The GREAT Instrument

GREAT - the Consortium

MPIfR
KOSMA
MPS
DLR-PF

GREAT: German REceiver for Astronomy at Terahertz frequencies

Principle Investigator instrument - funded, developed & operated by

- MPI Radioastronomie
  - R. Güsten (PI)
  - S. Heyminck (project engineer, PA/QA)
  - B. Klein (FFT spectrometer)
  - C. Risacher (upGREAT)
- Universität zu Köln, KOSMA
  - J. Stutzki (Co-P: software)
  - U. Graf (system engineer)
  - K. Jacobs (HEB mixers up to 2.7 THz)
- DLR Planetenforschung
  - H-W. Hübers (Co-PI: 4.7 THz HEB & QCL)
- MPI Sonnensystemforschung
  - P. Hartogh et al. (CO-PI: CTS)

GREAT - System Overview

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- GREAT is a highly modular heterodyne spectrometer ($\Re \sim 10^8$)
- operating in science-defined frequency bands $1.25 < \nu < 4.7$ THz
- 2 out of currently 4 bands can be operated simultaneously
- channel availability (as of Feb 2015)
  - 2 low-frequency channels are operational since Early Science (2011)
  - mid frequency channel:
    - M_a operational; M_b on hold for mixer upgrade, waiting for commissioning slot
  - high-frequency channel (operational since 05/14)

Channel		Frequencies [THz]	Lines of interest	Status
low-frequency	L1	1.26 – 1.52	[NII], CO series, OD, H_2D^+	operational
low-frequency	L2	1.82 – 1.91	NH_3, OH, CO(16-15), [CII]	operational
mid-frequency	Ma	2.49 – 2.56	$^{(18)}OH(^2\Pi_{3/2})$,	operational
	Mb	2.67	HD	on hold
high-frequency	H	4.74	[OI]	operational
upGREAT	LFA	14x (1.9– 2.5)	CO(16-15), [CII] and above	commissioning Q2 15
upGREAT	HFA	7x [4.74]	[OI]	1 yr after LFA

System description

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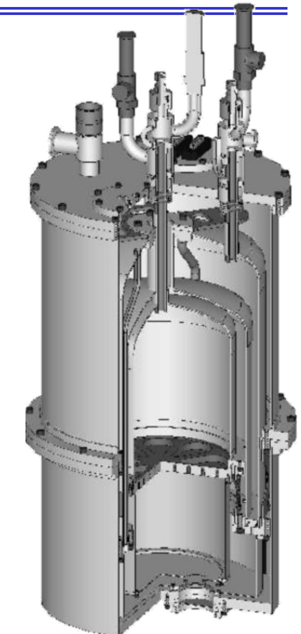
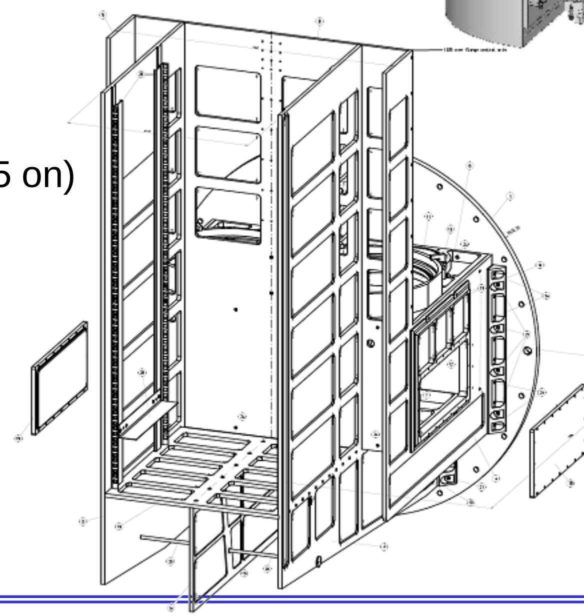


- operating up to two independent receiver channels simultaneously
- fully automated tuning procedure (LO, Mixer-BIAS, Diplexer)
- system is being updated now to be capable to operate the upGREAT channels (next talk)

channel independent components

- main structure : optics-compartments, LO-compartments, electronics rack
- cryostats : liquid Helium/Nitrogen cooled wet dewar,
  closed cycle for upGREAT channels
- calibration unit : liquid Nitrogen cooled cold-load, ambient temp. hot load
  from Mai 2015 on: Stirling cooler based cold-load
- IF-system : Input : 0.2 - 3GHz
  Outputs : 2 x 0 - 2.5 GHz (FFTS)
  from Mai 2015: Output 0 – 4 GHz
- Spectrometer : FFTS, XFFTS (FFTS-4G from Mai 2015 on)
- control-electronics : optics control, mixer-BIAS

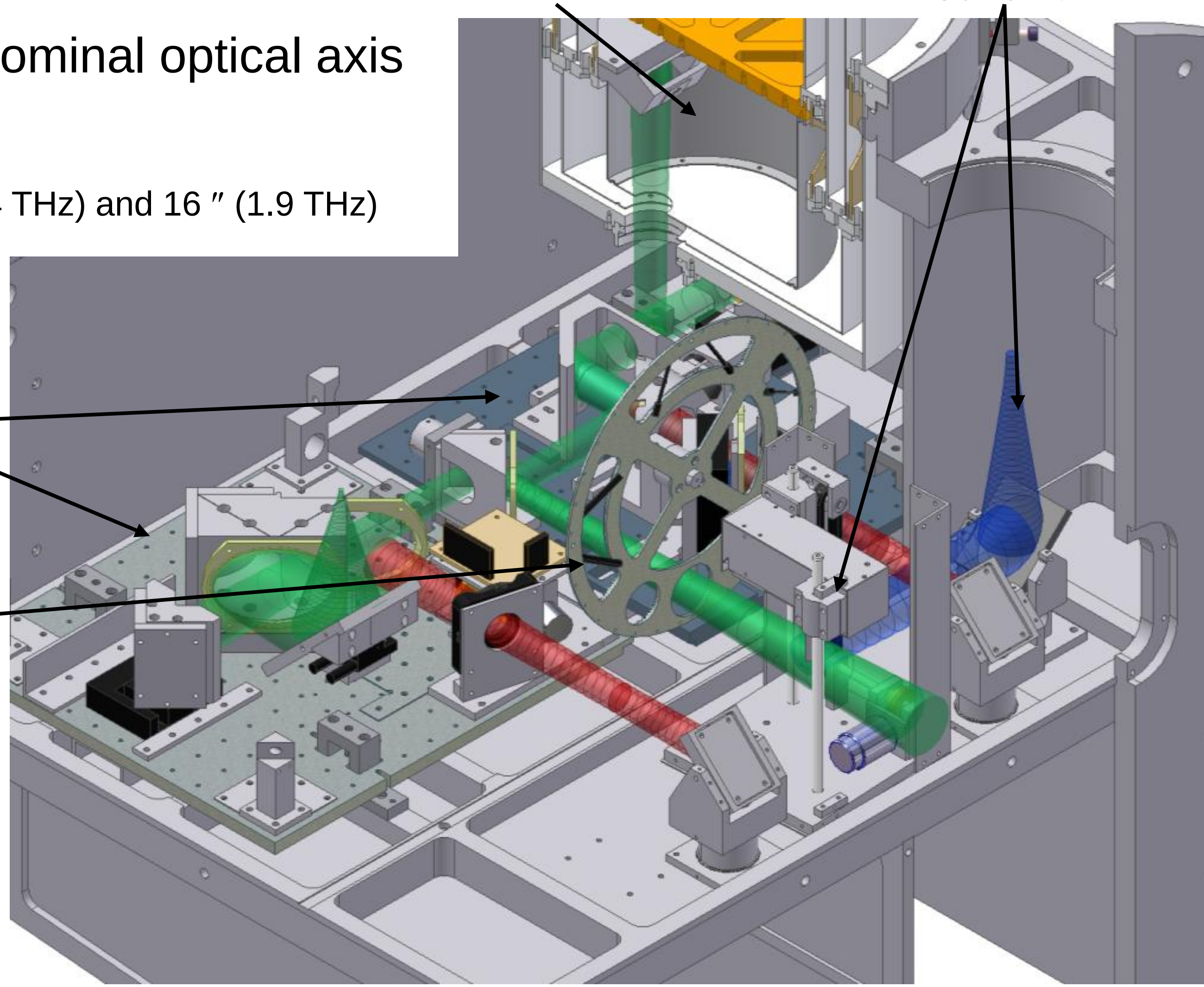


channel specific components

- optics : LO-coupling, matching mixer beam
  to the telescope focal plane
- LO-system : VDI solid state chains for all channels
  in operation so far
- mixer device : HEBs so far for all GREAT channels

GREAT optics

- ❑ pre-adjusted to the nominal optical axis
- ❑ diffraction-limited
  - ➢ HP beam-width: 22″ (1.4 THz) and 16 ″ (1.9 THz)



- ✓two optics-plates
- ✓LO-injection
- ✓Calibration unit
- ✓Beam-measurement setup

KOSMA waveguide mixer

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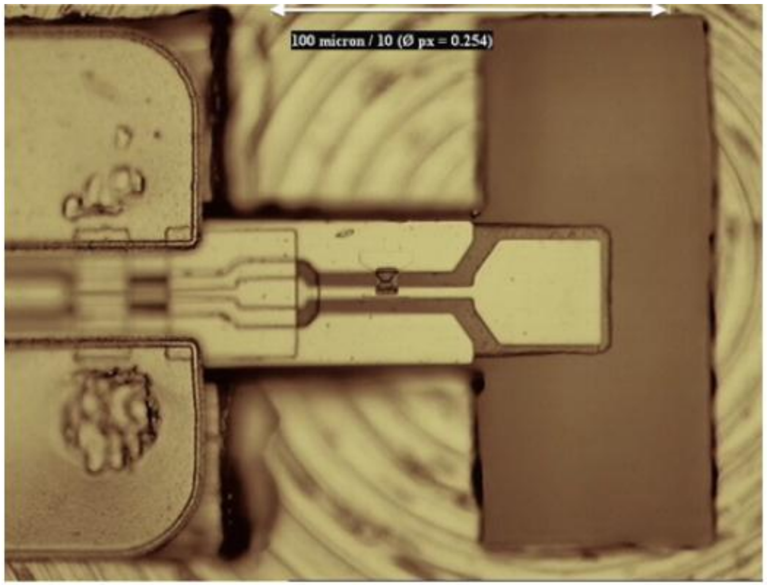
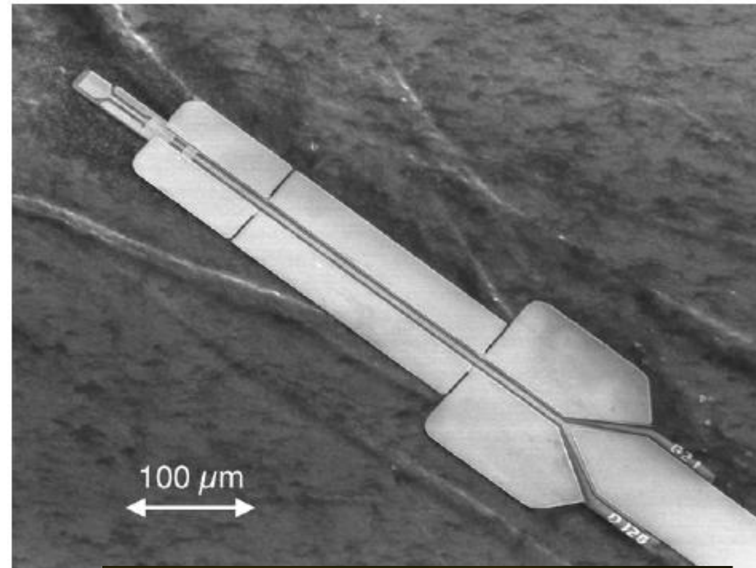
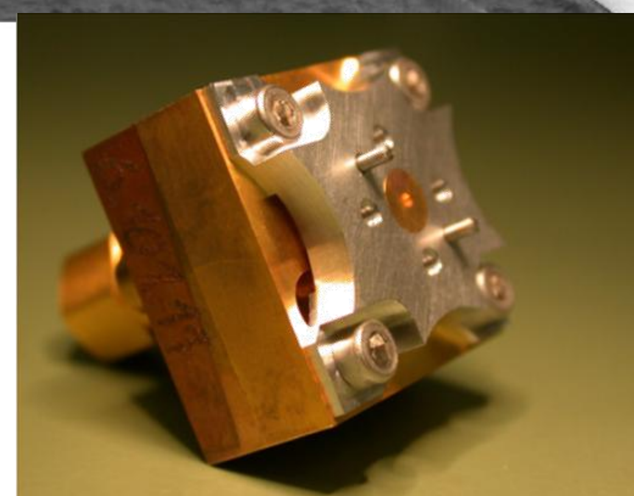
state of the art performance up to 4.7 THz!







- top (left to right)
  - optical image of the 1.9 THz HEB inside the wave-guide
  - SEM micrograph of a 2.5THz HEB on SiN substrate with beam-leads
- right:
  - mixer block with horn antenna and IF-connector

GREAT Spectrometers

GREAT operated over the last years a wide suite of back-ends

- integrating new technologies as available

➔ latest generation of FFTS: 4 GHz monolithic band-with, up to 128k channels possible *(see also Poster of B. Klein)*

Back-end spectrometer	Bandwidth [GHz]	Resolution [MHz]	Status
AOS: acousto-optical spectrometer	2 x 4 x 1.0	1.6	de-commissioned
CHIRP Transform spectrometer	2 x 0.22	0.056	de-commissioned
AFFTS: Fast Fourier Transform	2 x 1.5	0.212	until Mai 2015
XFFTS: Fast Fourier Transform	2 x 2.5	0.088/0.044	until Mai 2015
FFTS-4G: Fast Fourier Transform	24 x 4.0	0.120	from Mai 2015 on

Note: (#) spectral resolution is measured as equivalent noise bandwidth, the 3 dB bandwidth is generally smaller.

Solid-state LOs

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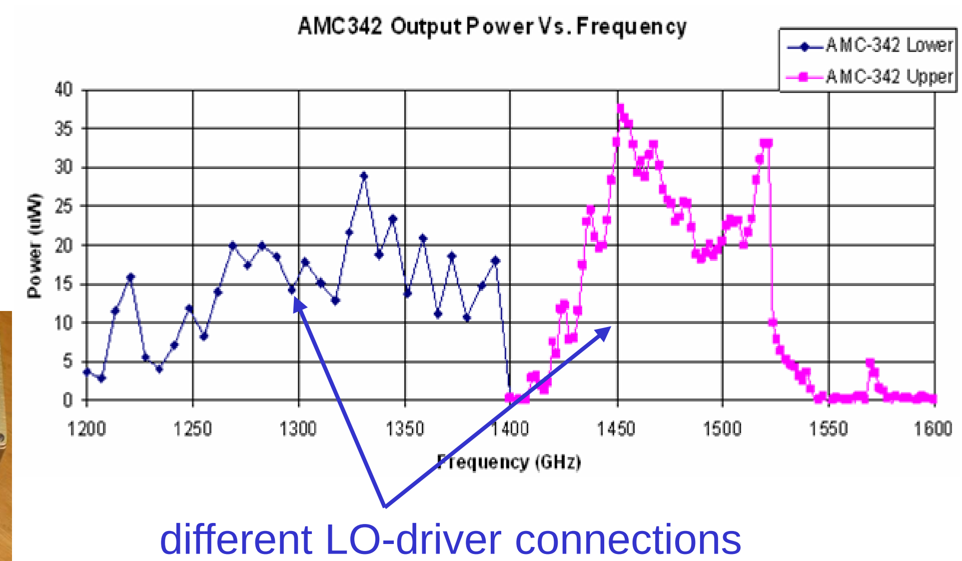
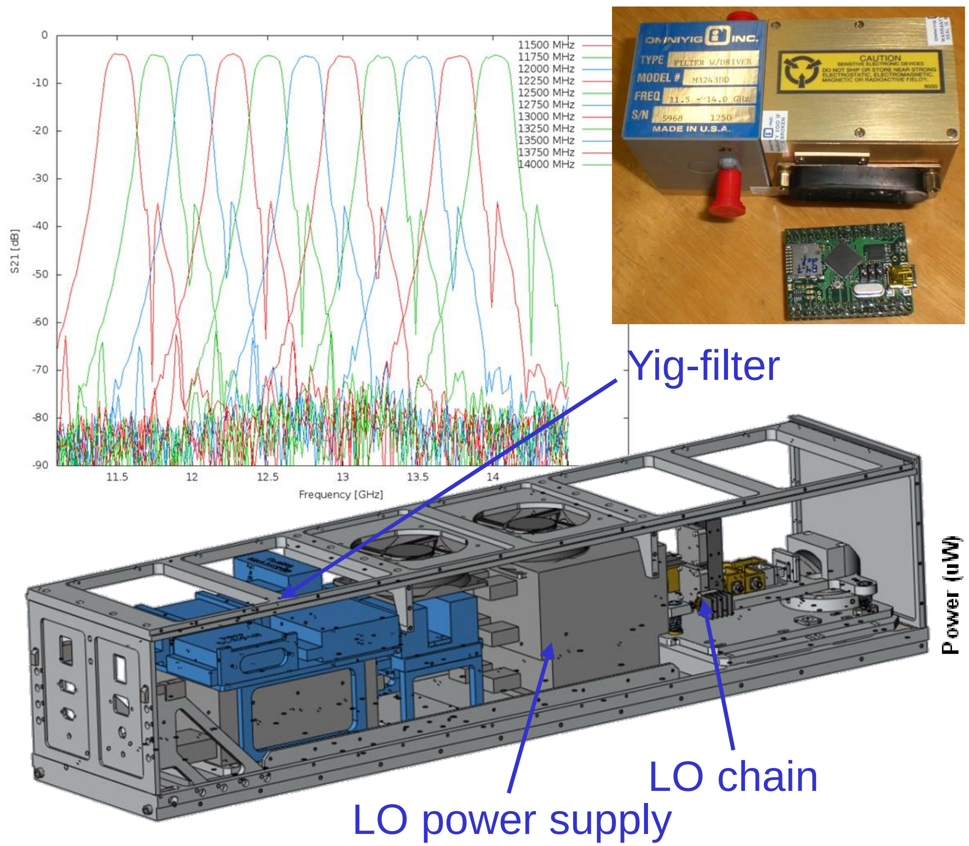
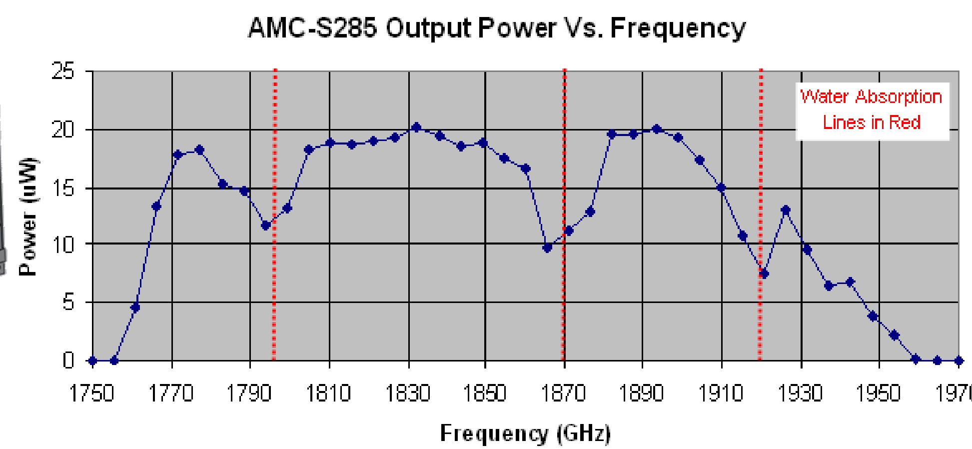
- Using VDI solid state chains for all channels except H-Band
  - large RF tuning range
  - Yig-filter (computer controlled) for L1
  - enough power for direct coupling in L-Band

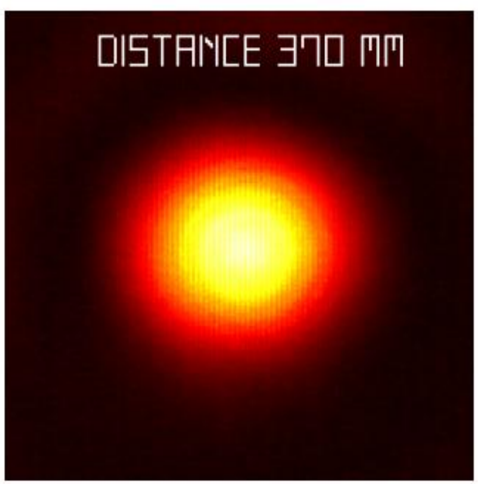




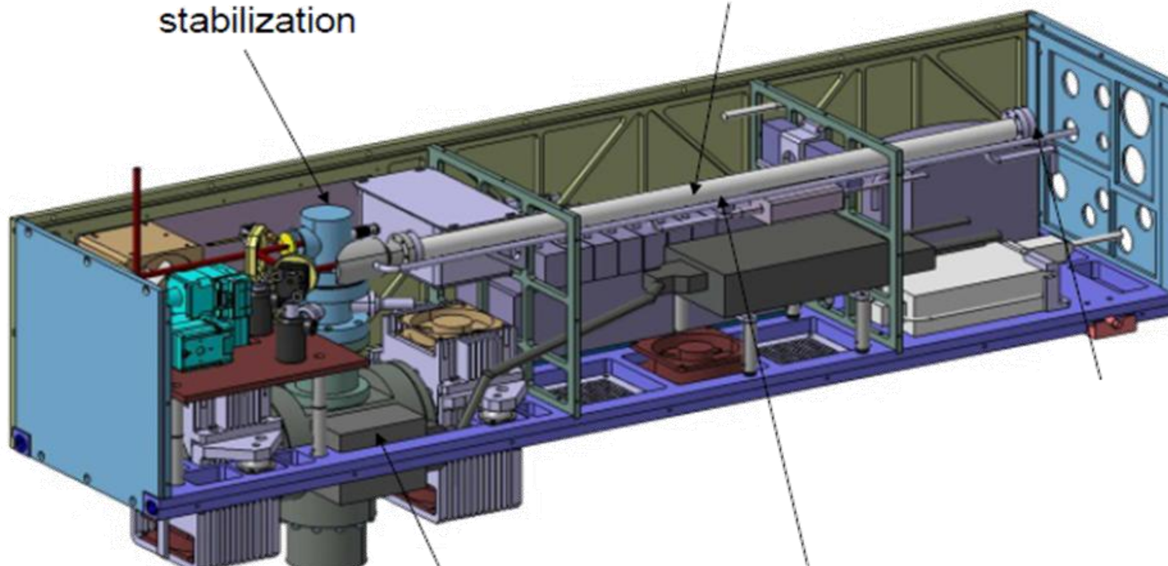


H-Band QCL LO

- working system @ 4.7THz !
- line-width is an issue
  - temperature stabilization alone: ~ 1.6 MHz intrinsic line-width
  - fast jitter broadens it to approx. 10 - 20 MHz
- tunability is limited to OI line



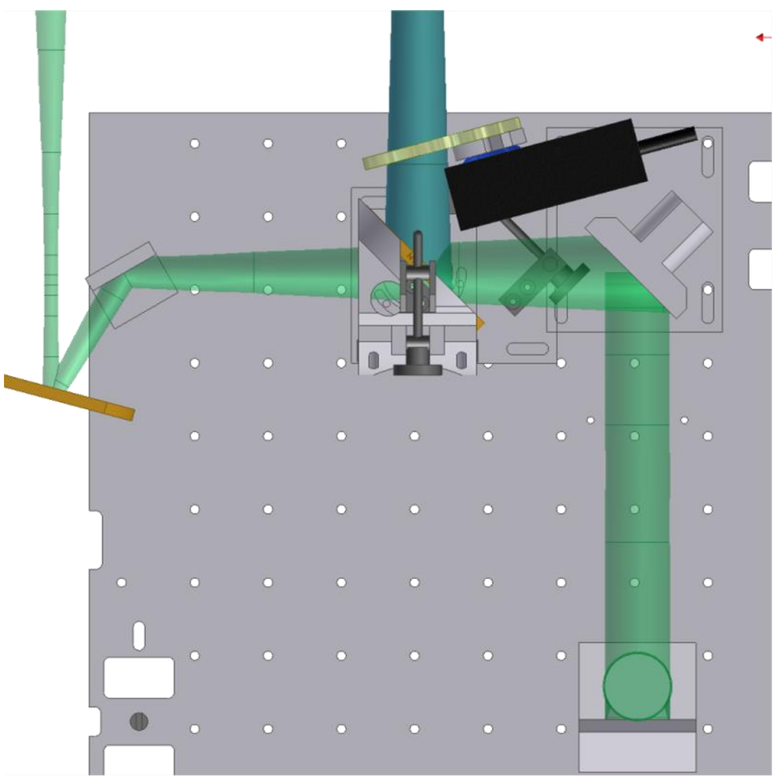
- QCL: 500mA/6.0V/45.6K
- approx. 320uW@waist position

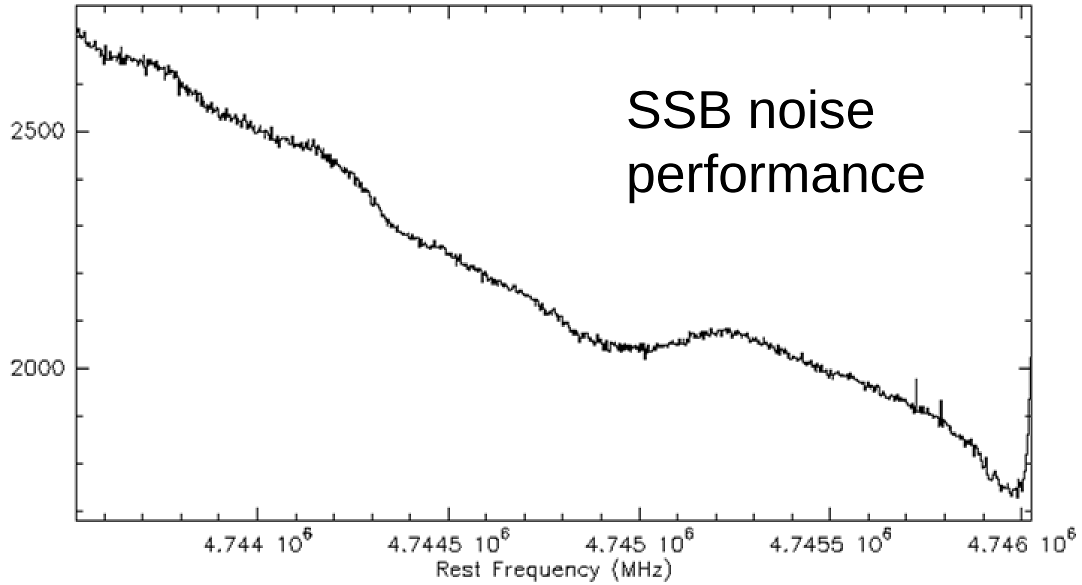


H-band @ 4.7 THz

In operation since Mai 2014

- observations of [OI] at 4.74 THz (mostly galactic, due to ATM)
- KOSMA waveguide NbN HEB pumped by a QCL local oscillator (DLR-PF)

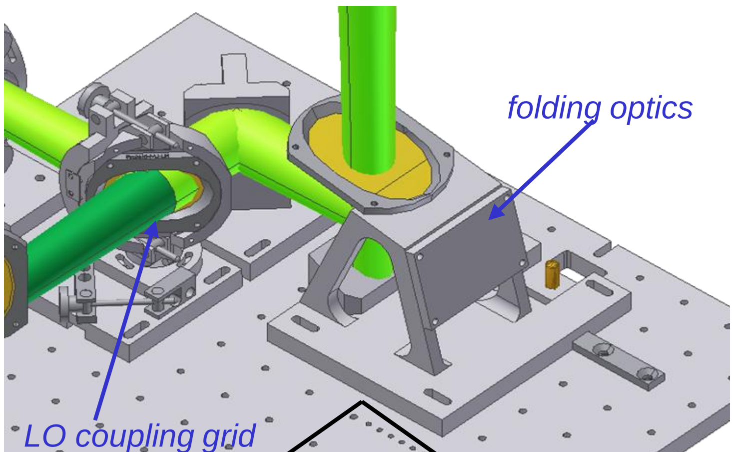


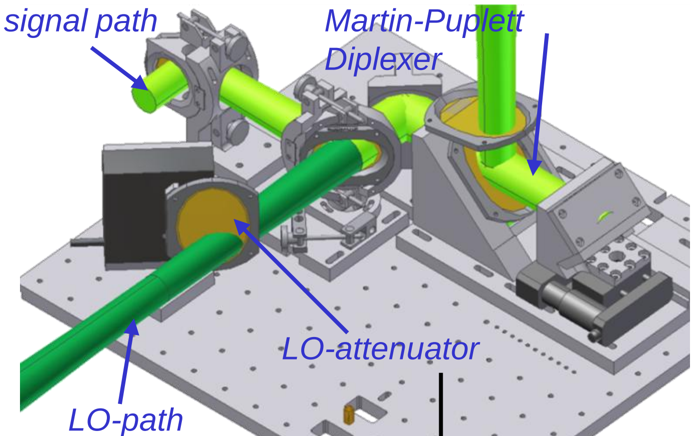


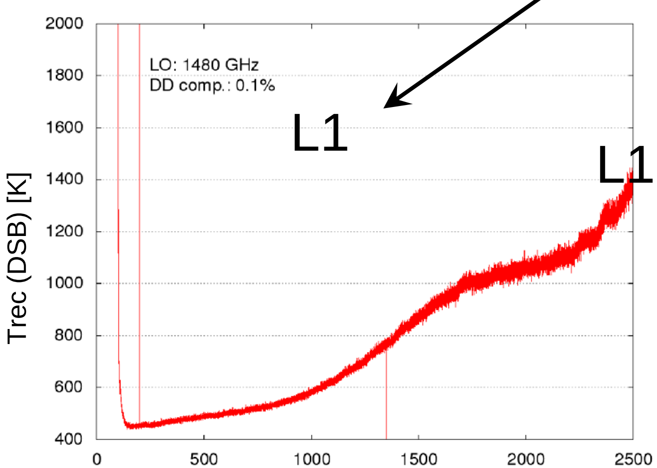
- state of the art noise performance
- Rx beam matches calculations
- spectroscopic Allan times ~ 30s

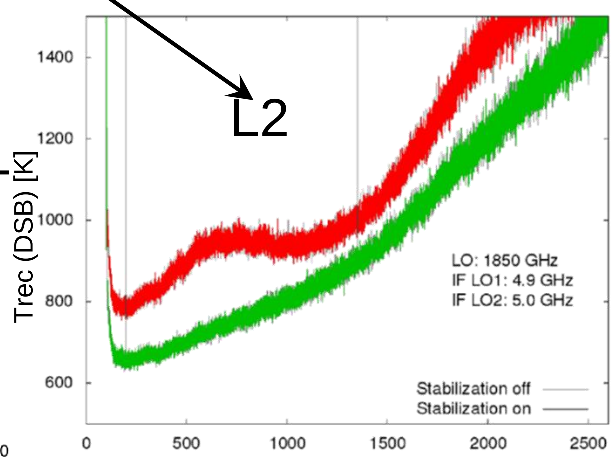
GREAT sensitivities: L& M-bands

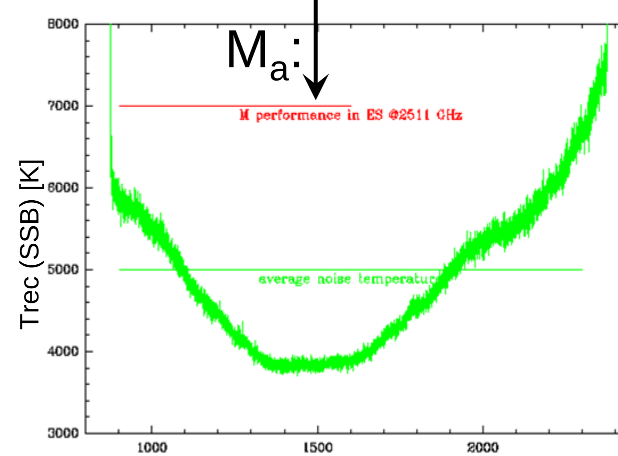
More powerful solid-state local oscillators (Virginia Diodes Inc.) allowed substituting Martin-Puplett diplexers with coupling grids in channels L1 & L2, thereby providing access to the most sensitive IF frequencies of the HEB.











Mixer IF [MHz]

System performance

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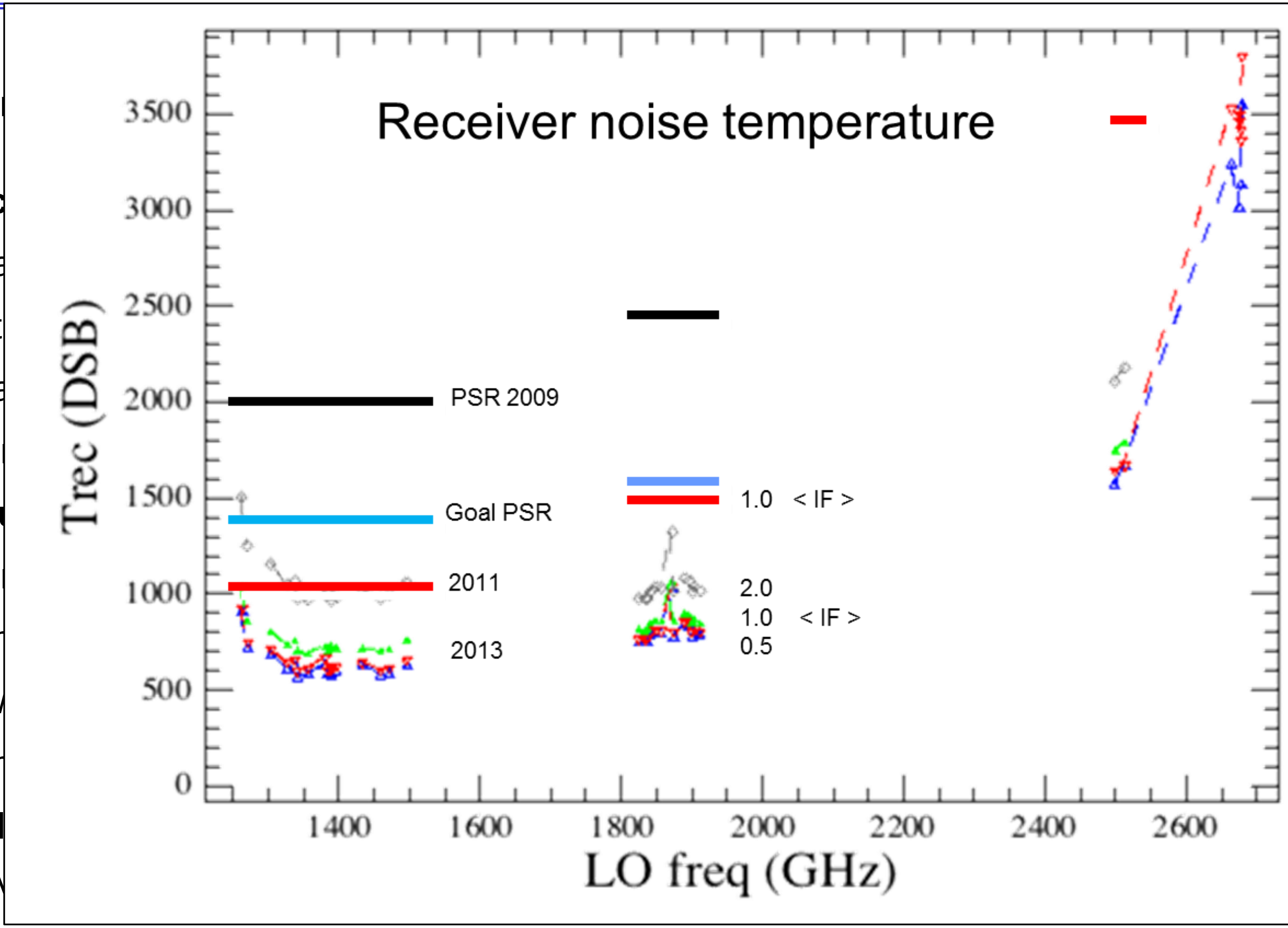

- H-Band with QCL LO and waveguide mixer

GREAT observing

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- classical observing mode:
  telescope position switching
- preferred for compact objects:
  chopping with secondary
  - dual beam switching with 1 – 2 Hz,
    throw up to several arcmin
- advised for extended structures:
  "on-the-fly" scanning
- GREAT is available to SOFIA communities in collaboration
  - „rules“ stated in Cycle 1-2 call-for-proposals
- GREAT as PI instrument operates in service mode only
  - observations are performed by the GREAT team
  - observations are executed via observing scripts
  - preparation supported by SMO (based on your uploaded AORs)
- GREAT delivers calibrated data in standard CLASS format
  - raw data (FITS format) into archive within 2 days after flight
  - quick look analysis (prelim. reduced) within 2 weeks
  - calibrated data within 45 days after end of flight series

GREAT detects first photons

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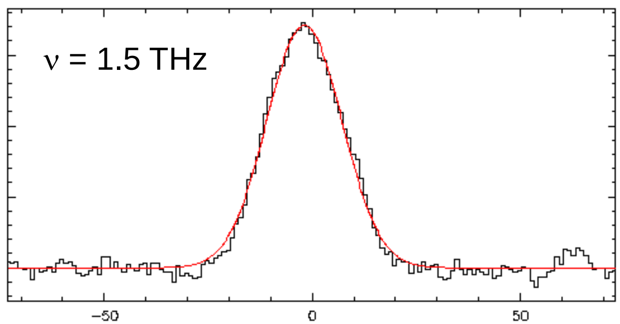
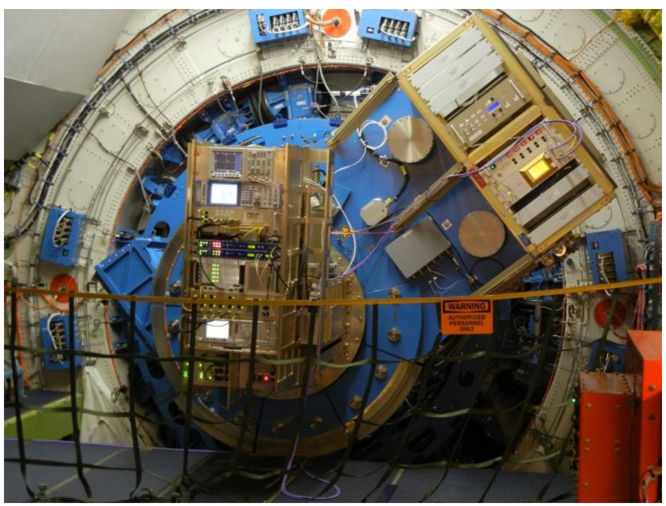
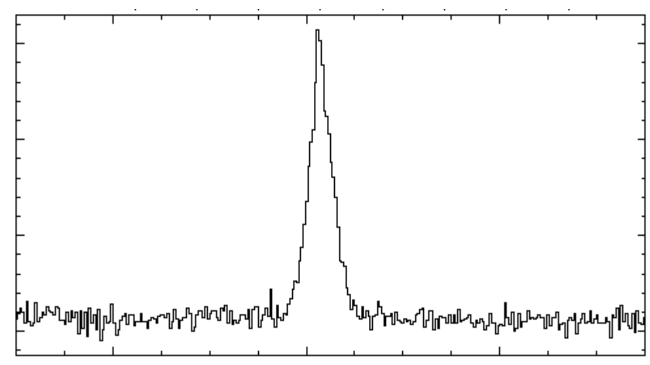
On April 1st 2011, GREAT successfully concluded its commissioning flight

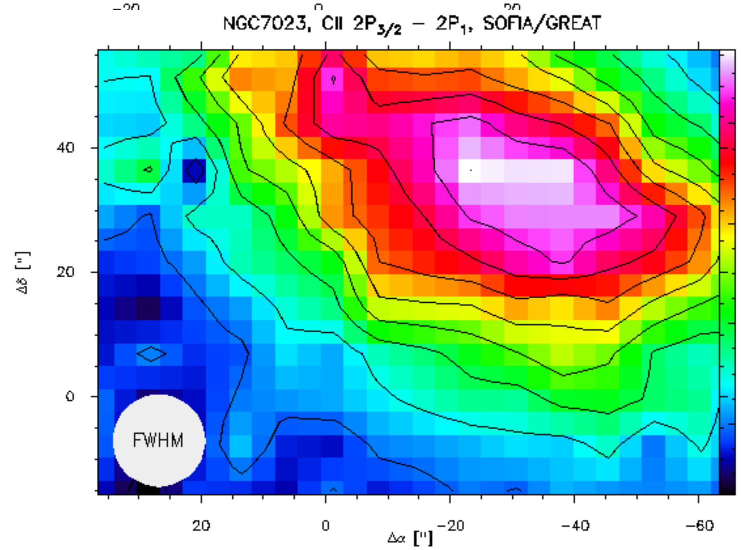
Total power scan across Saturn



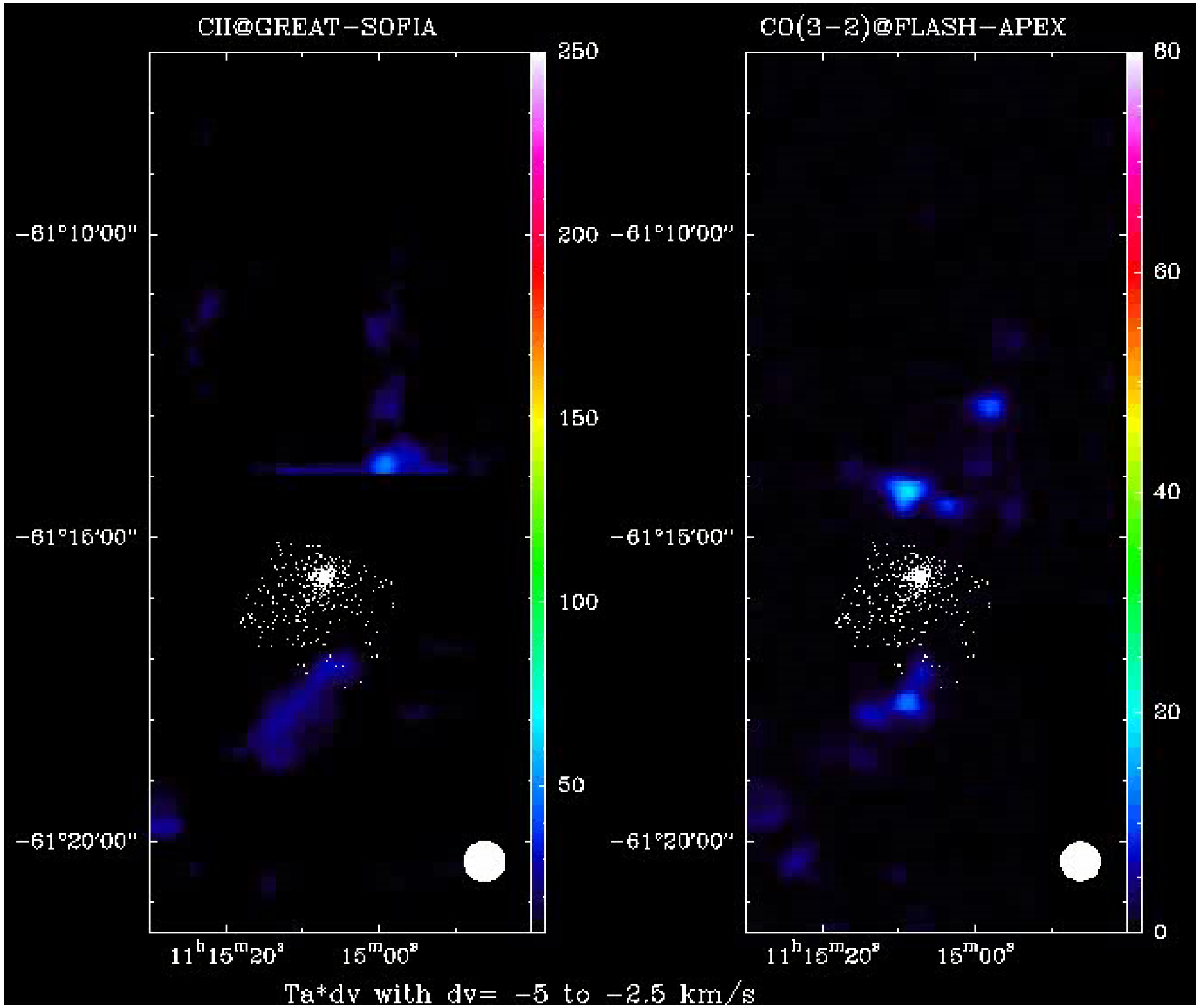


[CII] 1.9 THz towards NGC 7023





Milky Way's most active stellar nursery



A first impression of the violent kinematics of the gas in the associated cloud complex, extending north and south of the young star cluster. Several "hot spots", mostly sites of embedded star formation, are seen.

NGC 3603 is only visible at the southern skies.

Why single pixel channels?

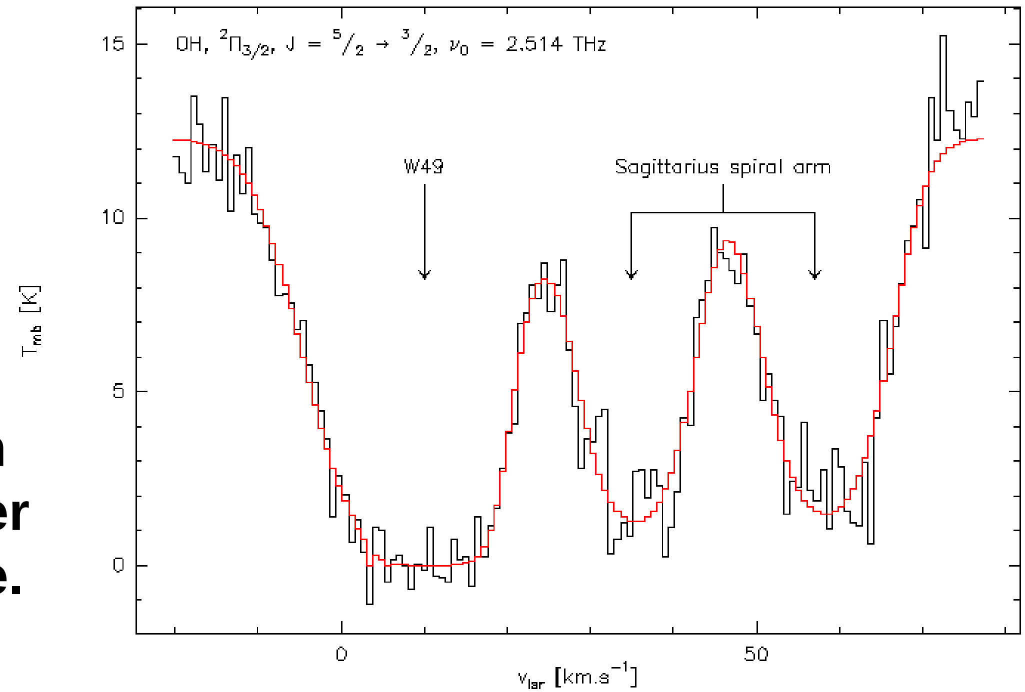
- performance
  - new technologies can be adapted faster
  - wider field of optimizations
  - ➔possibly better then array channels
- important for
  - compact sources
  - new lines
  - deep integrations
  - ….

The OH-ground state absorption was measured only 3 month after the 2.5 THz LO became available.

first >2 THz spectroscopy from SOFIA

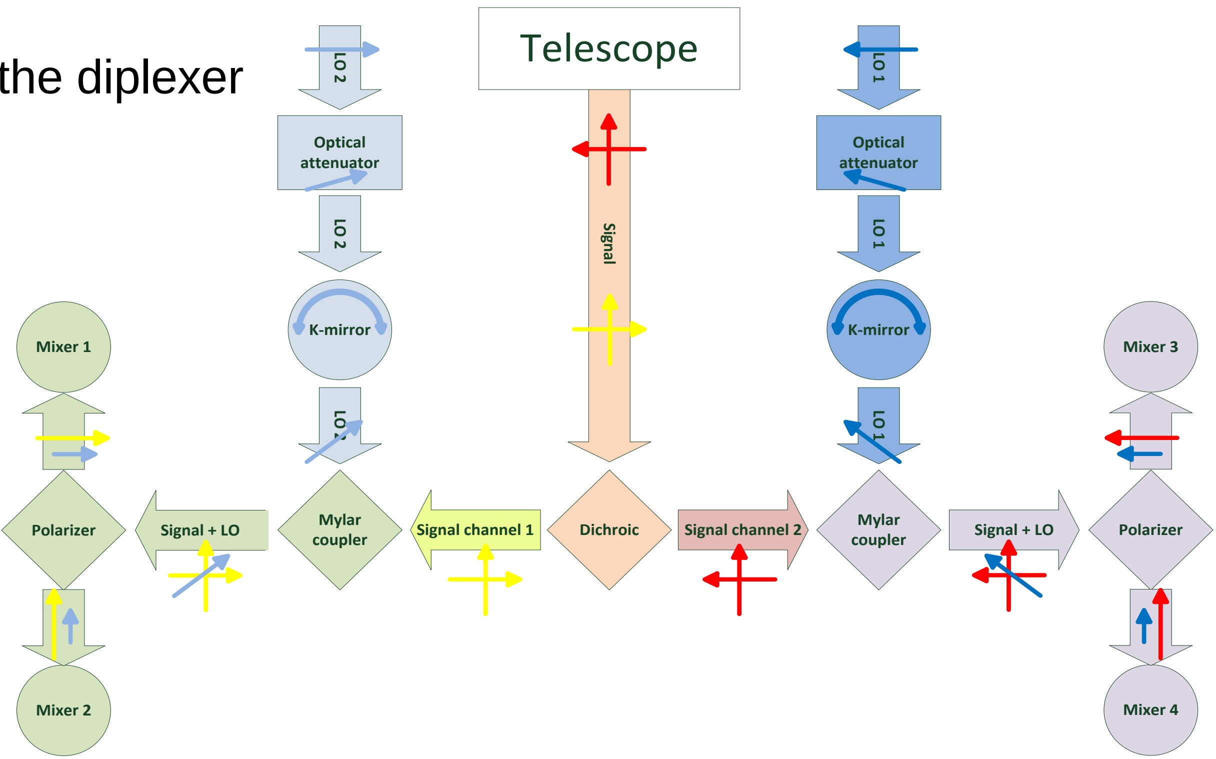
- OH ground-state absorption against W49N
- spectral features of Sagittarius spiral arm
- discovery of ^{18}OH towards W49N core

for details: H. Wiesemeyer - A&A 542 L7 (2012)



Improve existing channels

- dual polarization systems (all channels)
  - using a dichroic instead of polarizer to split channels
  - existing cryostats are already prepared for two mixers
  - infrastructure available in the upGREAT system frame
- channel specific:
  - higher power LO to avoid the diplexer or to lower LO-coupling
  - increase tuning range
  - new mixer
    - for better noise performance (e.g. for Mb @ 2.7 THz)
    - to increase IF bandwidth
- *right: optimized single pixel layout*



Additional frequency bands

- selection of science motivated additional GREAT channels
  - L0 - Band 600 GHz
  - L1 extension 1 – 1.26 THz
  - L2 extension atomic oxygen fine structure transition (2.06 THz)
  - Mc-Band 3.4 THz channel

Channel		Frequencies [THz]	Lines of interest	
requested band #1		0.52 – 0.62	CH, NH_3, $H_2{}^{18}O$, HCL ground-state	
requested band #2		1xx – 1.26	HF, NH_3(2-1), ??????	
low-frequency	L1	1.26 – 1.52	[NII], CO series, OD, H_2D^+	operational
low-frequency	L2	1.82 – 1.91	NH_3, OH, CO(16-15), [CII]	operational
upGREAT LFA		1.9 – 2.5		
requested band #3		1.9 – 2.1	[OI 145 μm], HeH^+	upGREAT LFA
mid-frequency	Ma	2.49 – 2.56	$^{(18)}OH(^2\Pi_{3/2})$,	operational
	Mb	2.67	HD	on hold (Nov ′14)
requested band #4		3.35 – 3.55	[OIII], …	
high-frequency	H	4.74	[OI 63 μm]	operational

there is a lot to do

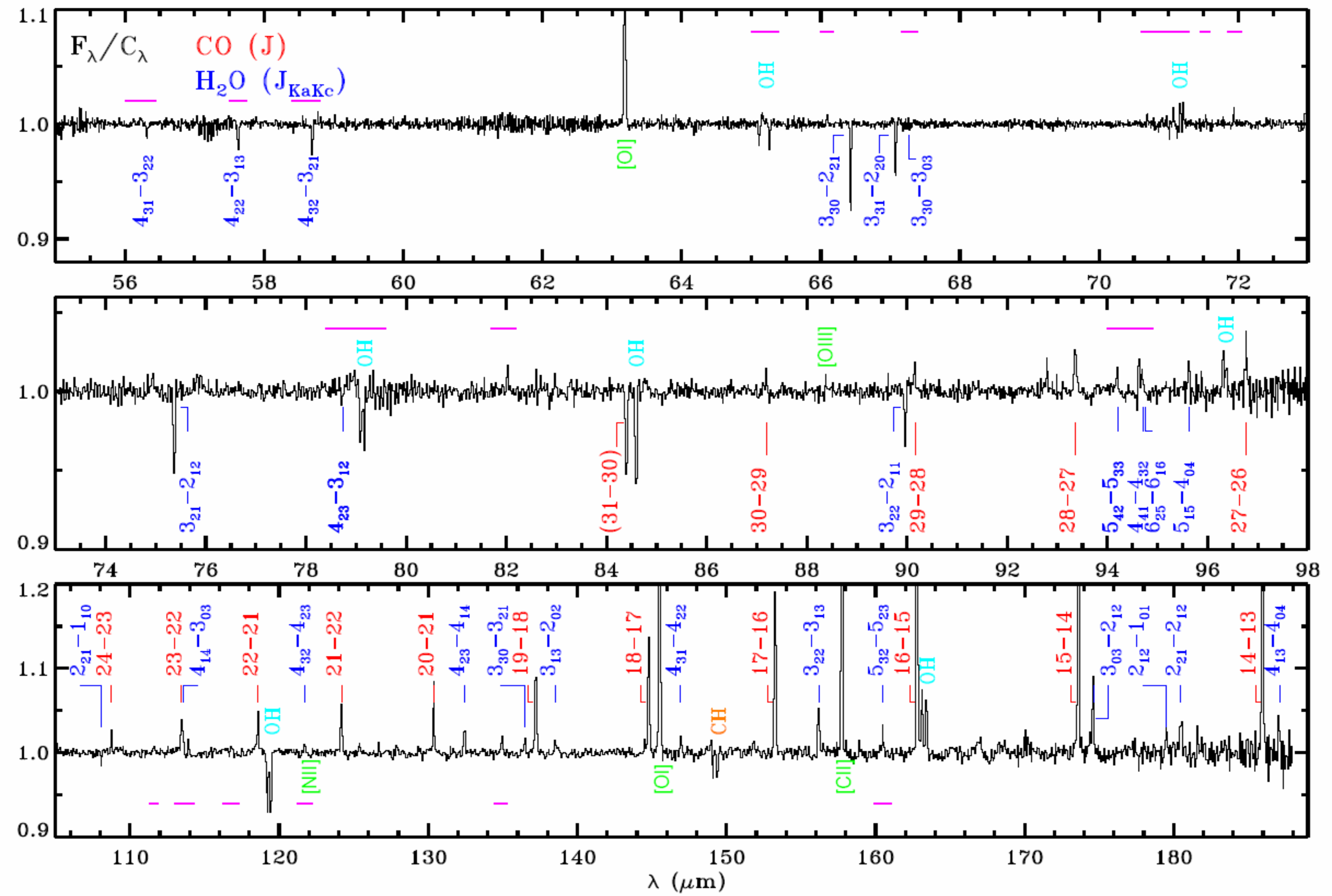
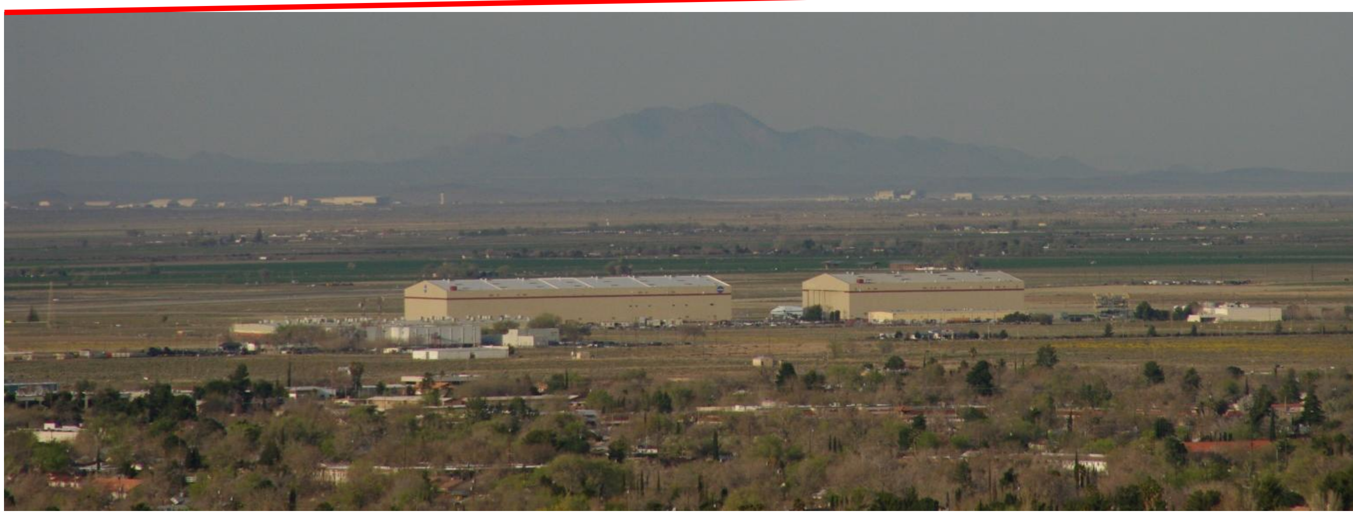


Fig. 1. Herschel-PACS continuum-normalized spectrum of W3 IRS5 at the central position. Lines of CO are shown in red, H_2O in blue, OH in light blue, CH in orange, and atoms and ions in green. Horizontal magenta lines show spectral regions zoomed in Figure C.1.

from A. Karska, A&A Nov. 2013

Overview

- GREAT instrument overview
- GREAT instrument performance
- observing with SOFIA / GREAT
  - incl. science highlights
- ongoing developments



Dryden Aircraft Operation Facility (Palmdale)

science results: 2.5 THz OH absorption

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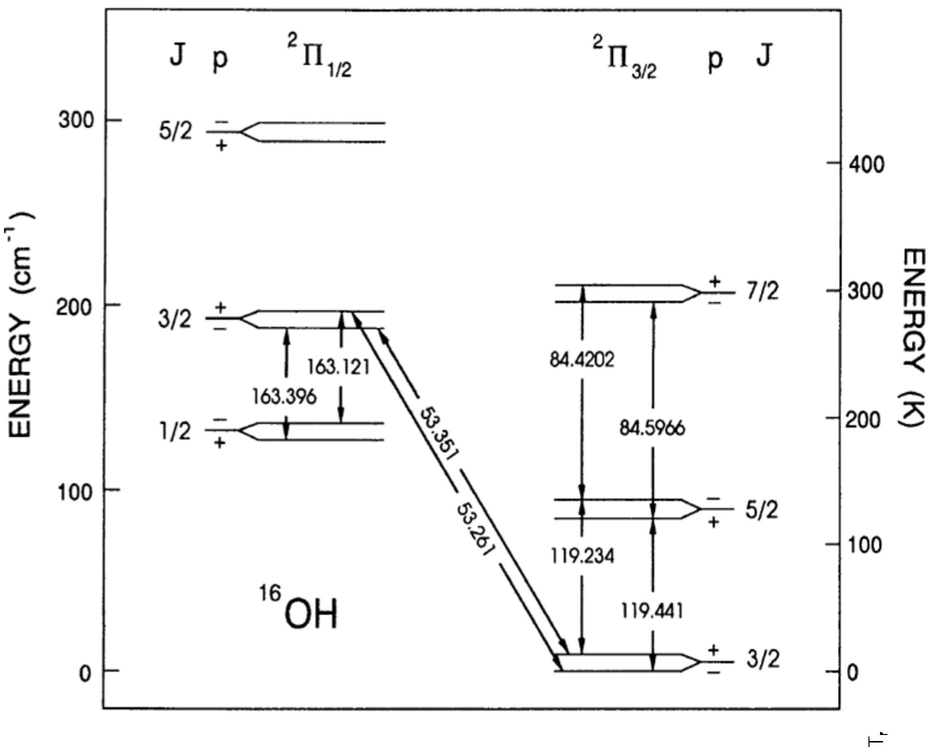

first >2 THz spectroscopy from SOFIA

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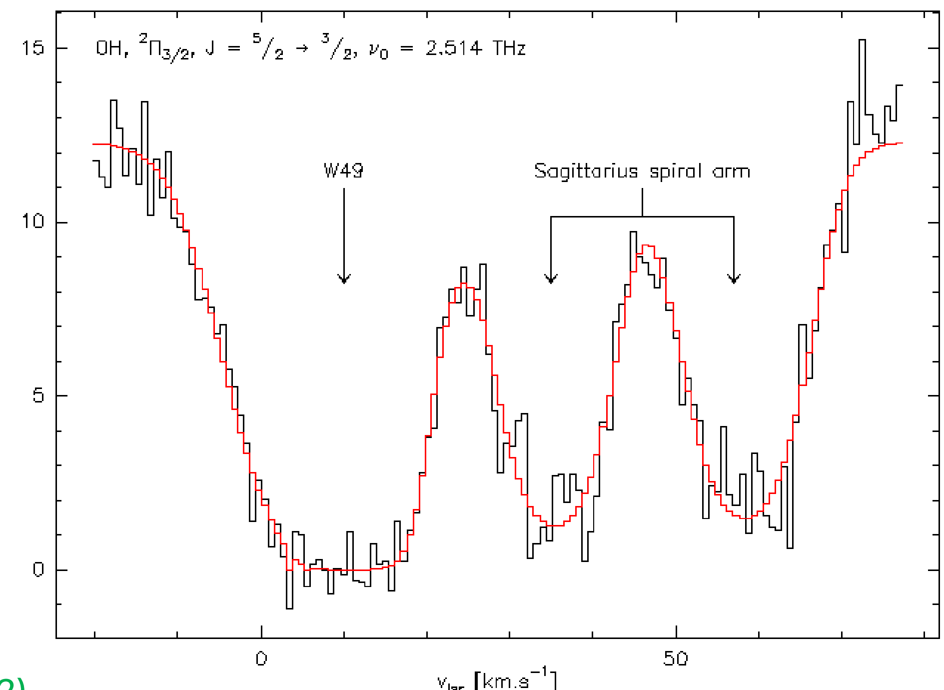
- discovery of ^{18}OH towards W49N core



- OH absorption towards W49N saturated
- [OH] ~ 10^{-7} to 10^{-8}, which is ~ [H_2O]

for details: H. Wiesemeyer - A&A 542 L7 (2012)

Dual polarization layout

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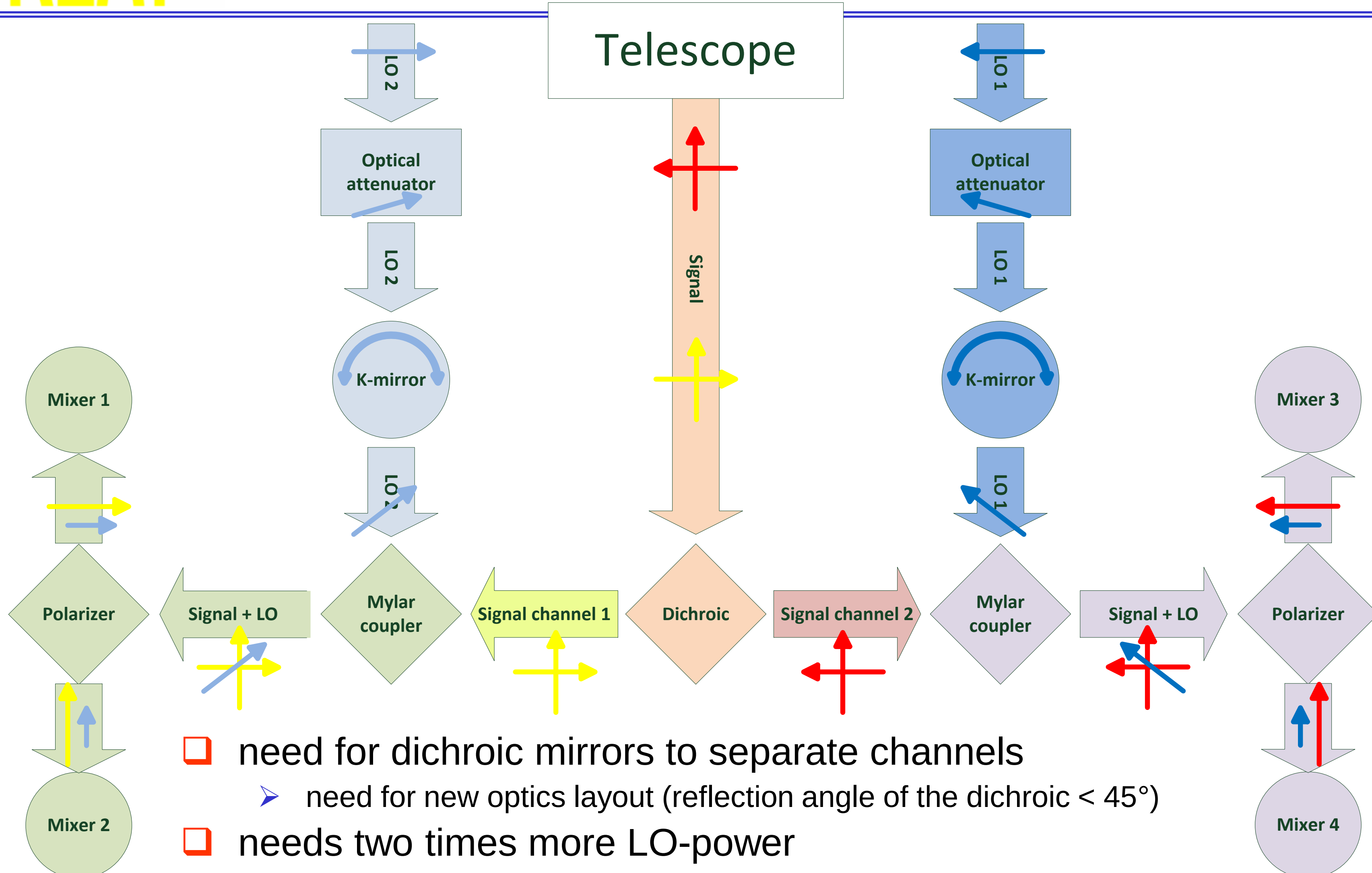
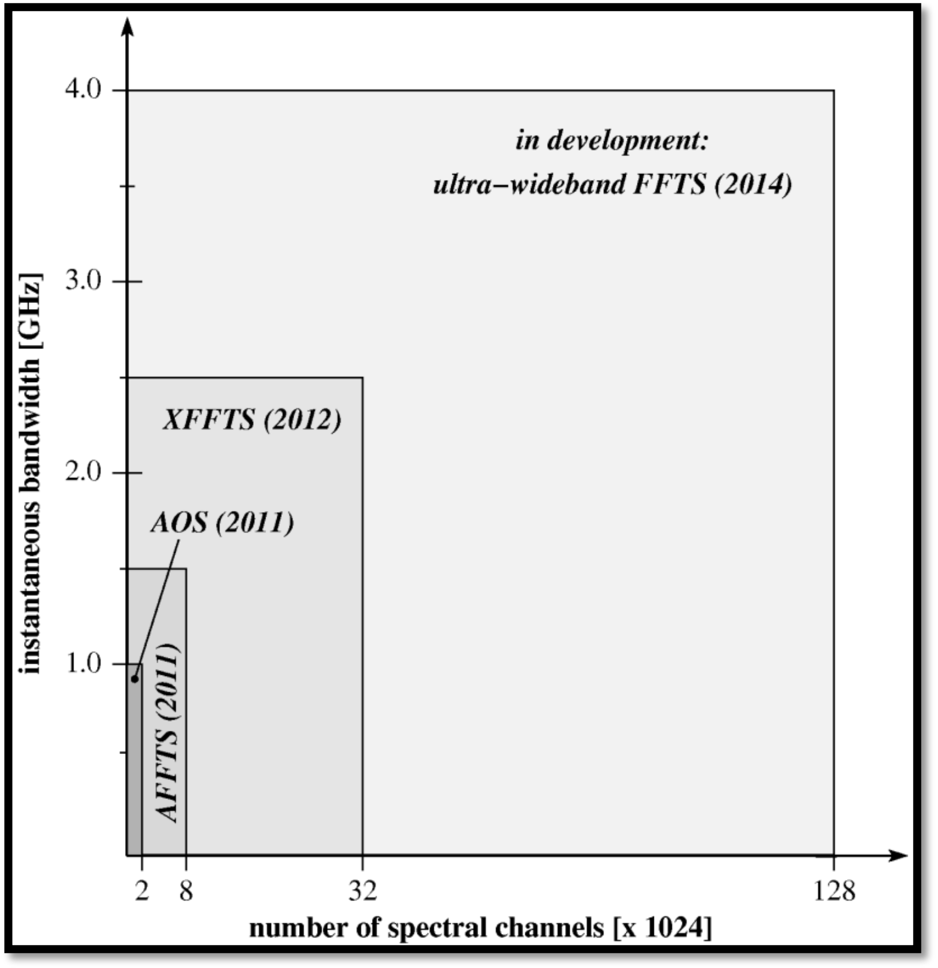


- ❑ need for dichroic mirrors to separate channels
  - ➢ need for new optics layout (reflection angle of the dichroic < 45°)
- ❑ needs two times more LO-power
- ❑ need to adjust LO-power separately for each channel (e.g. with a LO K-mirror)


4.0
3.0
2.0
1.0
instantaneous bandwidth [GHz]
in development:
ultra–wideband FFTS (2014)
XFFTS (2012)
AOS (2011)
AFFTS (2011)
2
8
32
128
number of spectral channels [x 1024]