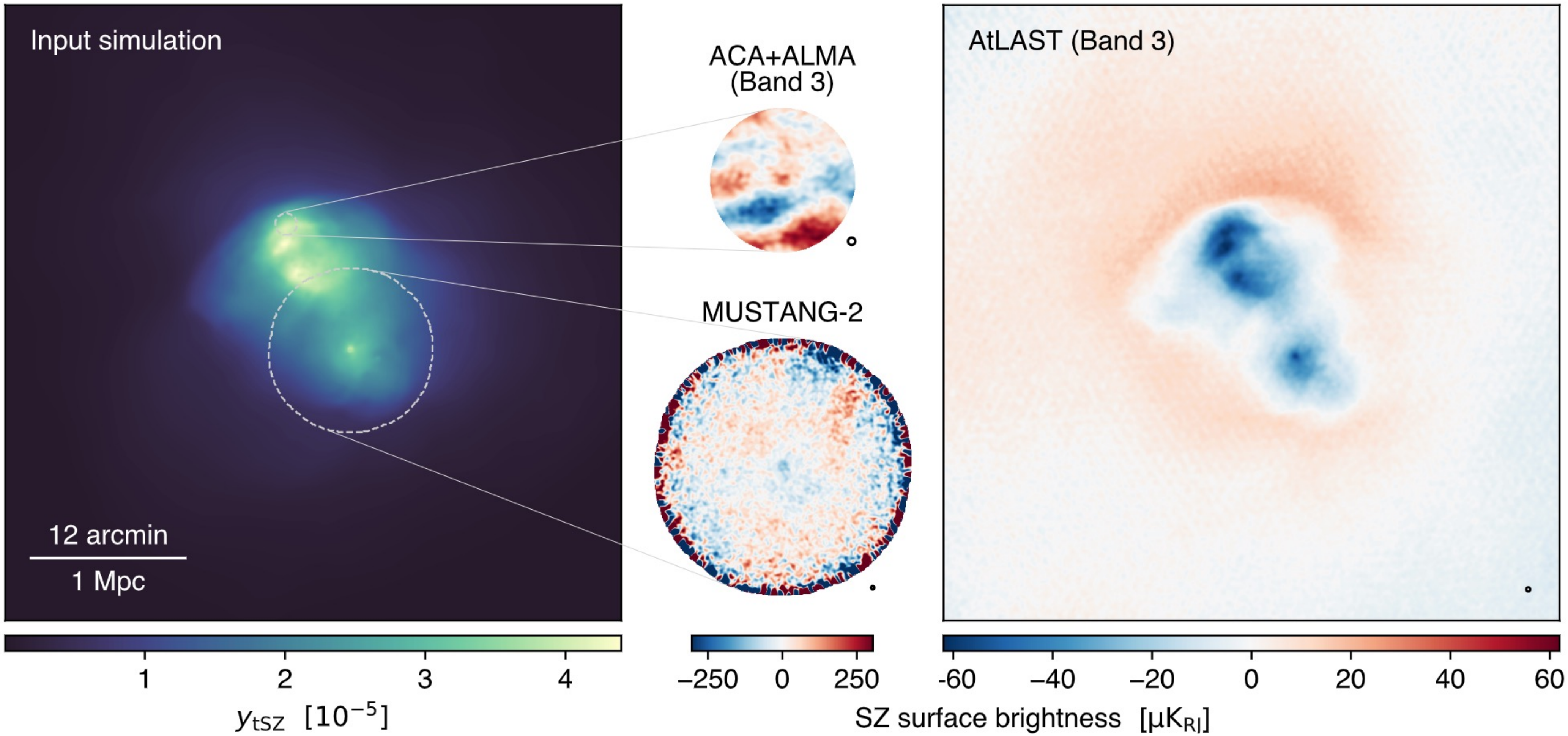
A more complete SZ view of clusters:



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8 hours on source for all simulations. Assumes 50k detectors at 90 GHz for AtLAST mock. See Di Mascolo et al. 2025

Phase 1: AtLAST Design Study

- Officially ran from March 2021 to Aug 2024.
- Major accomplishments: 8 refereed science cases in Open Research Europe, publication of conceptual design (Reichert et al. 2024, Mroczkowski et al. 2025) and optical design concepts (Gallardo et al. 2024, Puddu et al. 2024), power generation concept (Viole et al. 2024), kinetic energy recovery (Kiselev et al. 2024), operations plan (Hatziminaoglou et al. AtLAST memo), extensive characterization of the site wind conditions (in prep including De Breuck and Otarola), instrumentation concepts outline (van Kampen AtLAST memo), observation simulators (van Marrewijk, Morris, et al. 2025) and much more.
- Importantly, this initial design study identified areas that require further development and study, and the new AtLAST2 development project (2025-2028) is working to address those.

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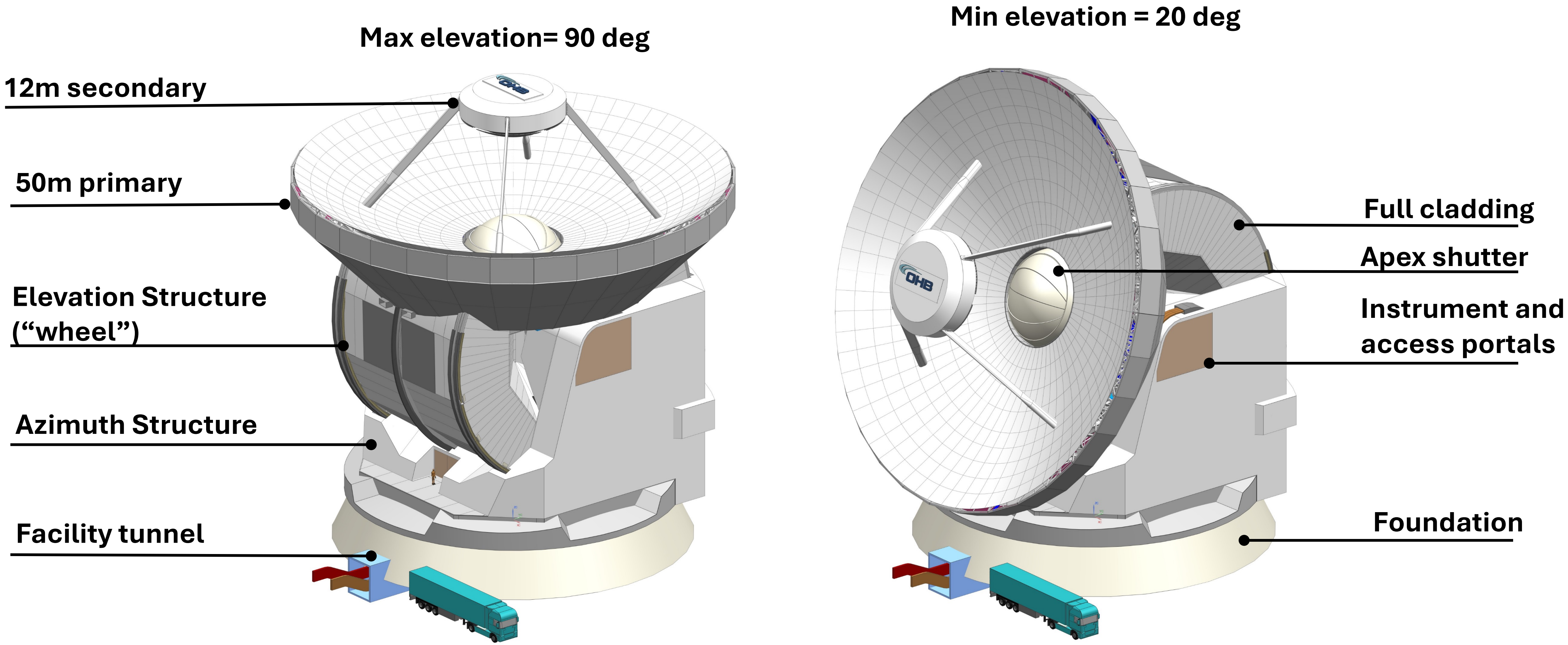
Design Overview

- Exposed Rocking Chair Design

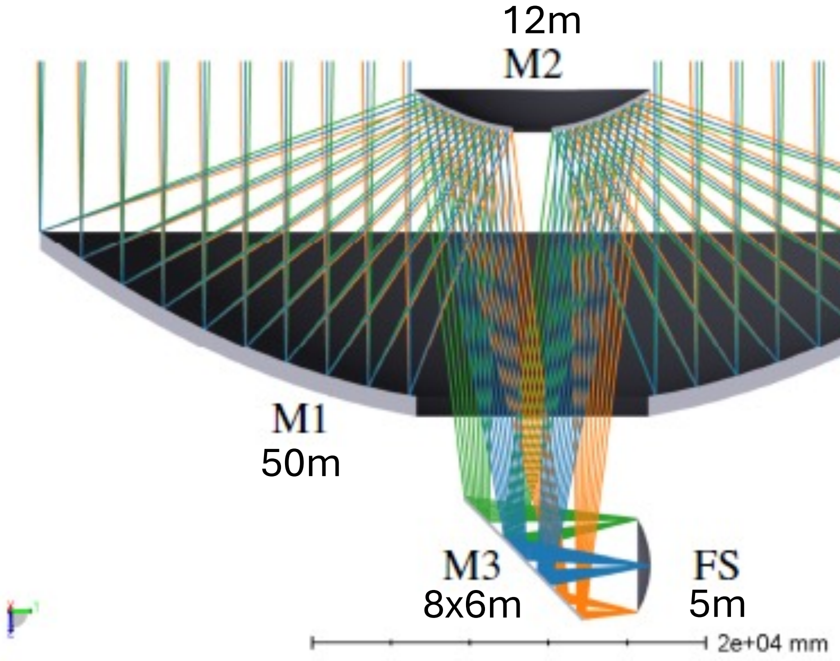


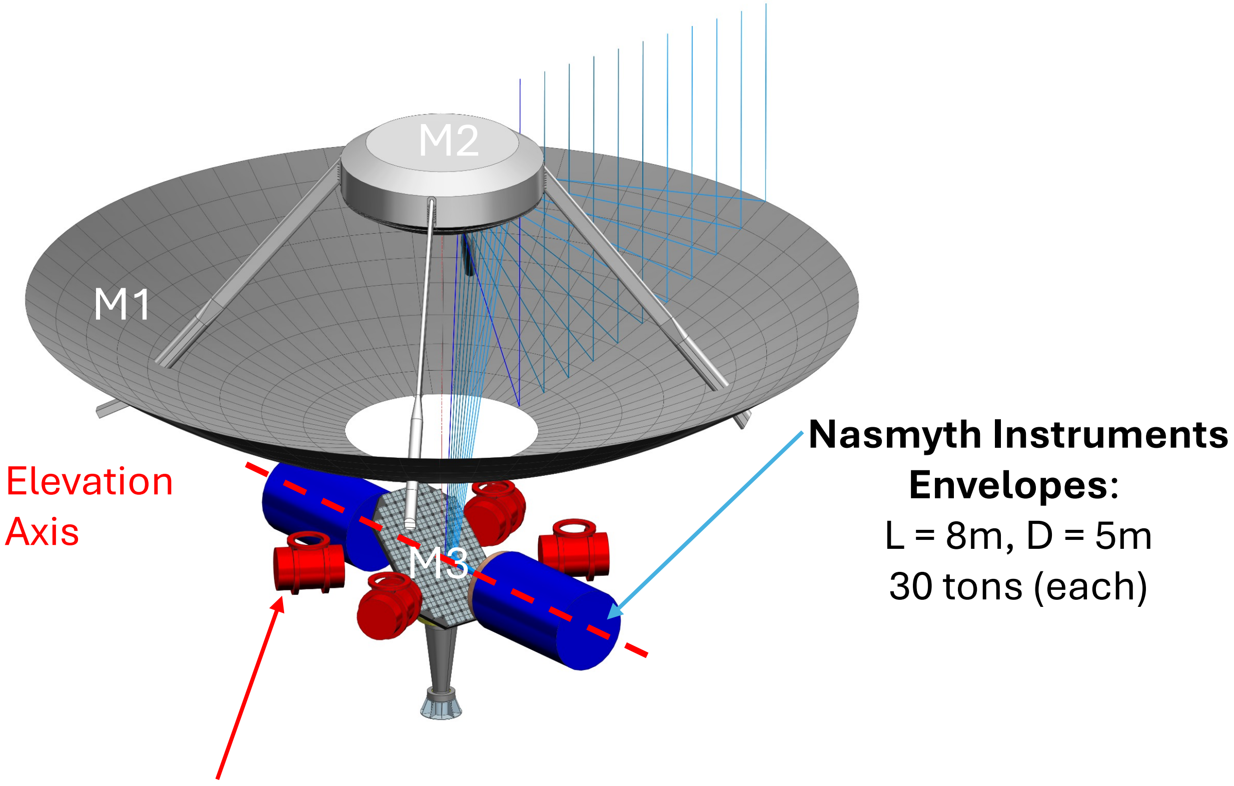
Mroczkowski et al. 2025 (A&A 694A, 142)

Large FOV and Multiple instruments

- Optical Design, unprecedented receiver cabin space

Optical design by R. Hills (see AtLAST memo 1)





Cassegrain Instruments Envelopes:
L = 4m, D = 2.6m,10 tons (each)

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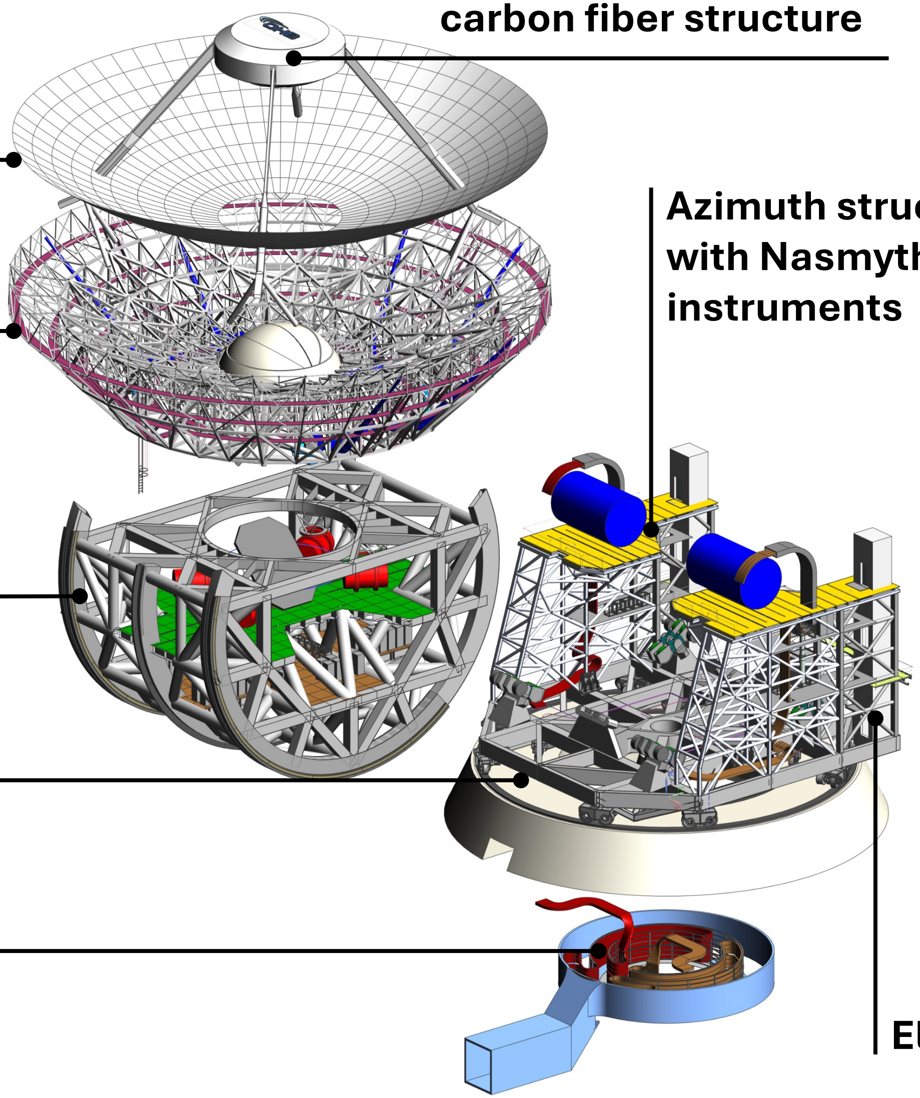
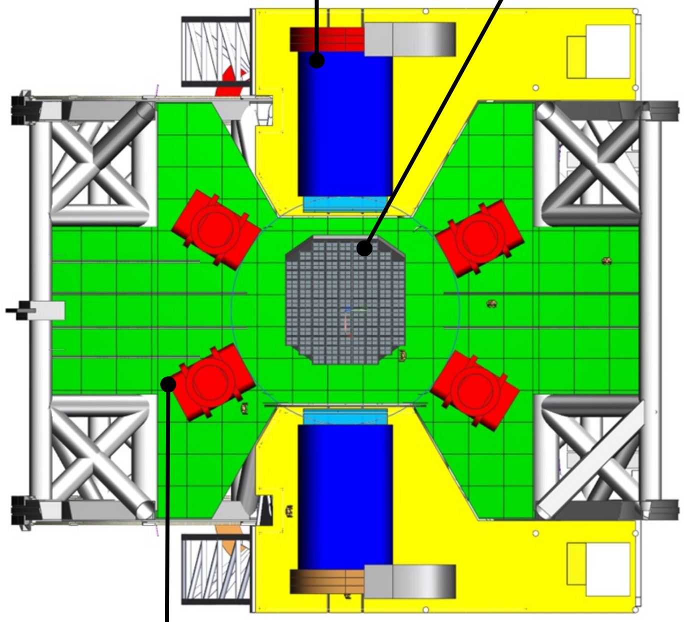
More details about AtLAST optics:
- SPIE Paper 13094-84 by Patricio Gallardo: Optical design for AtLAST
- SPIE Paper 13094-130 by Roberto Puddu: Physical optics characterization…

Design Overview

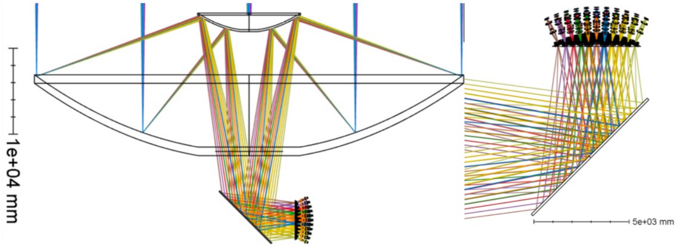
- Concept CAD Model

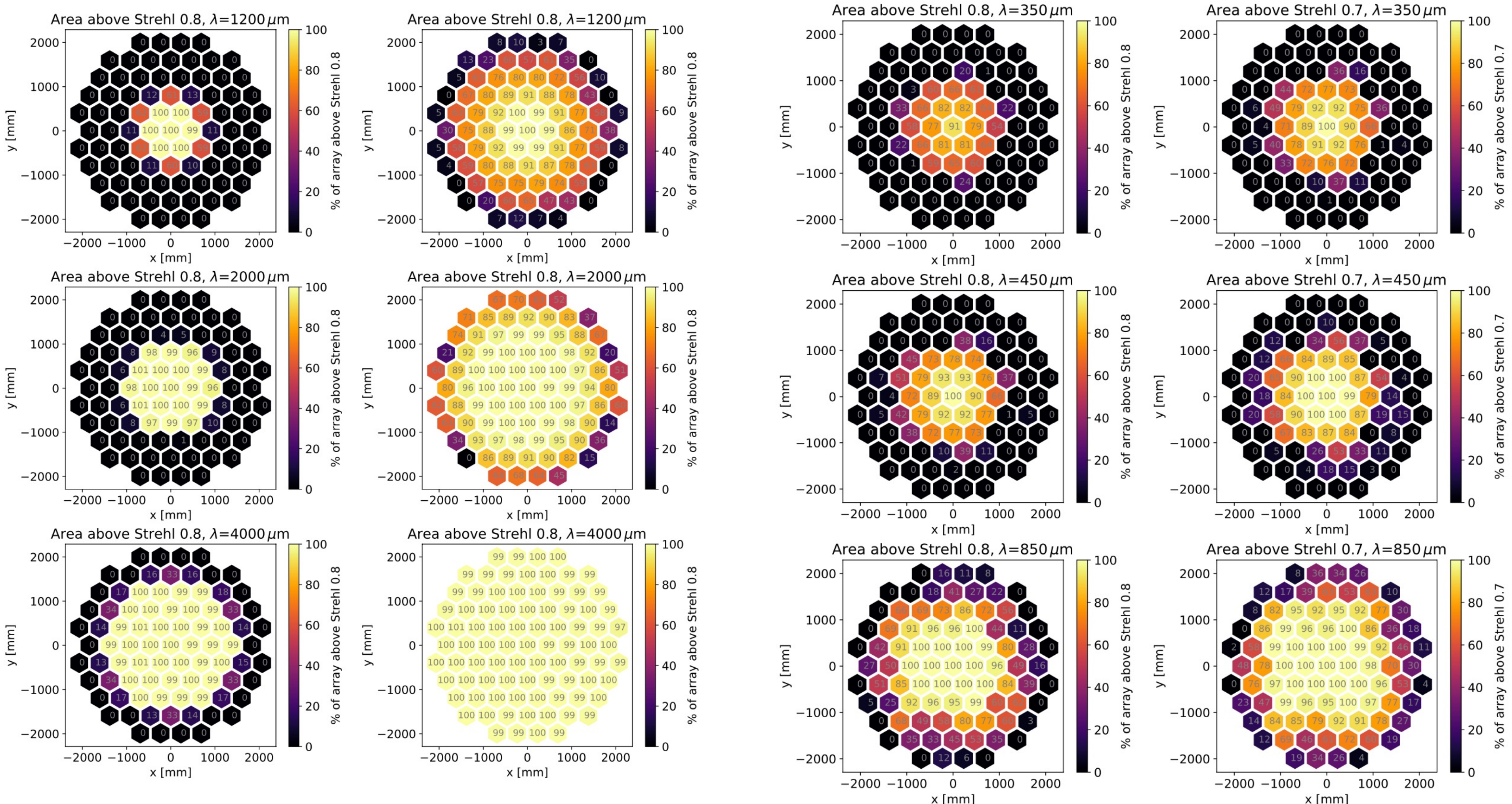




AtLAST receiver optics

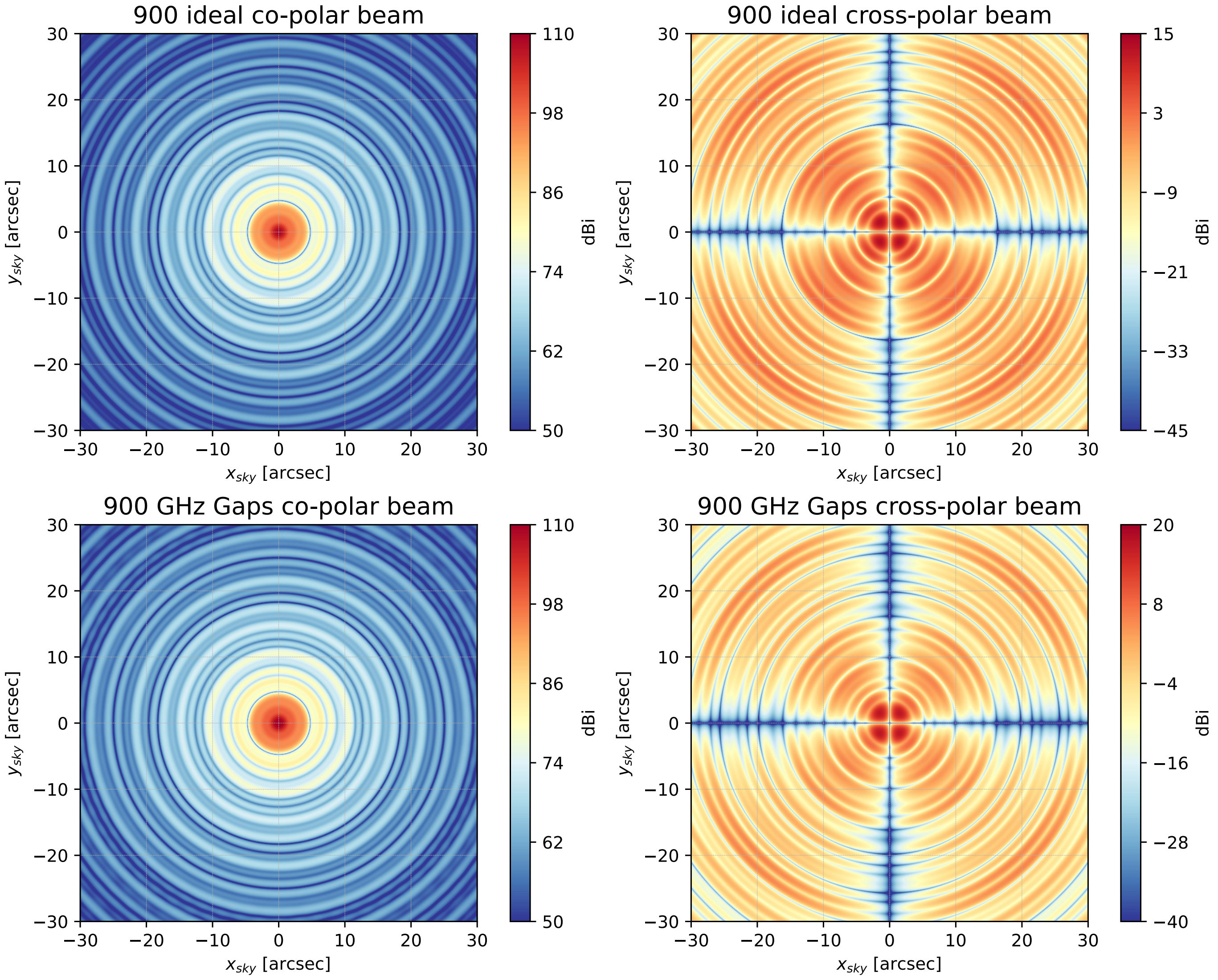
- **Focal plane has large size** (D=4.7m) and significant **curvature** but camera size is only a modest (~x2 diameter) scale up from that planned for CMB-S4
- Pato Gallardo (formerly here, now at U Penn) optimized the AtLAST optics and concepts for correction in the receivers.





AtLAST Beam properties

- Puddu et al. 2024 (arXiv:2406.16602, SPIE proceedings) carried out extensive physical optics calculations.
- Simulating a 50-meter up to 950 GHz took some clever tricks in TICRA/GRASP to make it manageable.
- Showing 900 GHz case (worst)



Ideal case

With panel gaps

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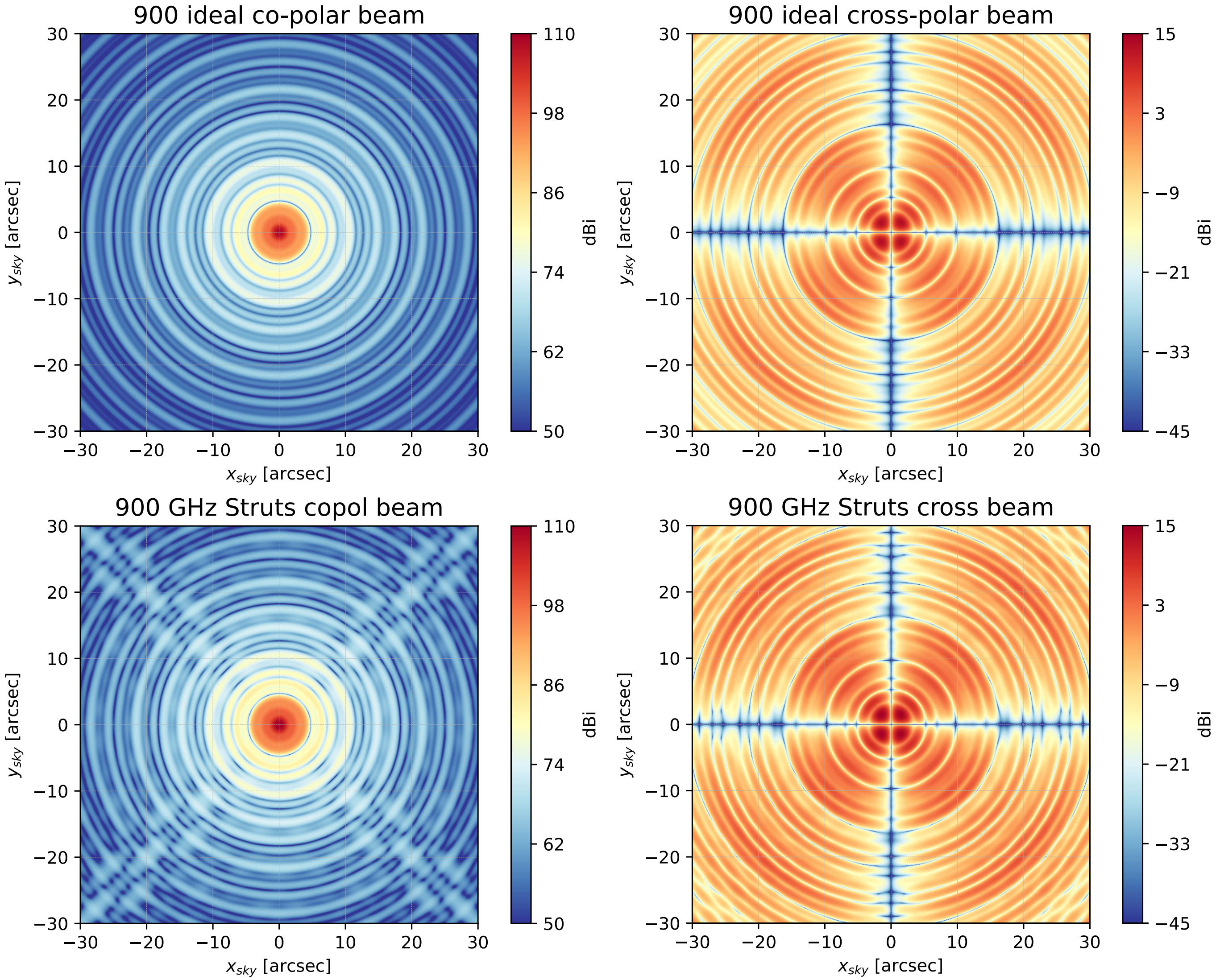

Ideal case

With struts

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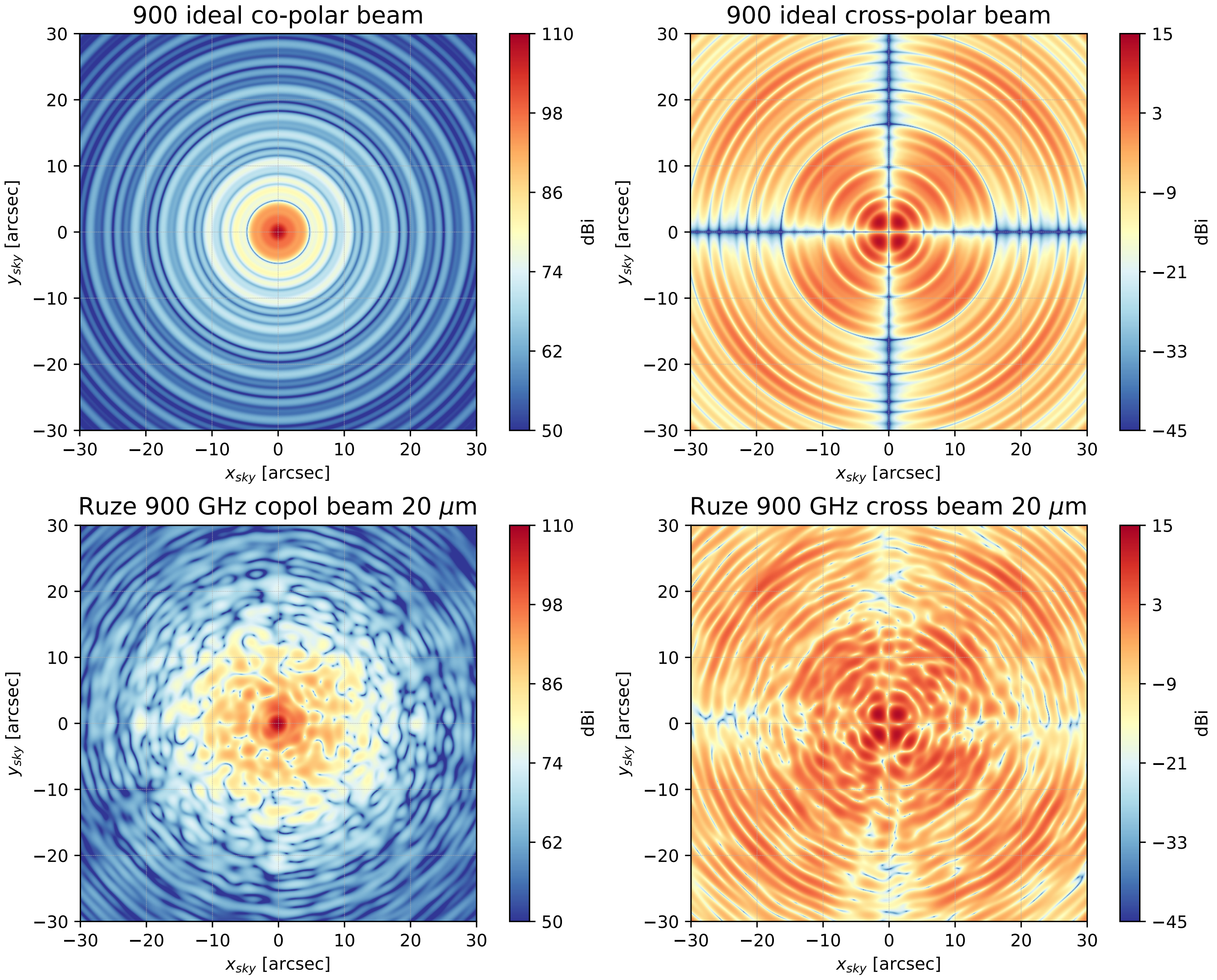

Ideal case

With 20 micron Ruze Scattering

AtLAST Beam: overall performance at 900 GHz

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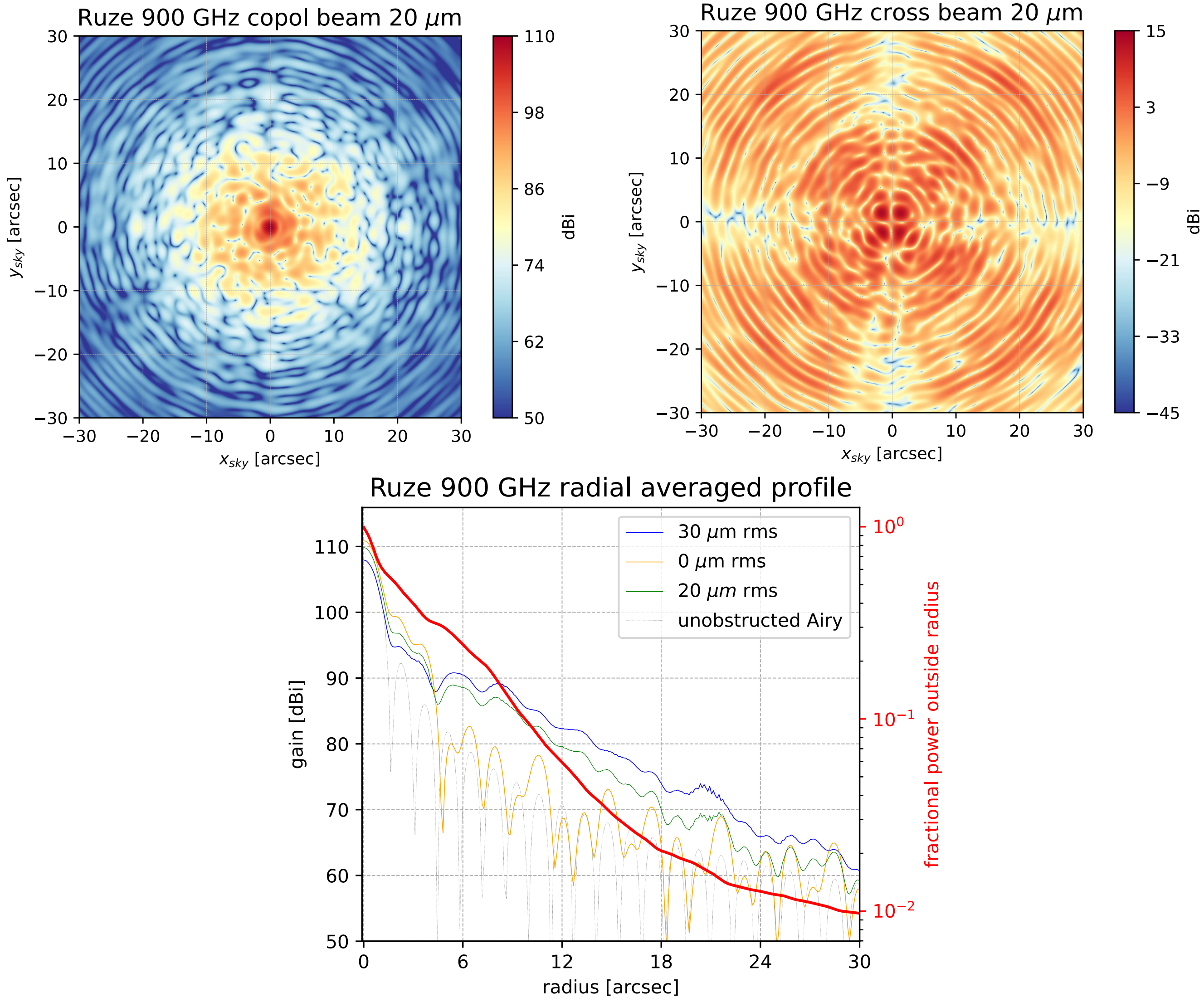

So… what now?

- AtLAST2 (https://cordis.europa.eu/project/id/101188037) is happening!
- AtLAST website details the work packages; see https://atlast-telescope.org/atlast2.
- We actively encourage instrument builders to join and help inform the instrumentation concepts that will achieve AtLAST's next-generation science goals. This is independent of region.
- We also encourage astronomers, astrophysicists, cosmologists, planetary scientists, and solar physicists to get involved in further defining the science cases (again, regardless of region).
- AtLAST has the potential to become the one mm/submm large aperture telescope we get in this generation. The next generation(s) need such a telescope to map the mm Universe, so let's make it happen.

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AtLAST2 work package overview:

1. Coordination, community engagement, and impacts
2. Design Review and first light instrument definitions
3. Telescope Technology Demonstrations
4. Operations and user experience
5. Energy and sustainability
6. Upgraded tools for science users
7. Testing with pathfinder telescopes

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Work package 2.1: Design Reviews

- Conceptual Design Review (CoDR):
  - CoDR assessed the AtLAST design from the phase I design study.
  - The main areas of CoDR were the concepts for the optical, structural, control systems, and materials.
  - The aim was to reveal any key areas in the telescope concept design that need improvement over the next 3 years. Fortunately, those identified were largely in sync with activities already undeway.
- Preliminary Design Review (PDR):
  - Near the end of AtLAST2, to ensure we are ready for the final engineering design phase.
  - Note that “PDR” has different meanings to different groups. We define it as the readiness review before final engineering and implementation details are fully worked out.

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Work package 2.2: first-light instrumentation

Spectroscopic receivers

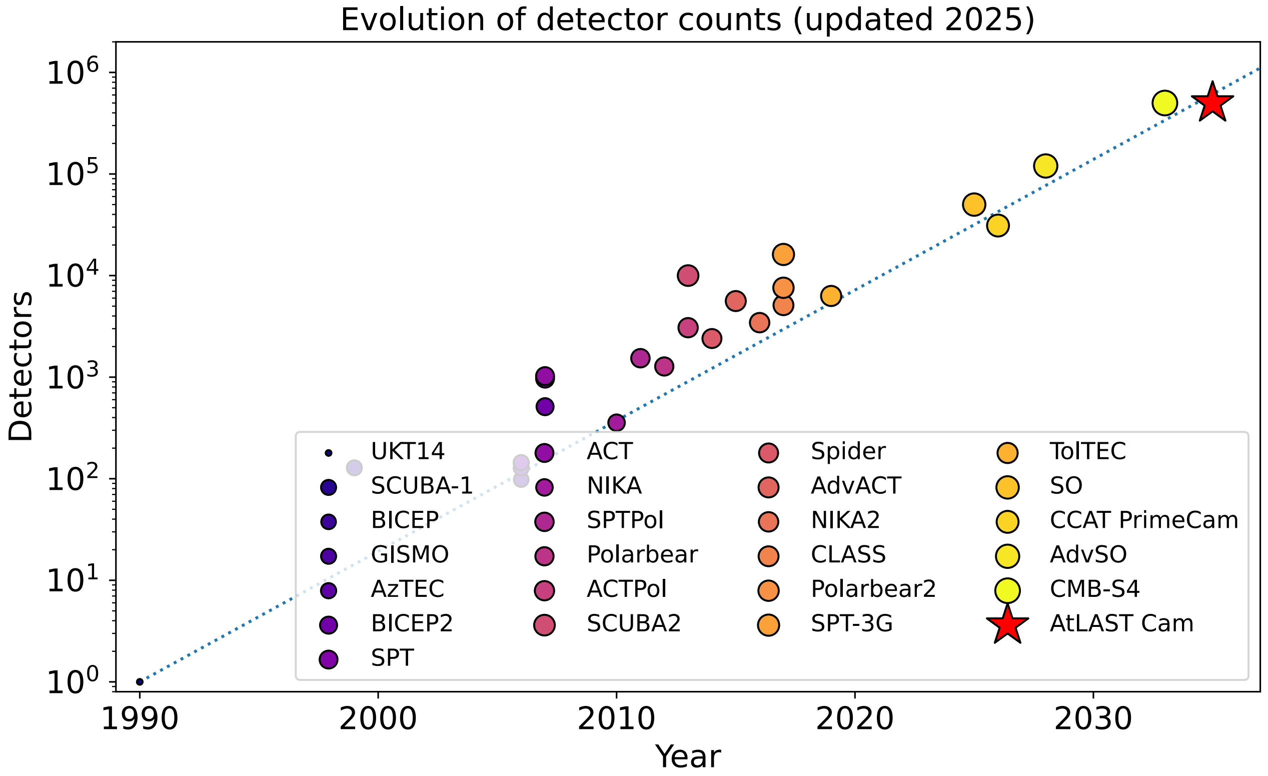
1. A 1000-pixel heterodyne focal plane array(FPA) providing high spectral resolution (dv < 1 km/s) to probe chemical complexity.
2. A direct-detection, ultra-wide bandwidth integral field unit (IFU) with R~300-1000 for galaxy evolution and tomography.
3. Single-beam, multi-frequency receiver for mmVLBI and EHT campaigns.
4. *Perhaps* a multi-object spectrograph (MOS), depending on science demand.

Continuum cameras

- "AtLAST Cam": a multi-chroic continuum camera comprising ~0.5 million detectors likely covering 8 bands (see Di Mascolo et al. 2025)

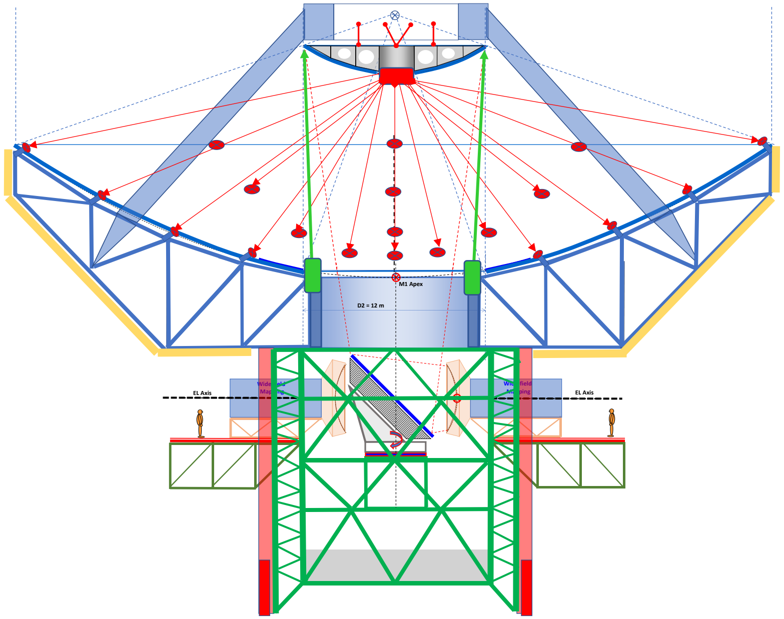
- Multi-chroic solar imager (see Kirkaune et al. 2025, submitted to OJAp).

Below: a compilation of submm detector counts vs year using a variety of technologies. Extrapolation suggests 0.5-megapixel cameras in the mid-2030s, and gigapixels by 2060 (e.g. a fully-populated IFU).



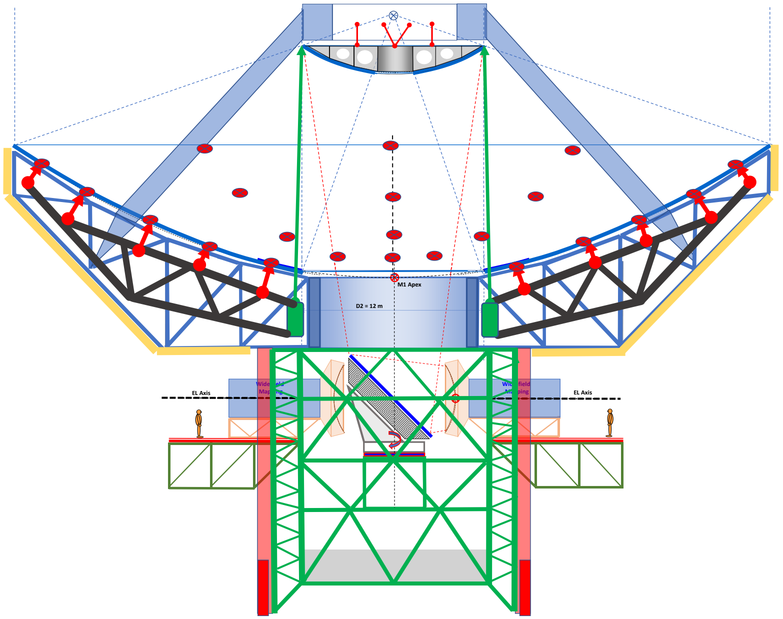
Work package 3: maturing the metrology system and telescope design

Alternative A



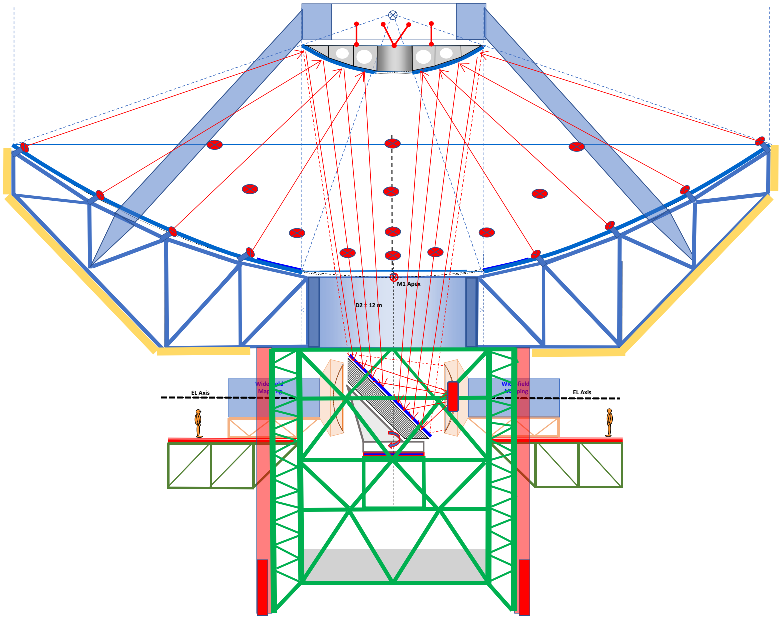
M1 Shape Control via Etalons (laser metrology)
M2 Position Control Etalons

Alternative B



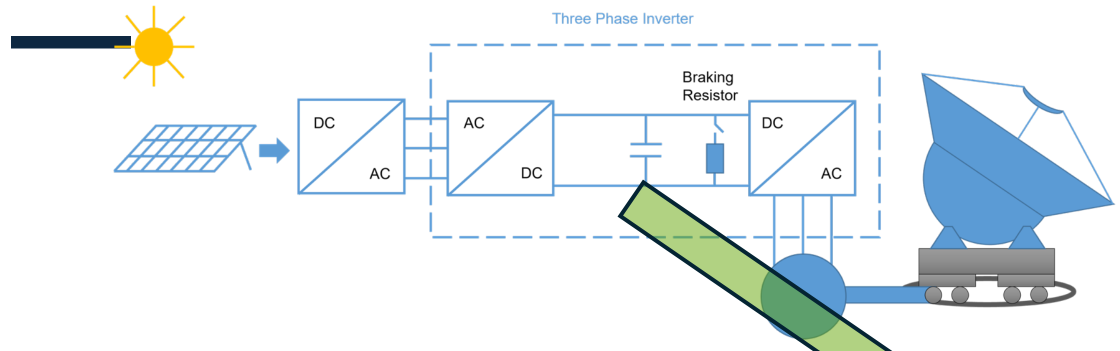
M1 Shape Control via Depth Sensors on thermal stable substructure
M2 Position Control e.g. via Etalons

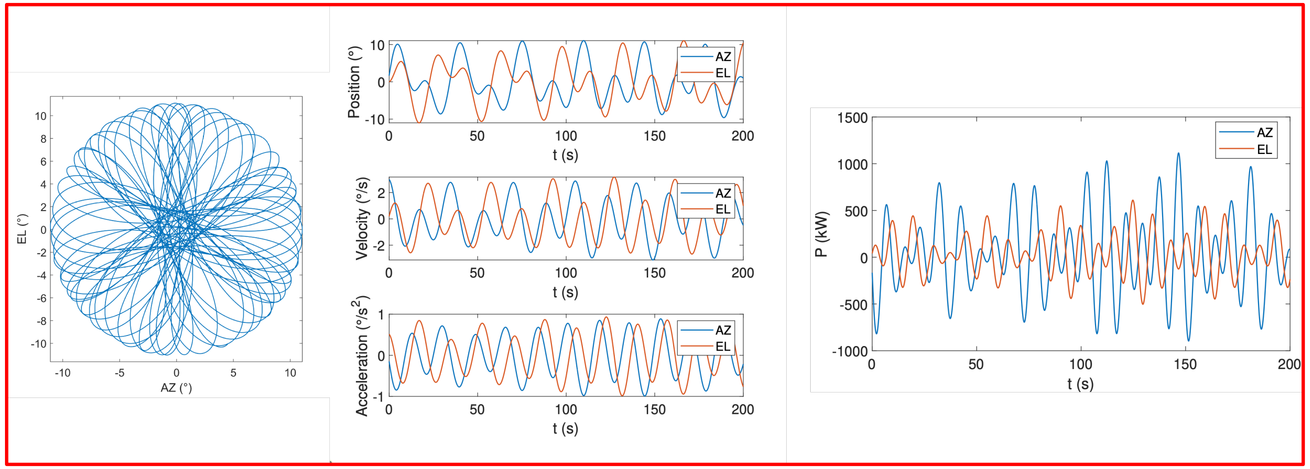
Alternative C



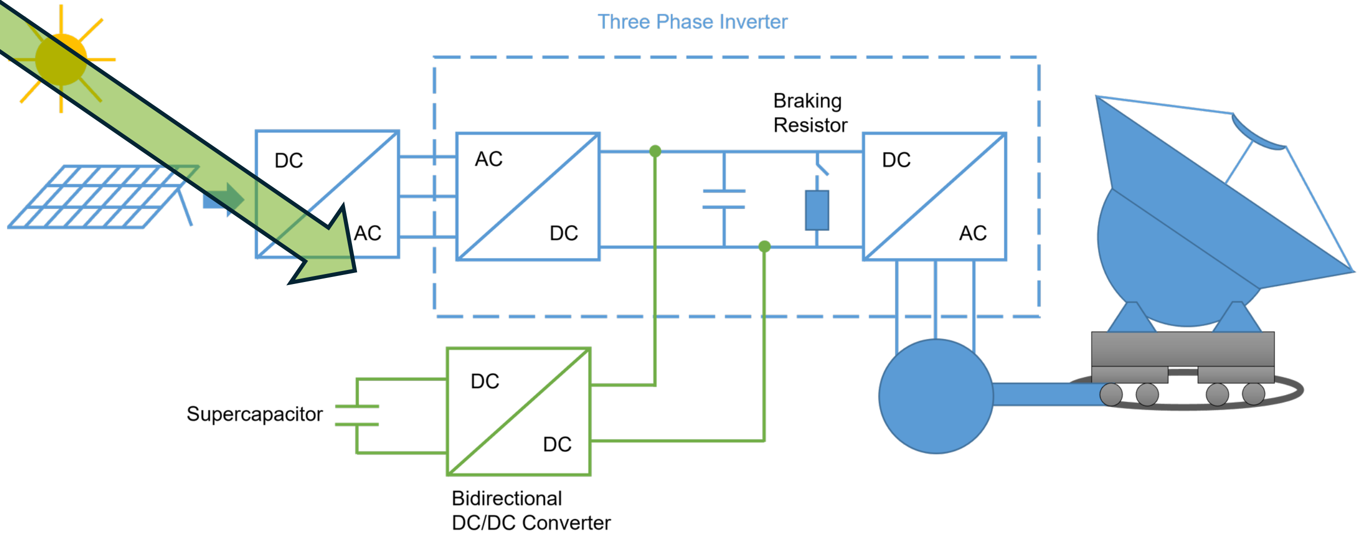
Overall Wavefront Control via Microwave Interferometer in beam path (demonstrated on Nobeyama 45-m; see Tamura et al. 2022)

WP3 + WP7: kinetic energy recovery system





- A simple modification to the standard drive system can recover >80% of the kinetic energy normally dissipated in braking!
- By pre-charging the supercapacitors, our system also offers power shavings.
- We will test this system on APEX and design a system for the 64-m SRT in this phase.



See Kiselev et al. (2024SPIE13094E..0EK)

Atacama Large Aperture Submillimeter Telescope

AtLAST

Thanks!

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Backup slides!

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Summary of Technical Specifications and Instrument concepts for AtLAST

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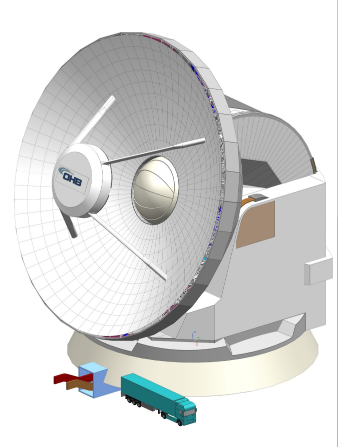
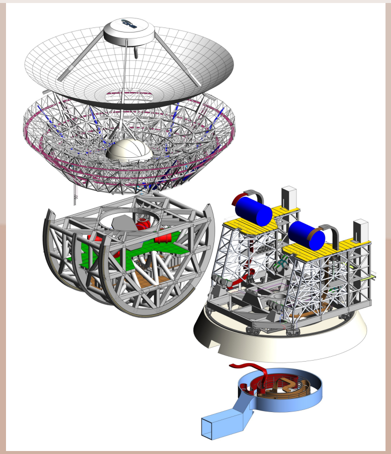
Summary of Instrumentation:

- First light / first generation concepts (see AtLAST Science Cases):
    - Multi-band continuum receivers with >120k detectors spanning 90-950 GHz.
    - Heterodyne receiver focal plane arrays with ~1000 feeds and spectral resolution R~10^6 (< 1 km/s). Science cases will determine bands, though likely 70-116 GHz, 200-400 GHz, 580-720 GHz, and 850-950 GHz with ≥32 GHz instantaneous bandwidth.
    - Direct-detection spectrometers (R~300-1000) covering 200-400 GHz instantaneous bandwidth for extragalactic tomography and cosmology through intensity mapping.
    - Single beam, multi-band receivers for mmVLBI and EHT campaigns.
- Entire volume behind primary will house instrumentation, electronics, and support equipment.
- 6 instrument bays: the 4 smaller instruments will be Cassegrain-mounted and can be up to 10 tons and up to 2.6 meters in diameter (red in figure below).
- The 2 larger instruments will be Nasmyth-mounted (blue, below) and up to 30 tons and up to 5 meters in diameter (i.e. 5 times larger than the biggest receivers now fielded).

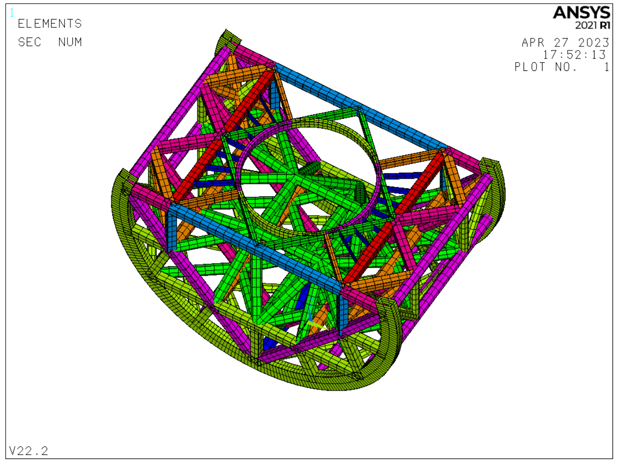


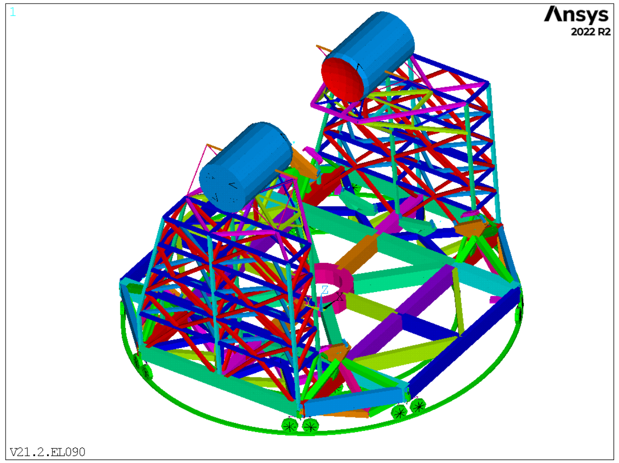


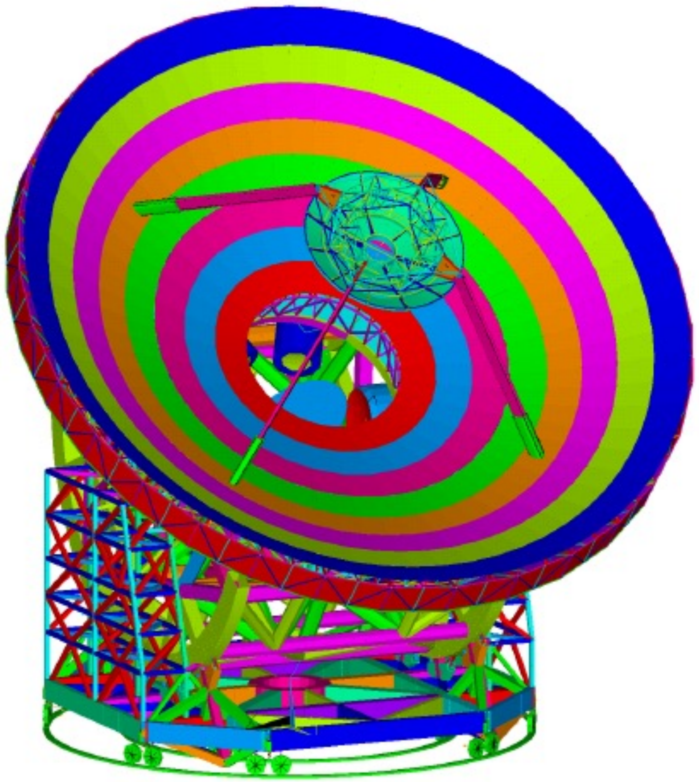
Verification with Finite Element Modelling

STATIC LOAD CASES IN OVERALL MODEL

Elevation wheel structure



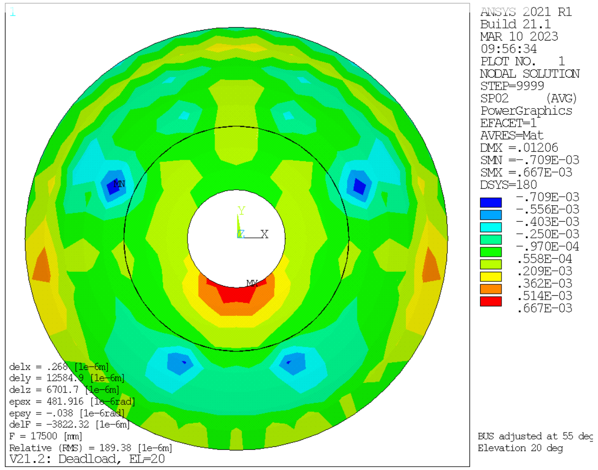




Example surface plots

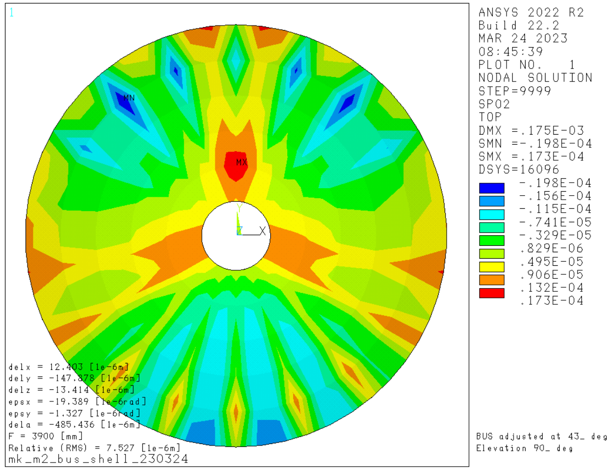
M1 Requirement < 200 µm rms under gravity without active surface

189.4 µm rms @EL=90°



M2 Requirement < 10 µm rms under gravity

7.5 µm rms @EL=90°

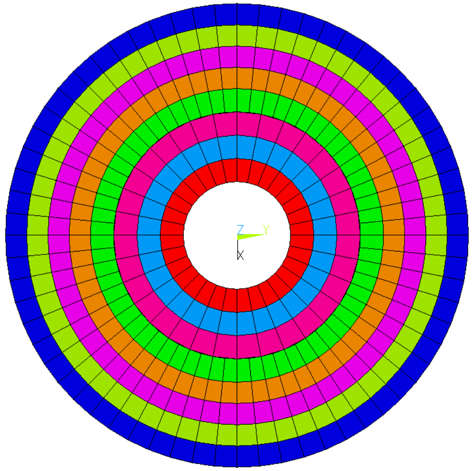


Note: gravity is reproducible and correctable (e.g. GBT 100-m)

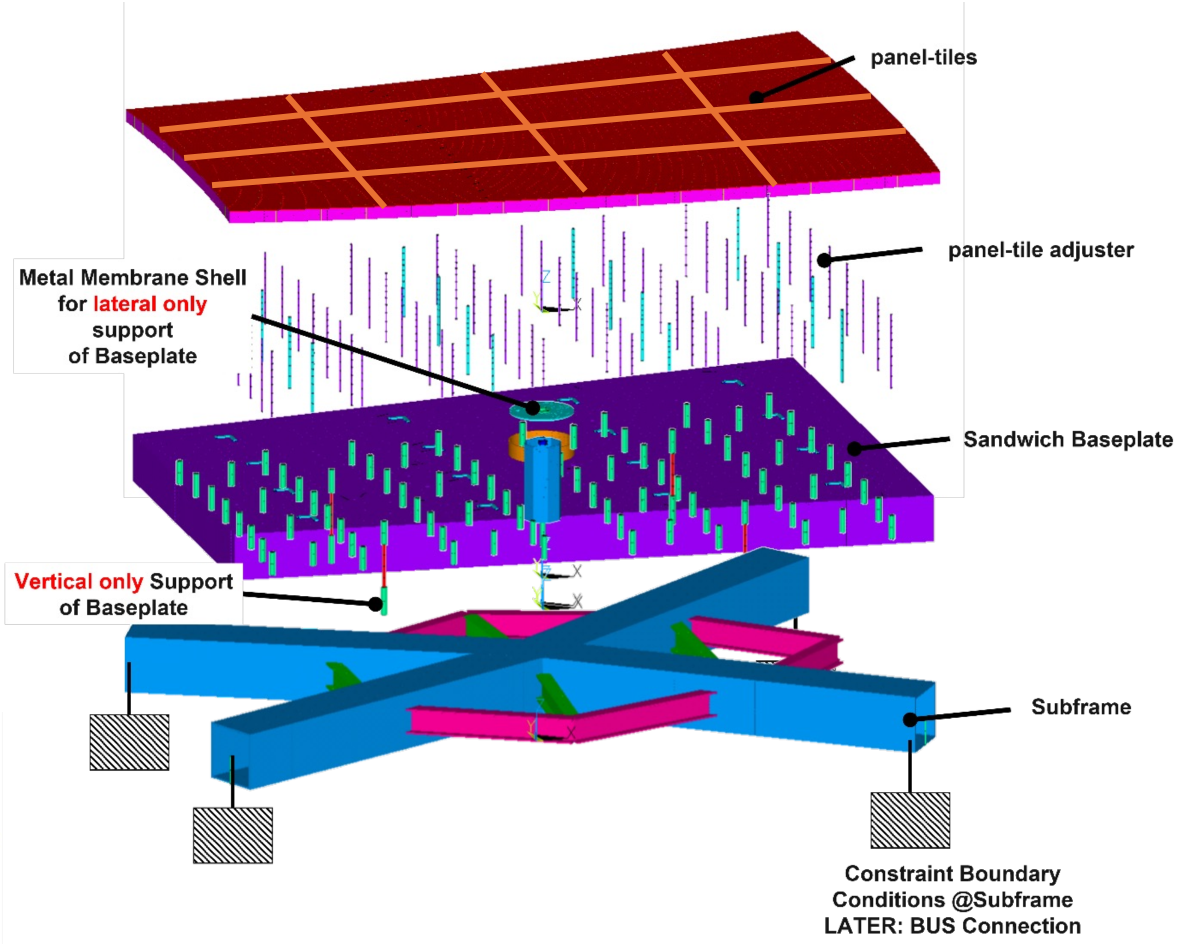
Verification with Finite Element Model

ACTIVE MAIN REFLECTOR SEGMENTS

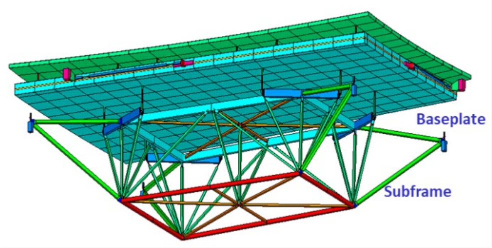
416 panel segments



simplified FE panel segment model

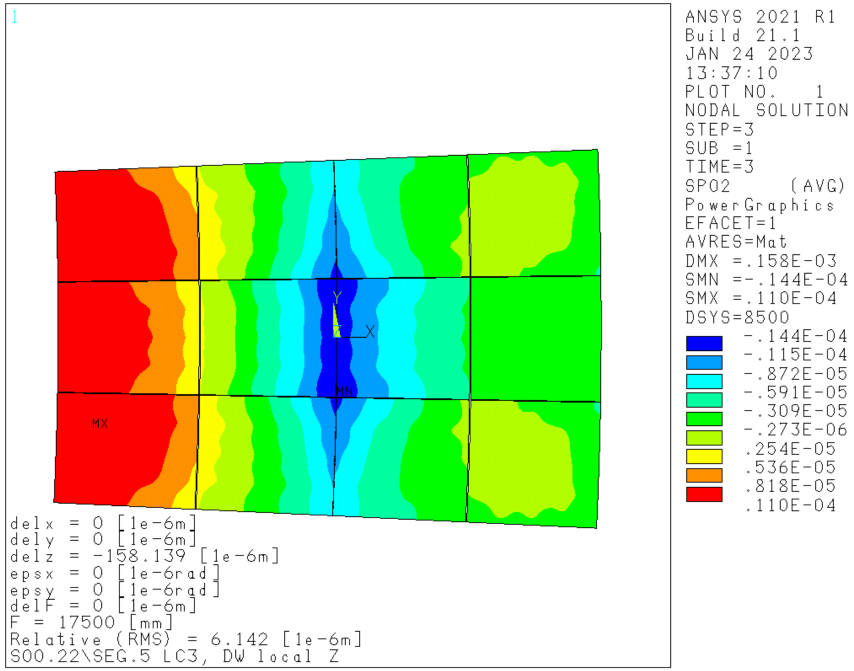


Inspiration LMT



Requirement < 8 µm rms under gravity

6.1 µm rms @EL=90° (exemplary)



AtLAST sens_calc and sens_calc_spec

- https://github.com/atlast-telescope/sens_calc and https://github.com/atlast-telescope/sens_calc_spec were developed in 2018 by Sean Bryan, based on his Bolocalc code used for TolTEC (https://ui.adsabs.harvard.edu/abs/2018SPIE10708E..0JB/abstract)
- The former is for continuum / multi-chroics, while the latter is more appropriate for direct-detection spectrometers.
- Pros: easy to use if you want mapping speeds for direct-detection instruments (KIDs, bolometers), including intensity mapping or tomography experiments
- Cons: assumes background-limited performance by default, not appropriate for heterodyne receivers.

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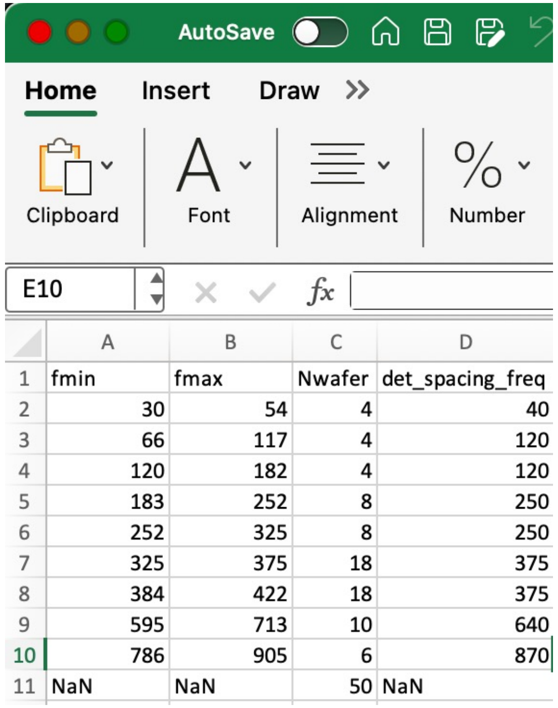
AtLAST sens_calc example

- Takes xls file as input. This contains band centers, bandwidths, detector counts, etc.
- Python code contains detector (e.g. 2 f-λ) spacings, aperture efficiencies, and a factor to conservatively estimate how far from background limited we'll be.
- Output: table with mapping speeds



	A	B	C	D
1	fmin	fmax	Nwafer	det_spacing_freq
2	30	54	4	40
3	66	117	4	120
4	120	182	4	120
5	183	252	8	250
6	252	325	8	250
7	325	375	18	375
8	384	422	18	375
9	595	713	10	640
10	786	905	6	870
11	NaN	NaN	50	NaN

python run_instrument_model_from_excel.py

Output CSV with:

- Number of 150 mm wafers needed
- number of detectors
- beam size
- detector loading,
- mapping speeds in several units (e.g. deg^2/mJy^2/hour),
- and several noise figures (NEP, NEFD)

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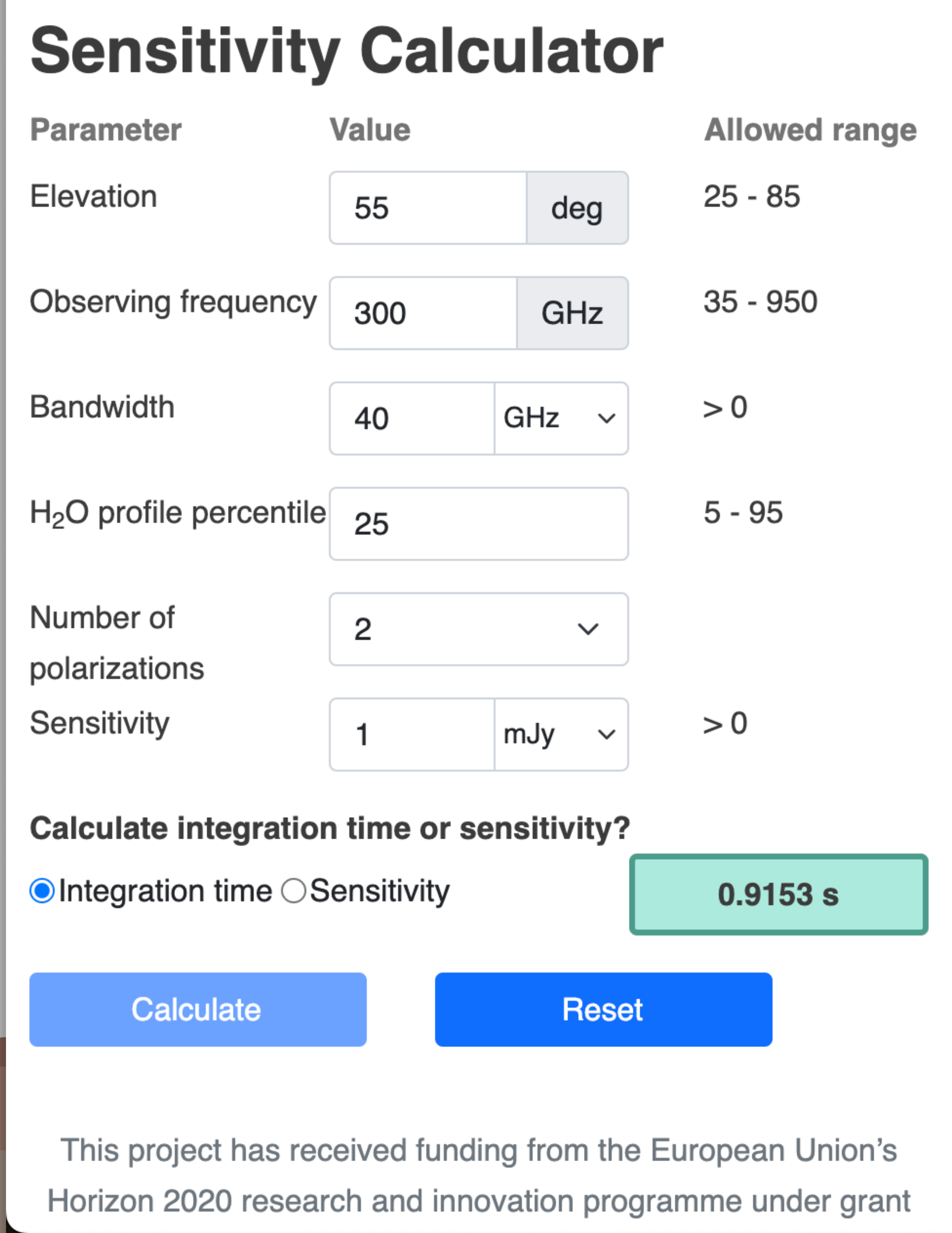
AtLAST sensitivity calculator

- Now the standard for AtLAST, and being developed further by WP6
- Pros: easy to use, well tested against e.g. the ALMA sensitivity calculator
- Cons: primarily tuned for single beam, while our focal plane is optimized for many, many beams.
- Currently only uses noise levels appropriate for heterodyne receivers.
- The ability to take input bandwidths in km/s and provide outputs in RJ brightness temperature (much like the ALMA sensitivity calculator does) would be nice.



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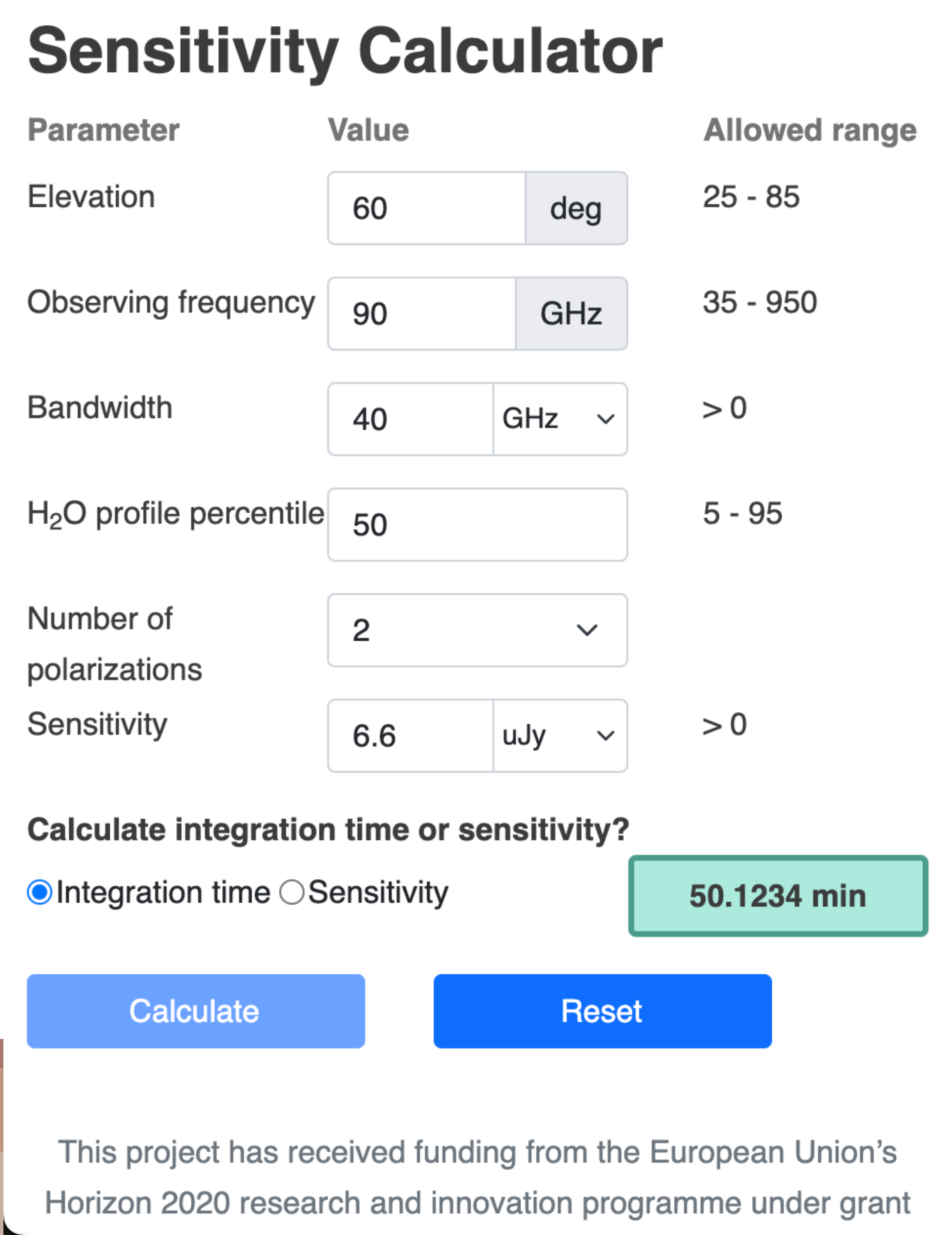
AtLAST sensitivity calculator example

- Example: SZ science case calls for a 90 GHz continuum sensitivity (in a 40 GHz bandwidth) of 6.6 microJy/beam in a 4000 deg^2 survey.
- Beam FWHM is 1.13 lambda/D = 15.5”, solid angle is pi*$(FWHM/2)^2$/ln(2) = 270 sq. arcsec.
- For a large area map made with many detectors, the detector are never off source (so, we can ignore on/off source efficiencies).
- If we want to finish this survey in 5000 hours, we need ~32k detectors in that band (assuming heterodyne-like noise where bolometers/KIDs excel).



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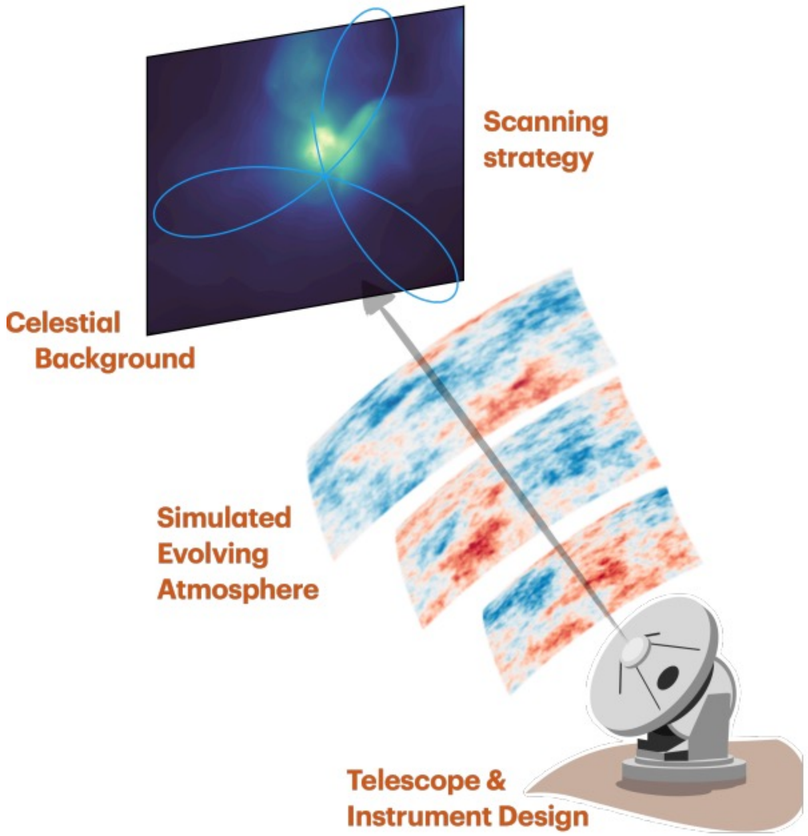
maria

- Does full 3d modelling of the atmosphere, including the near-field/far-field effects, tested in Morris et al. 2022, 2025 against ACT data. See van Marrewijk et al. 2024 (https://ui.adsabs.harvard.edu/abs/2024OJAp....7E.118V/abstract) for information on its application to observation planning.
- Produces time ordered data (TODs) which can then be mapped using built-in linear algebra mapmaker (van Marrewijk et al. 2024) or an external mapmaker (e.g. `minkasi`).
- Now applied to solar observations. Talk to Mats and see Kirkaune et al. (submitted) soon.
- Pros: realistic atmosphere, realistic format of time ordered data, easy to use jupyter notebooks, and soon will take advantage of GPUs (Wuerzinger et al. in prep)
- Cons: more of a learning curve? Needs more realistic detector and photon bunching noise (like `tiempo` has, next)



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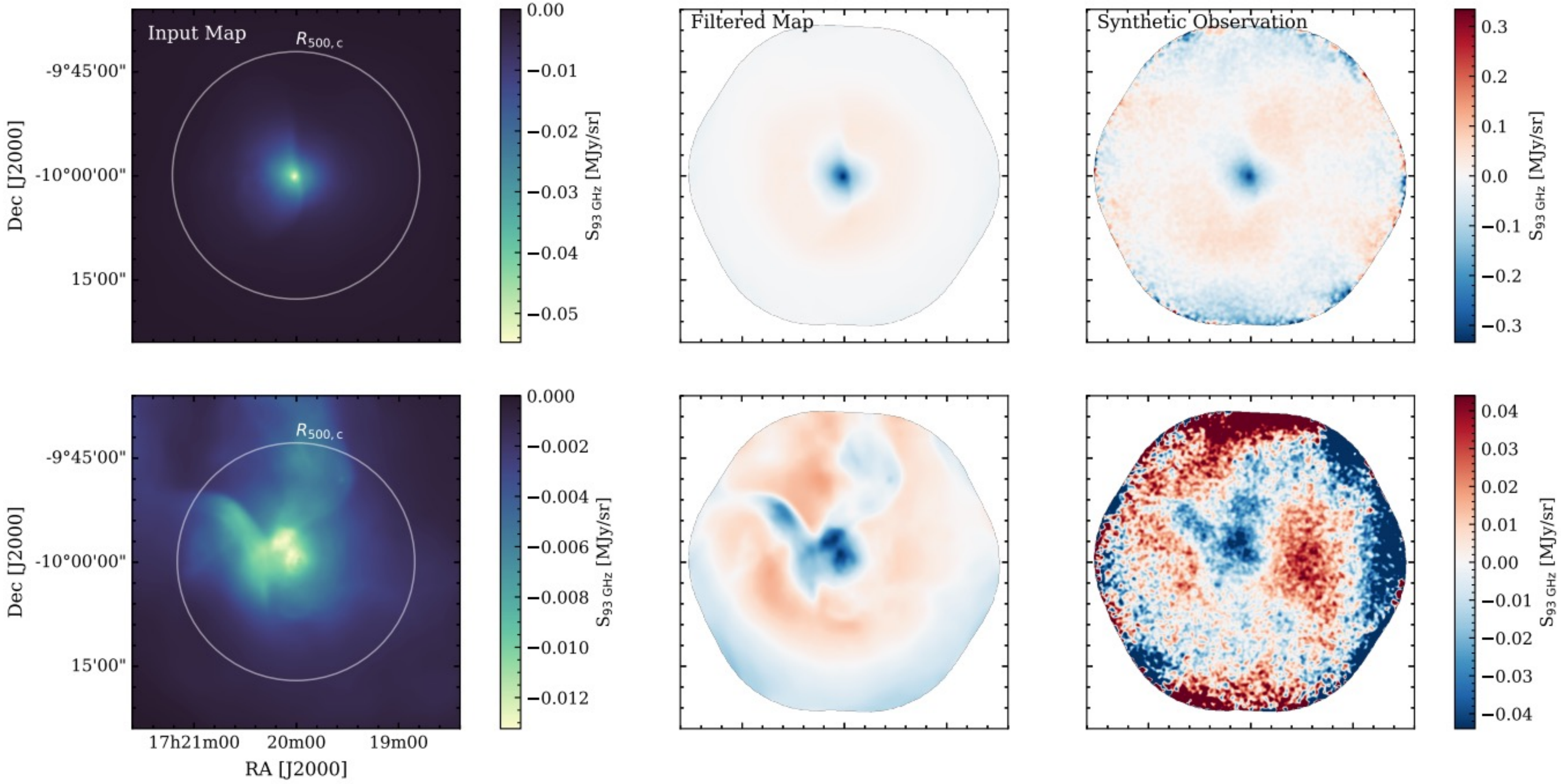
maria

- Input, noise-free, and realistic output maps shown for 2 example observations
- See `maria` AtLAST forum talk by Joshiwa van Marrewijk for further details
- Future tutorial to be given by Thomas Morris



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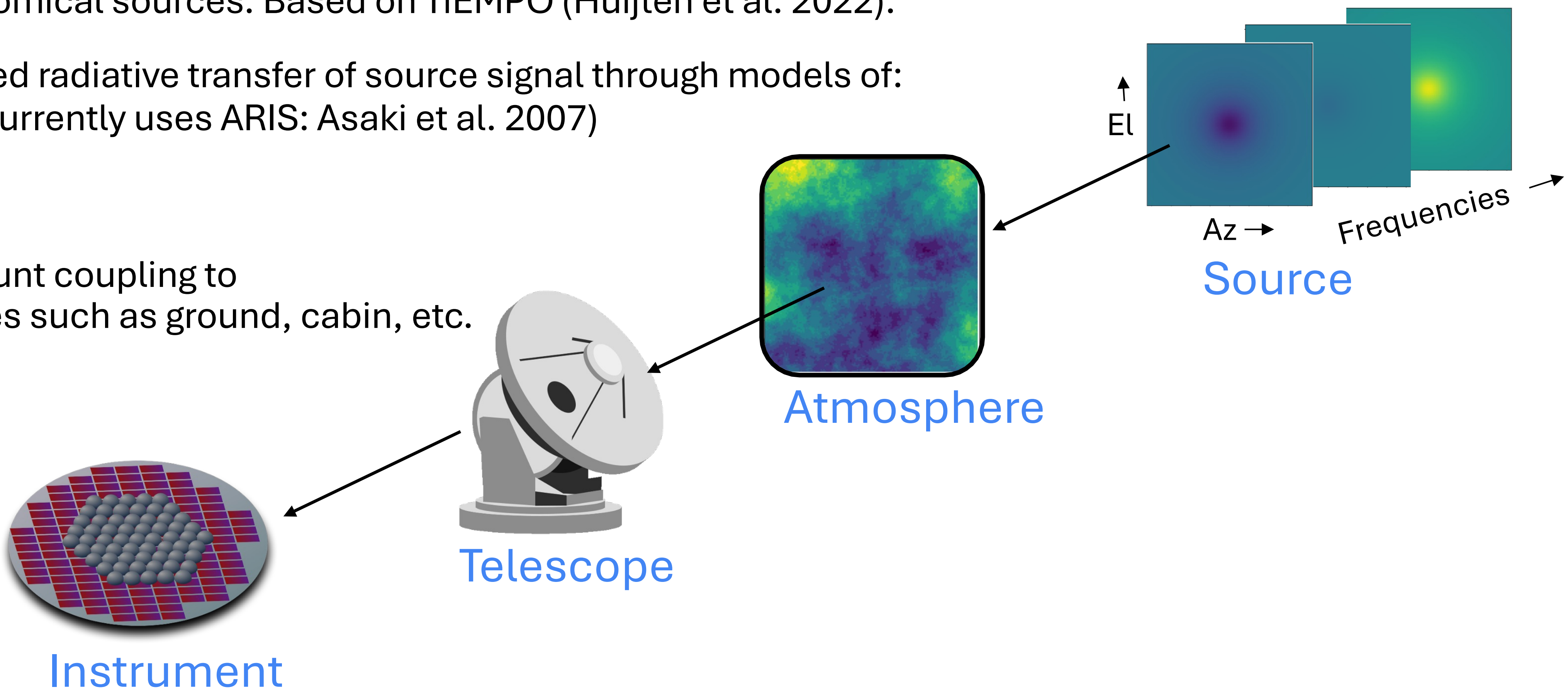
Gateau (see Arend Moerman's poster)

GPU-accelerated (CUDA) simulator for spectroscopic ground-based submm observations of arbitrary astronomical sources. Based on TiEMPO (Huijten et al. 2022).

Models cascaded radiative transfer of source signal through models of:
- atmosphere (currently uses ARIS: Asaki et al. 2007)
- telescope
- instrument

Takes into account coupling to parasitic sources such as ground, cabin, etc.



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Slides courtesy Arend Moerman (TU Delft)

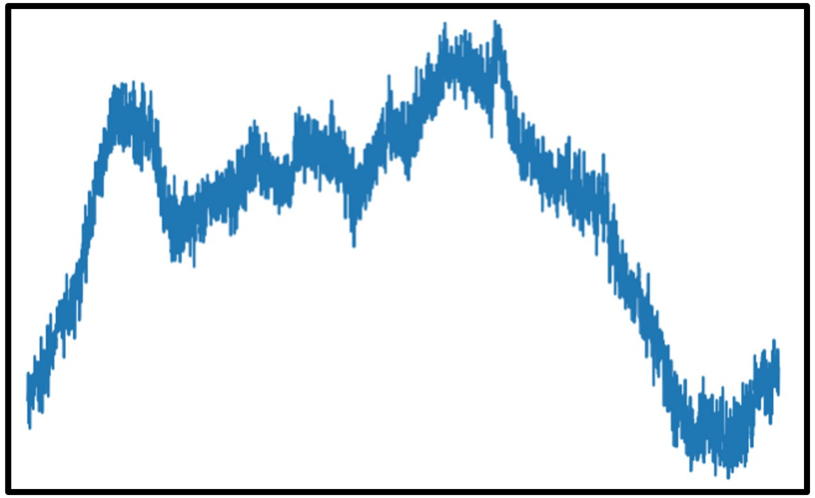
Gateau (see Arend Moerman's poster)

Cascaded signal is integrated over spectral response of each channel to calculate received power time-ordered data (TOD) for that channel.

Noise calculation is based on physical principles:
- Photon noise (Shot noise & bunching)
- Quasiparticle generation-recombination noise
and added as Gaussian white noise to received power TOD.

Atmospheric fluctuation (~1/f noise) imposed through radiative transfer cascade.

TiEMPO2 can be used to test observation strategies, noise removal techniques, instrument designs, etc.



Noisy TOD produced with TiEMPO2

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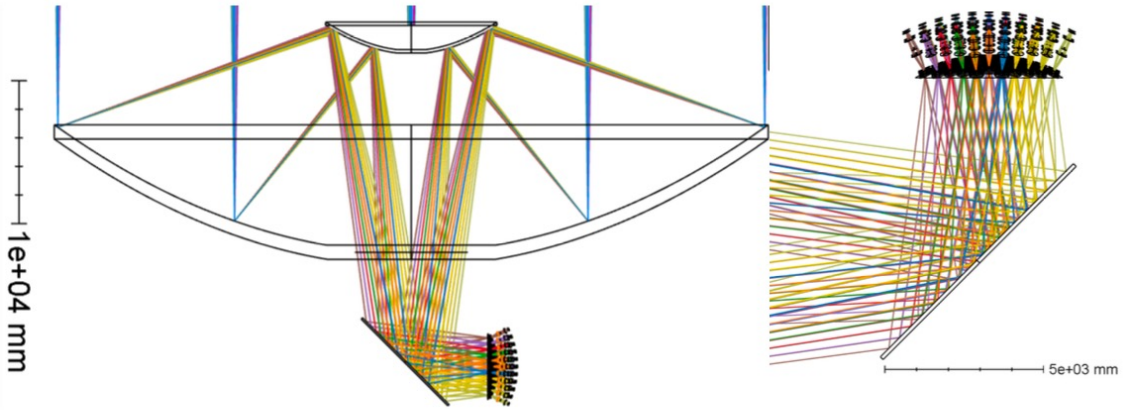
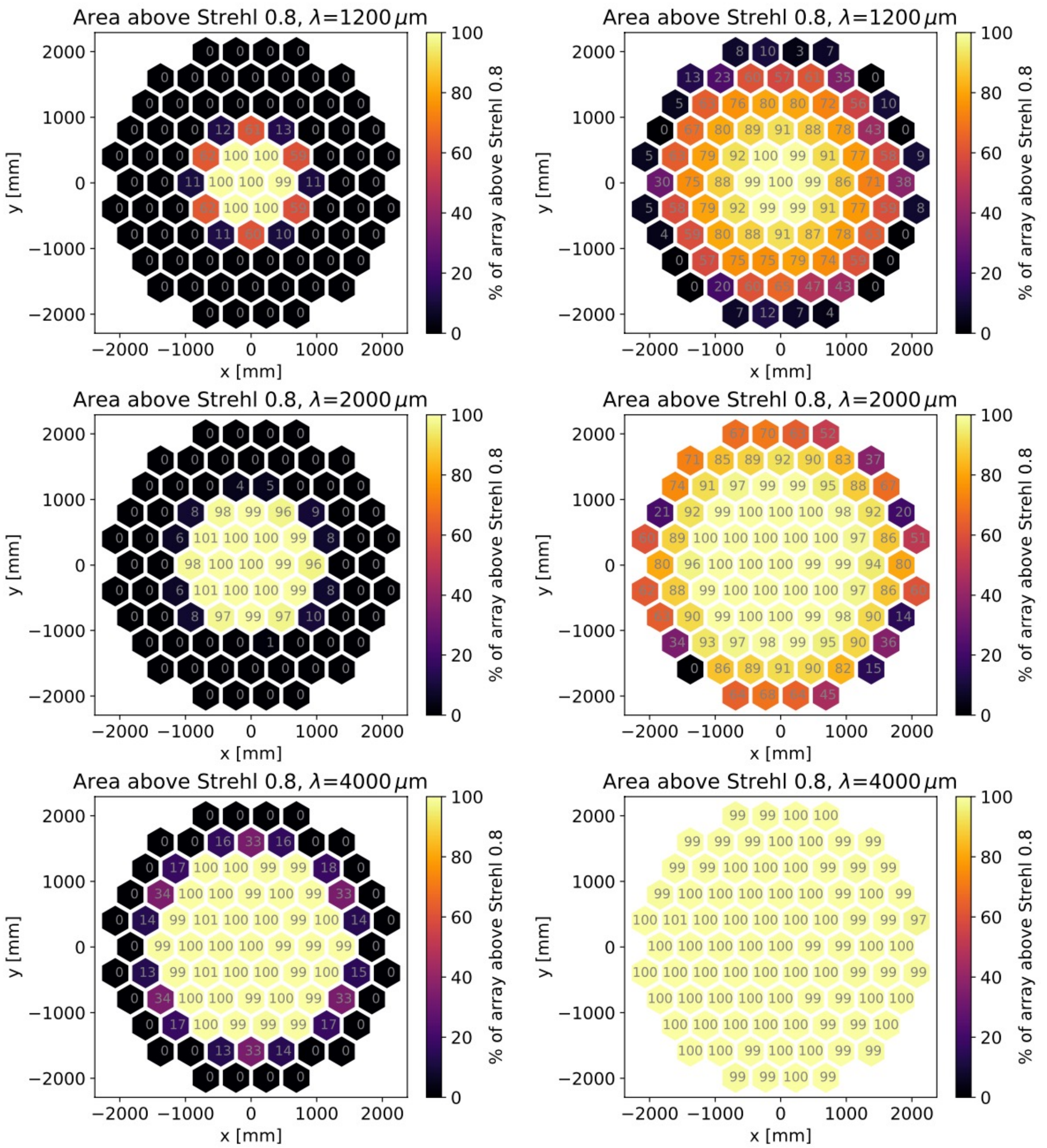
Slides courtesy Arend Moerman (TU Delft)

Optical corrections

Gallardo et al. 2024

- With a huge (4.7 meter) focal surface, the idea is to break it up into modular cameras. Each camera then has corrective optics to recover a large field of view.
- Lower frequencies (<300 GHz) are shown on right. Left column is *uncorrected*; right column is *corrected*.





Optical corrections

- Higher frequencies (>300 GHz) are shown on right. Left column corrected and diffraction-limit (Strehl=0.8).
- The right column relaxes the requirement for diffraction limited optics (Strehl=0.7).
- Gallardo et al. 2024 noted that this is for 3 lenses, and that additional optimization using 4 lenses can improve this.