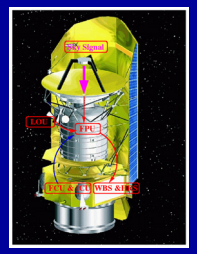
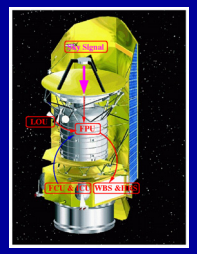


Heterodyne Instrument for the Far Infrared (HIFI)

for the Herschel Space Observatory

Thijs de Graauw
On behalf of the HIFI consortium

thijsdg@sron.rug.nl

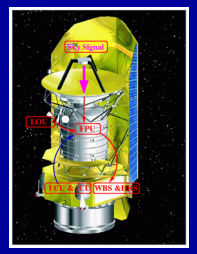


HIFI Top Level Requirements

- Frequency coverage:
  - 480 – 1250 GHz (625-240 μm)
  - 1410 – 1910 GHz (212-157 μm)
- Near-quantum noise limit sensitivity (goal <3hν/k)
- Instantaneous IF bandwidth): 4 GHz (in 2 polarisations)
- Frequency Resolution 140 kHz – 280 kHz – 1 MHz
- Calibration Accuracy: 10% baseline; 3% goal
- With Herschel: 12"- 40"

HIFI designed for:
- Spectral Scans
- Spectral line surveys

thijsdg@sron.rug.nl



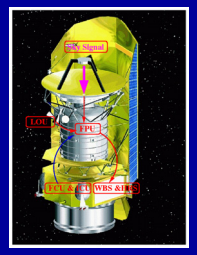
HIFI Steering Cie, etc..

- Th. de Graauw — PI, — SRON, NL
- T. G. Phillips — Co-PI, — Caltech,USA
- J. Stutzki — Co-PI, — KOSMA, Germany
- E. Caux — Co-PI, — CESR, France

- G. Tofani — LeadCo-I; — CAISMI, Italy
- J. Martin-Pintado/P.Planesas — LeadCo-I, — OAN, Spain
- L Nordh/R. Liseau — Lead Co-I, — Univ. Stockholm, Sweden
- R. Sczerba — Lead Co-I, — Copernicus Astr. Inst. Poland
- A. Benz — Lead Co-I, — ETH, Switzerland
- M. Fich — Lead Co-I, — Univ. Waterloo, Canada
- A. Murphy — Lead Co-I — DIAS, Ireland

- A. Tielens — HIFI Project Scientist — SRON, NL
- N. Whyborn — HIFI Instrument Scientist — SRON , NL
- K. Wafelbakker — HIFI Project Manager — SRON, NL
- P. Roelfsema — HIFI ICC Manager — SRON, NL
- F. Helmich — secretary — SRON. NL

- WBS S/S lead — R. Schieder — KOSMA
- LO S/S lead — R. Guesten — MPIfRA
- HFS/S lead — J. Pearson — JPL

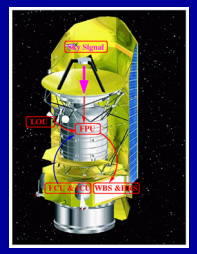


Institutes Participating in the HIFI Hardware

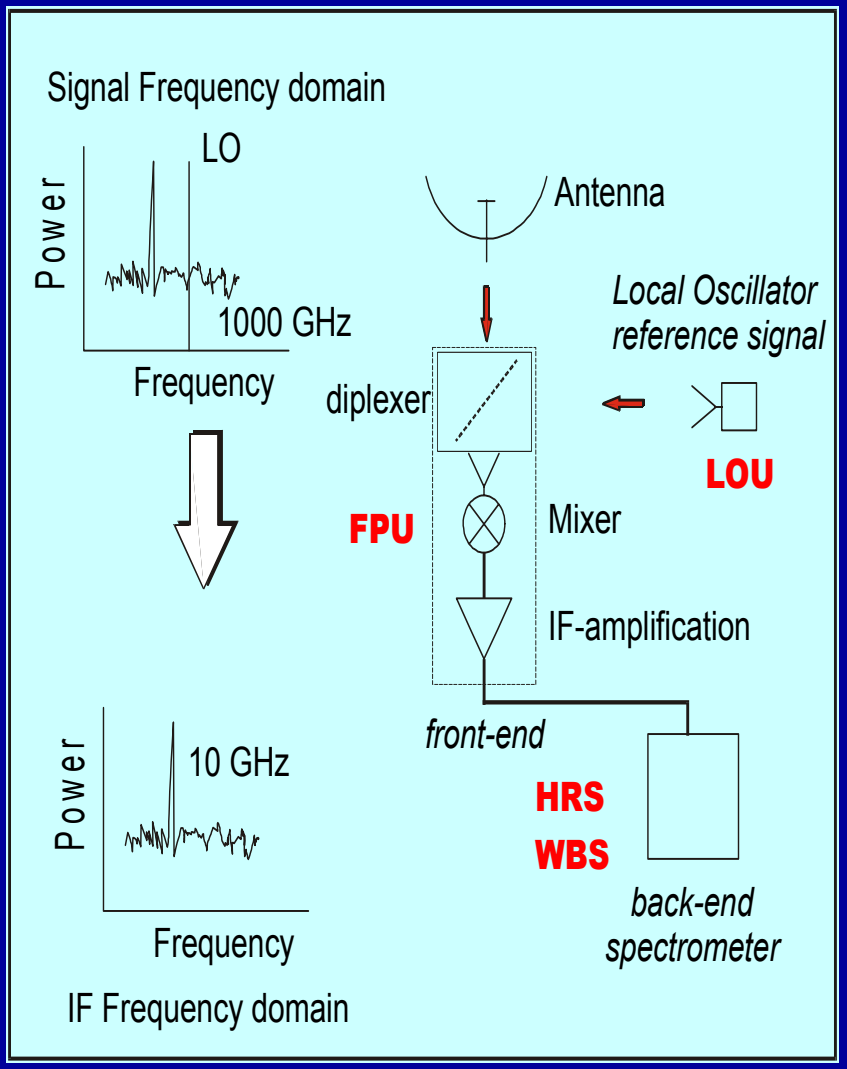
The Netherlands: SRON Groningen/SRON Utrecht DIMES, University of Delft	USA: Caltech and JPL, Pasadena Univ. of Amherst
France: CESR Toulouse LRM-DEMIRM with IRAM Observatoire de Bordeaux	Germany: KOSMA, I. Physikalisches Institut, Köln Max Planck Inst. Für Aeronomie, Lindau Max Planck Inst für Radioastronomie Bonn
Italy: CAISMI-CNR, Florence IFSI, Frascati	Poland: Space Research Center, Warsaw
Spain: Centro Astronómico de Yebes/OAN	Sweden: Onsala and Chalmers TH, Göteborg
Switzerland: ETH, Zürich	Canada: CSA
Ireland: Maynooth College NUI	With contributions from Taiwan in the development

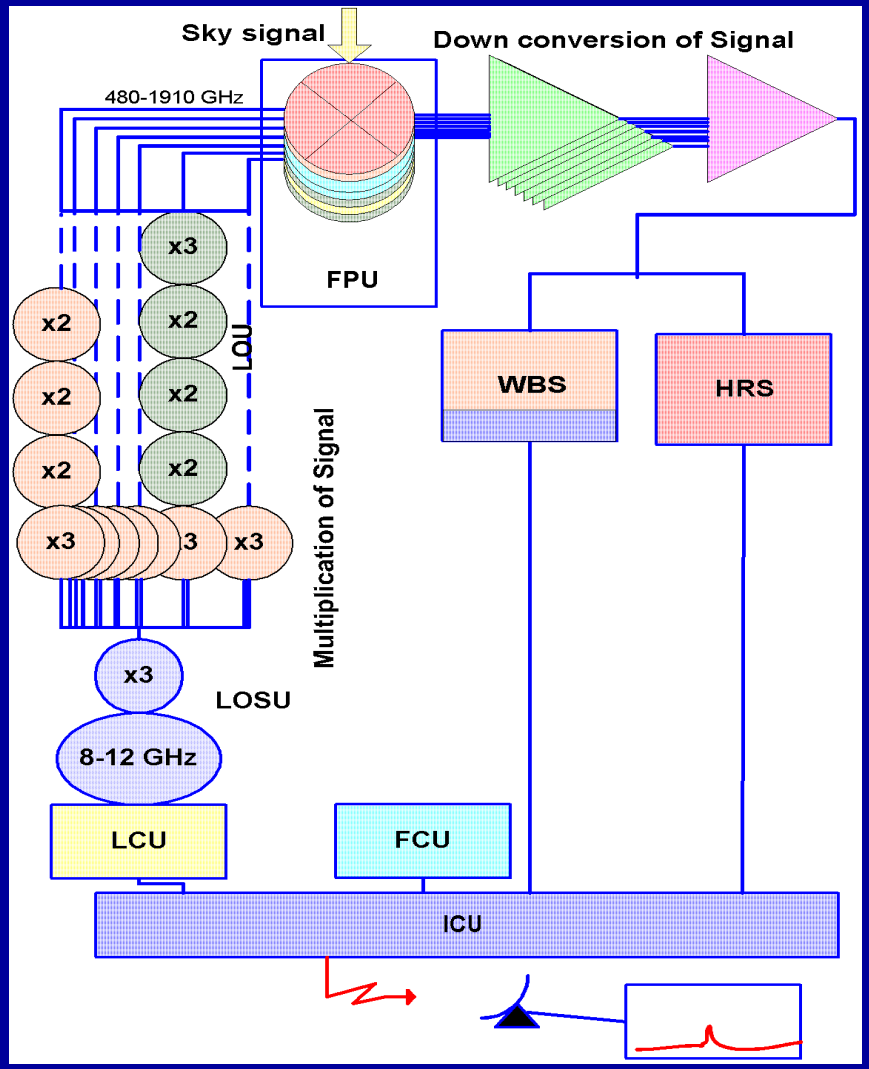
~10 countries; > 20 institutes

thijsdg@sron.rug.nl



Heterodyne Technical Principle and Modular Approach in HIFI





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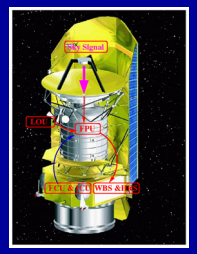
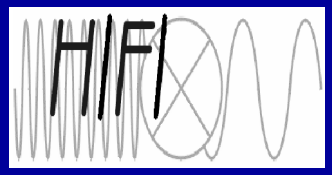
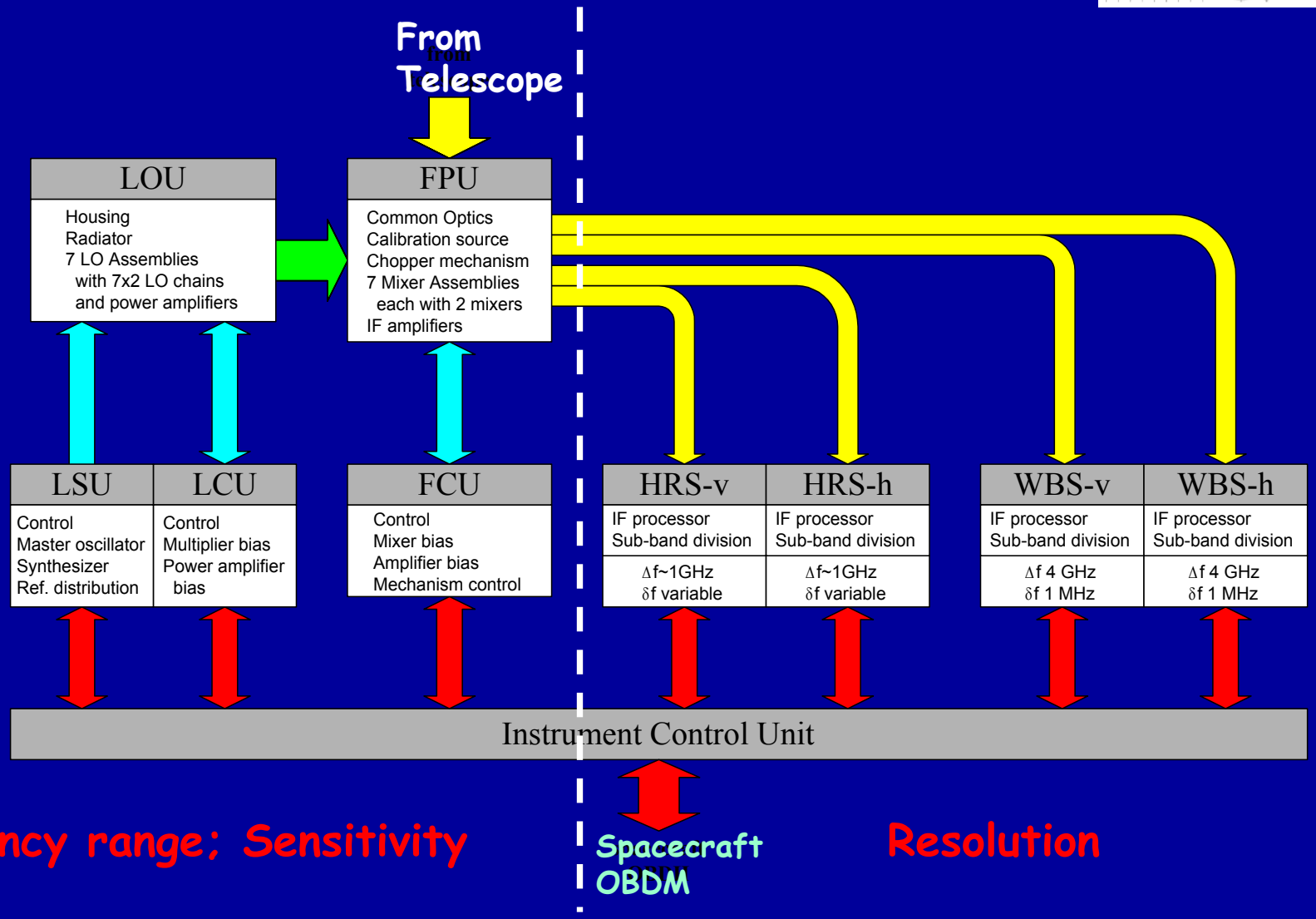


Design block diagram

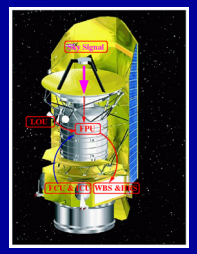




Frequency range; Sensitivity

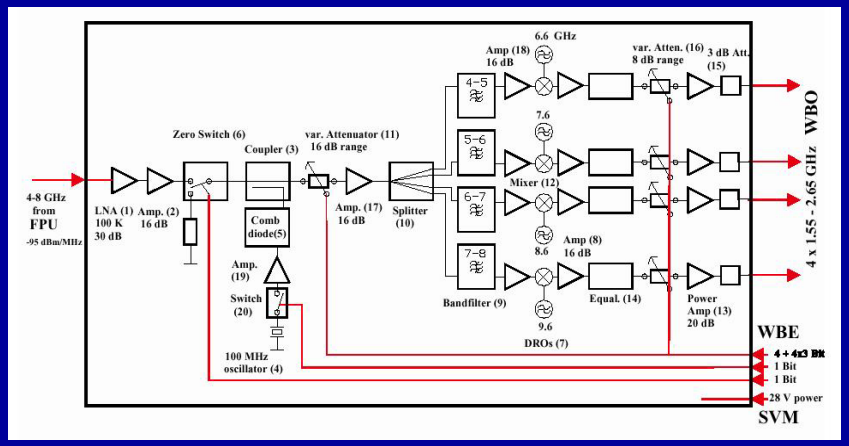
Resolution

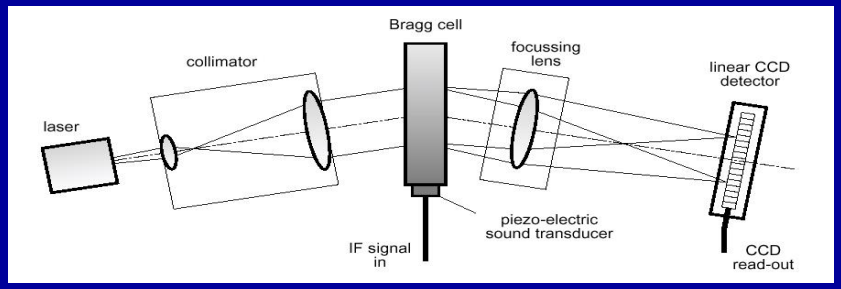
thijsdg@sron.rug.nl



Wide Band Spectrometer (KOSMA)

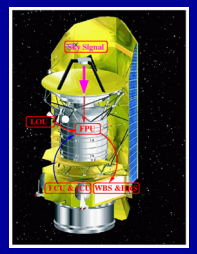
The WBS is an Acousto-Optical Spectrometer that covers the 4 GHz instantaneous bandwidth in 4 sections. The spectral resolution is 1 MHz. This is equivalent to 0.6 km/s at 480 GHz and 0.15 km/s at 1.9 THz





SWAS Heritage!!

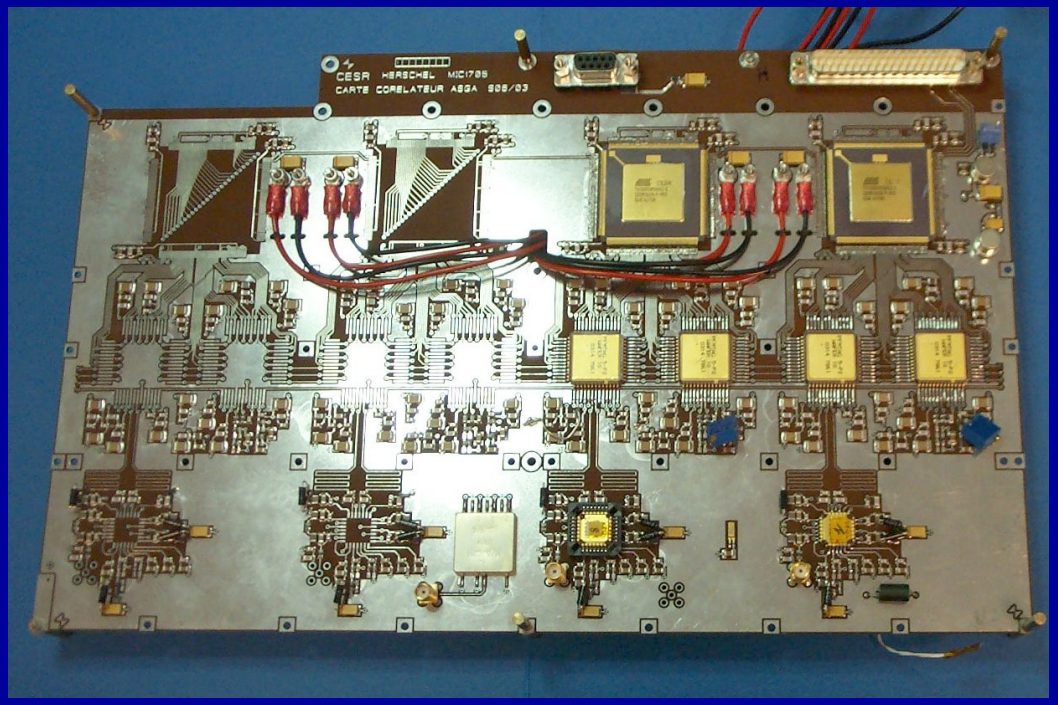
thijsdg@sron.rug.nl

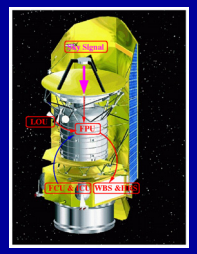


HRS autocorrelator:CESR/Bordeaux

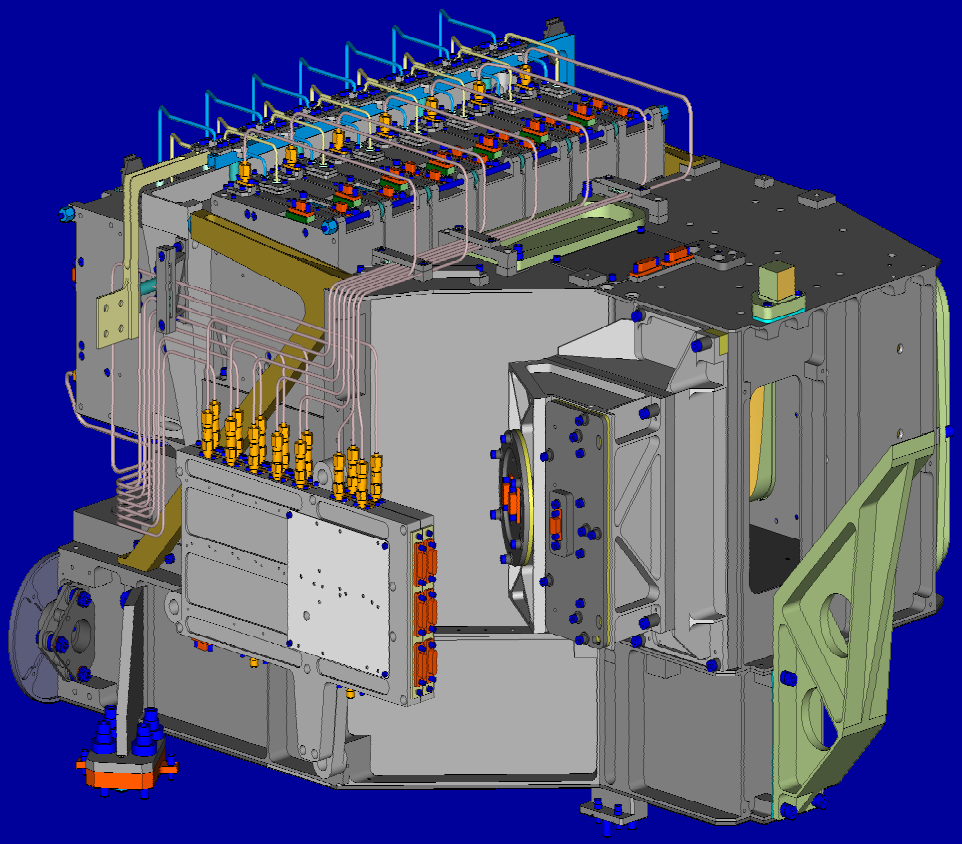
The HRS is a hybrid digital auto-correlator

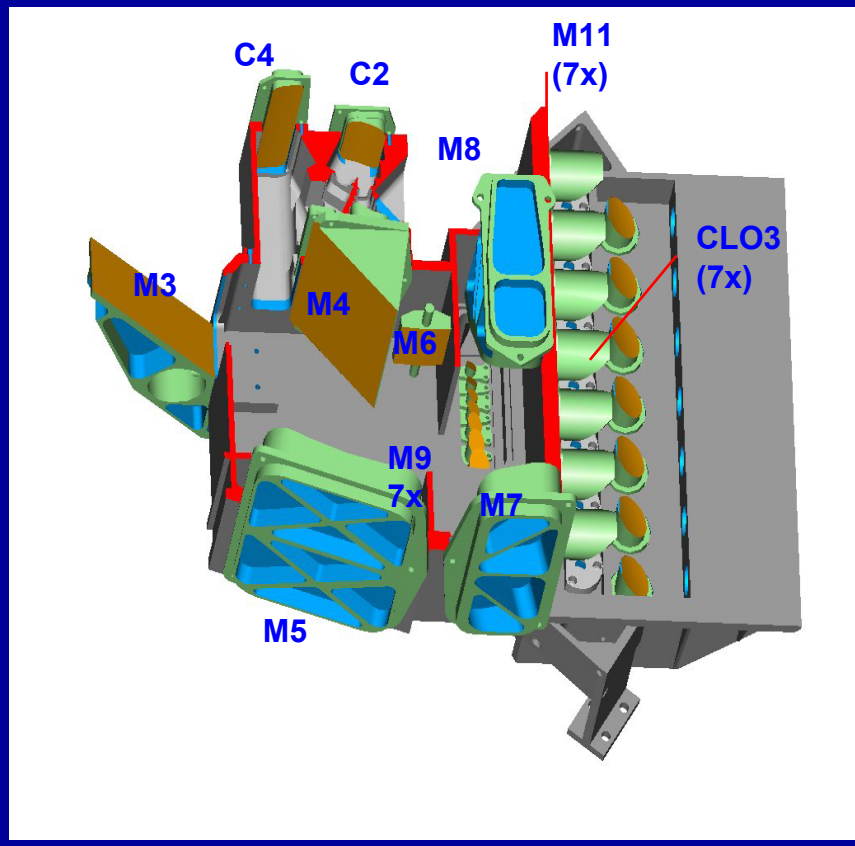
Wide Band:	2p x 4b x 500MHz,	R = 1MHz
Medium Resolution:	2p x 4b x 250MHz,	R = 536kHz
Normal Resolution:	2p x 2b x 250MHz,	R = 268kHz
High Resolution:	2p x 1b x 250MHz,	R = 134kHz





HIFI-Focal Plane Unit (SRON)





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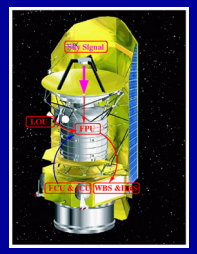
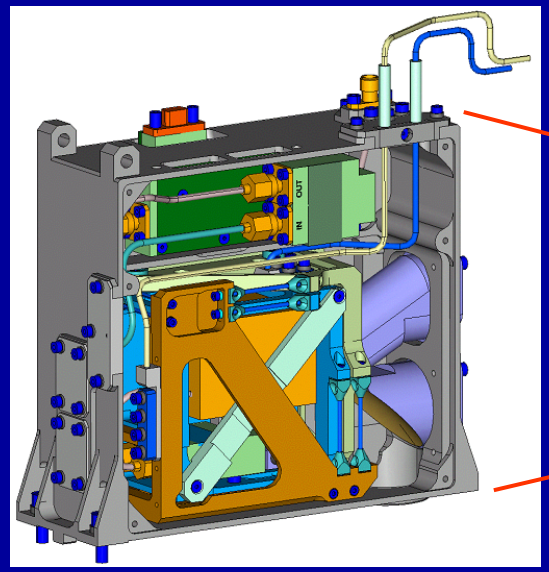
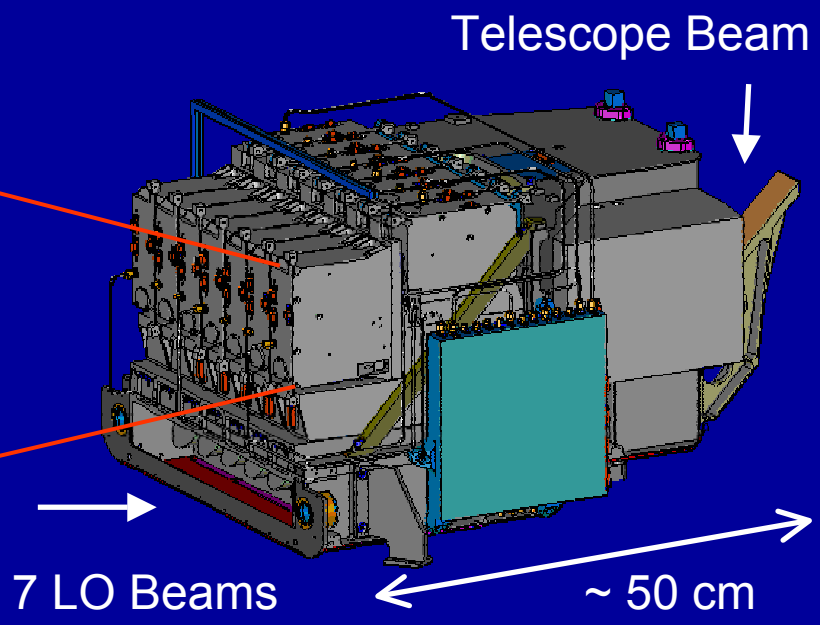


The HIFI FPU and MSA





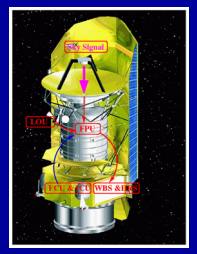
Each Mixer Sub-Assembly with

- Focussing optics
- One mixer
- Two IF isolators
- One IF cryo-amplifier
- Cabling etc.

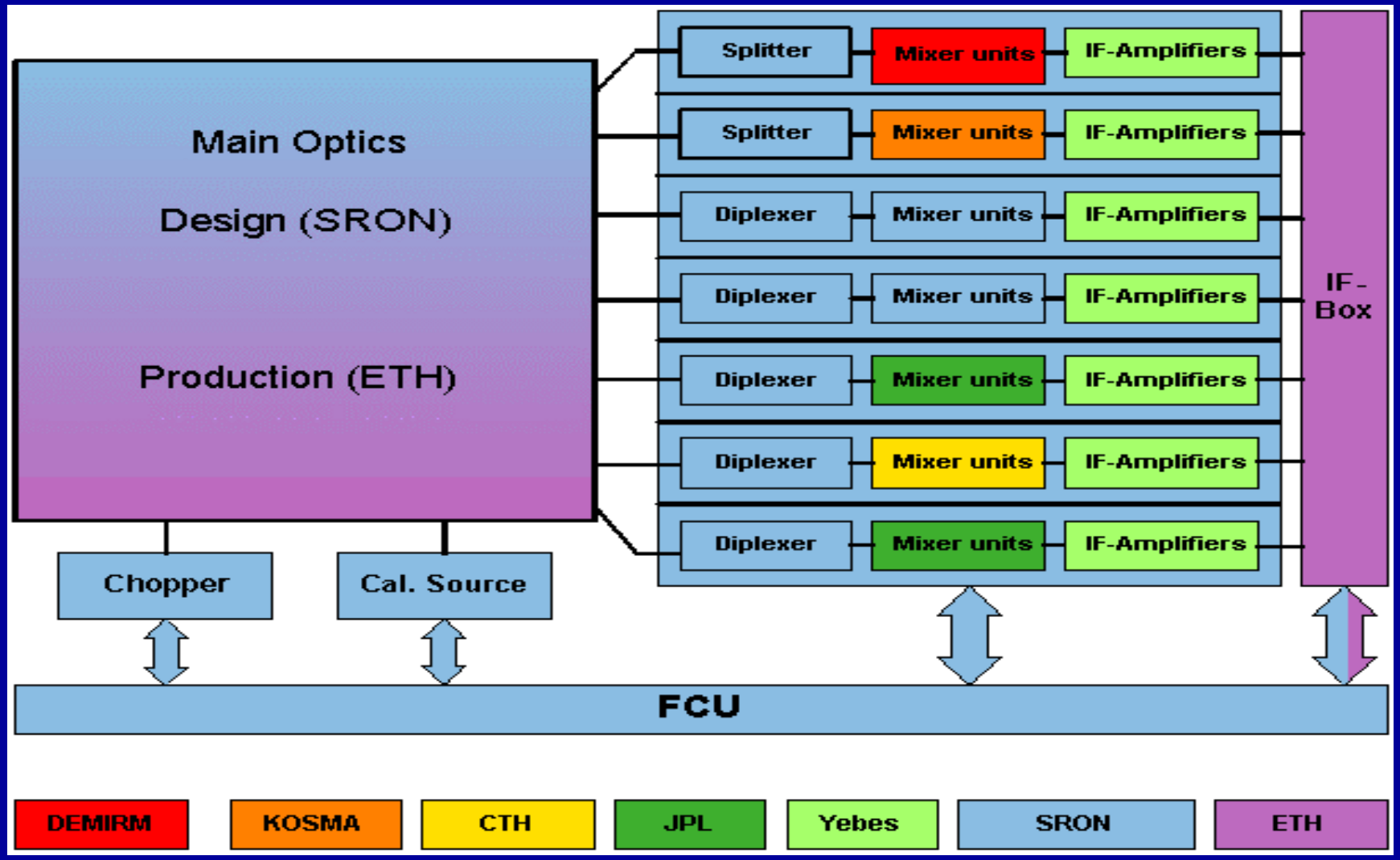
Focal Plane Unit includes

- Imaging optics
- LO + telescope beam combination
- 14 (2 x 7) Mixer Sub-Assemblies (MSA)

thijsdg@sron.rug.nl



HIFI FP S/S Functional Diagram



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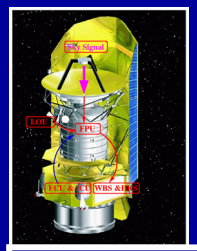
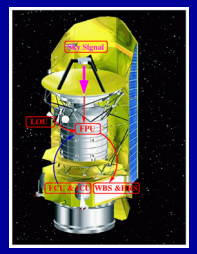


The Focal Plane Subsystem Signal Chain

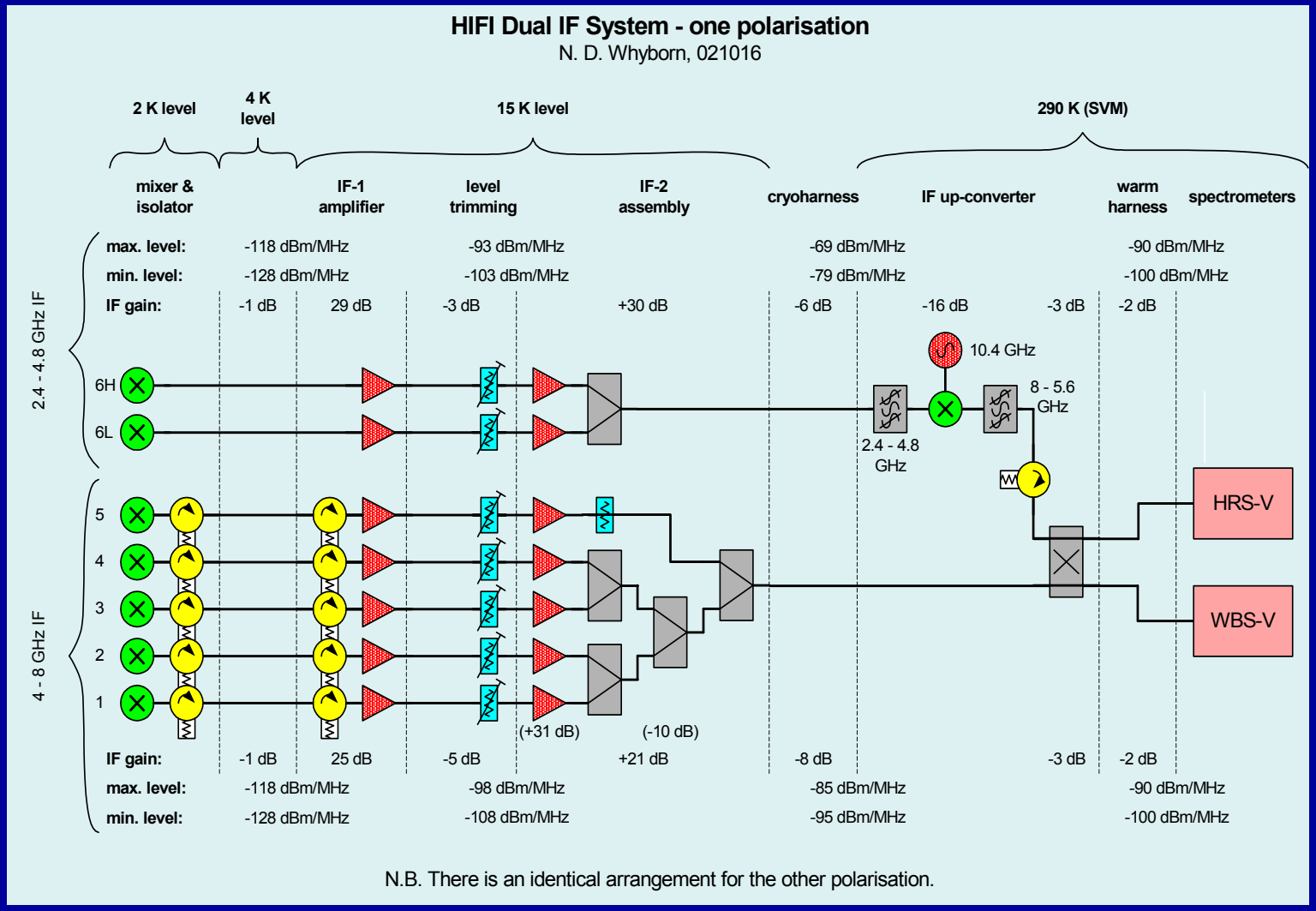
Mixer Technology Baseline

mixer band	frequency range	mixer element	matching circuit	feed and coupling structure
1	480 – 640 GHz	SIS $Nb\text{-}Al_2O_3\text{-}Nb$	Nb on Nb microstrip	corrugated horn and waveguide
2	640 – 800 GHz	SIS $NbTiN\text{-}Al_2O_3\text{-}Nb$	Al on NbTiN microstrip	corrugated horn and waveguide
3	800 – 960 GHz	SIS $NbTiN\text{-}Al_2O_3\text{-}Nb$	Al on NbTiN microstrip	corrugated horn and waveguide
4	960 – 1120 GHz	SIS $NbTiN\text{-}Al_2O_3\text{-}Nb$	Al on NbTiN microstrip	corrugated horn and waveguide
5	1120 – 1250 GHz	SIS NbTiN-AlN-NbTi	Al on NbTiN microstrip	lens and twin slot planar antenna
6L	1410 – 1703 GHz	HEB NbN phonon cooled	Al co-planar waveguide	lens and twin slot planar antenna
6H	1703 – 1910 GHz	HEB NbN phonon cooled	Al co-planar waveguide	lens and twin slot planar antenna

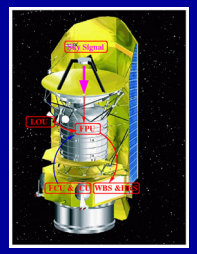
thijsdg@sron.rug.nl



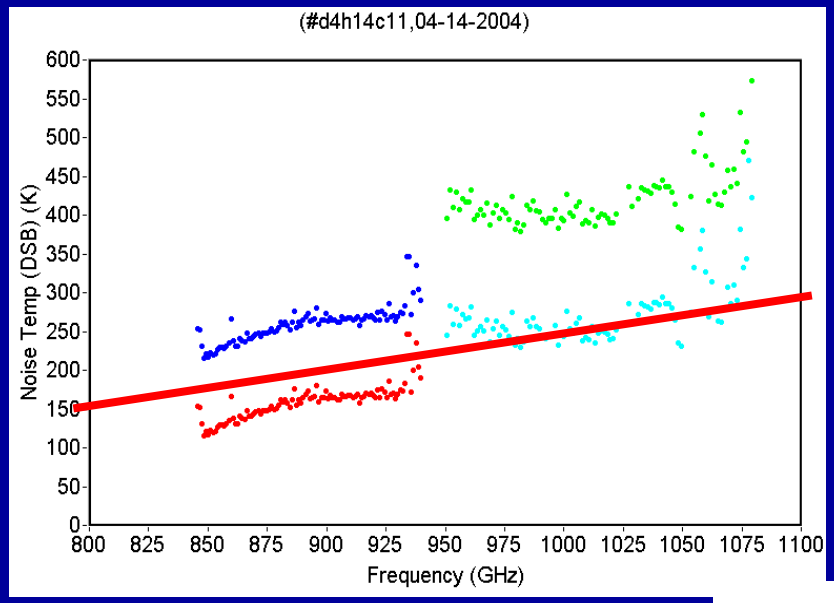
HIFI IF signal chain

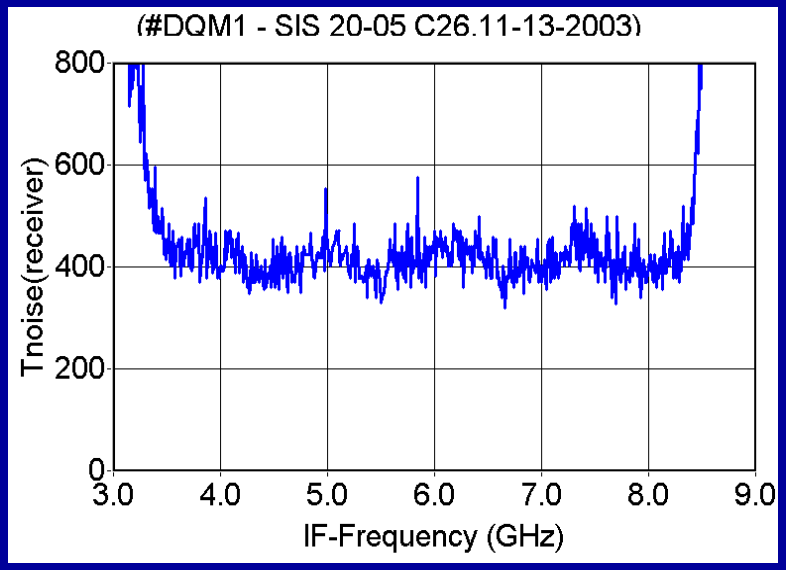


thijsdg@sron.rug.nl



Mixers band-3/4 Status

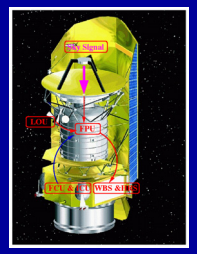




Adjusted for HIFI cold optics

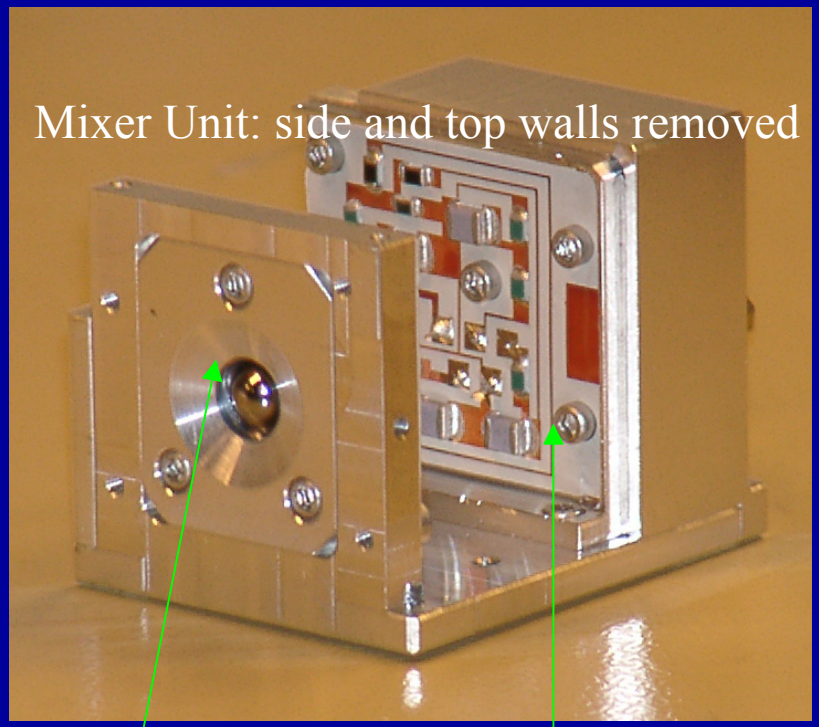
Top 10 High density devices band 3 (batch 20-10)

Device	Tag	Trec,4K (K)	Trec,2K (K)	Topt(K)	Gopt	Tmixer(K)	**THIFI(K)**	FTS	Comments
F06	d3h14c11	330	260	64	0.82	151	**161**	goed	2K gemeten
F23	d3h14c13	310	250	64	0.82	143	**153**	loopt beetje op	2K gemeten
C78	d3h11c10	350	270	64	0.82	159	**169**		2K gemeten
A65	d3h14c17	310	250	64	0.82	143	**153**	loopt op	
F77	d3h14c10	320	260	64	0.82	151	**161**	loopt sterk op	In QM?
F59	d3h14c9	400	330	64	0.82	208	**218**	goed	
A59	d3h14c6	400	330	64	0.82	208	**218**	goed	2K gemeten
C20	d3h11c9	400	330	64	0.82	208	**218**		2K gemeten
A25	d3h14c16	400	330	64	0.82	208	**218**	loopt sterk op	

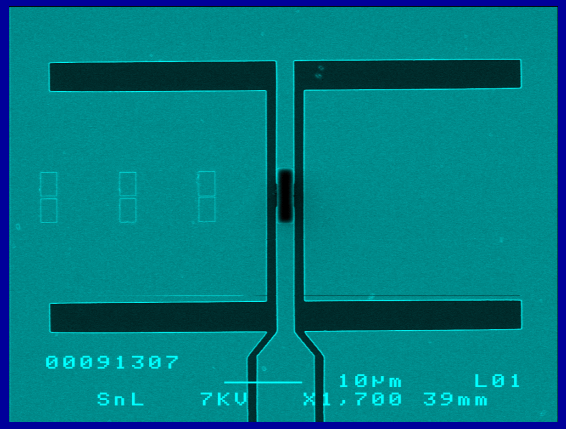


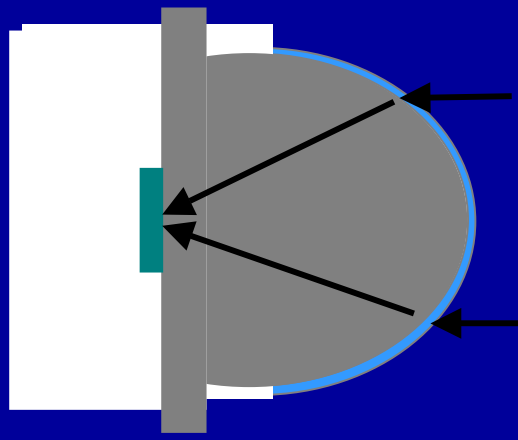
Band 6 Mixers

RF band:	***Band 6L***	***1410 GHz to 1750GHz***
	Band 6H	***1626 to 1910 GHz***
RF coupling:	***Quasioptical***	***F# = 4.25***
IF band:	***2.4 – 4.8 GHz***	



Double-slot antenna, made of 200nm Au

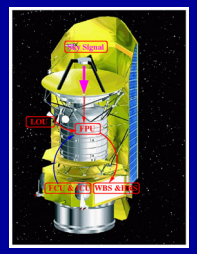




Silicon substrate

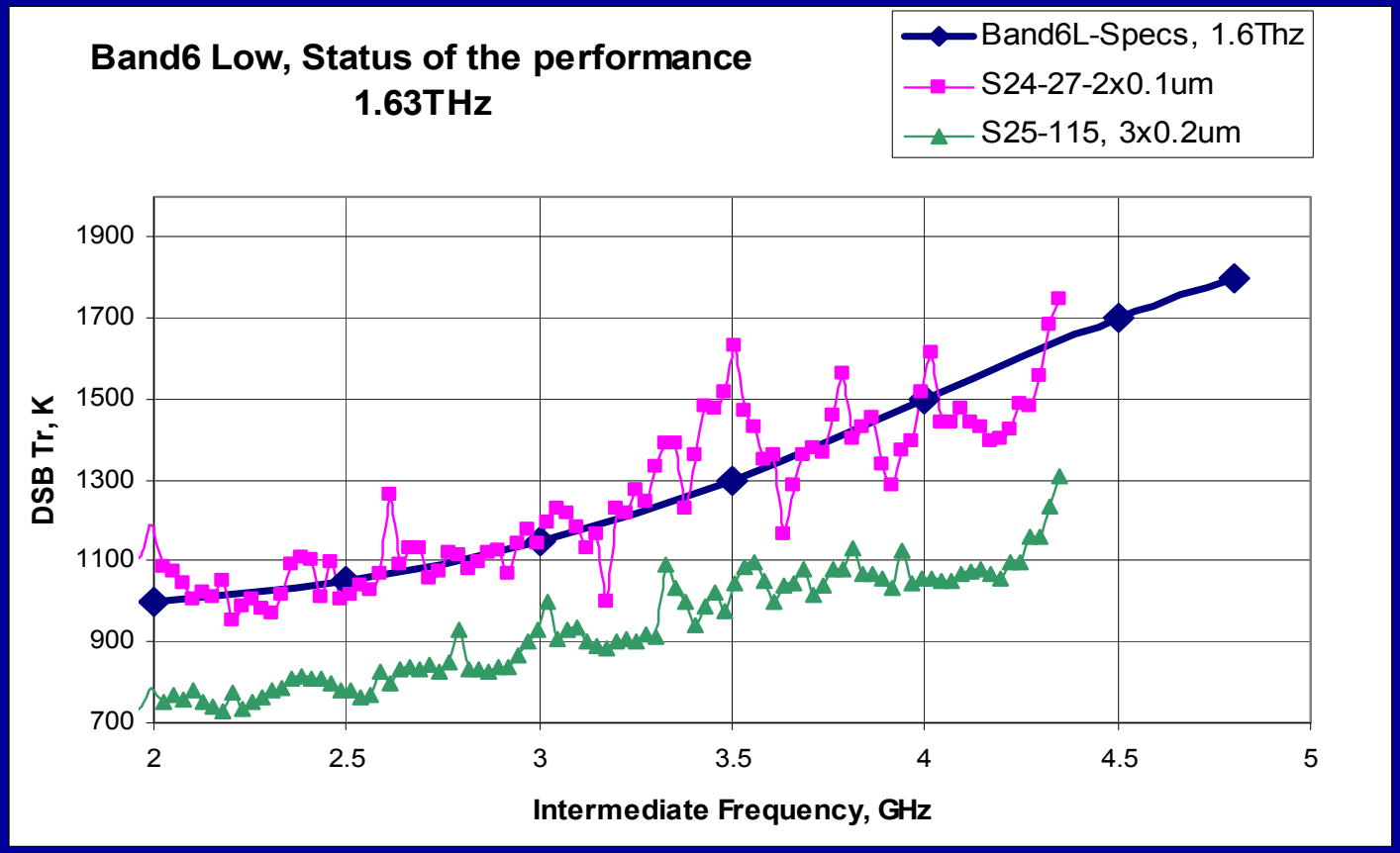
CHALMERS
Chalmers University of Technology

thijsdg@sron.rug.nl



Mixer Unit-6 IF performance

Results:
Not yet operating 2.4 – 4.8 GHz IF, will be shortly
Measurement with 2 – 4 GHz IF looks very good
Problem with LO power compliance



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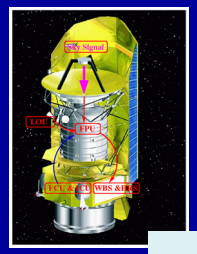
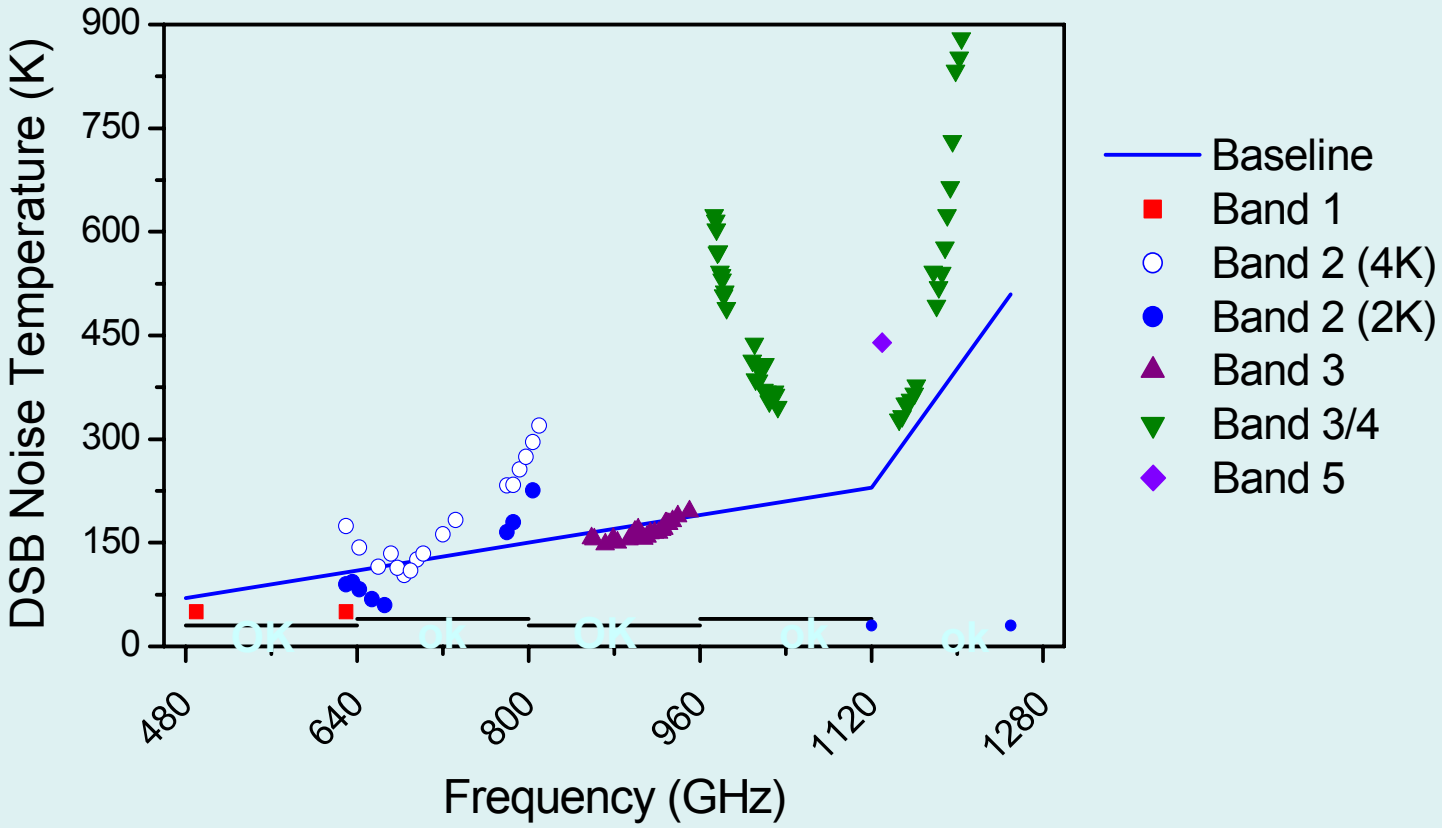


HIFI SIS Mixer performance Status



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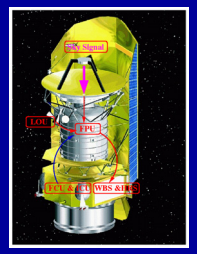
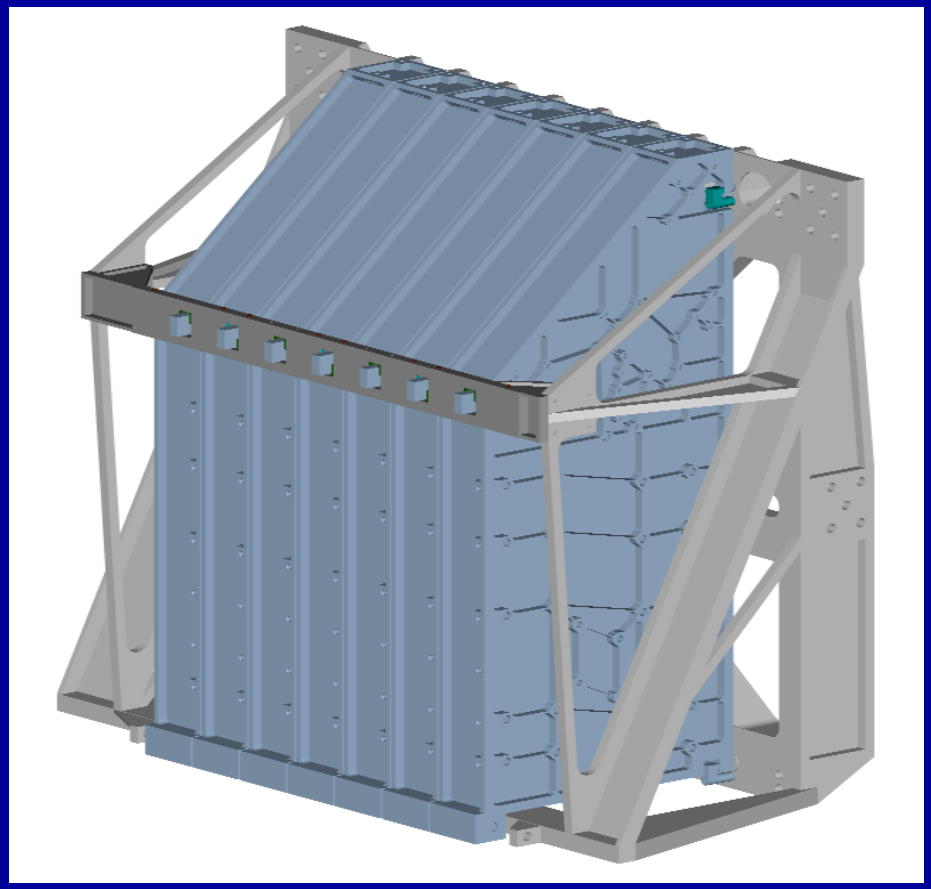
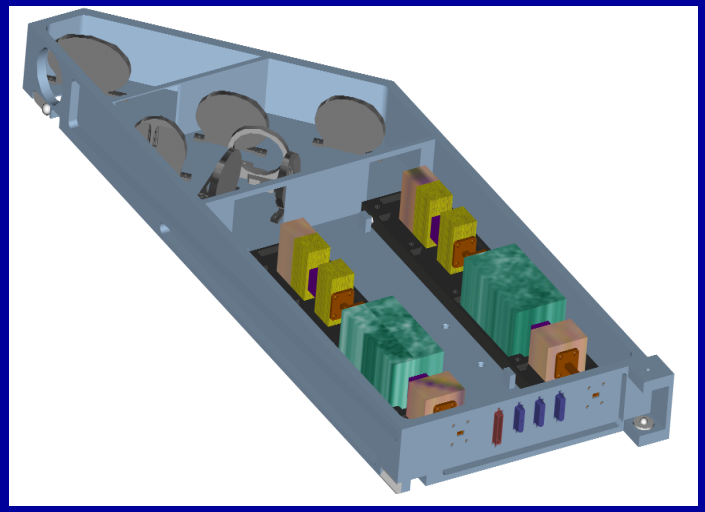


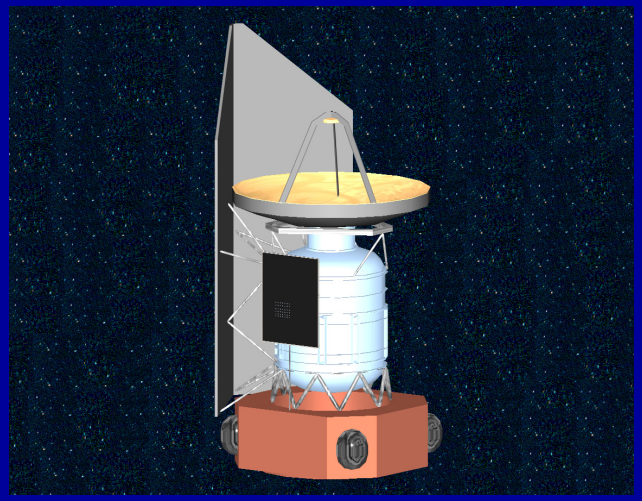
Instrument Design – LO

LOU with 7 LO Assemblies



LO Assembly with two Multiplier Chains





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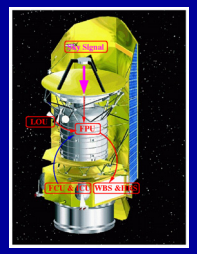
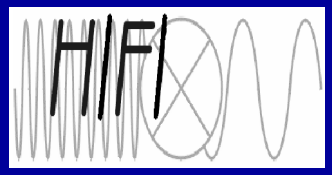
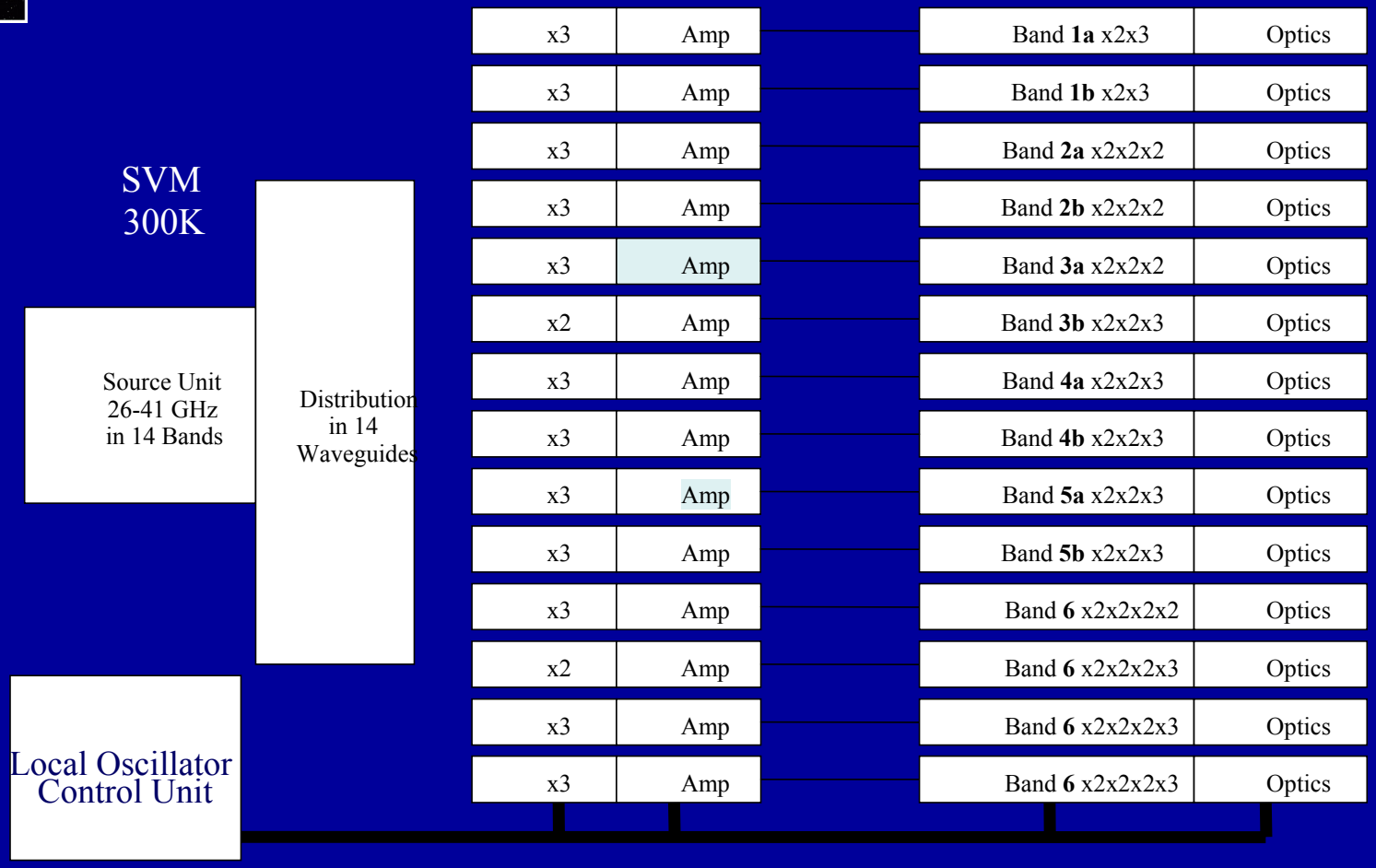


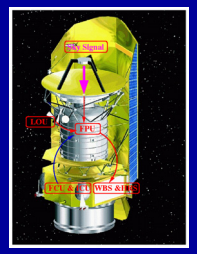
HIFI – LO Multiplication scheme



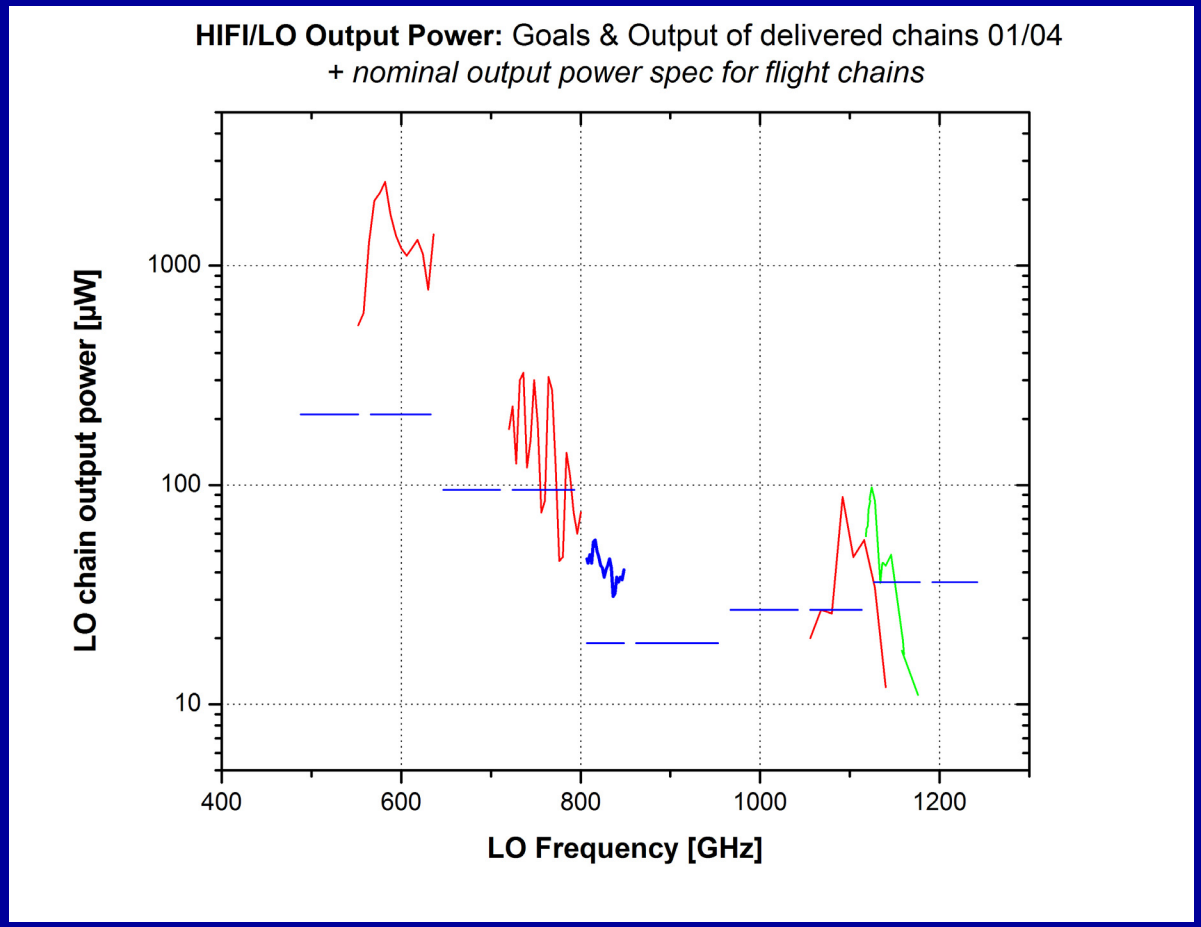


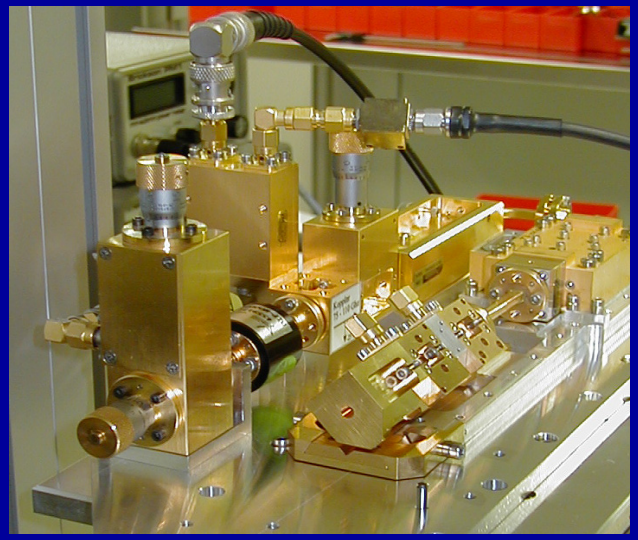
The local oscillator signal is created by several steps of doubling and tripling of a signal of about 100 GHz. Above the multiplying scheme for the 6 bands is given.

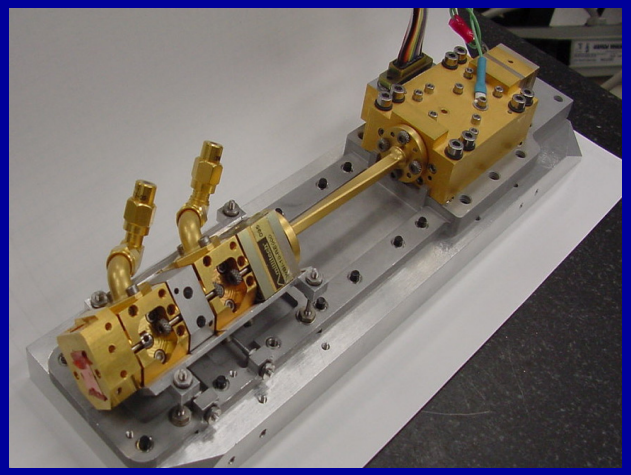
thijsdg@sron.rug.nl



LOU Chains bands 1-4 (MPIFRA-RPG): Results







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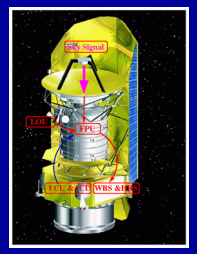
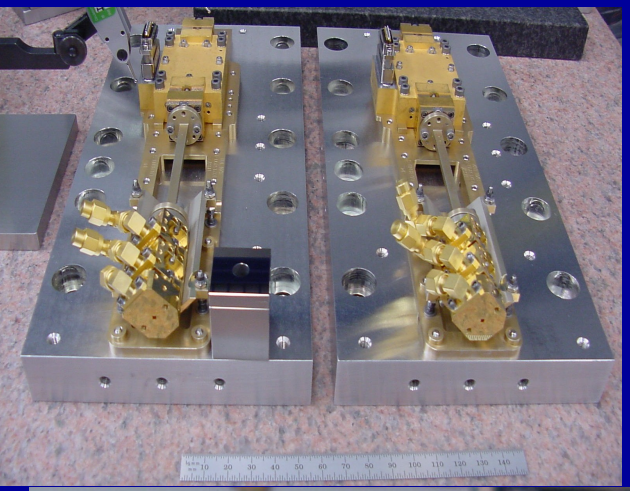
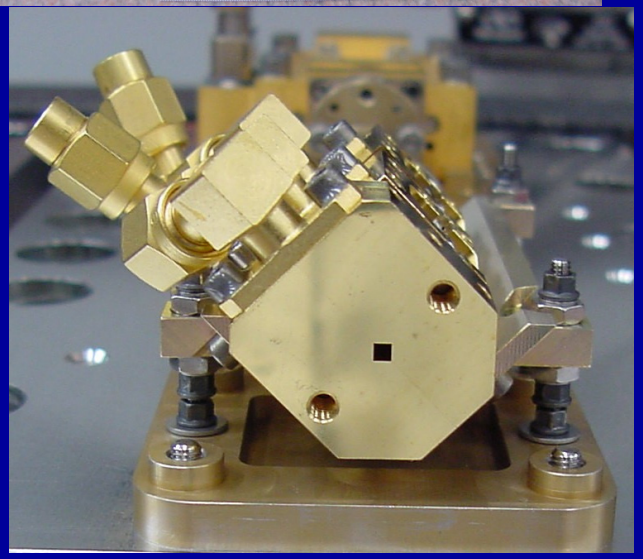
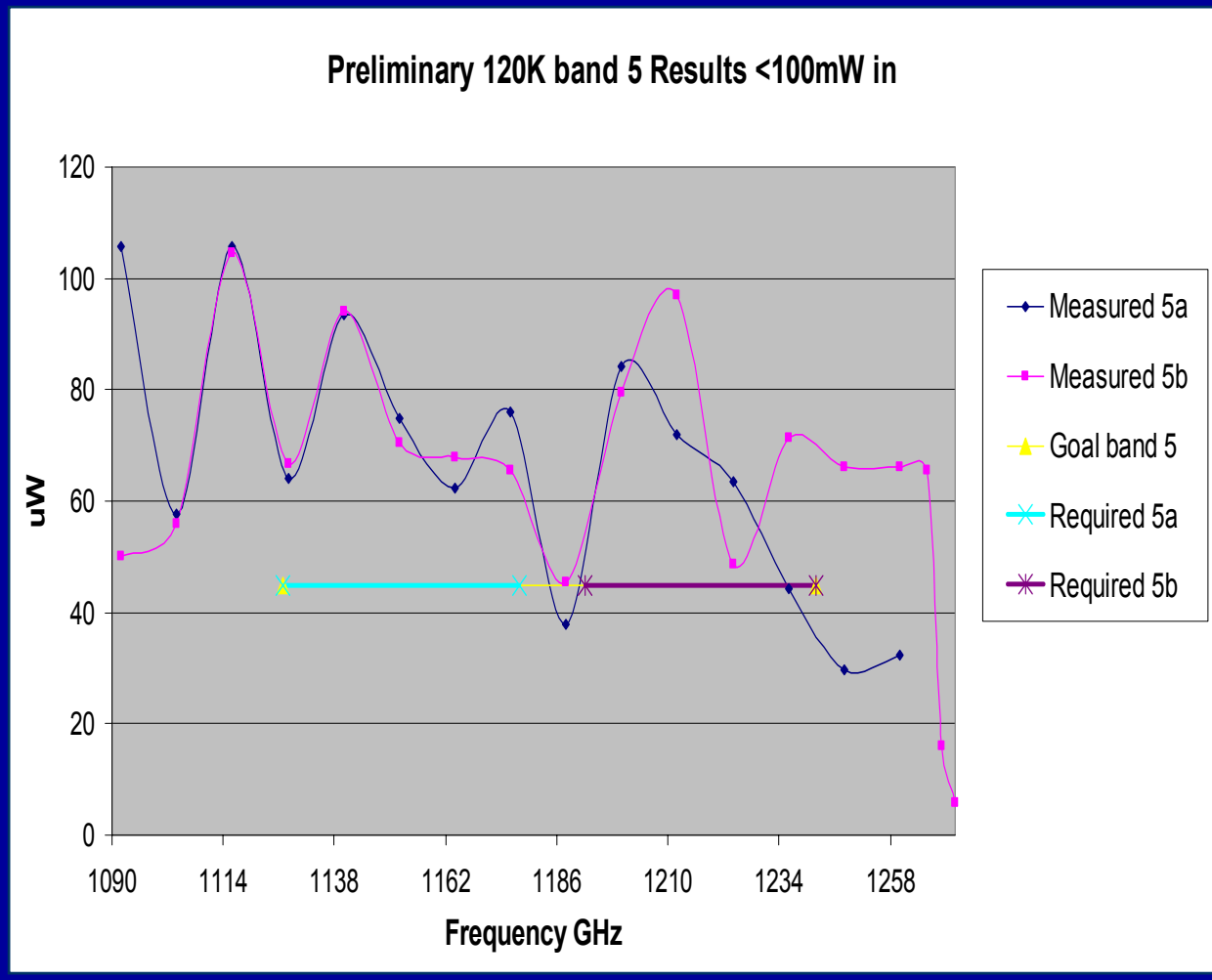


Band 5 FM Chains (JPL): Performance







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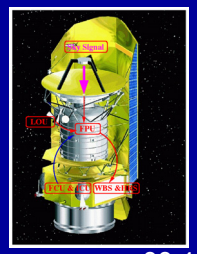
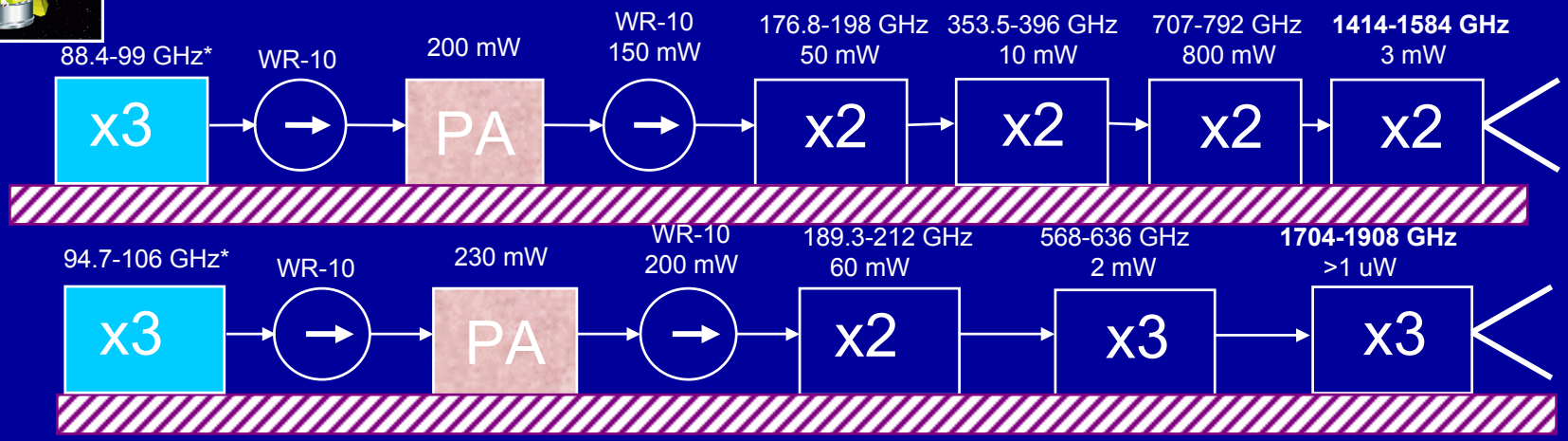
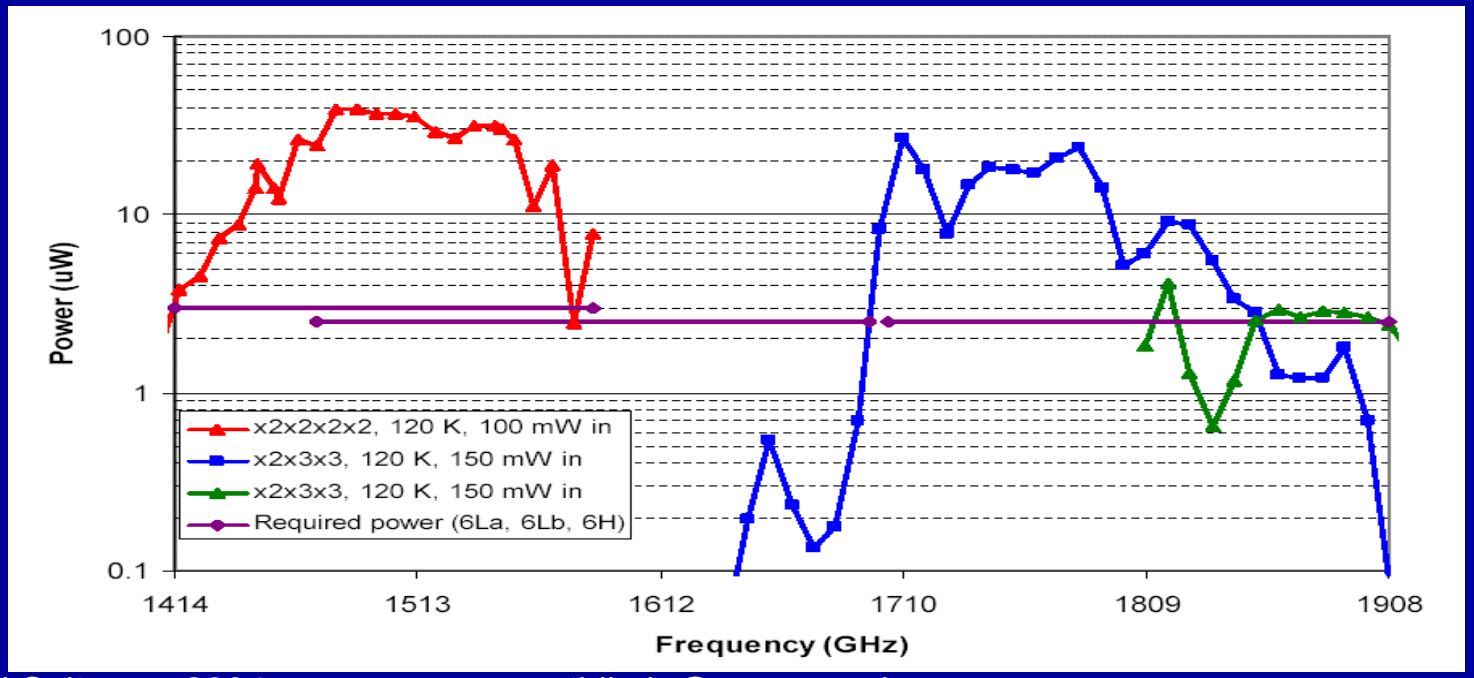


Band 6 Low and High (JPL): Performance





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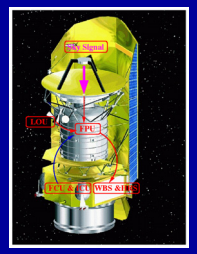
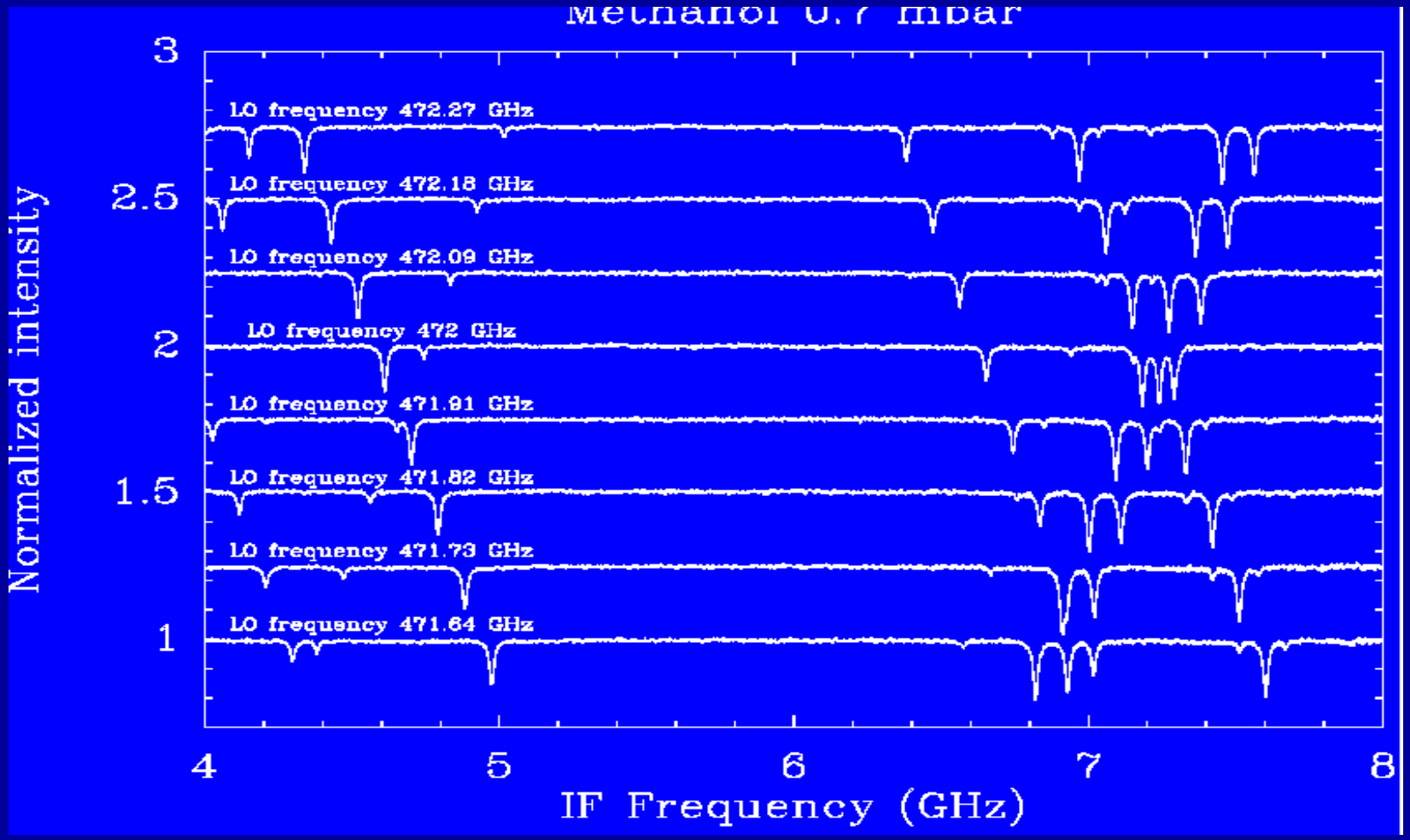


HIFI-FPU DM tests with methanol in gas cell



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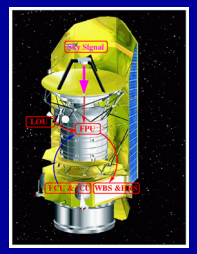

Expected HIFI sensitivities

	1	2	3	4	5	6
Frequency Range (GHz)	480-640	640-800	800-960	960-1120	1120-1250	1410-1910
Receiver Noise (DSB, Baseline) (K)	90	130	170	210	370	650
Receiver Noise (DSB, Goal) (K)	84	120	160	190	210	650
Flux Limit (5σ, 1hr, $R=10^4$) (Jy)	1.5	2.0	2.3	2.5	2.7	4.6
Flux Limit (5σ, 1hr, $R=10^4$) (mK)	3.4	4.4	5.1	5.6	6.0	10
Line Flux limit (5σ, 1hr, 10^4) (10^{-18} Wm^{-2})	0.9	1.4	2.0	2.6	3.2	7
Line scan (1σ,24hrs, f=1MHz) (mK) Angular resolution (arcsec)	16 40"	16	16	16	16	34 12"
Spectral Resolution (MHz)	0.14 – 0.28 – 1.00					

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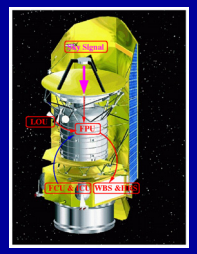
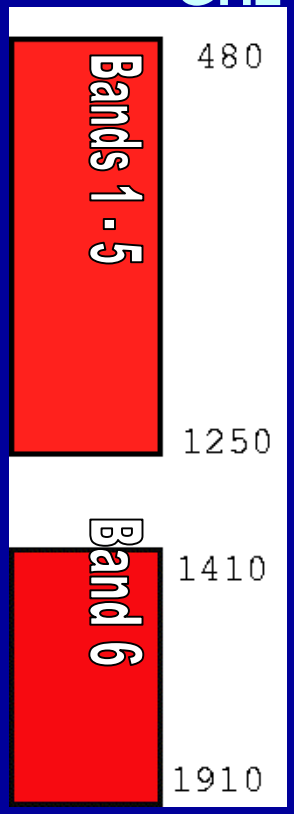
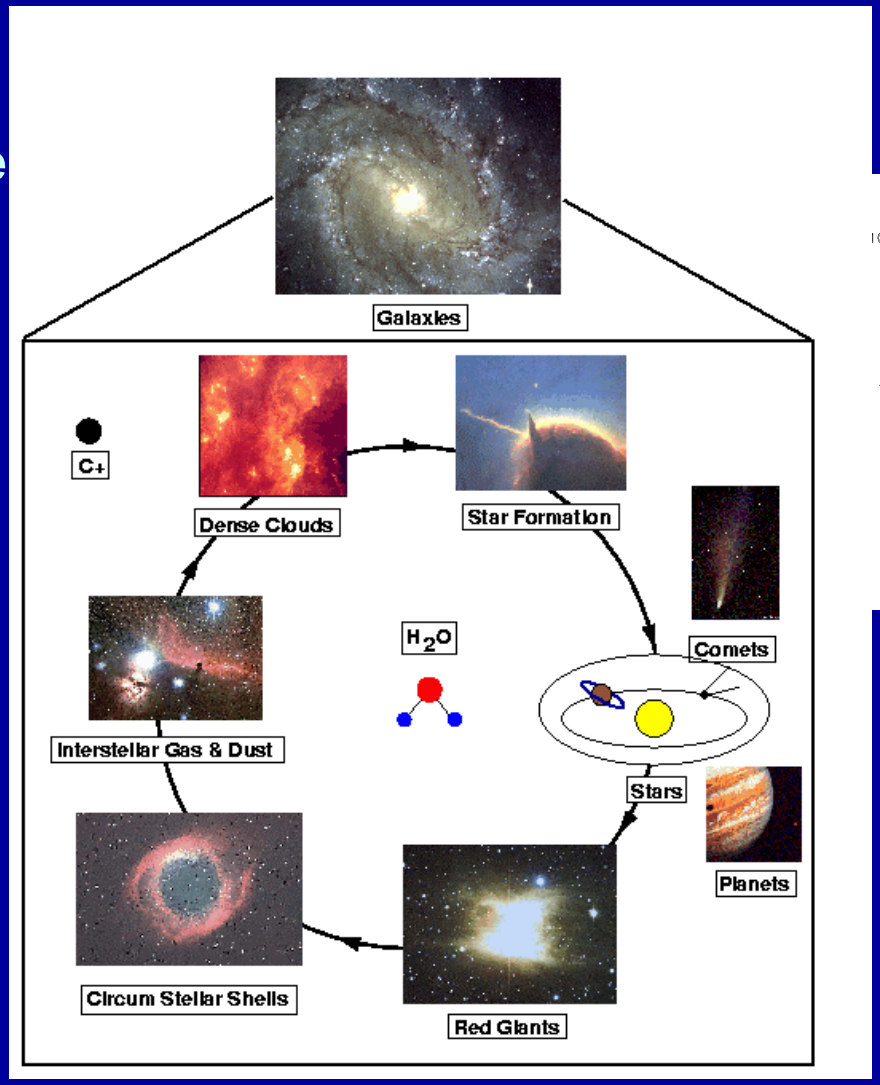


Science Requirements and HIFI: Life cycle of ISM and Stars

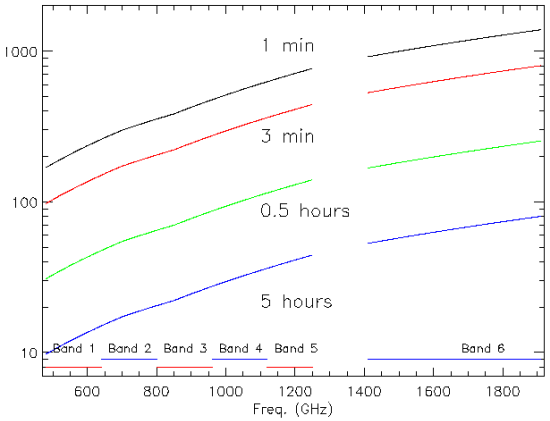
Frequency range

GHz





Sensitivity



IF and Resolution:

IF: 4 GHz

Res. WBS: 1 MHz

Res. HRS: 0.27, 0.14 MHz

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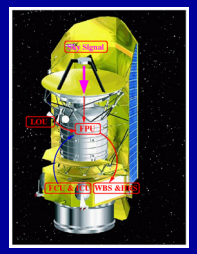
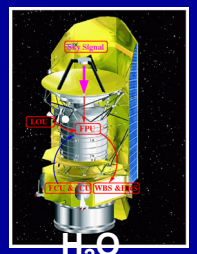


Herschel-HIFI
Unique and Core Science Drivers

		HIFI Bands					
	Science Drivers:	1	2	3	4	5	6
UNIQUE	Water	X-H-S			X-H-S	X-S	X-H-S
	Molecular complexity Line Survey	X	X	X	X	X	X
&							
CORE SCIENCE	Diffuse ISM	X-H-S		X-H	X		X-H-S
	HD						
	Star Formation	X	X	X	X	X	X
	Death of Stars	X	X	X	X	X	X
	ISM in Galaxies	X	X				X
	[C II] at high z	X-S	X-S	X-S	X-S	X-S	
	SSO: Comets	X-H					
	SSO: Planets	X	X			X	X

X = Required Band **H** = HRS Required **S** = Goal Sensitivity Required

thijsdg@sron.rug.nl



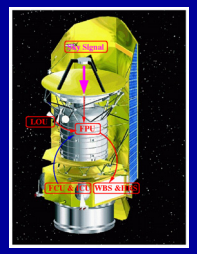
Science with HIFI –Spectroscopy Atoms/Ions/Hydrides

H_2O Transition	Freq. (GHz)
6_{24}-7_{17}	488.5
1_{10}-1_{01}	556.9
5_{32}-4_{41}	620.7
2_{11}-2_{02}	752.0
4_{22}-3_{31}	916.2
5_{24}-4_{31}	970.3
2_{02}-1_{11}	987.9
3_{12}-3_{03}	1097.4
1_{11}-0_{00}	1113.3
3_{12}-2_{21}	1153.1
6_{34}-5_{41}	1158.3
3_{21}-3_{12}	1162.9
7_{44}-6_{51}	1172.5
4_{22}-4_{13}	1207.6
2_{20}-2_{11}	1228.8
$7_{4,3}$-$6_{5,2}$	1278.3
$6_{2,5}$-$5_{3,2}$	1322.0
5_{23}-5_{14}	1410.6
7_{26}-6_{33}	1440.8
6_{33}-5_{42}	1542.0
6_{43}-7_{16}	1574.2
4_{13}-4_{04}	1601.2
2_{21}-2_{12}	1661.0
2_{12}-1_{01}	1669.9
4_{32}-5_{05}	1713.9
3_{03}-2_{12}	1716.8
5_{33}-6_{06}	1716.9
6_{33}-6_{24}	1762.0
7_{35}-6_{42}	1766.2
6_{24}-6_{15}	1794.8
7_{34}-7_{25}	1797.2
5_{32}-5_{23}	1867.7
6_{34}-7_{07}	1880.7
3_{31}-4_{04}	1893.7

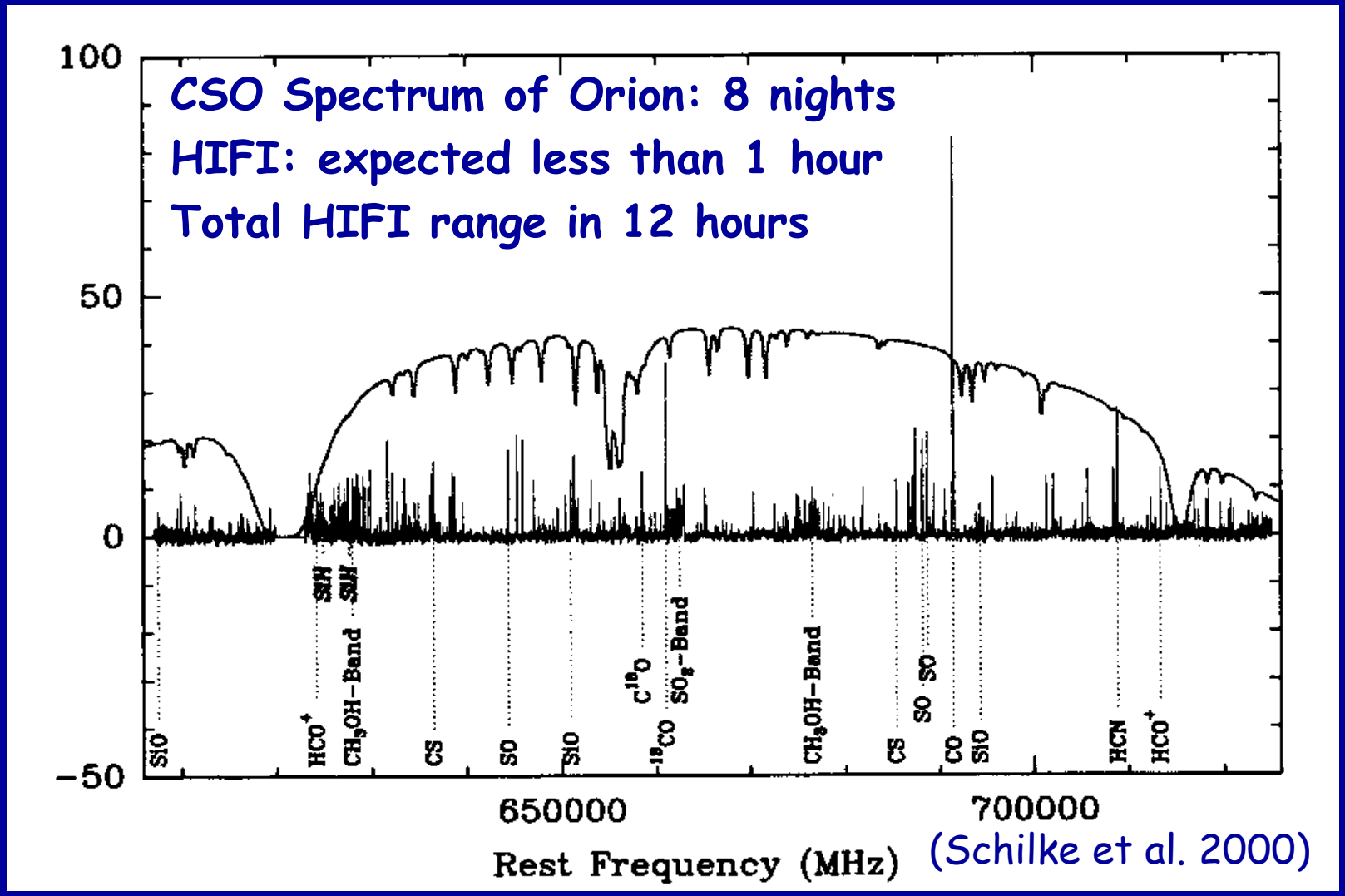
Hydride	Transition	Freq (GHz)
PH	$^3\Sigma^-$, N=1-0	498.0
HBr	J=1-0	500.6
CH	$^2\Pi_{3/2}$,J=3/2-$\Pi_{1/2}$,J=1/2	532.7
o-H_2O	$J_{KaKc}=1_{10}$-1_{01}	556.9
NH_3	$J_K=1_0$-0_0	572.5
HCl	J=1-0	625.9
SiH	$^2\Pi_{1/2}$, J=3/2-1/2	660.0?
CH^+	J=1-0	835.1
p-NH_2	$J_{KaKc}=1_{11}$-0_{00}	917.9
NH	$^3\Sigma^-$ N=1-0	974.6
OH^+	J=1-0	984.5
p-H_3O^+	$J_K=1_0$-0_0	984.6
NH^+	$^2\Pi_{1/2}$,J=3/2-1/2	1038.1
HF	J=1-0	1232.7
SH	$^2\Pi_{3/2}$,J=5/2-3/2	1382.9
HFe		1411.
o-H_3O^+	$J_K=1_1^+$-1_1^-	1655.8
OH	$^2\Pi_{1/2}$,J=3/2-1/2	1837.8

Atom /Ion	Transition	Freq. (GHz)
^{12}C	^{3}P J=1-0	492.2
	^{3}P J=2-1	809.3
^{13}C	^{3}P J=1-0	492.2
	^{3}P J=2-1	809.4
$^{12}C^+$	^{2}P J=3/2-1/2	1900.5
$^{13}C^+$	^{2}P J=3/2-1/2	1900.55
$^{14}N^+$	^{2}P J=1-0	1461.1
$^{15}N^+$	^{2}P J=1-0	1461.1
Mg	^{3}P J=1-0	601.3
	^{3}P J=2-1	1220.6

thijsdg@sron.rug.nl



HIFI Spectral Surveys



(Schilke et al. 2000)

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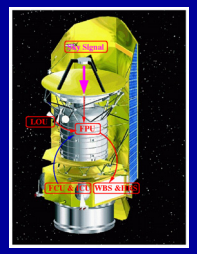
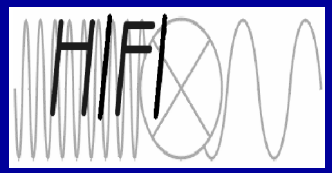
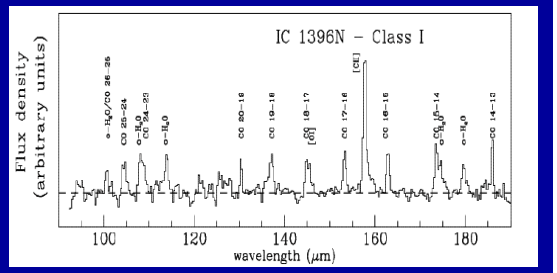
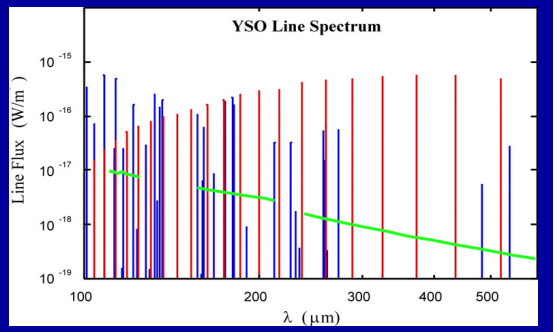
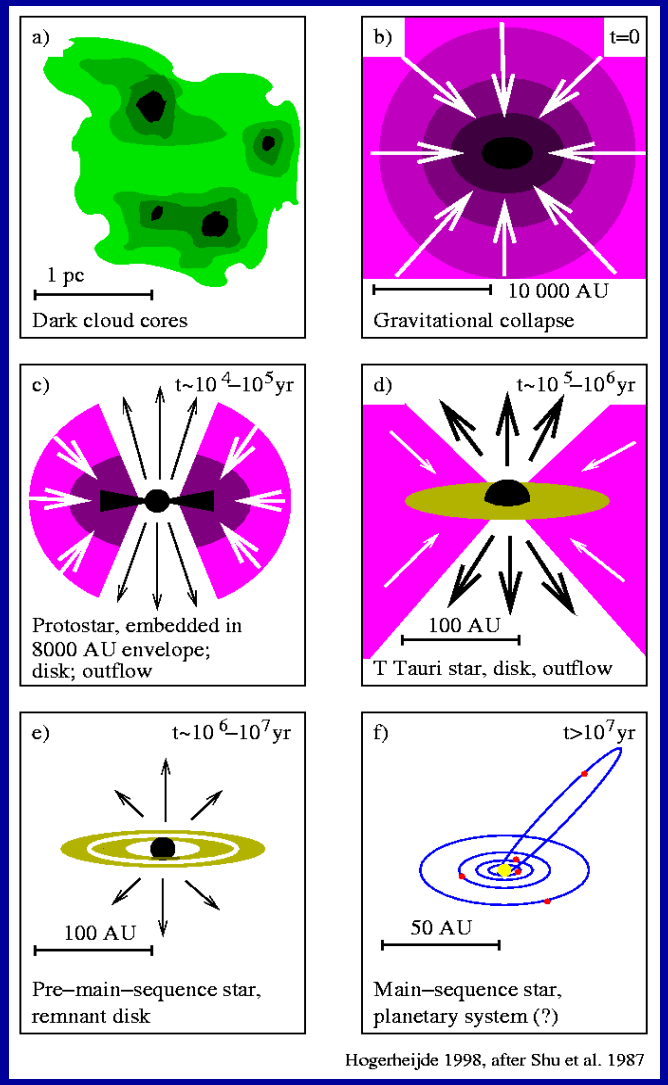


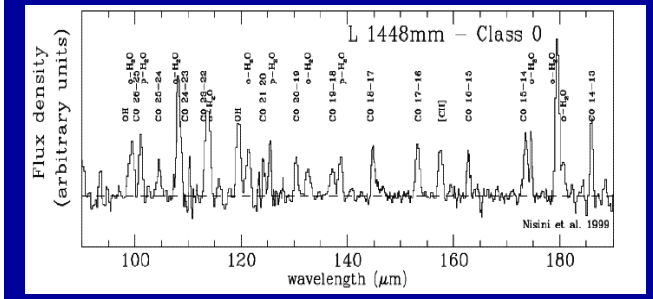
Star Formation Investigations

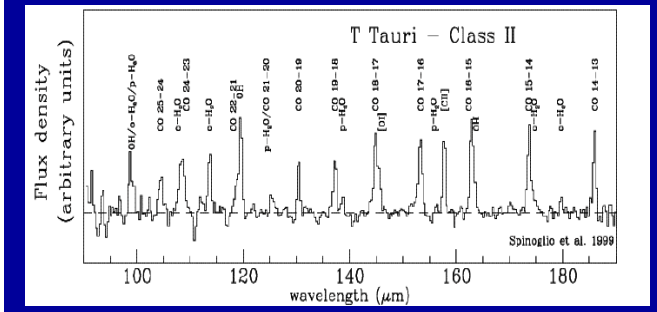












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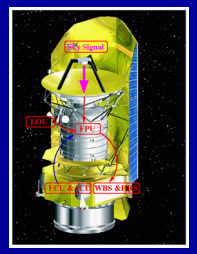
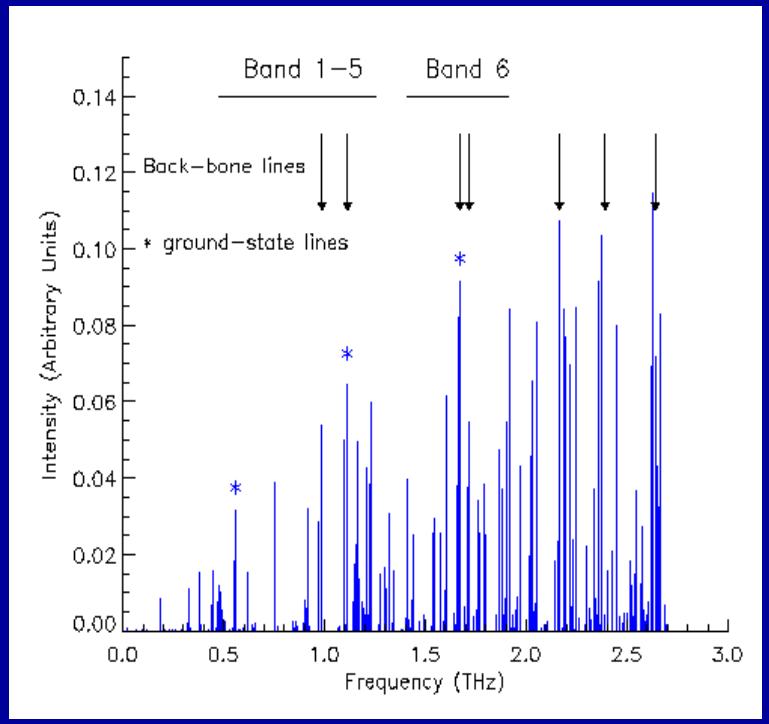
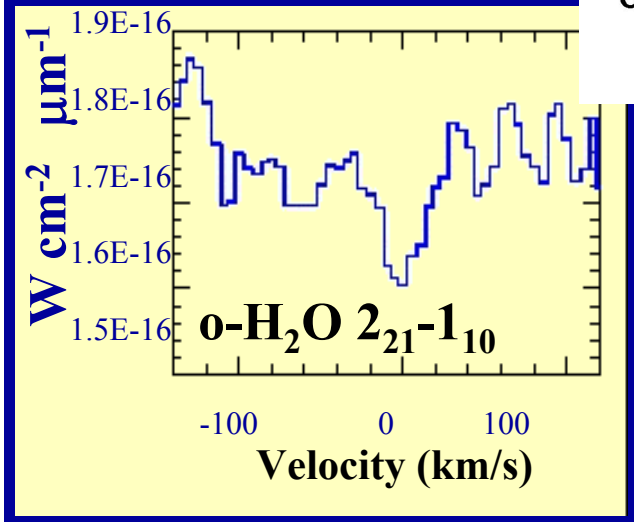
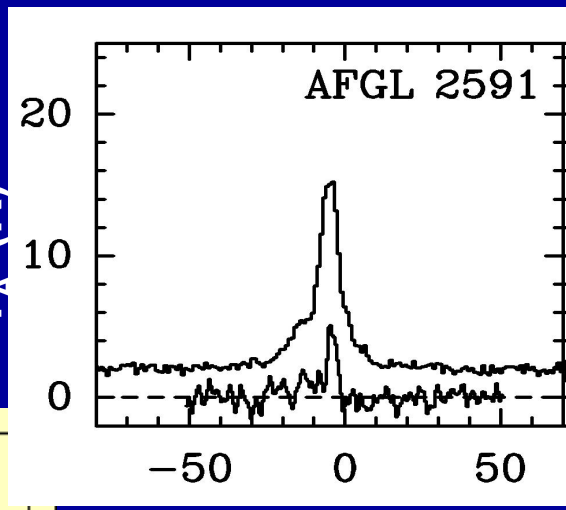


Water Lines Galore

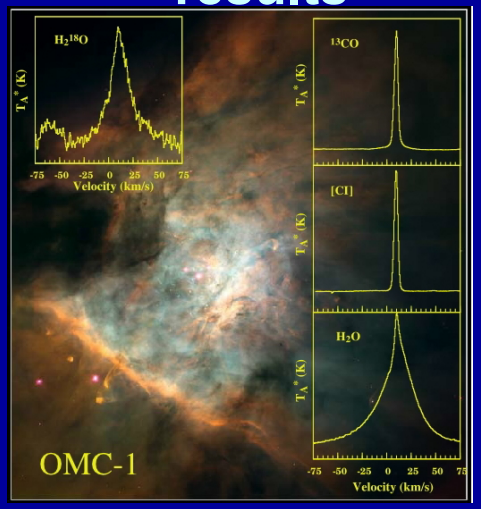


ISO- LWS: 108





SWAS results



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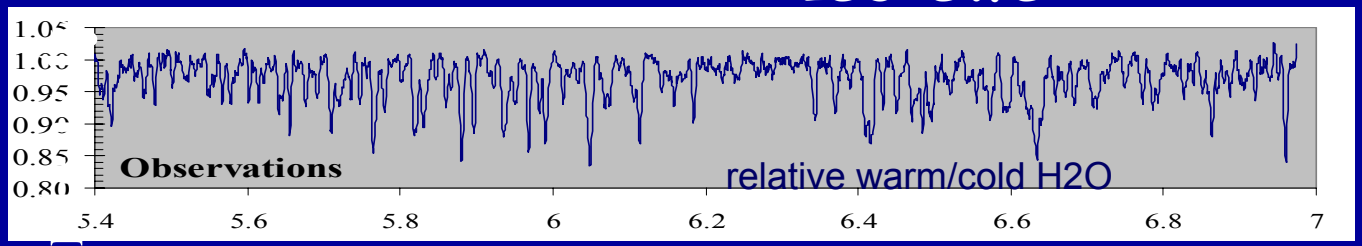
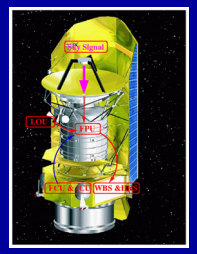
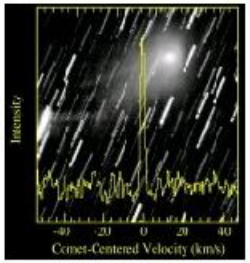


Wavelength (μm)

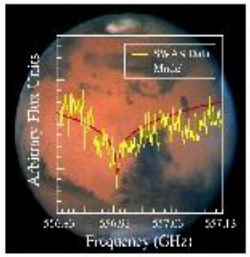
thijsdg@sron.rug.nl



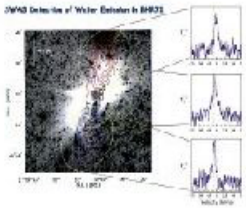
HIFI Science: Water in the Universe

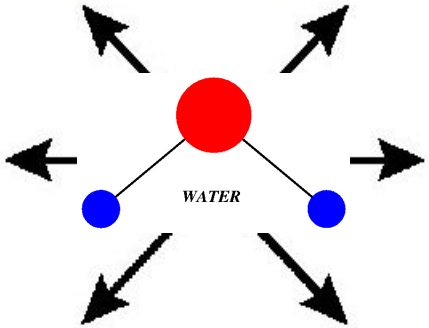


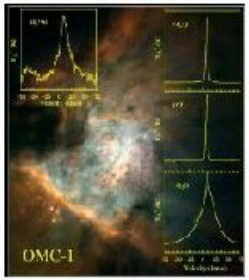
A SWAS spectrum of comet Lee



A SWAS spectrum of the planet Mars

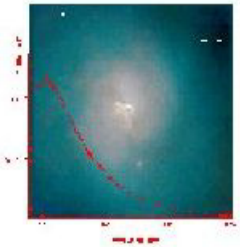




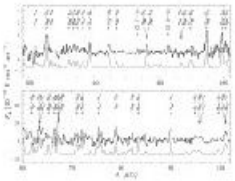


Spectra of BHR 71

The Orion Molecular Cloud



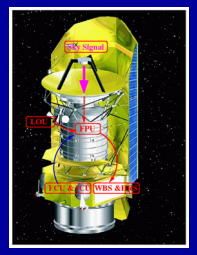
A spectrum of Arp 220



Water in an envelope around a mass–losing star.

As observations by ISO and SWAS have shown water is present all over the Galaxy. The high resolving power, high sensitivity and large frequency coverage of HIFI, combined with Herschel's small beam will extend our knowledge by orders of magnitude

thijsdg@sron.rug.nl

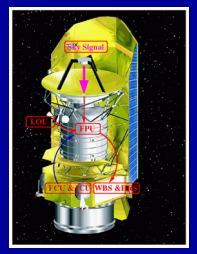


H_2O as chemical and physical probe with high spectral resolution

- H_2O abundance shows large variations in Star Forming regions: $<10^{-8}$ – $3.\ 10^{-4}$ => unique diagnostic for different physical regimes
- Traces basic processes of freeze-out onto grains and evaporation, which characterize different stages of evolution
  Dense cores --> YSO's --> disks --> comets
- H_2O's role in the thermal balance: when and where does H_2O become dominant heating or cooling agent?
- H_2O as a dynamical probe of high density gas: infall - outflow - quiescent gas – mixing – etc.
- H_2O and the Oxygen chemistry: Ion-molecule; high temperature; evaporation and freeze out; etc..
- HDO/H_2O: determined by gas-phase or grain-surface processes? Relation with comets?

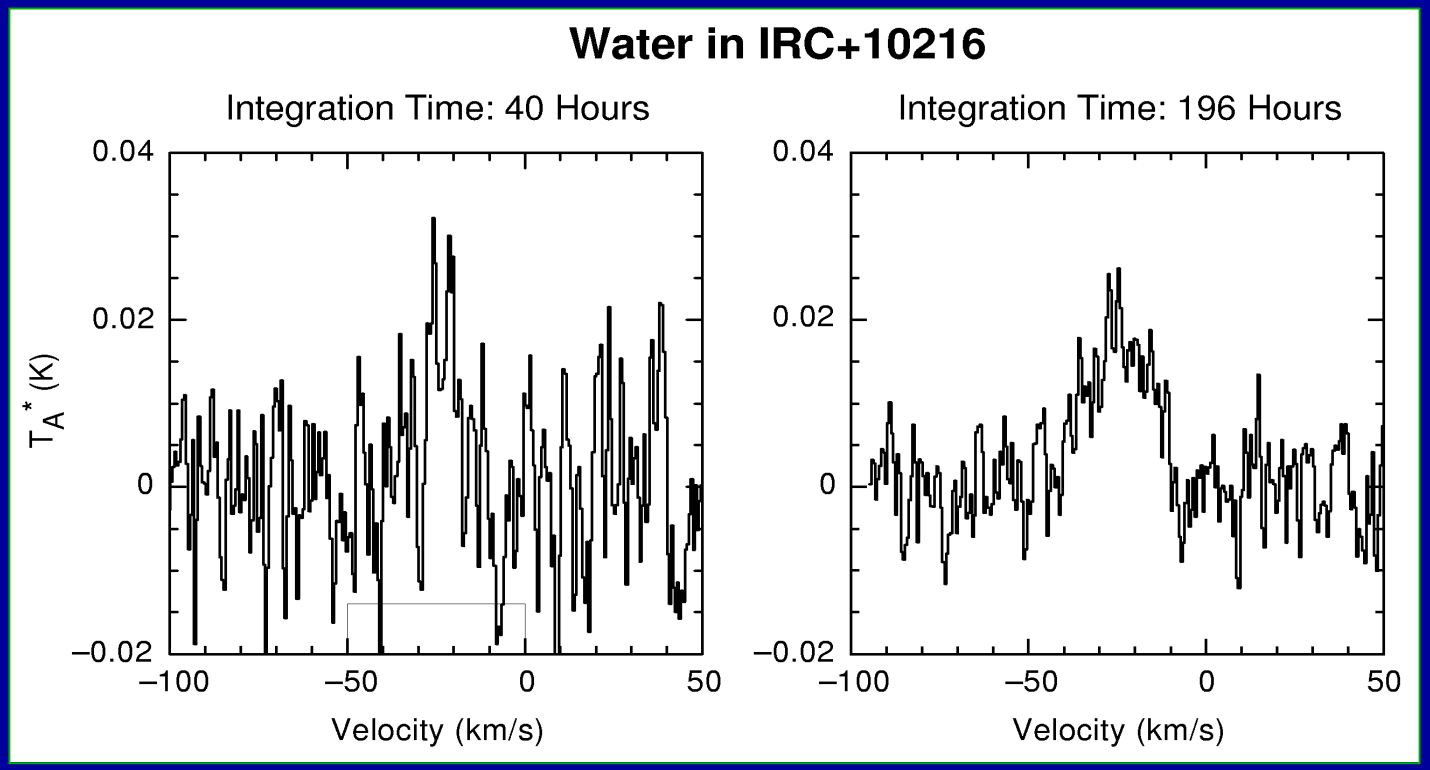
H_2O in the Universe: a legacy by HIFI

thijsdg@sron.rug.nl



SWAS detection of water vapor around the *carbon*-rich star IRC 10216 (Melnick et al.)

H2O abundance implied is ~ 10-6 Collection of orbiting icy bodies, as an analogue to the Solar System's Kuiper Belt, being vaporized by the large luminosity of the star. Required mass of water ice ~ ten Earth masses, comparable to the initial mass assumed for our Kuiper Belt. Models predict water abundance, H2O/H2, is ~ 10-12



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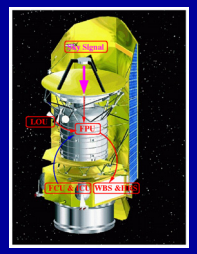

Implications of the SWAS results for HIFI Observations

- Water detection toward IRC+10216 argues for the presence of a planetary system around another star
- SWAS observations demonstrated the potential of high resolution molecular spectroscopy as a great tool to probe extra-solar planetary systems
- Herschel/HIFI is ~ 1000 times more sensitive than SWAS to emission from unresolved sources ➔ significant expansion of discovery space
- HIFI can detect many far-IR water lines: line ratios probe the spatial distribution of the water and provide a test of the comet vaporization hypothesis

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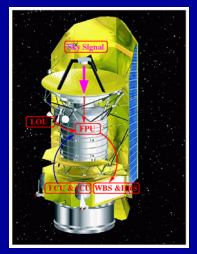

Observing with Herschel-HIFI

- dual beam switching (fast)
- position switching (slow)
- frequency switching

- on-the-fly mapping (with FS or LS)
- frequency survey (scan)

- chopper (wheel) type calibration
- asteroids as primary calibrators?

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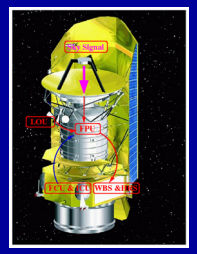

Observing with Herschel-HIFI Limitations

- One pixel and one frequency at a time (second mixer is there for redundancy)
  Future: Arrays of mixers/LO's and spectrometers
- Herschel Telescope diffraction limit 40"-12"
  Many different physical regions in one beam;
  Observing strategies and line selection helps to unravel;
  Pointing of telescope problematic for higher frequencies.
  Future: larger FIR Space Telescopes (arcsecs) and interferometers (subarcsecs)