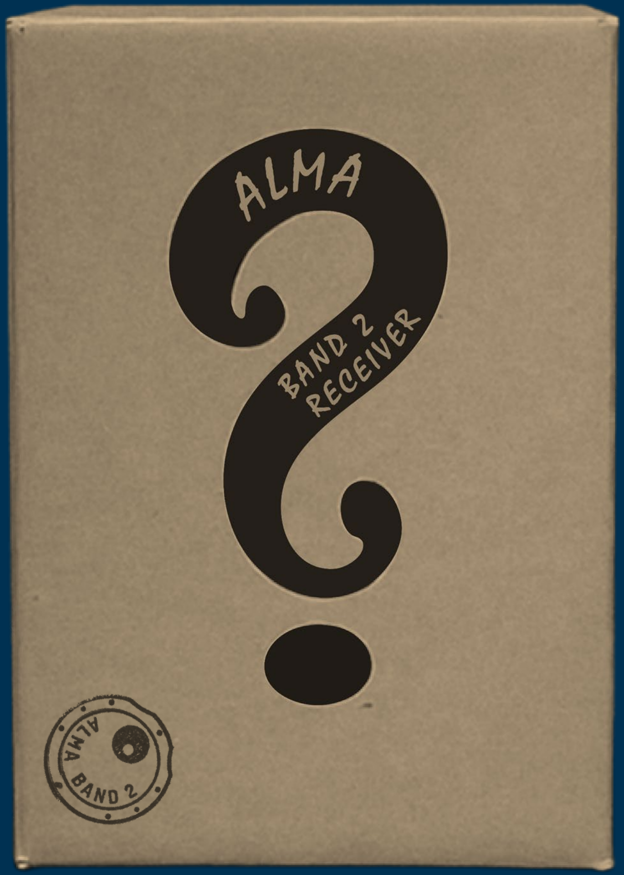


UNBOXING THE ALMA BAND 2 RECEIVER

Fabrizio Villa

Istituto Nazionale di Astrofisica

Osservatorio di Astrofisica e Scienza dello spazio di Bologna

Unveiling the ALMA band 2 Workshop

On behalf of the ALMA band 2 Consortium and Collaboration

COLLABORATION AND BAND 2 CONSORTIUM

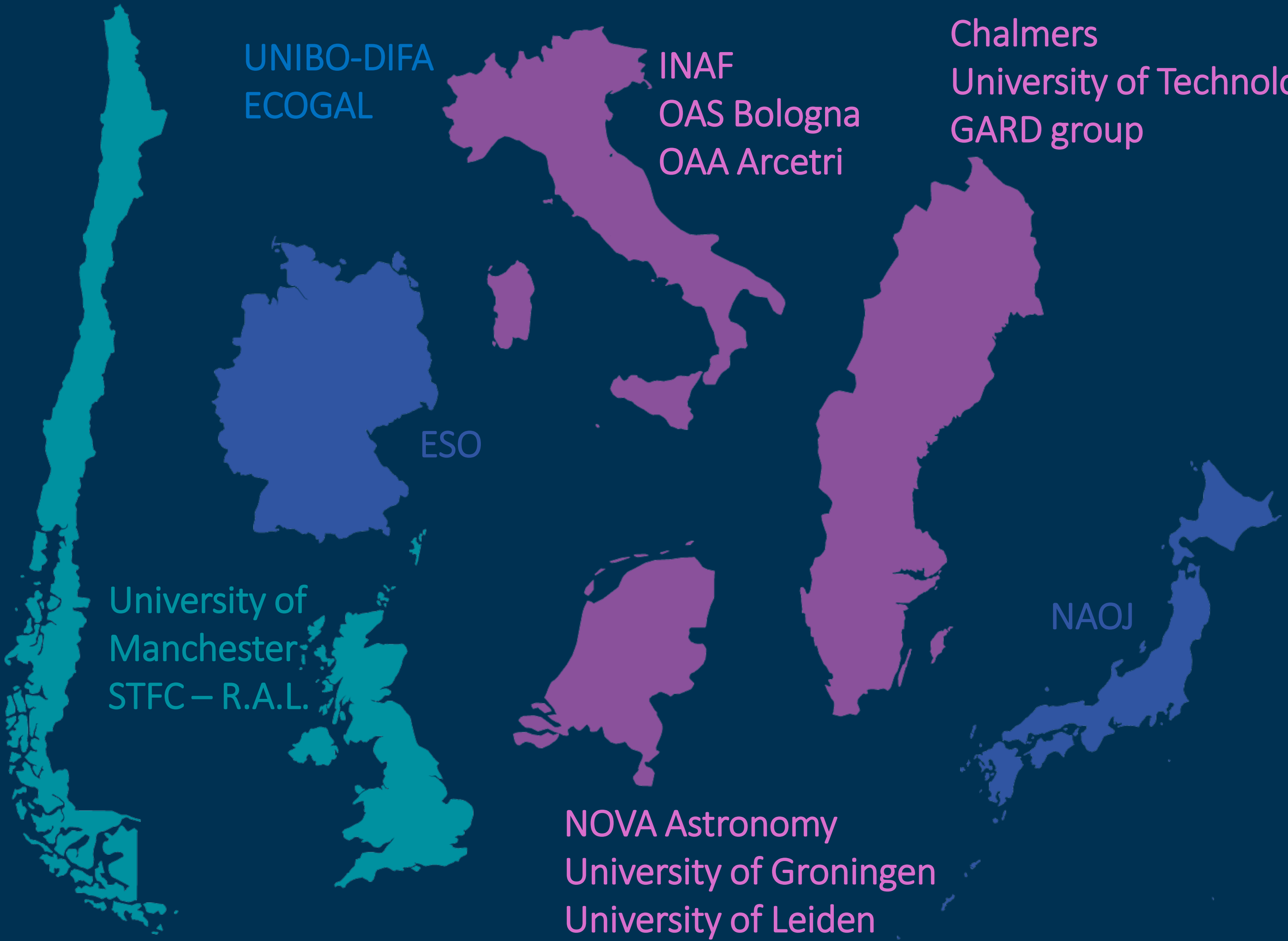
Band 2 Consortium For Production

Band 2 Production Partners and Providers

Band 2 Development studies Partners

ESO is also the funder

NOVA is also producing the WCA



Countries not in scale ;-)
mapssvg.com, CC BY 4.0

Band 2 Collaboration and Consortium for Production

ROLE OF THE PARTNERS

PAS: Provisional Acceptance on-Site
PAI: Preliminary Acceptance In-house

ESO:

- Project Management
- Low Noise Amplifier procurement and testing (MPIfR-IAF, LNF)
- Ancillary components procurement
- System testing at OSF (PAS)

NAOJ

- Feed-OMT procurement and testing
- Lens procurement and testing

UNIBO-ECOGAL

- Support to ESO for LNAs testing

ALMA

- System testing at AOS (PAS)
- Installation on Antennas

NOVA:

- Overall Consortium Project management
- Quality and Product Assurance
- System Engineering
- CCA production, integration and testing (PAI)
- WCA production, Integration and Testing (PAI)

GARD

- Local Consortium project management
- Thermal and Mechanical Design
- RF design
- Prototyping, support for production
- System Engineering

INAF

- Local Consortium project management
- Development phase
- Partial prototyping and production testing
- System Engineering

SUMMARY

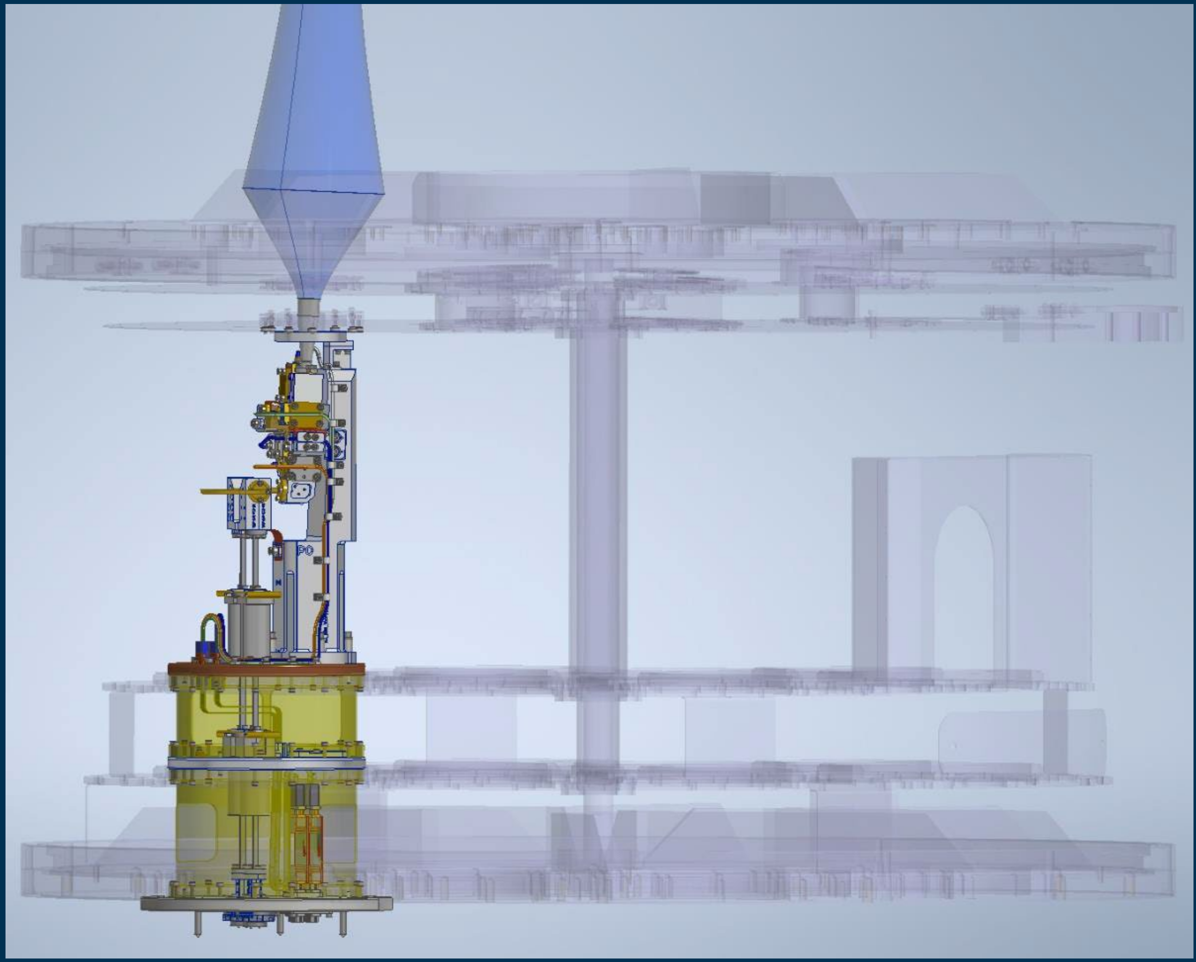
- Milestones
- Design framework
- IR filters and cryostat
- Cryogenic aspects
  - IR filters
  - Thermal contraction
- Noise and gain budget
- Solved issues
  - LNAs
  - Optics
- Unboxing the CCA
- Conclusions

ACHIEVED MILESTONES

- Band 2 Receiver is the result of 8 years of development studies, 3 years of optimization for production and 2 years of full production
  - Development studies (started in 2012)
  - Preliminary Design Review (PDR) Passed, 2nd half of 2017
  - Critical Components Baseline Selection, mid 2019
  - Phase 1: Kick-off (KO) for design and production phase, early 2020
  - Critical Design Review (CDR) passed, early 2023
  - Gateway review (ESO review), early 2023
  - Interferometric First Light, mid 2023
  - Manufacturing Readiness Review (MRR) passed, 2nd half of 2023
  - Pre-production completion, early 2024
  - Phase 2: Start of Production, early 2024
  - Phase 2: Mid of production, mid 2025
  - Science Verification, end of 2025
  - Band 2 offered in Cycle 13th, 2026
  - Unveiling the band 2 workshop, today!

DESIGN FRAMEWORK

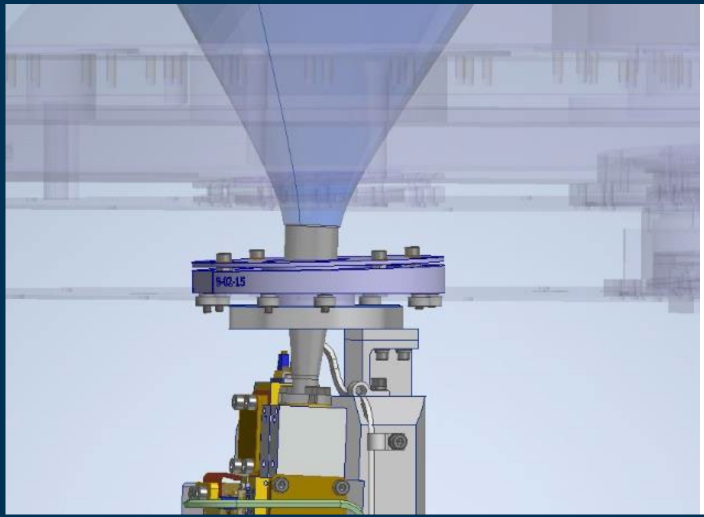
- **67-116 GHz RF bandwidth**
  - 2-18 GHz IF bandwidth (Sideband sep. Mixer 2SB)
  - 32 GHz IF bandwidth (USB + LSB)
- **Use of LNAs instead of SIS mixers**
  - 4K cooling stage not used
  - Tunable gain / optimization
- **Lens based re-imaging optics**
  - Lens made of UHMWPE
  - Lens alignment is necessary when mounted on the cryostat
  - Reflective optics design not feasible
  - Silicon lens was also investigated, but not reliable for ALMA long term usage.

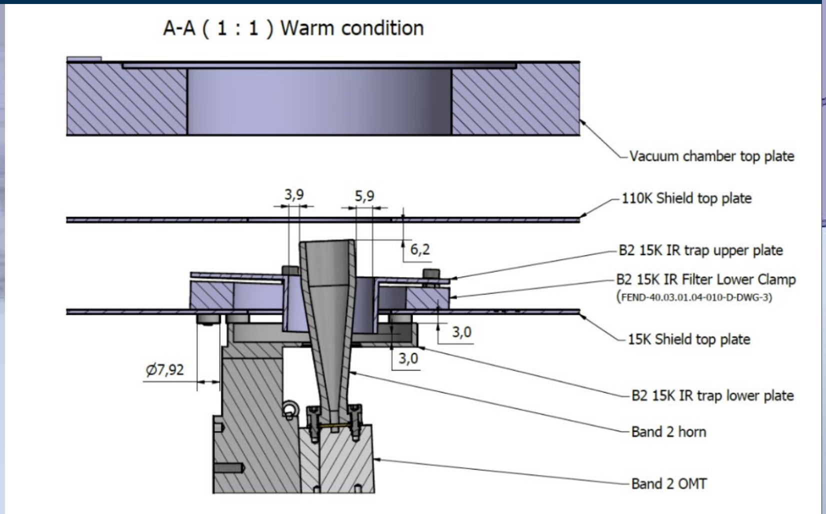


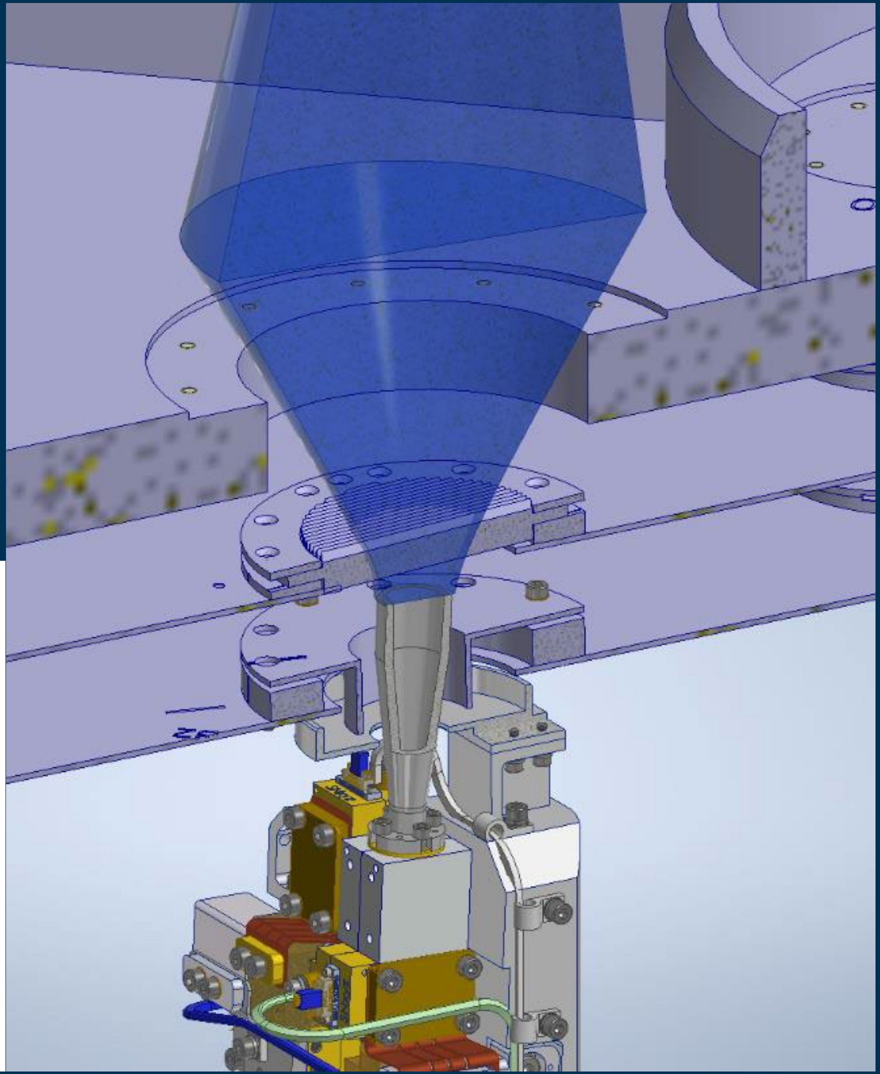
Courtesy V. Belitsky, GARD

CRYOGENIC ASPECTS 1/2

- The 15K filter installed in ALMA has been removed
  - The horn passes through the 15K shield to avoid truncation
  - Dedicated thermal shield designed and mounted on the CCA pillar
- The 110K filter has been changed to allow wideband operation of the Band 2 receiver
  - Same material, same dimensions and I/F
  - Different design to cover 67-116 GHz range

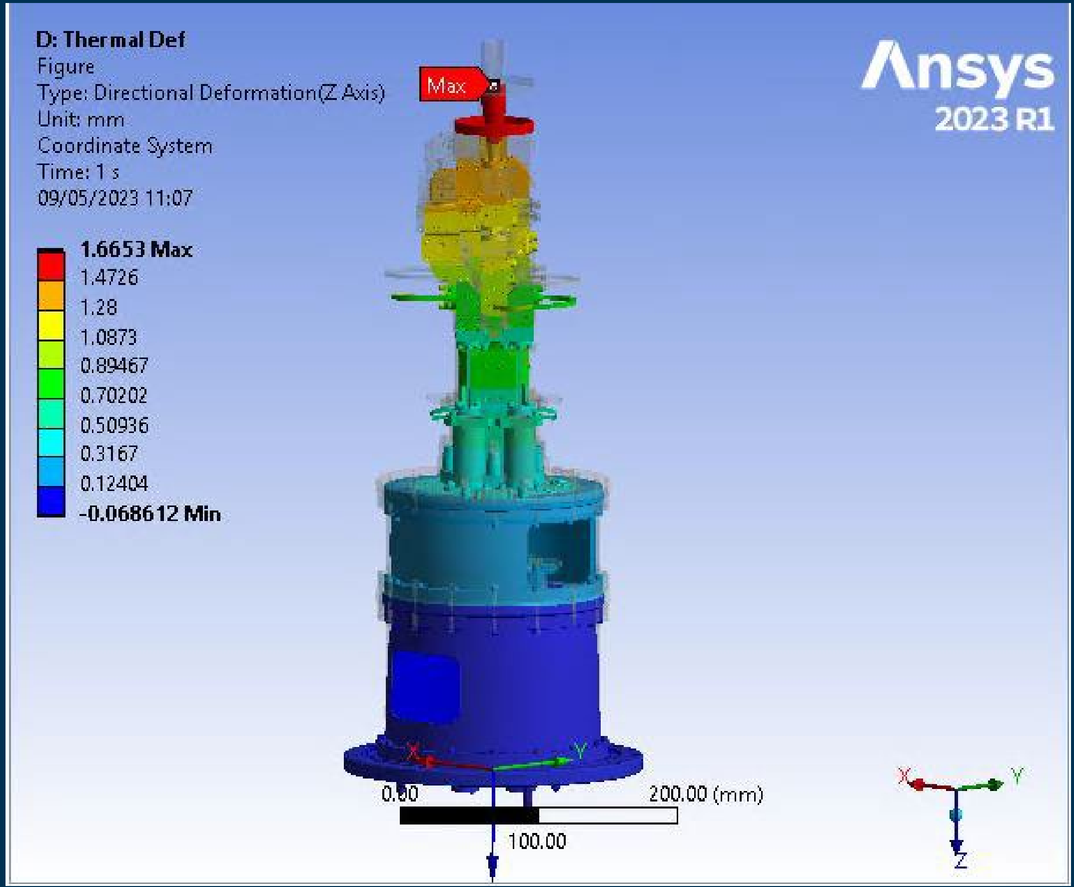






CRYOGENIC ASPECTS 2/2

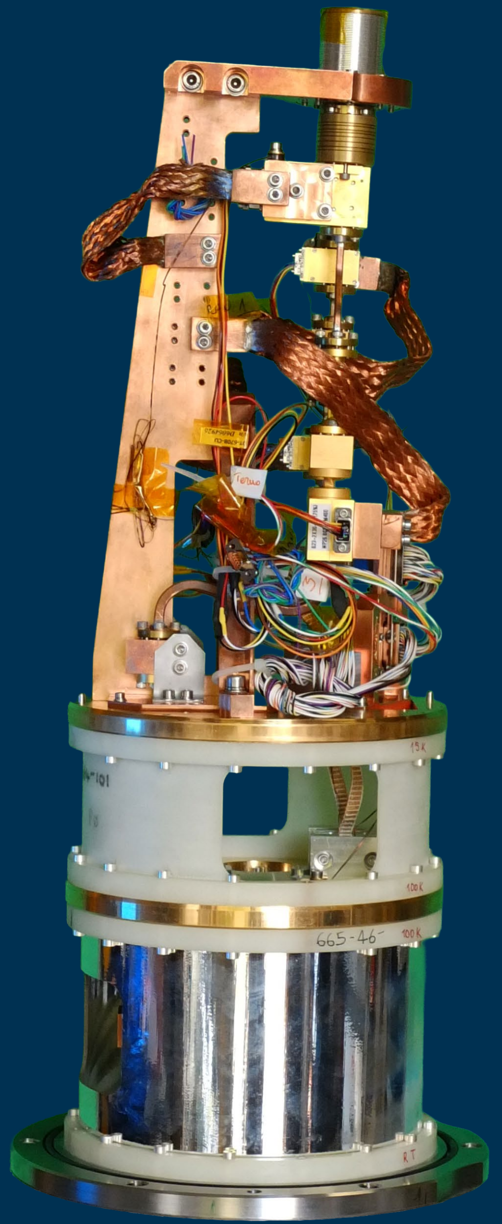
- Band 2 CCA thermal contraction/deformation in the direction along the CCA
  - The contraction along the axis Z is 1.67 mm and largely associated with thermal contraction of the fibreglass spacers of the CCA body and the pillar (deformations are shown with exaggerated scale)
  - Accurate design of the CCA has been done, accounting for and compensating for that.



ALMA Band 2 Prototype Cold Cartridge Assembly Design Report, FEND-40.02.02.00-0197-C-REP
Credits for the analysis GARD

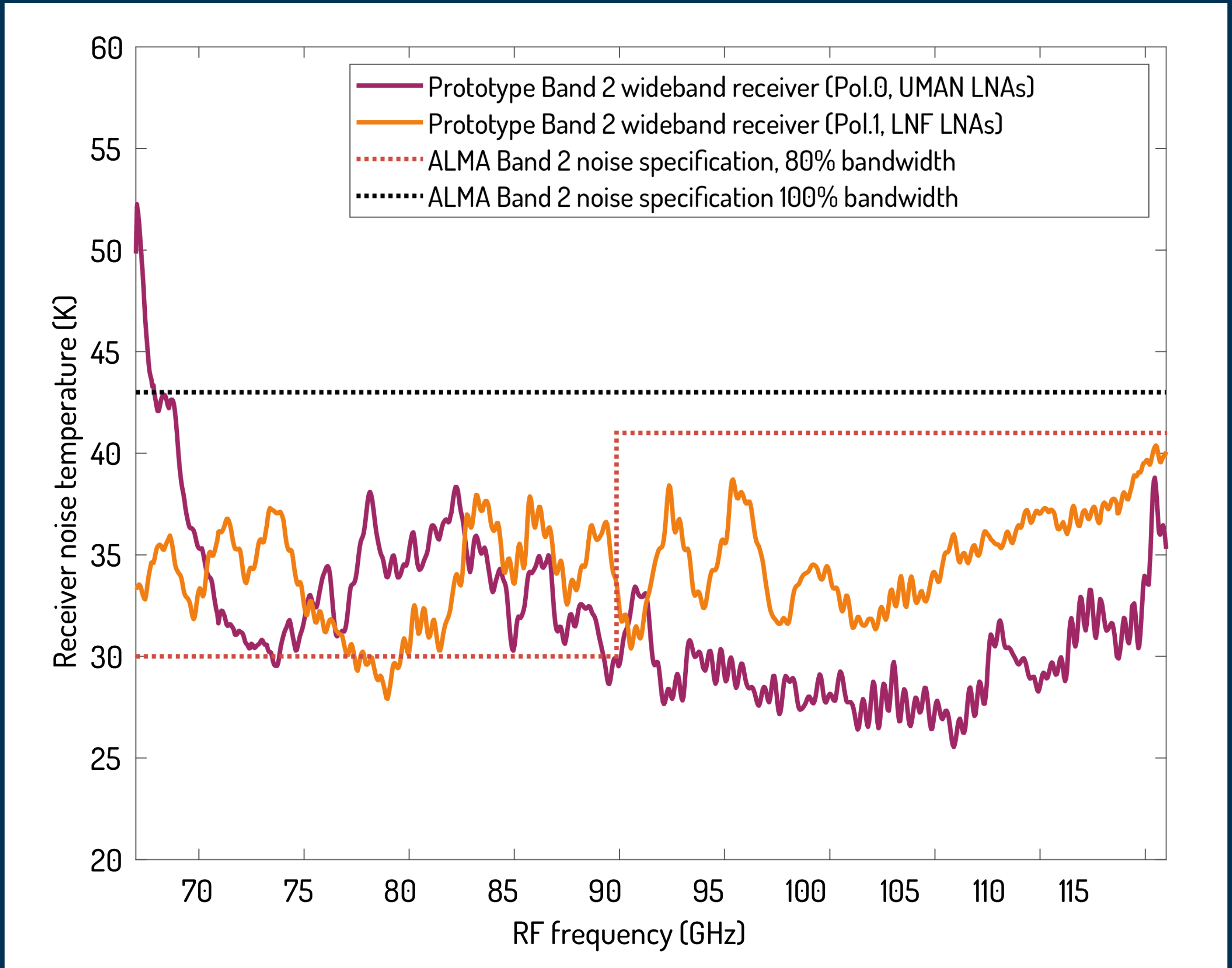
NOISE AND GAIN BUDGET (MRR)

COMPONENT	Physical / Eff. noise Temperature [K]	Gain [dB]	Cumulative Gain [dB]	Noise Contribution [K]	Noise Contribution [%]
Lens	300	-0.037	-0.037	3.858	11
110K IR filter	110	-0.025	-0.109	0.762	2.17
Horn	15	-0.004	-0.138	0.016	0.050
OMT	15	-0.088	-0.226	0.321	0.910
Cryo LNAs	27	46	45.774	29.342	83.700
RF output WG	200	-5	40.774	0.004	0.010
RF WG feedthrough	300	-0.35	40.424	0.002	0.010
Waffle iron interface	300	-0.15	40.274	0.001	0.000
Downconverter	2450	-15	25.274	0.237	0.680
IF section	160 / 300	21	46.2474	0.515	1.48



BAND 2+3 NOISE PDR (2017)

- Noise definition for Band 2
  - concatenation and slight modification of the ALMA Band 2 and Band 3 requirements
- 67-90 GHz range:
  - ≤ 30K over 80% of the frequency range
- 90-116 GHz range:
  - ≤ 41 K over 80% of the frequency range
- 67-116 GHz range
  - ≤ 43K over 100% of the frequency range



Adapted from P. Yagoubov, A&A 634, A46 (2020)

ENCOUNTERED ISSUES

AMPLIFIERS

- Selected amplifiers too 'noisy' to guarantee noise requirements, especially at lower frequencies
- 1st LNA changed on the road to improve noise performance (use of MPIfR/IAF LNAs) especially at lower frequencies

SOLVED in 2021

OPTICS

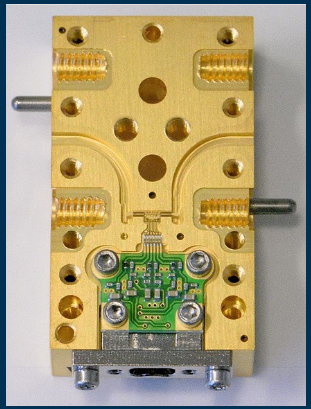
- Lens truncation too high to guarantee noise requirements while maintaining optical efficiencies requirements
- Lens design optimized to minimize truncation especially at lower frequencies (asymmetric lens)

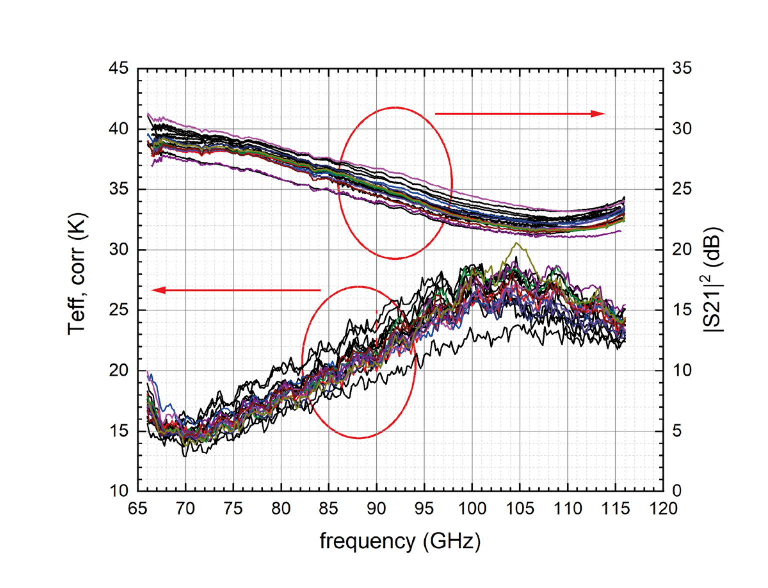
SOLVED in 2024

NEW AMPLIFIERS AVAILABLES TO ESO

- Urgent and test campaign during summer 2021
  - New amplifiers available to ESO, mounted on the pre-prototype at INAF
  - New potential provider identified
  - Noise measurements fully within specs
- Extensive work to adapt the mechanical and RF interfaces with the current band 2 design

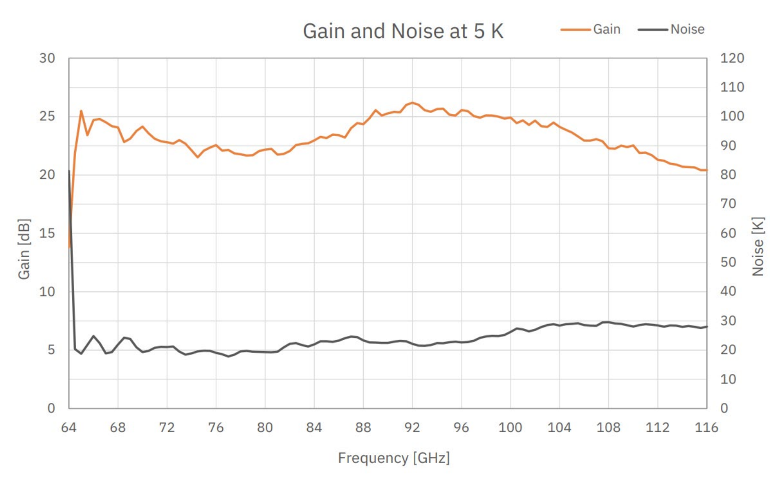
SELECTED CRITICAL COMPONENTS (LNAs)





1st LNA: MPIfR / IAF

2nd LNA: Low Noise Factory

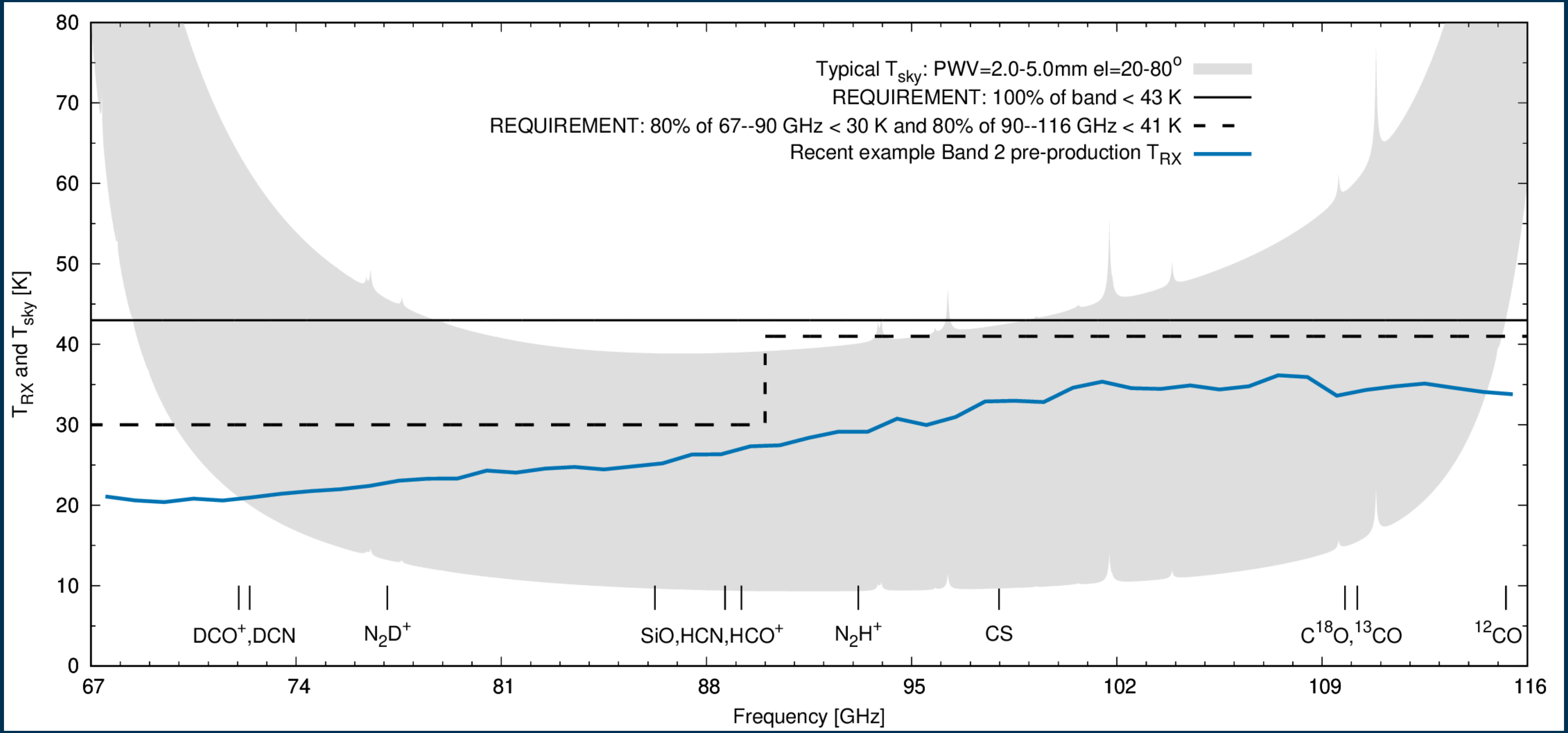


The Promises and Challenges of the ALMA Wideband Sensitivity Upgrade, ESO Garching, June 24-28, 2024

N. Phillips (2024), ALMA Band 2, https://zenodo.org/records/13681547

P. Pütz (2024), InGaAs mHEMT MMIC Technology for Low Noise Amplifiers in Radio Astronomy, https://zenodo.org/records/13681551

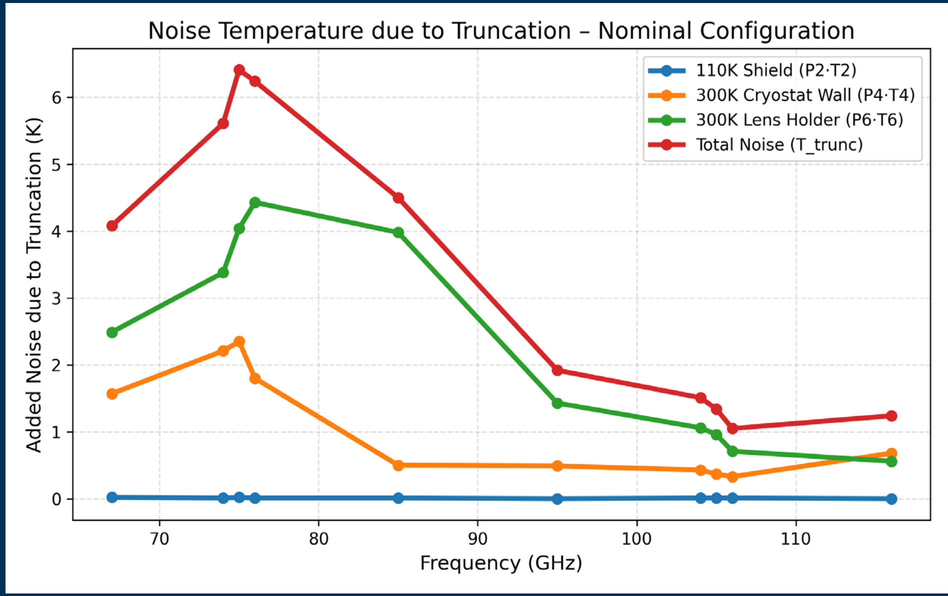
NOISE OF PRE-PRODUCTION UNITS

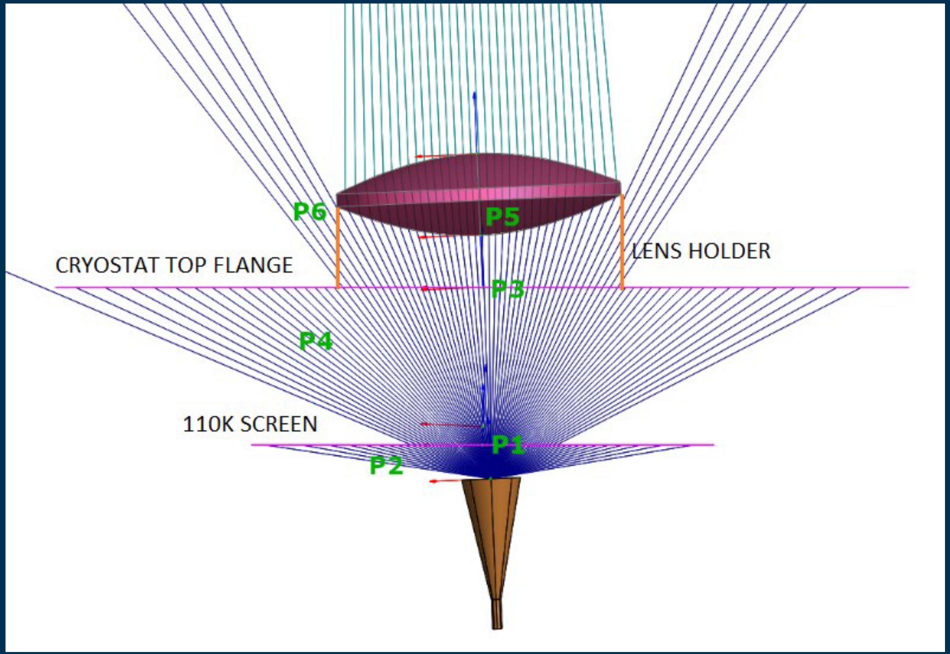


Courtesy J. Barkhof, NOVA

WARM OPTICS

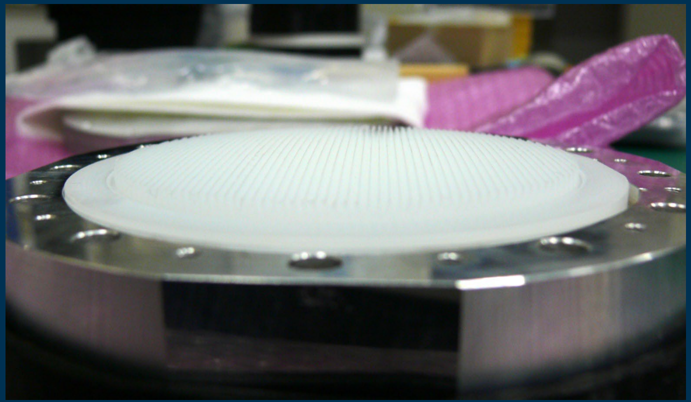
- Although Band 2 design already tried to minimise truncations, there were still several K noise added by truncation at the lens
- Optimizing the lens design with more free parameters we were able to move the edge of the lens closer to the cryostat, improving noise up to 4K, while not degrading beam performances

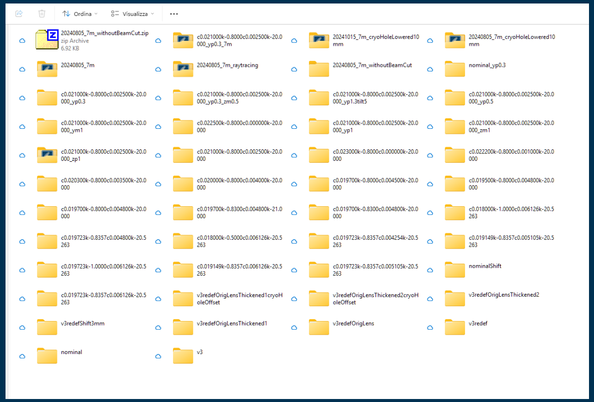


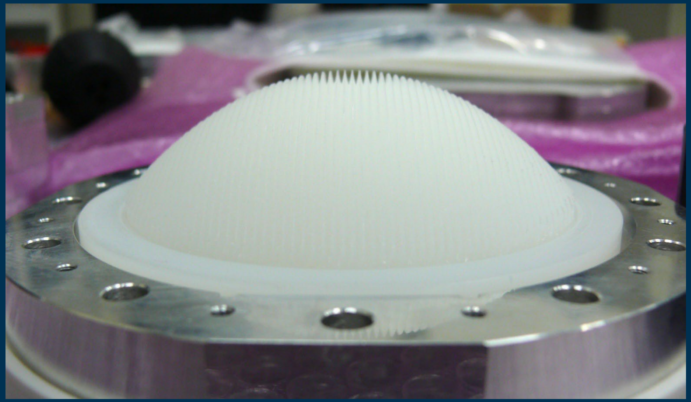


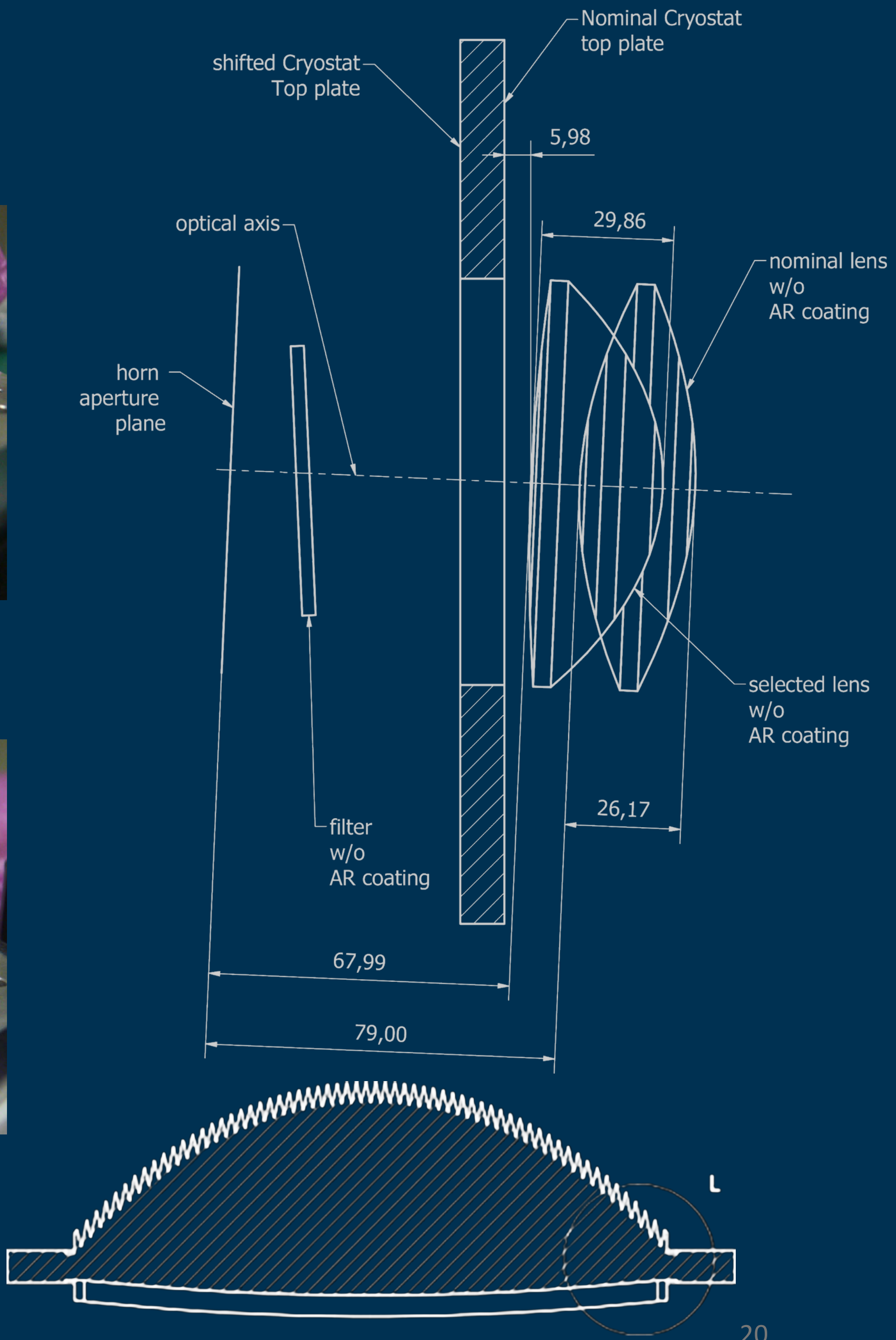
LENS DESIGN OPTIMIZATION

- Optimised design done by ESO (and INAF)
- Approx 30 designs considered and simulated
- Manufactured and delivered by ESO/NAOJ

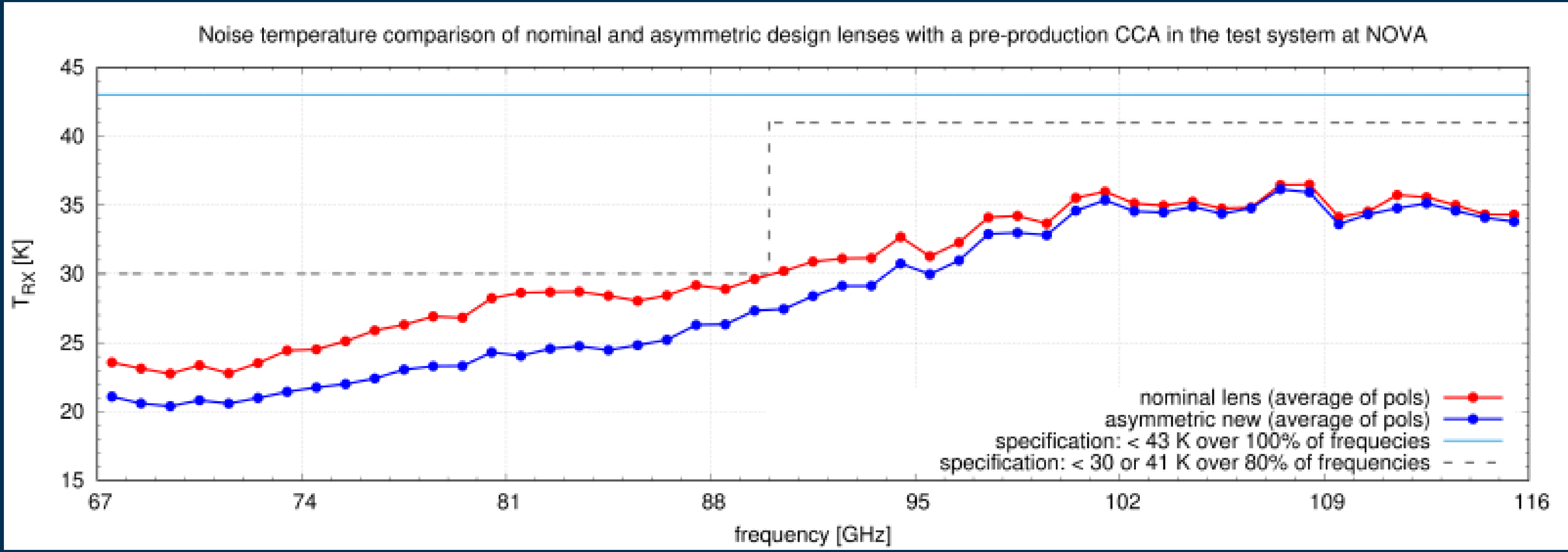








PERFORMANCES OF THE OPT. LENS



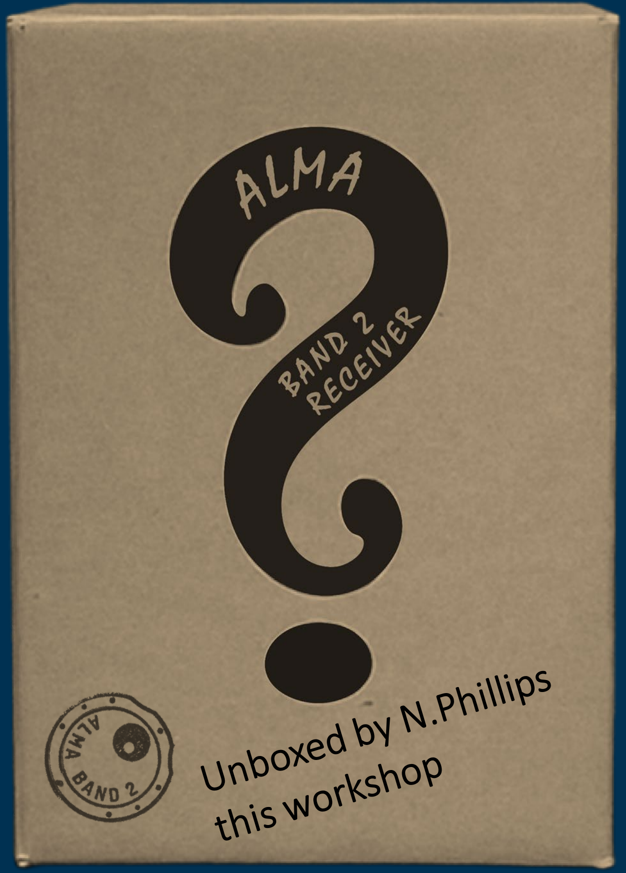
Superior noise performance

Estimated and **measured Optical performances**

Aperture and polarisation efficiencies maintained and **within specifications**

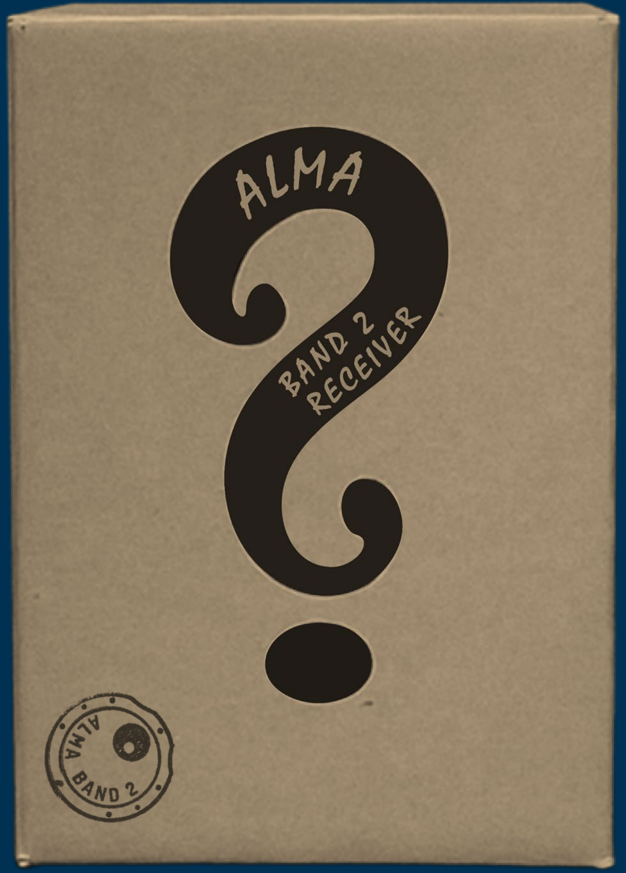
UNBOXING THE BAND2

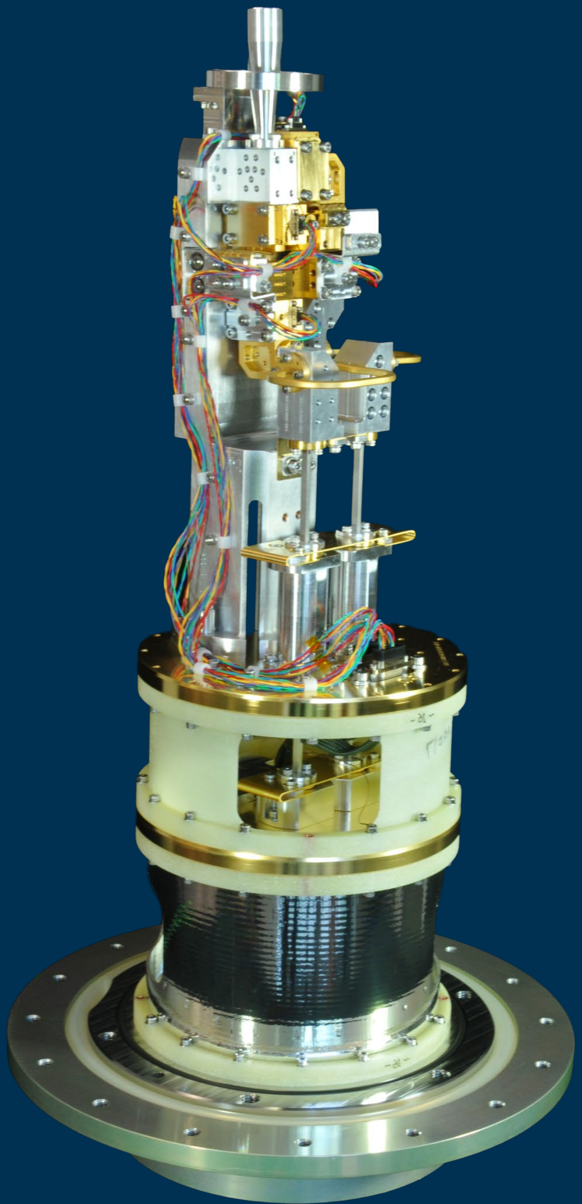
WARM CARTRIDGE ASSEMBLY

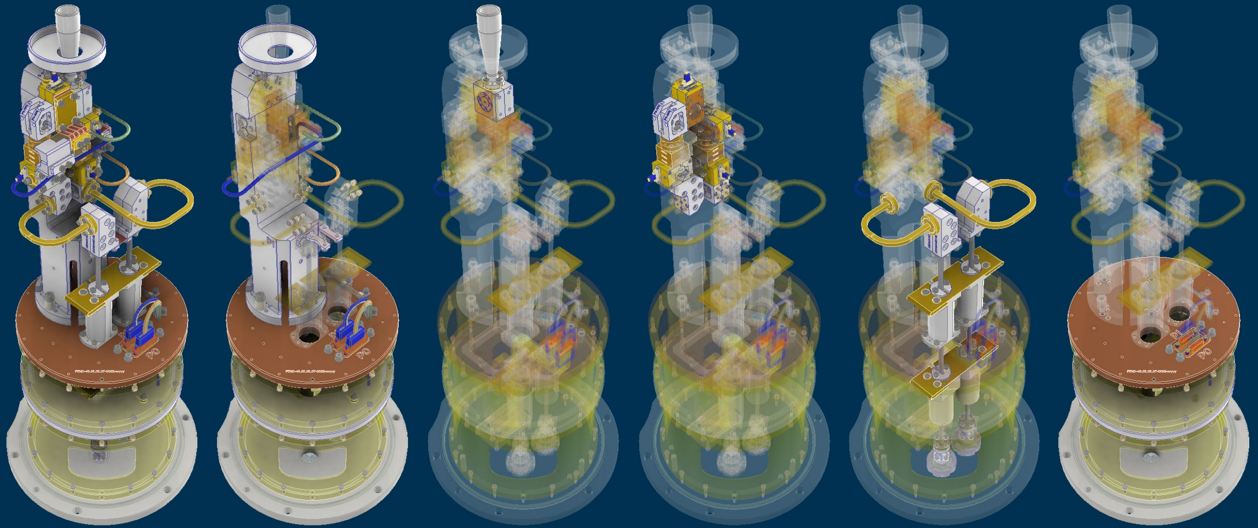


Covered by N. Phillips' presentation

COLD CARTRIDGE ASSEMBLY







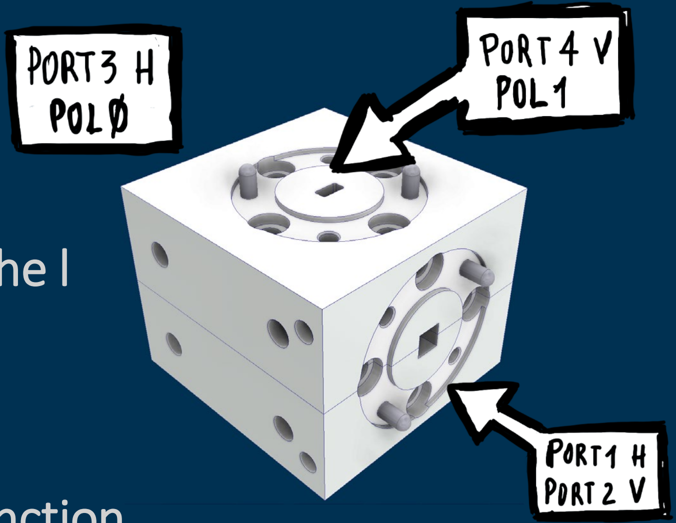
FEED-OMT ASSEMBLY

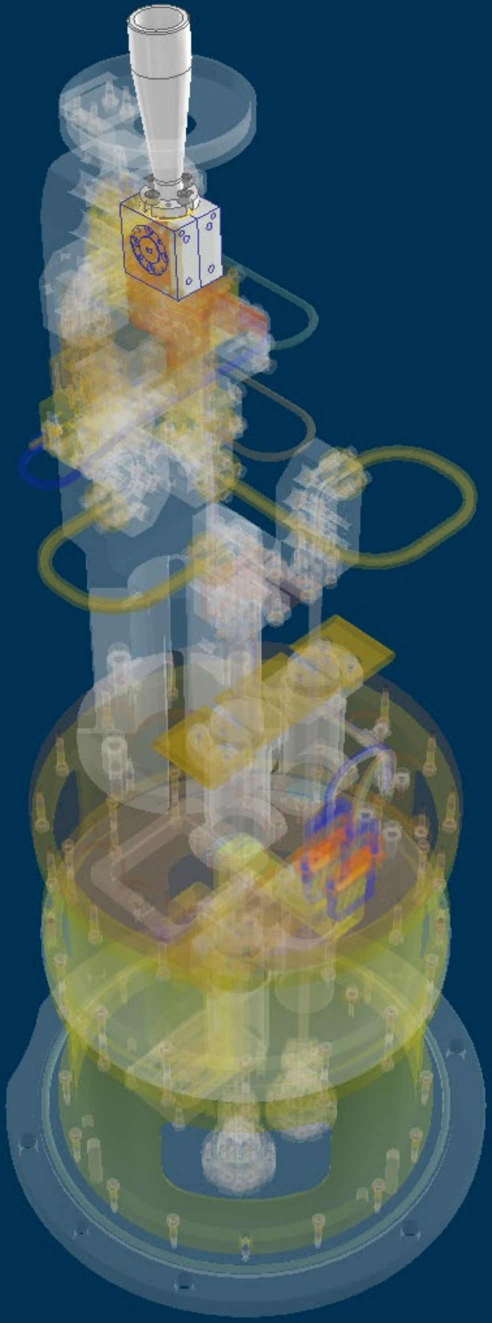
✦ FEEDHORN

- Corrugated horn design
- Optical efficiencies (coupled with the l
- Naturally low-loss component

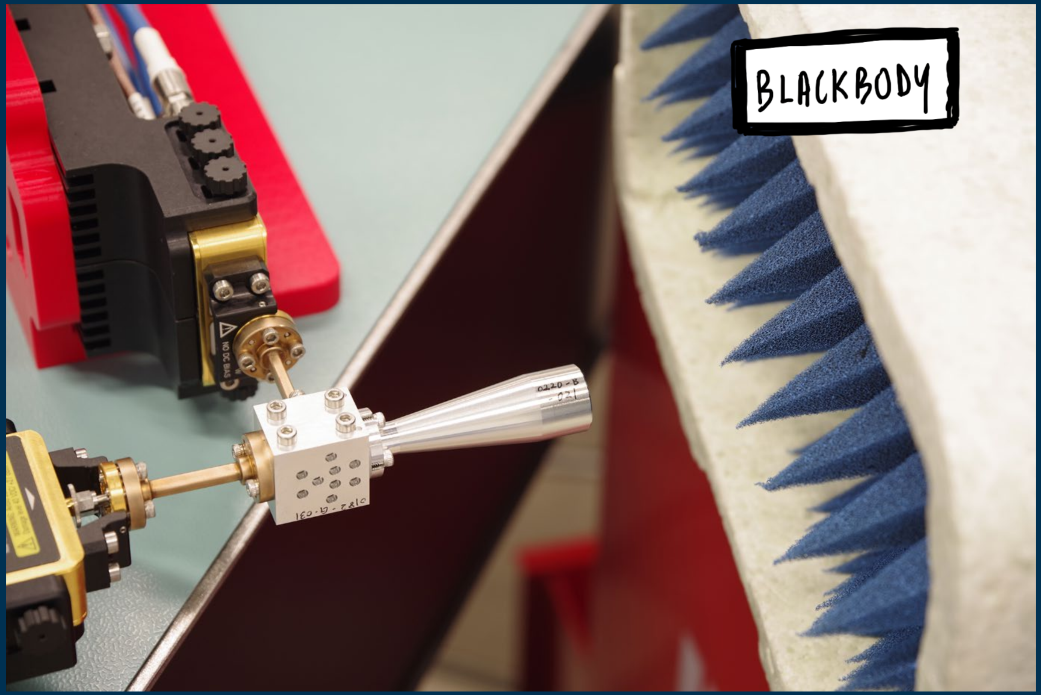
✦ OMT

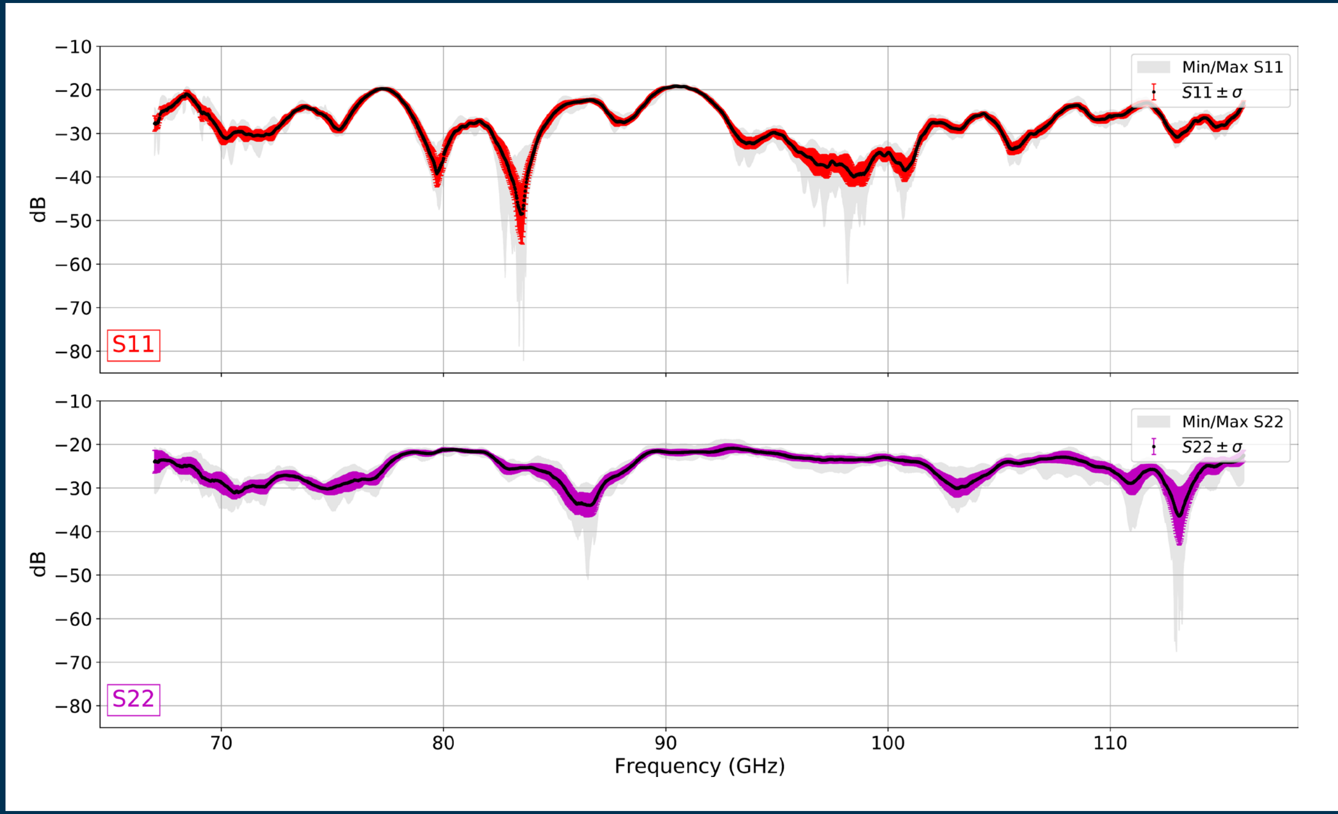
- double-ridged waveguide Boifot junction
- Polarisation separation
- Polarisation efficiency
- Critical component for RF Bandwidth
- Contributes to noise





FEED-OMT PERFORMANCE





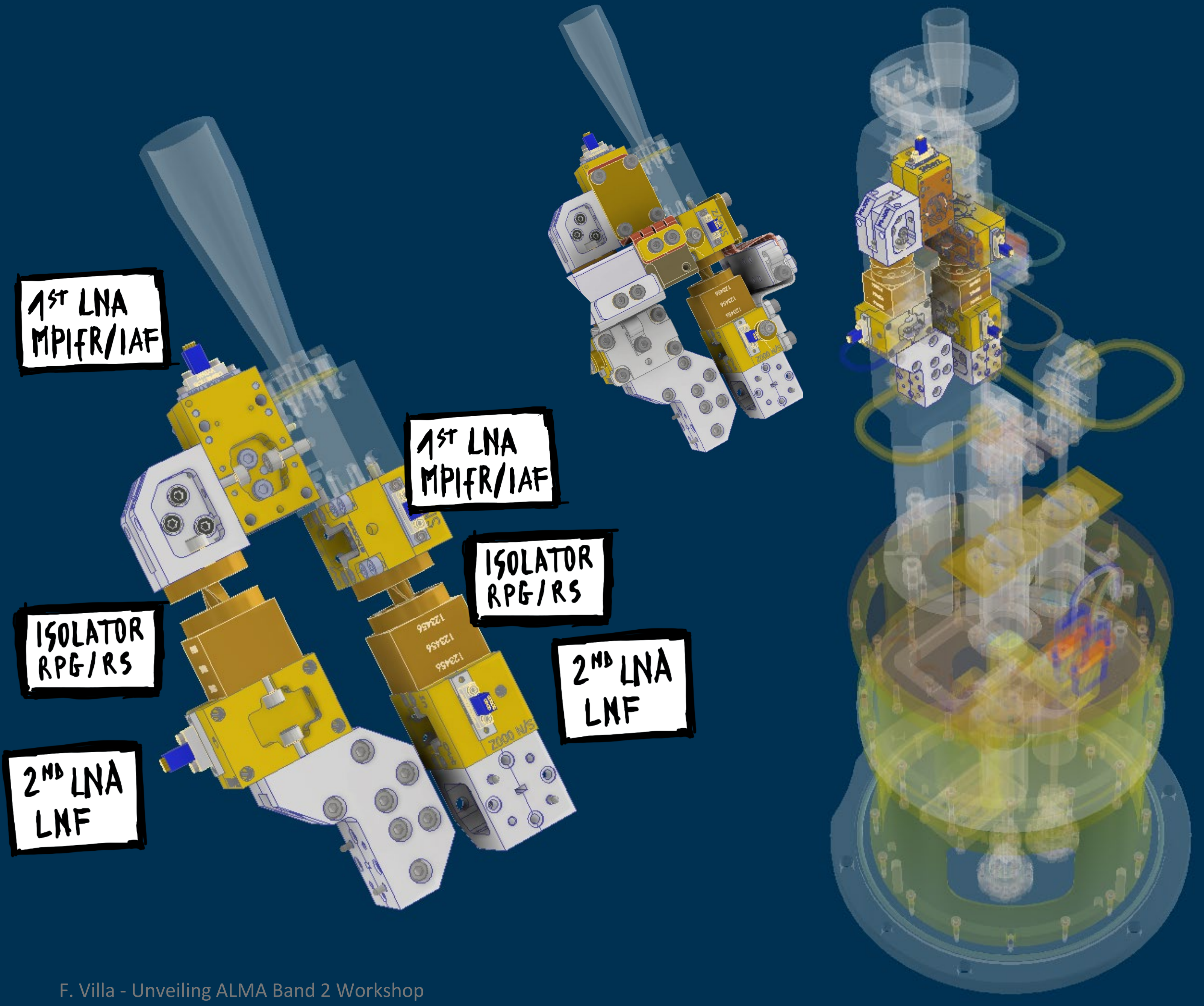
Courtesy of A.E. Camisasca (Unibo, INAF)

K. Kaneko (2024) Summary of wide-band receiver optics studies at NAOJ over the last decade, https://zenodo.org/records/13681519

Masui, S., Sakai, R., Kojima, T.;, Kaneko, K., (2025) Characterization of ALMA Band 2 Orthomode Transducers at Cryogenic Temperatures, IEEE Trans. Instrum. Meas. , 74, 1–8, https://doi.org/10.1109/tim.2025.3556827

AMPLIFIER'S SECTION

- 1st LNA
  - MPIfR – IAF
- Isolator
  - Radiometer Physics GMBH R&S
- 2nd LNA
  - Low Noise Factory
- Waveguides Compoments
  - NOVA / GARD
- Interface Definition
  - INAF
- Opt. and Tuning
  - ESO / UNIBO-DIFA
- Integration
  - NOVA

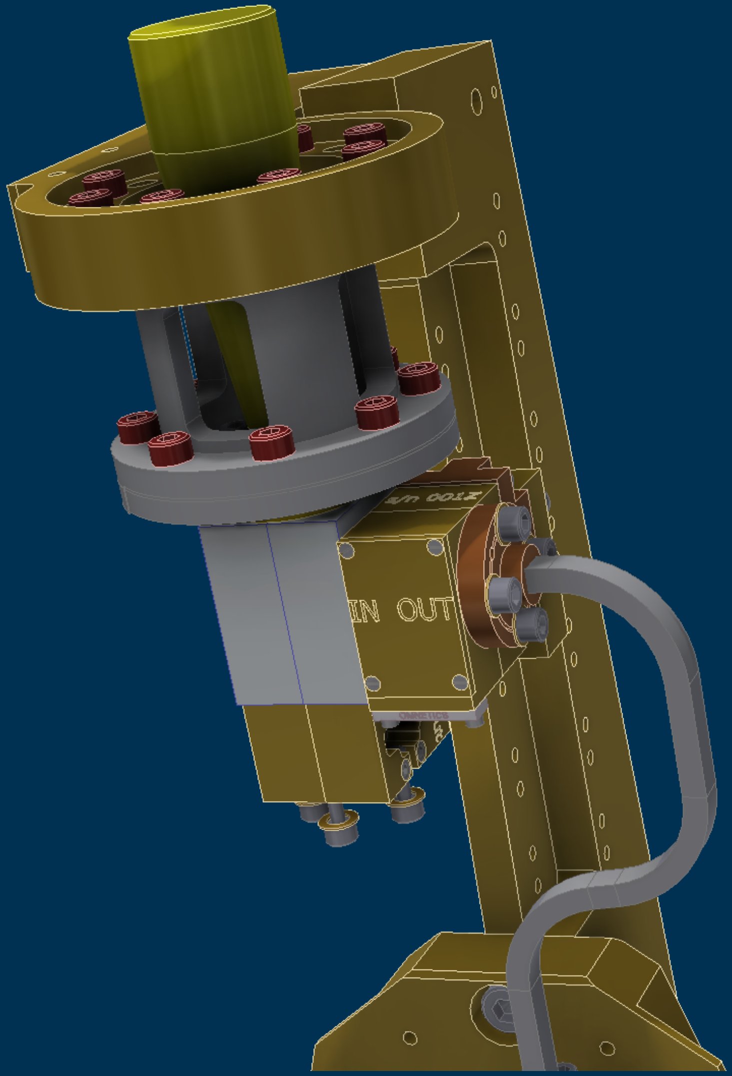


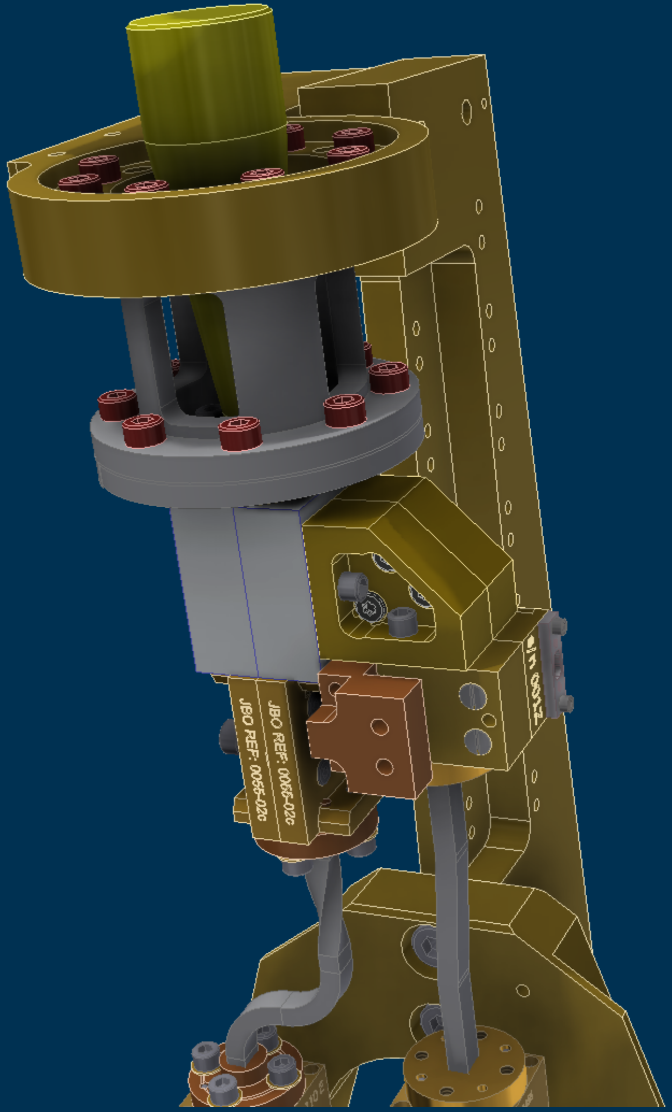
EXAMPLE: 90° WAVEGUIDE BEND

- Dedicated test with the pre-prototype
  - With and without the bend
  - Difficult noise measurement
  - Several noise measurements compared
  - S-parameter test done at ambient temperature

Added Noise:

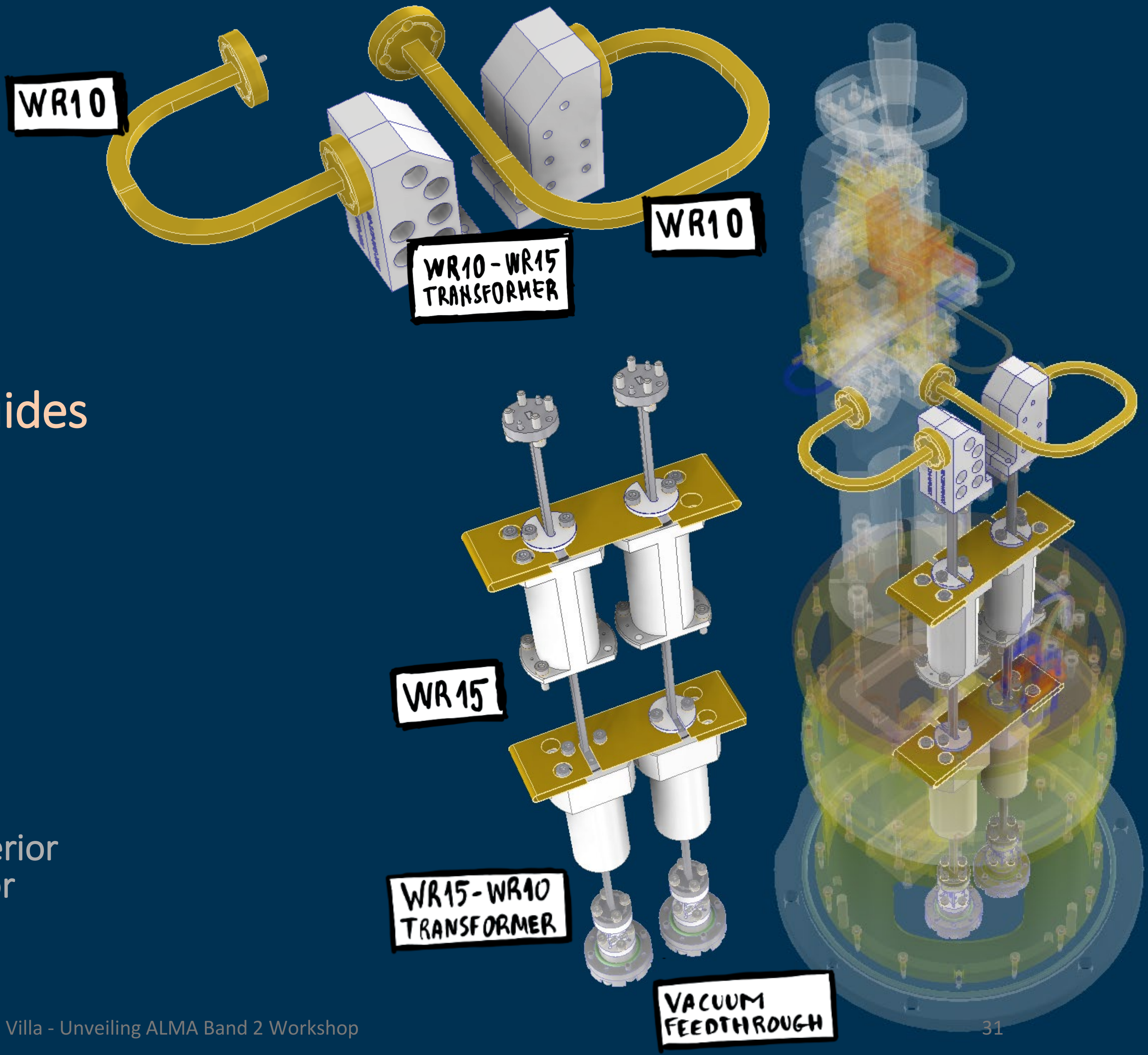
0,51K ± 0,27 K



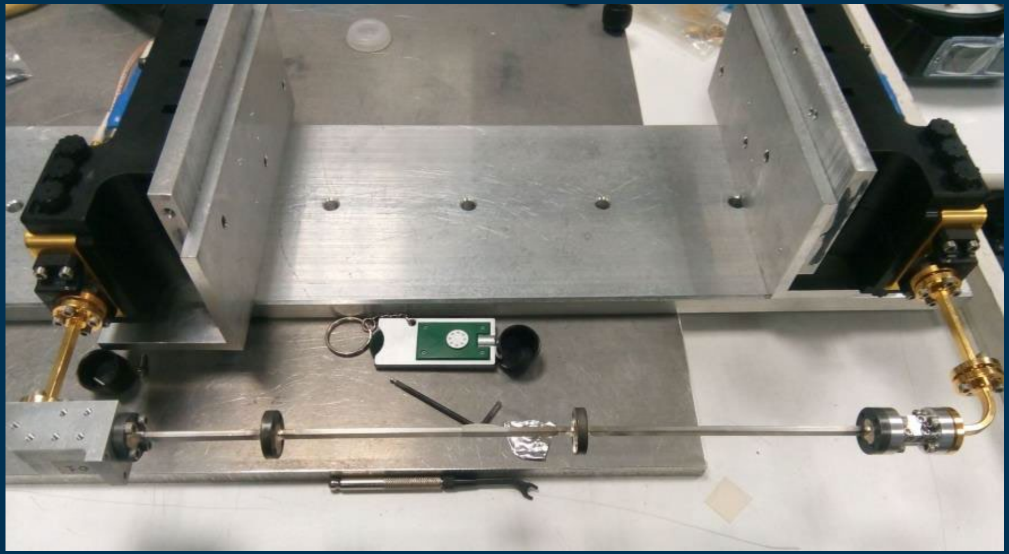


SIGNAL TRANSPORTATION

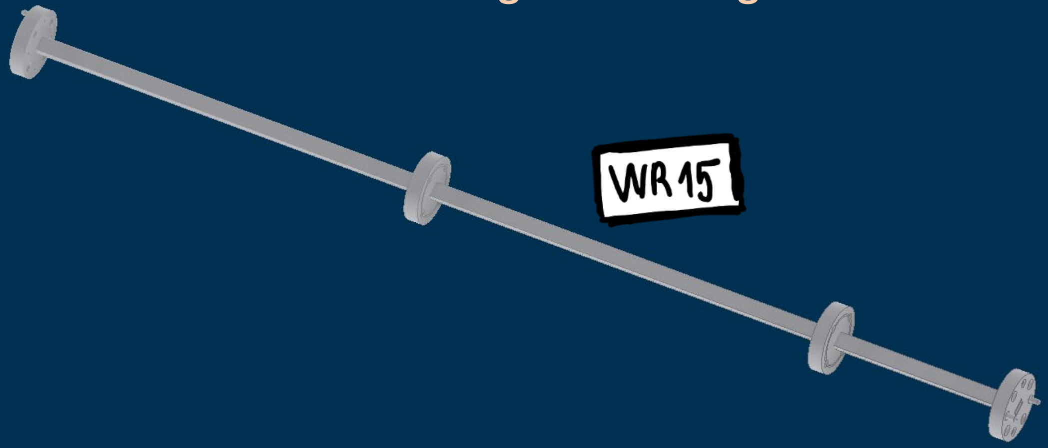
- 15K Waveguides
  - U-shaped WR10 gold-plated Copper
- 15K Transformers
  - WR10-WR15 split block adapters
- 15-300K WR15 straight waveguides
  - Provide the thermal break
  - lower attenuation
  - Low risk for high modes
- 300K transformers
  - WR15-WR10 split-block adapters
- Vacuum Feedthrough
  - Band5 design
  - Band 2 specific design (GARD) with superior performance but considered too risky for manufacturing

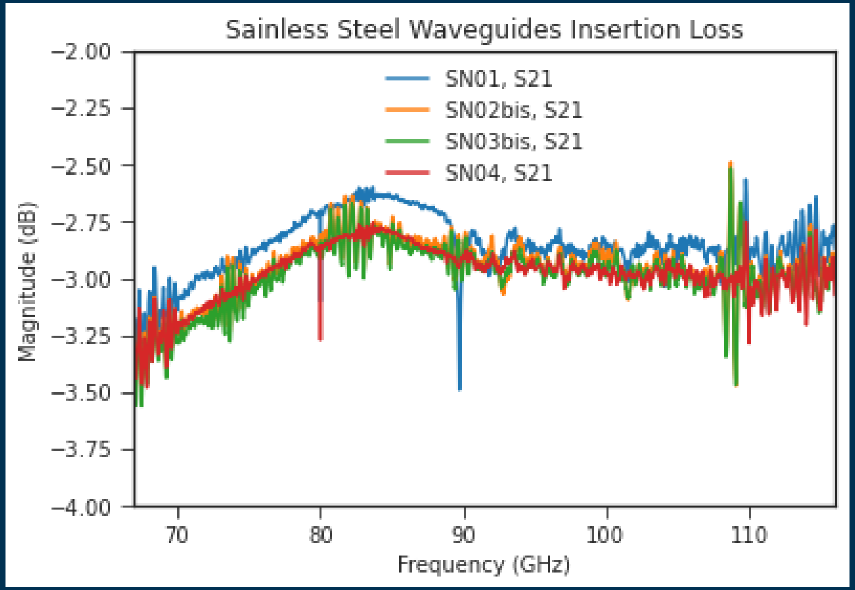


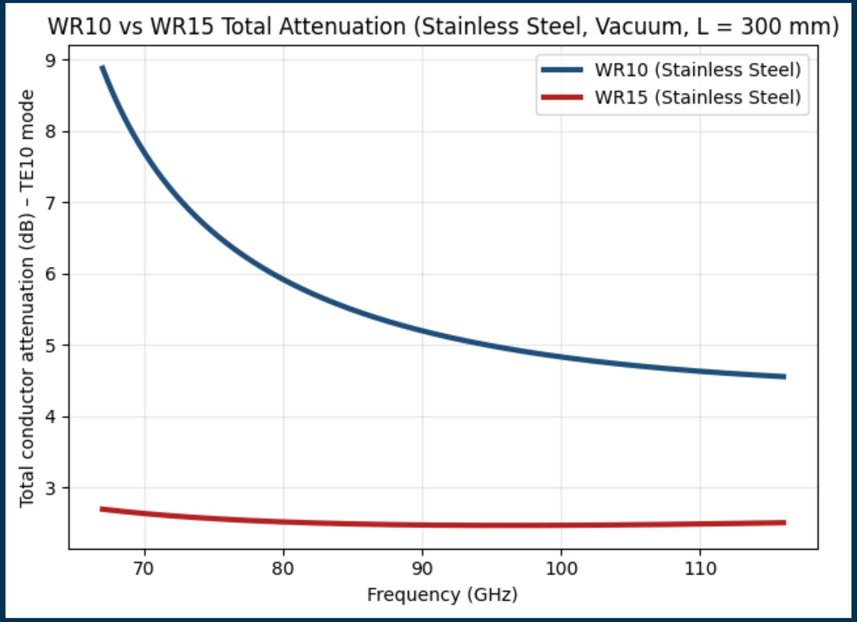
STAINLESS STEEL WAVEGUIDES



Waveguides testing at INAF-OAA

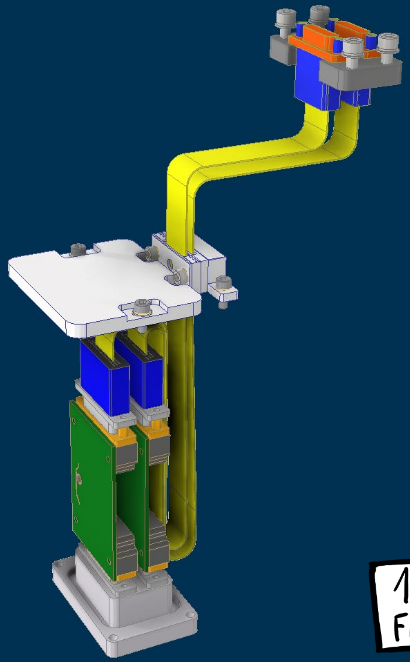


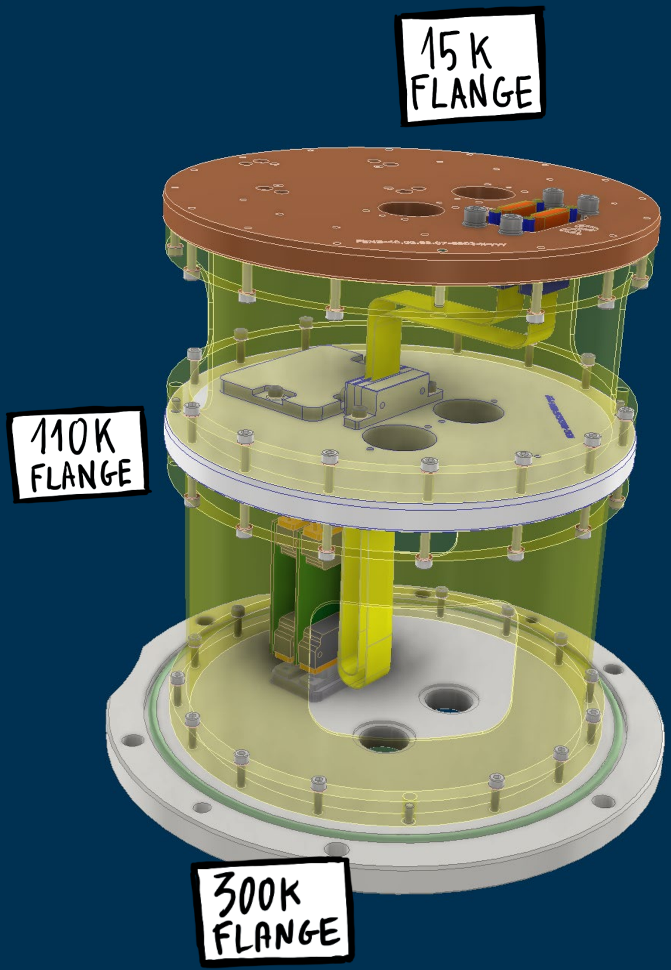




CCA BODY

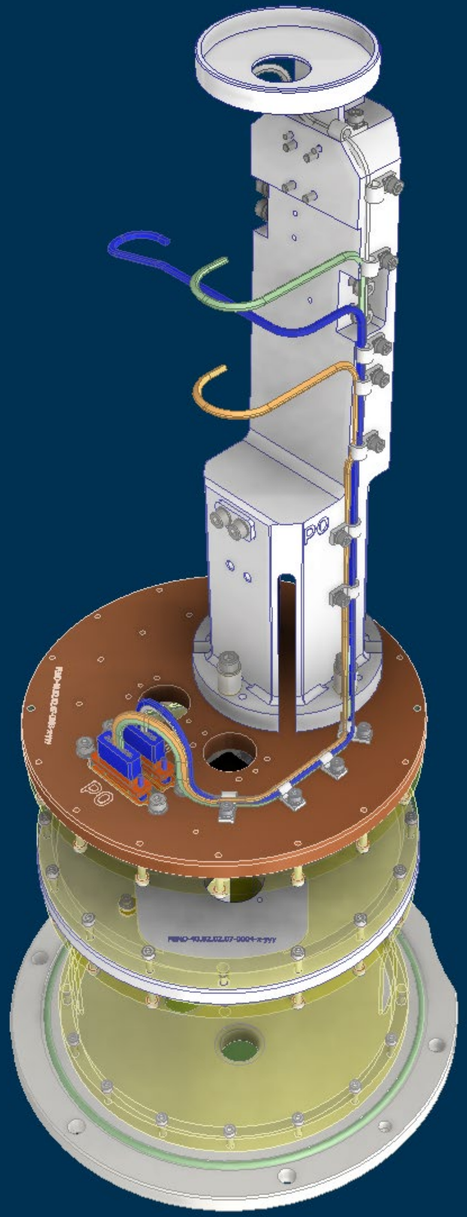
- CCA body measured for alignment
- 300K flange
  - Stainless steel
  - O-ring for vacuum
- 110K flange
  - Stainless steel
- 15K flange
  - Copper
- ESD board
- Harness

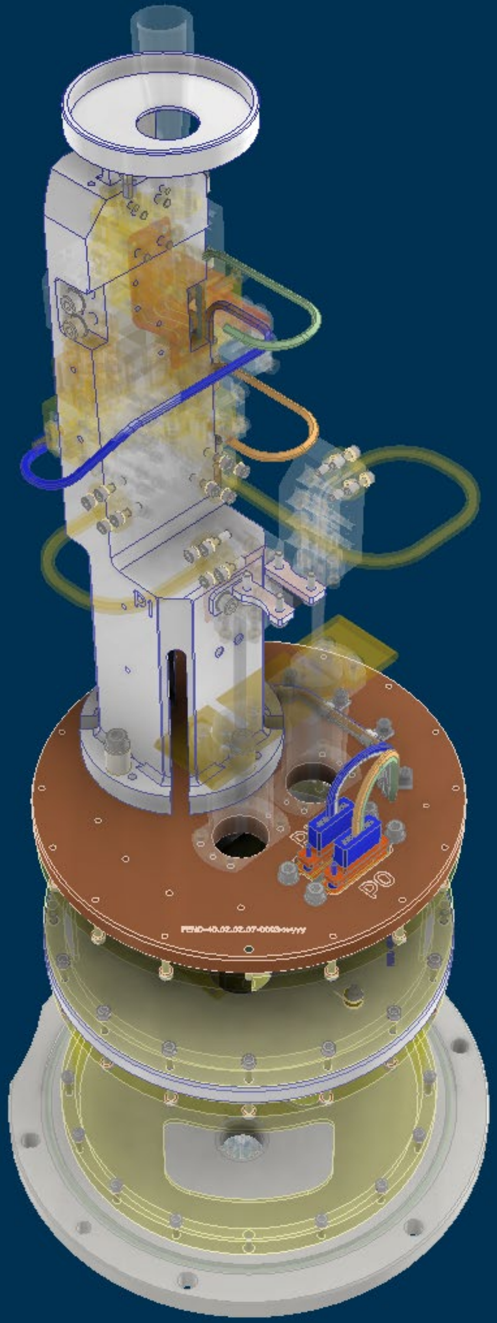




CRYOGENIC STAGE

- Pillar
  - Designed to facilitate the integration
- Cryo harness
  - LNAs bias
  - Temperature sensors
- 15K shield
  - Substitutes the 15K filter





PRODUCT AND QUALITY ASSURANCE

Mariëlle Bekema, Rob de Haan Stijkel, Albert Koops, and Ronald Hesper
Sub-mm Instrumentation group, NOVA (NL)
"**Product and quality assurance at production of ALMA receivers**", Proc. SPIE 13099, Modeling, Systems Engineering, and Project Management for Astronomy XI, 130991C (23 August 2024); https://doi.org/10.1117/12.3018326

- ✦ Product & Quality Assurance is a fundamental key to success
  - ♦ Traceability of parts (in & out)
  - ♦ Inspection phase
  - ♦ Cleaning phase
  - ♦ Verification phase
  - ♦ documentation

ANALYSIS OF INCOMING INSPECTION DATA

ALMA project	*CCA B9*	*CCA B5*	*CCA&WCA B2 preproduction*
Parts per CCA	*1228*	*1411*	*956&247*
Total amount of receivers per band	*66 (+20% spare)*	*66 (+2 CCAs spare)*	*6*
Total parts ordered	*97258*	*103003*	*5736&1482*
Total of rejected parts per project	*8038*	*3012*	*213*
Percentage of rejected parts per project	*8.26%*	*2.9%*	*2.9%*

Table: analysis of data of non-conformities of parts in the incoming inspection reports of ALMA receivers

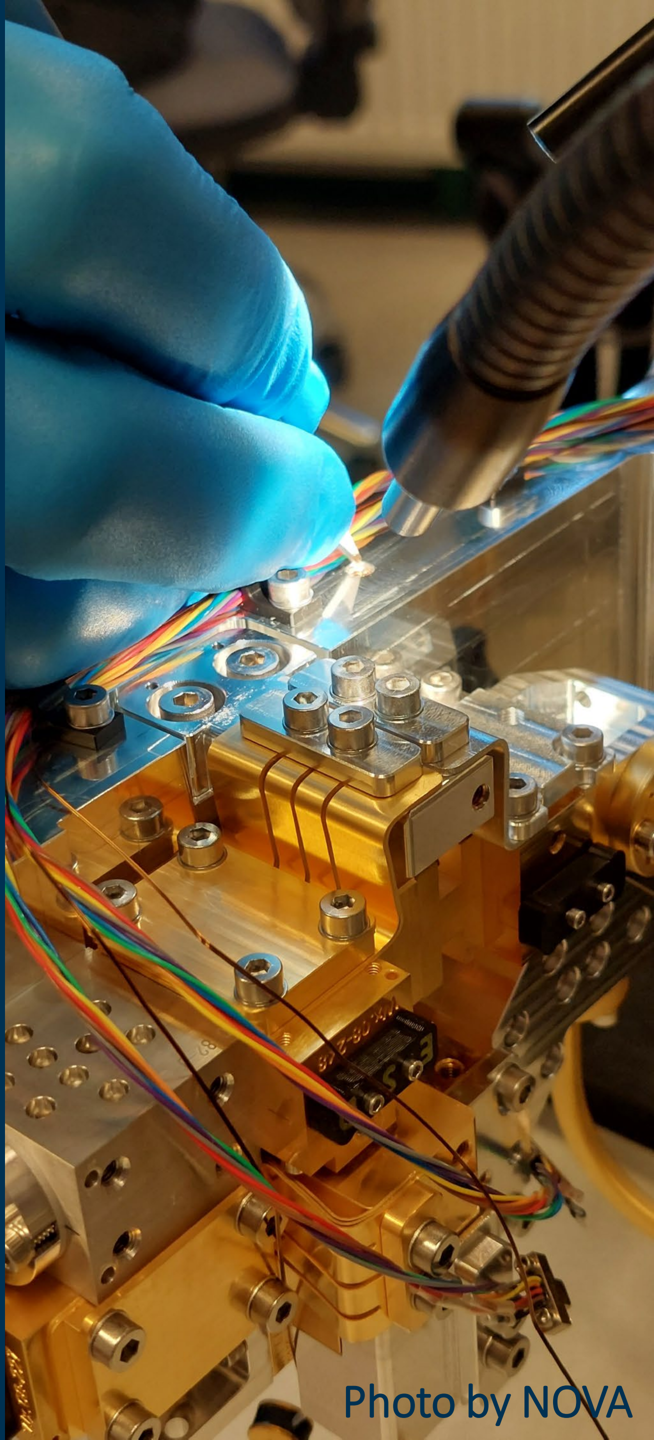


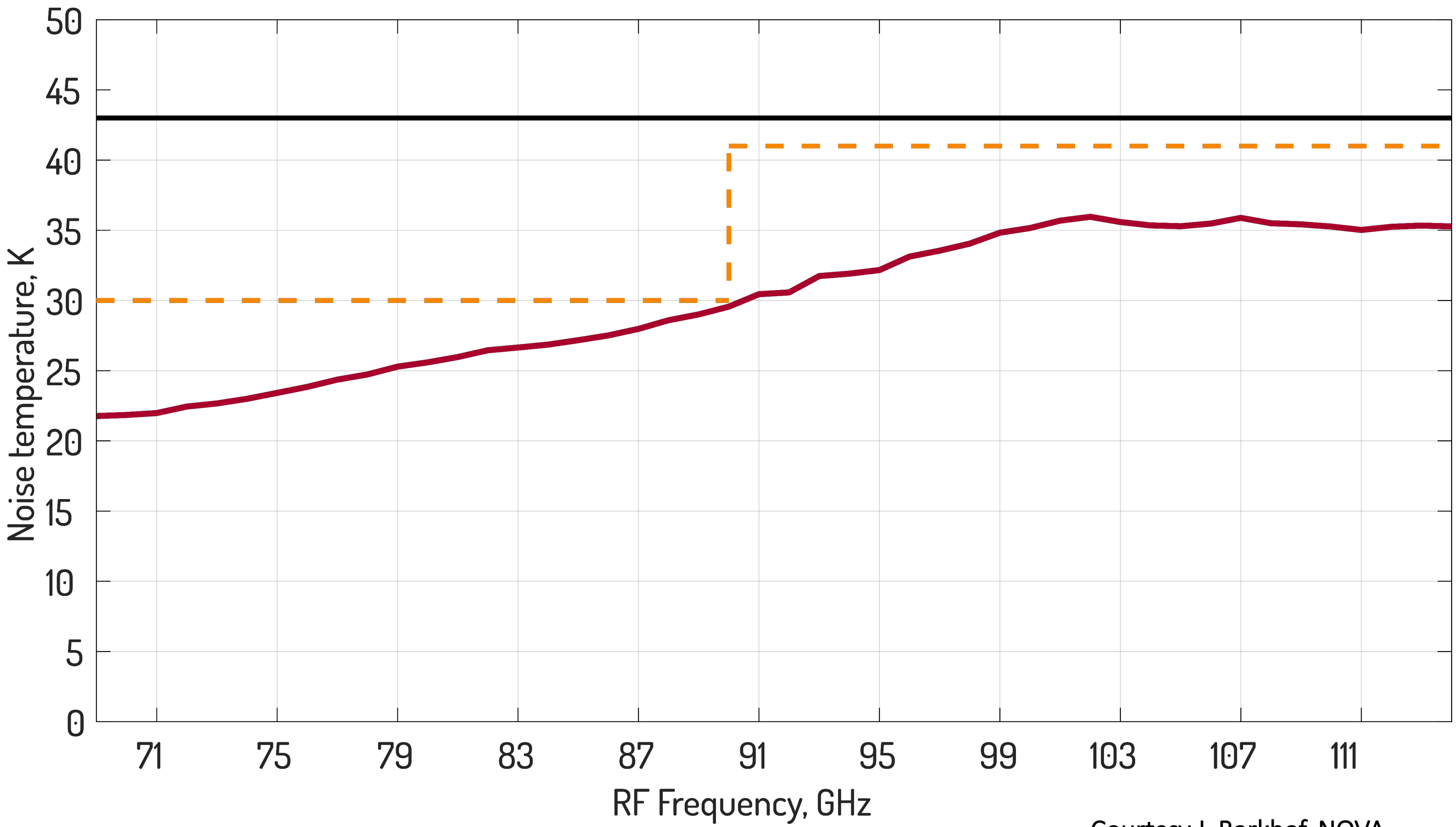
Photo by NOVA

INTEGRATION AND SYSTEM TESTS

- CCA and WCA tests are done at NOVA
- LNAs cryogenic tests and tuning are done at ESO with the support of UNIBO-Ecogal
  - See next talk (A. Camisasca)
- Feed-OMT / lens tests are done at NAOJ and INAF
- Final Acceptance tests are done at ALMA OSF

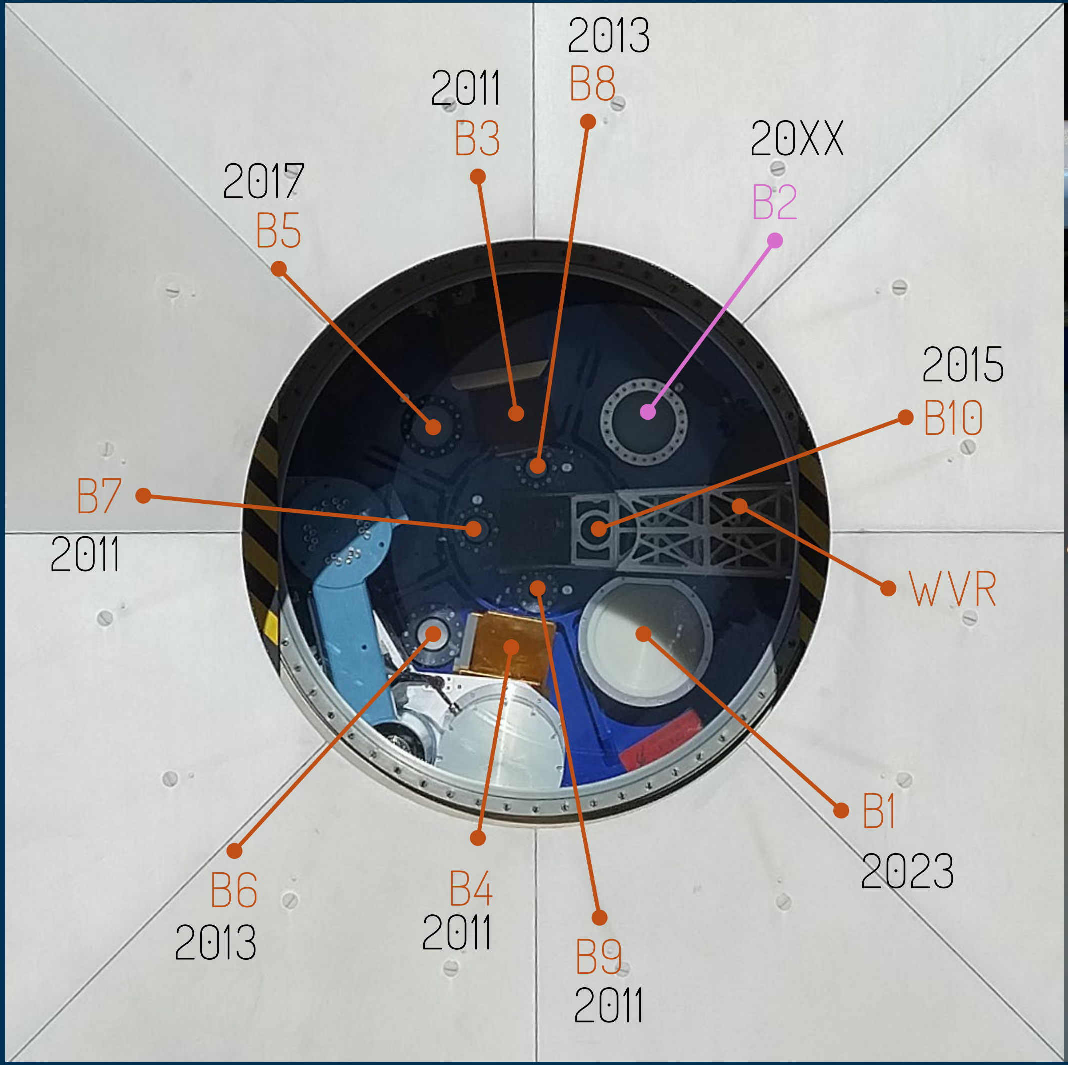
Testing facility at NOVA (photo by Liz Humphreys)

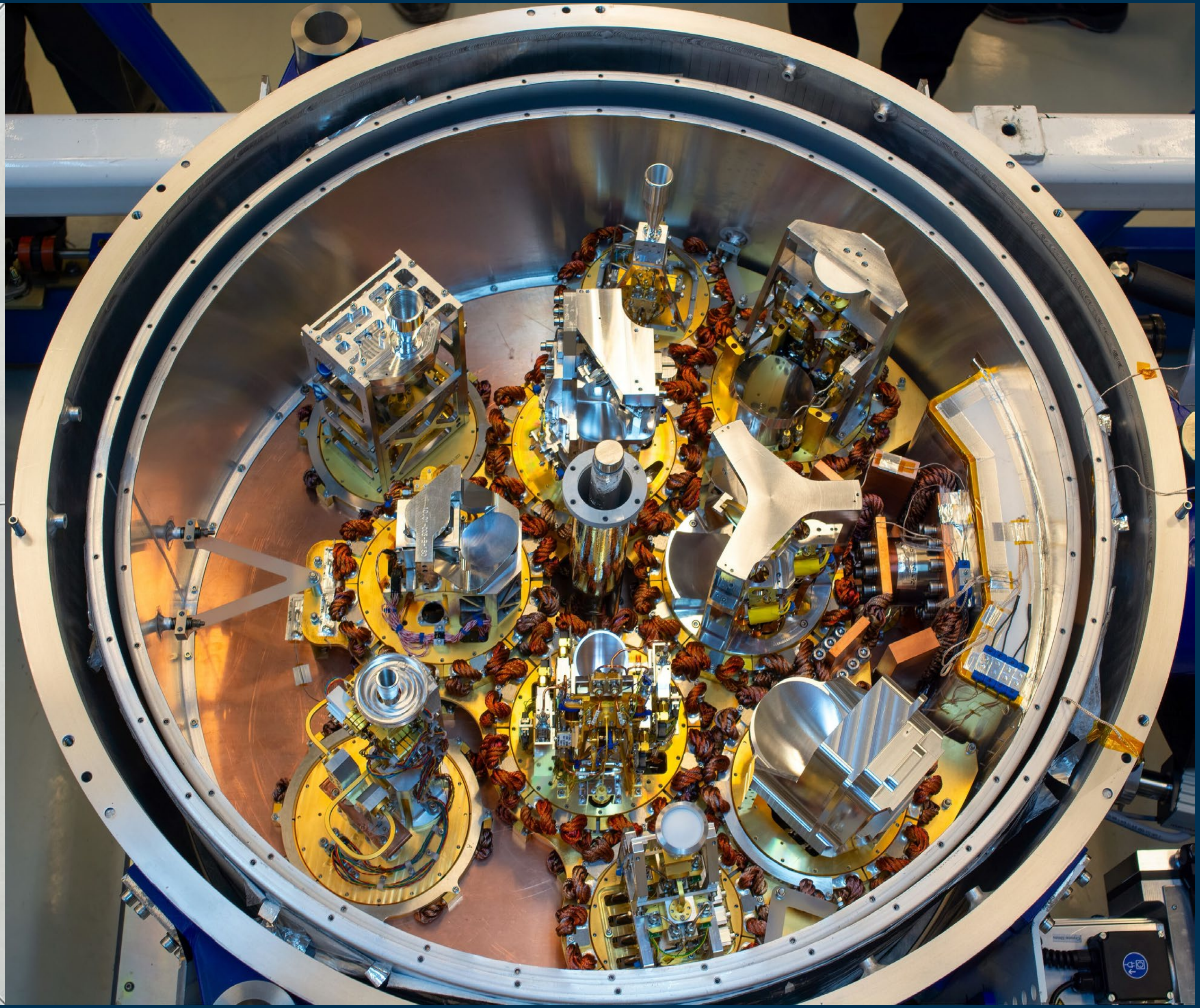
NOISE AVERAGED OVER PRODUCTION



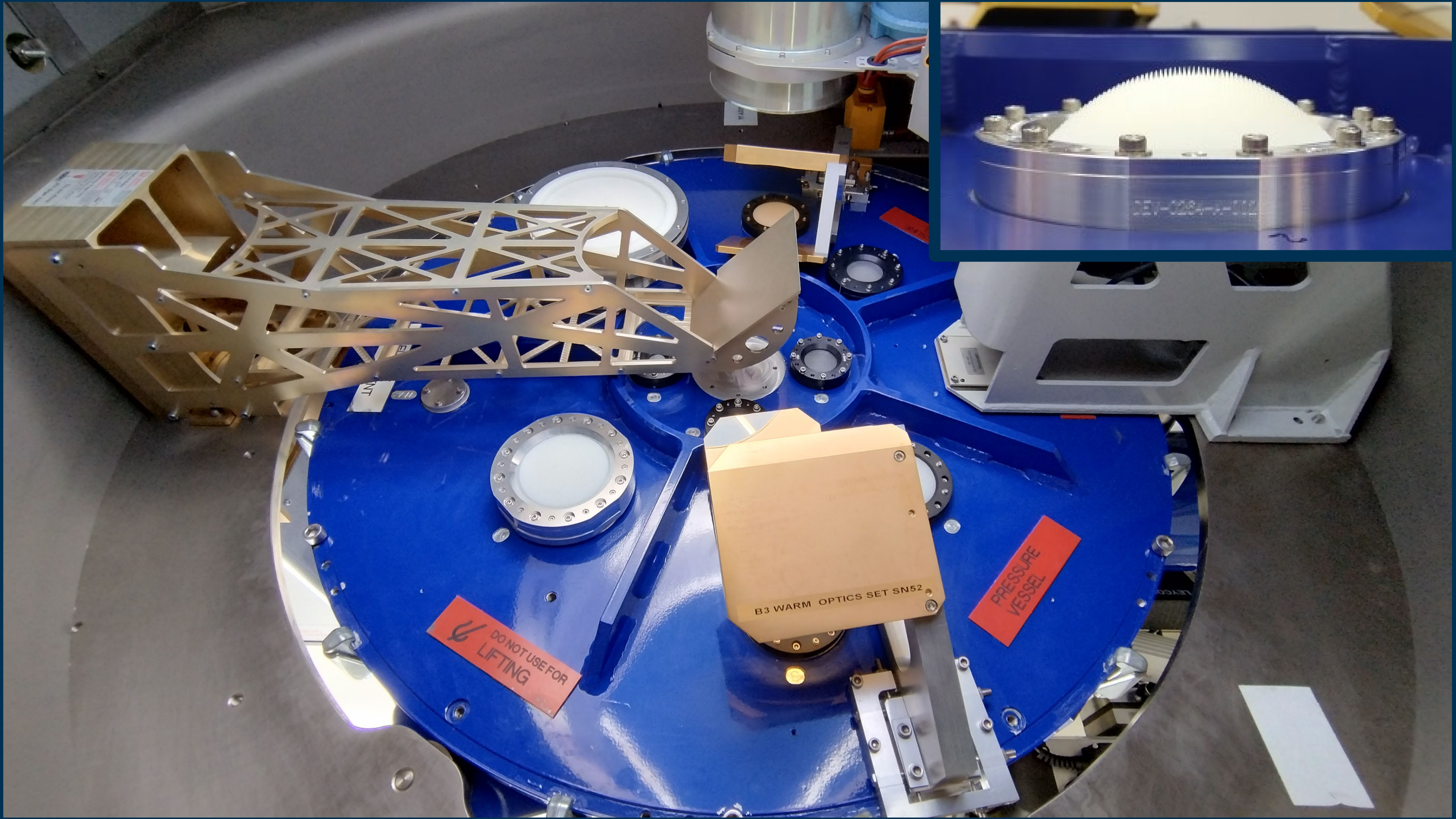
Courtesy J. Barkhof, NOVA

ALMA FOCAL PLANE OPENED





ALMA FOCAL PLANE



ALIGNMENT TOLERANCES

- Beam characteristics (12m)
  - Tilt of the chief ray from cryostat: 2.48°
  - Semi-angle subtended by subrefl.: 3.58°
- Total Requirement of output beam offset: 3.5 mrad
- Alignment Estimation based on
  - Manufacturing tolerances
  - Mounting tolerances
  - Interface tolerances
  - Optical tolerances
- The Lens – Cryostat interface mostly contributes to the misalignment
  - Lens alignment required at OSF during integration.

			RSS		
		Mean value	Lower limit	upper limit	unit
Feed-Cryostat Tolerances	shift	0	-0.089	0.089	mm
	tilt	0	-0.133	0.133	mrad
Lens-Cryostat Tolerances	shift	0	-0.500	0.500	mm
	tilt	0	-0.830	0.830	mrad
Total Feed-Lens-Cryostat Tolerances	shift	**0**	**-0.508**	**0.508**	**mm**
	tilt	**0**	**-0.841**	**0.841**	**Mrad**
Efficiency Criterion satisfied (eff >0.825)					
Feed-Lens-Cryostat Tolerances	shift		NOT	NOT	
	tilt		YES	YES	
Feed-Cryostat tolerances	shift		YES	YES	
	tilt		YES	YES	

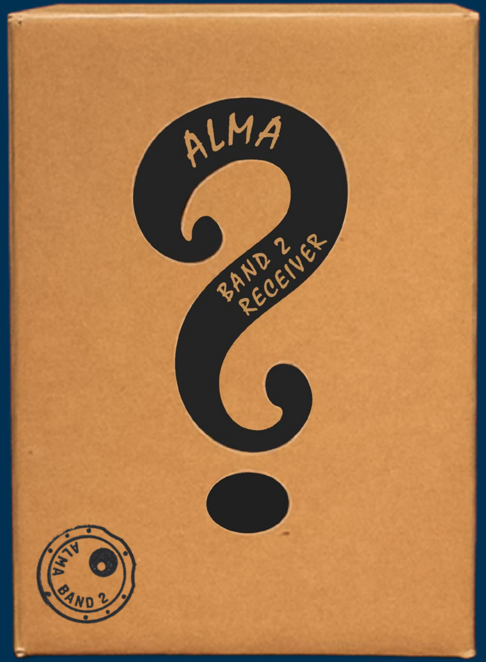
Total calculated misalignment:
3.03 mrad

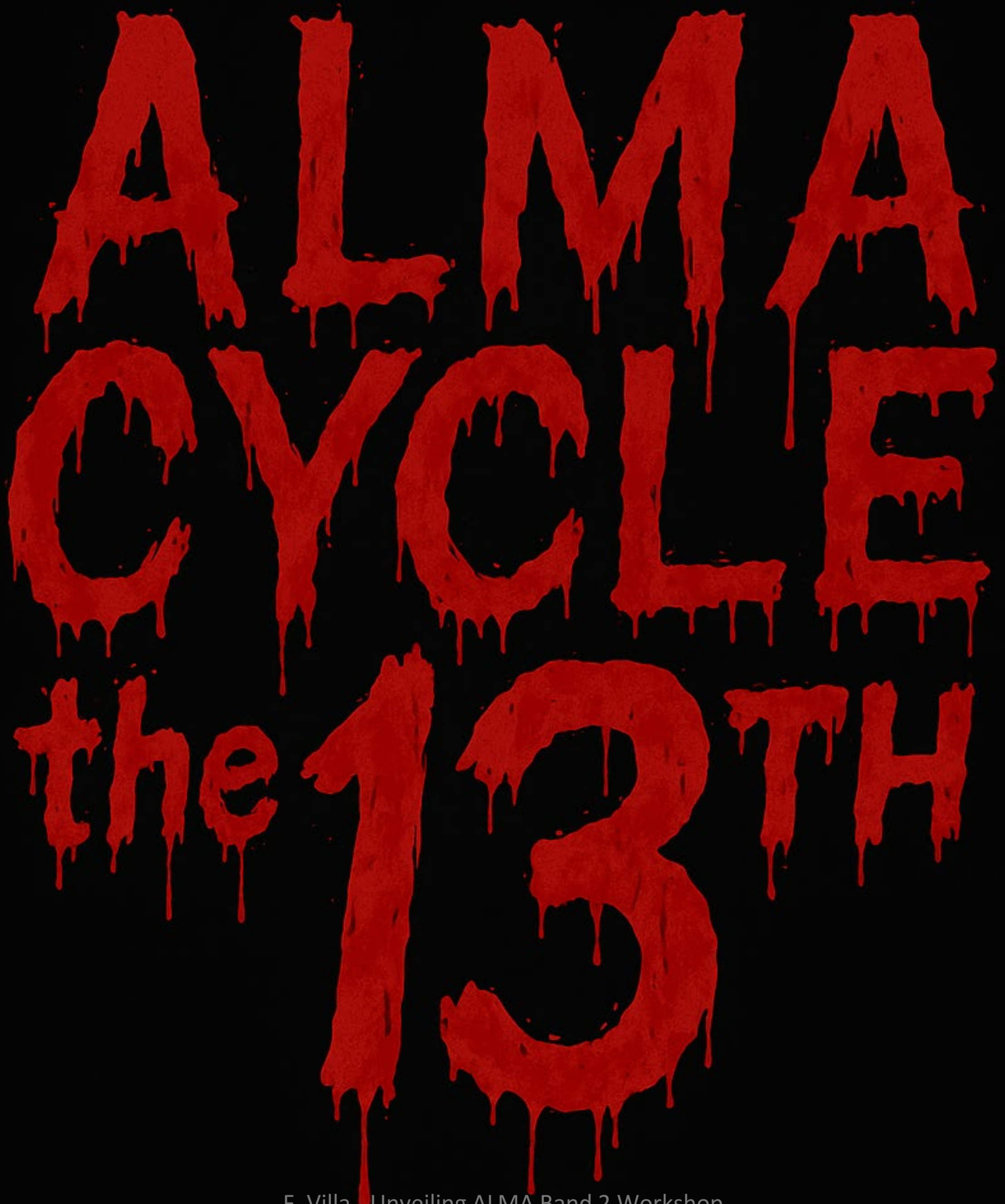
Alignment Requirement:
< 3.50 mrad

Optical efficiency criterion (NAOJ)
> 82.5 %

CONCLUSIONS

- ALMA Band 2 was a major challenge in terms of noise and bandwidth
- The early development strategy to go beyond technological limits was highly effective in the ALMA upgrade program
- The strong collaboration between ESO, the consortium, and partner institutions was key to resolving challenges efficiently and successfully meeting the project timescale




ALMA
CYCLE
the 13TH