HEterodyne Receivers for OST (HERO)

HERO team, STDT team, NASA engineering team

Presented by M.C. Wiedner

Context

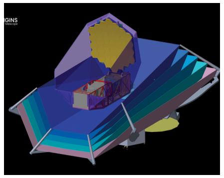
NASA HQ selected 4 Large Mission Concept Studies to be submitted to Decadal Survey.
One will be selected for launch ~ 2035:

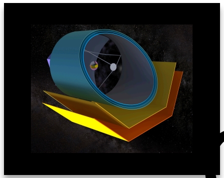
LUVOIR
Large UV/Optical/IR surveyor

LYNX
X-Ray surveyor

HABEX
Habitable Exoplanet Imaging Mission

OST (Origins Space Telescope)
FarIR surveyor



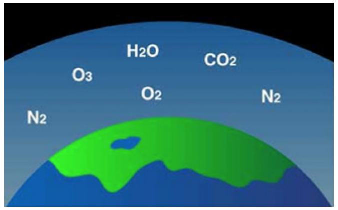


OST Science Program

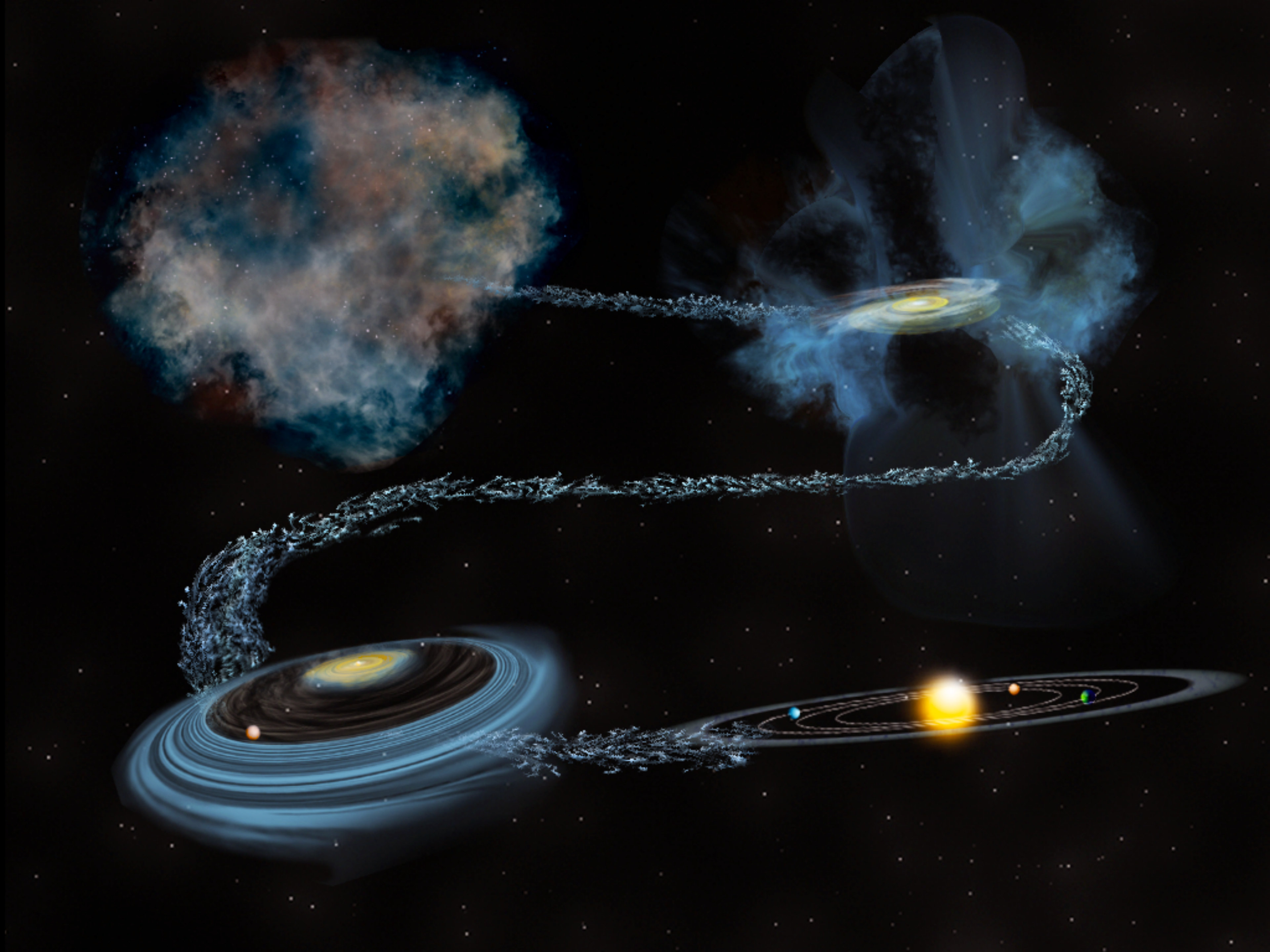
OST is a mid- and far-IR observatory whose design is driven by community-prioritized science to answer three questions:

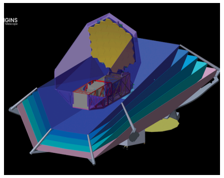
1. How do galaxies form stars, grow their central supermassive black holes, and make heavy elements over time?
   - ➢ Probe the universe deeply in key diagnostic spectral lines without the adverse effect of dust extinction

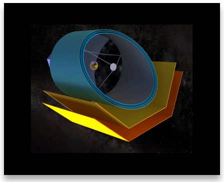
2. How do the conditions for habitability develop during the process of planet formation?
   - ➢ Follow the trail of water (vapor and ice) from the interstellar medium to nascent planets



3. How common are life-bearing planets orbiting M dwarf stars?
   - ➢ Biosignatures in the mid-infrared







Science Traceability Matrix

NASA Astrophysics Theme	OST Science Goal/Question	Science Objectives	Science Requirements		Instrument Requirements			
			Science Observable	Measurement Requirement	Parameter	Technical Requirement	Instrument(s)	Projected Performance
How did we get here?	How do the conditions for habitability develop during the process of planet formation?	Measure the water content in all evolutionary stages and across the stellar mass range A to B, tracing water vapor and ice at all temperatures between 10 and 10,000 K down to fundamental chemical limits at the 99% confidence level (to what does the confidence level refer?)	Measure water (H2O) content of 9 starless cores in diverse environments to a maximum distance of 1 kpc.	Strengths of the ground state water tranitions, ortho H2O 538 um and para H2O 269 um, to 1 sigma sensitivity limit 1x10-21 W m-2 (2 mK) per velocity channel, and with 0.2 km s-1 velocity resolution to obtain spectrally resolved line profiles. Line intensity maps of 9 known starless cores obtained in 90 hours with spatial resolution better than 0.1 pc.	Wavelength range	269 μm and 538 μm	Heterodyne spectroscopy with HERO	111-617 um
					Angular resolution	20 arcsec		22 arcsec at 538 um
					Spectral line sensitivity	1×10^{-21} W m^{-2} per velocity channel (2 mK), 1 σ		4x10-21 W m-2 per velocity channel at 480 um
					Spectral Resolving Power	1.5×10^{6}		10^7
					Field of View	1' x 1'		2.1'x2.1'
					Field of Regard	|b| < 30 deg		all sky

Instrument Requirements:

λ: 268 and 538 μm

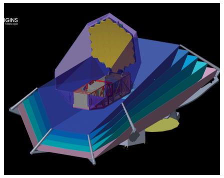
Spatial Res: 20”

Line Sensitivity: 10-21 Wm^{-2} (2mK)

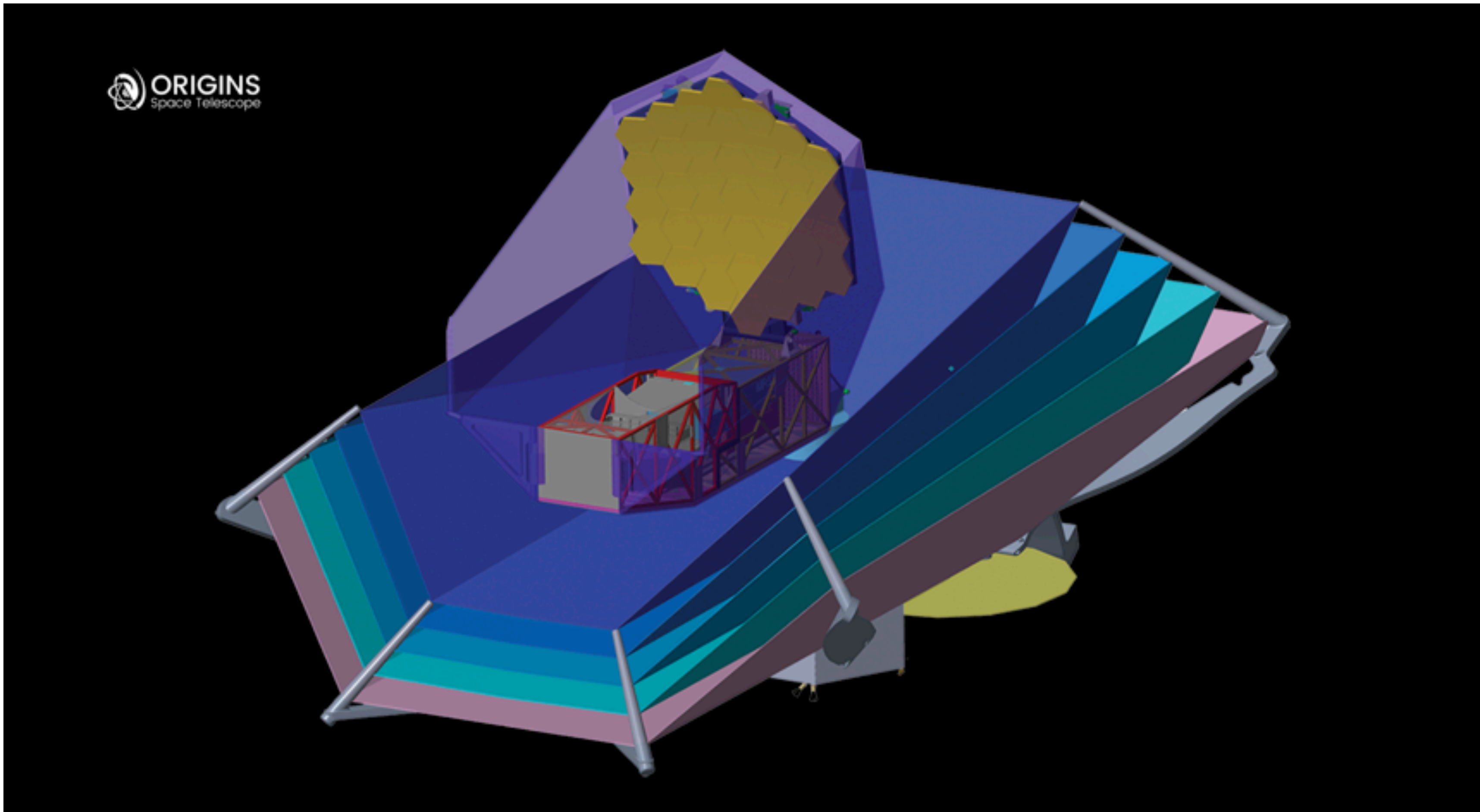
Spectral Res: 1.5×10^{6}

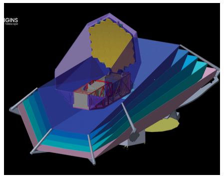
Field of View: 1’ x 1’

Field of Regard: |b| < 30 deg

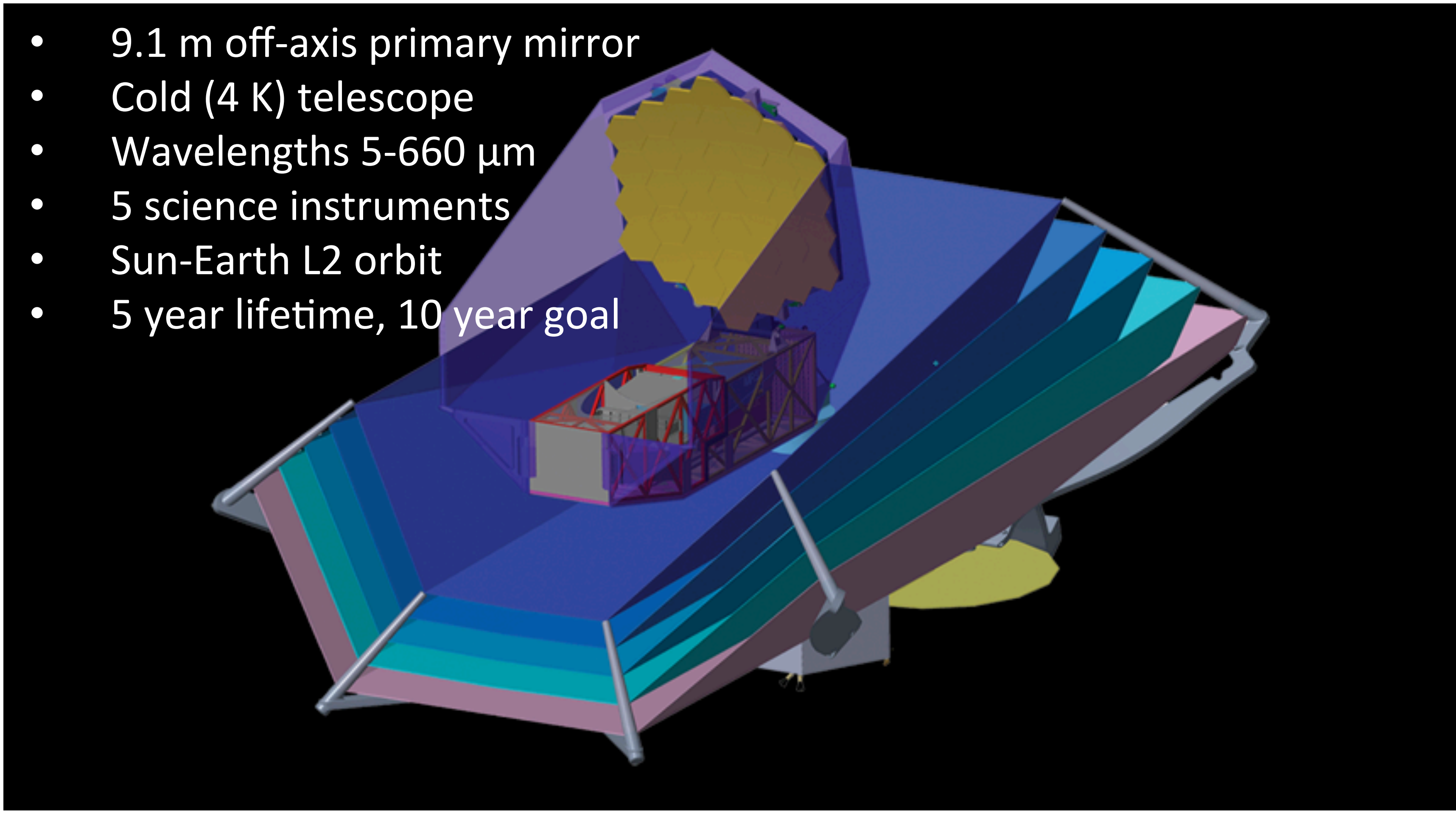


OST concept 1



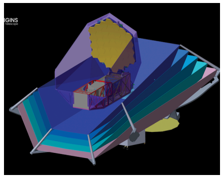


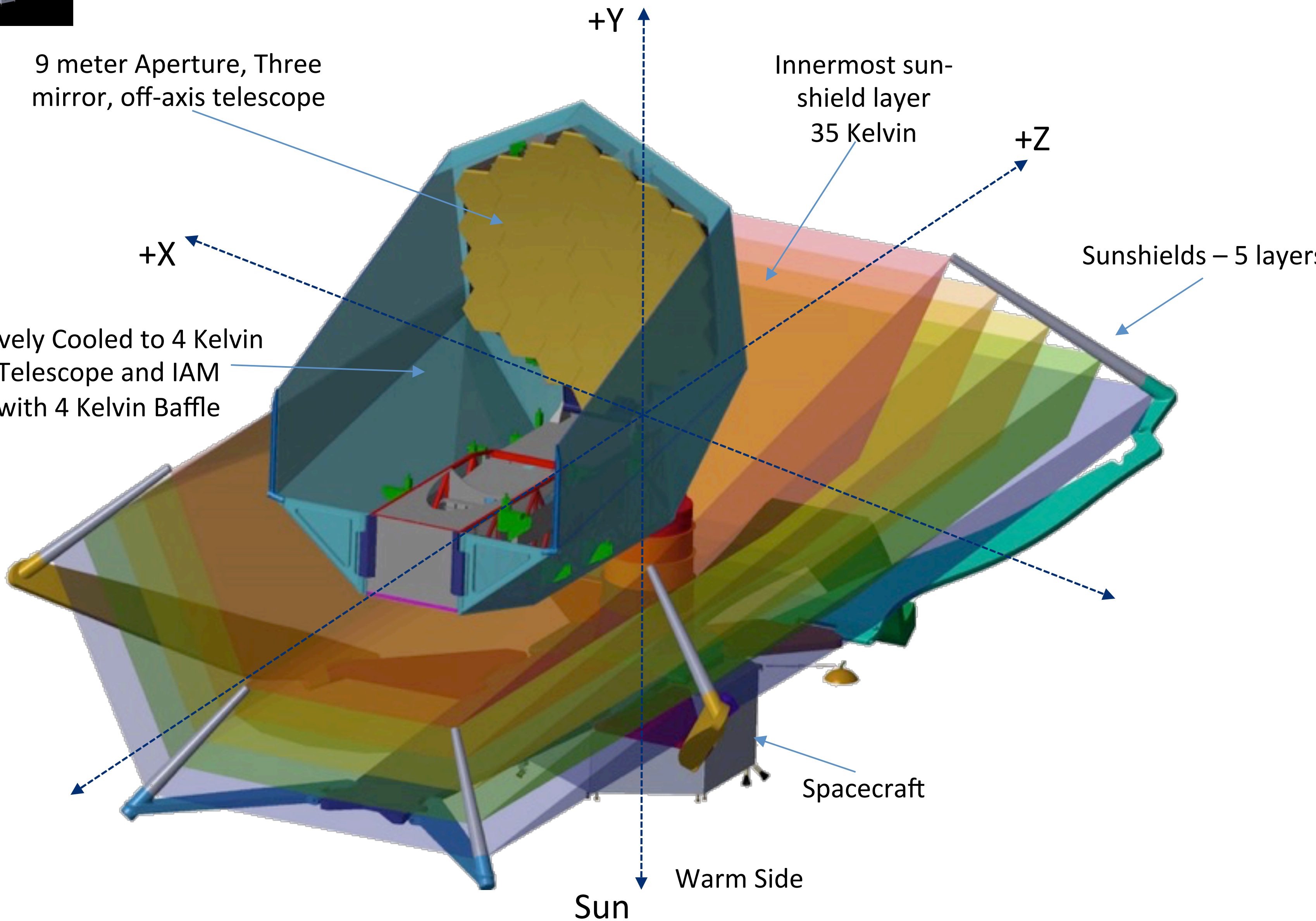
OST concept 1

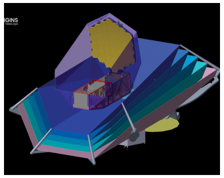


- 9.1 m off-axis primary mirror
- Cold (4 K) telescope
- Wavelengths 5-660 μm
- 5 science instruments
- Sun-Earth L2 orbit
- 5 year lifetime, 10 year goal

Concept 1 OST Observatory

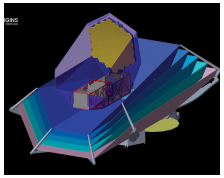






Instruments, Concept 1

		Wavelength (μm)	Observing Modes
MISC	Mid-Infrared Imager, Spectrometer, Coronagraph	5-38	• Imaging, spectroscopy • Coronagraphy (10^{-6} contrast) • Transit Spectrometer < 10 ppm stability)
MRSS	Medium Resolution Survey Spectrometer - IFU	30-660	• Multi-band Spectroscopy
FIP	Far-Infrared Imager and Polarimeter	40, 80, 120, 240	• Broadband imaging • Field of view: 2.5'x5', 7.5'x15' • Differential polarimeteric imaging
HERO	Heterodyne Receiver for OST	63-66 , 111-610	• Multi-beam spectroscopy
HRS	High Resolution Spectrometer	25-200	• Spectroscopy



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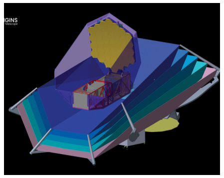
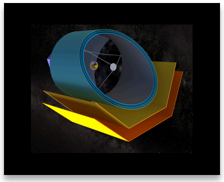
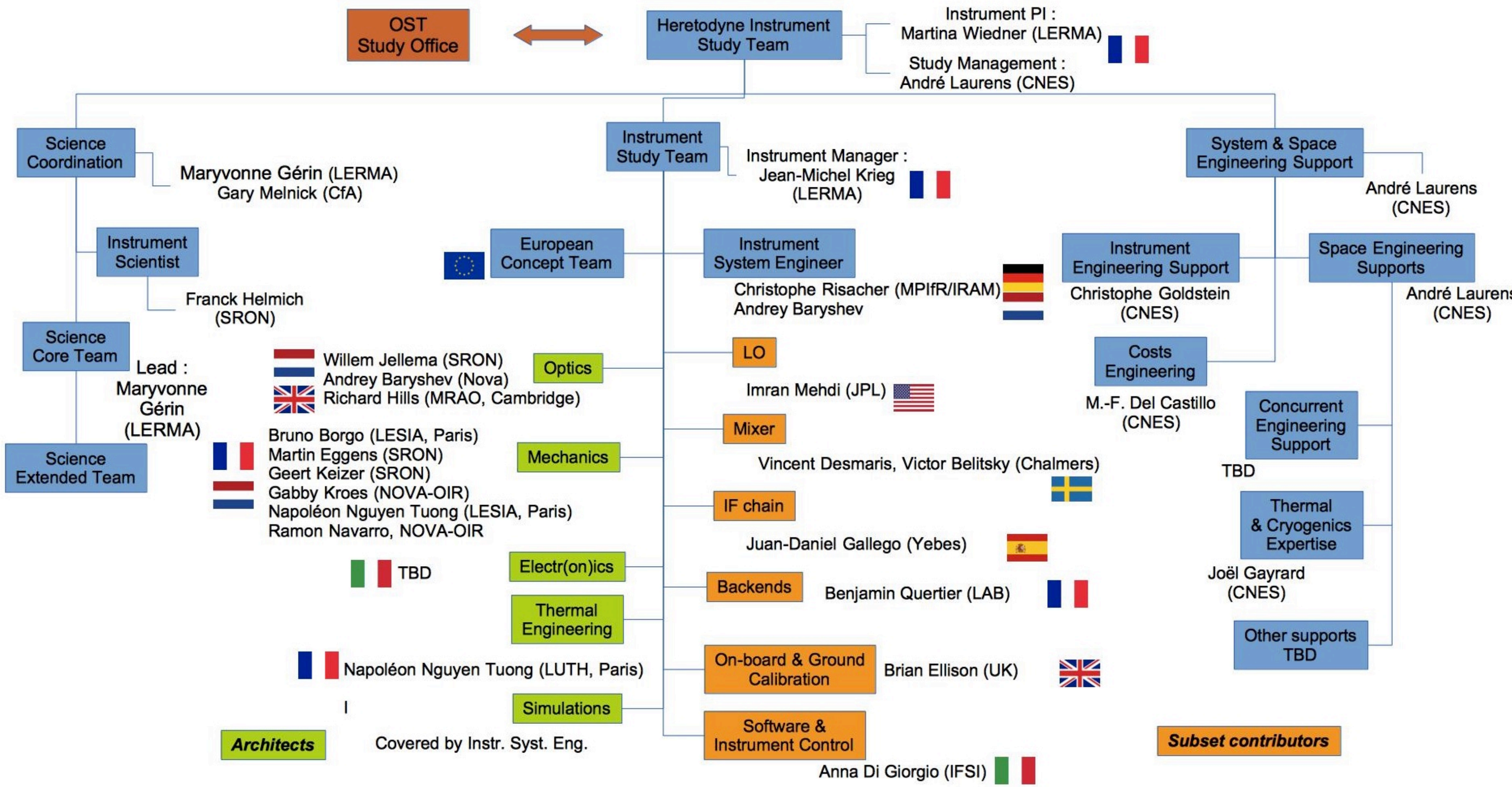
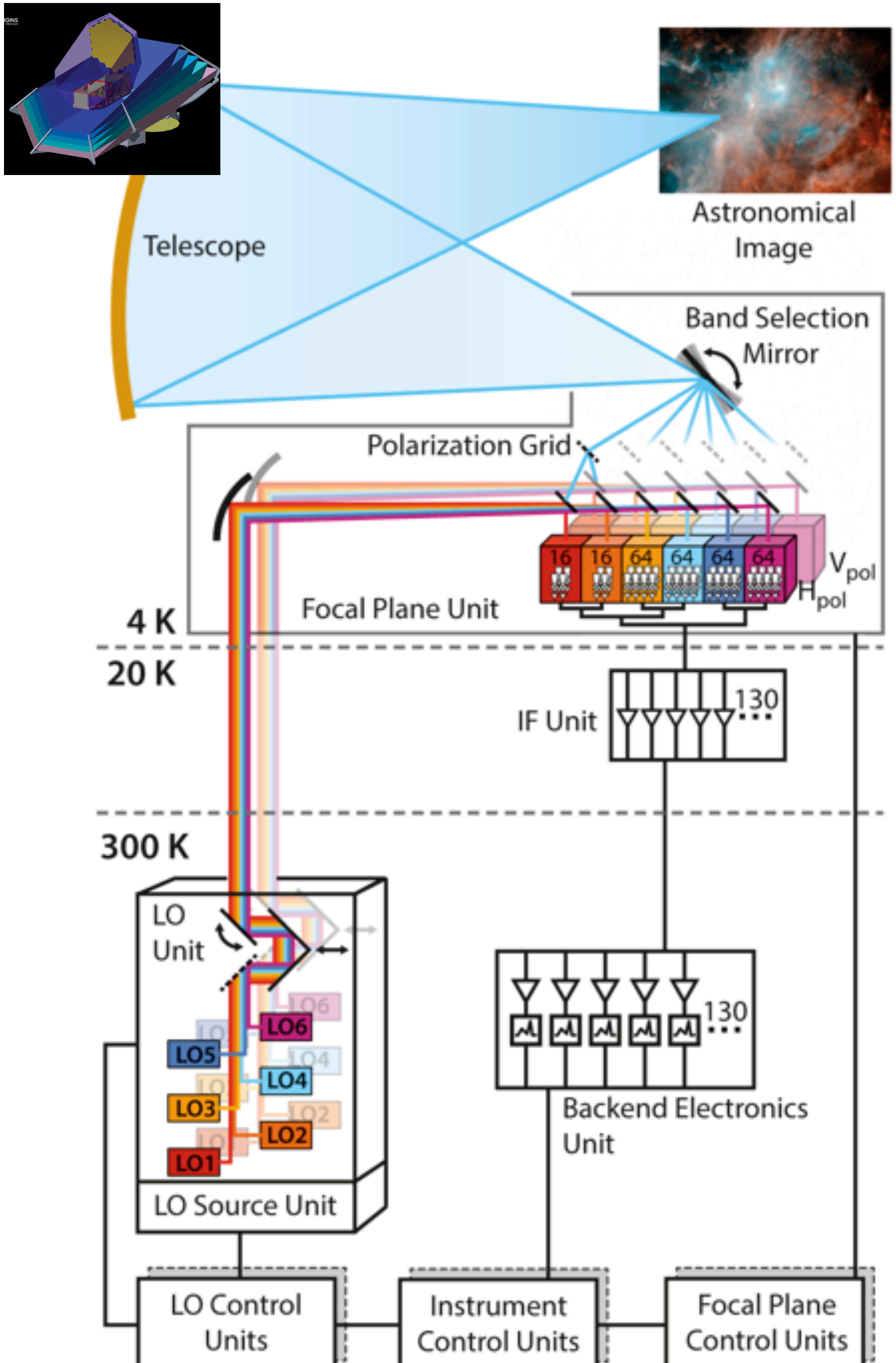




HERO technical team

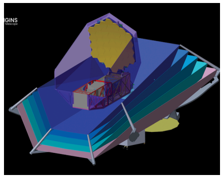
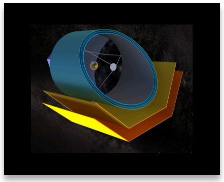




HERO Instrument

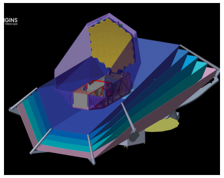
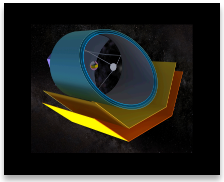
Heterodyne focal plane array with wide frequency coverage

- R = 10^5 to 10^7
- 468 – 2700 GHz, 4.7 THz
- 8 GHz IF
- 2x16 SIS, 2x64 HEB

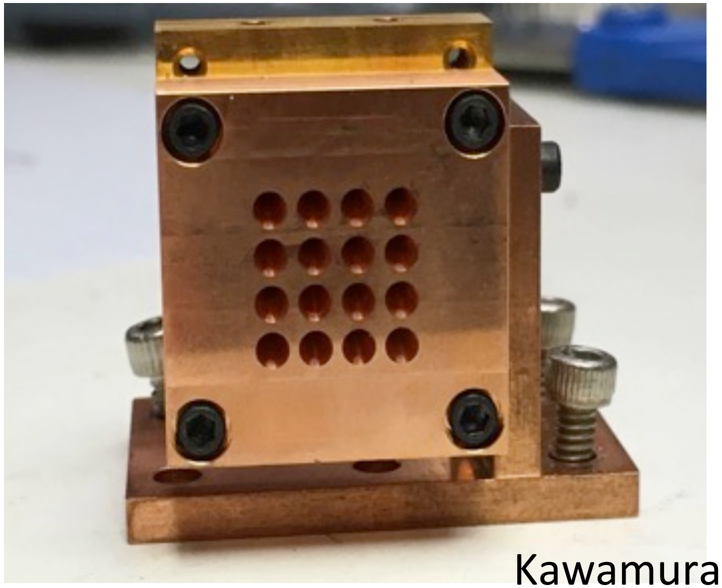
HERO challenges

- 4K dissipation: 100mW for 5 instruments
  - 4K amplifier 0.5 mW/pixel
- Mixers:
  - Large heterodyne arrays 2 x 64 pixels
  - Large frequency coverage 486 – 2700 GHz, 4.7 THz
  - 8 GHz Bandwidth for HEB (and SIS)
- LO:
  - LO at 4.7 THz
  - LO injection distance: ~ 8m
- Instrument power < 400 W
  - LO power: (1 + 1) W/pixel
  - Spectrometer 1W/pixel

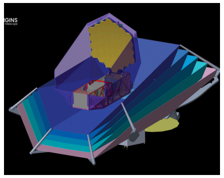
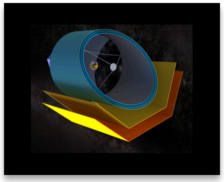
Mixers

- 4 x 4 x 2 polarizations SIS, 468-900 GHz, 8 GHz BW
- 8 x 8 x 2 polarizations HEB, 900 – 2700 GHz and 4.7 THz, 8GHz BW



Kawamura

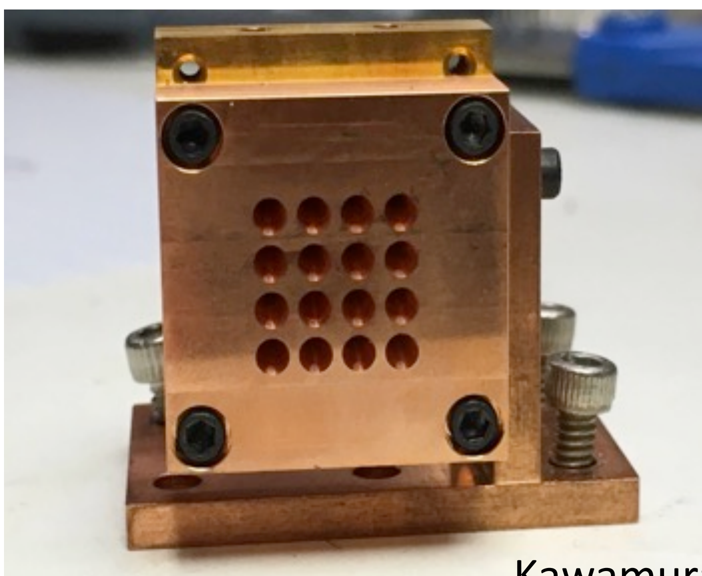
- LO and Sky injected in orthogonal polarizations
- 1 mixer per array, sidband separating – for sideband calibration
- SIS 10mm spacing
- HEB 5mm spacing
- On sky 2FWHM spacing

Mixers

1 → 64 pixel

- 4 x 4 x 2 polarizations SIS, 468-900 GHz, 8 GHz BW
- 8 x 8 x 2 polarizations HEB, 900 – 2700 GHz and 4.7 THz, 8GHz BW



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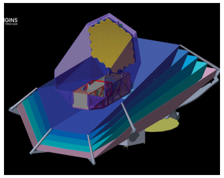
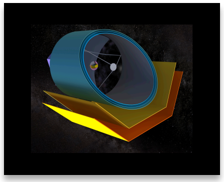
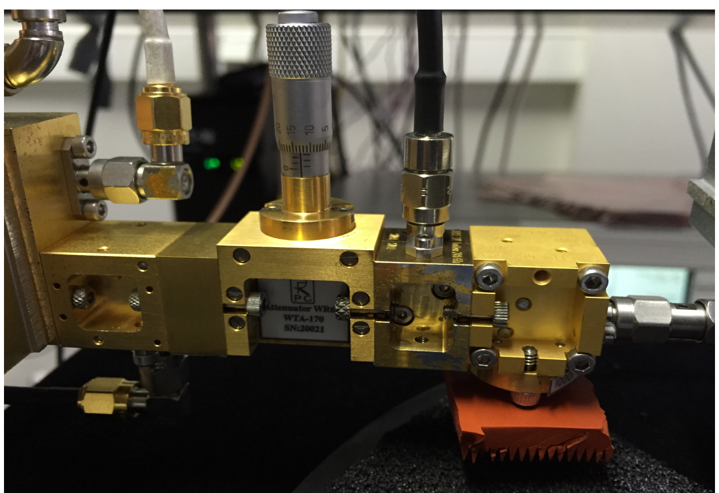



Local Oscillator

- Amplifier-Multiplier chains (AMC) at room temp (1W/pixel) including 4.7 THz
- Beam division in AMC
- LO source unit around 100GHz (1W/pixels)



A. Maestrini

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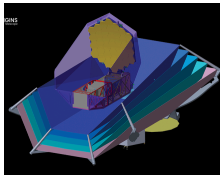
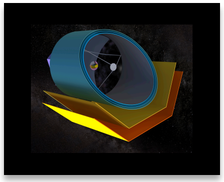
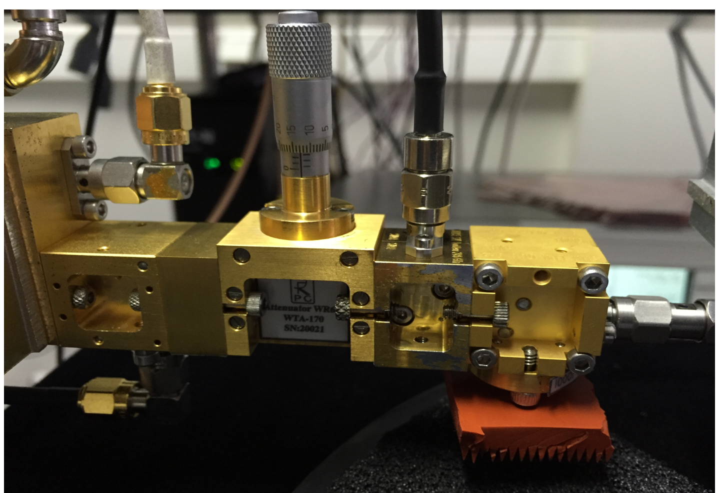




Local Oscillator

ΔRF 10% → 40%
1-2W/pixel

- Amplifier-Multiplier chains (AMC) at room temp (1W/pixel) including 4.7 THz
- Beam division in AMC
- LO source unit around 100GHz (1W/pixels)



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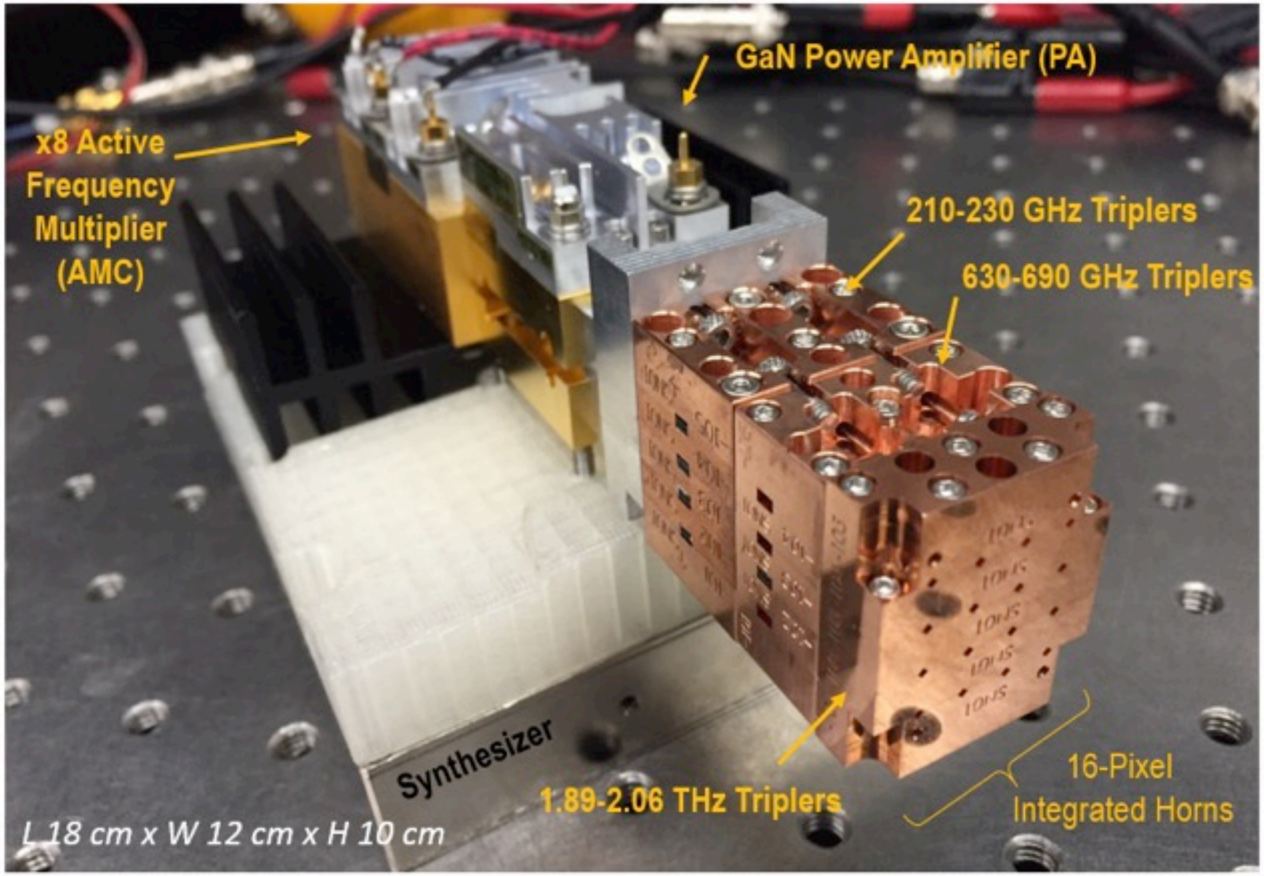
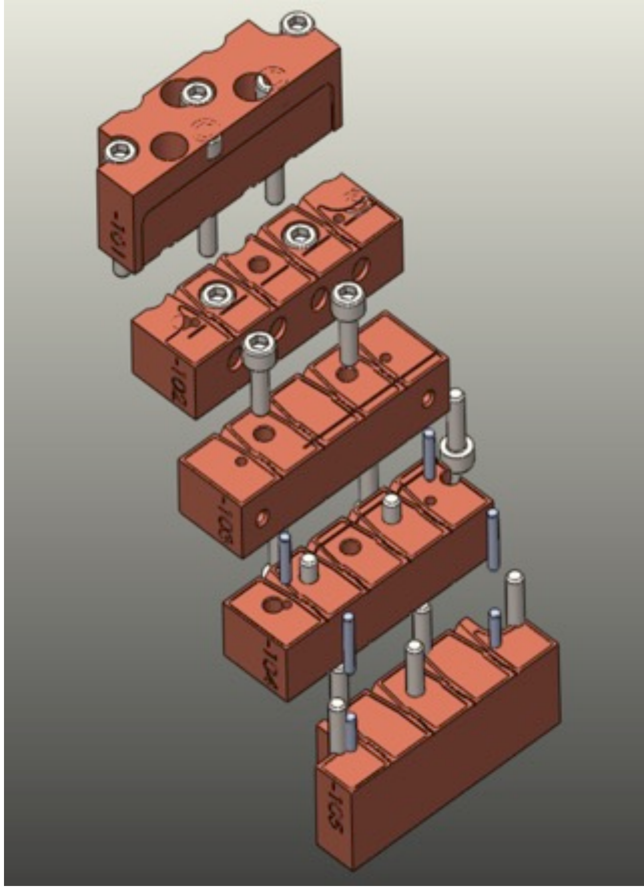
16-pixel 1.9 THz lo system: STACKING

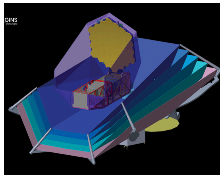


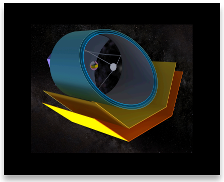


The LO module can be mounted with either two or four 1x4 pixel layers vertically stacked to form 8-pixels or 16-pixel configurations..

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

X3X3X3 Architecture



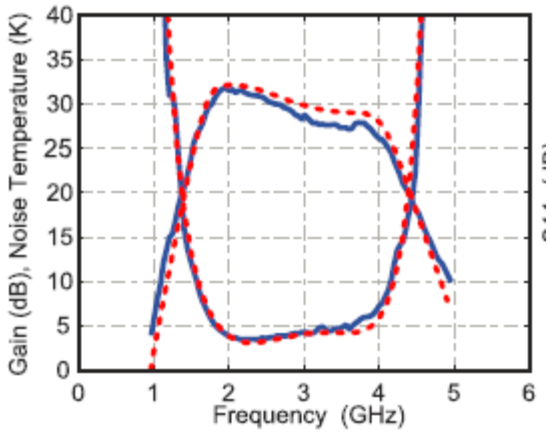


SiGe Amplifiers – Innovative technology

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

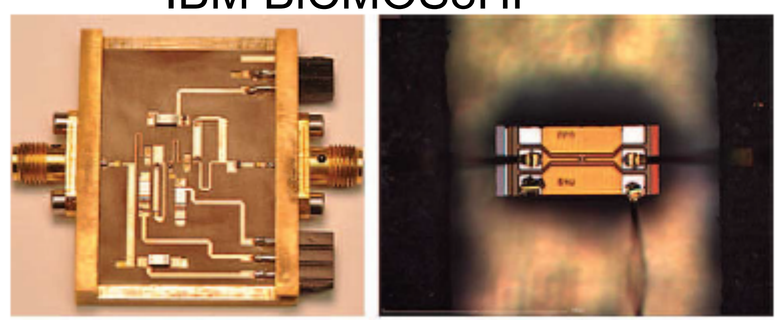
Ultra-Low-Power Cryogenic SiGe Low-Noise Amplifiers: Theory and Demonstration

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

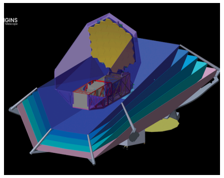


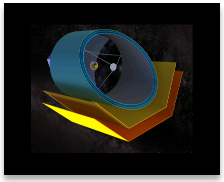
(a)

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



(a) (b)





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5mW → 0.5mW

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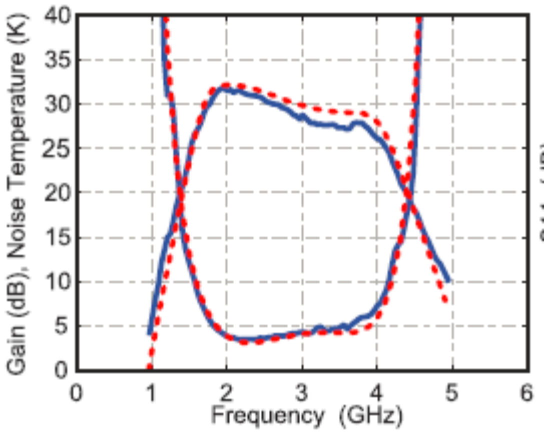

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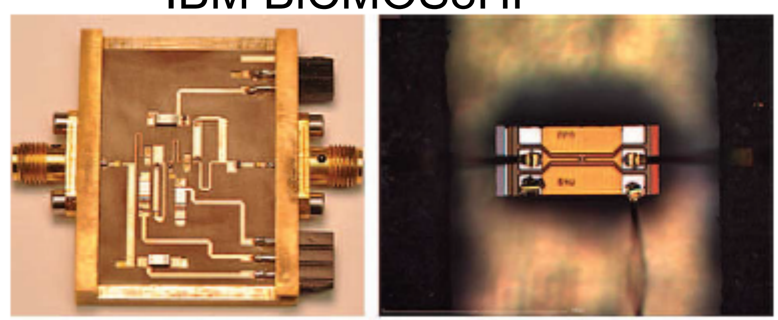
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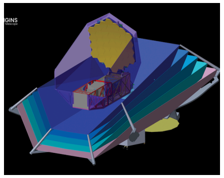
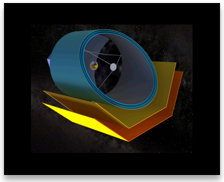
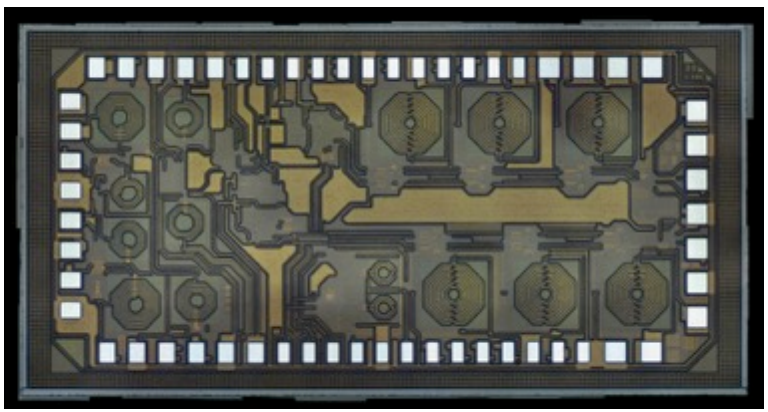
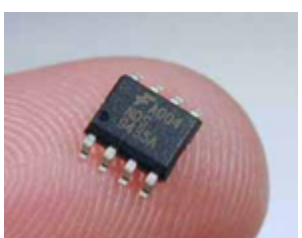
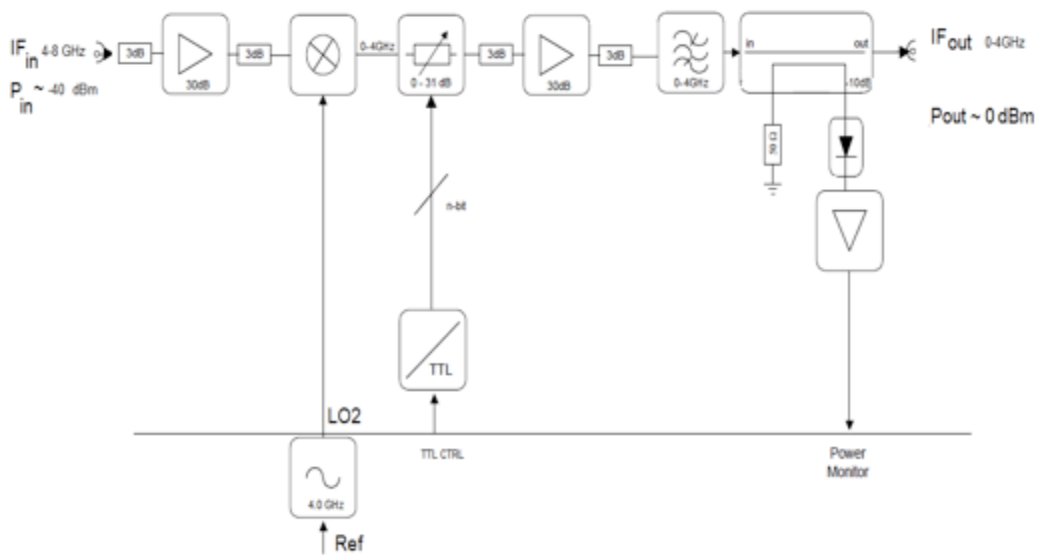



Warm IF chain

- 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.







MPIfR dFFTS4G spectrometer

Max-Planck-Institut für Radioastronomie

digital Signal Processing dSP

History of our FFTS development

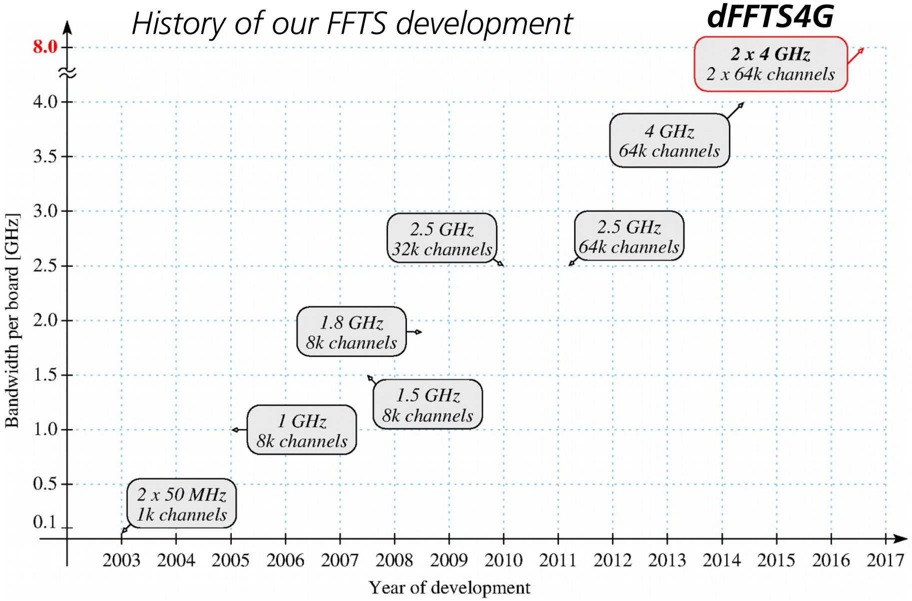


Photo: dFFTS4G spectrometer crate

Technical data of a dFFTS4G board:

- Input bandwidth: 2 x 4 GHz (0 – 4 GHz)
- Spectral channels: 2 x 64k
- Spectral resolution: 71 kHz (ENBW)
- Power consumption: max. 70 W (~9 W / GHz)

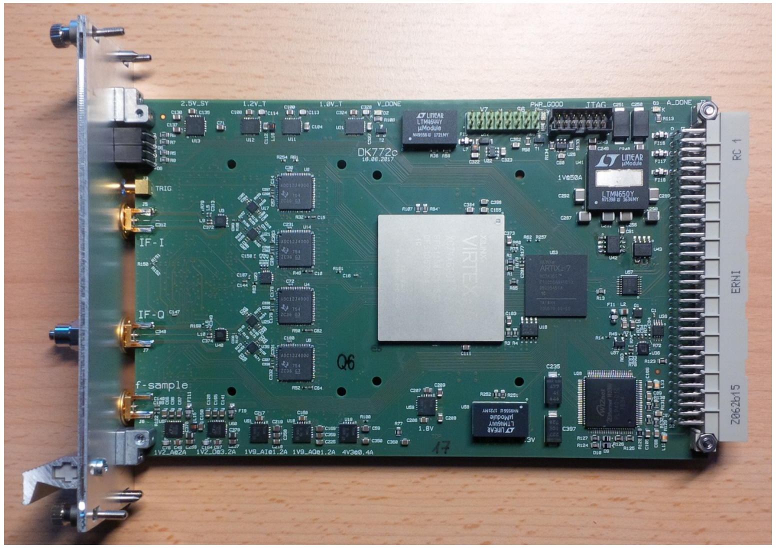


Photo: dFFTS4G spectrometer board

Technical specifications of a dFFTS4G 19” crate :

- Total bandwidth: 8 x 2 x 4 GHz = 64 GHz
- Spectral channels: 8 x 2 x 64k = 1 Million (1024k)

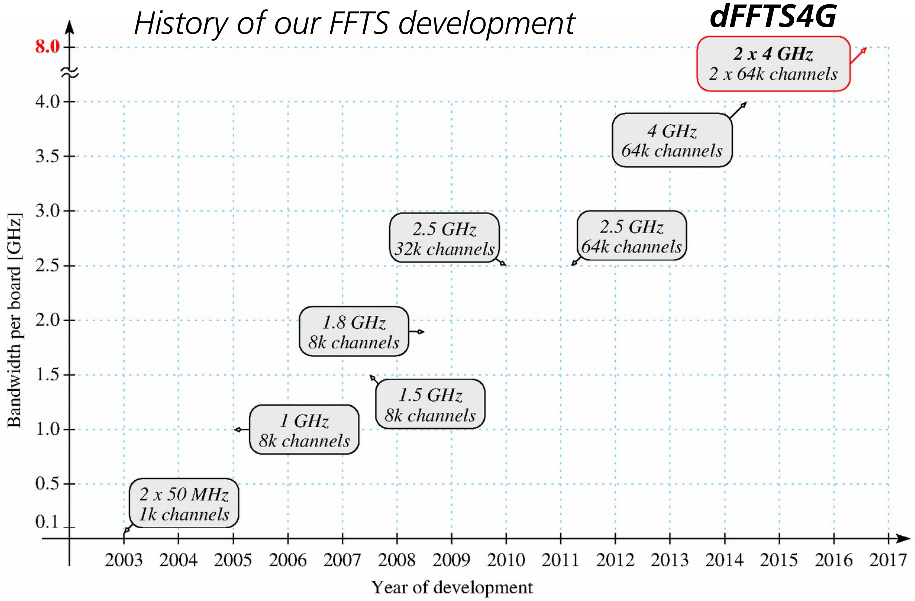
Bernd Klein, 2018

Max-Planck-Institut für Radioastronomie

digital Signal Processing dSP

MPIfR dFFTS4G

70W → 1 or 2W



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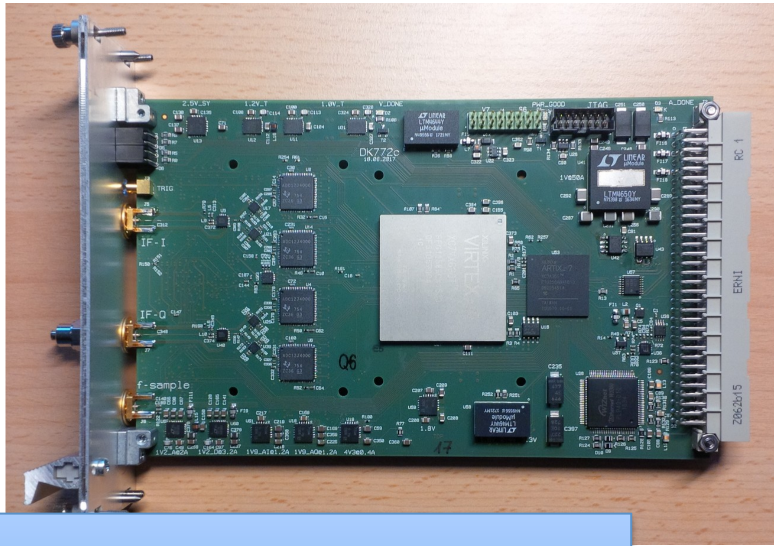


Photo: dFFTS4G spectrometer crate

d

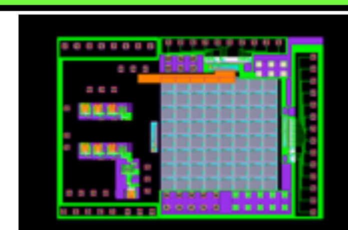
crate :

024k)

Group in Bordeaux (LAB)

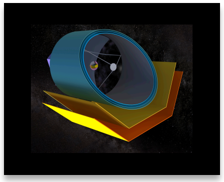
Bernd Klein, 2018

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
		

Subsystem Description	TRL N≤4	TRL N>4	Heritage	Comments
Multiplied LO, f <2THz	9	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	6	4	HERSCHEL, STO-2, SOFIA	Higher power handling capability for lower stages; higher output power; CMOS synth; GaN amps
HEB mixers	7/8	4	HERSCHEL, SOFIA, STO-2	Compact arrays; efficient IF extraction; balanced designs
SIS mixers	8/9	5	HERSCHEL	Compact arrays with efficient IF extraction
IF LNAs	9	4	HERSCHEL	InP technology mature; need to advance SiGe technology with lower DC power
Backend	9	4	STO-2, SOFIA	FPGA systems are mature, however, need ASIC based solutions for large arrays
Calibration	9	8	HERSCHEL, SOFIA, STO-2	
Bias electronics	9	5	HERSCHEL	Low power electronics, 5 if multiplexing is needed
Optical	9	8	HERSCHEL	
ICU	9	7	Herschel	
Tip/Tilt mechanis	8	8	Herschel (one axis)	

Need TRL 5 by 2025 → Detector Roadmap Workshop 29/30 March 2018



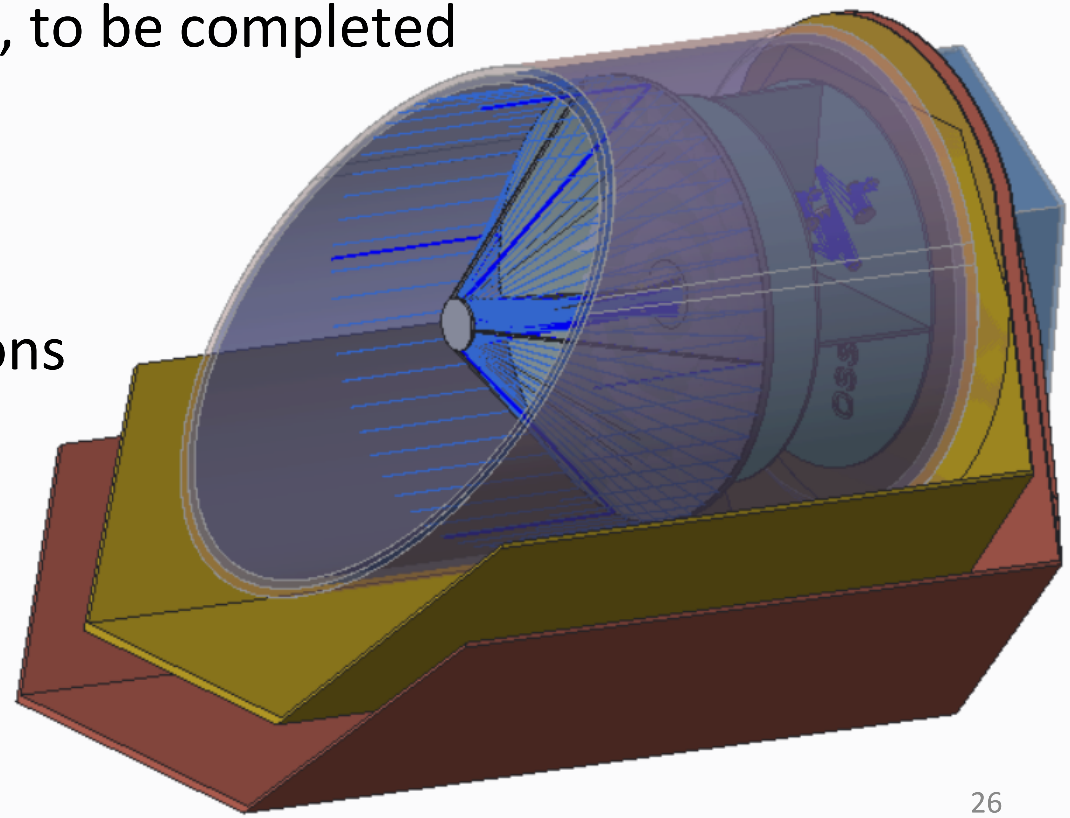
OST Concept 2

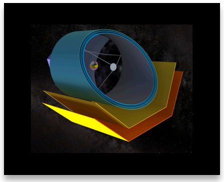
- Smaller, less ambitious
- JWST size collecting area: ~25 m^2
- Minimal deployment (minimum unfolding)
- Preliminary designs started, to be completed by end of summer 2018

- Design driven by
  the 3 main science questions

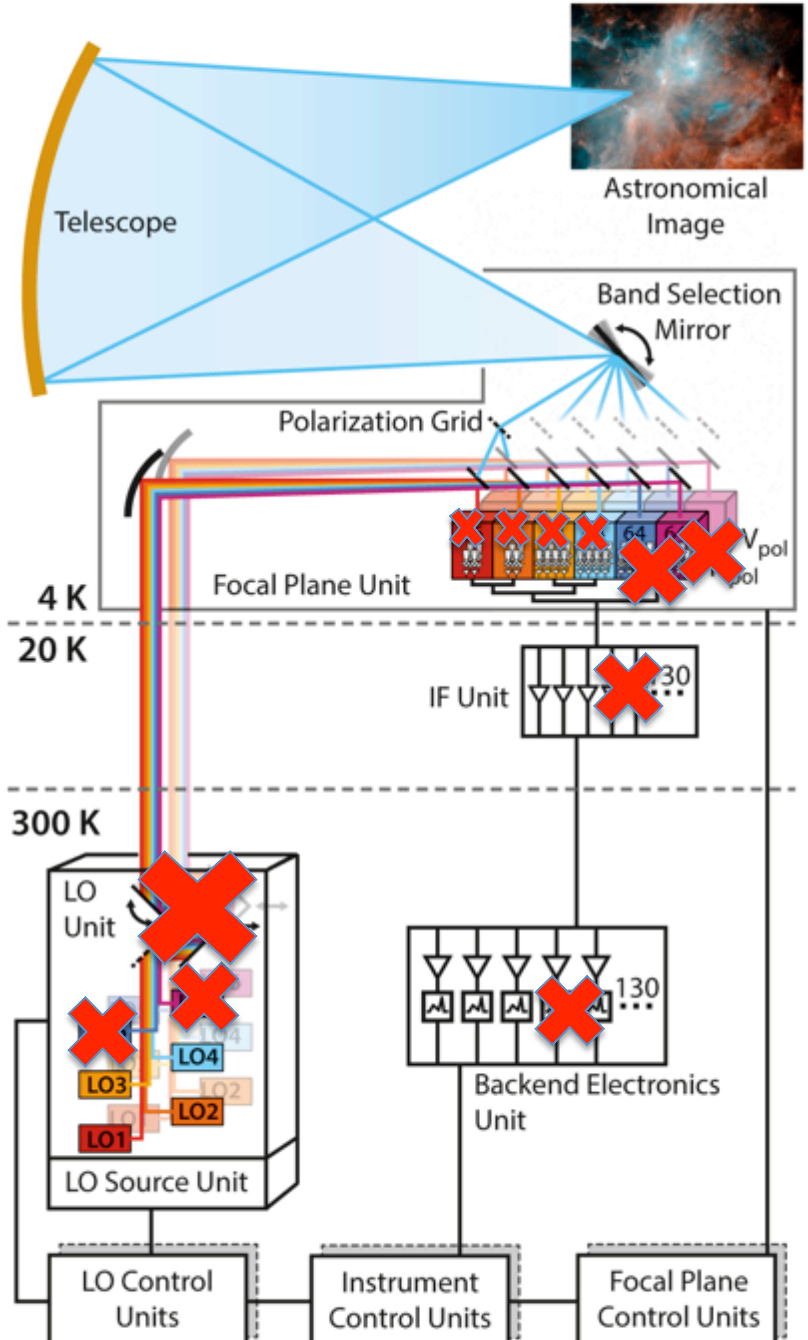
3 baseline instrument

+ little HERO upscope





Little HERO

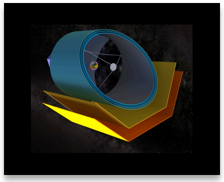
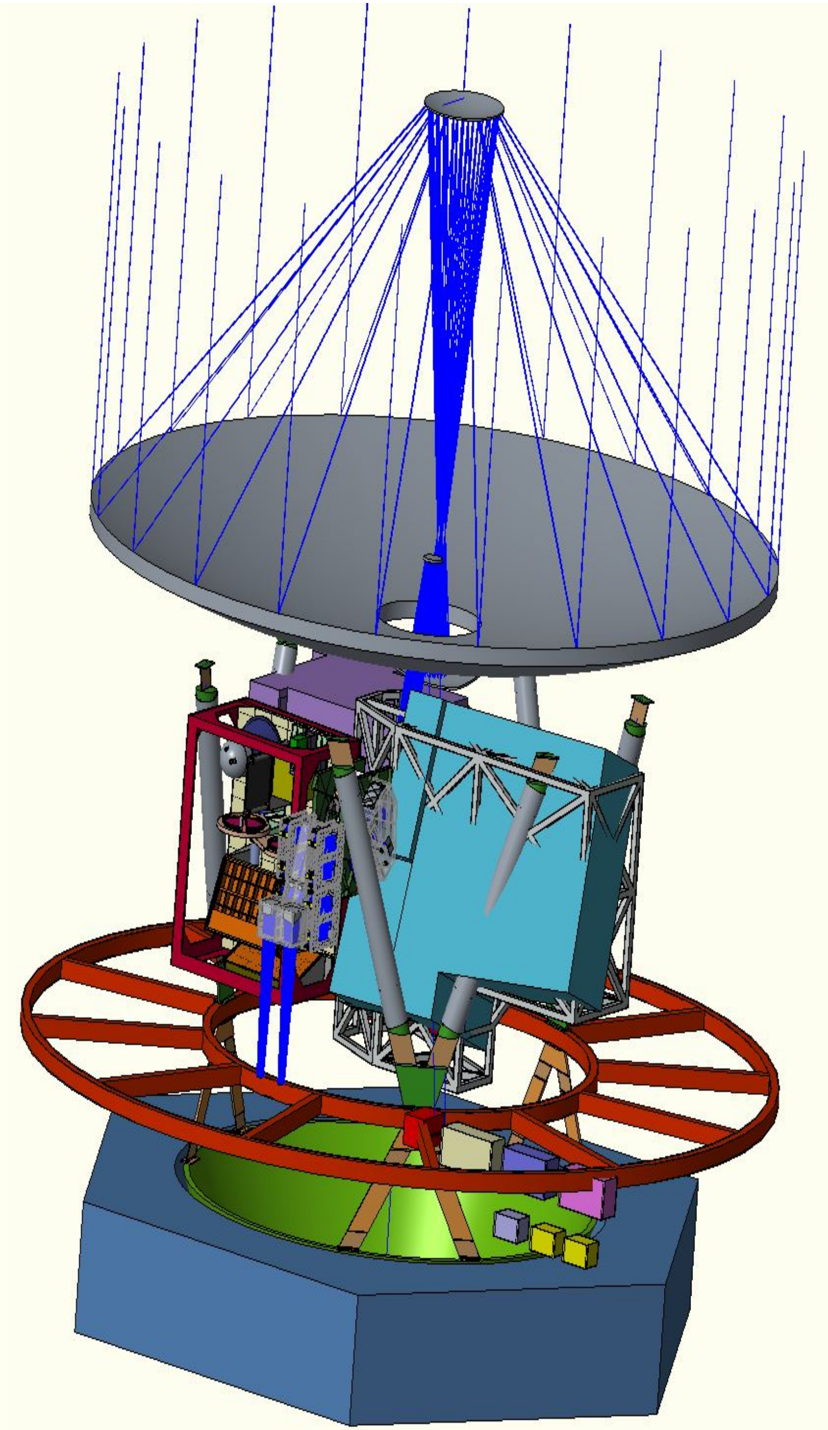


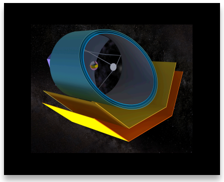
2x16 → 2x9 pixels
2x16 → 2x9 pixels
2x64 → 2x9 pixels
2x64 → 2x9 pixels
2x64 → 0 pixels
2x64 → 0 pixels

6 bands → 4 bands
(no 63 microns)

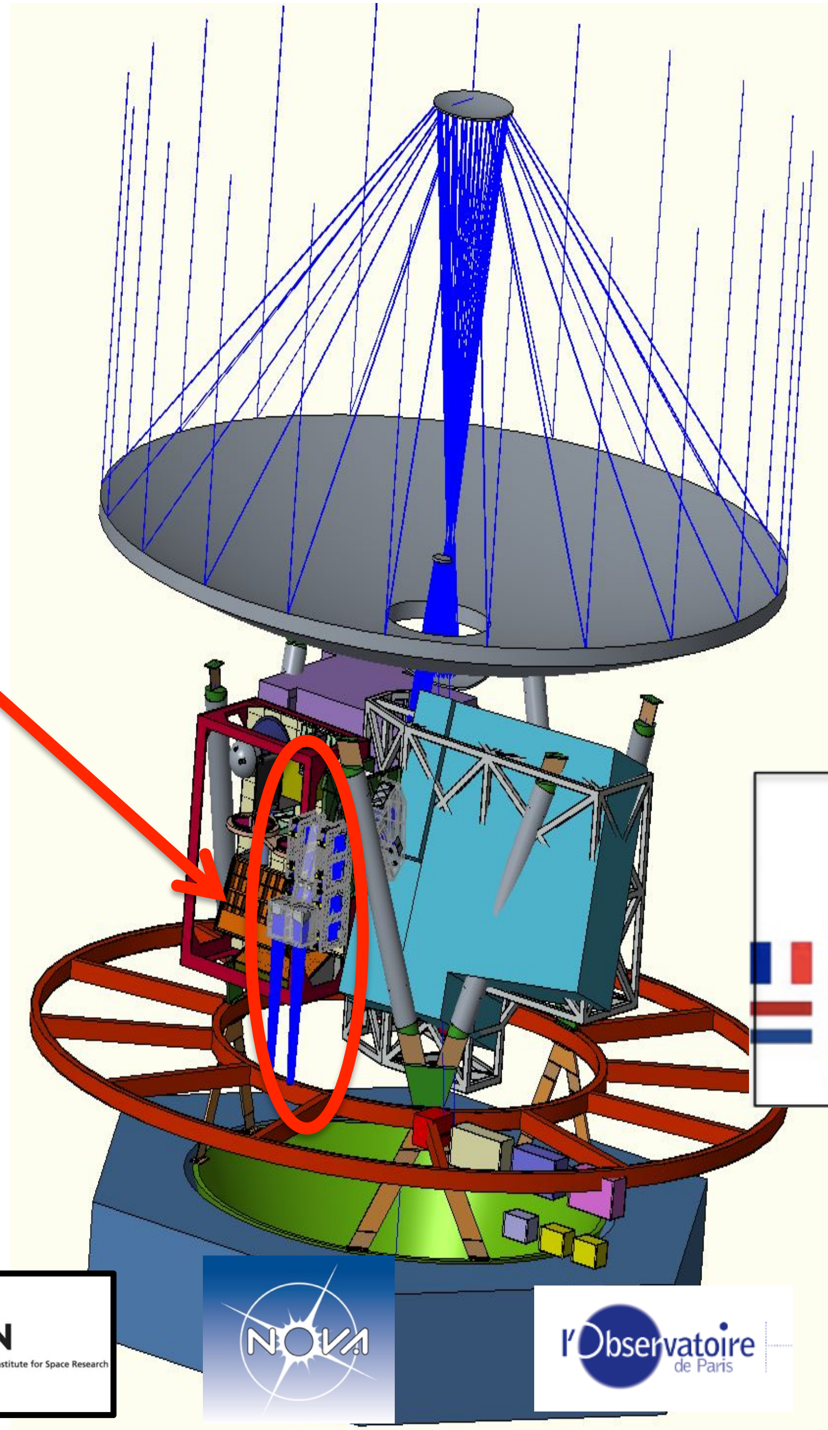
130 IF/backend → 40

Simple LO relay



HERO on OST



Optical and Mechanical Design of little HERO:

Willem Jellema (SRON) Andrey Baryshev (Nova) Richard Hills (MRAO, Cambridge)	Optics
Bruno Borgo (LESIA, Paris) Martin Eggens (SRON) Geert Keizer (SRON) Gabby Kroes (NOVA-OIR) Napoléon Nguyen Tuong (LESIA, Paris) Ramon Navarro, NOVA-OIR	Mechanics

university of groningen

SRON Netherlands Institute for Space Research

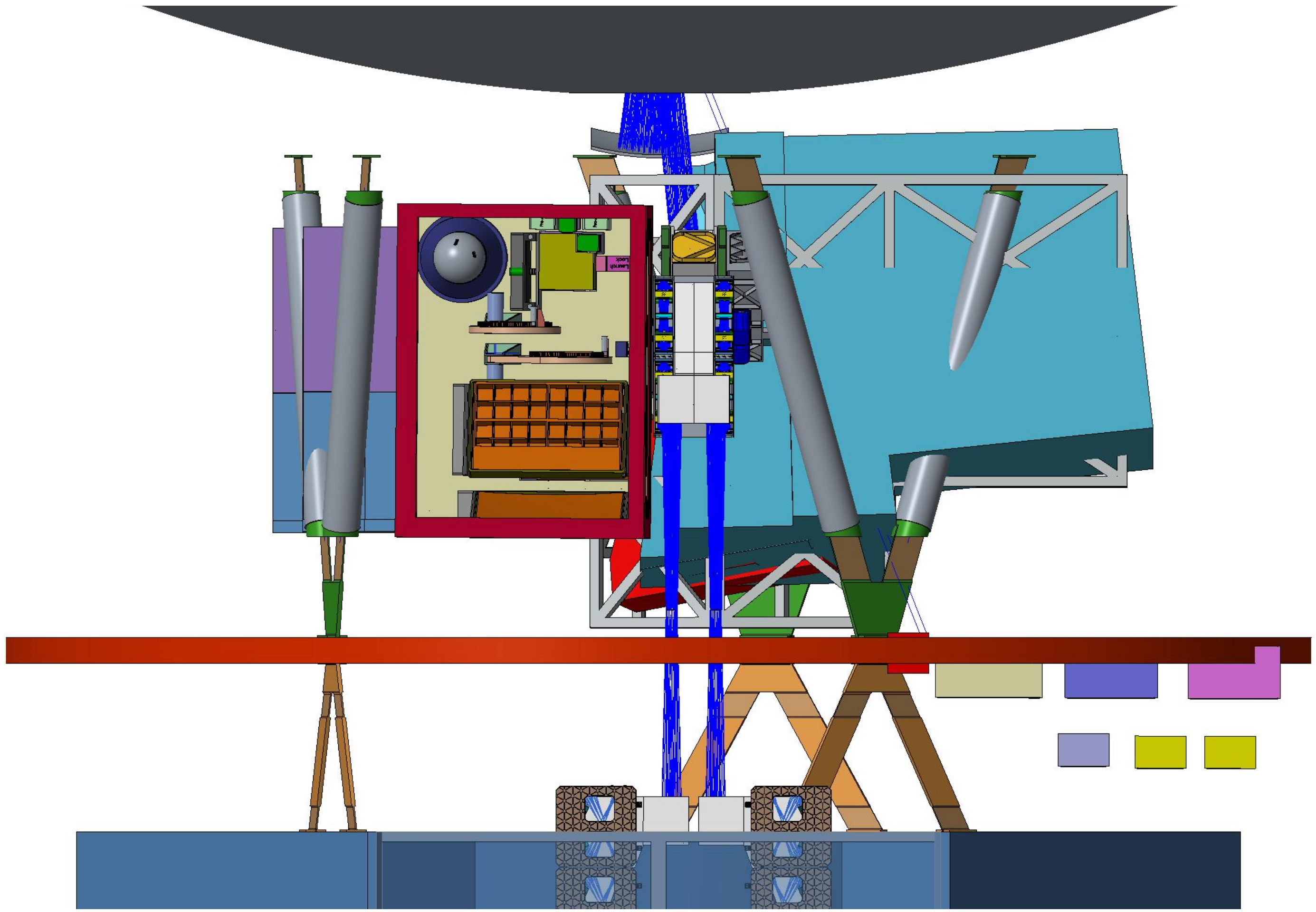
NOVA

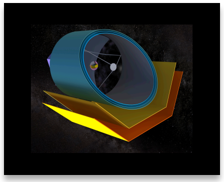
l'Observatoire de Paris

MRAO CAMBRIDGE

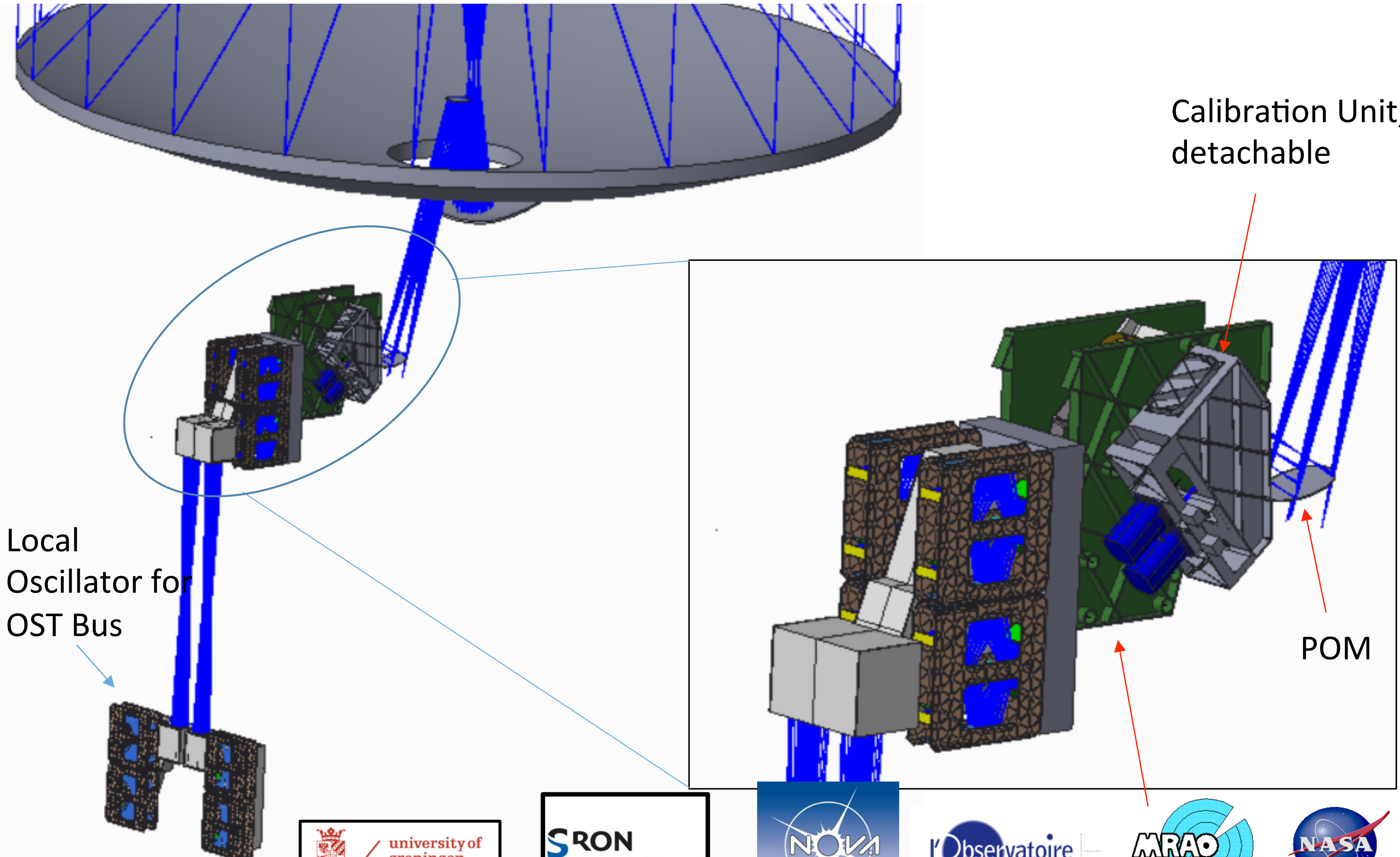
NASA

Little HERO on OST 2

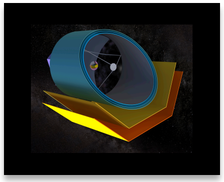




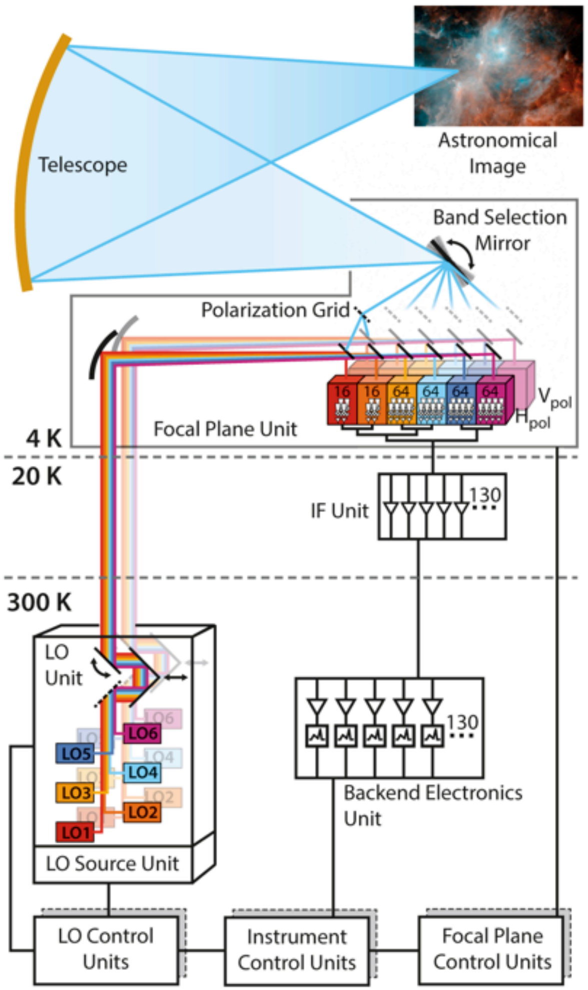
Little HERO



Calibration Unit,
detachable
POM
Local
Oscillator for
OST Bus

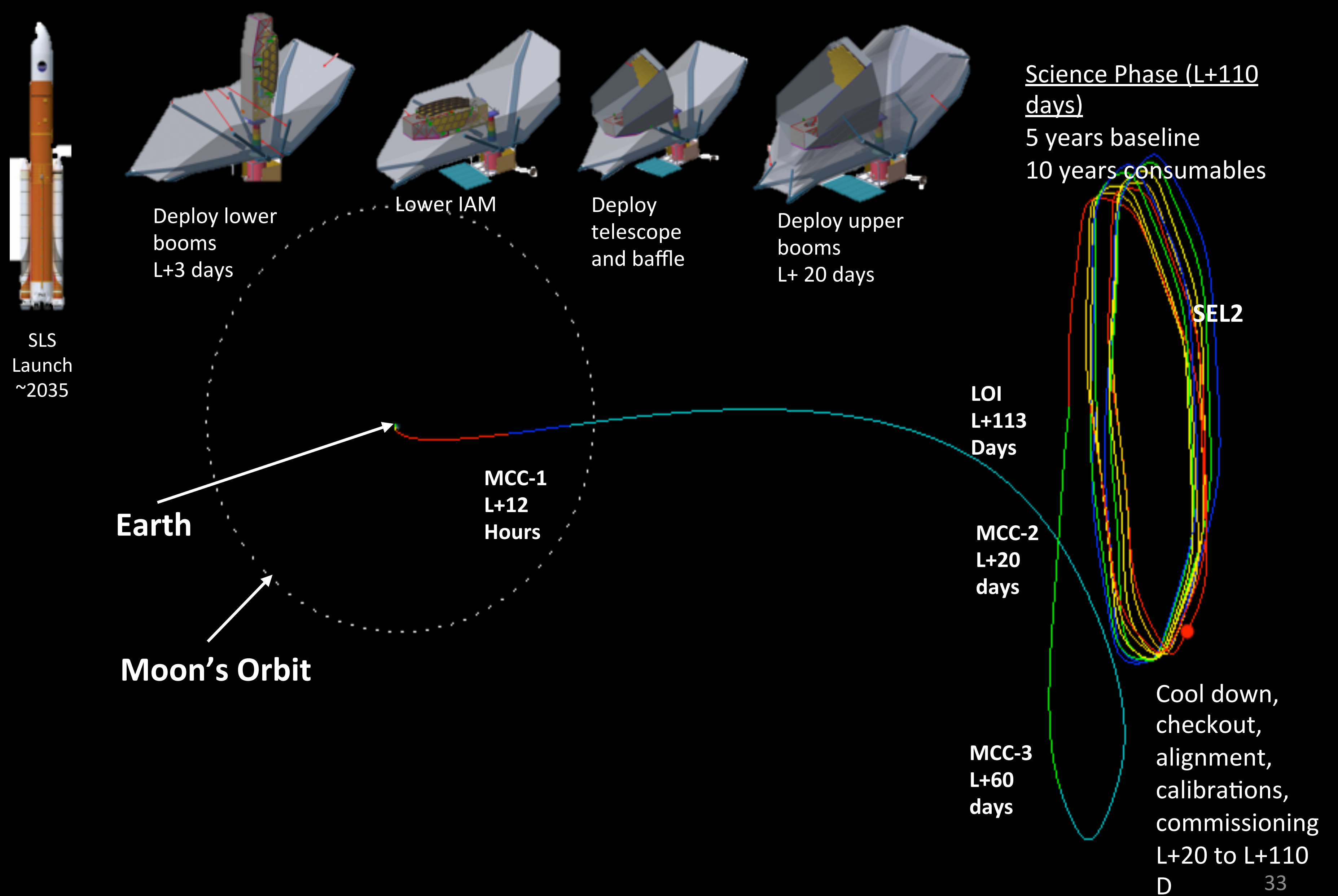


Summary (little) HERO

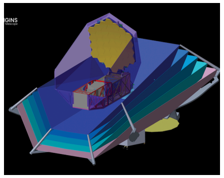


- New generation heterodyne array receiver
- Builds on HIFI/Herschel, (up)GREAT, ALMA experience but surpasses it
- Focal Plane Arrays
- Frequency coverage: 486 – 2700 GHz
- Very realistic,

  but **instrumental development required**


SLS
Launch
~2035
Deploy lower
booms
L+3 days
Lower IAM
Deploy
telescope
and baffle
Deploy upper
booms
L+ 20 days
Science Phase (L+110
days)
5 years baseline
10 years consumables
SEL2
LOI
L+113
Days
MCC-1
L+12
Hours
Earth
Moon's Orbit
MCC-2
L+20
days
MCC-3
L+60
days
Cool down,
checkout,
alignment,
calibrations,
commissioning
L+20 to L+110
D

Backups

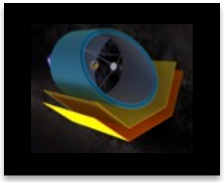


HERO’s Fact Sheet

- Around 63µm, and 111 - 641µm
- 32 to 128 spatial pixels, each with ~8000 specral channels
- Resolution: up to $\Delta\lambda/\lambda = 10^7$

Col.	2	3	4	5	6	7	8	9	10	11	12	13	14
Band	νmin	νmin	λmax	λmin	Max $\Delta\lambda/\lambda$	IF BW2	Mixer	# pixels	# pixels	Trx	Beams	T_{rms} (mK)	Line Flux
	(GHz)	(GHz)	(µm)	(µm)		km/s	Type	Fall-back	Goal	K (DSB)	arc sec	in 1h at $\lambda/\Delta\lambda$ $=10^6$	W/m^2 at 5σ, 10^6 res 9m tel. 1h
1	468	648	641	463	10^7	4301	SIS	2x4	2x16	40	15.2	2.0	2.1 E-21
2	648	900	463	333	10^7	3101	SIS	2x4	2x16	80	10.9	3.4	4.9 E-21
3	900	1260	333	238	10^7	2222	HEB	2x4	2x64	110	7.9	3.9	7.9 E-21
4	1242	1836	241	163	10^7	1559	HEB	2x4	2x64	200	5.6	6.0	1.7 E-20
5	1836	2700	163	111	10^7	1058	HEB	2x4	2x64	300	3.8	7.4	3.1 E-20
6	4536	4752	66	63	10^7	517	HEB	2x4	2x64	500	1.8	8.6	7.5 E-20

14 Receiver noise for 1h integration at 10^6 resolution (0.3 km/s) using one polarization.
15 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 (app eff. 0.9) as designed for OST Concept 1.



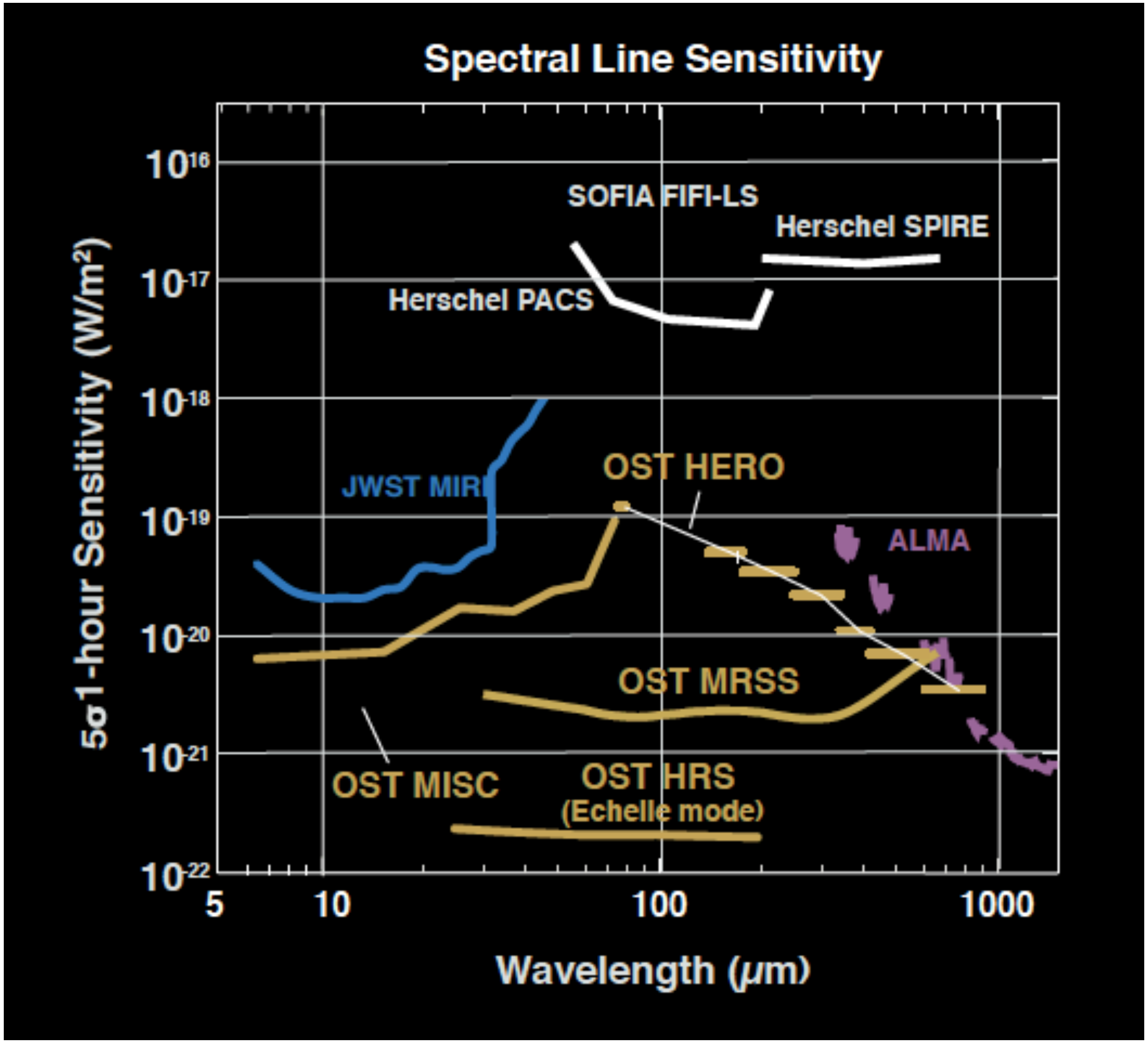
Little HERO fact sheet

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_2$0, H_2^{18}0,** HDO NH$_3$	50	2.6	6.4 E-21
2	756	1188	397	252	10^7	2469	SIS	2x9	**$H_2$0, H_2^{18}0** H_3O^+	100	4.2	1.6 E-20
3	1188	1782	252	168	10^7	1616	HEB	2x9	**$H_2$0, 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.

Instrument Performance



Instrument Performance