Instituto Geográfico Nacional
Organismo Autónomo Centro Nacional de Información Geográfica

Terahertz receivers for future space-borne VLBI missions

Yebes Observatory's perspective

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*On behalf of Yebes's receiver and amplifier groups

Credits: Miguel Gómez

GOBIERNO DE ESPAÑA
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INSTITUTO GEOGRÁFICO NACIONAL
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"A way of making Europe"

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for future missions

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Outline of the talk

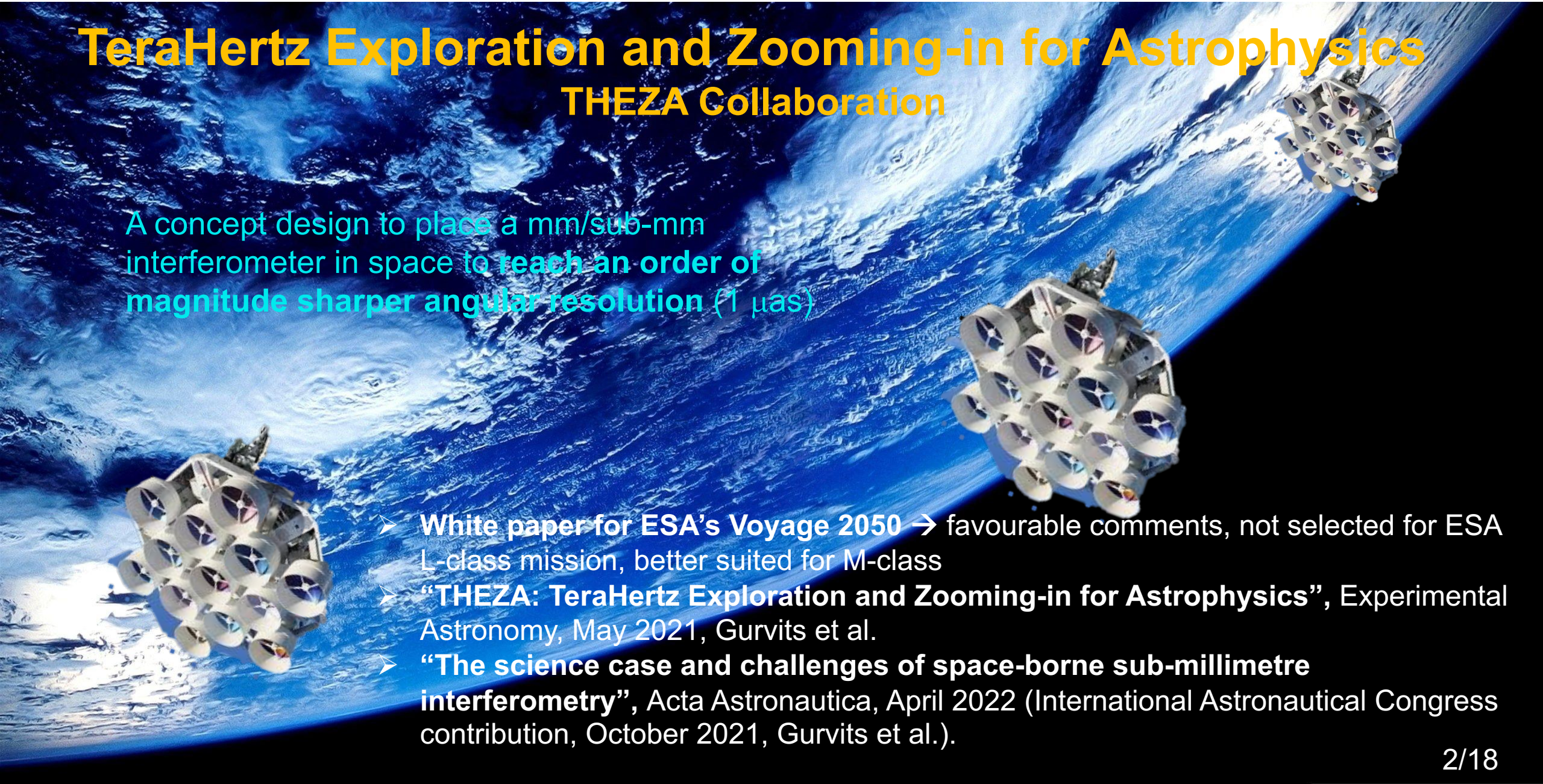
- Introduction to the THEZA concept
- THEZA key science themes
- Overview of terahertz capable receivers for space missions: **Martina Wiedner's review!**
- Contributions from Yebes Observatory

The THEZA concept

TeraHertz Exploration and Zooming-in for Astrophysics

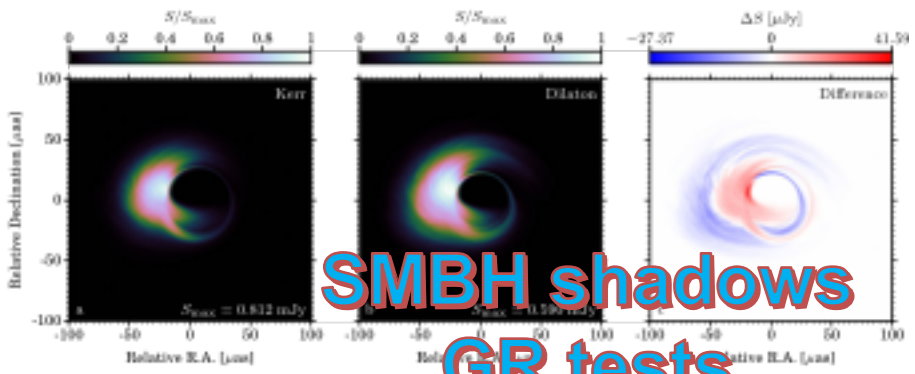
THEZA Collaboration

A concept design to place a mm/sub-mm interferometer in space to **reach an order of magnitude sharper angular resolution** (1 μas)

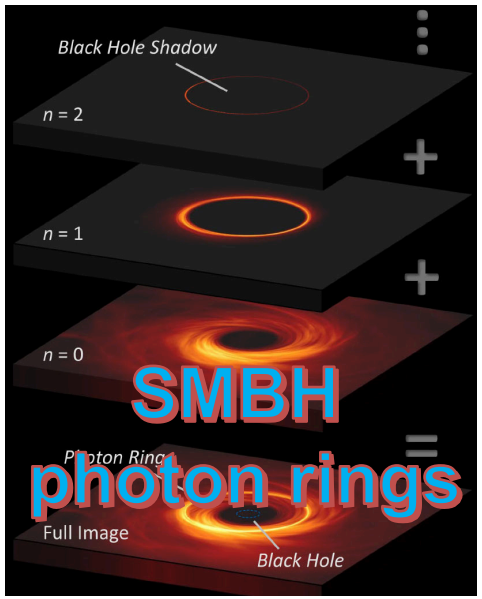


- **White paper for ESA's Voyage 2050** → favourable comments, not selected for ESA L-class mission, better suited for M-class
- **"THEZA: TeraHertz Exploration and Zooming-in for Astrophysics"**, Experimental Astronomy, May 2021, Gurvits et al.
- **"The science case and challenges of space-borne sub-millimetre interferometry"**, Acta Astronautica, April 2022 (International Astronautical Congress contribution, October 2021, Gurvits et al.).

THEZA key science themes enabled by sharper vision



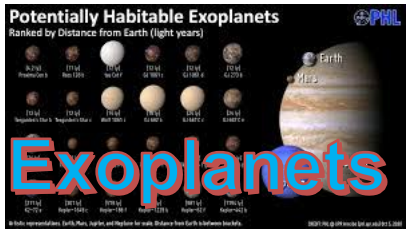
SMBH shadows
GR tests



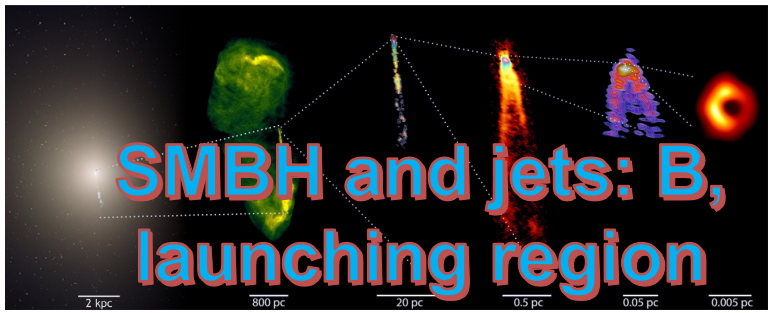
SMBH
photon rings

Water
megamasers

SETI INSTITUTE



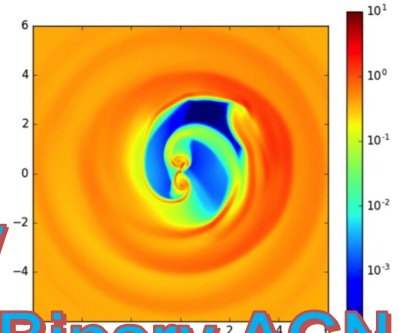
Exoplanets



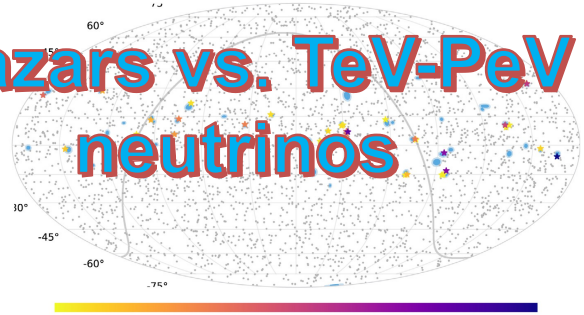
SMBH and jets: B, launching region

Time and X-ray domain synergies

Water in protoplanetary disks



Binary AGN



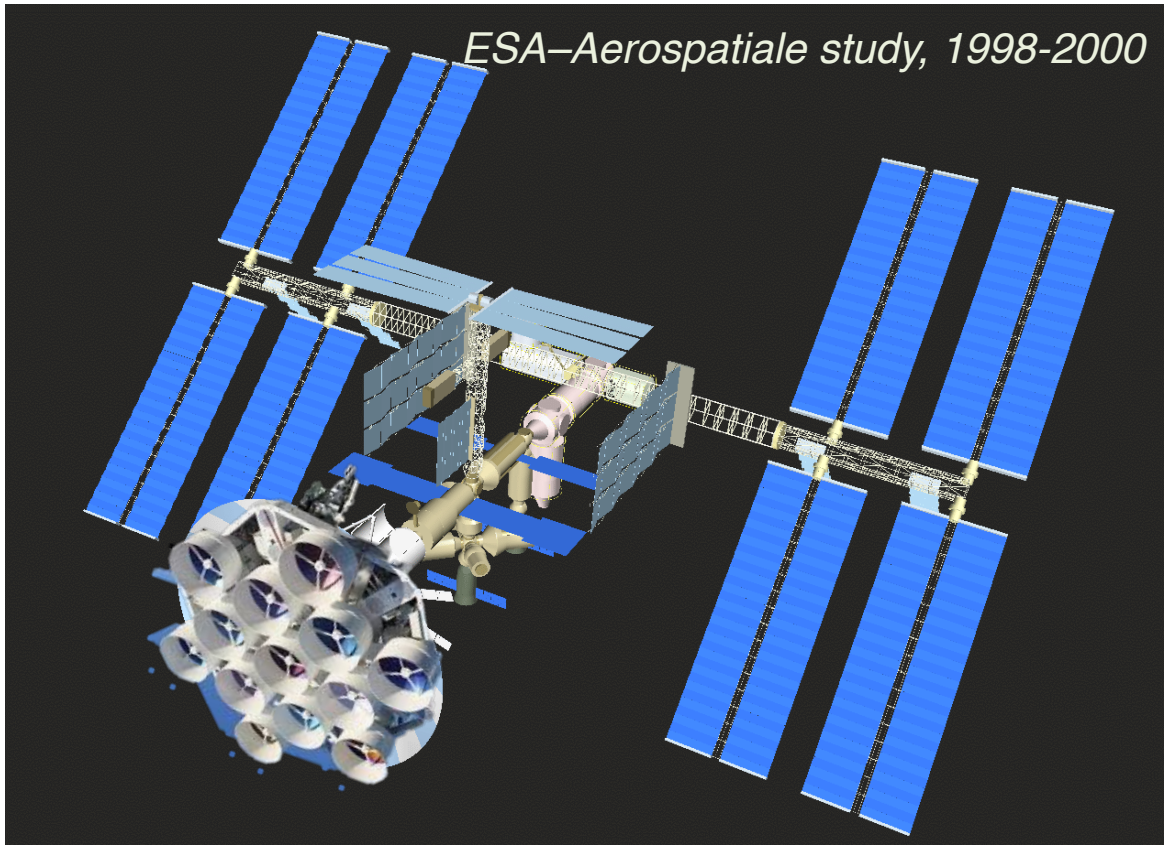
Blazars vs. TeV-PeV neutrinos

The THEZA concept: coherent receiver requirements

1 μas benchmark goal → up to **THz frequencies**
→ **space-borne** mission

100-fold increase in number of observable targets e.g. supermassive BH shadows at 230 GHz → **interferometric sensitivities** achieved with several hours on-source integration and 32GHz b/w (10m+phased-up ALMA baseline) → **very broadband receivers, approaching quantum noise limit.**

Expandable configuration **aperture phased array** → **multi-element receiver** (**Side Note:** also important for MultiView technique for ultra-high precision relative astrometry at lower frequencies, Rioja&Dodson 2020).

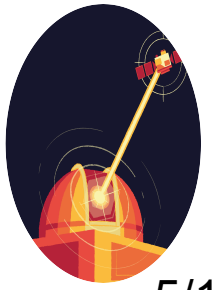


The Yebes Observatory

- ✓ **Singular infrastructure in Spain** for A&A and Space Geodesy R&D
  - **40m radio telescope** competitive access through TAC for single dish and VLBI, participation in cutting edge research
  - **13m radio telescope** for VGOS and RAEGE geodetic networks

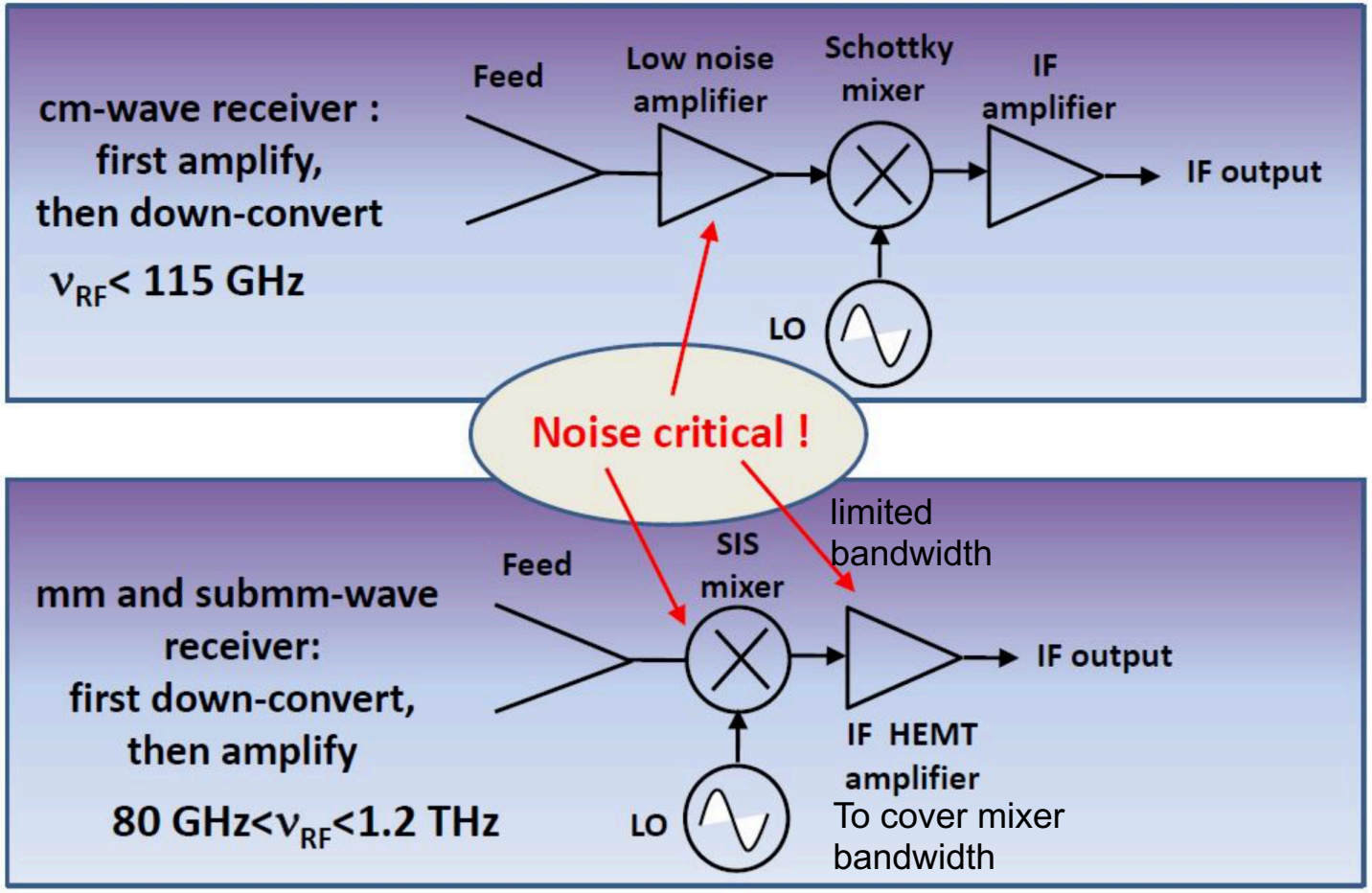
- ✓ More than 35 years developing **state-of-the-art complete receivers** for radio astronomy, spacecraft tracking, space geodesy and space missions
- ✓ About to become the **first geodetic fundamental station** in Spain:

  VLBI + GNSS + **SLR (New!)**

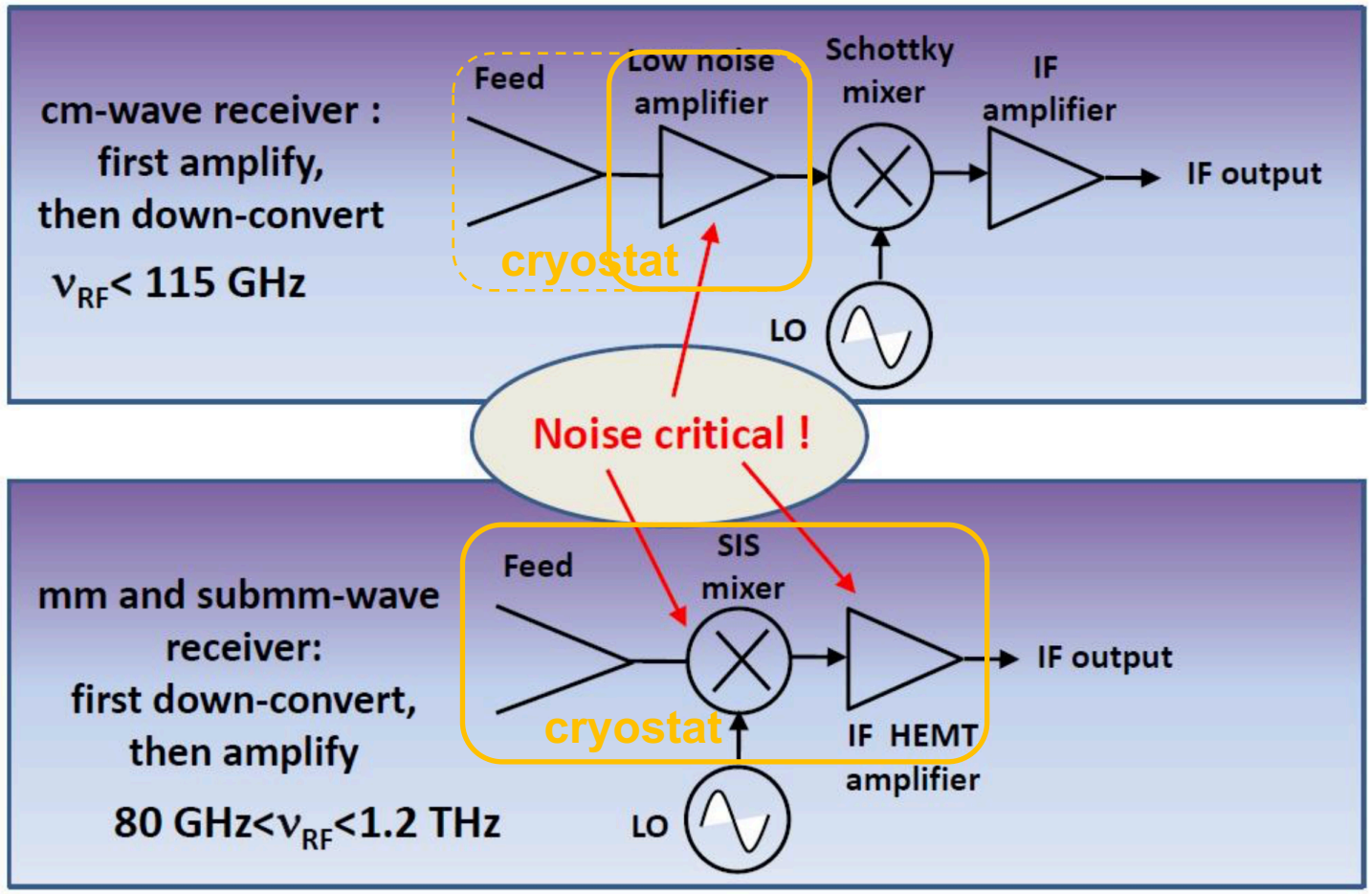


- ✓ Staff ~60 people: scientists, engineers and technicians

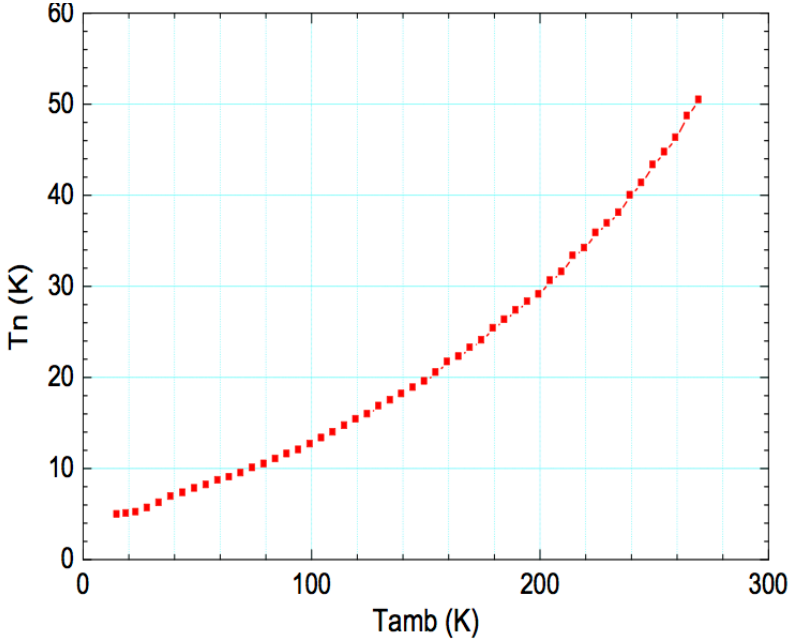
Terahertz cryogenic heterodyne receivers for space-borne VLBI



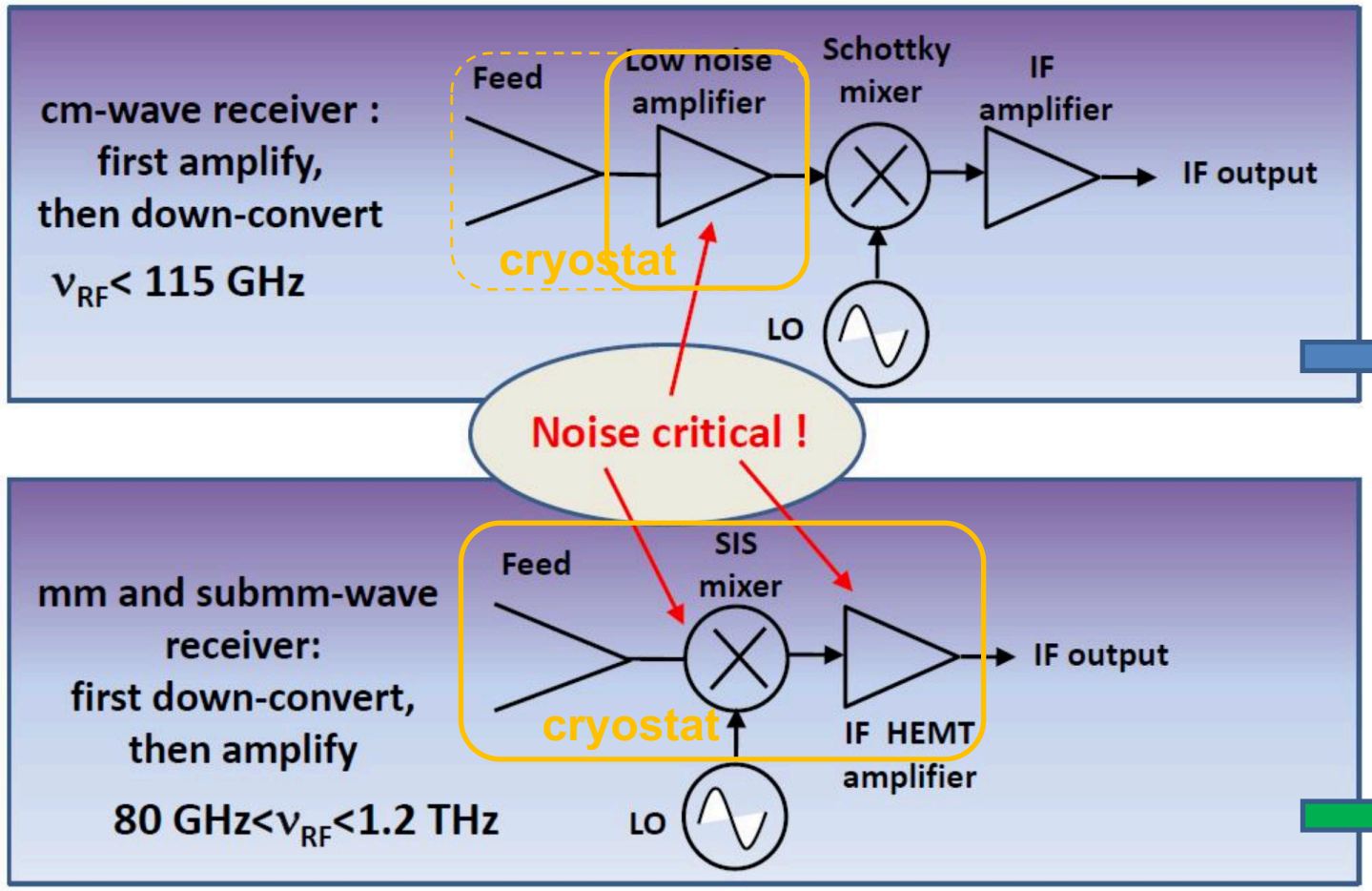
Terahertz cryogenic heterodyne receivers for space-borne VLBI



Receiver noise vs. Room Temperature



Terahertz cryogenic heterodyne receivers for space-borne VLBI



Direct amplification towards THz regime in **incipient development**
Current limit 150 GHz
To be considered for mission in 30+ yrs

Space-borne THz missions high TRL TODAY
Yebes' expertise

Development of cryogenic amplifiers in Yebes

✓ **Some history:**

- 60s: Maser, Parametric — 18 K @ 8.45 GHz in 1964, JPL
- 70s: GaAs FET amplifiers — 13 K @ 1.3 GHz in 1979, NRAO
- 80s: GaAs HEMTs — 5.5 K ! @ 8.5 GHz in 1988, GE-NRAO
- 90s: InP HEMTs — 4.6 K @ 8.5 GHz in 1999, ETH-CAY
  3.0 K @ 8.5 GHz in 2002, TRW-CAY
  2.0 K ! @ 4-8 GHz in 2002, TRW-CAY
- 00s: metamorphic HEMTs, MMICs
  Higher frequencies: SIS (< 1 THz) and HEBs (> 1 THz) heterodyne mixers

✓ Yebes is leader in development of **very low noise cryogenic amplifiers**, based on InP HEMT technology, in collaboration with European and North American foundries:

- ETH (Switzerland)
- Fraunhofer Institute for Applied Physics (Germany)
- NGS-JPL (US)
- Chalmers University (Sweden)

✓ **Close collaboration needed** to develop state-of-the-art cryogenic transistors:

- Definition (material, layer structure, layout)
- Cryogenic characterization (noise performance only possible in a test LNA), model for “small signal” not available from manufactures of HEMTs

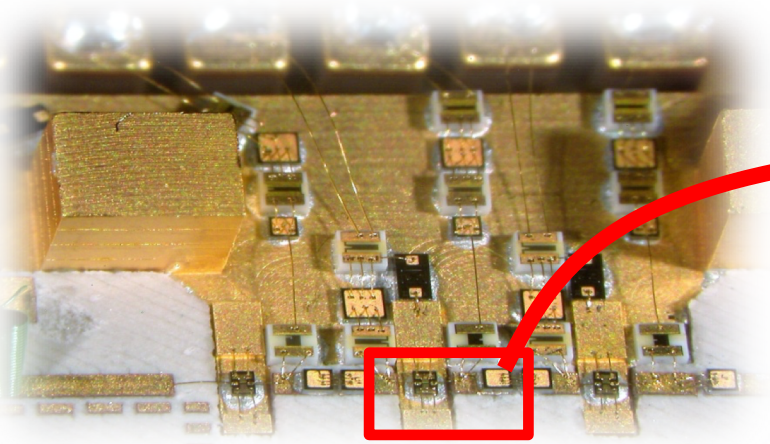
Cryogenic amplifiers in Yebes: Hybrid vs. MMIC technology

Advantages and applications	MMIC	Hybrid
Reproducibility	↑ same batch	variable
Cost	Large series	Short series
Design to prototype cycle	Slow	Fast
Ease of assembly	↑	↓
Module size and "integrability"	↑	↓
Tunability	↓	↑
Ultimate noise performance	40 – 150 GHz [1]	1-60 GHz [2]

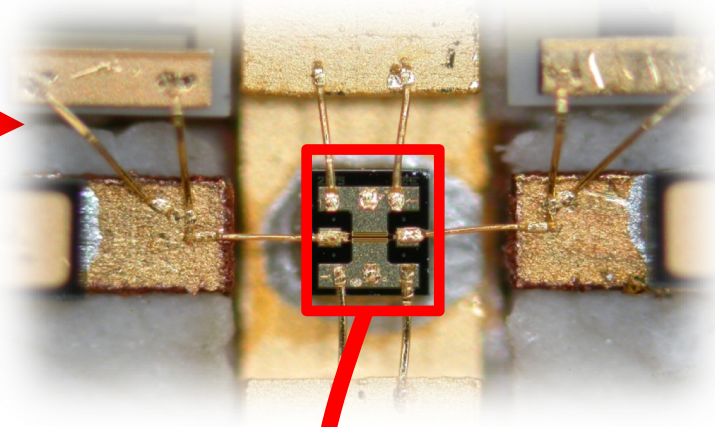
[1] Less competitive than hybrids at lower frequencies (higher input losses) and worse than SIS mixer + IF LNA at higher frequencies (> ~100 GHz).

[2] Worse than MMICs at high frequencies due to parasitics of discrete components, limitations of interstage circuit fabrication and interconnections by bonding wires

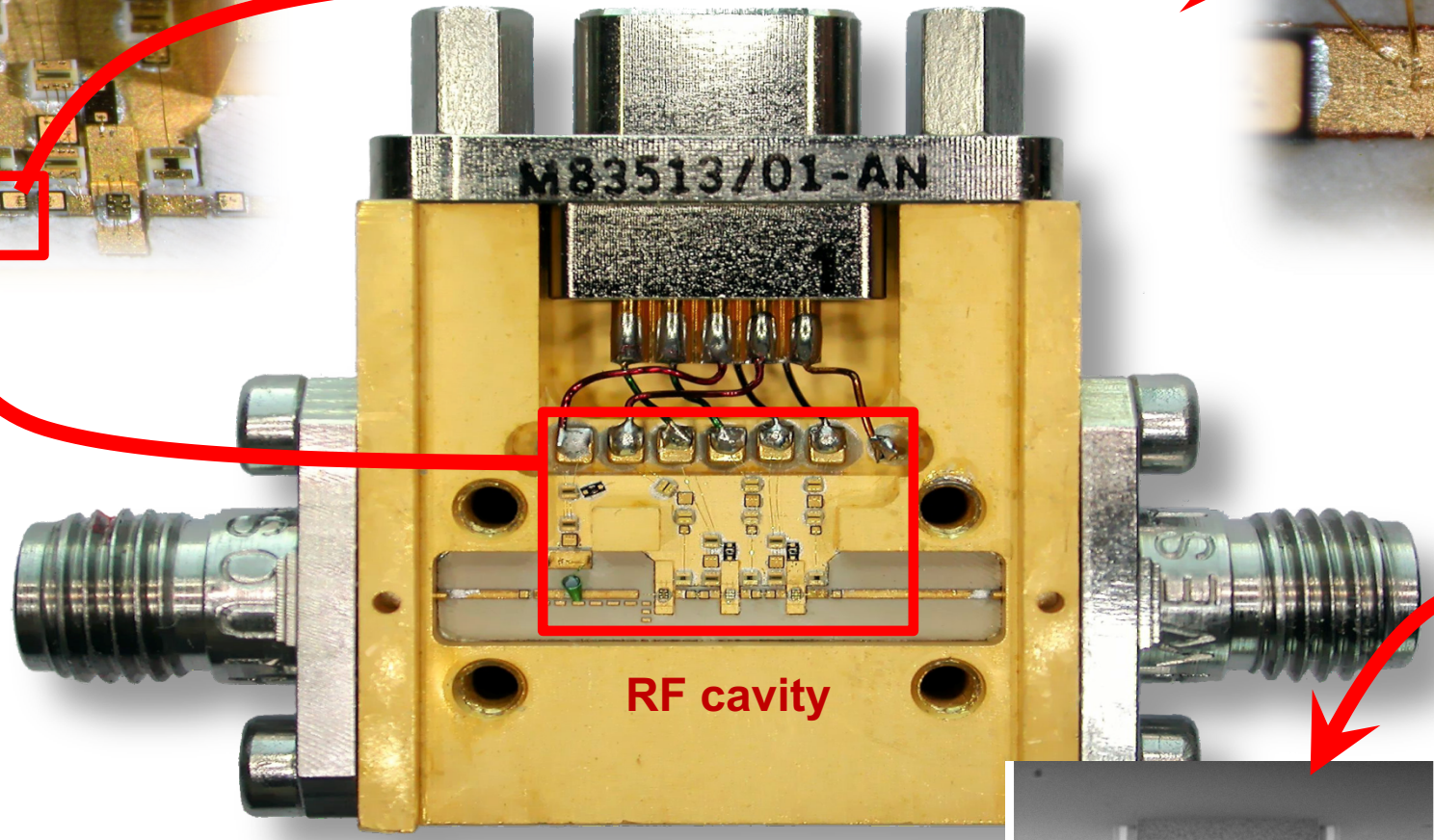
Cryogenic receivers in Yebes: Hybrid technology



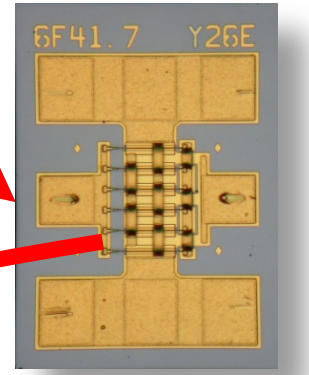
Ultrasonic bonding:
15 µm gold wire



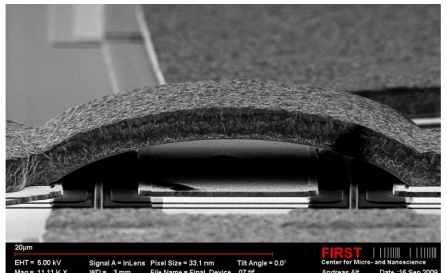
Chip components:
transistors, resistors,
capacitors, diodes, etc.



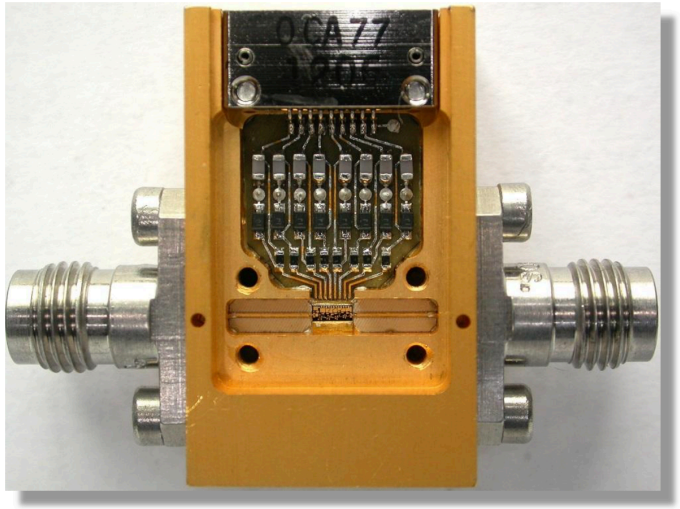
RF cavity

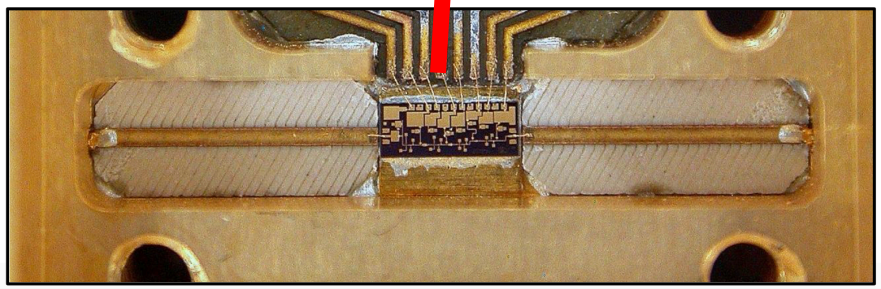


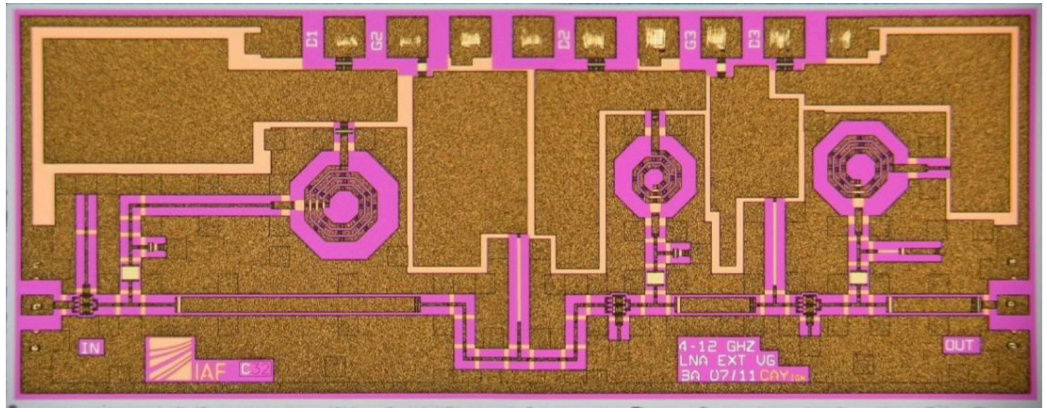
HEMT InP transistor

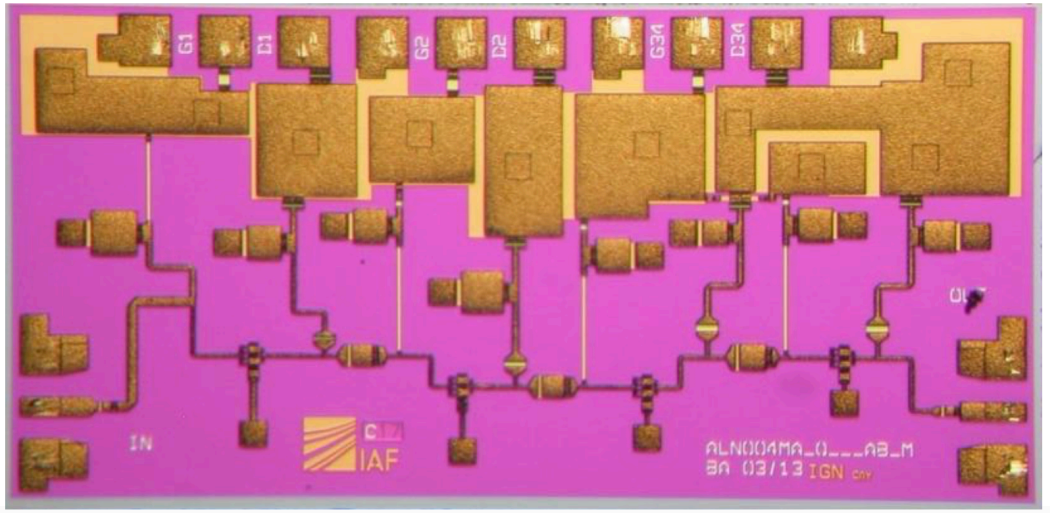


Cryogenic receivers in Yebes: MMIC technology



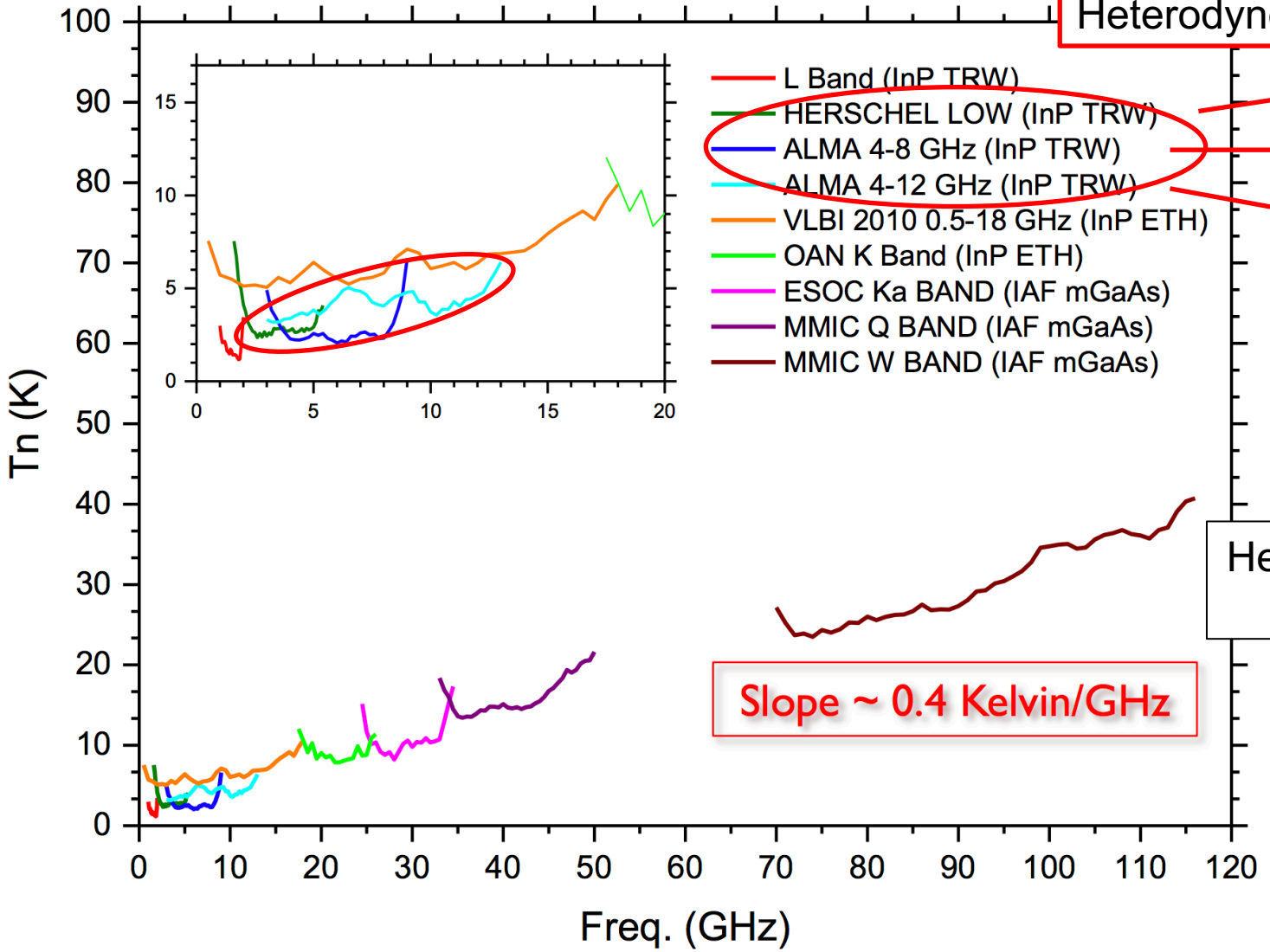






Development of cryogenic amplifiers in Yebes

Noise temperature of various YEBES amplifiers (Tamb=15K)



Heterodyne cold mixing for ~THz regime

HIFI LOW: 480-1272 GHz

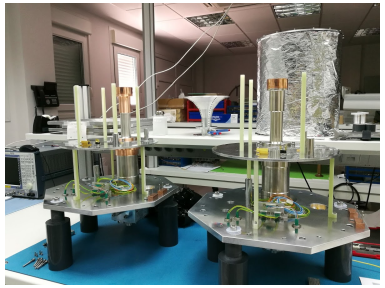
ALMA Band 7: 275-373 GHz

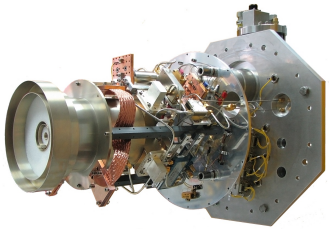
ALMA Band 9: 602-720 GHz

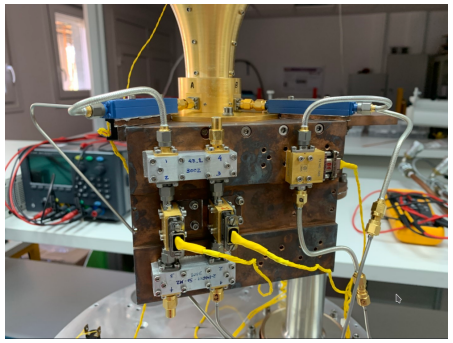
Heterodyne direct amplification for < 120 GHz regime

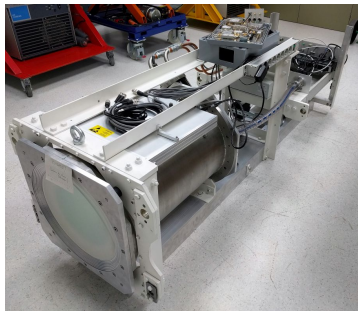
Slope ~ 0.4 Kelvin/GHz

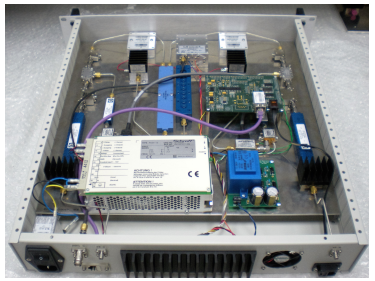
Cryogenic receivers in Yebes: Examples for THEZA

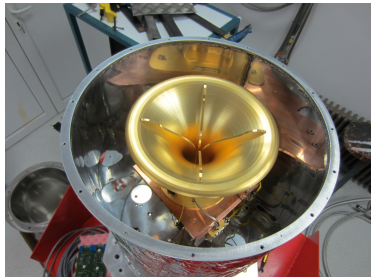


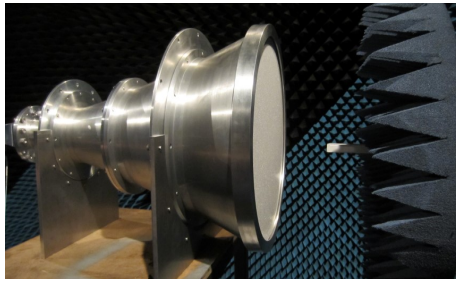


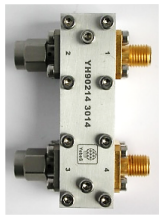


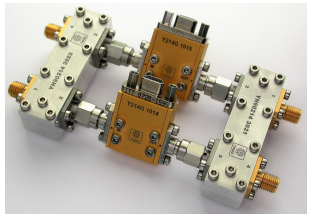


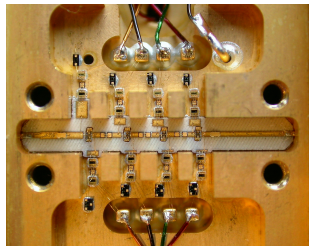


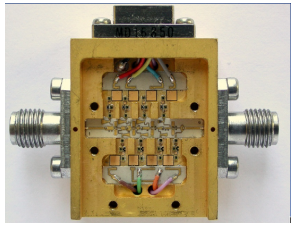


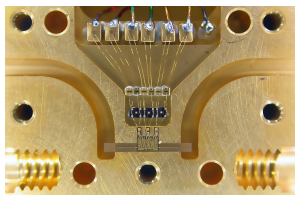


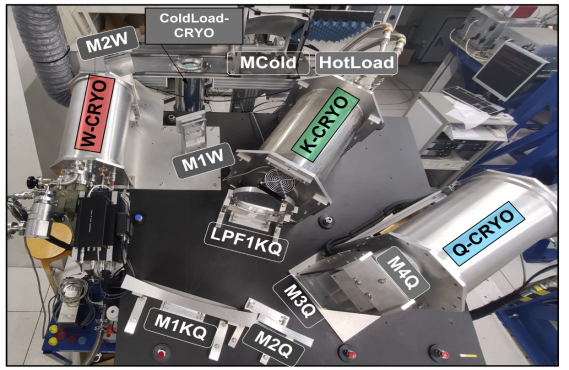


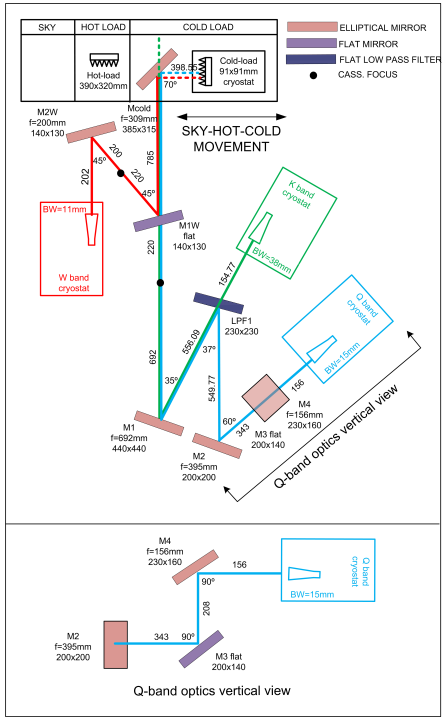




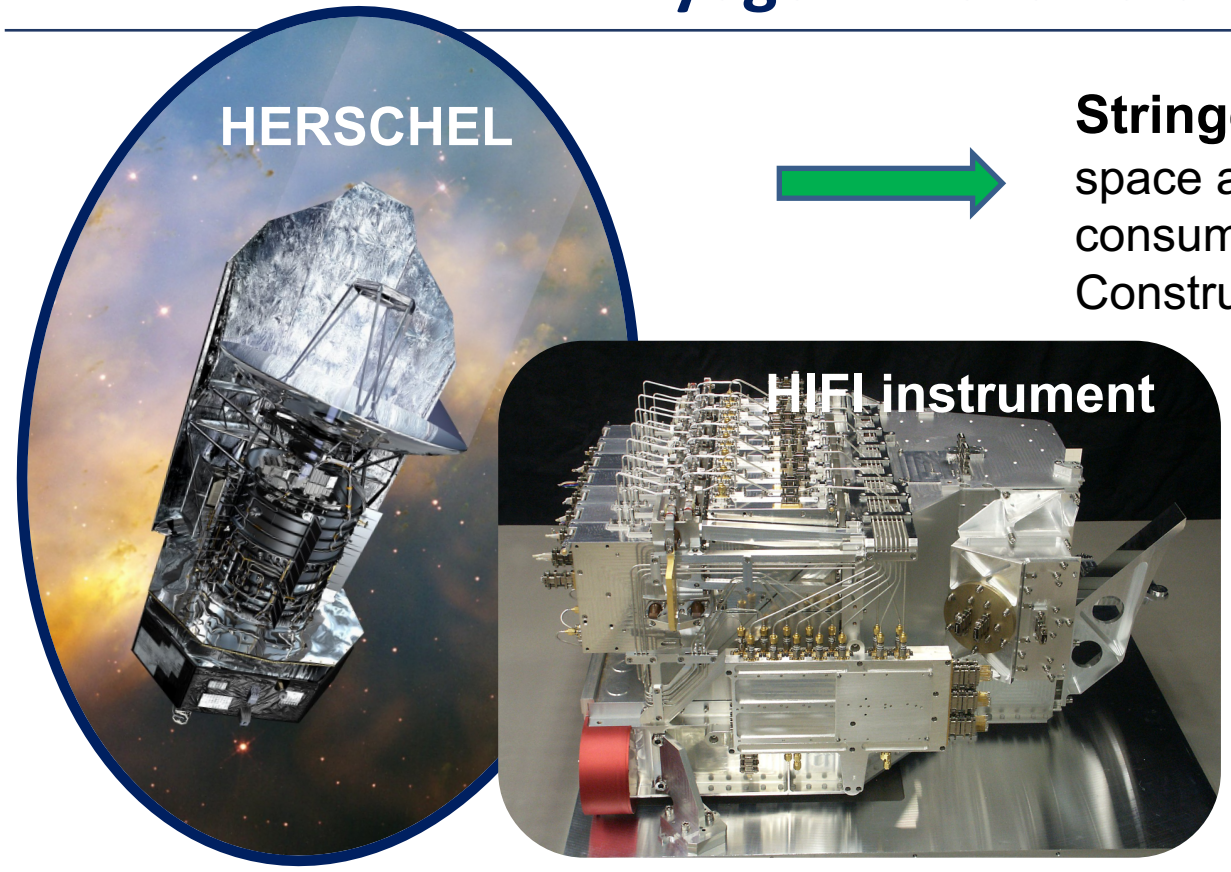




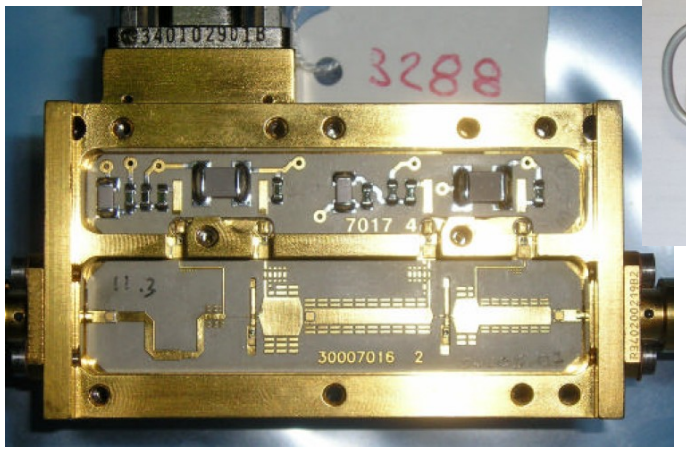


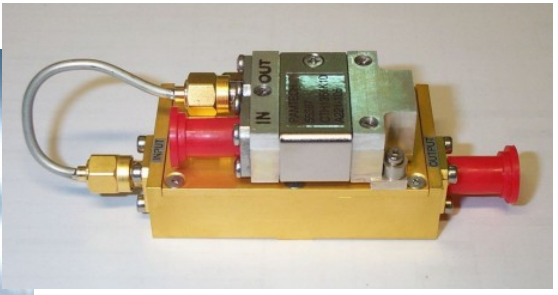


Cryogenic receivers in Yebes: Herschel HIFI



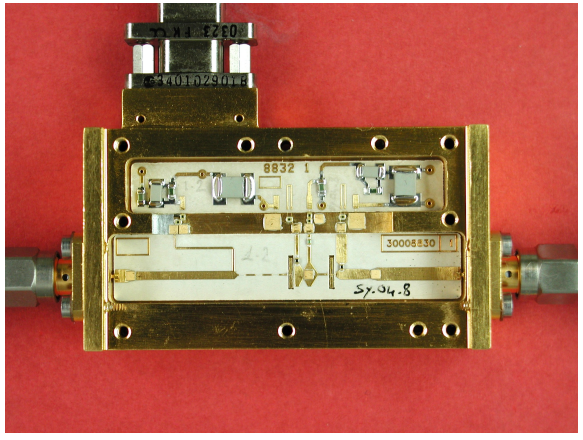
Stringent requirements from HIFI consortium: first space application of InP MMIC HEMTs, with low power consumption <5mW, wideband 4 GHz, and very low noise <5K
Construction transferred to Spanish industry, x40 flight certified





4-8 GHz
480-1272 GHz SIS
HIFI LOW (bands 1-5)

Dual side-band heterodyne detector
Dual lineal polarisation (H and V)
Single pixel instrument with 11-44” HPBW
WBS: Wide Band Spectrometer
(HSR: High-resolution spectrometer)

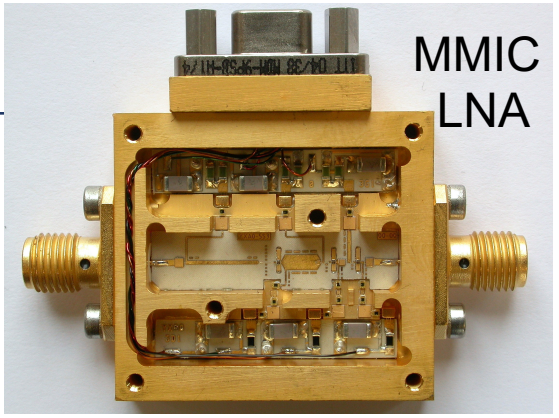


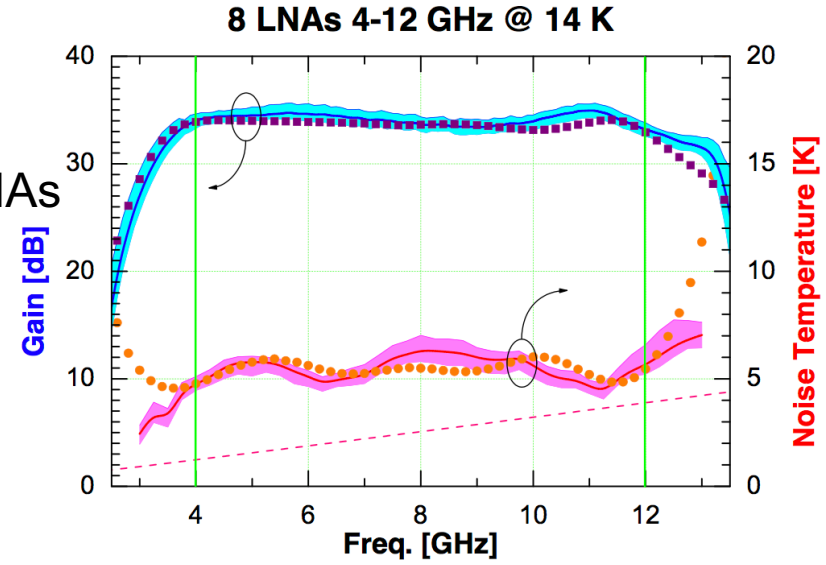
2.4-4.8 GHz
1430-1906 GHz HEB
HIFI HIGH (bands 6-7)

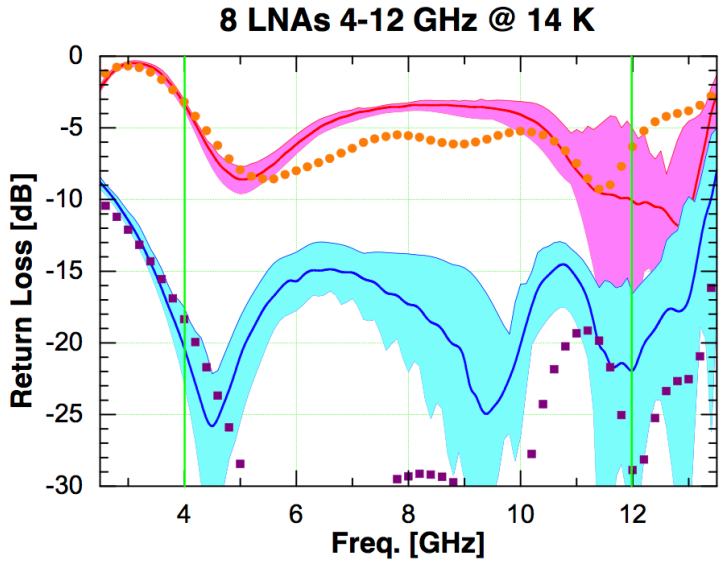
Cryogenic receivers in Yebes: ALMA Band 9

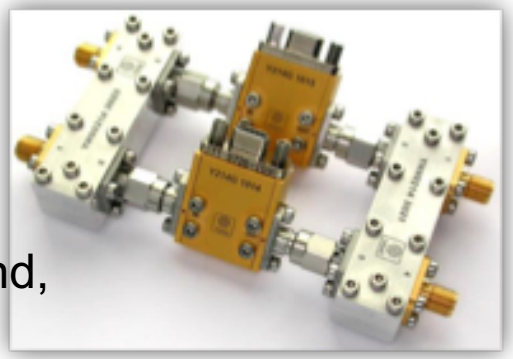
NOVA Band 9 SIS receivers with Yebes LNAs

ALMA Band 9 LNAs
602-720 GHz



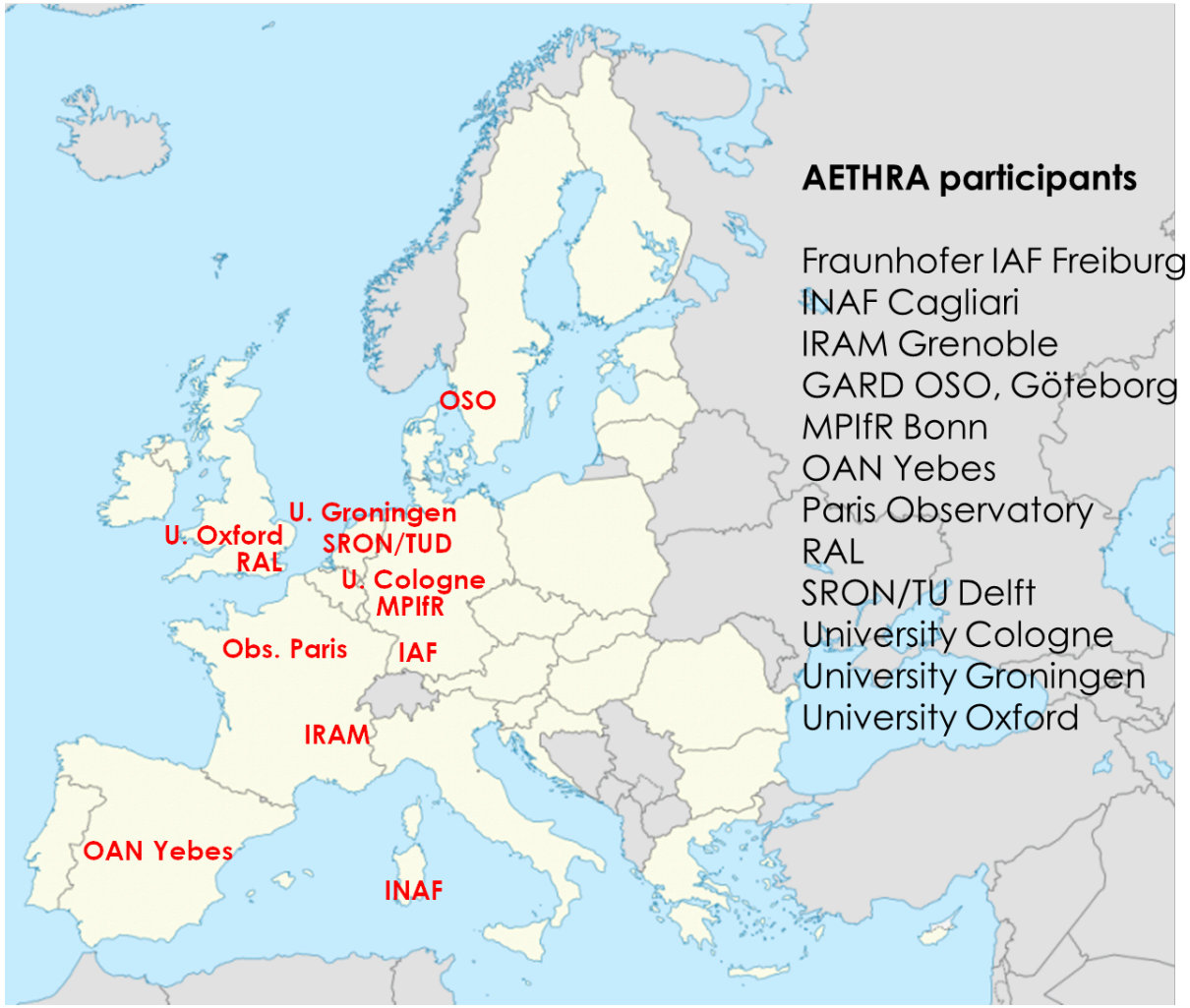






Contract with ESO for development of next generation ultra-wide band LNAs: developed 2 prototypes with different designs for 4-20 GHz band, surpassing requirements. Added balanced LNAs using passive 90º hybrids

Cryogenic receivers in Yebes Observatory: multi-pixel receivers

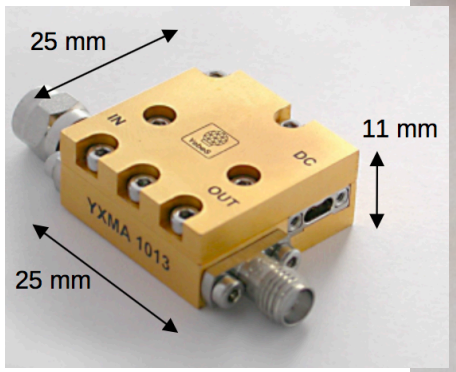


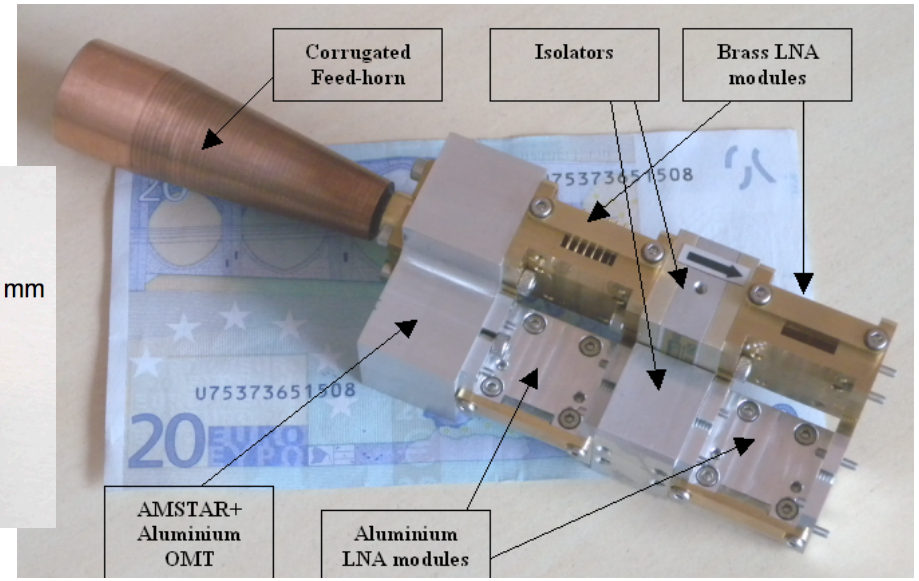
RadioNet legacy: AMSTAR+, AETHER, AETHRA

Lower noise, wider bandwidth, integration into **focal plane arrays**

Frequencies: 80 GHz < f < 1 THz

Technologies: HEMT, SIS and HEB mixers





Not only prototypes:

IRAM 30m EMIR, NOEMA, APEX, Yebes 40m CX, etc.

Stringent requirements for heterodyne multi-pixel receivers: volume and thermal load limitations, miniaturisation.

Conclusions

- ✓ **Possible to realise “Next Generation SVLBI” at high freqs.**
- ✓ **Suitable receiver technology** already (or almost) in place for space-borne THz missions
- ✓ **Experience of Yebes Observatory:** space-borne, low noise, low power consumption, wide-band and multi-pixel receivers
- ✓ **International collaborations** joining forces, Yebes participation in RADIOBLOCKS Horizon Europe, starting 2023.

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Many thanks!

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***On behalf of Yebes's receiver and amplifier groups**

https://astronomia.ign.es/web/guest/icts-yebes/acercade

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