Heterodyne Array Receivers for Space and Ground Based Applications

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DOI:
10.5281/zenodo.5549563

Publication date:
2021

Heterodyne Array Receivers for Space and Ground Based Applications

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Origins Team, HERO Team

Outline

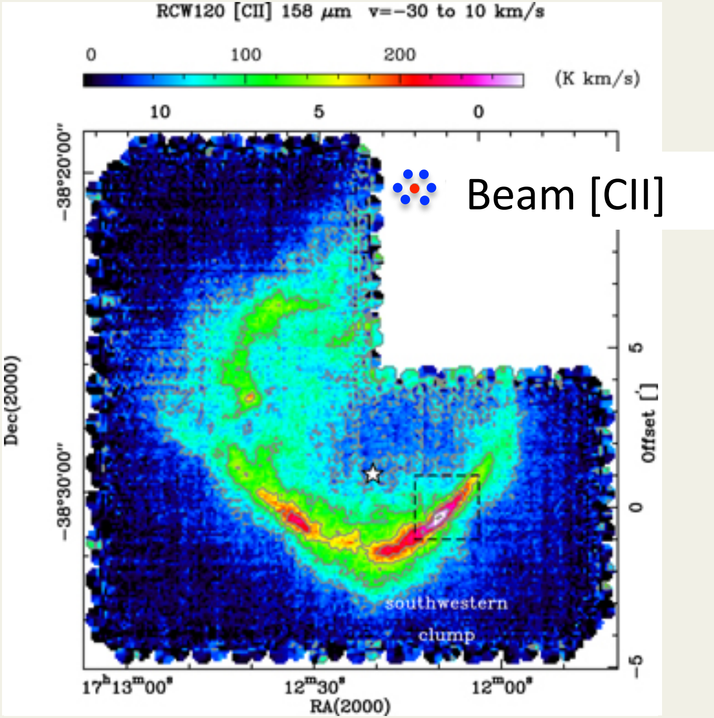
I. Motivation & Rx Requirements

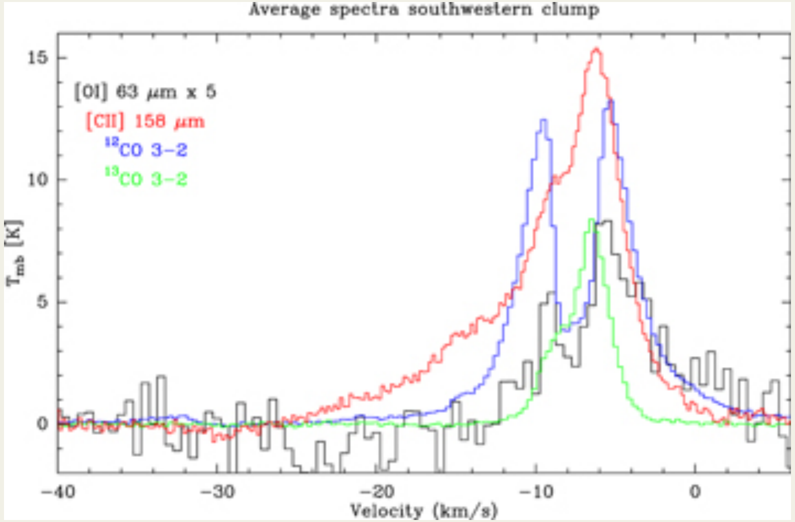
II. Previous Heterodyne Array Rx

III. HEterodyne Receiver for the Origins space telescope

IV. Conclusion

Motivation





Integrated [CII] map of the massive star RCW120 mapped with upGREAT/ SOFIA, Schneider et al. 2020

Requirements

- ALMA or space: small arrays
  - Efficient
  - Reliable
  - For space: low energy consumption, small vol and weight
- Single Dish (e.g. AtLAST, CCAT'): large arrays (100 to 1000 pixels)
  - Close packaging
  - Simplified structures for fabrication
  - Efficient readout

Previous Heterodyne Array Rx

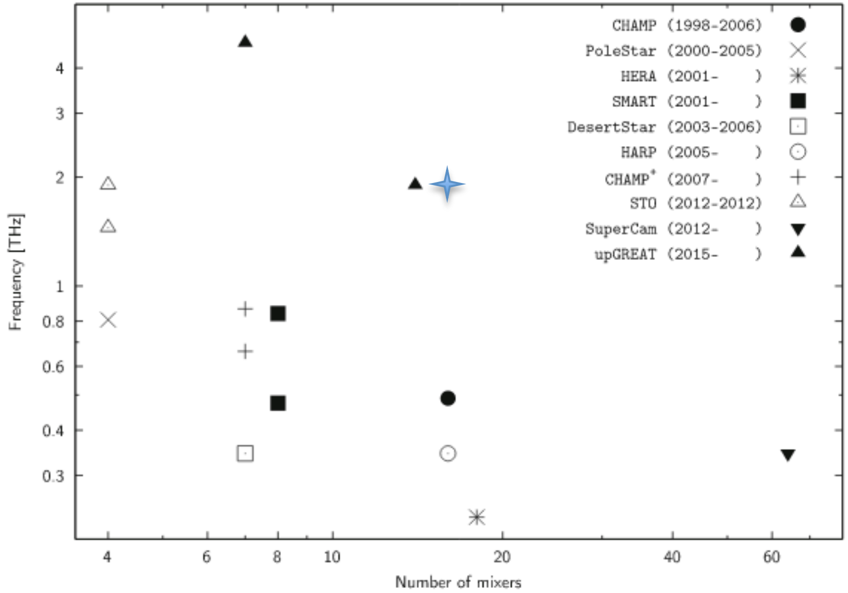


Fig. 2 Pixel count and operating frequency of heterodyne receivers above 200 GHz. The approximate period of activity is also given

Graf et al. 2015

Previous Heterodyne Array Rx

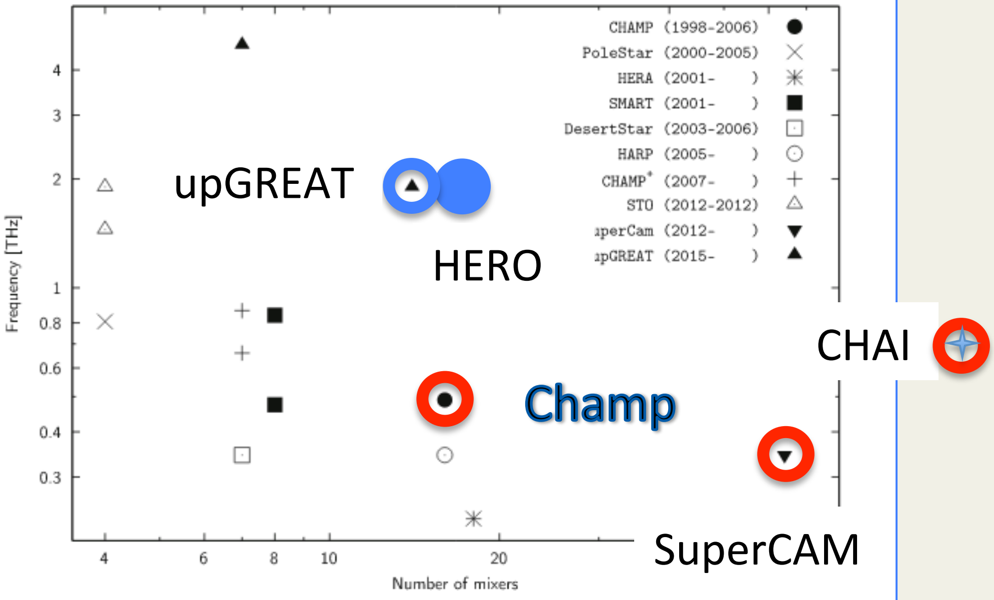


Fig. 2 Pixel count and operating frequency of heterodyne receivers above 200 GHz. The approximate period of activity is also given

Graf et al. 2015

Ground

- CHAMP 2x8 pixels , 490 GHz
- SuperCAM 64 pixels, 350 GHz
- CHAI 2x64 pixels, 490 et 810 GHz

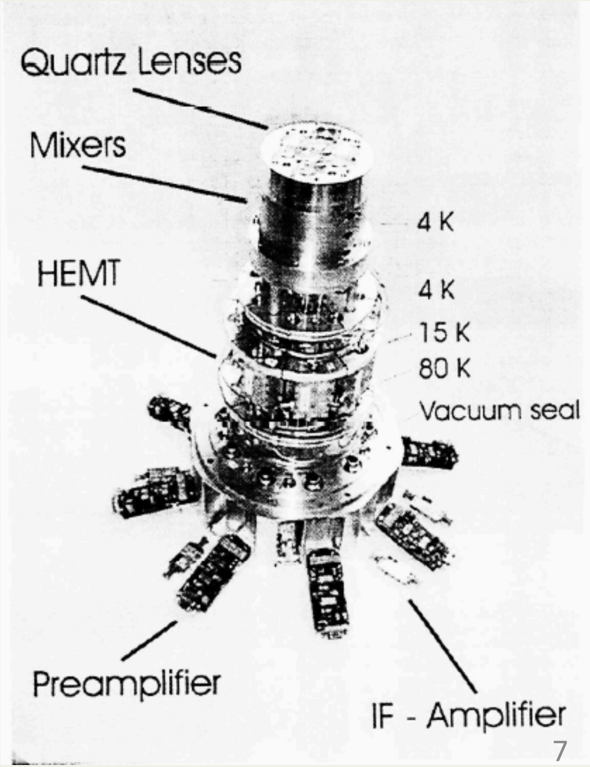
Space

- upGREAT 2x7 pixels , 2700 GHz
- HERO 2x2x9 pixel, 486 to 2700 GHz

CHAMP – 2x8 pixels

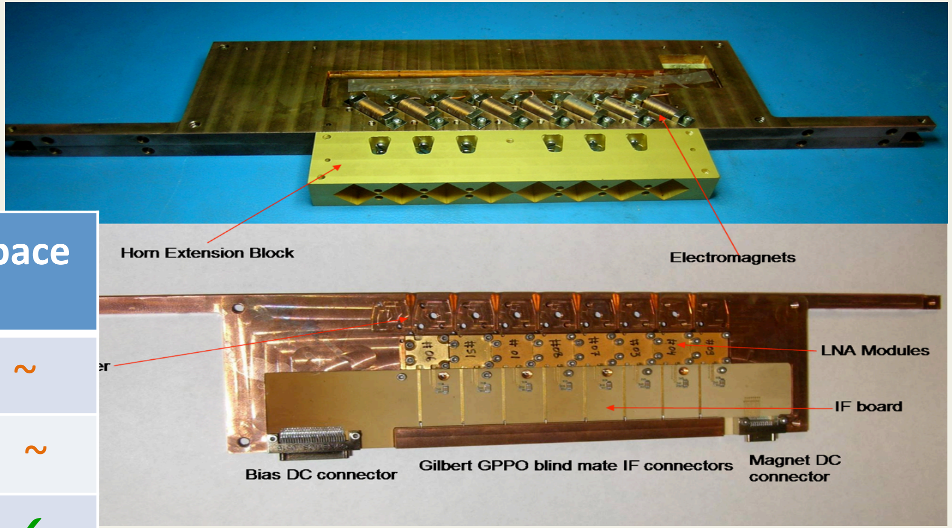
- 450 - 498 GHz, on CSO
- 1998 – 2005 (?)

Innovations:	**Large N**	**space**
Pixel Spacing 1.4	✓	✓
Martin-Puplett-Interferometer For LO and SSB	✗ ✗	~ ~
Cold Optics 15K	✗	✓
Derotation by turning cryostat	✗	✓



SuperCam - 64 pixels

- 320 – 360 GHz on HHT

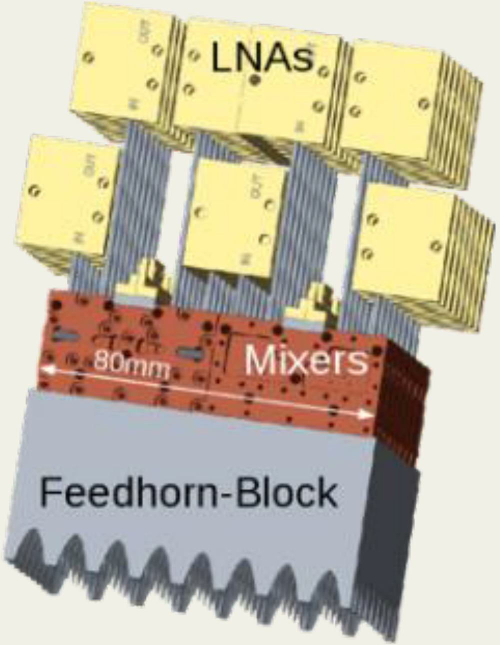


Innovations:	Large N	space
Monolythic block of several px	✓	~
LO divided in wave guide	✗	~
LO superposition by Mylar	✗	✓
DFTS	~	✗

CHAI – 2 x 64 pixels

- 455-495 GHz & 800-820 GHz
- CCAT'

Innovations:	Large N	space
Balanced SIS	✓	✓
LO distribution by wave guide	✗	✓
Modular mixer blocks	✓	~
LNA separated from mixers	✓	✓
Miniaturization of bias circuit	✓	✓



CHAI – 2 x 64 pixels

- 455-495 GHz & 800-820 GHz
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Talk by Netty Honingh

Innovations:		
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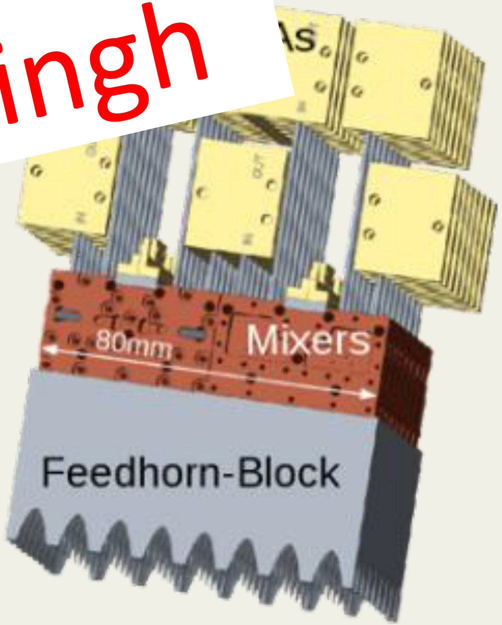
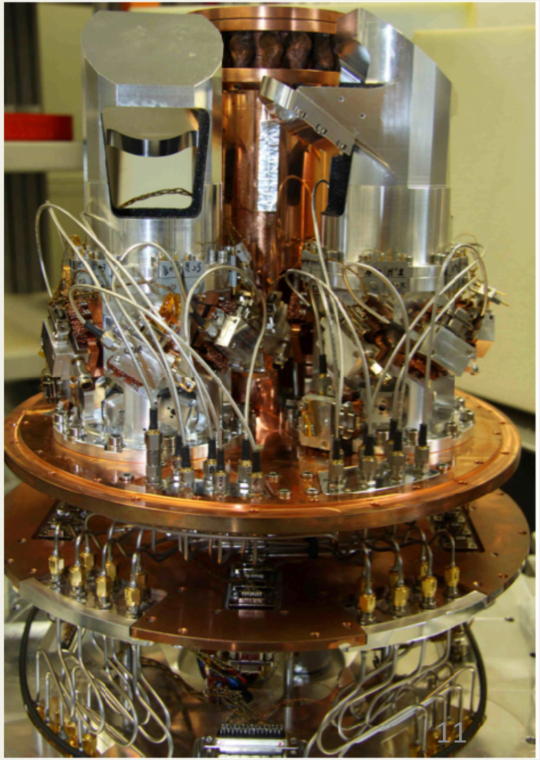
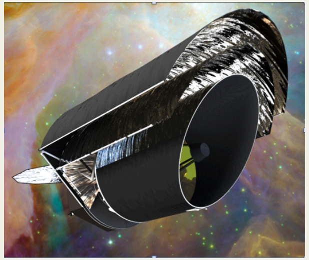


upGREAT – 2 x 7 pixels

- 1830 - 2070GHz (/2500GHz)
- SOFIA

Inovations:	Large N	space
THz	✗	✓
Wideband RF (12% - 32%)	✓	✓
airborne	~	✓





Origins Space Telescope

Wavelength coverage: 2.8-588 µm

Telescope: 5.9 m (4'' @ 100 µm) →

25 m^2 (=JWST area)

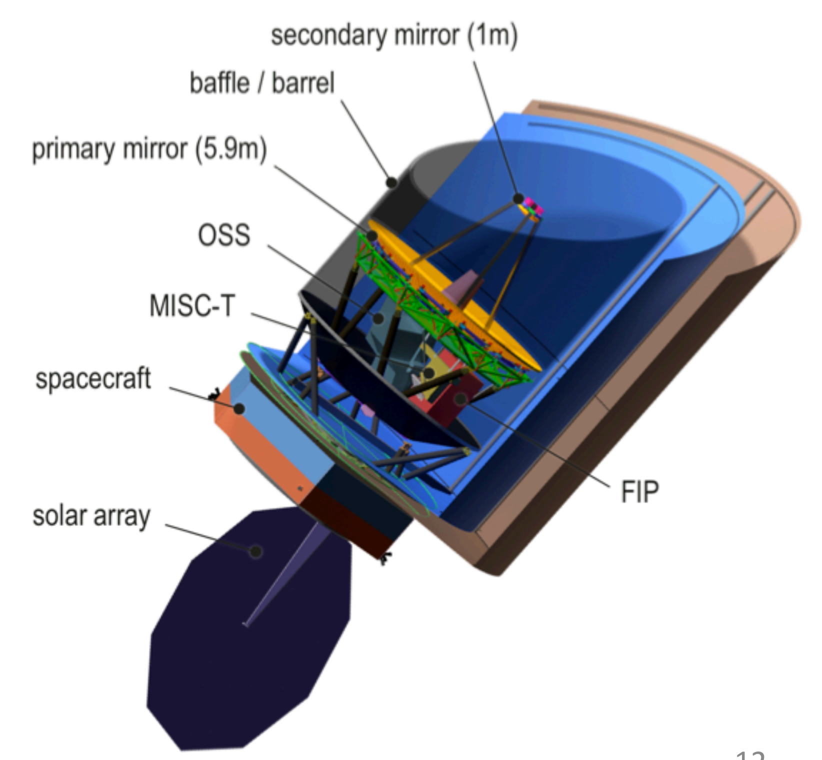
diffraction-limit: 30 µm

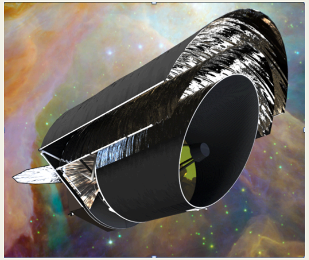
temperature: 4.5 K, cryocoolers

Agile Observatory for surveys: 60" per second

Mission: 10 year propellant, serviceable

Orbit: Sun-Earth L2





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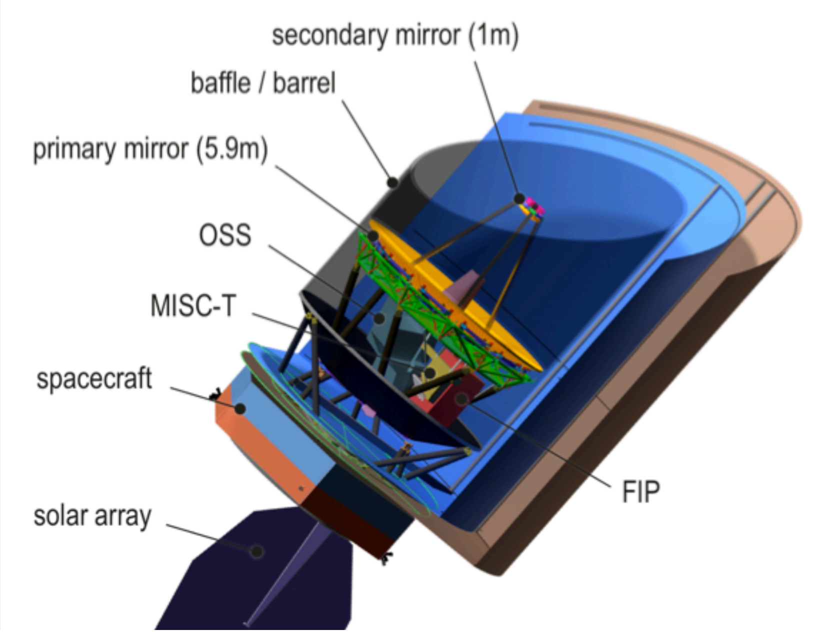
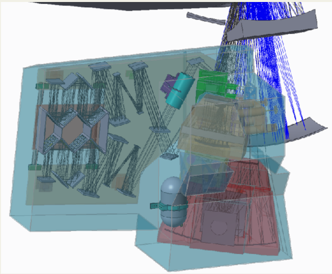


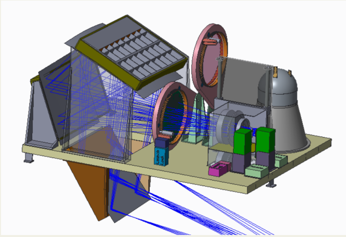
Origins is 1 of 4 mission concept studies
Submitted to Astro2020 Decadal Review

![ORIGINS Space Telescope]

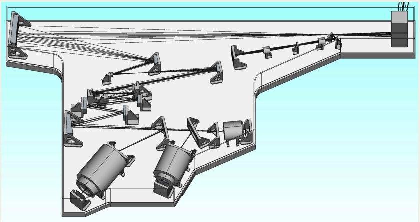
Five Instruments

OSS: Origins Survey Spectrometer
- -25-588 µm R~300, survey mapping
- -25-588 µm R~43,000, spectral surveys
- -100-200 µm R~325,000, kinematics





MISC-T: Mid-Infrared Spectrometer Camera Transit
- -Ultra-Stable Transit Spectroscopy
- -2.8-20 µm R~50-295



FIP: Far-infrared Imager Polarimeter
- - 50 or 250 µm, Large area survey mapping
  (inst. field 3'.6 x 2'.5, 13'.5 x 9')
- - 50 or 250 µm, polarimetry

5 Instruments

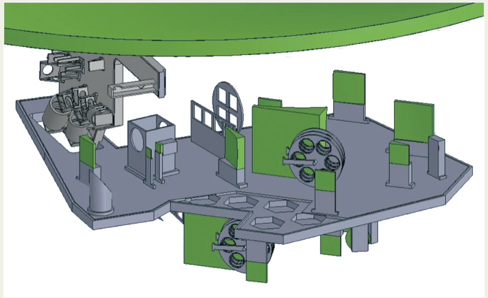
HERO: HEterodyne Receiver for Orgins

111 to 617 μm,

R up to 10

3 x 3 arrays

dual-polarization, dual-frequency

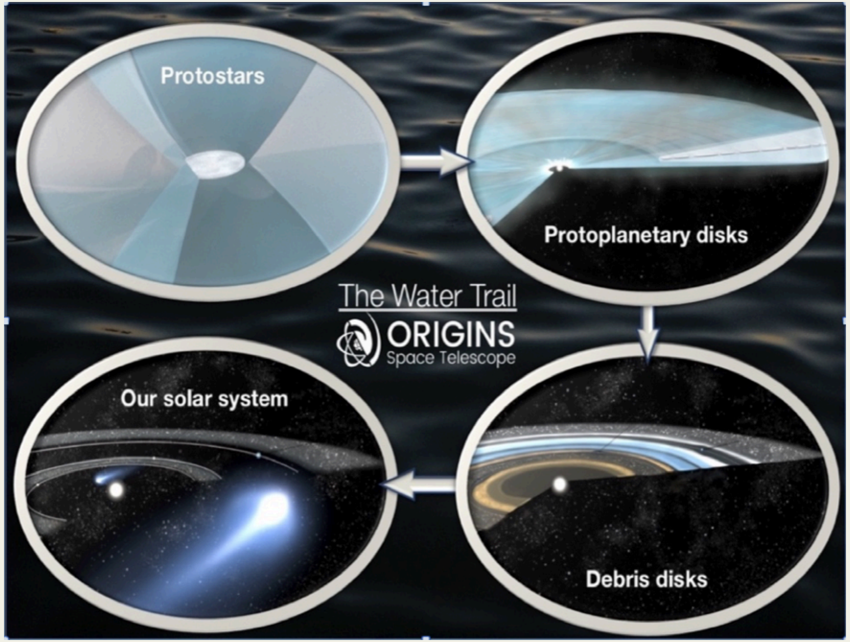


MISC-T: Mid-Infrared Wide Field Imager

- 3x3 arcmin
- 5-28 μm R~5-300

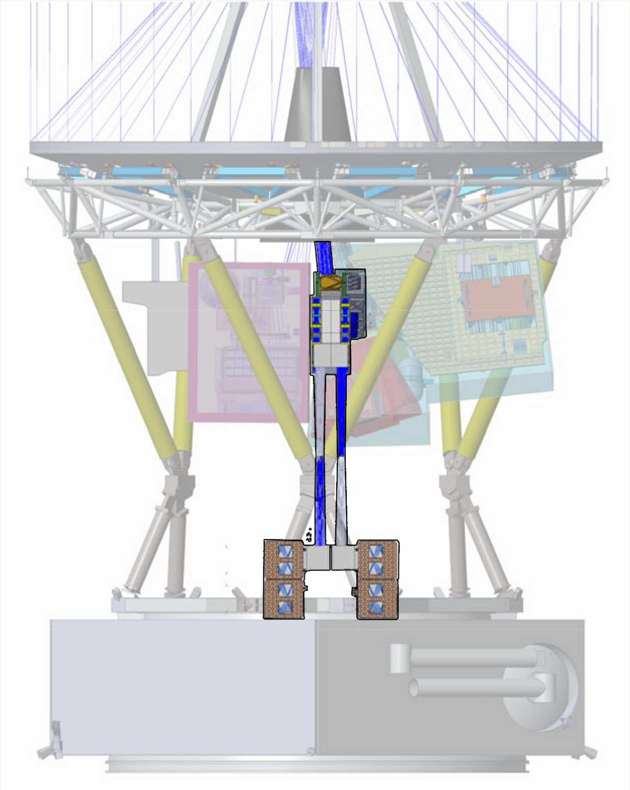
Science case for HERO

Trail of water during planet formation



- Water's birth in starless cores
- Supply to disk around protostars
- Early planet formation in protoplanetary disks

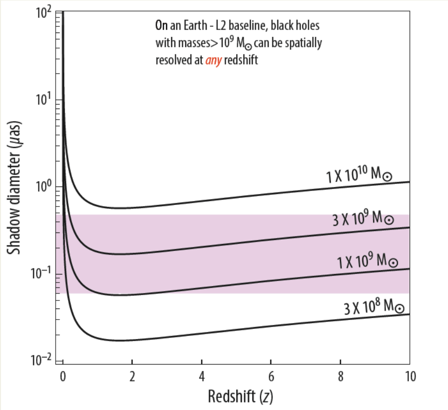
HERO - HEterodyne Receiver for Origins

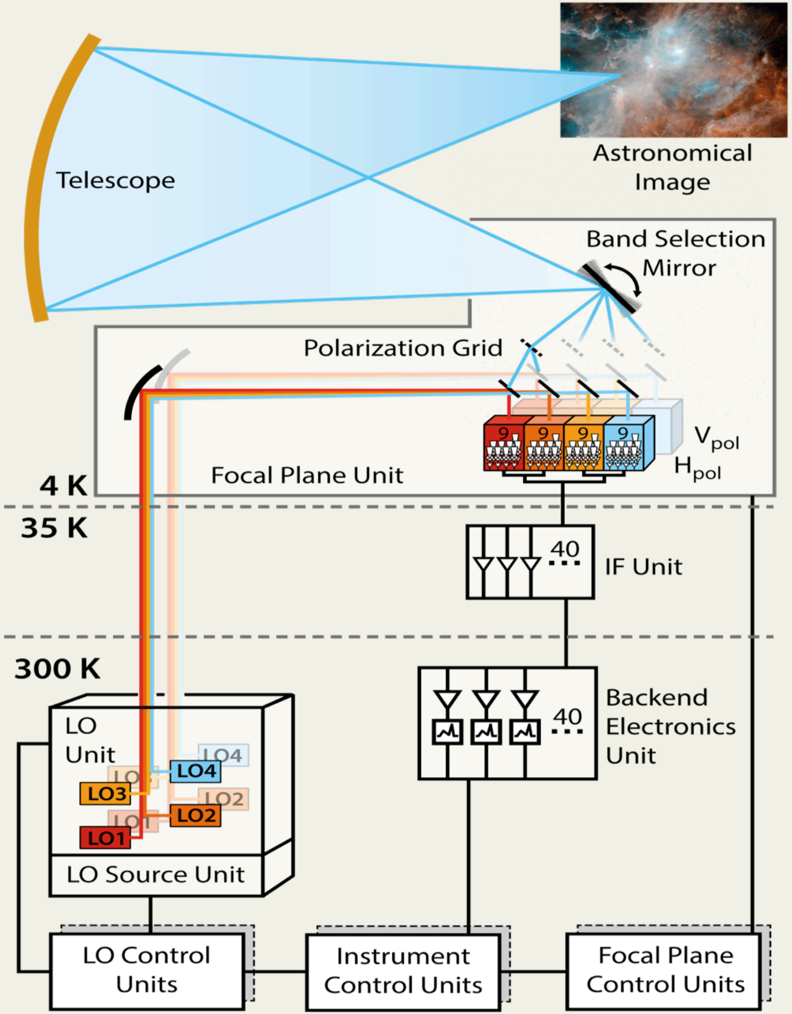


- European led study
- 111- 617 µm (486-2700 GHz)
- up to $R \sim 10^7$, Spectral imaging
- 9 pixel x 2 pol. x dual band

  total 36 times 6 GHz instantaneously

Possible extension:
EHT : Earth – L2
@ 85, 230, 345 and 690 GHz
→ 10^6 BH shadows
→ Resolving photon ring





First Heterodyne Array Receiver for Space

	Component	**HERO**
LO	**Multiplied LO Technology**	Cascaded Multipl. + On-chip. Power Combining +. 3D integ.
	DC power/pixel	2 W
	Fractional Bandwidth	45 %
Mixer + HEMT	**Mixer Technology**	SIS, HEB
	LNA Technology	Low-power SiGe HEMT
	DC power/pixel	0.5 mW
	Mixer. Assembly	Waveguide
Back end	**IF Processing**	GaAs HEMT ampl
	Spectrometer Tech.	CMOS based SoC
	DC Power/pixel	2W
	IF Bandwidth	8 GHz
Total DC power per pixel		4 W

HERO - Mixers

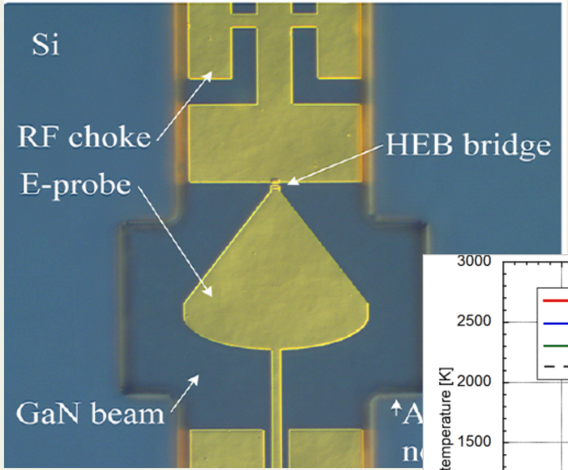
- Waveguide
- OMT
- balanced
- DSB, one 2SB

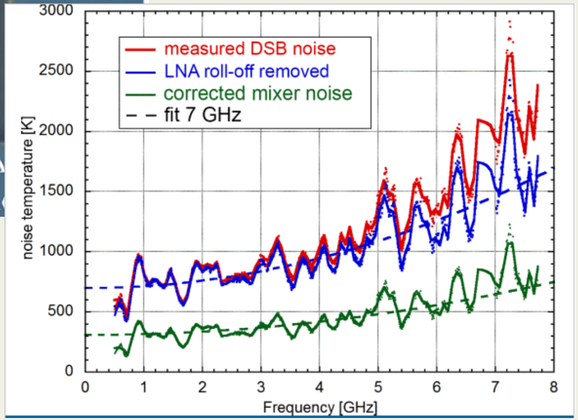
(3x3) array x 2 polarizations x 2 bands

Footprint of 10 x 10 mm^2 SIS

5 x 5 mm^2 HEB

On sky: 2FWHM spacing



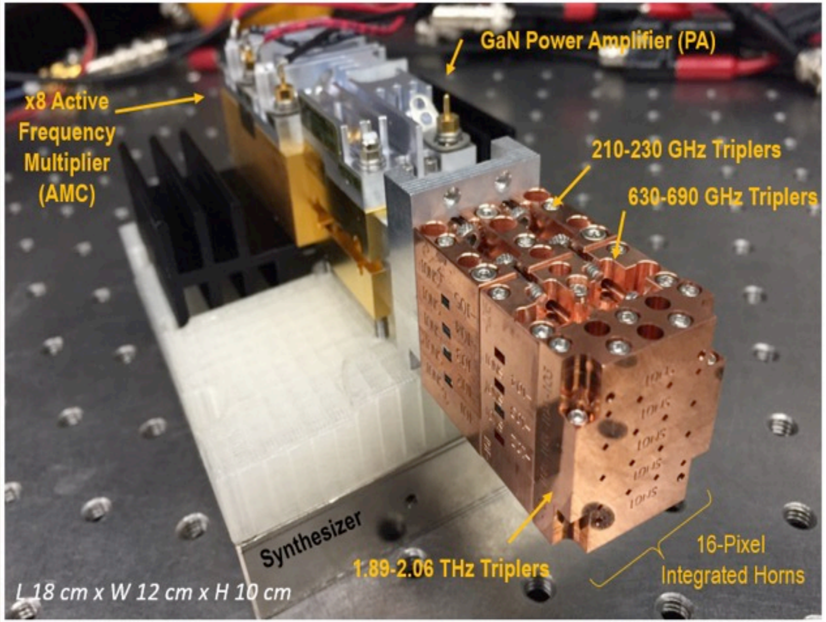


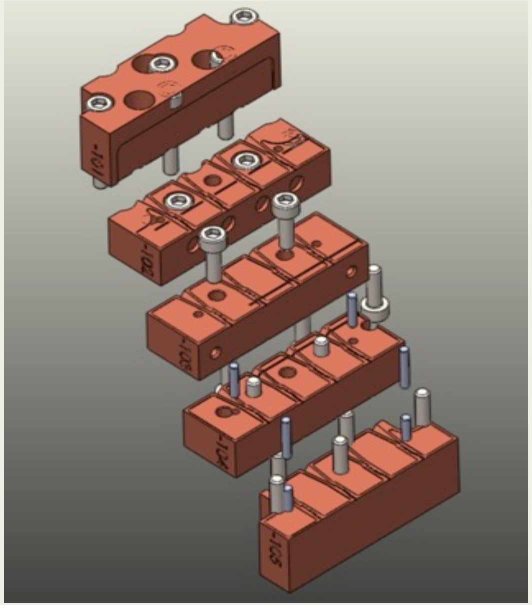
Wideband HEB, Krause, Belitsky et al.

Local Oscillators

- Wideband:
  - E.g. VDI
    - 1100 -1700 GHz → 42%
    - 1400 -2200 GHz →44%

16-pixel 1.9 THz Lo system: STACKING





X3X3X3
Architecture

The LO module can be mounted with either two or four 1x4 pixel layers vertically stacked to form 8-pixels or 16-pixel configurations..

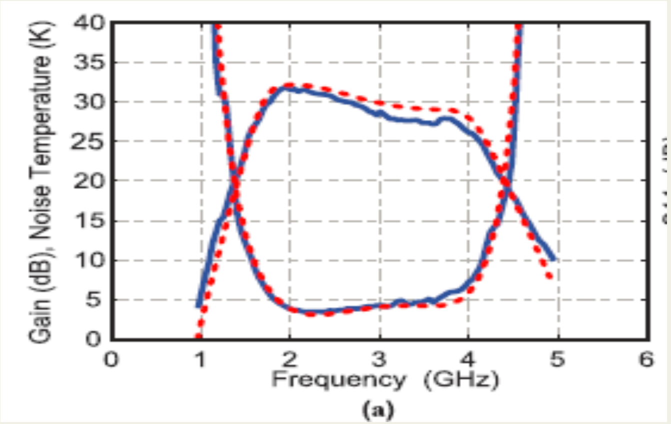
Power Consumption= 2.3 Watts/pixel or
1.25 Watts/pixel using W-band CMOS synthesizers

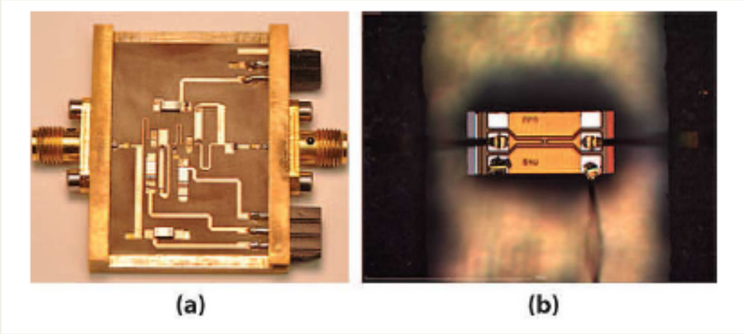
SiGe Amplifiers – Innovative technology

IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 64, NO. 1, JANUARY 2016

Ultra-Low-Power Cryogenic SiGe Low-Noise Amplifiers: Theory and Demonstration

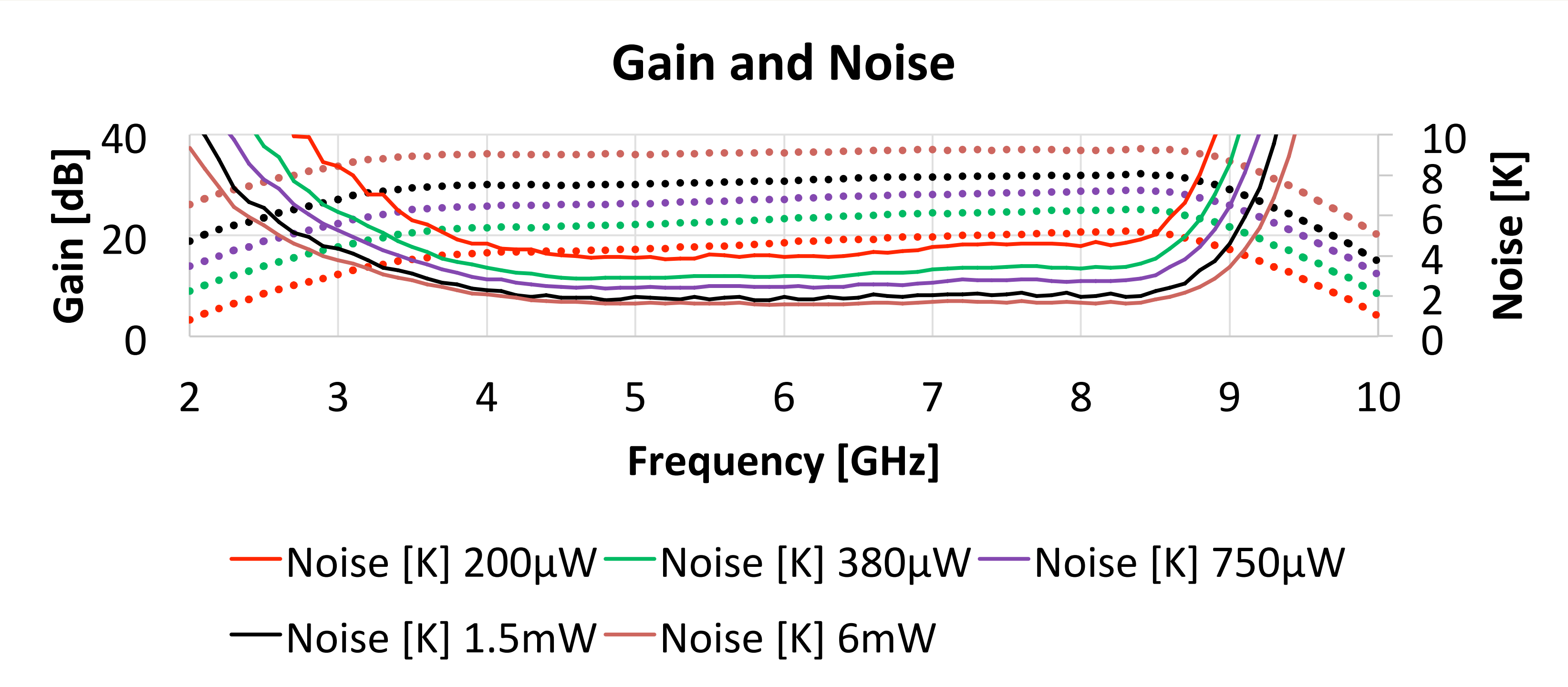
Shirin Montazeri, *Student Member, IEEE*, Wei-Ting Wong, *Student Member, IEEE*,
Ahmet H. Coskun, *Student Member, IEEE*, and Joseph C. Bardin, *Member, IEEE*





Band= 1.8-3.6 GHz
Pdis= 0.3 mW
IBM BiCMOS8HP

InP Amplifiers

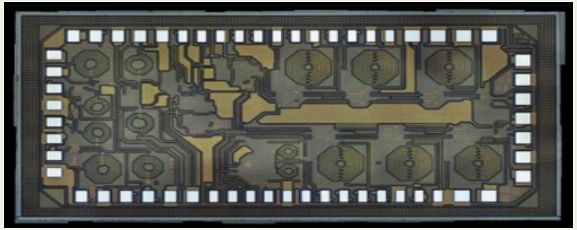


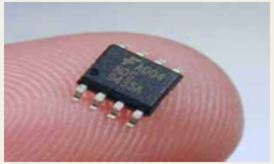
Data by J. Schleeh, Low Noise Factory.

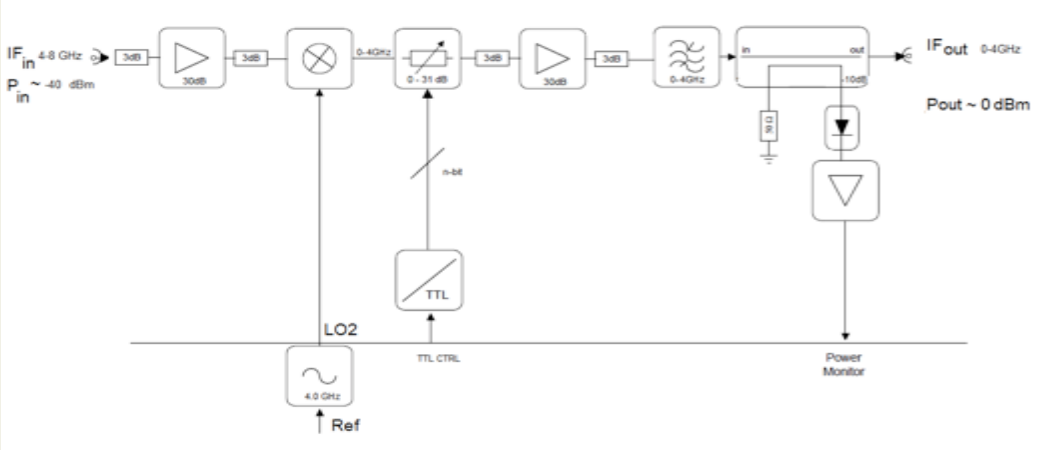
Warm IF chain

For many channels WIFC using IC instead of individual components

– built on one Complementary Metal-Oxide Semiconductor (CMOS) chip that is approximately 1.5mm x 1.5mm in size.



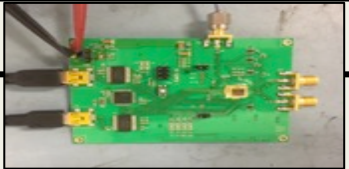


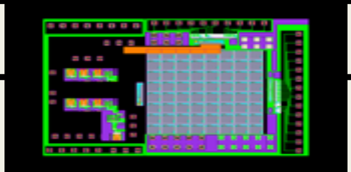


Slide by R. Plume

Existing Spectrometer Comparison

Design Parameter	Demonstrated CMOS Spectrometer System Spectrochip SVII Spectrometer (UCLA/JPL) 2017 [3]	Spectrochip SVIII Spectrometer (UCLA/JPL) Available Late 2018
Processor Bandwidth (MHz)	3000	6000
Channel Count (#)	4096	8192
FFT Window Type	Hanning	PFB
FFT Format	Real	Real
Bit Resolution (#)	3	3
Power (W)	1.75 W	1.65 W
Size (cm^3)	10x8x2 cm	6x8x2 cm
Packaging Technique	Ribbon-Bond	Flip Chip
Weight (Kg)	0.12 Kg	0.12 Kg
Core Technology	65nm CMOS	28nm HPC CMOS





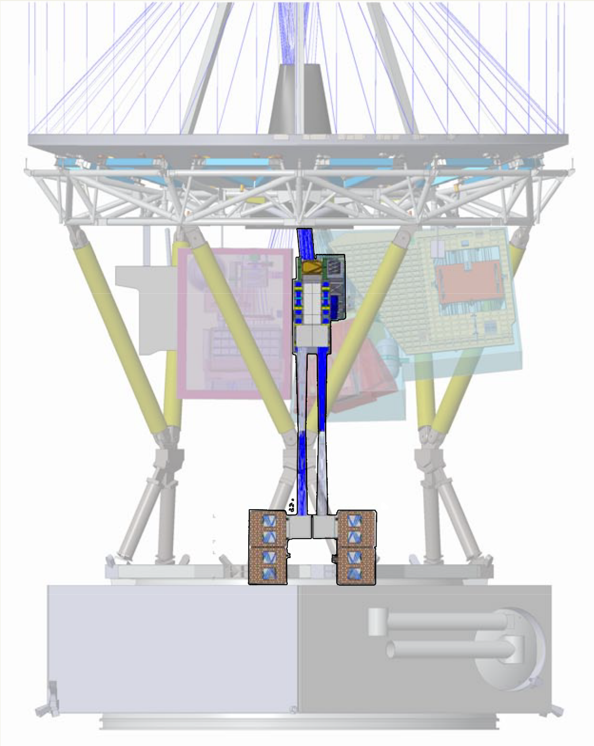
Adrian Tang (UCLA, JPL)

e.g. Tang, A et al. 2021, "*Sub-Orbital Flight Demon-stration of a 183 / 540-600 GHz Hybrid CMOS-InP and CMOS-Schottky-MEMS Limb-Sounder*",

IEEE MW. 1, 2, 560

HERO

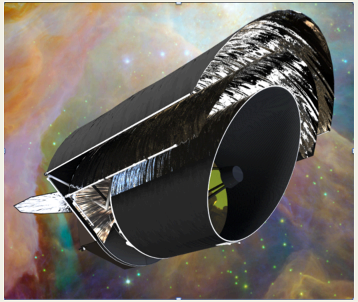
Innovations:	Large N	space
Wide RF (> 40%)	✓	✓
Low power LO (< 2W/ pixel)	✓	✓
LO and sky superposed by pol. Grid + OMT	✗	✓
Superposition of LO bands	✗	✓
LNA < 1 mW	✓	✓
Integrated IF circuit	✓	✓
Low Power Spectrometer	✓	✓



Conclusion

For space applications:

- Heterodyne array receivers become feasible
- Biggest challenge cooling and power consumption
- TRL needs to be increased

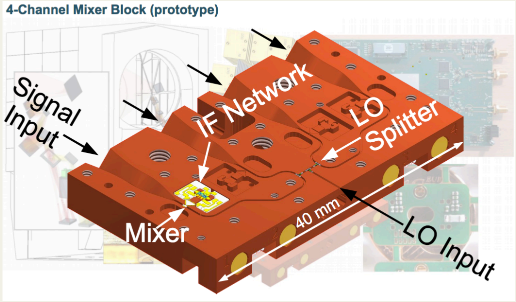


Origins

On the ground:

Large arrays (100 to 1000 pixels)

- # pixels increases
- Miniturization and simplifications take place (e.g. CHAI)
- Further simplification in fabrication desirable



Chai

Backup Slides

TRL of HERO

Subsystem Description	TRL	Heritage	Comments
Multiplied LO, f <2THz	5	HERSCHEL, MIRO, STO-2, SOFIA, JUICE(SWI)	CMOS synthesizer for reduced power; higher output power for N>4; compact assembly
Multiplied LO, f>2 THz	4	HERSCHEL, STO-2, SOFIA	Higher power handling capability for lower stages; higher output power; CMOS synth; GaN amps
HEB mixers	4	HERSCHEL, SOFIA, STO-2	Compact arrays; efficient IF extraction; balanced designs
SIS mixers	5	HERSCHEL	Compact arrays with efficient IF extraction
IF LNAs	4	HERSCHEL	InP technology mature; need to advance SiGe technology with lower DC power
Backend	4	STO-2, SOFIA	FPGA systems are mature, however, need ASIC based solutions for large arrays
Calibration	8	HERSCHEL, SOFIA, STO-2	
Bias electronics	5	HERSCHEL	Low power electronics, 5 if multiplexing is needed
Optical	8	HERSCHEL	
ICU	7	Herschel	
Tip/Tilt mechanis	8	Herschel (one axis)	

Need TRL 5 by 2025 → Heterodyne Developement Roadmap

HERO fact sheet

Col.	2	3	4	5	6	7	8	9	10	11	12	13
Band	νmin	νmax	λmax	λmin	Max Δλ/λ	IF BW2	Mixer	# pixels	Line	Trx	T_{rms} (mK)	Line flux per time
	(GHz)	(GHz)	(μm)	(μm)		km/s	Type	HERO		K (DSB)	in 1h at λ/Δλ =10^6	W m^{-2} $s^{0.5}$, 9m, 5σ
1	486	756	617	397	10^7	3865	SIS	2x9	**H_20, $H_2{}^{18}0$,** HDO NH_3	50	2.6	6.4 E-21
2	756	1188	397	252	10^7	2469	SIS	2x9	**H_20, $H_2{}^{18}0$** H_3O^+	100	4.2	1.6 E-20
3	1188	1782	252	168	10^7	1616	HEB	2x9	**H_20, $H_2{}^{18}0$** H_3O^+, NH_3, N^+	200	6.8	4.0 E-20
4	1782	2700	168	111	10^7	1071	HEB	2x9	**HD**, C^+	300	8.4	7.3 E-20

Molecular line observations required for water trail theme

12 Receiver noise for 1h integration at 10^6 resolution (0.3 km/s) using one polarization.

13 Detectable point source line flux at 5 sigma, for 1h pointed integration (on+off source) in two polarization, with a 5.9 m primary mirror (coll area $25m^2$, app eff 0.8) as designed for OST Concept 2.