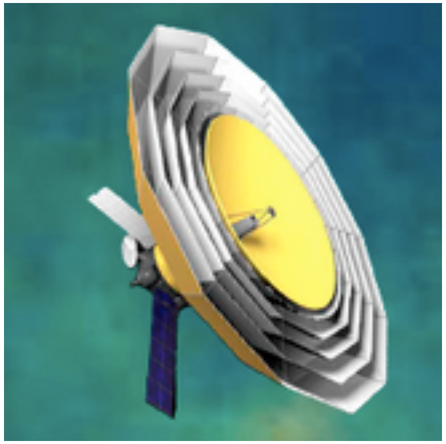
Imaging Heterodyne Spectrometer Concept and Science Case

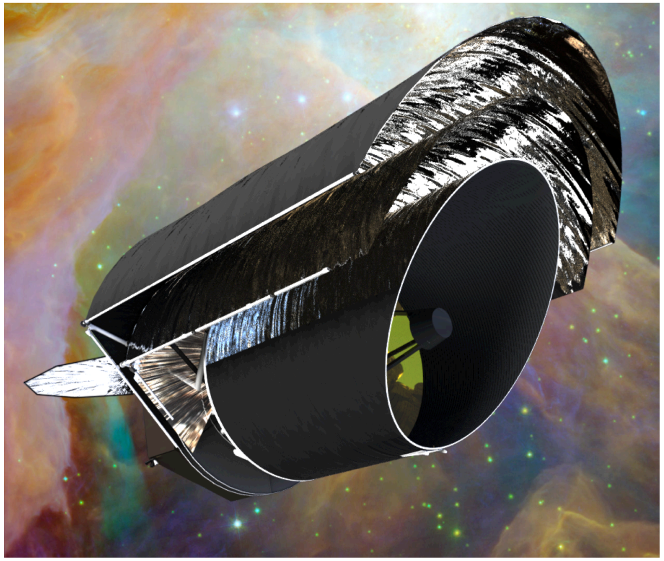
using the example of the Heterodyne Receiver for Origins

Presented by M.C. Wiedner



ORIGINS Space Telescope

This talk largely uses what we have learned from HERO on Origins



Origins is a NASA study of a large IR satellite submitted to the decadal survey 2020
PI M. Meixner, A. Cooray
origins.ipac.caltech.edu
https://asd.gsfc.nasa.gov/firs/docs/

HERO is HEterodyne Receiver for Origins

Outline

- Key Science Drivers

→ Modest Imaging Heterodyne spectrometer

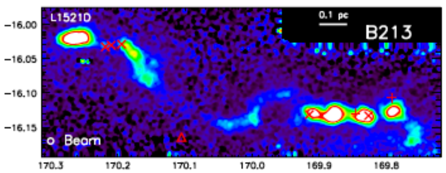
- Additional Science Drivers

→Ambitious Imaging Heterodyne Spectrometer

ORIGINS Space Telescope

Key Science Drivers

- The Trail of Water (H_2O, $H_2{}^{18}O$, HDO)



- Determining the Cosmic Ray Flux in the Milky Way and in Nearby Galaxies

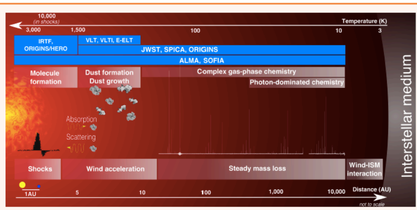
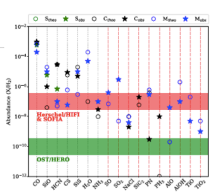
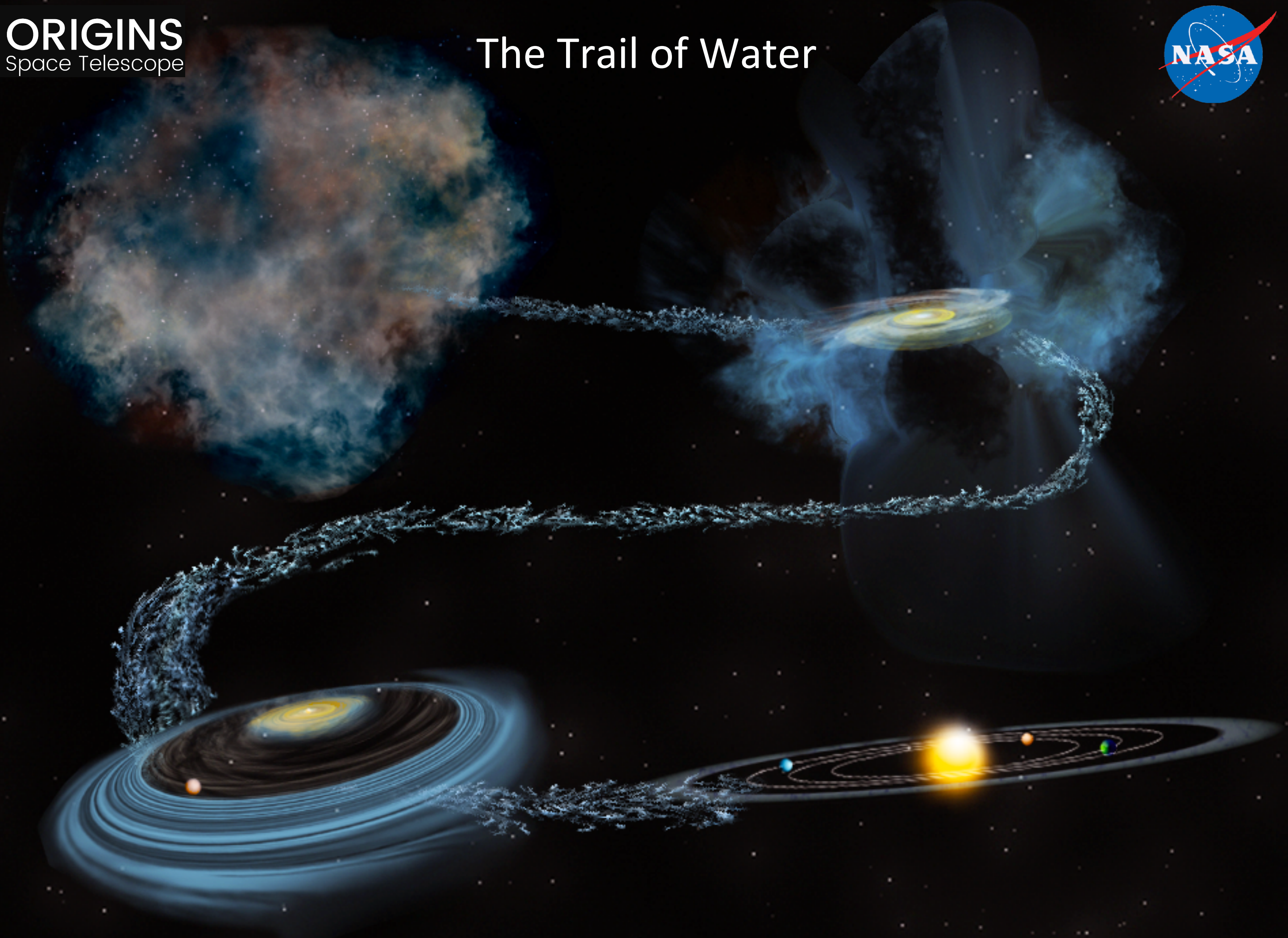


FIGURE 2: AGB outflow structure. *White boxes:* major chemical and physical processes, *blue boxes:* contribution of existing, planned, and proposed facilities.

- Fundamentals of Dust Formation and Evolved Stars



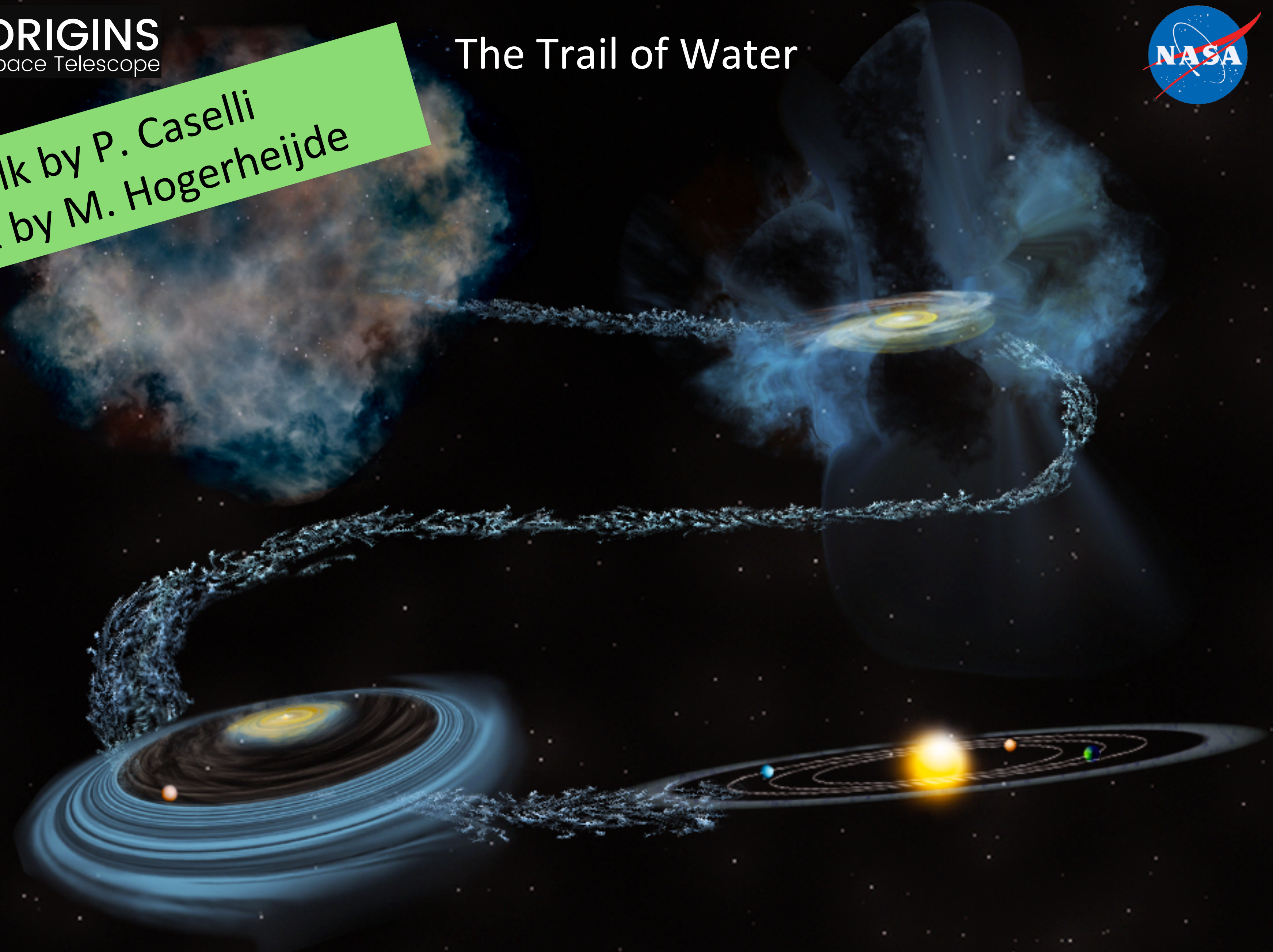
The Trail of Water



Science case developed by E. Bergin, K. Pontoppidan, G. Melnick, M. Gerin, et al.

The Trail of Water

Talk by P. Caselli
& by M. Hogerheijde



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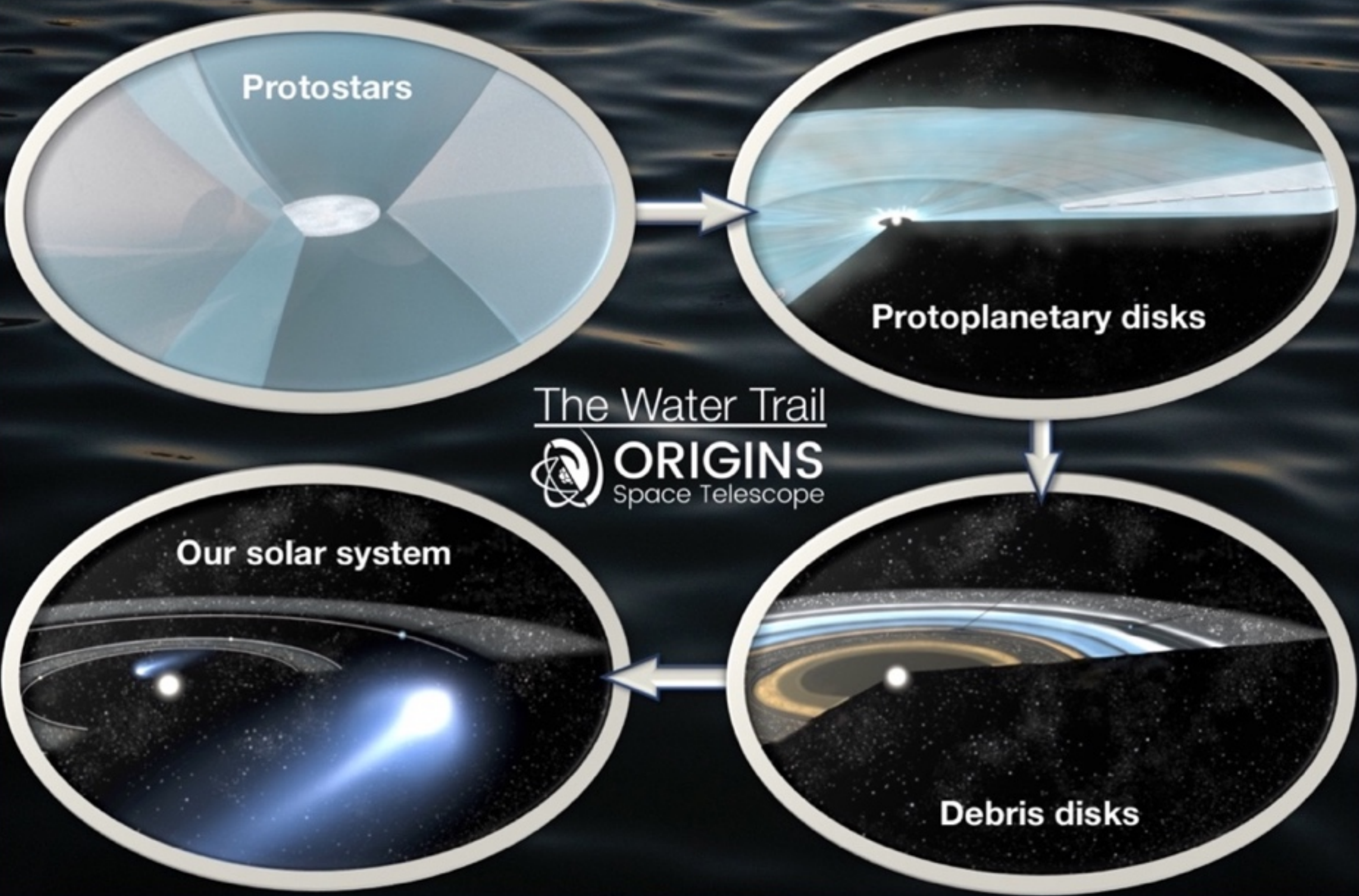
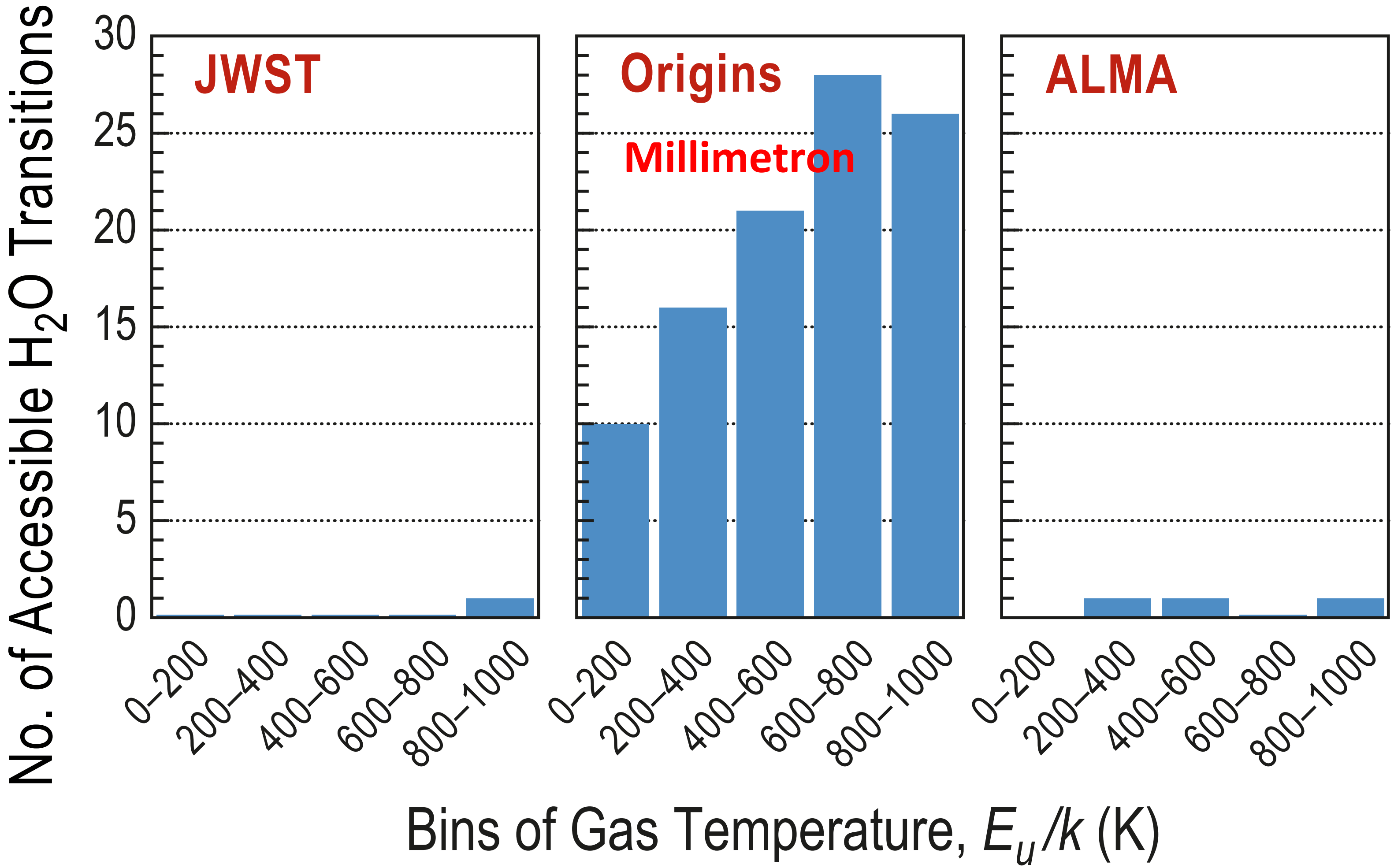
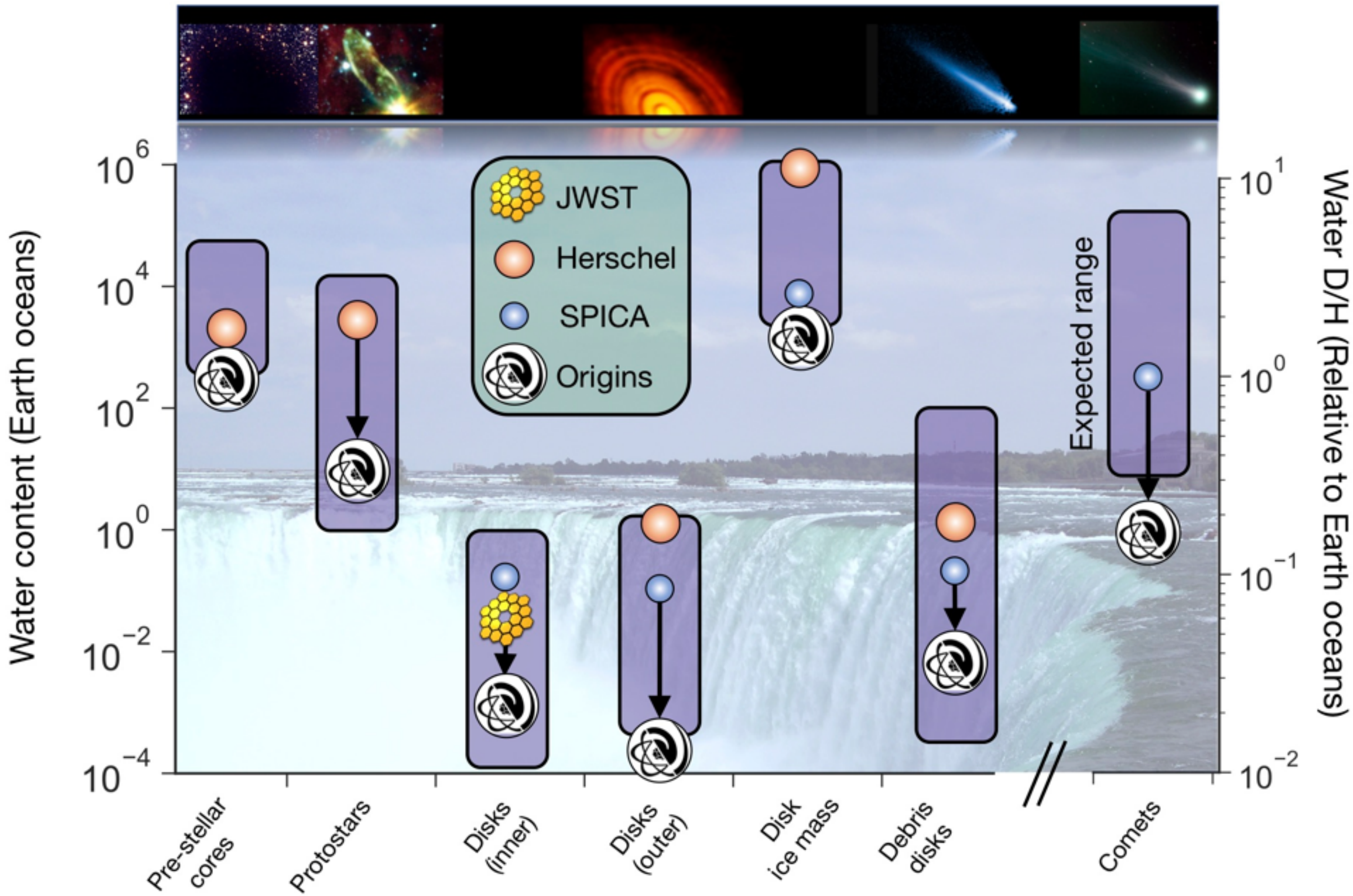
ORIGINS
Space Telescope



To Follows the Trail of water → submm observations



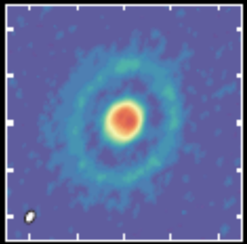
Sensitivity improvements with Origins (5.9 m primary, 4.5 K)



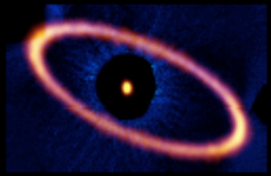
HOW DID WE GET HERE: THE WATER TRAIL

- Water's birth in star-less cores: HERO maps of ground state lines in 10 sources for 300 hours.

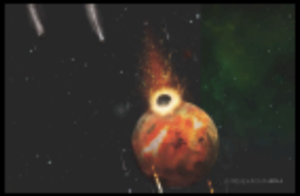
- Supply to a young disk in protostars: OSS survey of $H_2{}^{18}O$ towards 50 sources with HERO followup for 150 hours



- Early planet formation in protoplanetary disks: OSS survey of 1000 sources with HERO followup: 1250 hours

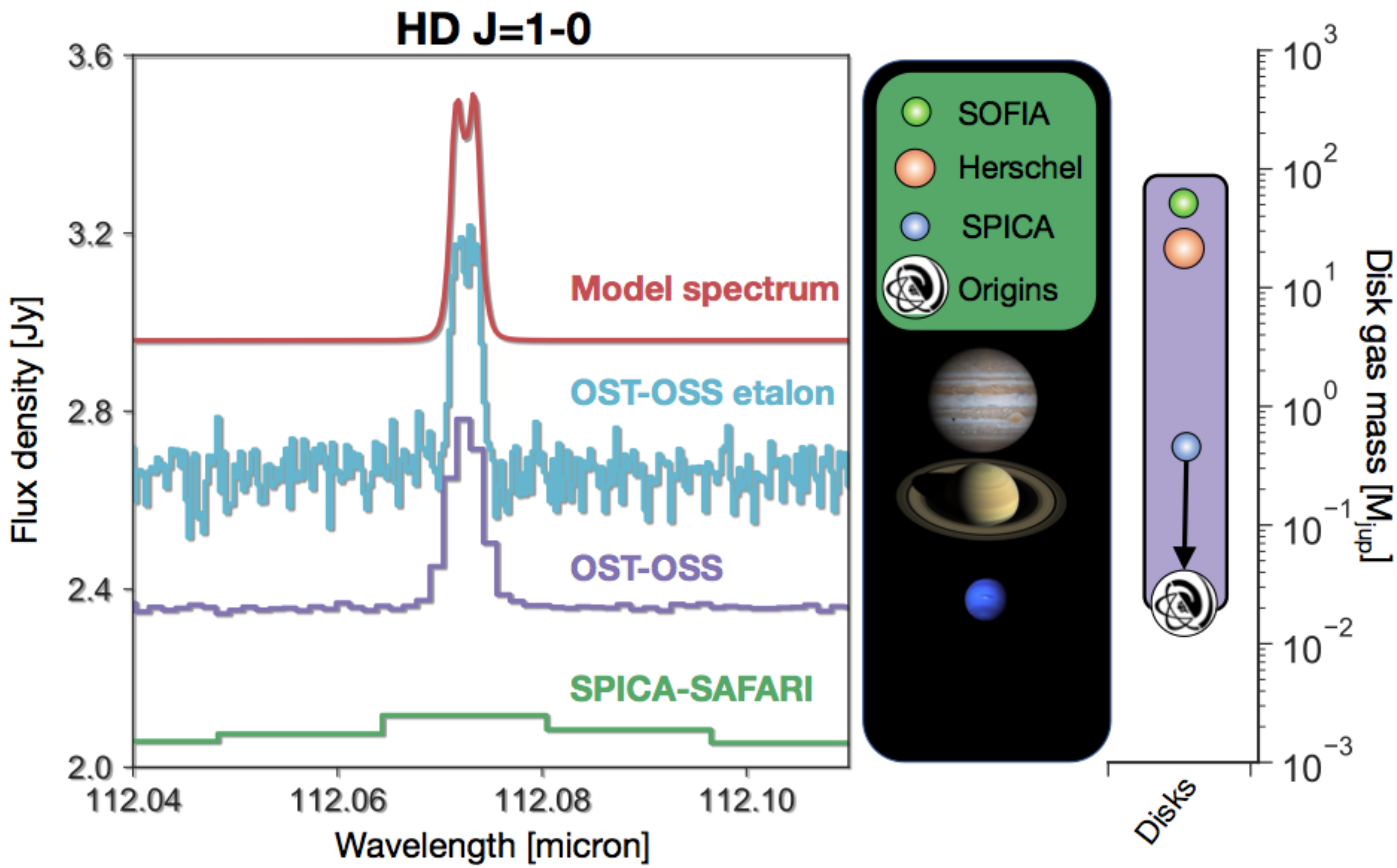


- Late planet formation in debris disks: OSS observations of O I, C II, and H_2O in 30 systems/ positions for 100 hours

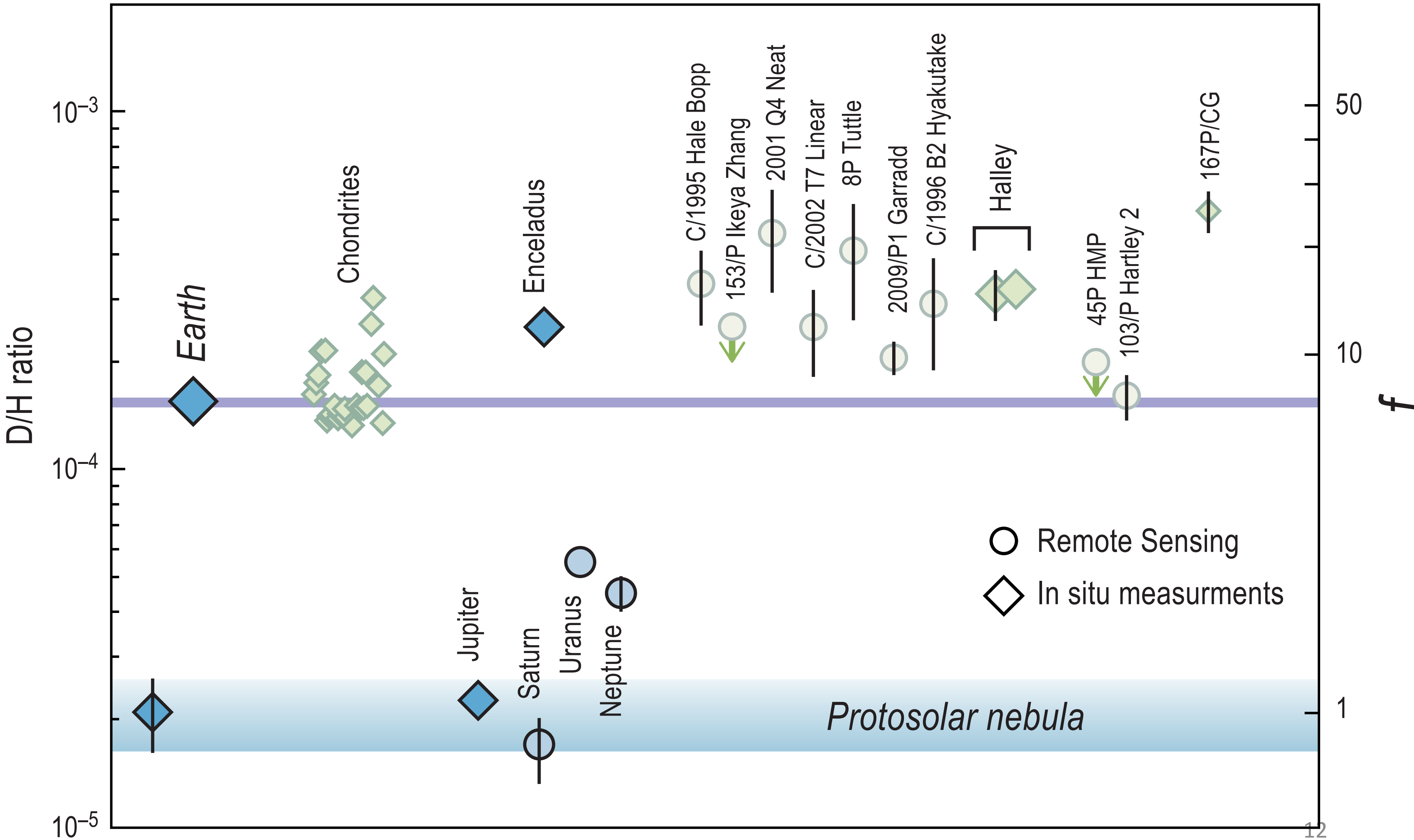


- Supply of life's ingredients to terrestrial worlds: OSS observations of > 100 comets for 200 hours

Measurements of Disk Mass



How was water delivered to Earth?



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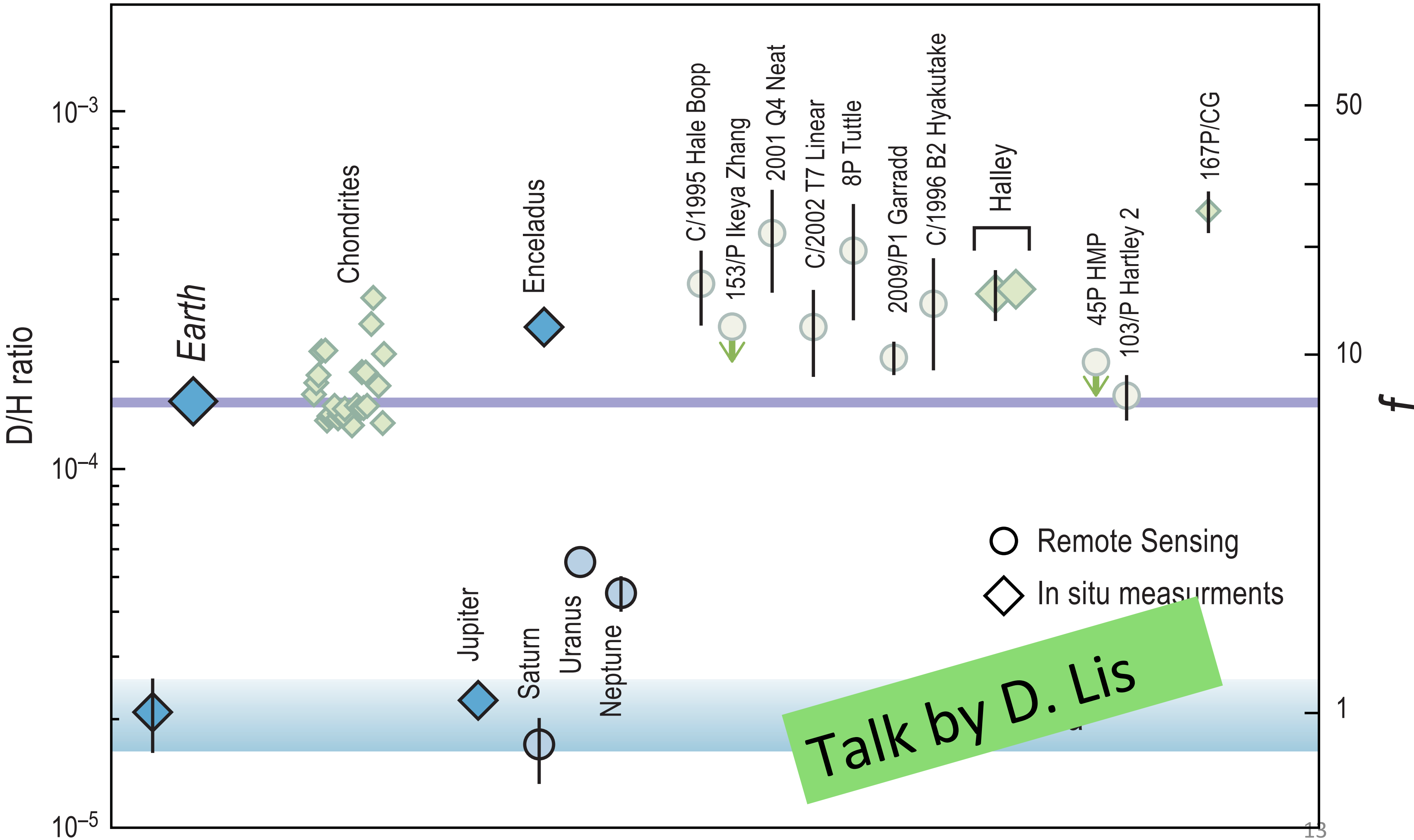
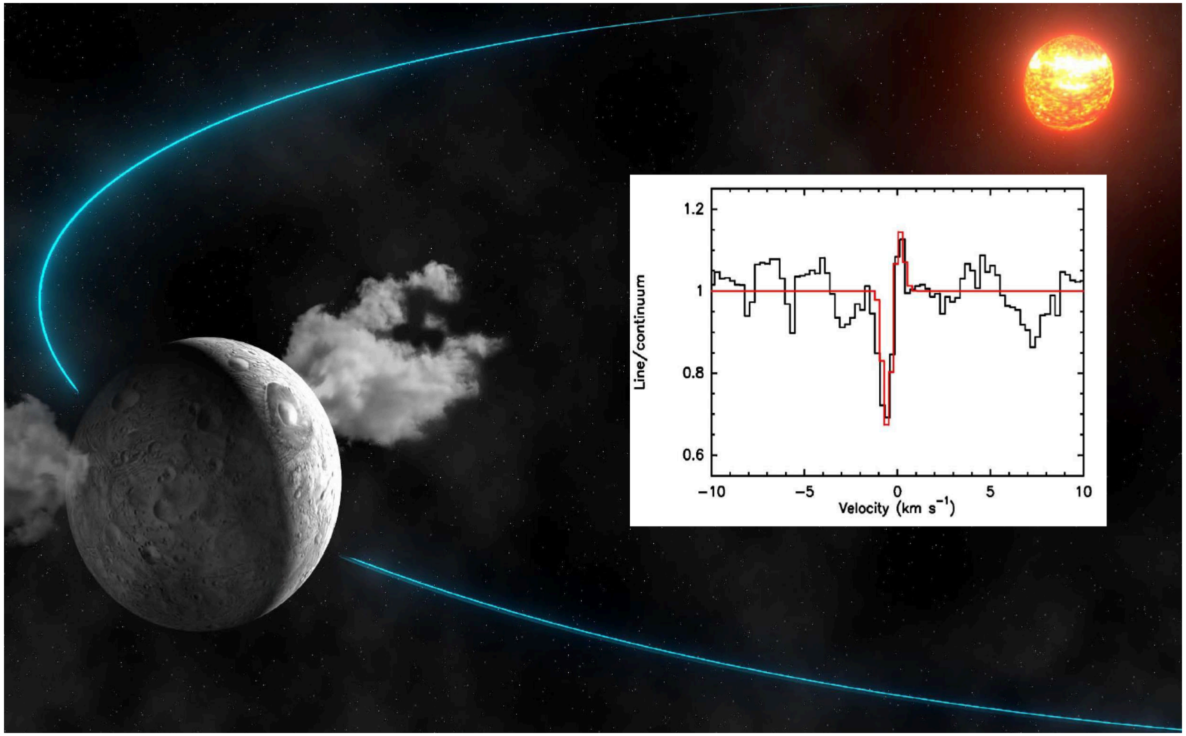


Water in the Solar System

Water is ubiquitous in our Solar System



Water the dwarf planet Ceres. (Kueppers et al, 2014, Nature).

Water in the Solar System

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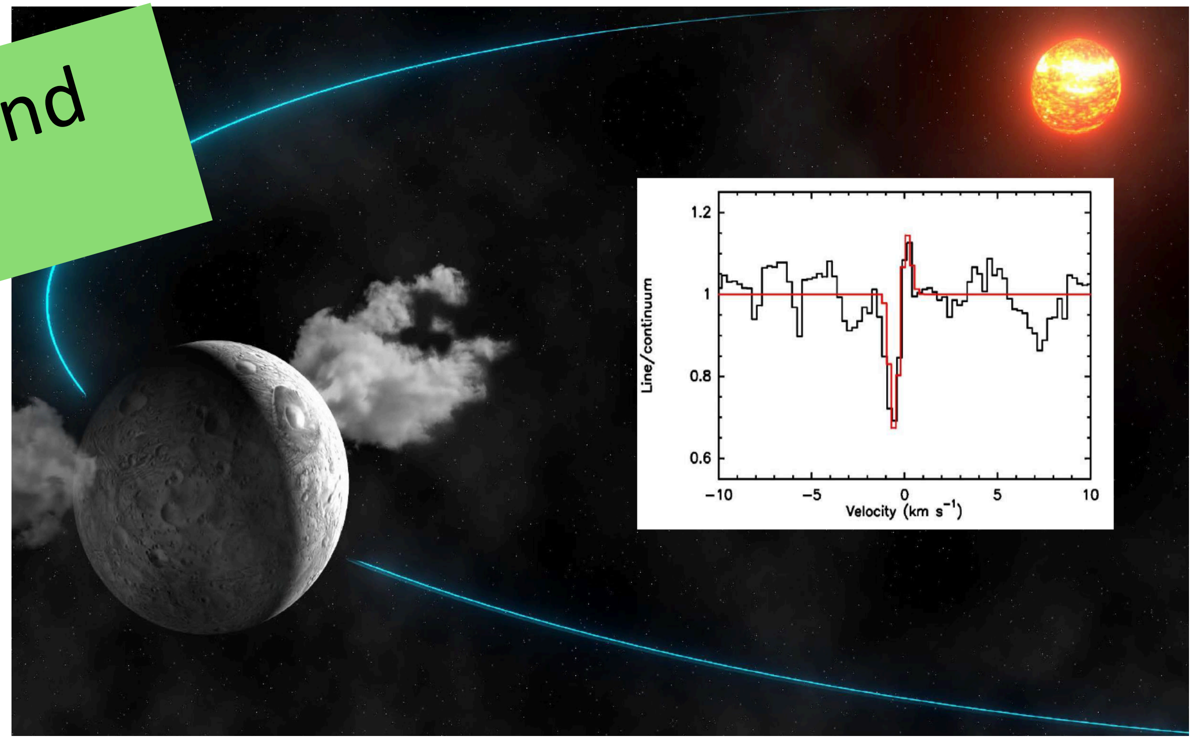
Talk by D. Lis and P. Hartogh



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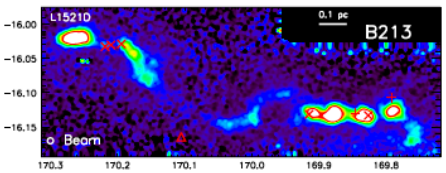
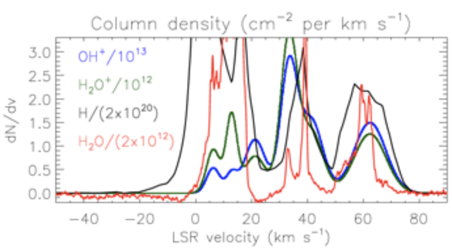
ORIGINS Space Telescope

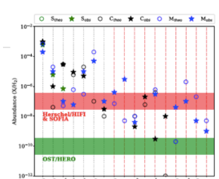
Key Science Drivers



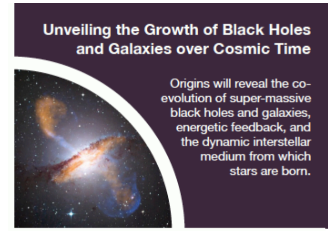
- The Trail of Water (H_2O, $H_2{}^{18}O$, HDO)



- Determining the Cosmic Ray Flux in the Milky Way and in Nearby Galaxies

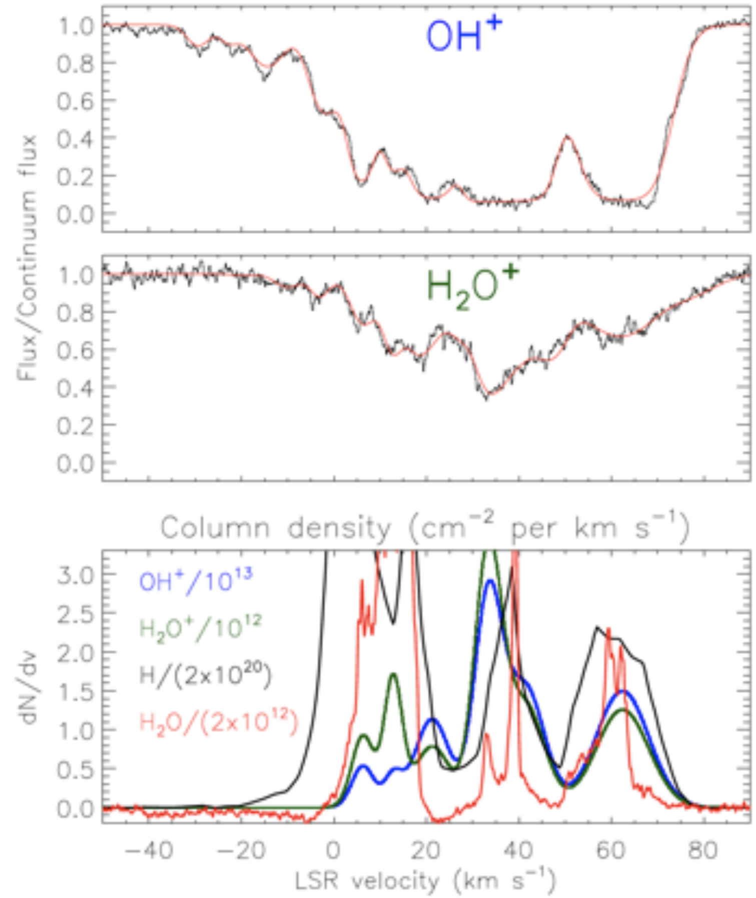


- Fundamentals of Dust Formation and Evolved Stars



Cosmic Ray Flux in the Milky Way and Nearby Galaxies

Low-energy cosmic-rays (CR) **control the heating, ionization and chemistry** of dense molecular clouds. In 100 hours, high-resolution spectroscopy with HERO can determine **cosmic ray ionization rate** along 40 sight-lines — addressing key questions about **the origin and distribution of cosmic rays.**



Herschel/HIFI absoprtion spectra obtained toward an extremely bright continuum source (Neufeld+ 2010)

(1) what is the typical The Cosmic Ray Flux in the Milky Way and Nearby Galaxies as a function of Galactocentric distance?
(2) how much does the CRIR vary from one molecular cloud to another?
(3) to what extent are CR excluded from dense molecular clouds?
(4) what are the sources (e.g. SNR) of low-energy CR?

The Origins Space Telescope:
Maryvonne Gerin, D. Neufeld

Slide by C. Battersby

Dust Formation around Evolved Stars

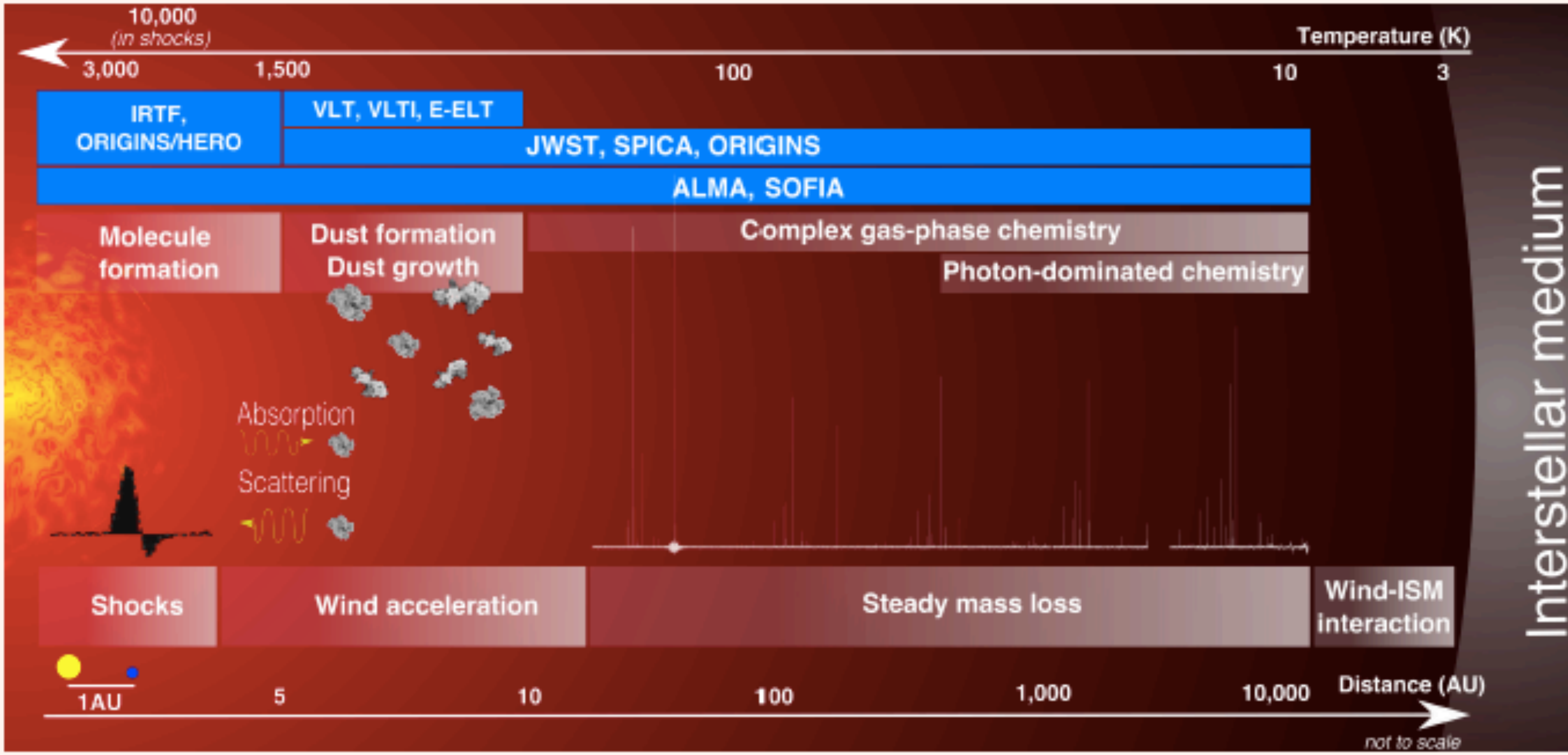
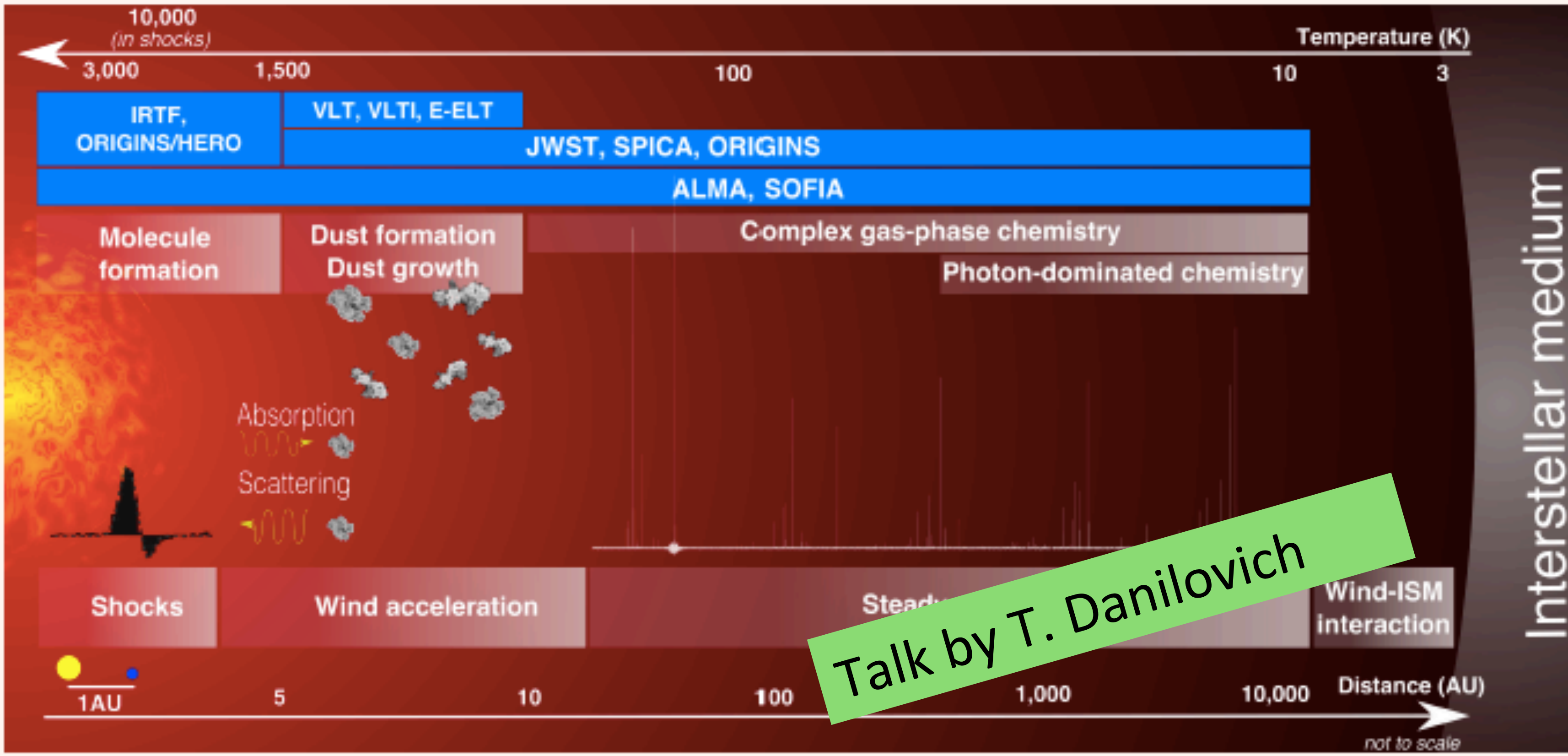


Figure 2: AGB outflow structure. *White boxes:* major chemical and physical processes, *blue boxes:* contribution of existing, planned, and proposed facilities.

From E. de Beck, Astro 2020 White Paper

Evolved Stars



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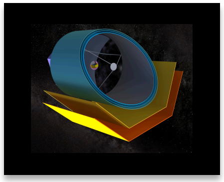
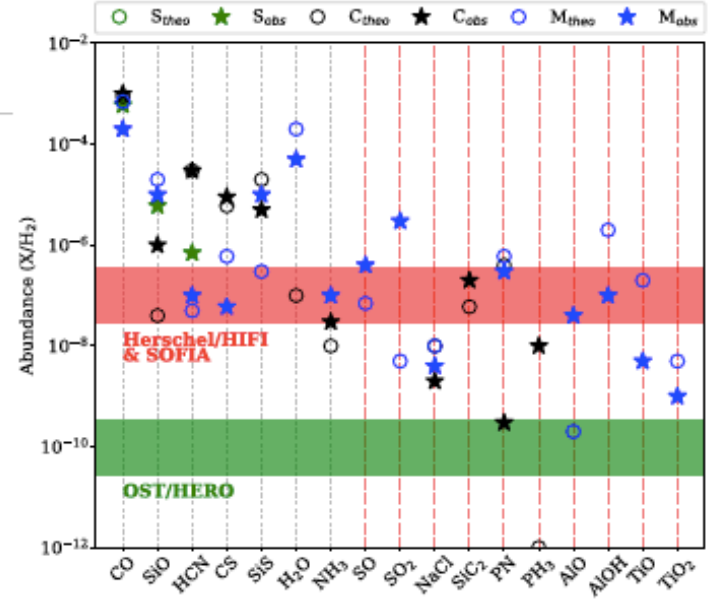


The birth path of dust

Goal

GAS >>?>> SOLID

- Identify molecules responsible for the formation of grains
- Identify molecules involved in the growth of grains
- Characterise cold dust



Observations

HERO: High-excitation transitions (> a few 100K) of some usual suspects containing e.g. Si, Al, Ti, Mg, Ca

+

OSS: MIR/FIR continuum observations of cold dust.

Models / results

<u>Gas phase</u>: depletion, in-situ formation (e.g. evaporation)
<u>Solid phase</u>: first grains (seeds), grain growth
<u>Mixed</u>: grain-surface reactions
<u>Mass-loss determination and wind dynamics</u>: dust properties as input

Outflows of evolved stars are the **only** sites where we can directly probe **dust grain formation**!

Heterodyne resolution is essential to disentangle the physics and the chemistry!

Slide by E. de Beck

Science Traceability

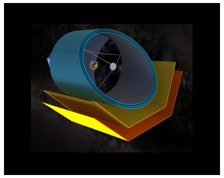
Science Objectives (Wide ranging. We highlight examples.)	Science Requirements		Instrument Requirements			
	Science Observable	**Measurement Requirement**	**Parameter**	**Technical Requirement**	**Ins**	**CBE Performance**
Case #3: Measure the water mass at all evo-lutionary stages of star and planet formation and across the range of stellar masses, tracing water vapor and ice at all temperatures between 10 and 1000 K. (Section B.2; An upscope science case to Theme-2 Objective #1)	Measure water (H_2O) content of starless cores in diverse environments. High spectral resolution follow up of young disks in proto-stars to determine the distribution of water within the disks	Line flux density of ortho H_2O 538 µm, para H_2O 269 µm, and other low energy transitions of water and its isotopes to sensitivity limit 1×10^{-20} W m^{-2} (3 mK) per 0.3 km s^{-1} velocity channel (5σ) to obtain spectrally resolved line profiles of 10 known starless cores and young disks in 100 h with spatial resolution ≤ 0.1 pc	Wavelength range	180µm to 550 µm	HERO (Up-scope Instrument)	111–617 µm
			Spectral resolving power R=λ/Δλ	$\geq10^6$ for velocity resolution		up to 10^7
			Angular reso-lution	≤ 25″ at 538 µm to resolve starless cores		23″ at 538 µm
			Field of view	1′ x 1′ to map starless cores		2′ x 2′
			Spectral line sensitivity	1×10^{-20} W m^{-2} per velocity channel (3 mK), 1 h (5σ)		6×10^{-21} W m^{-2} per velocity channel at 538 µm, 1 h (5σ)

Requirements:
180 to 550 microns
> 10^6 resolution
< 25”
1’ x 1’ array
1 x 10^{-20} Wm^{-2}

ORIGINS Space Telescope

HEterodyne Receiver for Origins (Modest Imaging Spectrometer)

ORIGINS Space Telescope

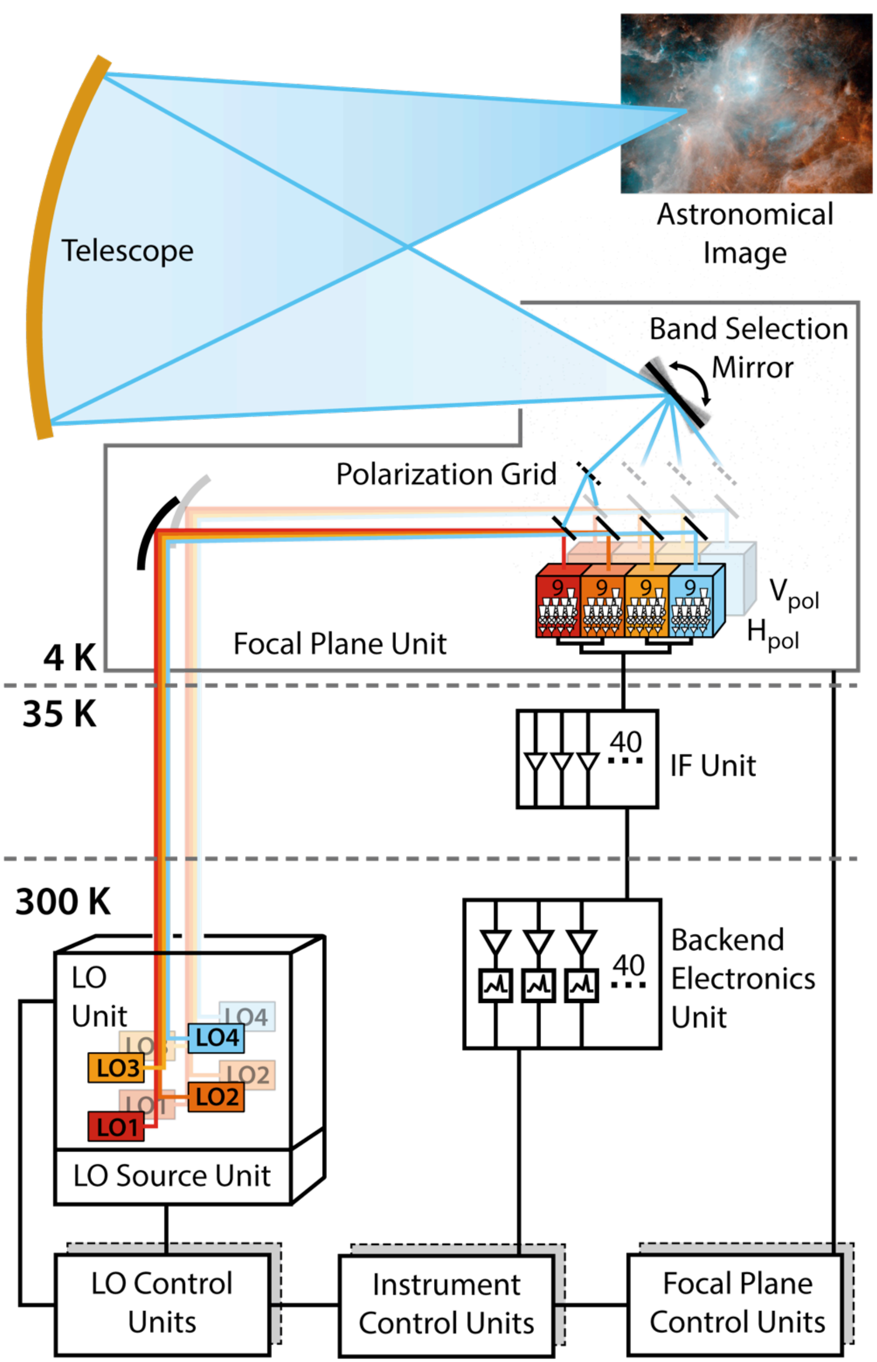


Little HERO fact sheet

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_2O**, **$H_2^{18}O$,** HDO NH_3	50	2.6	6.4 E-21
2	756	1188	397	252	10^7	2469	SIS	2x9	**H_2O, $H_2^{18}O$** H_3O^+	100	4.2	1.6 E-20
3	1188	1782	252	168	10^7	1616	HEB	2x9	**H_2O**, **$H_2^{18}O$** 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

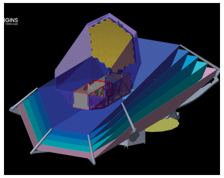
12 Receiver noise for 1h integration at 10^6 resolution (0.3 km/s) using one polarization.
13 Detectable point source line flux at 5 sigma, for 1h pointed integration (on+off source) in two polarization, with a 5.9 m primary mirror (coll area $25m^2$, app eff 0.8) as designed for OST Concept 2.

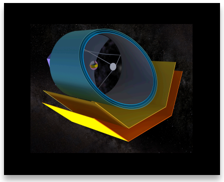


Heterodyne Focal Plane Array with wide RF

- $R = 10^6$ to 10^7
- 486 – 2700 GHz
- 6 GHz IF (goal 8 GHz)
- 3 x 3 FPA
- 2 polarizations

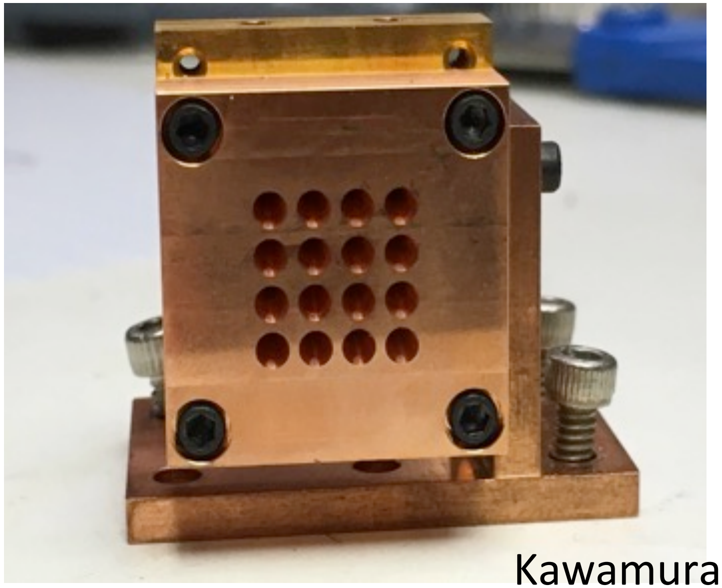
Satellite Constraints:
- Cooling power
- Power
- Mass, Volume





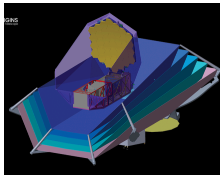
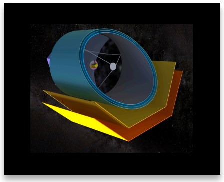
Mixers

- 3 x 3 x 2 polarizations SIS, 486-1188 GHz, 8 GHz BW
- 3 x 3 x 2 polarizations HEB, 1188 – 2700 GHz, 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

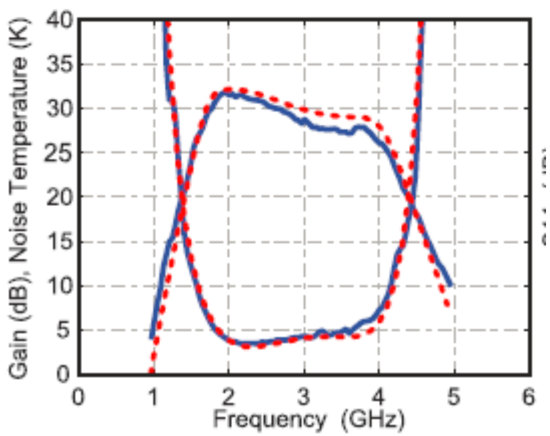
SiGe Amplifiers – Innovative technology

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

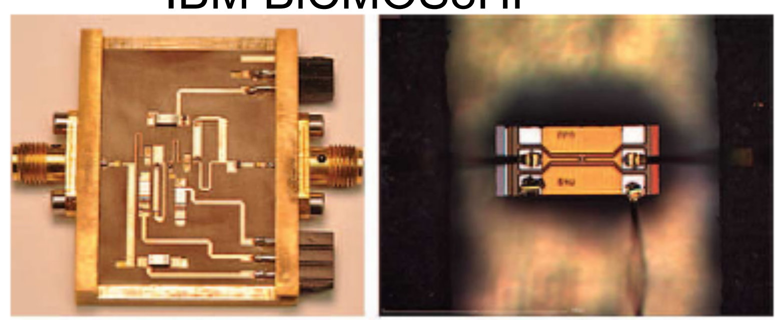
Ultra-Low-Power Cryogenic SiGe Low-Noise Amplifiers: Theory and Demonstration

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

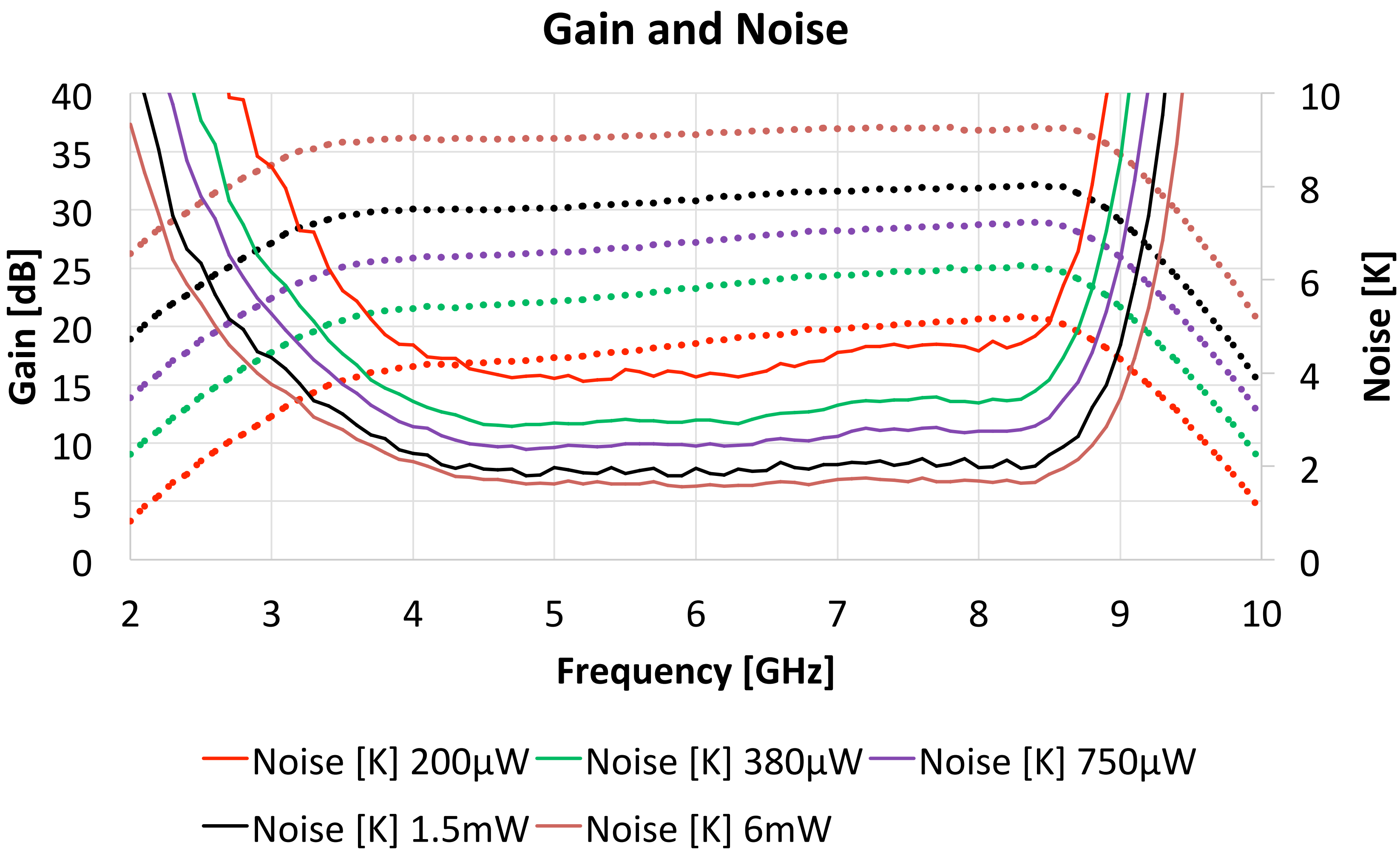
Band= 1.8-3.6 GHz
Pdis= 0.3 mW
IBM BiCMOS8HP



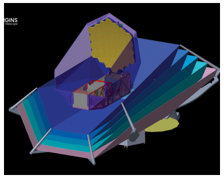
(a)


(a) (b)

InP Amplifiers

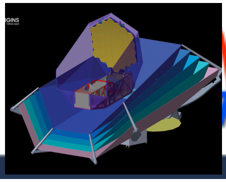


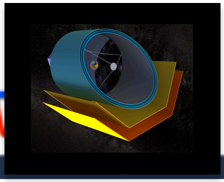
Data by J. Schleeh, Low Noise Factory.



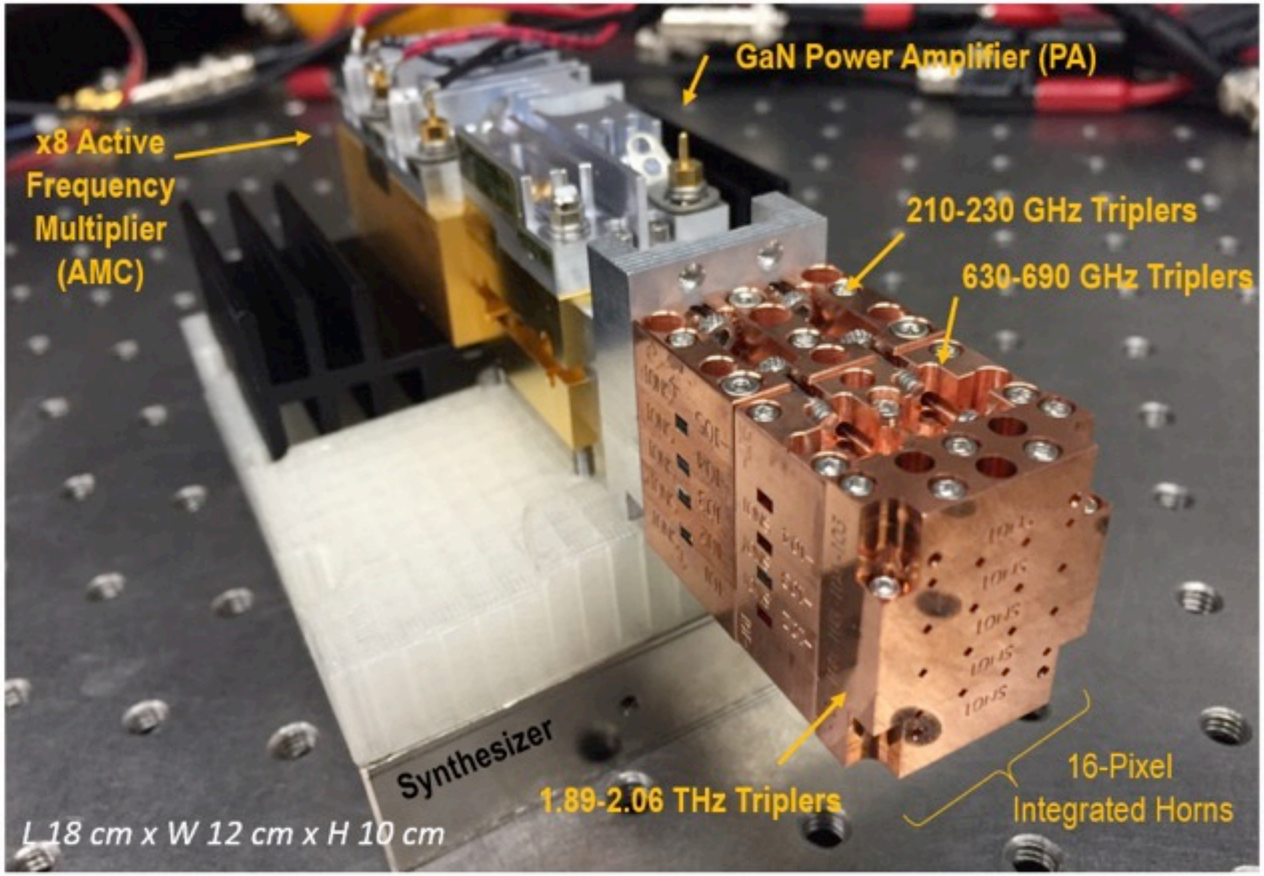
Local Oscillator

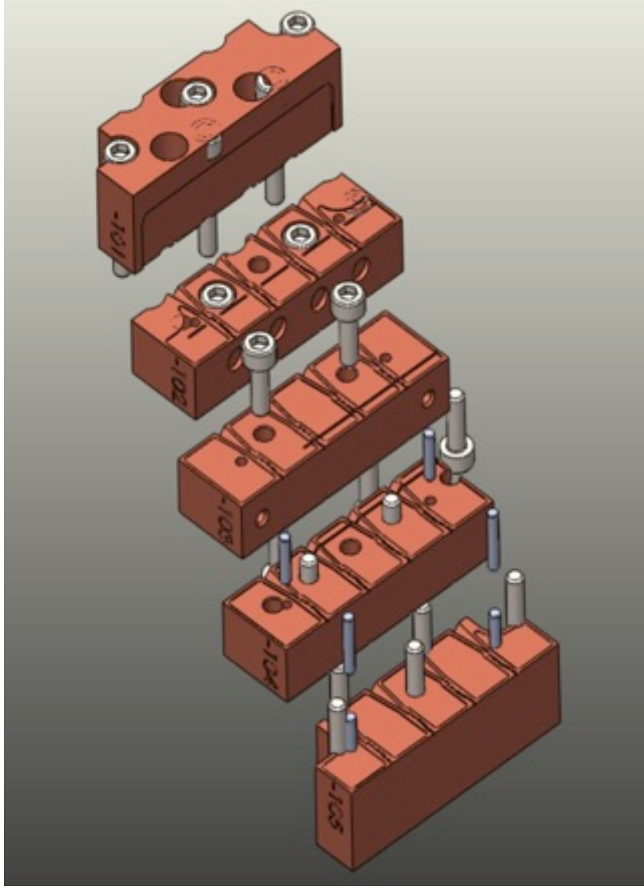
- Amplifier-Multiplier chains at room temp (1W/pixel)
- Beam division in AMC
- LO source unit around 100GHz (1W/pixels)





16-pixel 1.9 THz lo system: STACKING

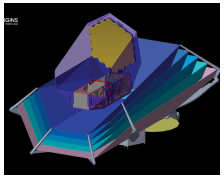
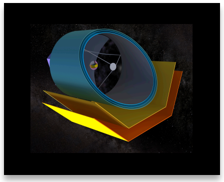




The LO module can be mounted with either two or four 1x4 pixel layers vertically stacked to form 8-pixels or 16-pixel configurations..

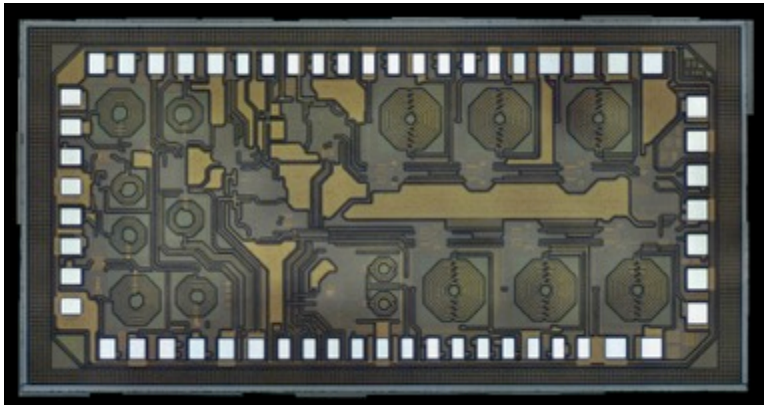
Power Consumption= 2.3 Watts/pixel or 1.25 Watts/pixel using W-band CMOS synthesizers

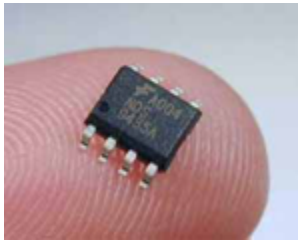
X3X3X3 Architecture

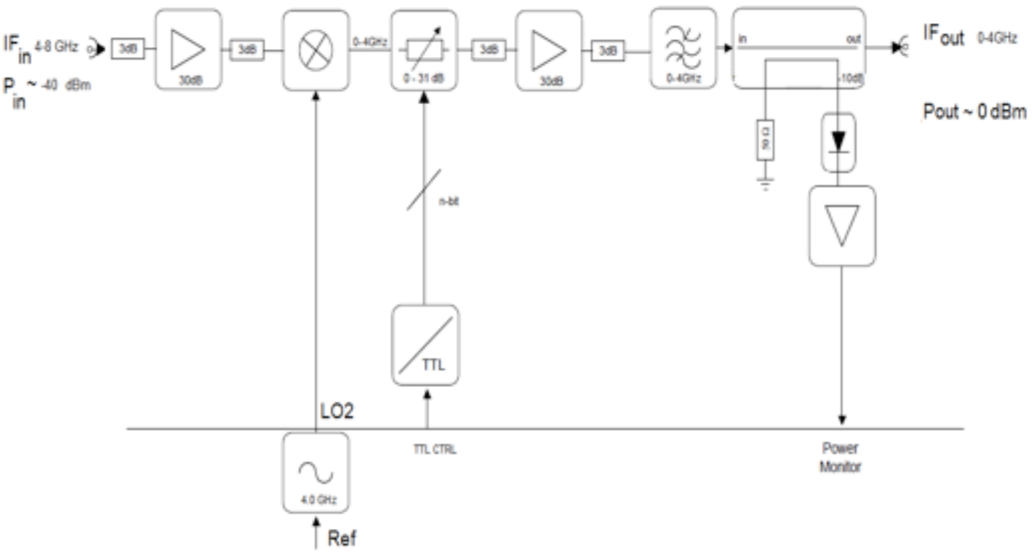



Warm IF chain

- 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.







Max-Planck-Institut für Radioastronomie

digital Signal Processing dSP

MPIfR dFFTS4G spectrometer

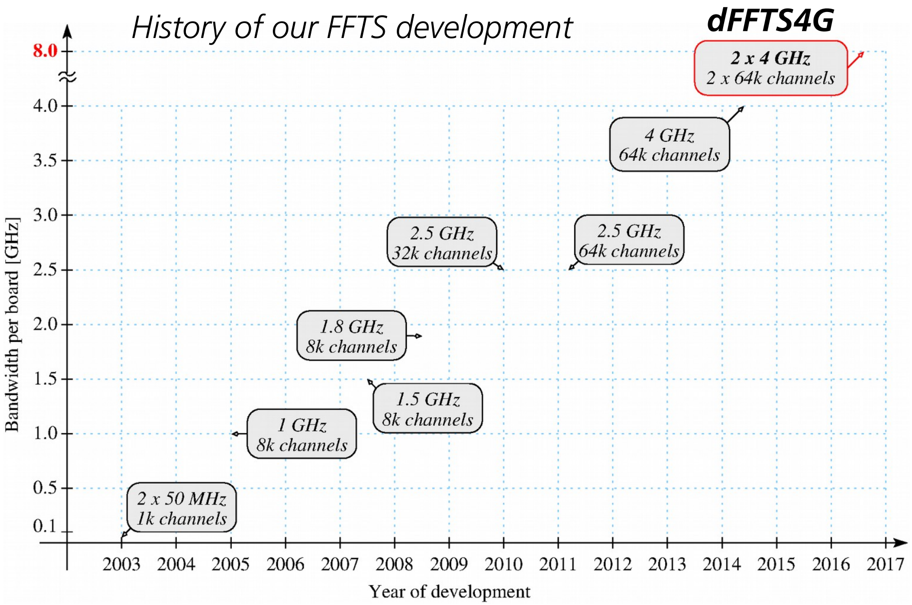


Photo: dFFTS4G spectrometer crate

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)

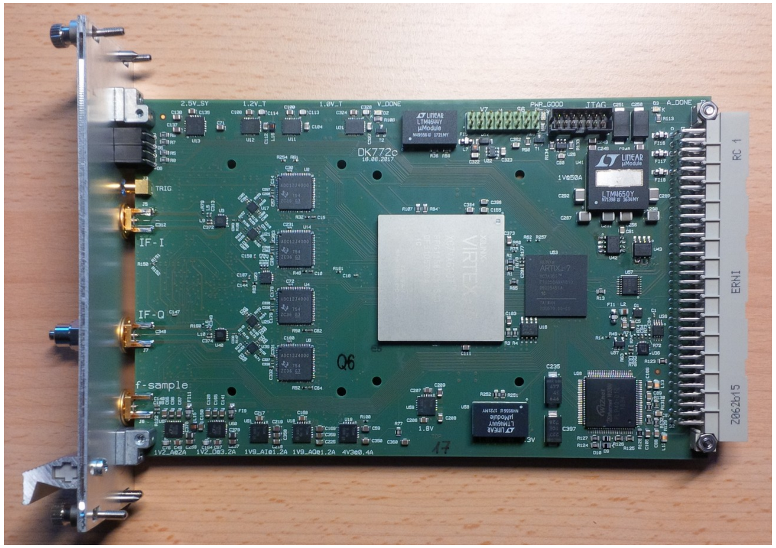
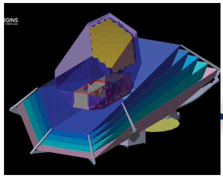


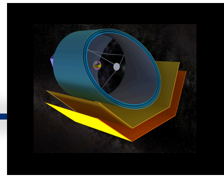
Photo: dFFTS4G spectrometer board

Technical specifications of a dFFTS4G 19” crate :

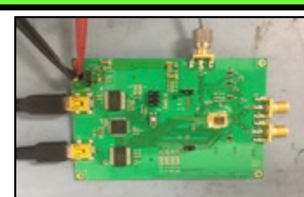
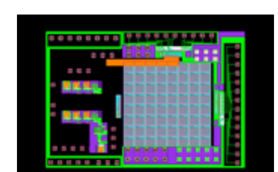
- Total bandwidth: 8 x 2 x 4 GHz = 64 GHz
- Spectral channels: 8 x 2 x 64k = 1 Million (1024k)

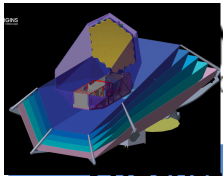
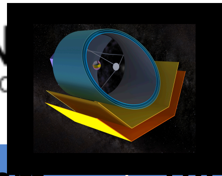
Bernd Klein, 2018





Existing Spectrometer Comparison

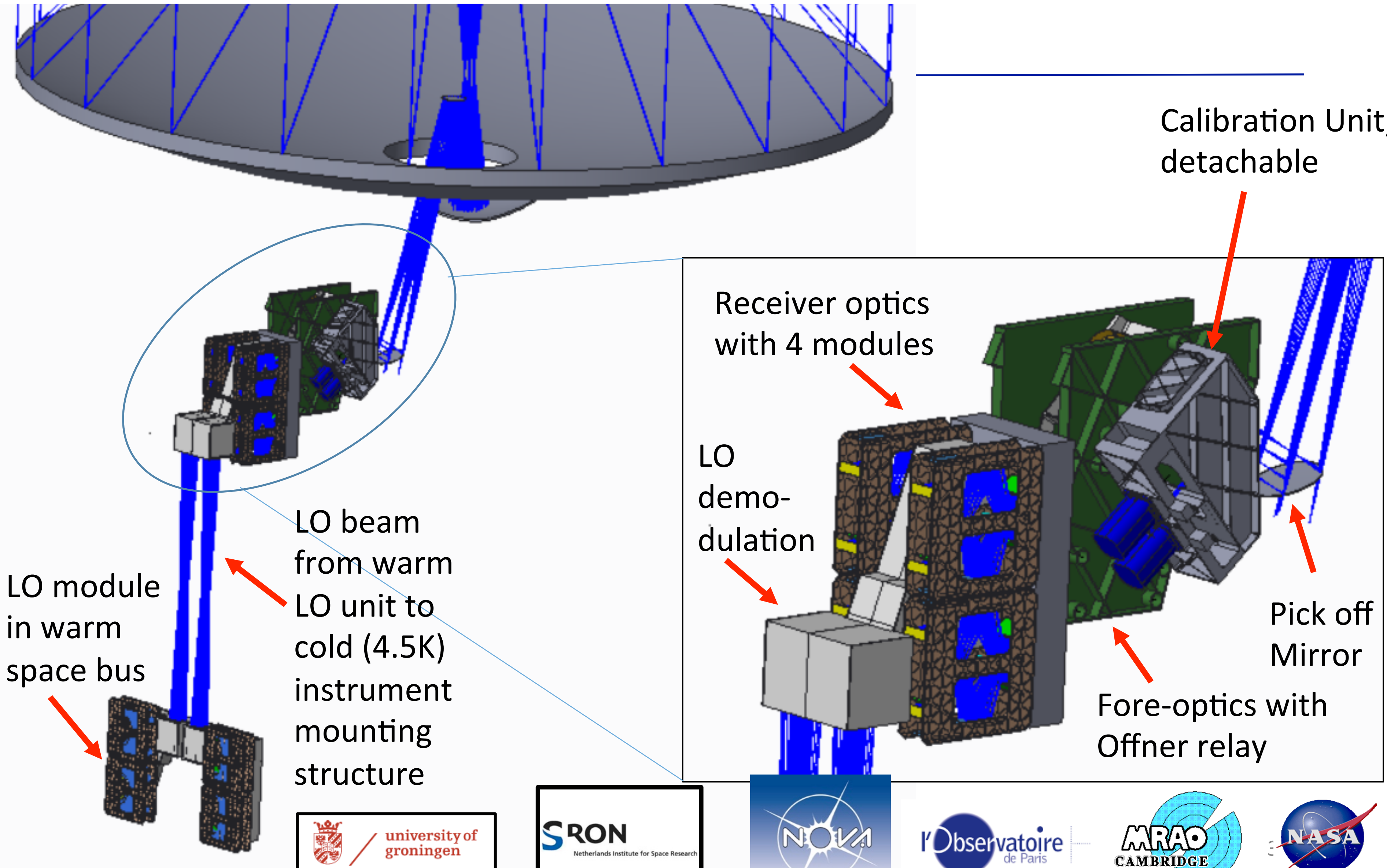
Design Parameter	Demonstrated CMOS Spectrometer System	
	Spectrochip SVII Spectrometer (UCLA/JPL) 2017 [3]	Spectrochip SVIII Spectrometer (UCLA/JPL) Available Late 2018
Processor Bandwidth (MHz)	3000	6000
Channel Count (#)	4096	8192
FFT Window Type	Hanning	PFB
FFT Format	Real	Real
Bit Resolution (#)	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
		

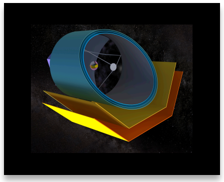
Subsystem Description	TRL N≤4	TRL N>4	Heritage	Comments
Multiplied LO, f <2THz	9	5	HERSCHEL, MIRO, STO-2, SOFIA, JUICE(SWI)	CMOS synthesizer for reduced power; higher output power for N>4; compact assembly
Multiplied LO, f>2 THz	6	4	HERSCHEL, STO-2, SOFIA	Higher power handling capability for lower stages; 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

HERO - optics



Calibration Unit, detachable
Receiver optics with 4 modules
LO demo-dulation
Pick off Mirror
Fore-optics with Offner relay
LO beam from warm LO unit to cold (4.5K) instrument mounting structure
LO module in warm space bus



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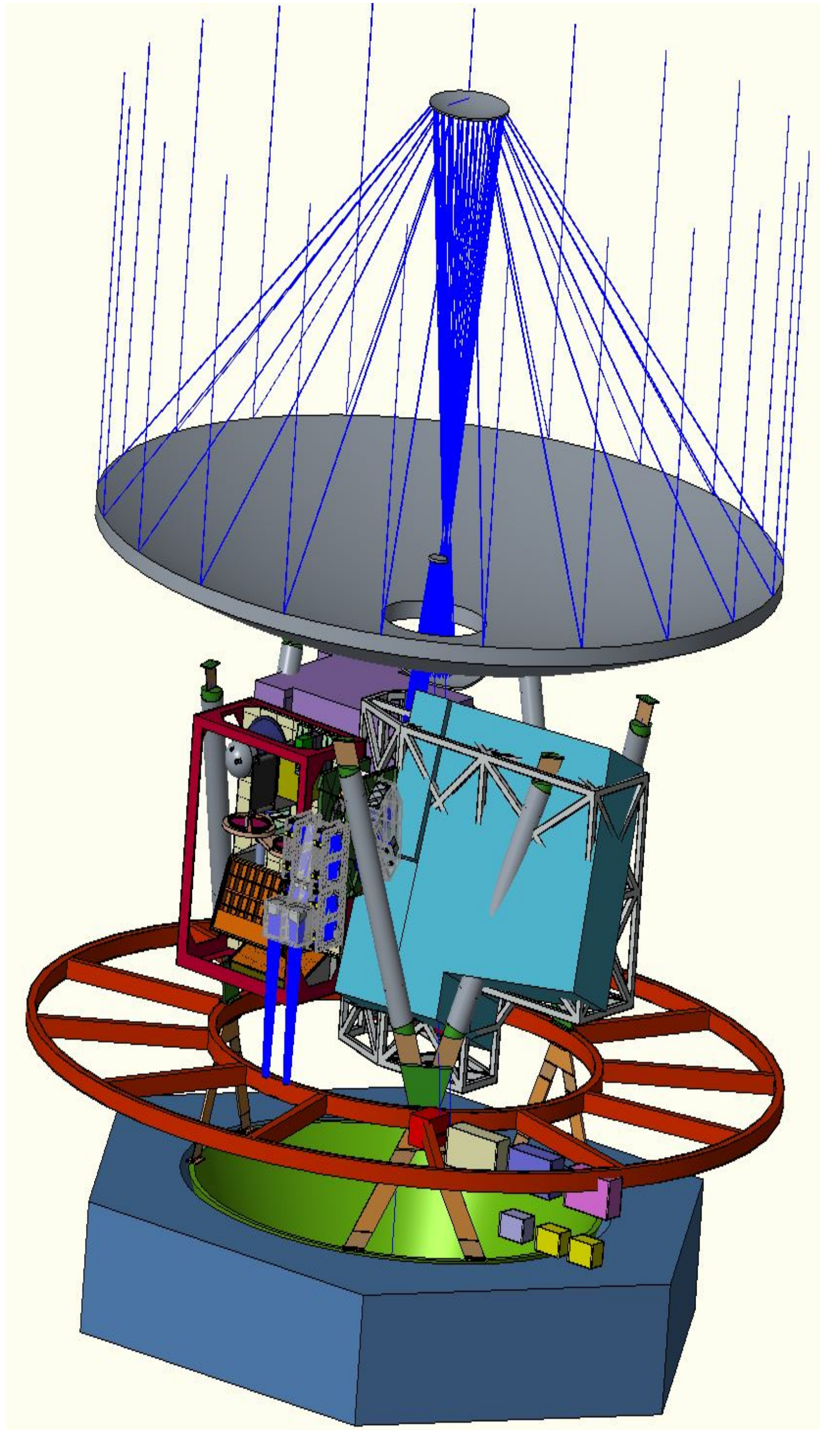
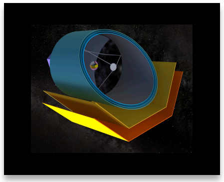
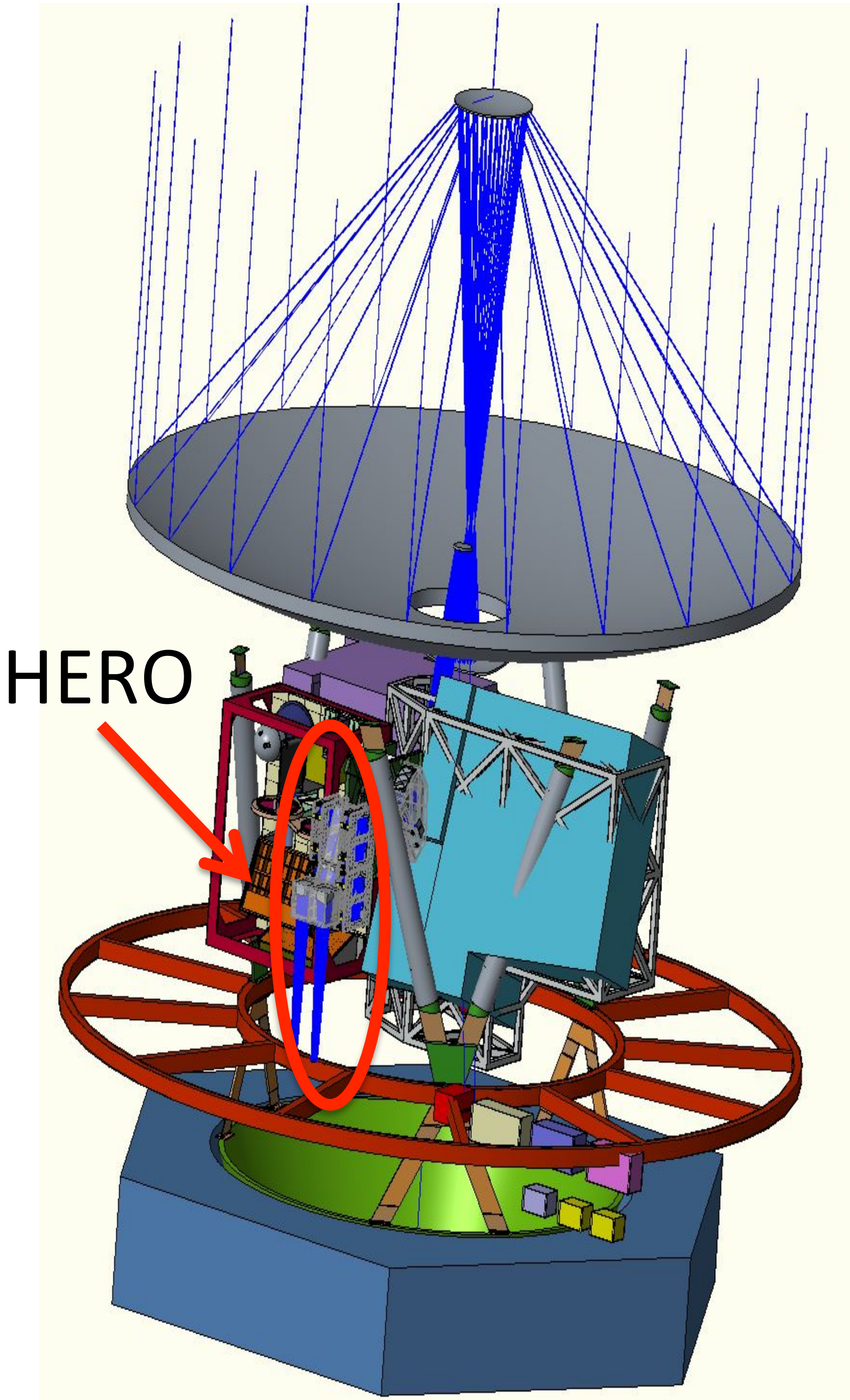
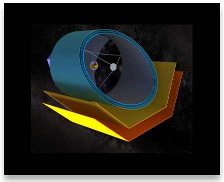






HERO



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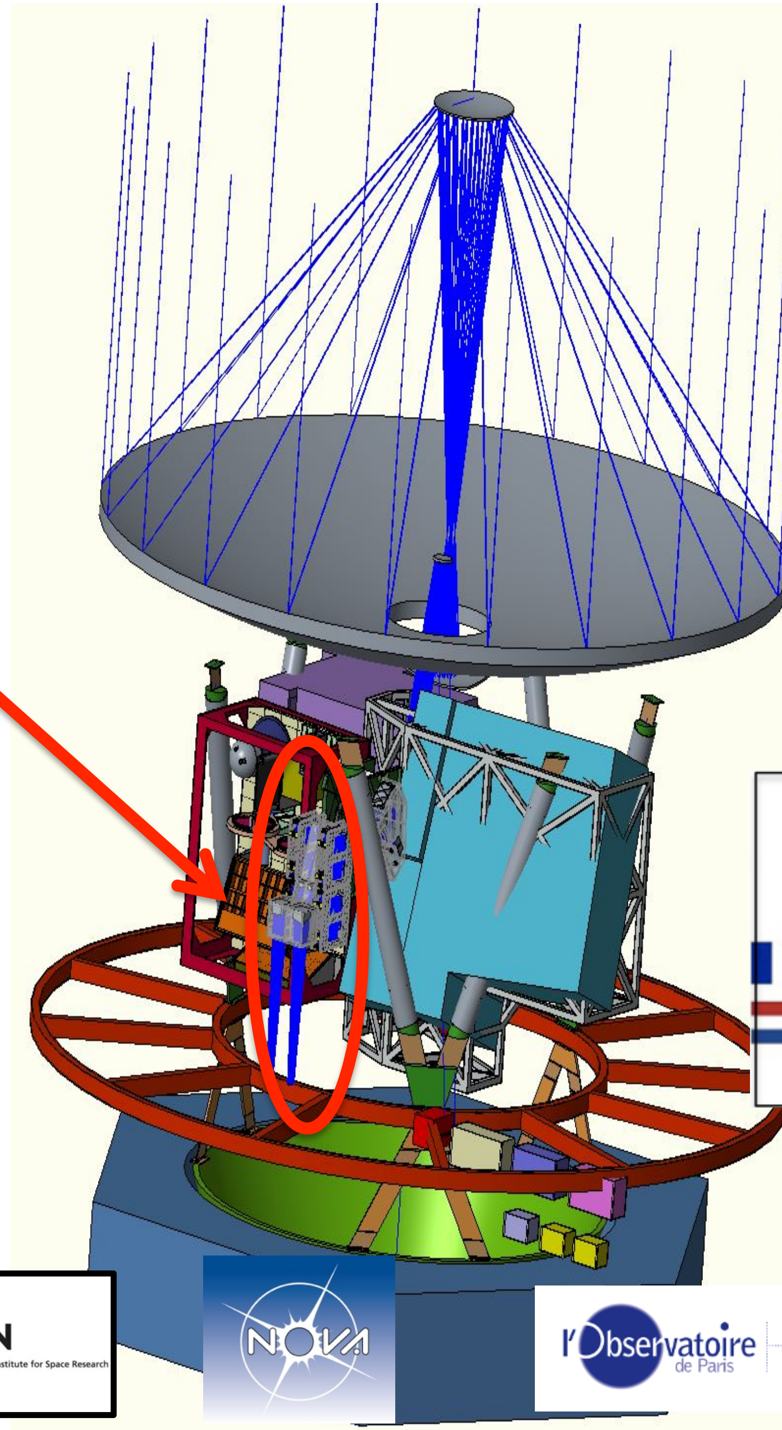
HERO on OST



Optical and Mechanical Design of little HERO:

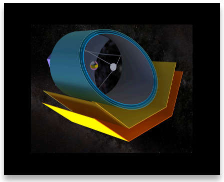
Willem Jellema (SRON)
Andrey Baryshev (Nova)
Richard Hills (MRAO, Cambridge)

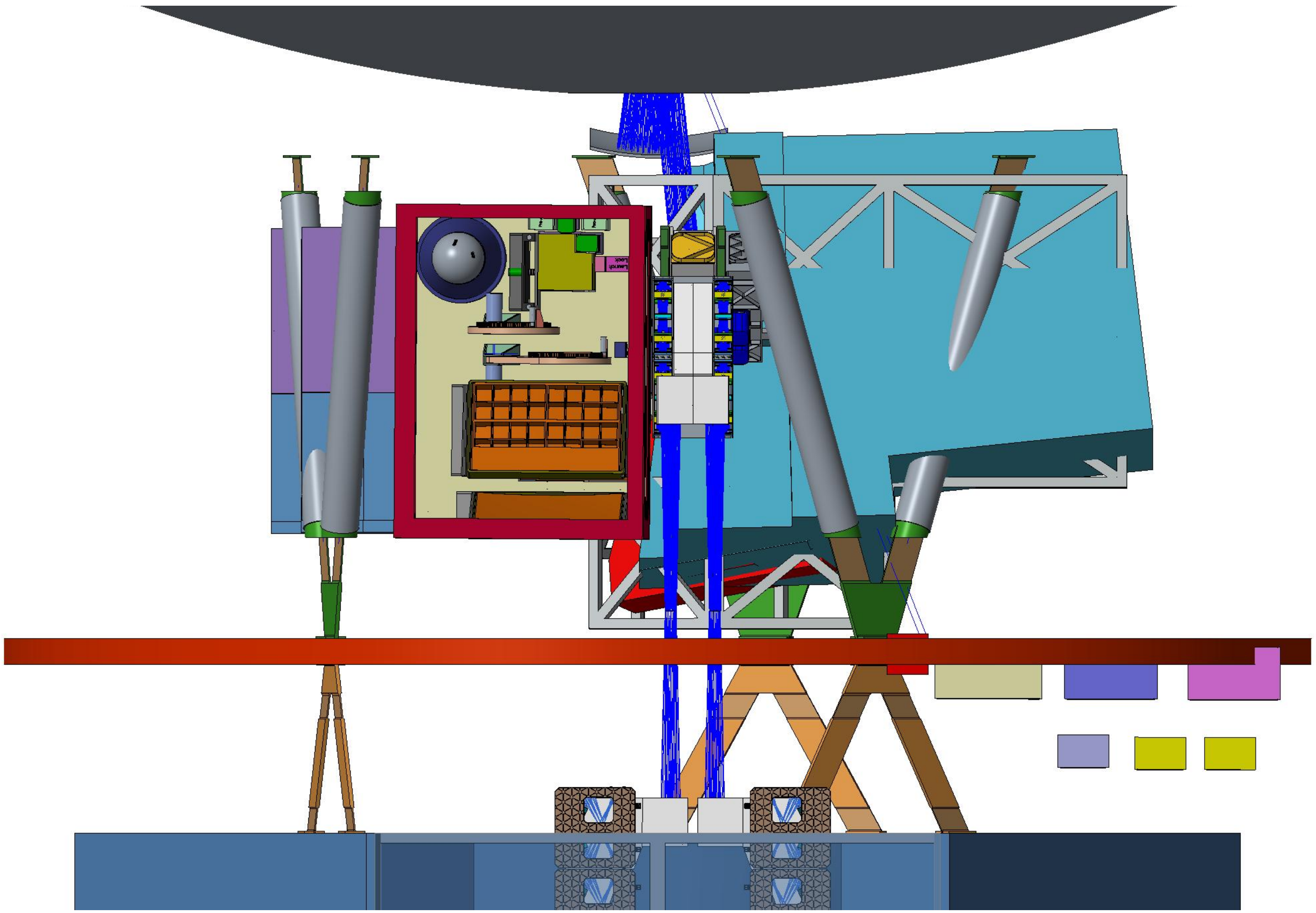
Optics

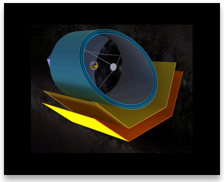
Bruno Borgo (LESIA, Paris)
Martin Eggens (SRON)
Geert Keizer (SRON)
Gabby Kroes (NOVA-OIR)
Napoléon Nguyen Tuong (LESIA, Paris)
Ramon Navarro, NOVA-OIR

Mechanics

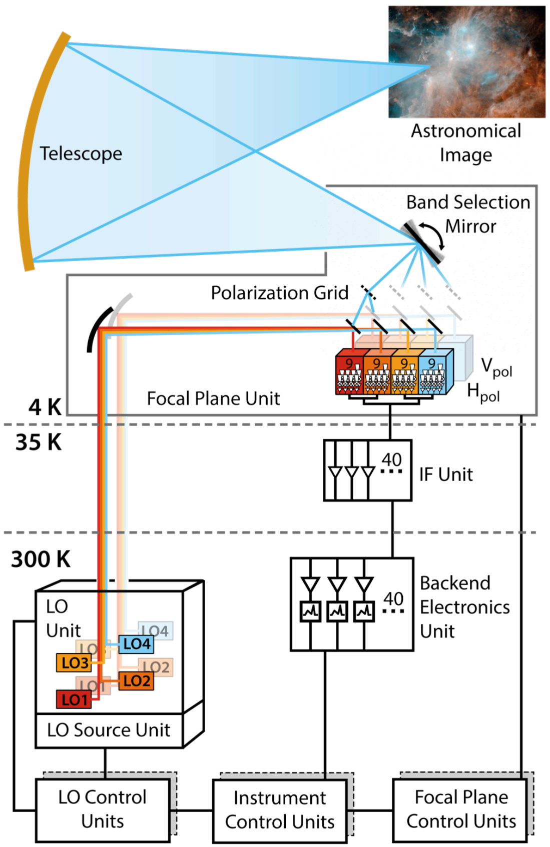
Little HERO on OST 2







Summary (little) HERO



- New generation heterodyne array receiver
- Builds on HIFI/Herschel, (up)GREAT, ALMA experience but surpasses it
- 2x9 pixels in 4 bands
- Frequency coverage: 486 – 2700 GHz
- Easily feasible, high TRL design

Millimetron Heterodyne Instrument for the Far-Infrared (MHIFI)

Bands: Red Priority-1; Grey, Possible Bands depending on science cases

Initial design based on Herschel HIFI

Band	Frequency (GHz/THz)	IFBW (GHz)/ Technology	Polarization	Array size/ Configuration
M1	**485 – 600**	**4-12 /(SIS)**	**H/V**	**3/Triangular**
M2	752 – 950	4-12 /(SIS)	H/V	3/Triangular
M3	**0.95 – 1.15**	**4-12 /(SIS)**	**H/V**	**7/Hexagonal**
M4	**1.60 – 2.10**	**1-6 /(HEB)**	**H/V**	**7/Hexagonal**
M5	2.45 – 3.00	1-6 /(HEB)	H/V	7/Hexagonal
M6	4.77 – 5.8	1-6 /(HEB)	H/V	7/Hexagonal
Post-cryo band	*500-600* *1.05-1.15*	*4 - 12 (Schottky)*	*H/V*	*Schottky diodes*

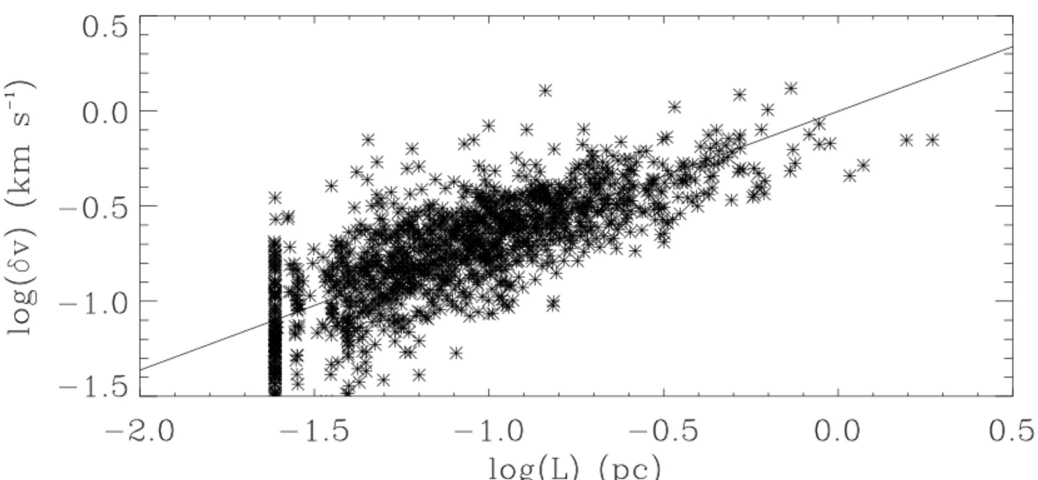

THINK
BIG

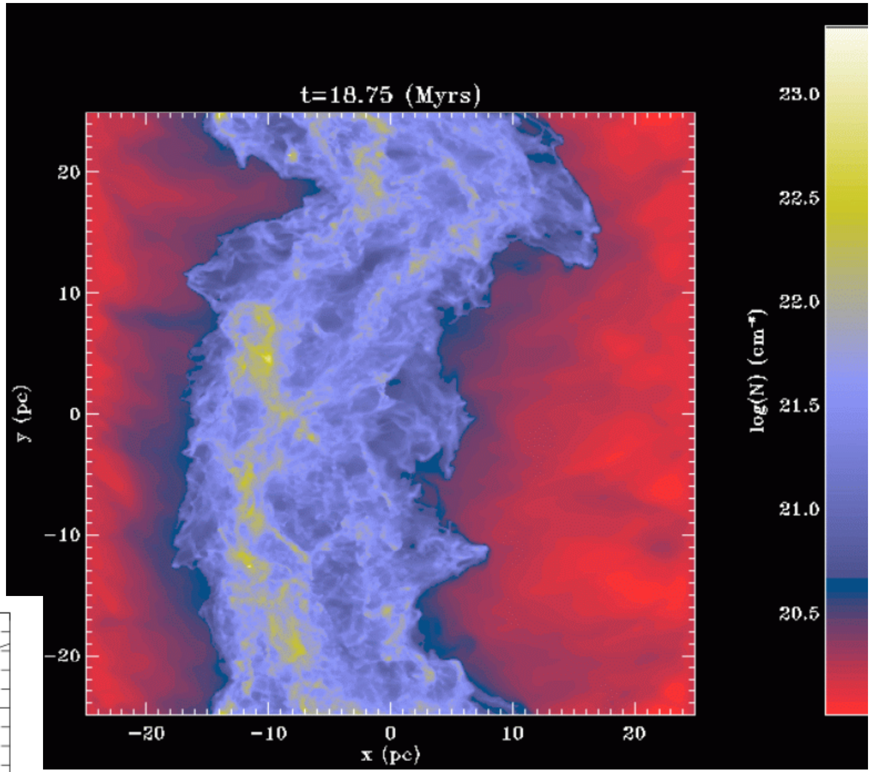
Turbulence in the ISM

ISM feeding as main driver of interstellar turbulence?

- Colliding flows unavoidably create turbulence
  - Mach-number of infall?
  - Impact relative to Galactic shear?
- Flows always chemically unstable
  - CO-dark material tracers

Size-linewidth relation of clumps in colliding flow



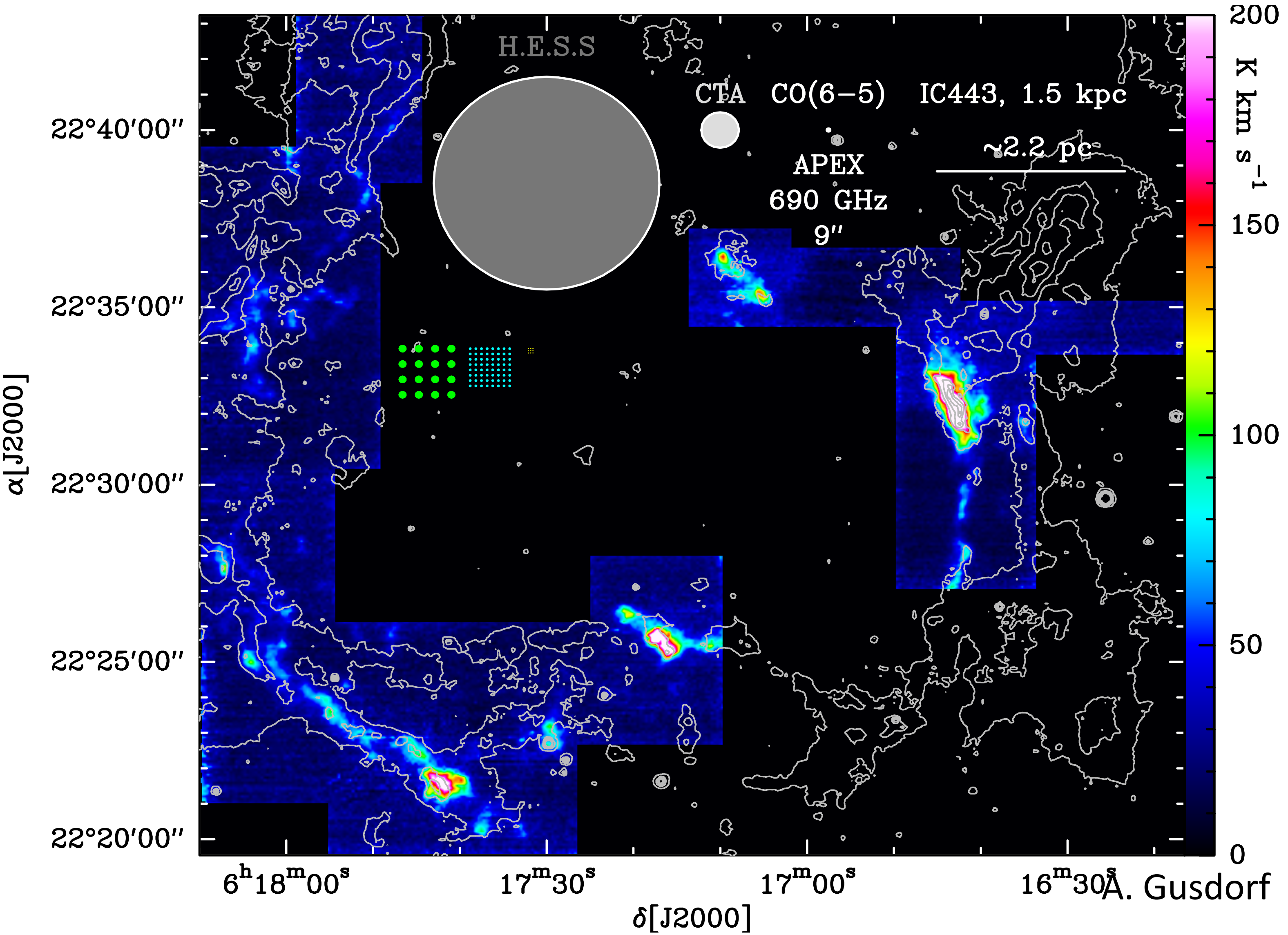


Colliding-flow simulation (column density map)

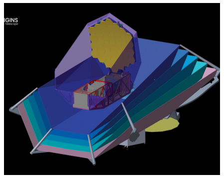
Klessen & Hennebelle (2010)

Slide by V. Ossenkopf-Okada

Spectral Line Mapping

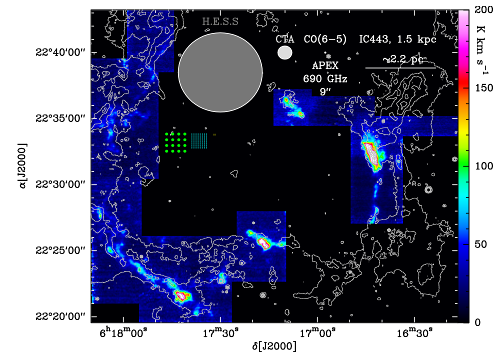


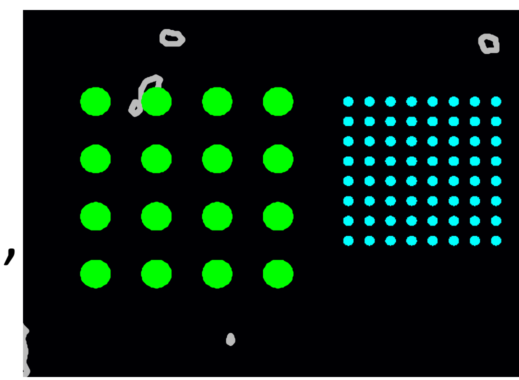
Á. Gusdorf

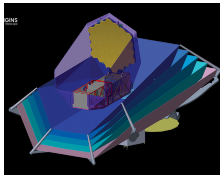


Observing modes

- 2 (linear) polarizations (pol. measurements possible)
- Focal Plan Arrays
  - with n pixels,
  - square arrays,
  - Separation two FWHM beams
  - 1 pixel 2SB (for calibration), n-1 pixels DSB
- 130 backend readouts,
  - can cover 2 bands/ dual frequency
  - Resolution configurable up to 10^7
- Calibration standard: internal hot/cold/pol,
- Sky chop (up to 3’) or selected off,
- Stare, dither, On-the-fly,







ORIGINS Space Telescope

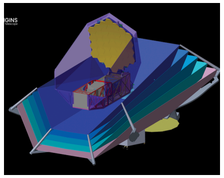
HERO's Fact Sheet

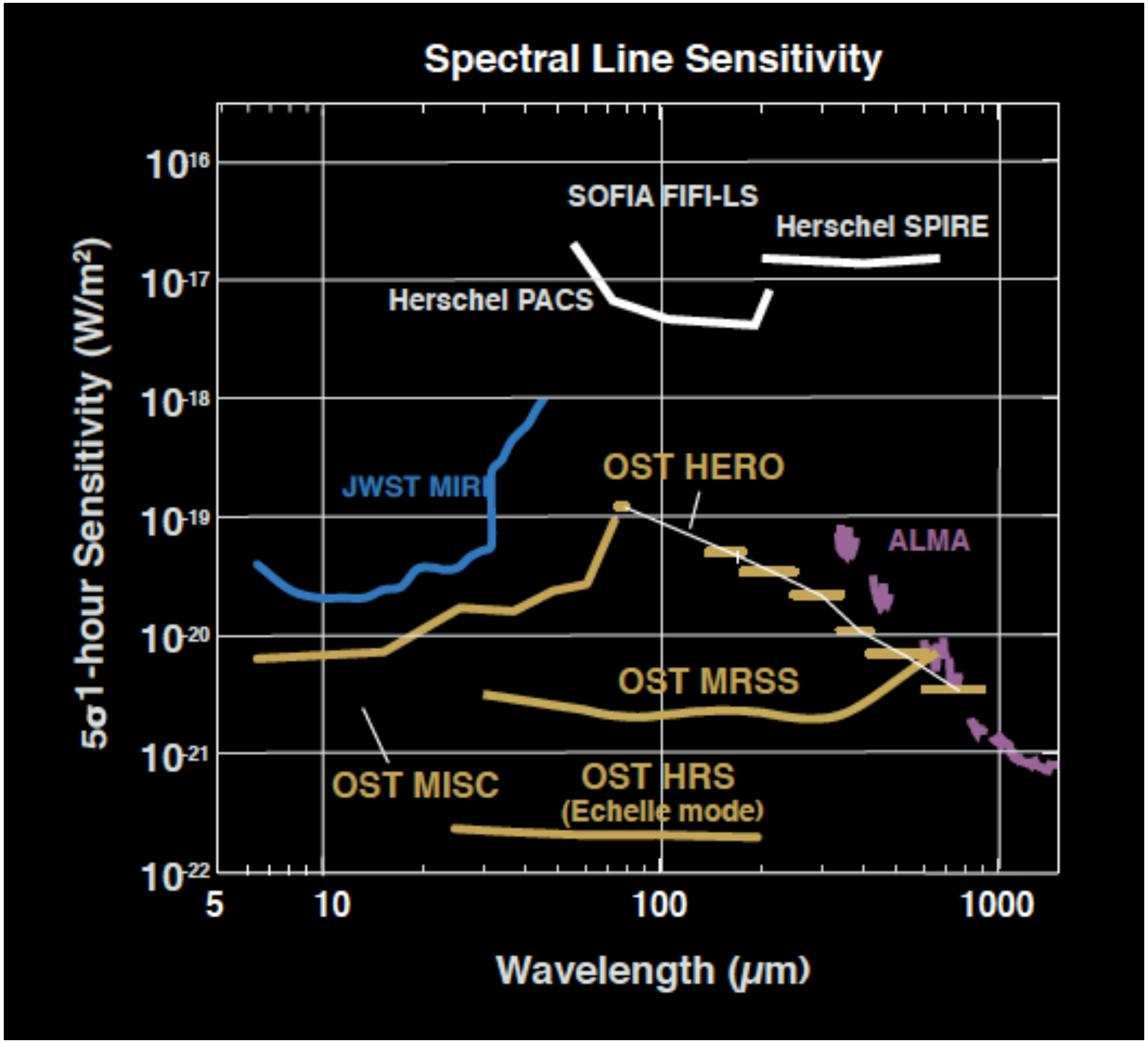
- Around 63μm, and 111 - 641μm
- 32 to 128 spatial pixels, each with ~8000 specral channels
- Resolution: up to $\Delta\lambda/\lambda = 10^7$

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

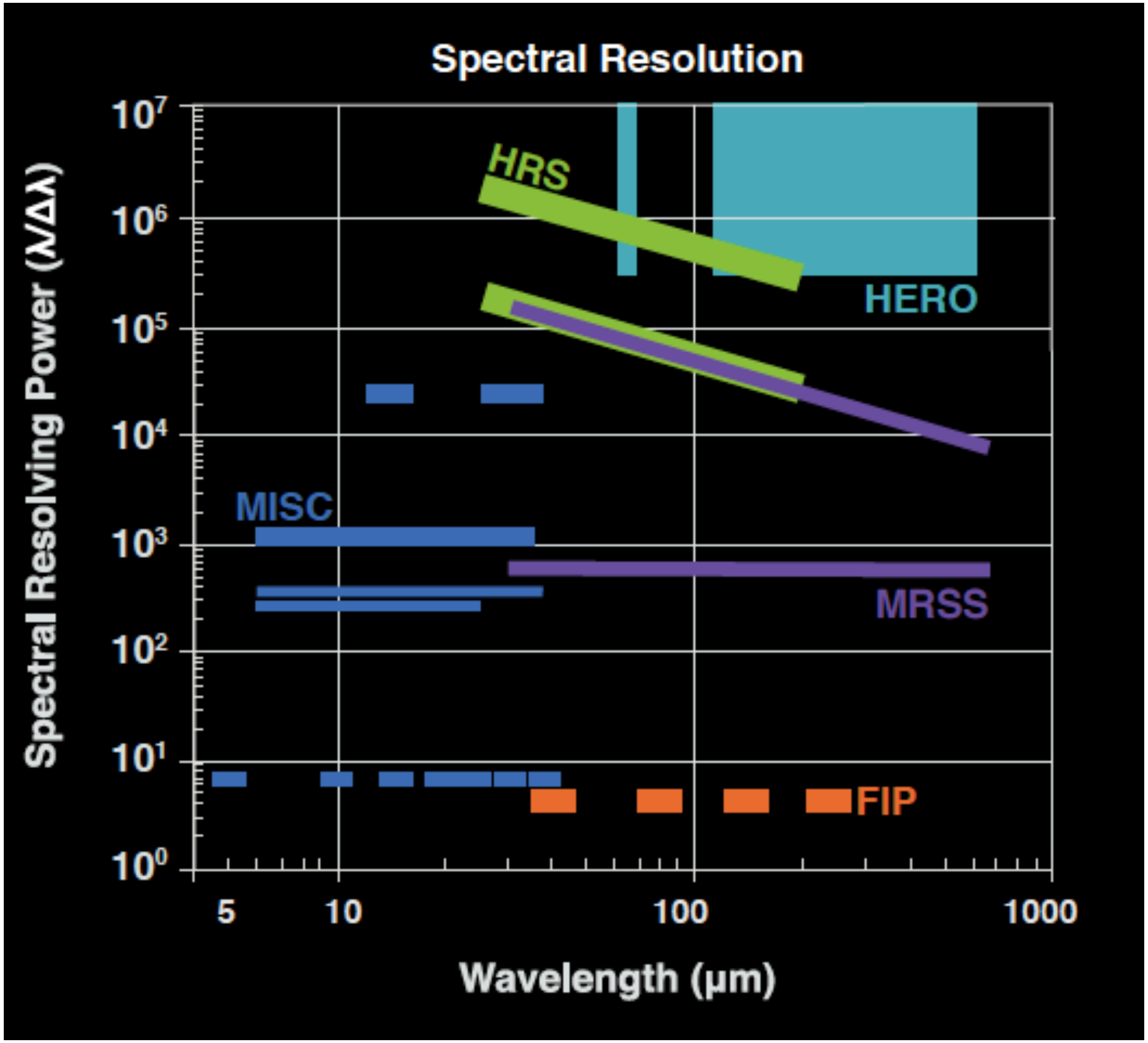
14 Receiver noise for 1h integration at 10^6 resolution (0.3 km/s) using one polarization.
15 Detectable point source line flux at 5 sigma, for 1h pointed integration (on+off source) in two polarization, with a 5.9 m primary mirror (app eff. 0.9) as designed for OST Concept 1.

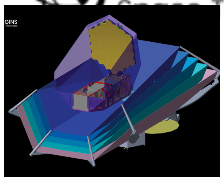
Instrument Performance

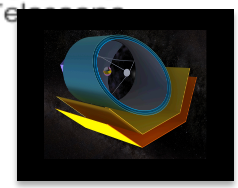




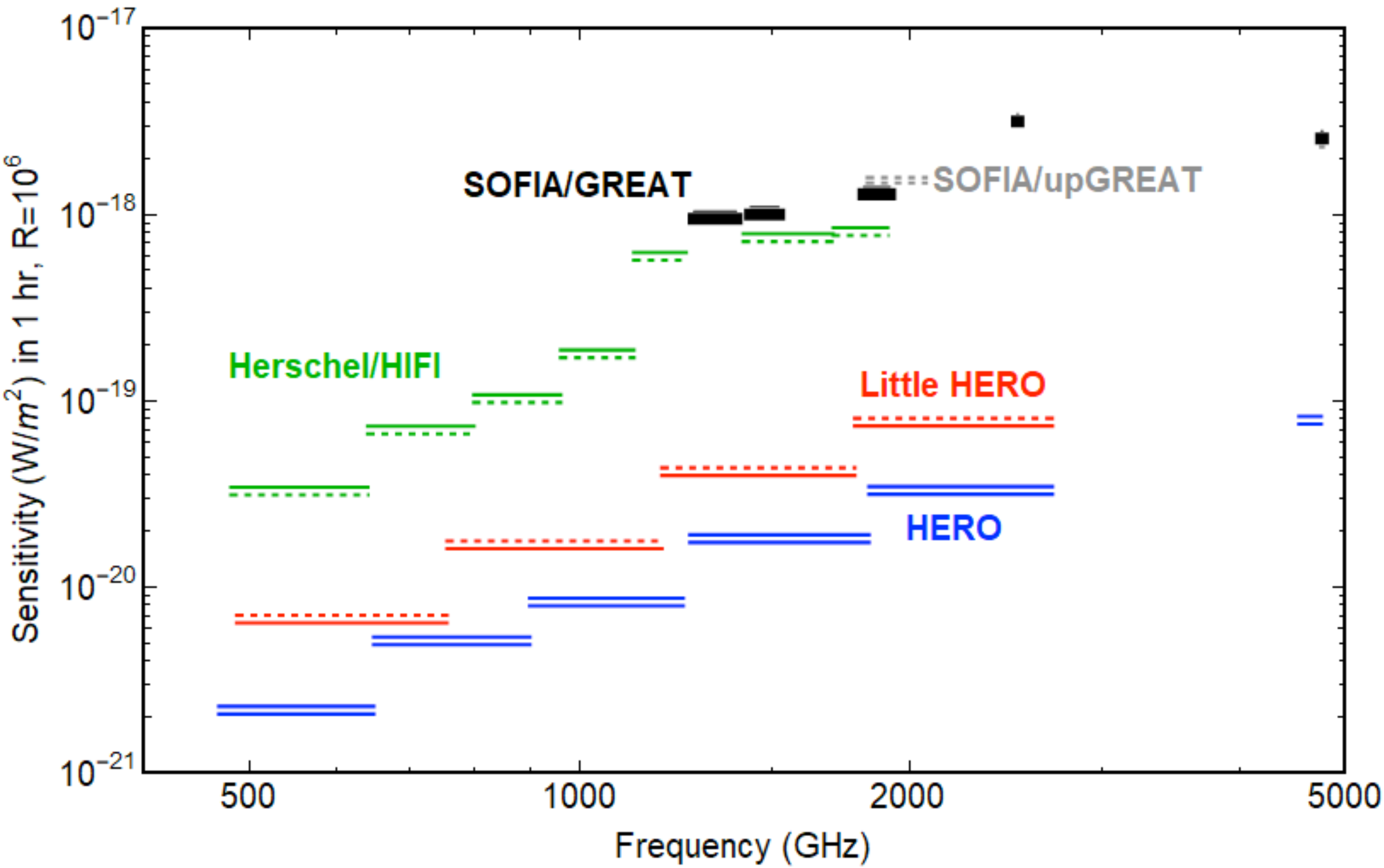
Instrument Performance

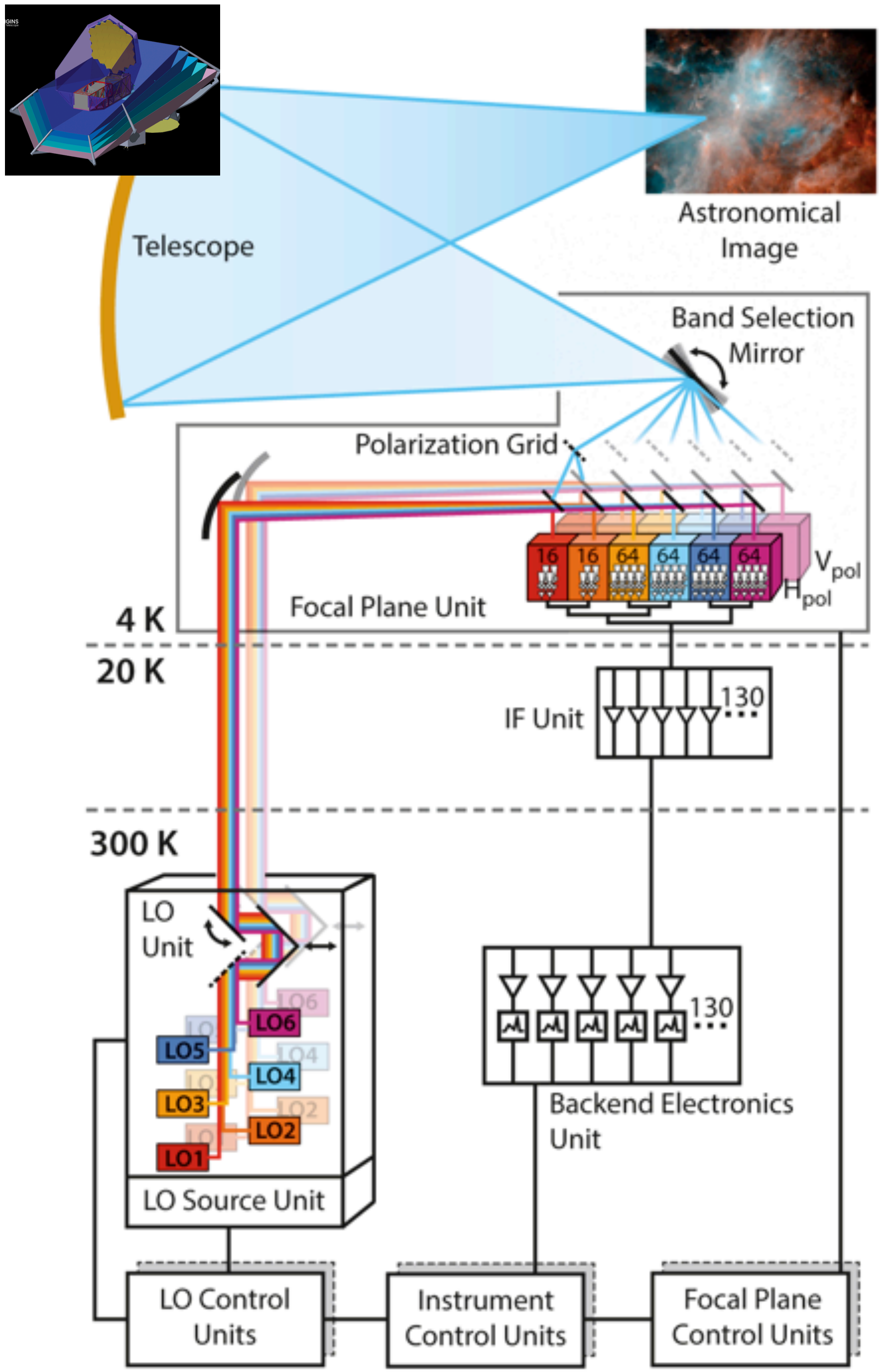






HERO sensitivity comparison

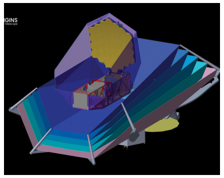




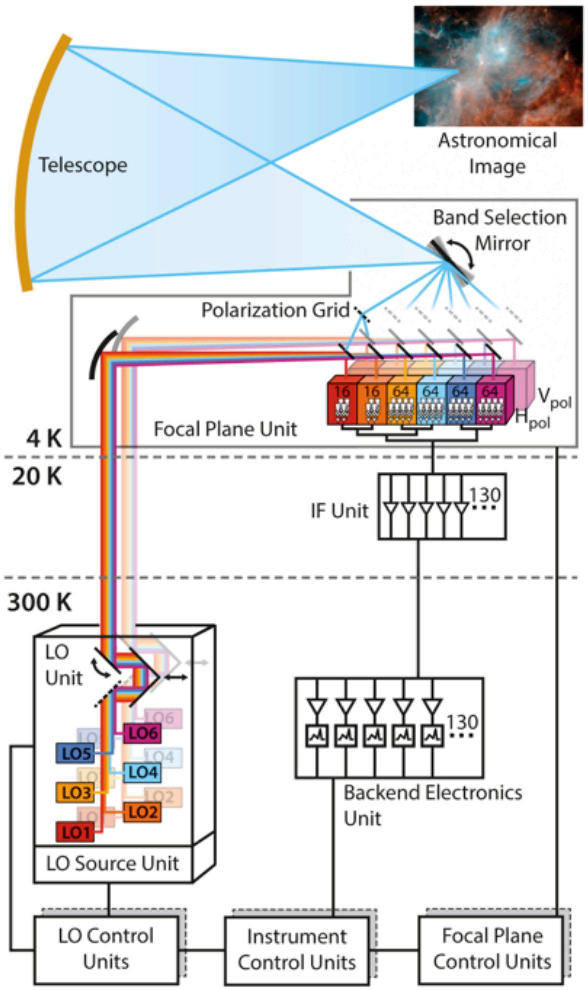
HERO Instrument

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

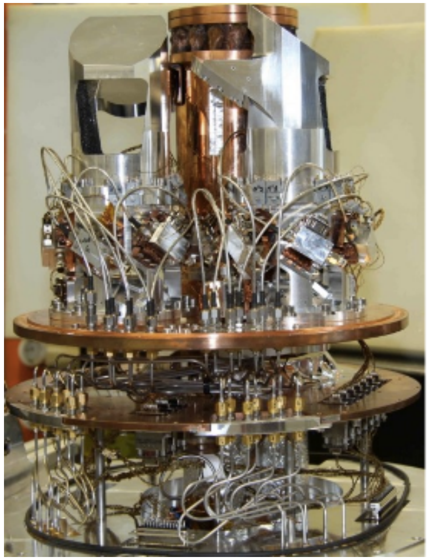


Summary HERO



- New era large heterodyne array receiver
- Builds on HIFI/Herschel, (up)GREAT, ALMA experience + recent R&D + innovative approach → largely surpasses current het. receivers
- In pixels: Up to 2x64 channels
- Frequency coverage: 468 – 2700 GHz, and 4.7 THz
- Feasible, high TRL design

Imaging heterodyne Spectrometers



Working imaging heterodyne Spectrometers:

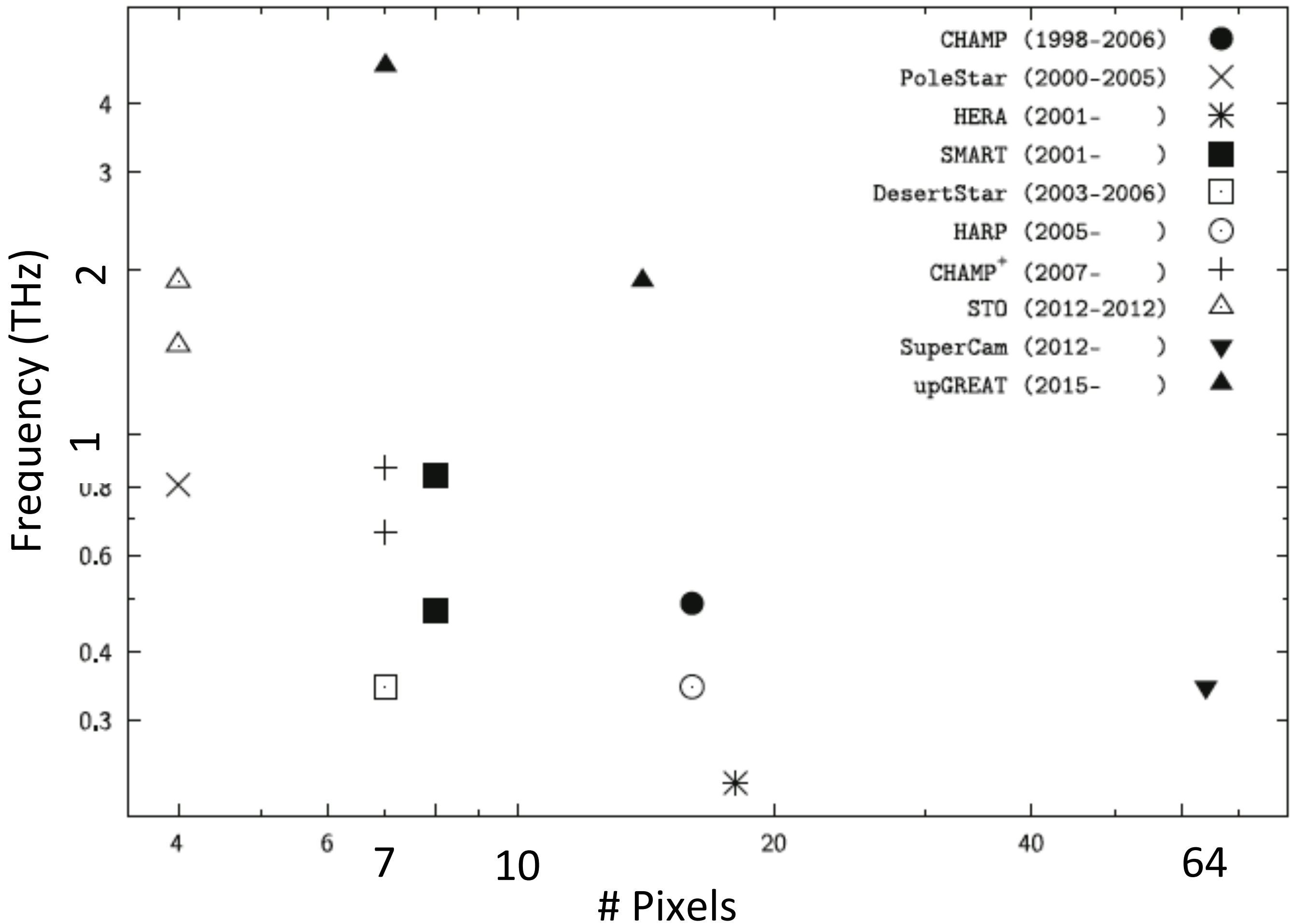
- Up-GREAT 7 x 2 pixels 1.9 – 2.5 THz, 4.7 THz
- STO2 : 4 @ 1.4, 4 @ 1.9, 1@ 4.7 THz
- SMART: 2 x 8 pixels between 460 and 880 GHz
- Harp B: 4x4 SIS mixers at 350 GHz
- Champ+: 7 pixels @ 620 to 720 GHz, spacing ~2.15·Θmb and 7 pixels @ 780 to 950 GHz
- Supercam: 8 x 8 pixels at 350 GHz

Under construction or designed:

- Gusto: 8 pixels @ 1.4, 1.9 and 4.7 THz
- Chai: 64 pixels @ 650 and 810 GHz
- IRAM: 49 pixels
- AtLAST 100s of pixels
- …

See also Workshop in Nunspeet March 2017

Overview



Graf et al. 2015 J. of Infrared Milli THz Waves

Conclusion

Science Cases for Heterodyne in Space:

- The trail of Water
- Cosmic Rays
- Evolved Stars
- Turbulence in the ISM

Imaging heterodyne spectrometers:

- Have been build for ground, airplane and balloon
- We are ready for the first in space!