GREAT, upGREAT, 4GREAT, super-GREAT ???

- GREAT enhancements -

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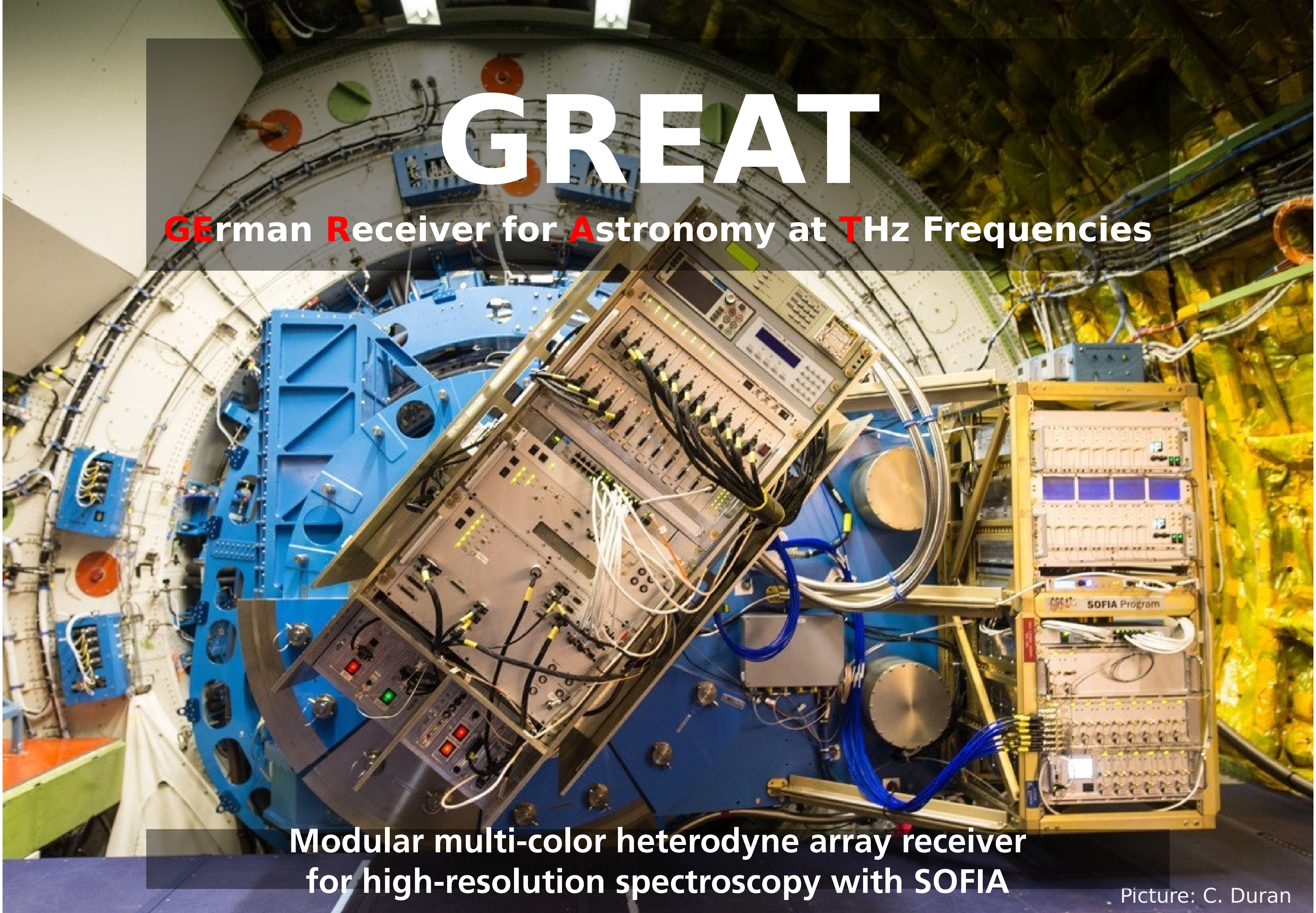

GREAT
GErman Receiver for Astronomy at THz Frequencies
SOFIA Program
Modular multi-color heterodyne array receiver
for high-resolution spectroscopy with SOFIA
Picture: C. Duran

GREAT – the Consortium

GREAT is a Principle Investigator instrument: funded, developed & operated by

The GREAT team

Max-Planck Institut für Radioastronomie

B.Klein (Co-PI, FFT spectrometer)
O. Ricken (system engineer)
N. Reyes (system engineer)

Universität zu Köln, KOSMA

J. Stutzki (PI, software)
U. Graf (system engineer)
K. Jacobs (HEB mixers development)

DLR Planetenforschung

H.-W. Hübers (Co-PI, QCL development)

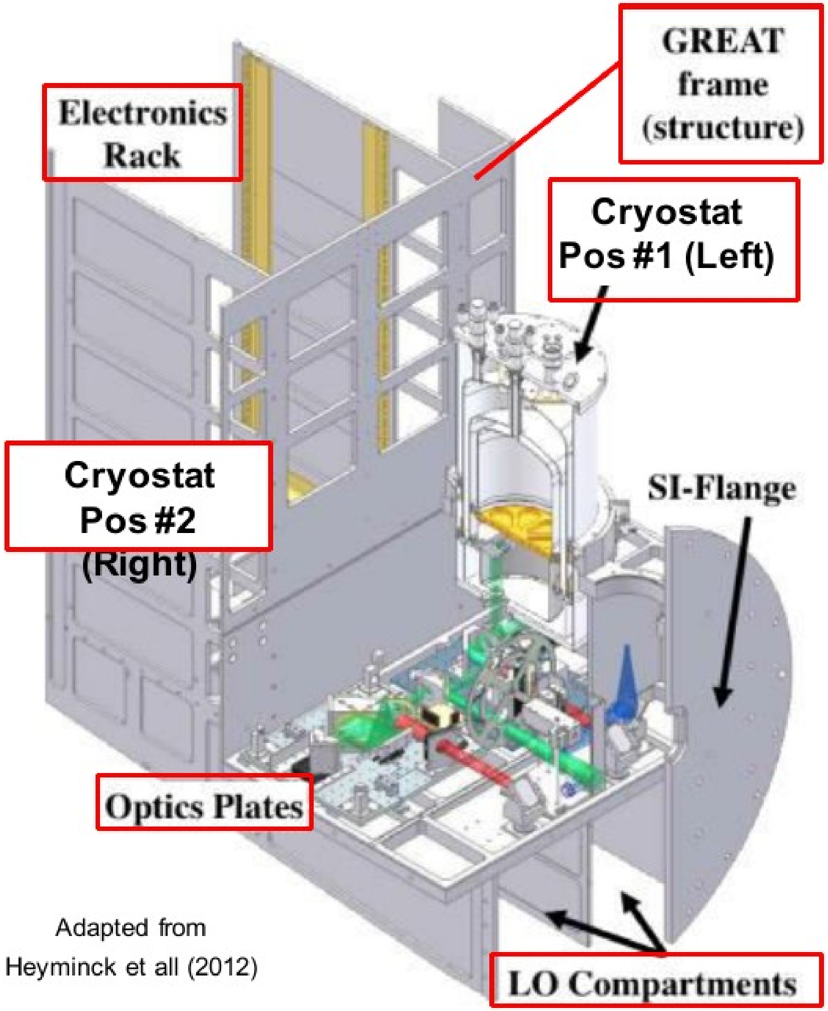
GREAT – Continuous System Upgrades

The modular design of GREAT allows to implement technological improvements within a short time-frame, keeping GREAT at the forefront in terms of performance / science.

Since commissioning in 2011 we have

- upgraded all our HEB mixers (much improved system noise temperatures)
- improved all local oscillator sources (and related, the common optics)
- replaced all our FFT spectrometer back-ends with latest technologies (wider IF bandwidth – defined by HEB roll-off)
- optimized mapping efficiency by introducing multi-pixel arrays (→ upGREAT)
- added new science opportunities by opening more sky frequency regimes (→ 4GREAT)

GREAT – System Overview



Channel: Cryostat + LO + Optics plate

GREAT is a highly modular heterodyne spectrometer (R ~ 10^8)

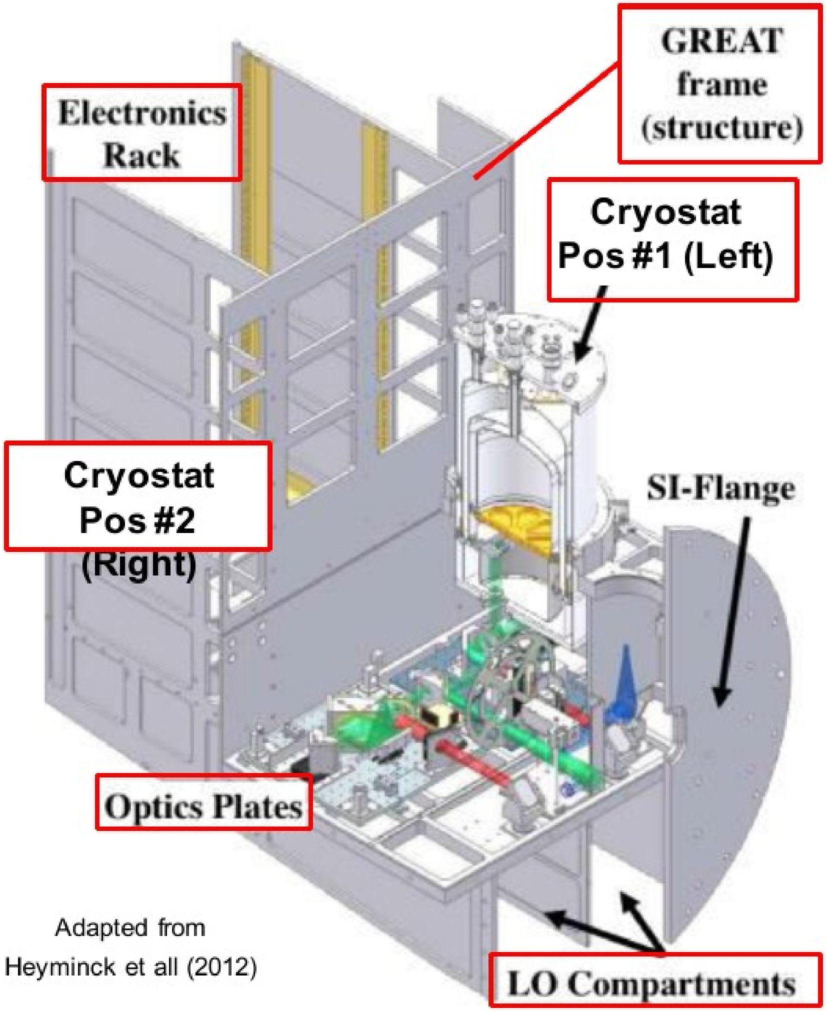
Operating in science-defined frequency bands between 490 GHz and 4.7 THz

Two cryostats can be operated simultaneously

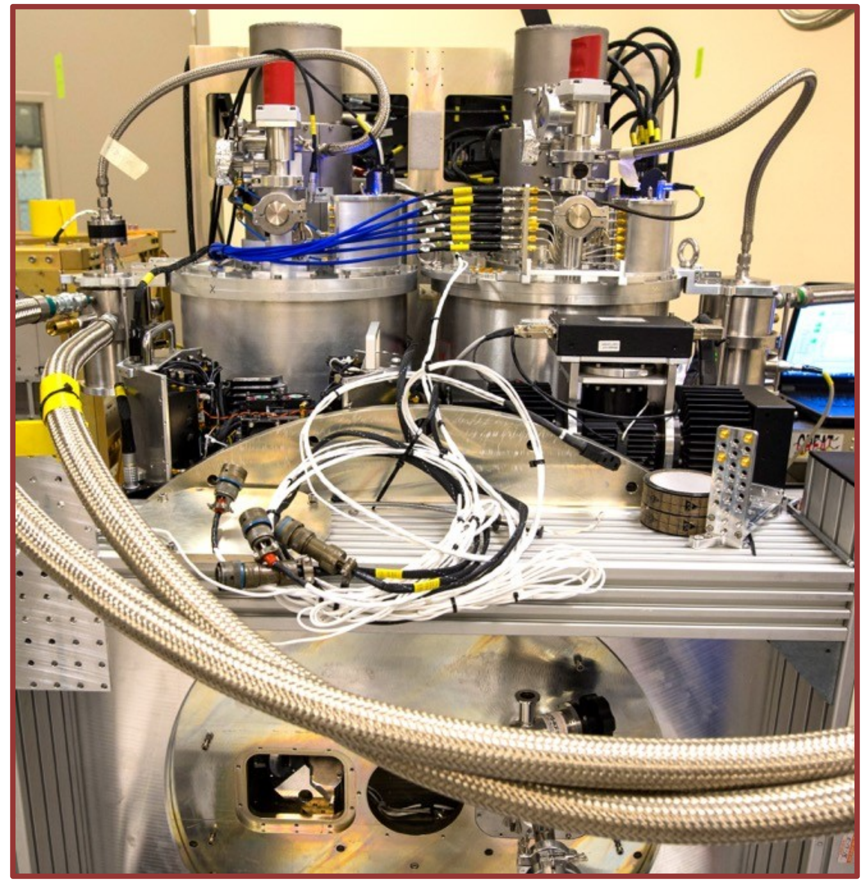
Since 2018 operation has been stream-lined to two configurations only:

LFA & HFA and 4G & HFA

GREAT – System Overview



Adapted from
Heyminck et all (2012)

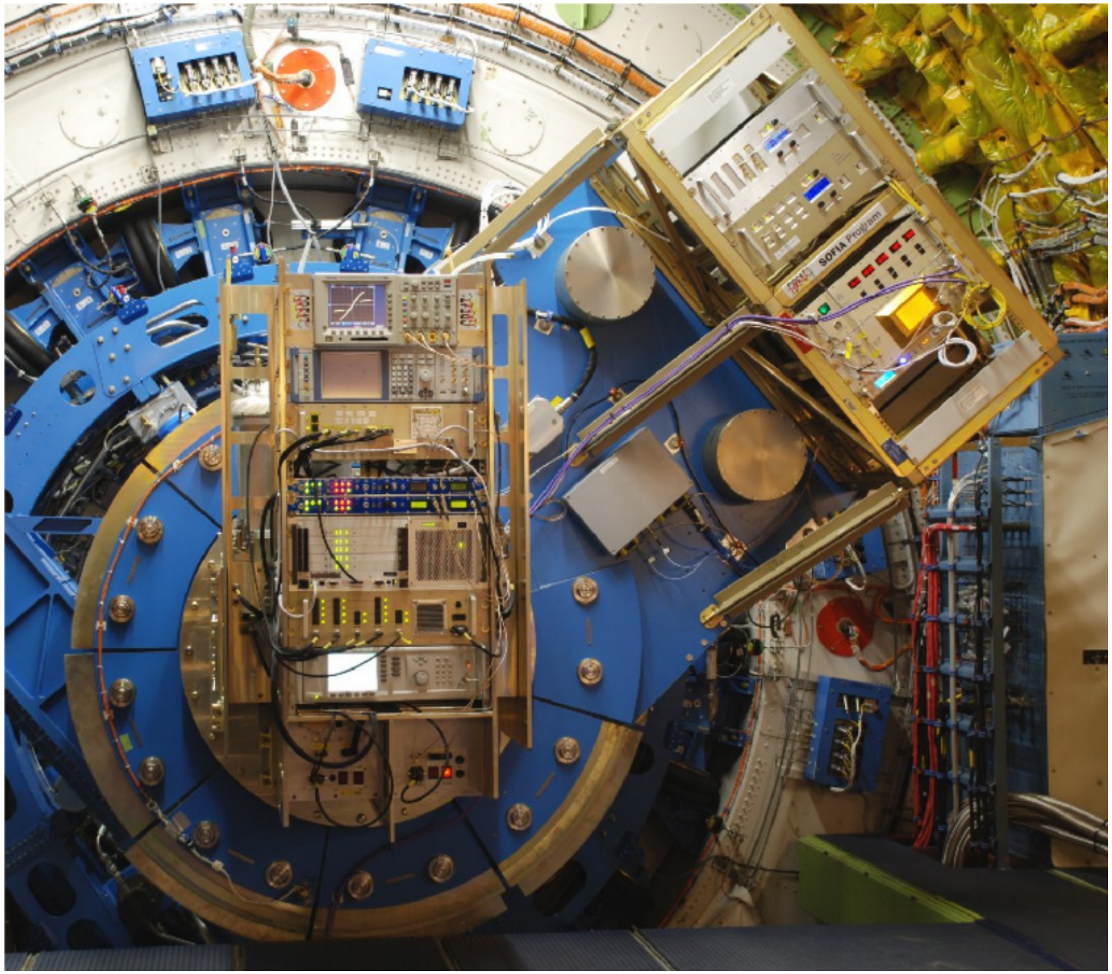


Channel: Cryostat + LO + Optics plate

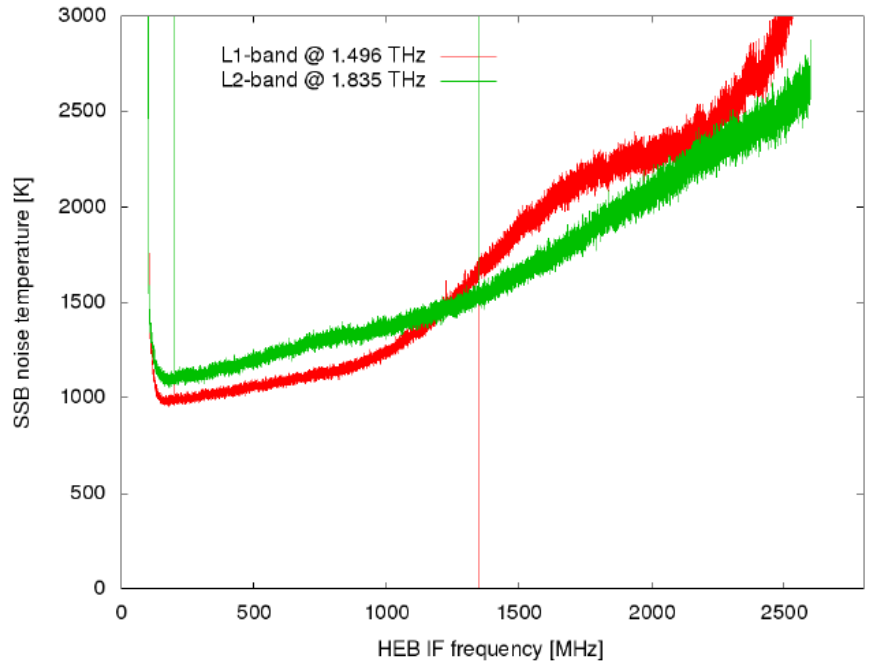
GREAT – singe pixel (2011-2014)

Receiver Name		Freq. range	Pixel configuration	Lines of interest
Original GREAT Cooling: Wet (LHe)	L1	1.26 – 1.52 THz	single pixel	CO series, [NII], OD, H_2D^+
	L2	1.82 – 1.91 THz	single pixel	NH_3, OH, CO(17-16), [CII]
	Ma	2.49 – 2.56 THz	single pixel	$^{18}OH(^2\Pi_{3/2})$
	H	4.74 THz	single pixel	[OI]

GREAT – singe pixel (2011-2014)



GREAT mounted to the instrument flange (2012)

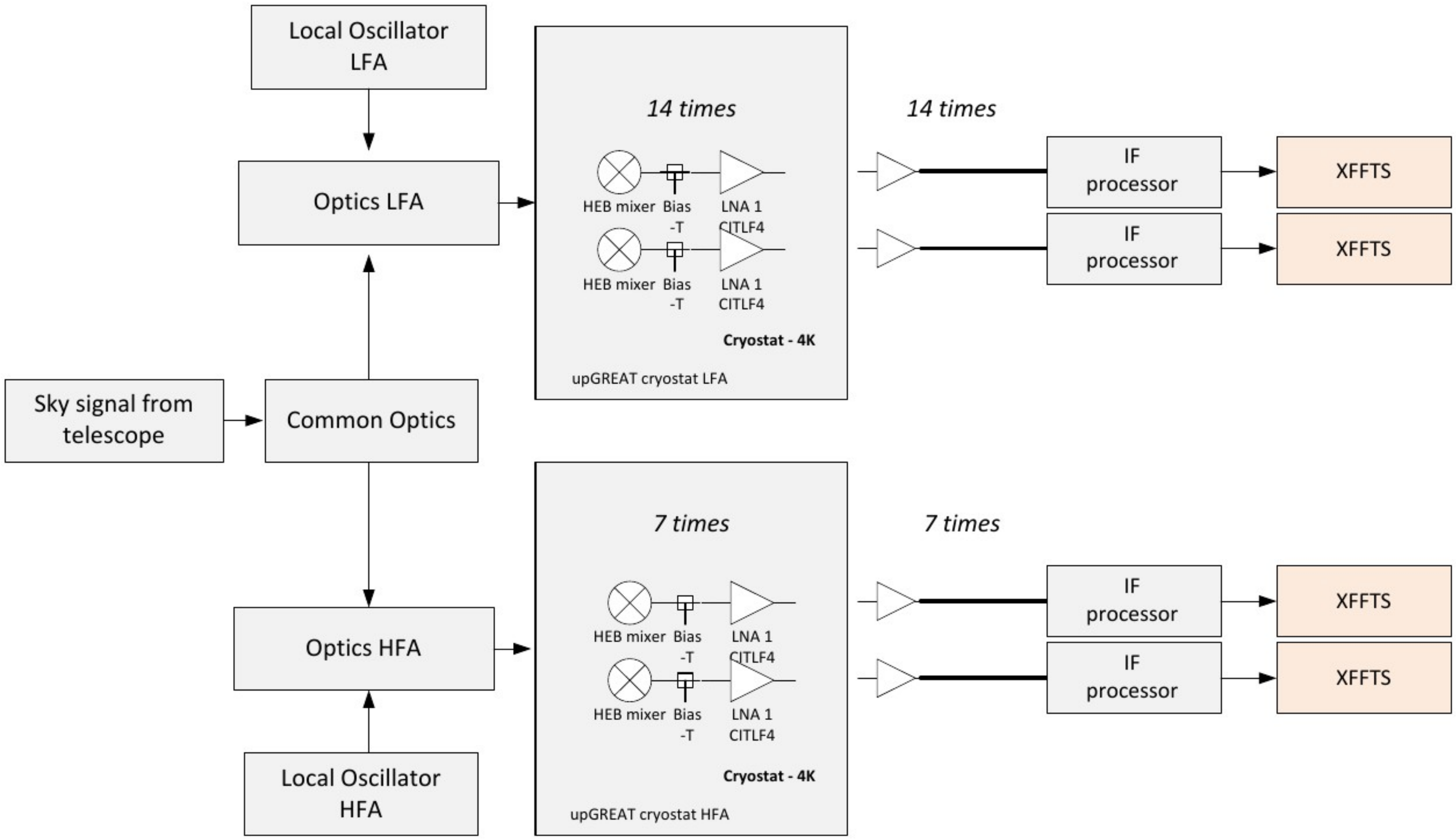


Receiver noise temperatures after improvements implemented for science cycle 1.

upGREAT – 7/14 pixel (2015 - now)

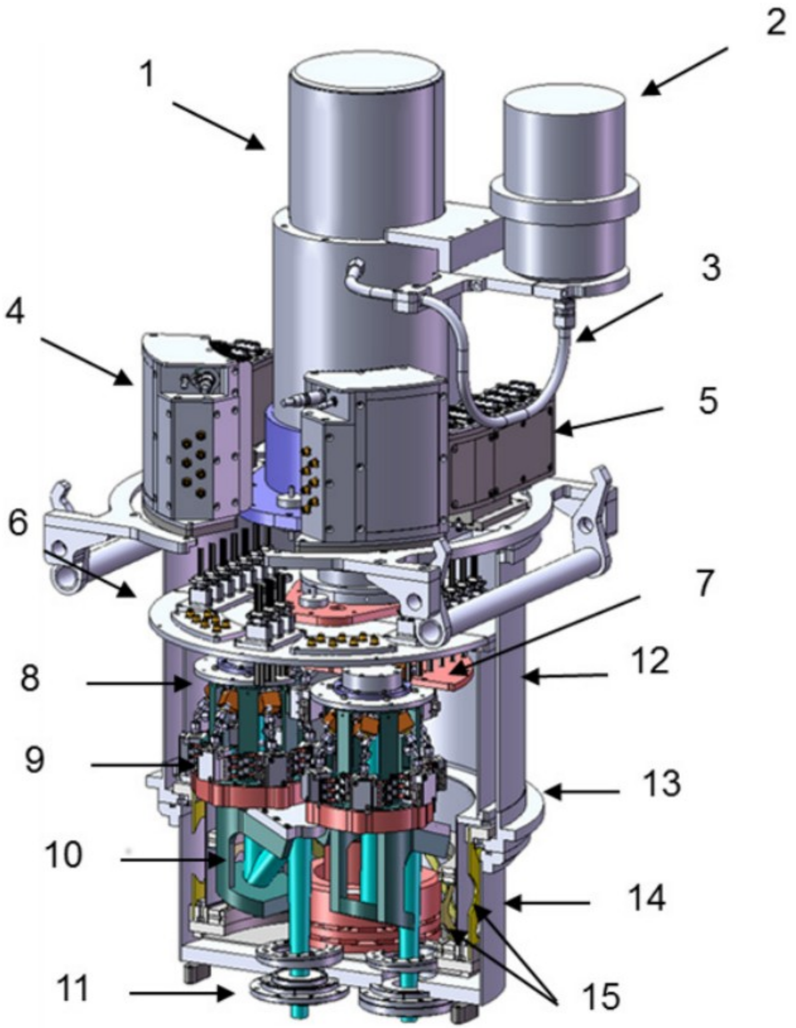
Receiver Name		Freq. range	Pixel configuration	Lines of interest
Original GREAT Cooling: Wet (LHe)	L1	1.26 – 1.52 THz	single pixel	CO series, [NII], OD, H_2D^+
	L2	1.82 – 1.91 THz	single pixel	NH_3, OH, CO(17-16), [CII]
	Ma	2.49 – 2.56 THz	single pixel	$^{18}OH(^2\Pi_{3/2})$
	H	4.74 THz	single pixel	[OI]
upGREAT Cooling: Cryo-Cooler	LFA	1.83 – 2.07 THz (goal 1.9–2.5 THz)	14 pixels	NH3, OH, CO series, [CII]
	HFA	4.745 THz ± few GHz	7 pixels	[OI]

upGREAT – 7/14 pixel (2015 – now)
- the concept -



Main components of the upGREAT LFA and HFA channels when operated in parallel onboard SOFIA.

upGREAT – 7/14 pixel (2015 - now)



3D-Model of the upGREAT cryostat

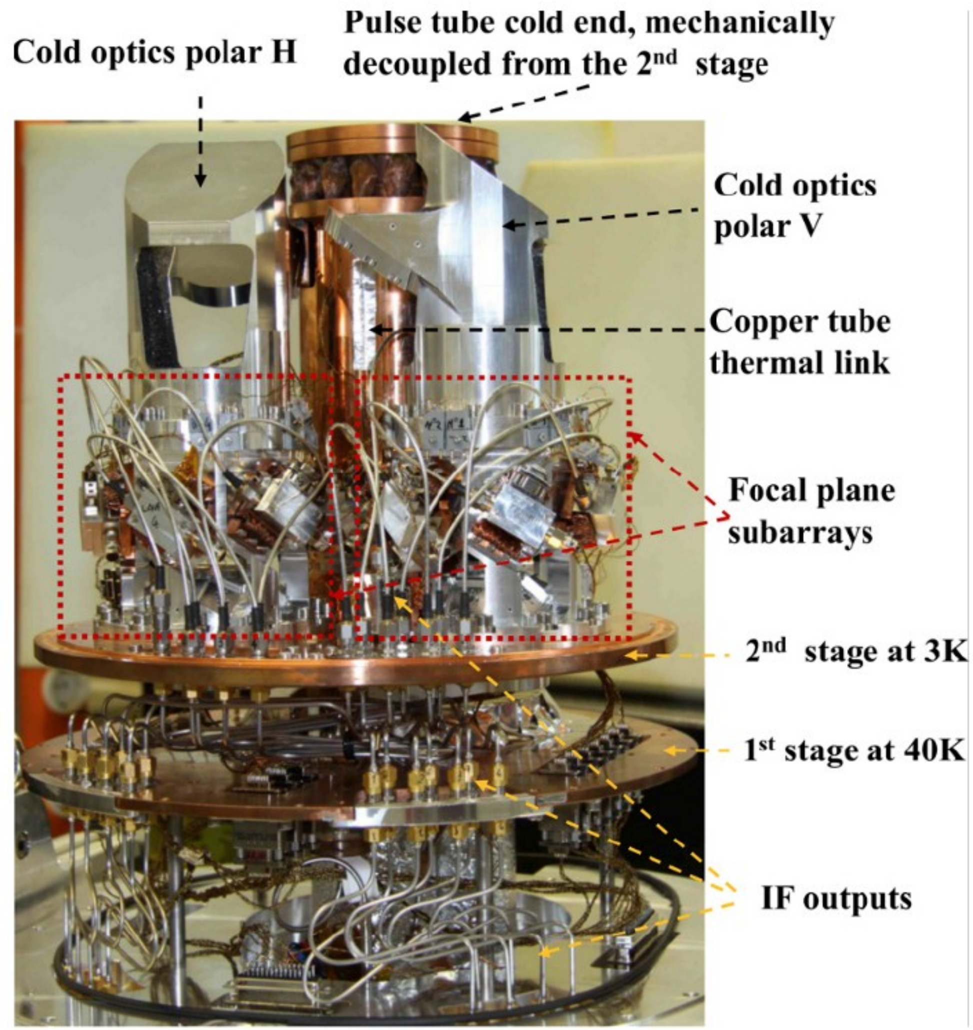


Photo of the inner part of the LFA cryostat

upGREAT – 7/14 pixel (2015 - now)

New SOFIA infrastructure:

In 2017, the installation of 2 compressors on board SOFIA was completed, allowing the simultaneous operation of 2 closed circuit coolers.

upGREAT – 7/14 pixel (2015 – now)
- system characteristics -

	Low Frequency Array (LFA)	High Frequency Array (HFA)
RF bandwidth	1.9-2.5 THz (goal)	~4.745 THz
IF bandwidth	0.2-4 GHz	0.2-4 GHz
HEB technology	waveguide-based HEB NbN on Si membrane	waveguide-based HEB NbN on Si membrane
LO technology	cooled photonic mixers (goal) / solid-state chains (baseline)	quantum cascade lasers (QCL)
LO coupling	beam splitter	beam splitter
Array layout	2x7 pixels for orthogonal polarizations in hexagonal configuration with central pixel	1x7 pixels in hexagonal configuration with central pixel
T_{REC}	~600-1200K DSB 0-4 GHz IF	~800-1600K DSB 0-4 GHz IF
Back-ends	0-4 GHz with min 16k channels	0-4 GHz with min 16k channels

upGREAT – 7/14 pixel (2015 – now)
- technical specifications -

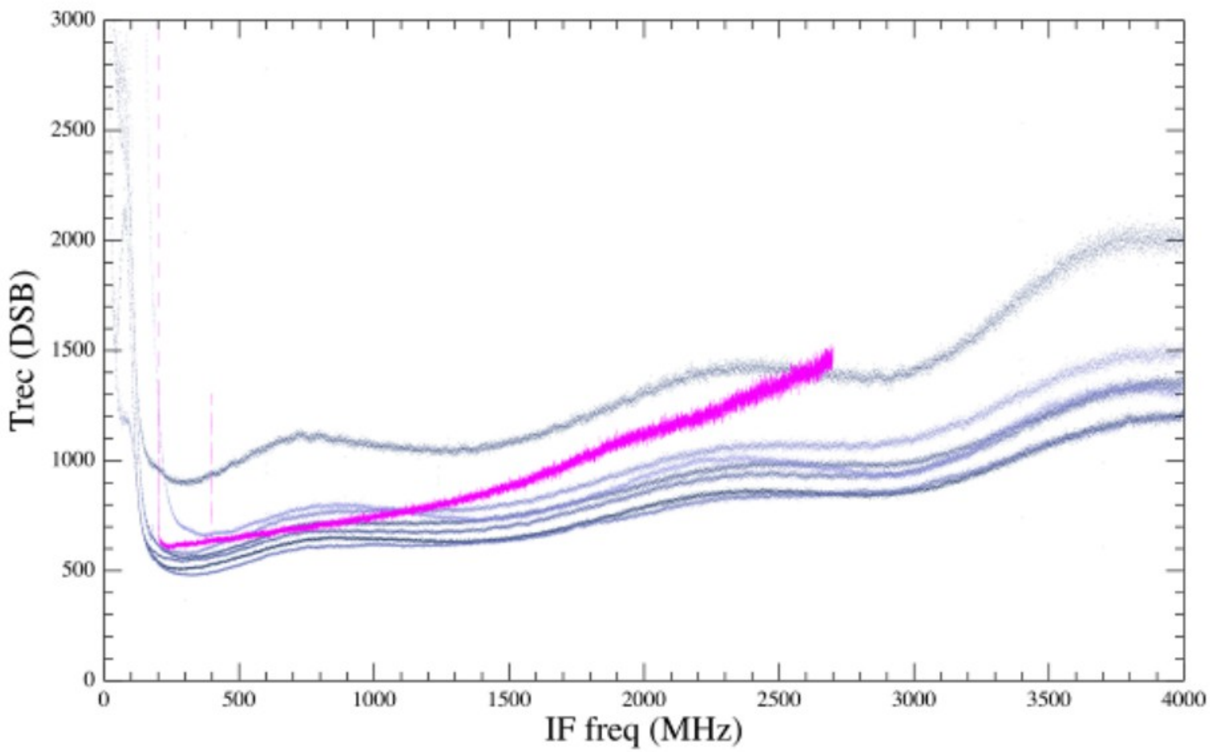
GREAT Configurations

Front-End	Frequencies (GHz)	Lines of Interest	DSB[6] Receiver Temperatures (K)
HFA [1]	4744.77749	[OI] 63 μm	1250
LFAH [2]	1835–2007	[CII] 158 μm, CO, OH, ${}^{2}\Pi_{1/2}$, ^{12}CH, ^{13}CH	1000
LFAV [2]	1835–2007 2060–2065	Same as LFAH, plus [OI] 145 μm	

Observer's Handbook for Cycle 9

upGREAT – 7/14 pixel (2015 – now)

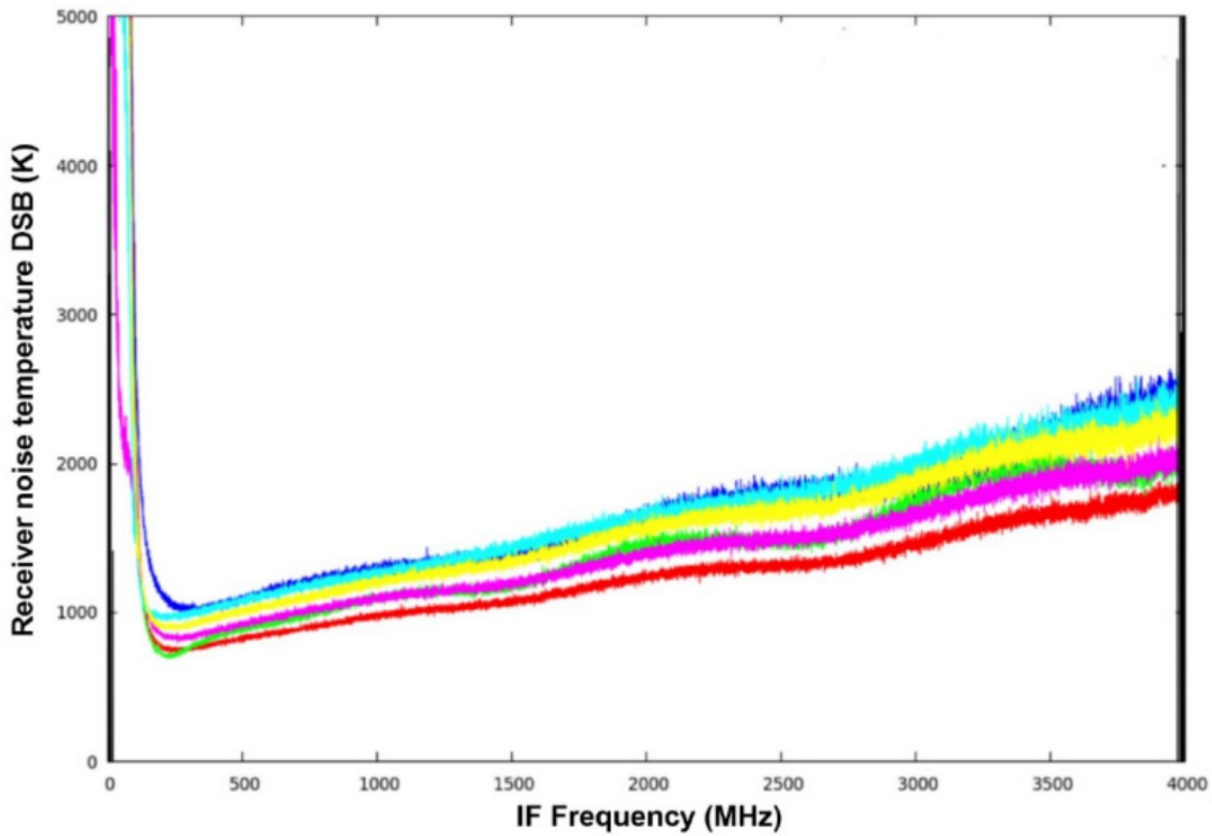
upGREAT / LFA performance:
Uncorrected Double sideband noise temperatures (K) at 1.9 THz versus IF frequency for the H-polarization LFA 7 channels.



upGREAT – 7/14 pixel (2015 – now)

upGREAT / HFA performance:

Double sideband noise temperatures of the 7 HFA pixels when pumped under best conditions



4GREAT – our latest addition (2018/19 - now)

4GREAT is a 4-frequency channel receiver for simultaneous operation

→ **4G-1** 480 – 635 GHz (HIFI spare flight SIS mixer, by LERMA / Obs. Paris)
→ **4G-2** 890 – 1100 GHz (HIFI spare flight SIS mixer, by SRON NL)
→ **4G-3** 1220 – 1500 GHz (replaces previous LHe L1 channel from GREAT)
→ **4G-4** 2480 – 2700 GHz (replaces LHe M channel from GREAT)

Optics:

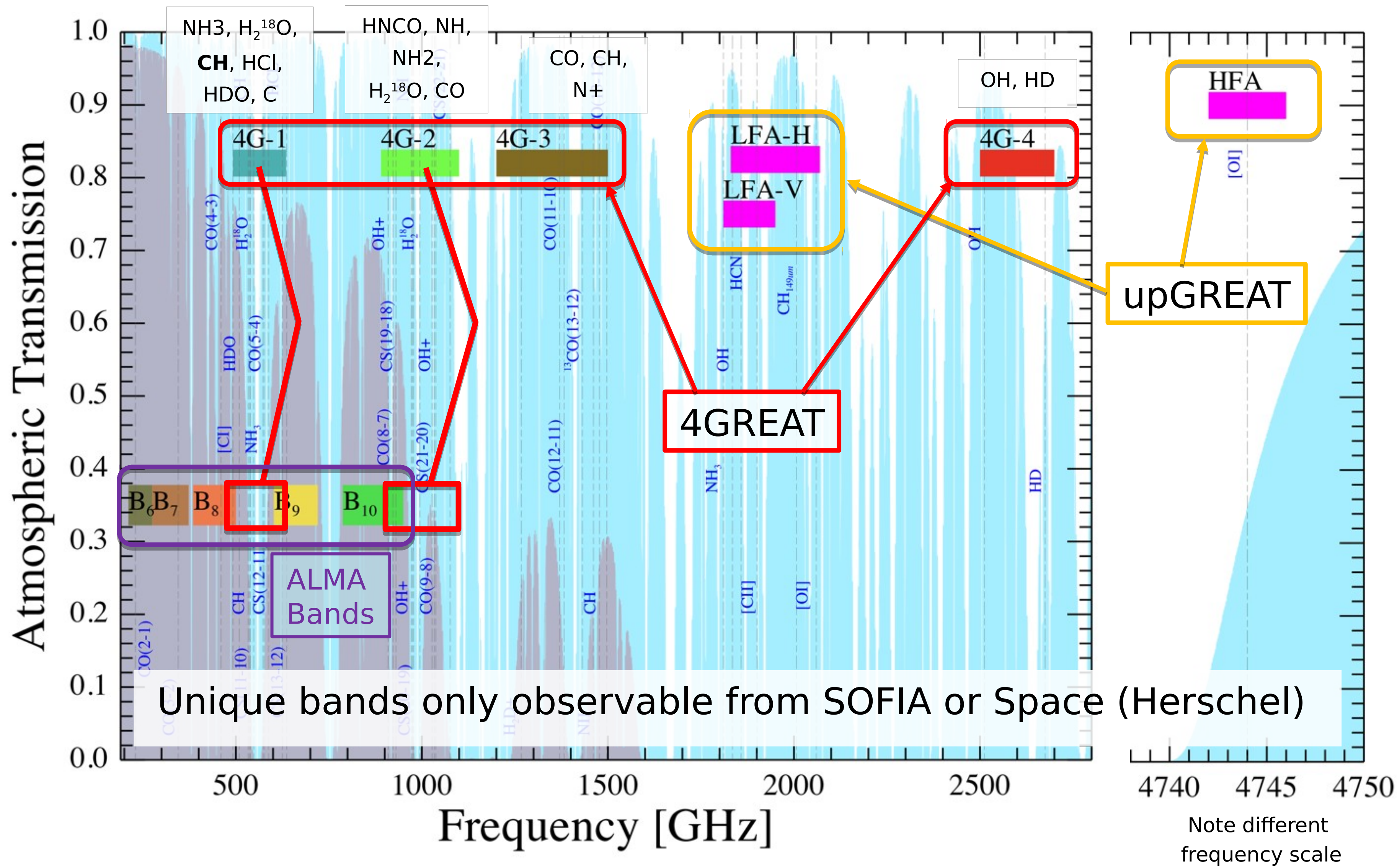
→ simultaneous 4 different „frequency bands" + HFA
→ frequency separation
→ operation in parallel with upGREAT / HFA (beam filtering)
→ optics for signal + optics for local oscillators
→ two LOs: hosting 4 LO sources now:
- a standard LO box as the other GREAT/upGREAT systems (4G-3, 4G-4)
- a smaller enclosure fro the 2nd LO box (4G-1, 4G-2)

Optics have to cover a wide range: 480 – 2700 GHz !

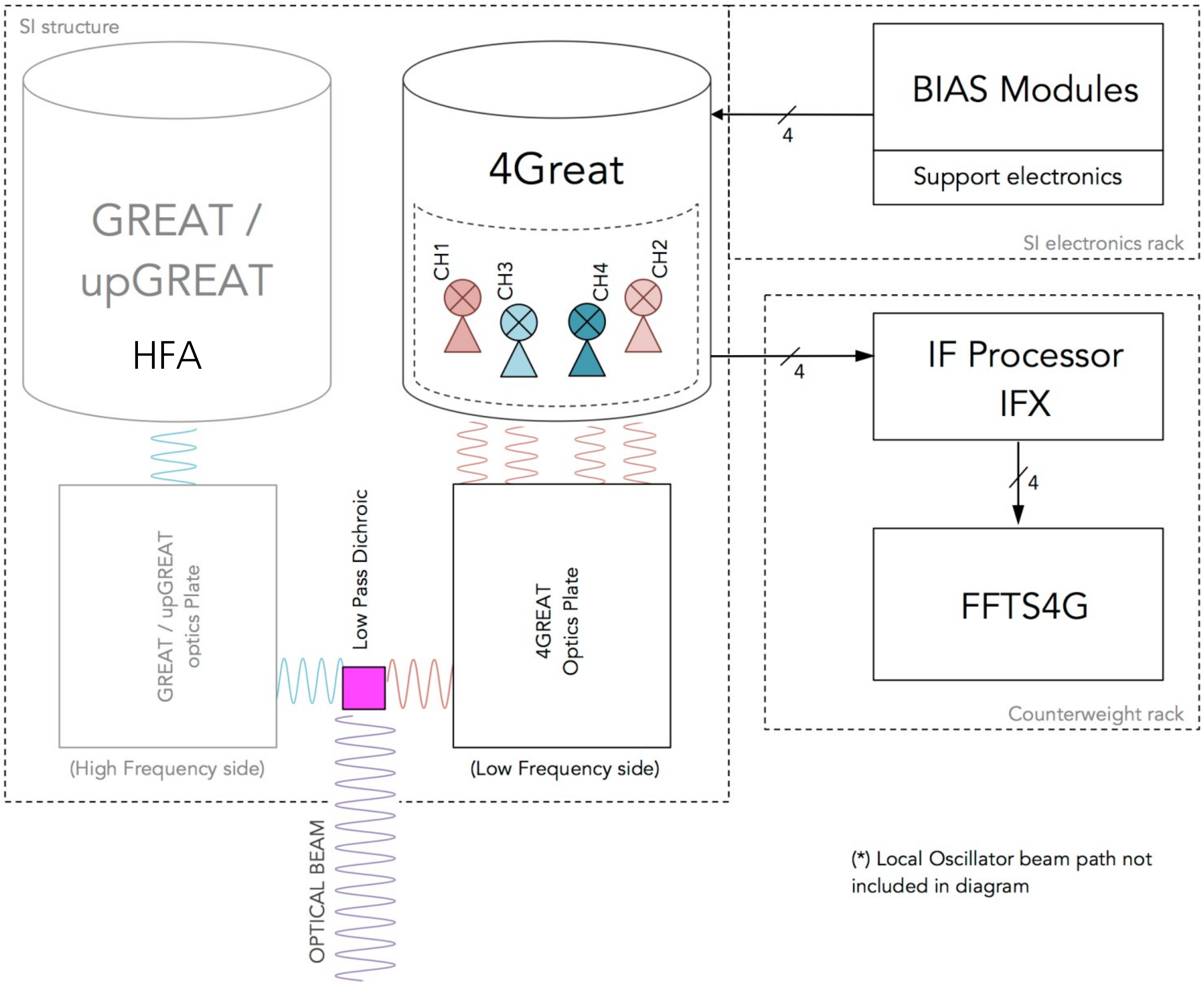
Cooling:

→ close cycle coolers (two compressors, same as for upGREAT LFA + HFA)

4GREAT – the multicolor extension of GREAT (2018/19 - now)

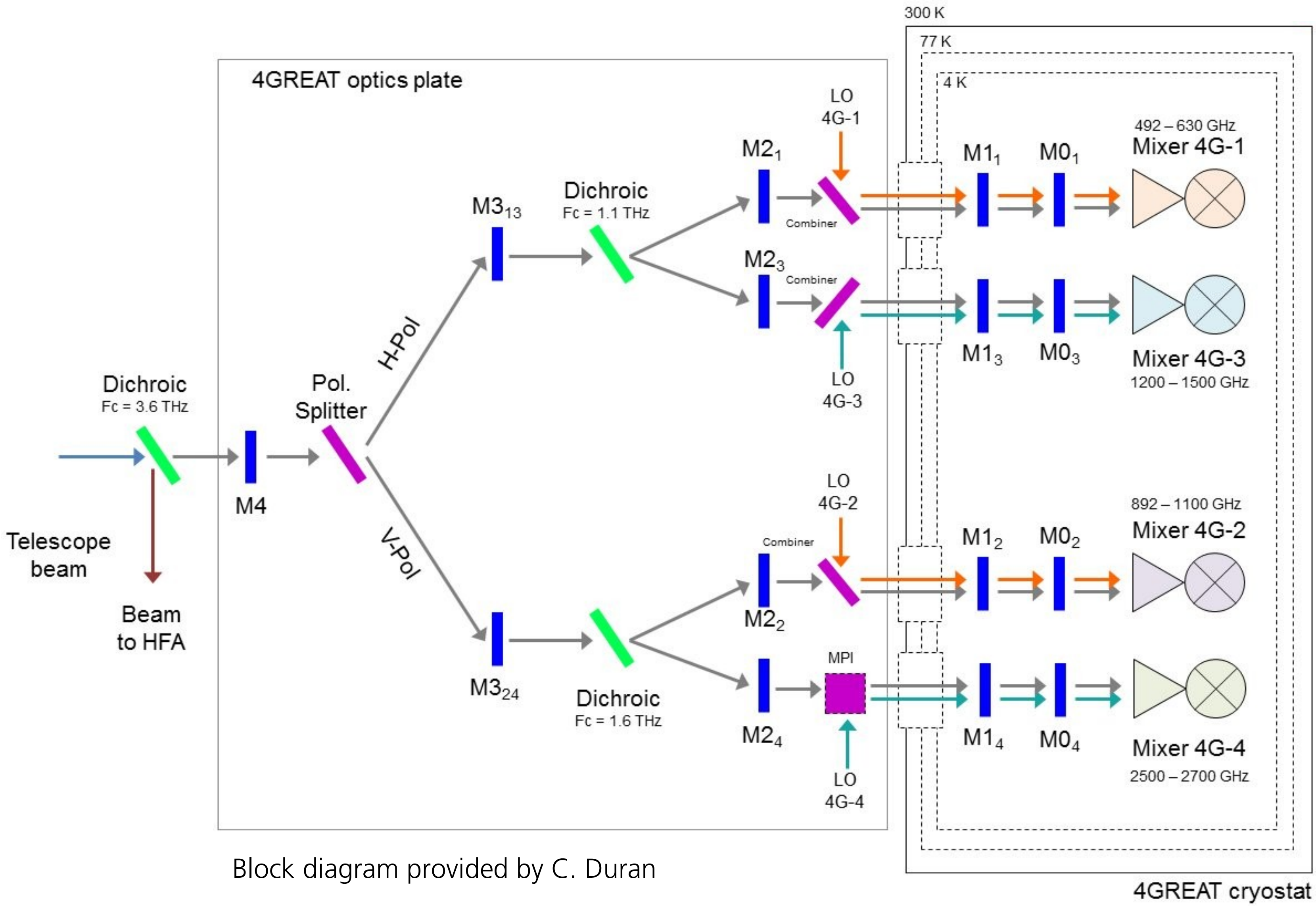


4GREAT – operation principle



(*) Local Oscillator beam path not included in diagram

4GREAT – optics design



Block diagram provided by C. Duran

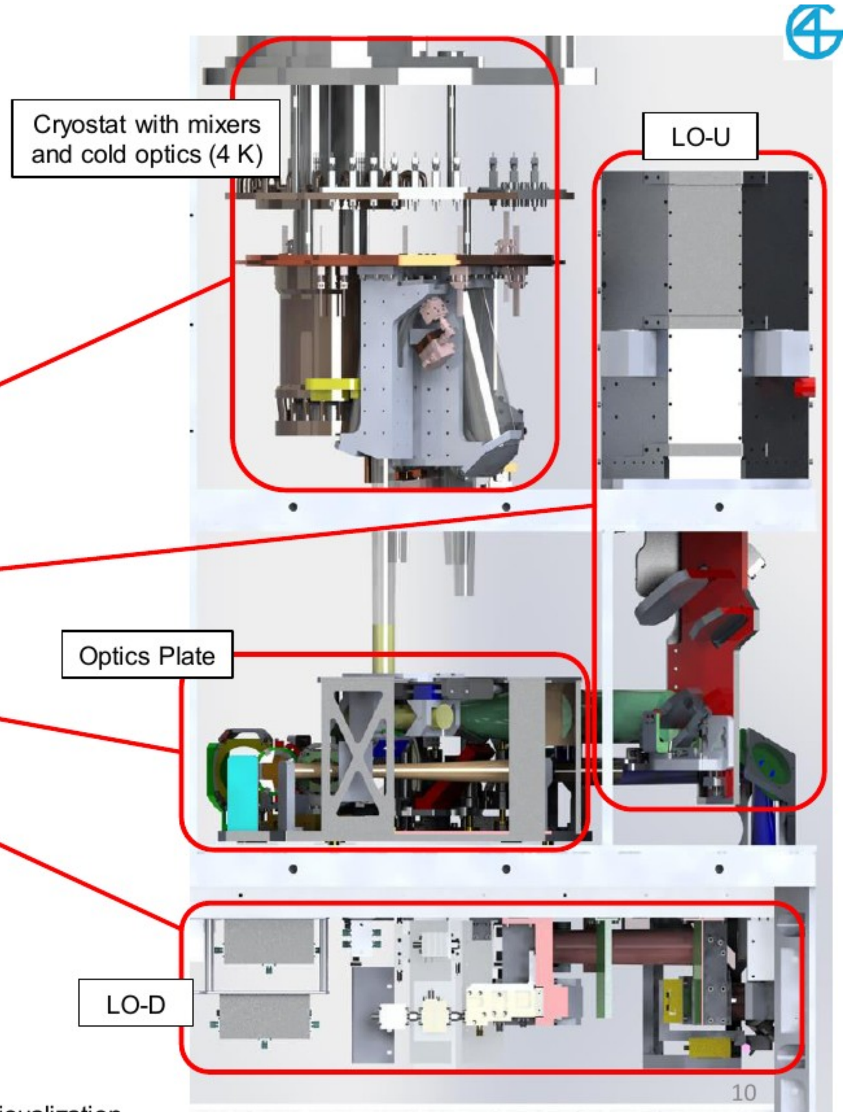
4GREAT – the multicolor extension of GREAT (2018/19 - now)

Channel	CH1	CH2	CH3	CH4
RF Bandwidth [GHz]	492 - 630	892 - 1100	1200-1500	2490 - 2700
IF Bandwidth [GHz]	4 - 8	4 - 8	0.5 - 3.5	0.5 - 3.5
Mixer	SIS	SIS	HEB	HEB
	Herschel HIFI - 1 (LERMA)	Herschel HIFI - 4 (SRON)	GREAT -L1 (KOSMA)	GREAT - M-HD (KOSMA)
Amplifiers (LNA / Warm Amp)	LNF-LNC4_8C (LNF)	LNF-LNC4_8C (LNF)	CITLF4 (CMT)	CITLF4 (CMT)
	AFS3-00100800 (Miteq)	AFS3-00100800 (Miteq)	AFS3-00100800 (Miteq)	AFS3-00100800 (Miteq)
Local Oscillator	S.S.Chain AMC563@LO-U (200uW)	S.S. Chain AMC581@LO-U (150uW)	S.S. Chain AMC627@LO-D (30uW)	S.S. Chain AMC616@LO-D (2.5 uW)
LO Coupling	Wiregrid Splitter	Wiregrid Splitter	Wiregrid Splitter	Diplexer
Optics	Common optic plate + Mixer block optics + LOU Optics	Common optic plate + Mixer block optics + LOU Optics	Common optic plate + Mixer block optics + LOD Optics	Common optic plate + Mixer block optics + LOD Optics
TRec (DSB)	120	350	1100	1700
IF Processor	IFX x 1. High Order BPF 4-8 GHz	IFX x 1. High Order BPF 4-8 GHz	IFX x 1. High Order BPF 0-4 GHz	IFX x 1. High Order BPF 0-4 GHz
Backend	FFTS4G. Nyquist Band 4-8	FFTS4G. Nyquist Band 4-8	dFFTS4G x 1ch	dFFTS4G x 1ch
Taper (dB)	11.86 - 16.54	12.25 - 16.09	13.29 - 14.78	14.35 - 13.68

4GREAT – hardware

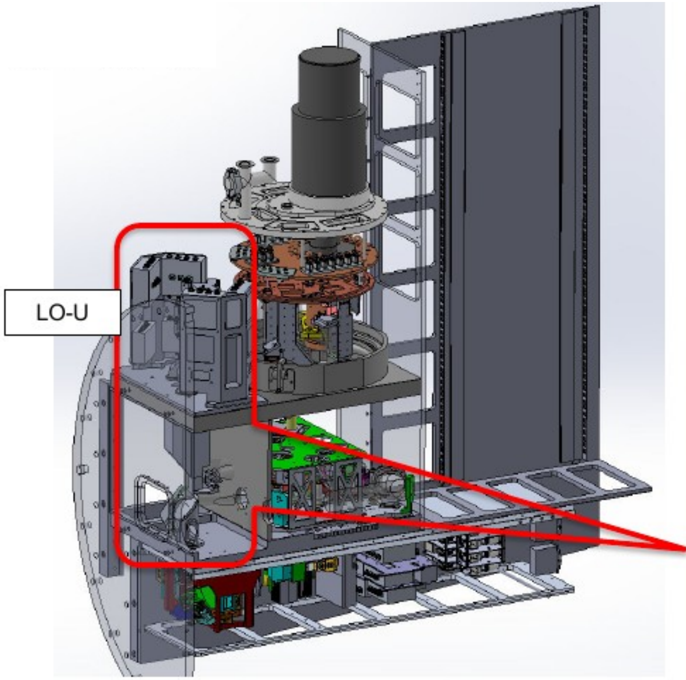
4 identifiable modules*

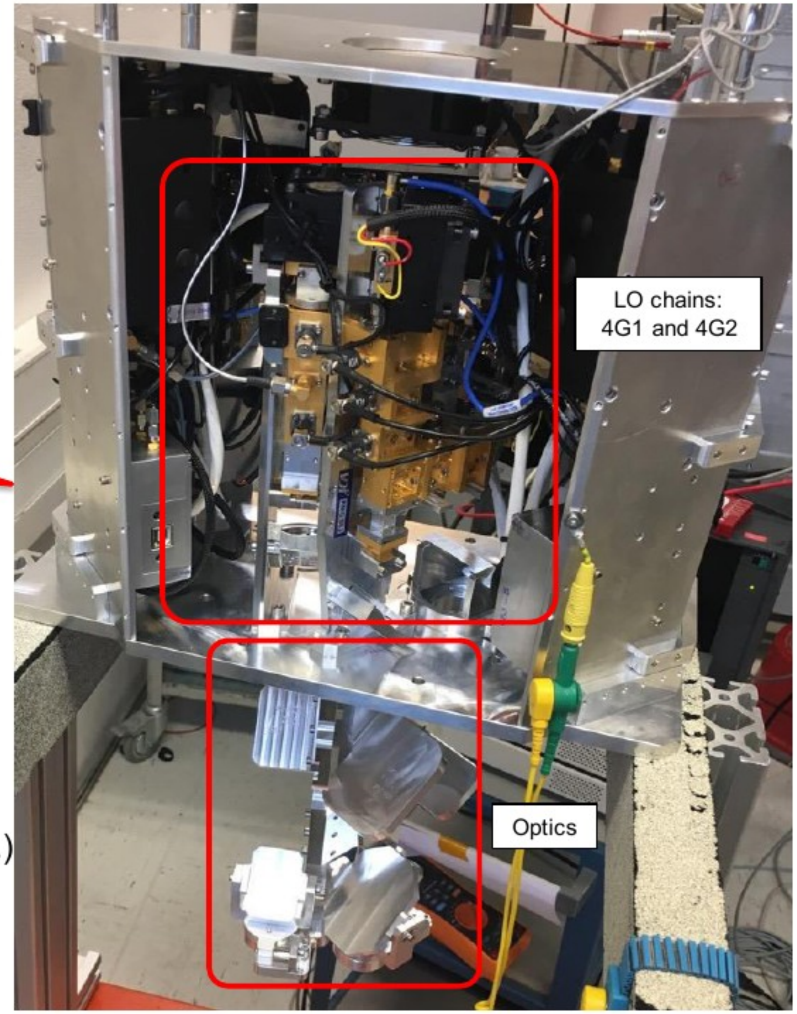
- 4GREAT Cryostat
- LO-U (LO 4G-1 | 4G-2)
- 4GREAT Optics Plate
- LO-D (LO 4G-3 | 4G-4)



(*) Some covers and panels have been removed for better visualization

4GREAT – LO-U





Optics for LO signal coupling

- 4G-1LO: Parabolic mirror + 2 GT
- 4G-2LO: Parabolic mirror + 2 GT

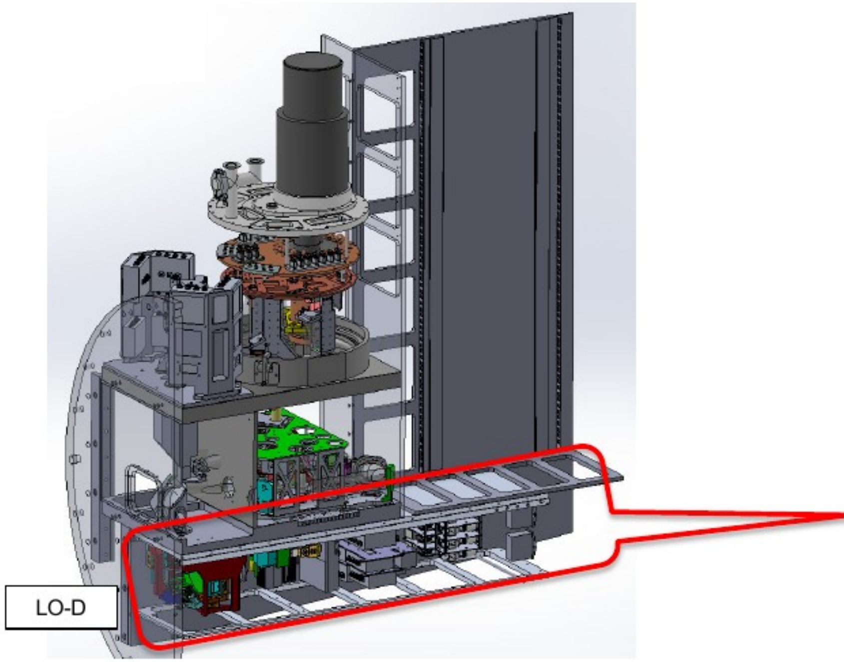
2 independent Solid State LO chains (Virginia Diodes Inc.)

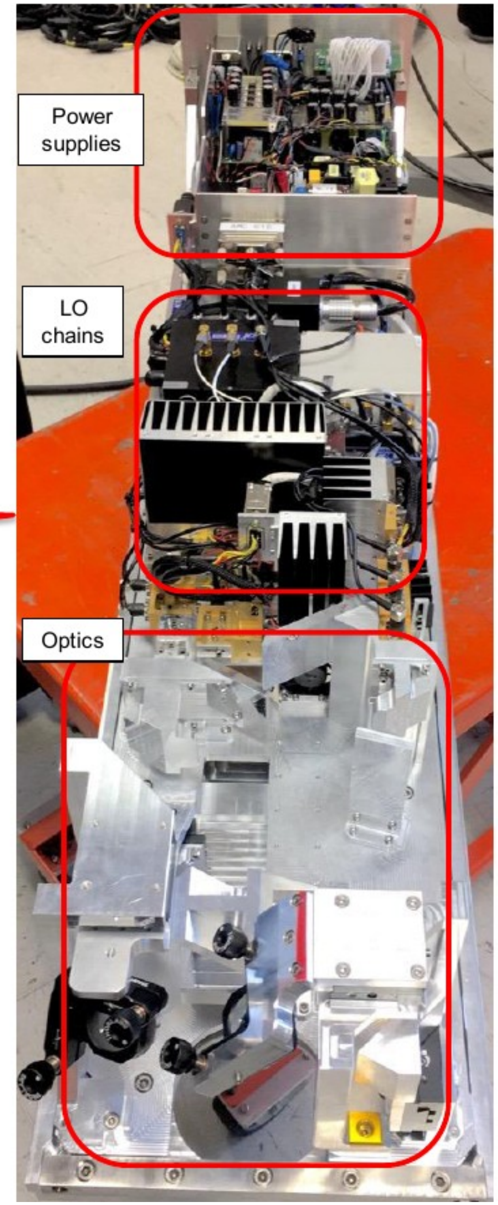
- 4G-1LO: 495 to 628 GHz, 200 μW.
- 4G-2LO: 890 to 1085 GHz, 150 μW.

Attenuators:

- 4G-1LO: Variable aperture wheel
- 4G-2LO: Rotary wire-grid

4GREAT – LO-D





Optics for LO signal coupling

- 4G-3LO: 1 Parabolic mirror + 1 GT + 1 ellipsoidal mirror
- 4G-4LO: Parabolic mirror + 2 GT

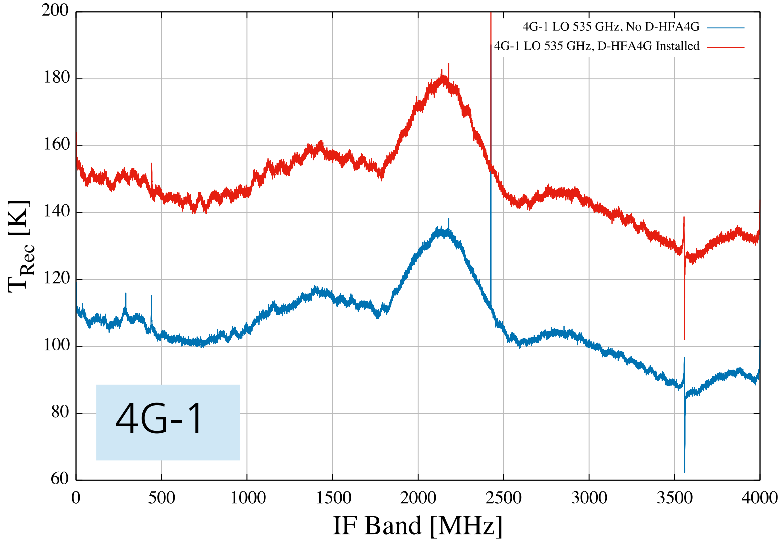
2 independent Solid State LO chains (VDI)

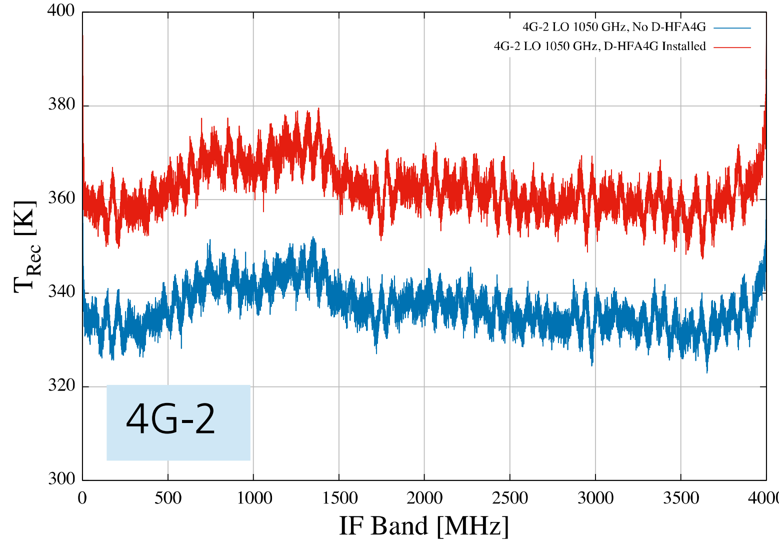
- 4G-3LO: 1240 to 1525 GHz, 30 μW
- 4G-4LO: 2490 to 2685 GHz, 2.5 μW

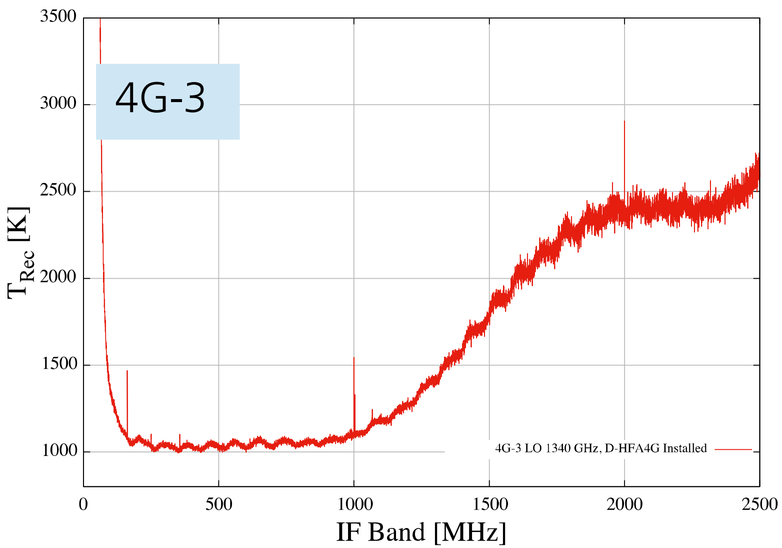
Power supplies for 4 x LO chains

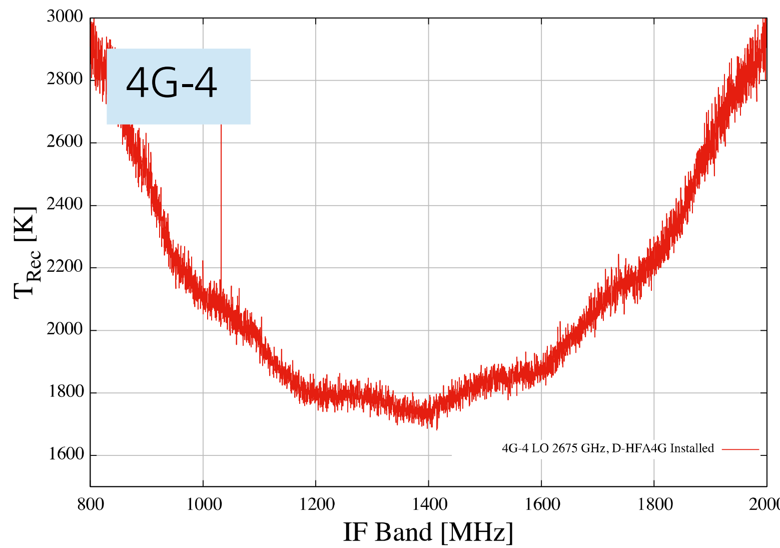
Rotary grids as attenuators.

4GREAT – Receiver temperatures (DSB)

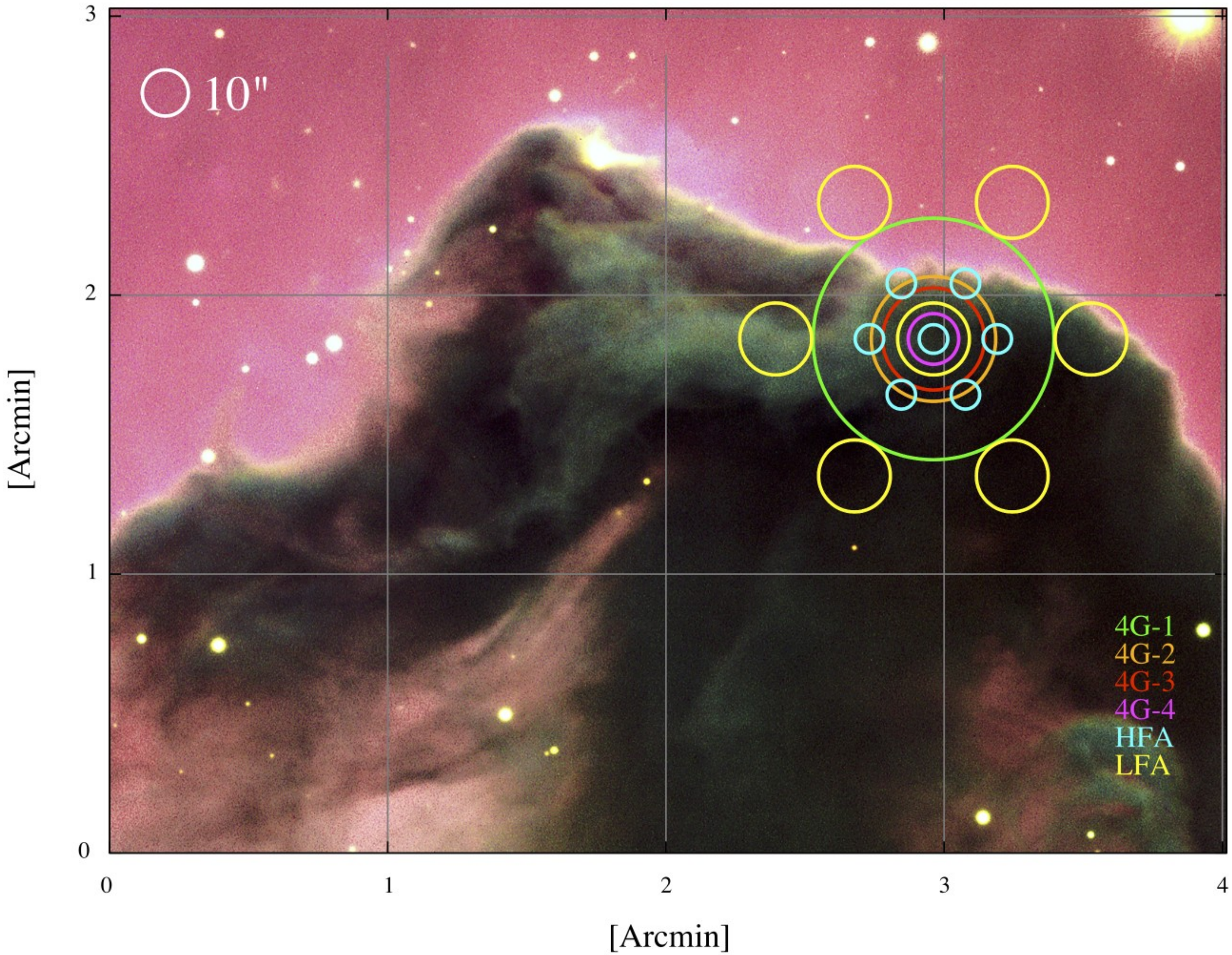




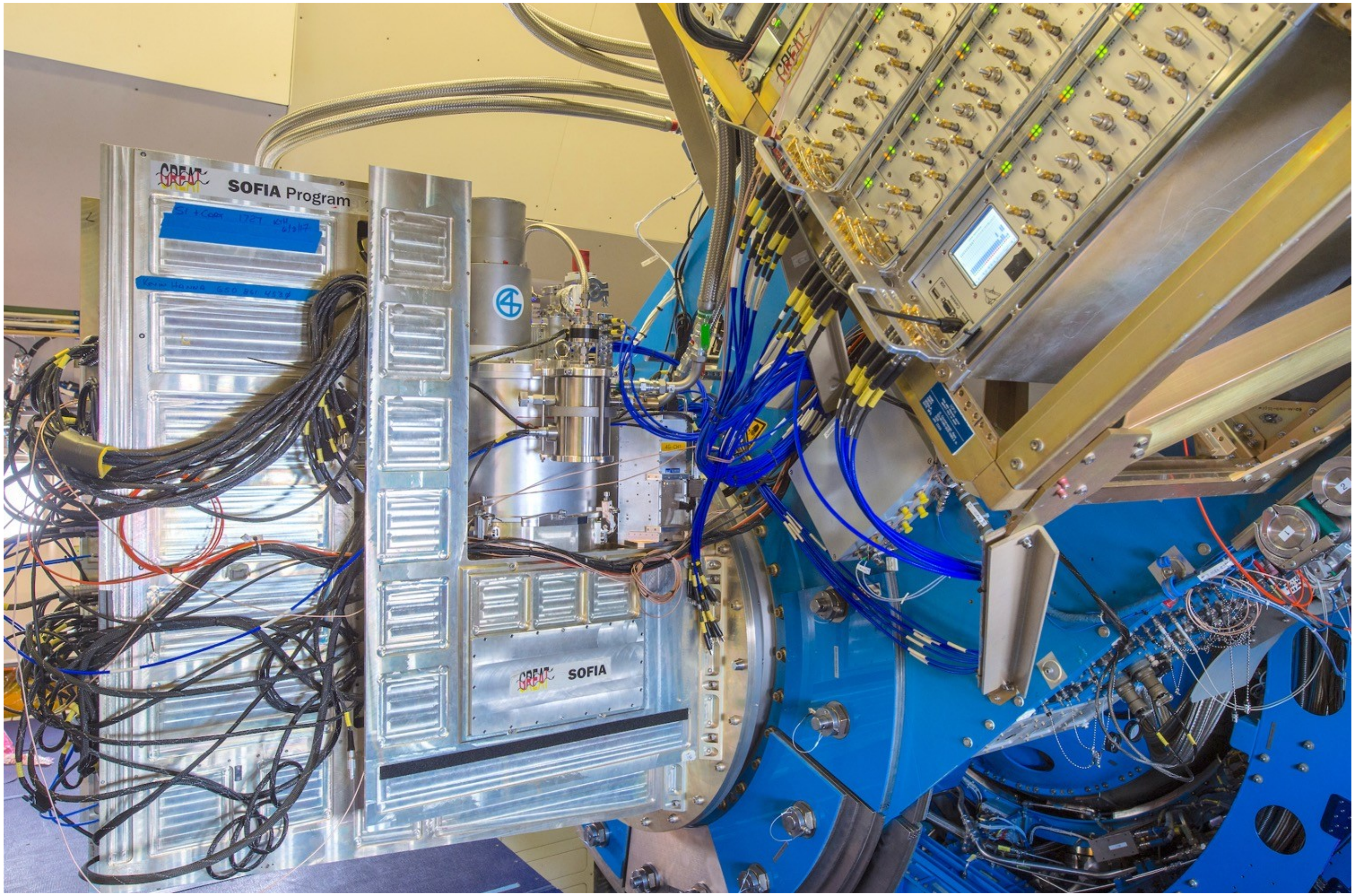




upGREAT + 4GREAT



4GREAT @ SOFIA



→ 4G-1, 4G-2 and 4G-4 integrated in March 2017, commissioned (NZ) 2017
→ 4G-3 integrated early 2028, commissioned (NZ) June-July 2018

GREAT – flight / publication records

Since first light on April 01, 2011 GREAT was operated

→ during all observing cycles, including Early & Basic Science
→ on all 5 New Zealand deployments
→ on 162 successful science flights in total (GT: 68, OT: 94)
→ more than 200 scientific projects

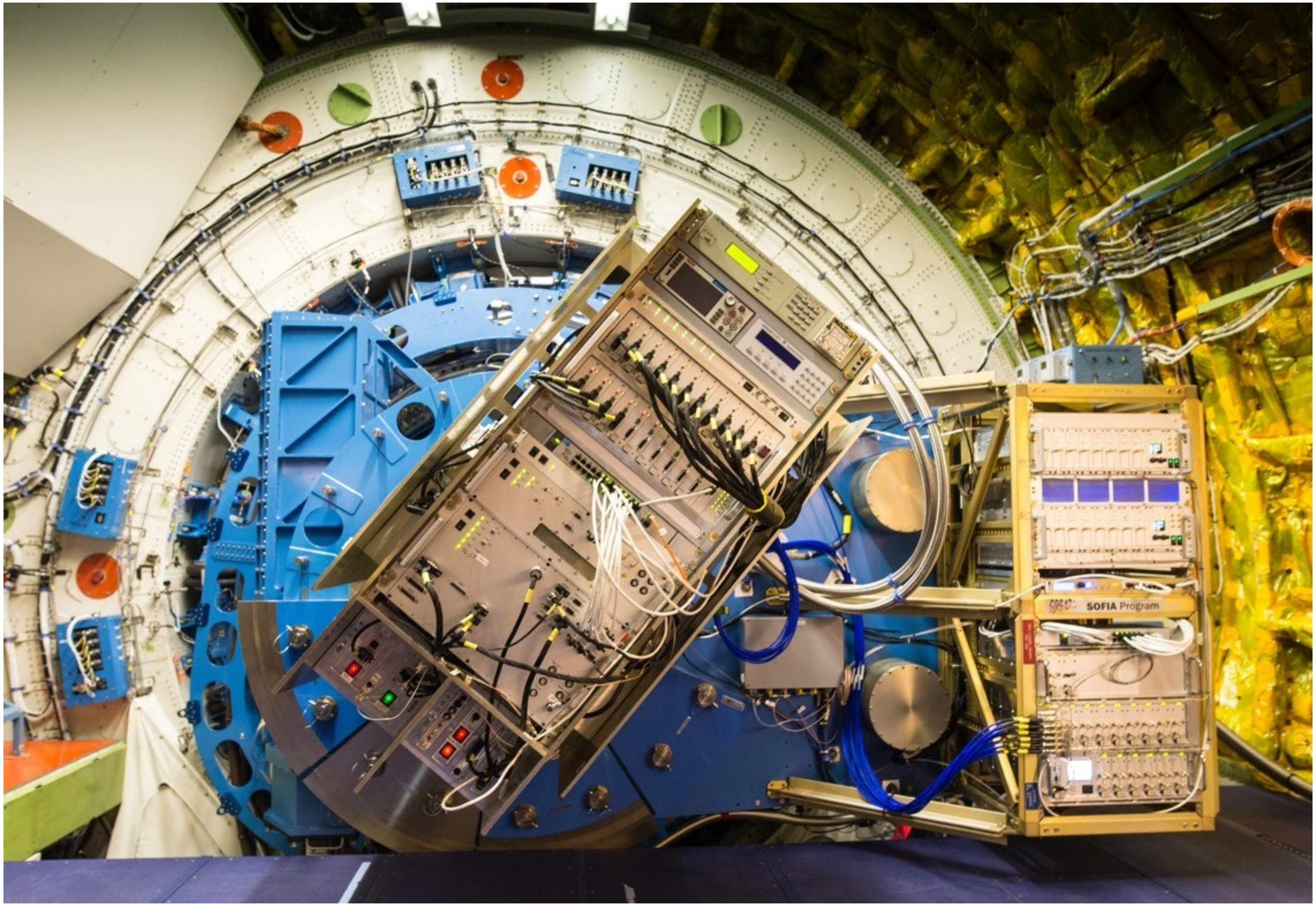
Total number of articles in refereed journals (published, in press) based on GREAT date:

→ science: 80 (3x Nature)
→ technical: 14 (1x IEEE best paper award for upGREAT)
→ publication list: https://www.mpifr-bonn.mpg.de/4482905/publications

Technical references:

→ GREAT S. Heyminck, et al., *GREAT: the SOFIA high-frequency heterodyne instrument*, A&A 542, L1 (2012)
→ upGREAT C. Risacher, et al., *The upGREAT 1.9 THz multi-pixel high resolution spectrometer for the SOFIA Observatory*, A&A 595, 34 (2016)
→ 4GREAT C. Duran, et al., *4GREAT – a four-color receiver for high-resolution airborne terahertz spectroscopy* (2020, in preparation).

The SI-Rack and the CW-Rack offer no further space for electronics



GREAT is already at the power and weight limit

upGREAT (HFA + LFA):

Summary of power consumptions

	Available per SOF-AR-ICD-SE03-2029	Estimation for LFA/HFA configuration
SOFIA power 115VAC UPS	2.0 kVA	1.6 kW
SOFIA power 115VAC FC	3.5 kVA	3.0 kW
SOFIA power 230VAC UPS	1.0 kVA	0.1 kW

Summary of rack weights

	Available per SOF-AR-ICD-SE03-2015	Estimation for LFA/HFA configuration
SI rack	600 kg	583 kg
CW rack	105 kg	99 kg
PI rack	273 kg	185.5 kg

4GREAT (HFA + 4G):

Summary of power consumptions

	Available per SOF-AR-ICD-SE03-2029	Estimation for HFA/4GREAT configuration
SOFIA power 115VAC UPS	2.0 kVA	1.7 kW
SOFIA power 115VAC FC	3.5 kVA	2.6 kW
SOFIA power 230VAC UPS	1.0 kVA	0.1 kW

Summary of rack weights

	Available per SOF-AR-ICD-SE03-2015	Estimation for HFA/4GREAT configuration
SI rack	600 kg	593 kg
CW rack	105 kg	99 kg
PI rack	272 kg (136kg per bay)	185.5 kg

A possible extension of GREAT:
Extension of the HFA 7 → 14 pixels

Already in mid 2018 the GREAT team discussed the extension of the HFA from now 7 pixels to 14 pixels (2x 7 pixel, dual polarization mode, similar to LFA) to improve the sensitivity at 4.7 THz.

→ At least another 7 HFA HEB mixers are required:
no spares available; new mixers have to be produced

→ The current bias electronics (SI rack) do not offer any further space for expansion:
Development of a new electronics.

→ The current IF processor would have to be extended by 7 chains:
With the current technology we run into weight and space problems in the CW rack!

→ The current FFT spectrometer has no capacity for another 7 IF channels:
But new developments are available: qFFTS4G (4x 4 GHz bandwidth per FFTS board)

→ Man power problem: some GREAT engineers in Bonn and Cologne have left the project; new instrument developers are very difficult to find

→ Because GREAT is a PI instrument it is operated by the team engineers.
Therefore these engineers have less time for new developments.

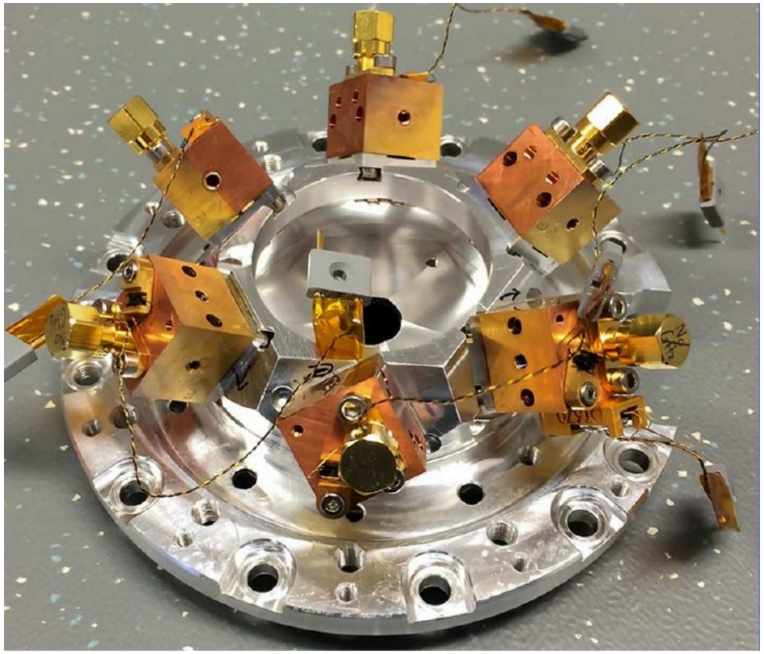
→ Unsure future of SOFIA (MoU NASA - DLR ends this year).
New instrument developments need longer-term perspectives!

→ J. Stutzki (PI, UzK) will retire in May 2022; K.Menten (MPI) will retire in Oct 2025.
It's not clear whether the successors will want to continue to do science with SOFIA.

Super-GREAT ???

Is it possible to develop a super-GREAT with 100 or more pixels?
<u>Answer:</u> Yes, but not with the current concept of GREAT.

Individual mixer approach (upGREAT) not attractive for large heterodyne array
→ multi-mixer blocks (e.g., SuperCam, CHAI) or fully integrated focal plane units are needed (see talks from Paul Goldsmith, Urs Graf and Chris Walker)



UpGREAT mixer plate
C. Risacher, et al, (2016)

Super-GREAT ???

Is it possible to develop a super-GREAT with 100 or more pixels?
<u>Answer:</u> Yes, but not with the current concept of GREAT.

Further challenges for a super-GREAT:

→ mixer, feed-horn, optics

→ powerful and easy tunable LOs and LO distribution
(solid state LO, QCL, photonic LO)

→ compact, low-power and lightweight bias-electronic,
IF processor and spectrometer back-ends

→ new software developments that allow easy and fast
tuning of the many mixers.

→ systems aspects: power-, space- and weight limitations

→ and finally: man power, funding and long development time