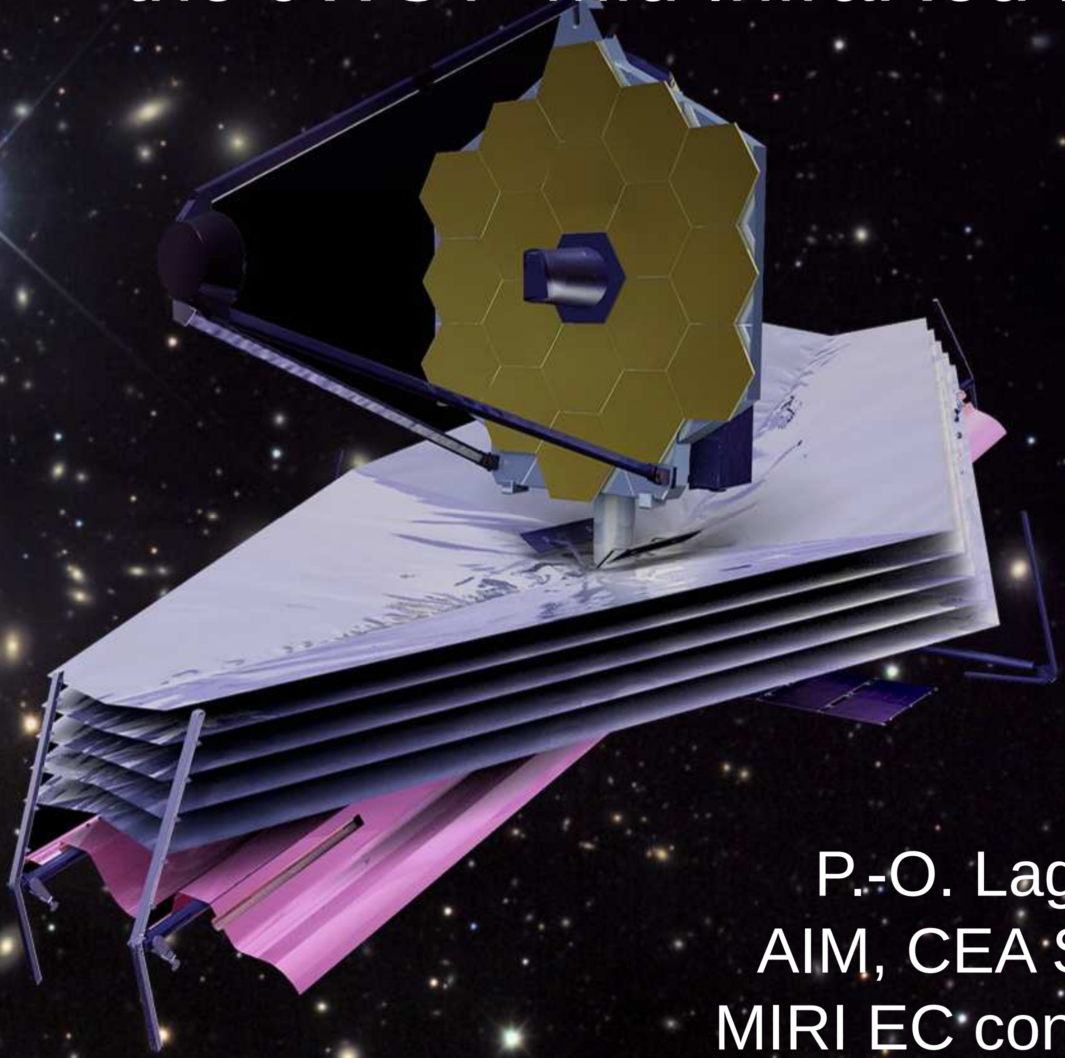
Exoplanet atmosphere characterisation with the JWST Mid InfraRed Instrument (MIRI)



Copyright: Stephen Kill, STFC

P.-O. Lagage
AIM, CEA Saclay
MIRI EC consortium

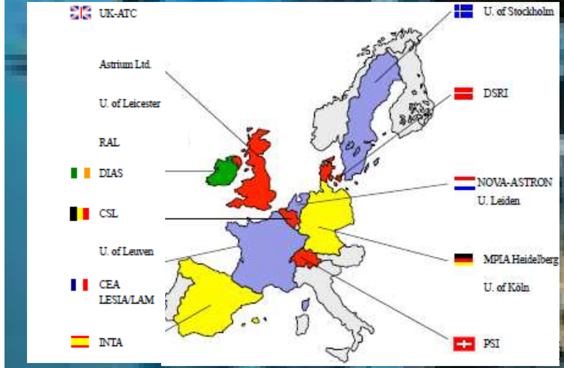
MIRI is a 50%-50% Europe-US share project

PI's G. Wright (ATC, UK) , G. Rieke (Arizona University)

A 5 to 28 μm imager and spectrometer

(The only JWST instrument in this λ range)

Opto mechanics + tests in Europe by a nationally funded consortium of European Institutes

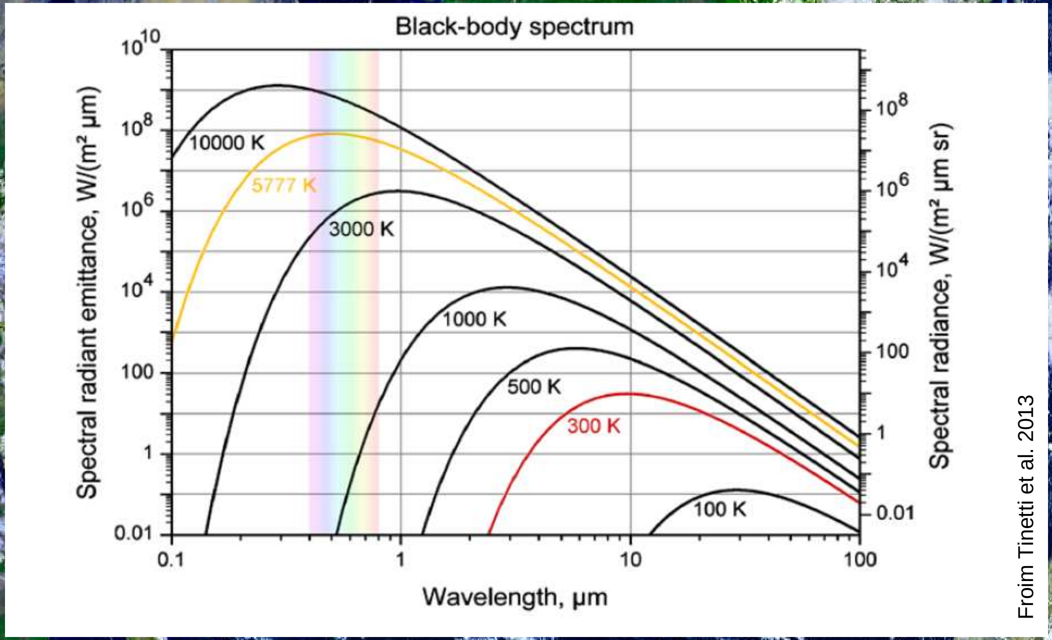


Detector and cryocooler In US (JPL)

Unlike the other JWST instruments, MIRI has to be cooled to 7K

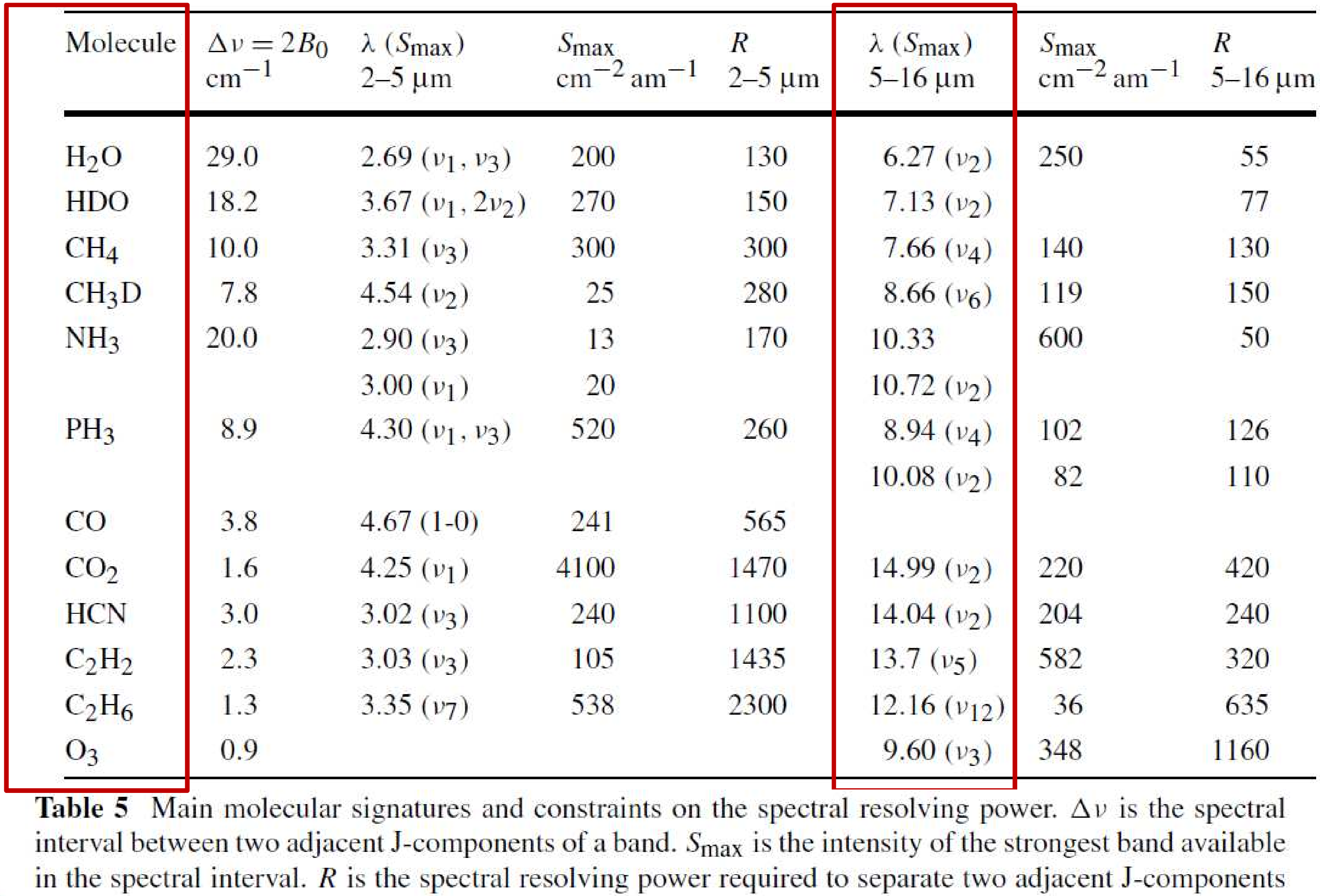
→ Dedicated cryocooler

MIRI best suited to detect the emission of “cool” objects.
5 – 27 microns → BB peak emission with T 600 K - 165 K.



Froim Tinetti et al. 2013

Main molecules have bands in the Mid-IR



Molecule	$\Delta\nu = 2B_0$ cm^{-1}	λ ($S_{\max}$) 2–5 μm	$S_{\max}$ cm^{-2} am^{-1}	R 2–5 μm	λ ($S_{\max}$) 5–16 μm	$S_{\max}$ cm^{-2} am^{-1}	R 5–16 μm
H_2O	29.0	2.69 (ν_1, ν_3)	200	130	6.27 (ν_2)	250	55
HDO	18.2	3.67 ($\nu_1, 2\nu_2$)	270	150	7.13 (ν_2)		77
CH_4	10.0	3.31 (ν_3)	300	300	7.66 (ν_4)	140	130
CH_3D	7.8	4.54 (ν_2)	25	280	8.66 (ν_6)	119	150
NH_3	20.0	2.90 (ν_3)	13	170	10.33	600	50
		3.00 (ν_1)	20		10.72 (ν_2)		
PH_3	8.9	4.30 (ν_1, ν_3)	520	260	8.94 (ν_4)	102	126
					10.08 (ν_2)	82	110
CO	3.8	4.67 (1-0)	241	565			
CO_2	1.6	4.25 (ν_1)	4100	1470	14.99 (ν_2)	220	420
HCN	3.0	3.02 (ν_3)	240	1100	14.04 (ν_2)	204	240
C_2H_2	2.3	3.03 (ν_3)	105	1435	13.7 (ν_5)	582	320
C_2H_6	1.3	3.35 (ν_7)	538	2300	12.16 (ν_{12})	36	635
O_3	0.9				9.60 (ν_3)	348	1160

Table 5 Main molecular signatures and constraints on the spectral resolving power. $\Delta\nu$ is the spectral interval between two adjacent J-components of a band. $S_{\max}$ is the intensity of the strongest band available in the spectral interval. R is the spectral resolving power required to separate two adjacent J-components

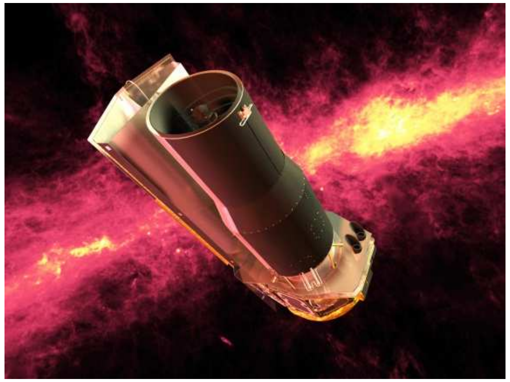
From Tinetti et al. AAR 2013

Very little in the mid-IR so far !

Not by lack of interest but by lack of facilities

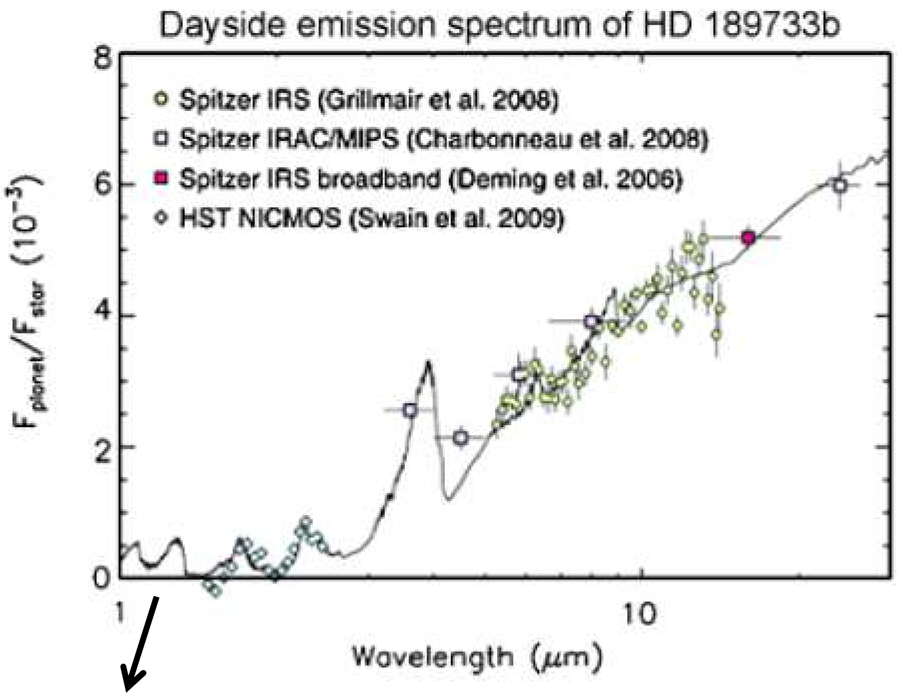
For transisting planets, spectra of only **2 giant** bright exoplanets :
HD 189733b, HD 209458 (cold Spitzer)

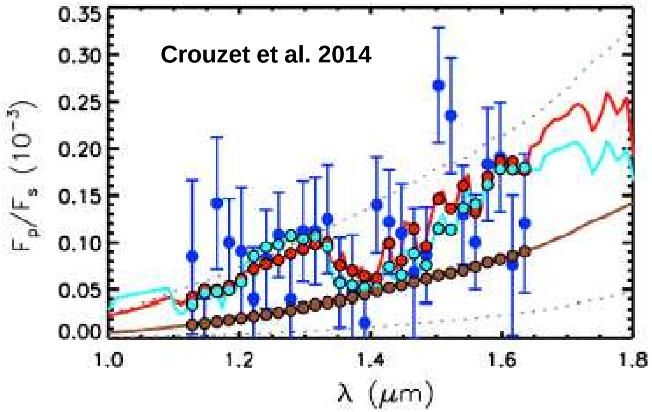
+ photometry of a few dozen of transiting exoplanets
expecially at 3.6 and 4.8 microns (warm Spitzer)



For direct imaged exoplanet: **nothing**
(Spitzer not the angular resolution and ground-based lack of sensitivity)!

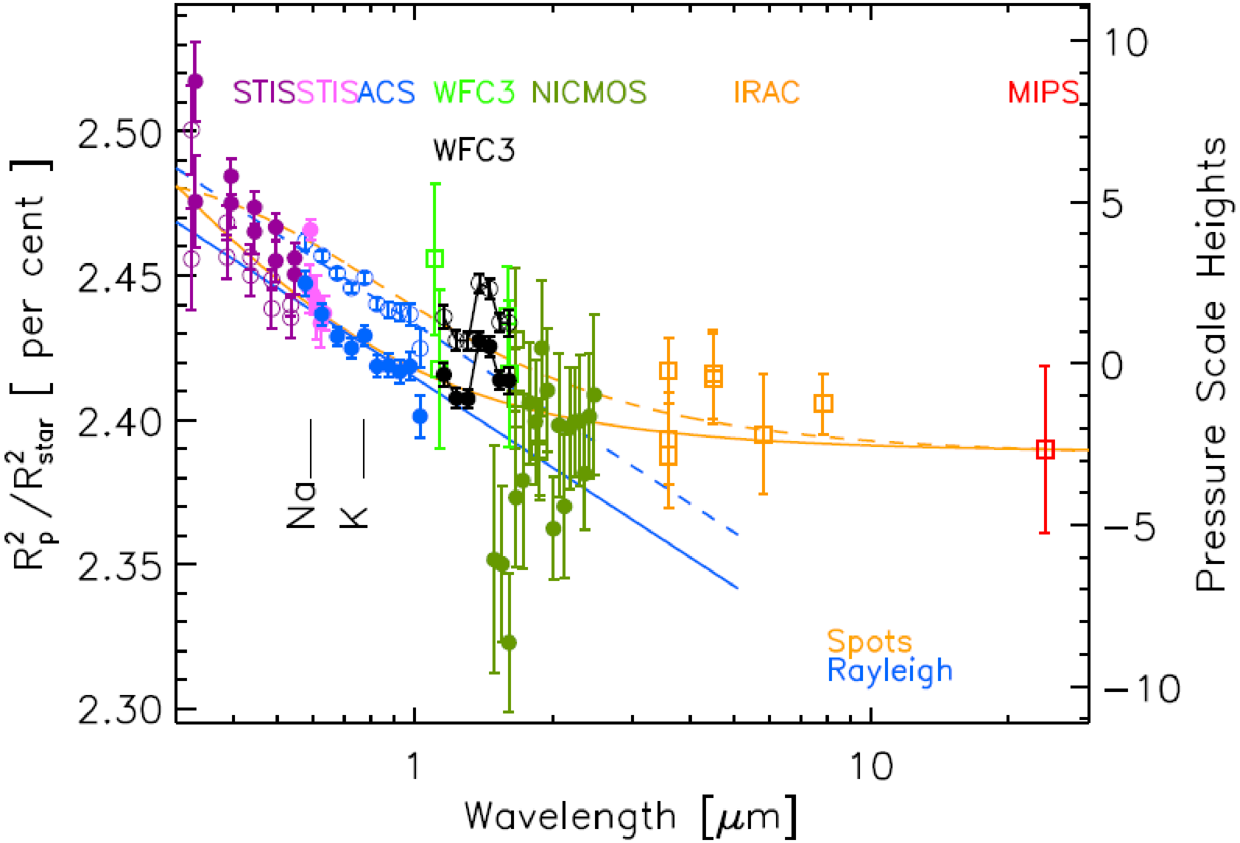
Emission spectra of HD 189733b





Transmission spectra of HD189733b

MIRI European Consortium



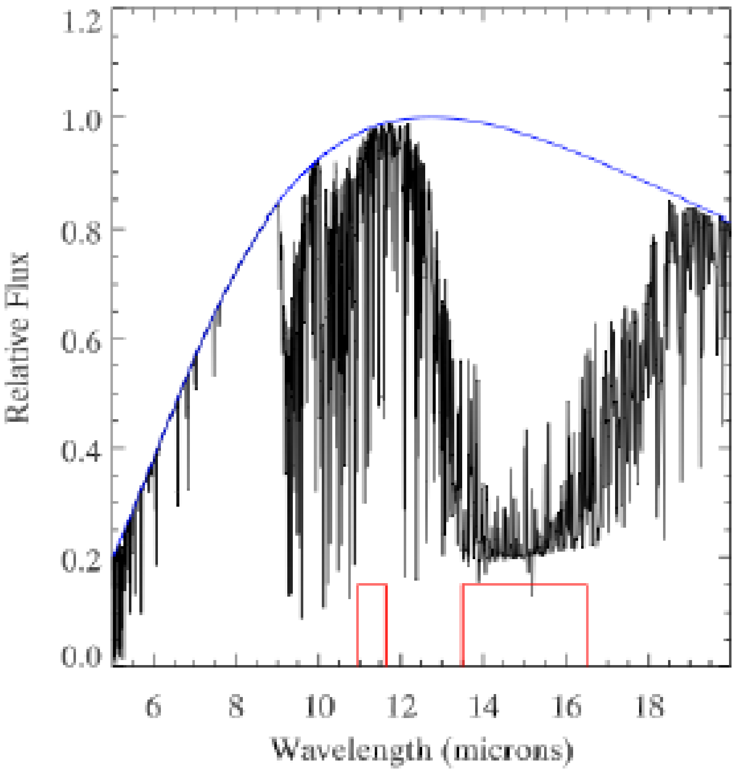
McCullough et al. 2014 and references there-in

No much observations …

but a lot of predictions !

A few examples

MIRI detection of CO_2 in Super-Earth emission?



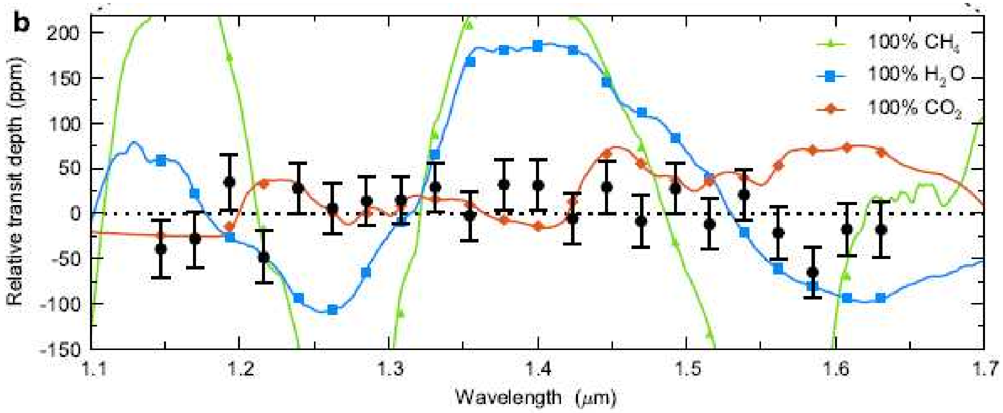
Deming et al. (2009) showing Miller-Ricci (2009) Super-Earth Emission spectrum and MIRI filters

- JWST MIRI filters (red boxes, left) may detect deep CO2 absorption in Super-Earth emission observations if hosts are nearby M dwarfs.
- Modeling shows that modest S/N detections possible on super-Earth planets around M stars IF data co-add well (Deming et al. 2009).

- Could detect CO2 feature in ~50 hr for ~300-400K 2 R_e planet around M5 star at 10 pc: IF the data SNR improves with co-additions

Silicate features

MIRI European Consortium

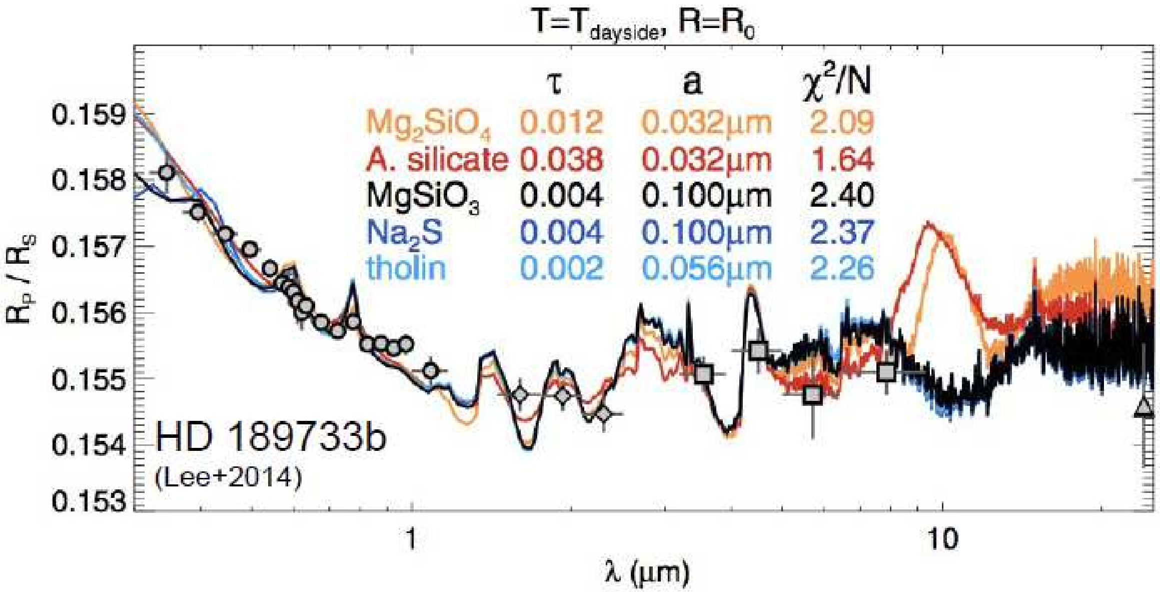


GJ1214b

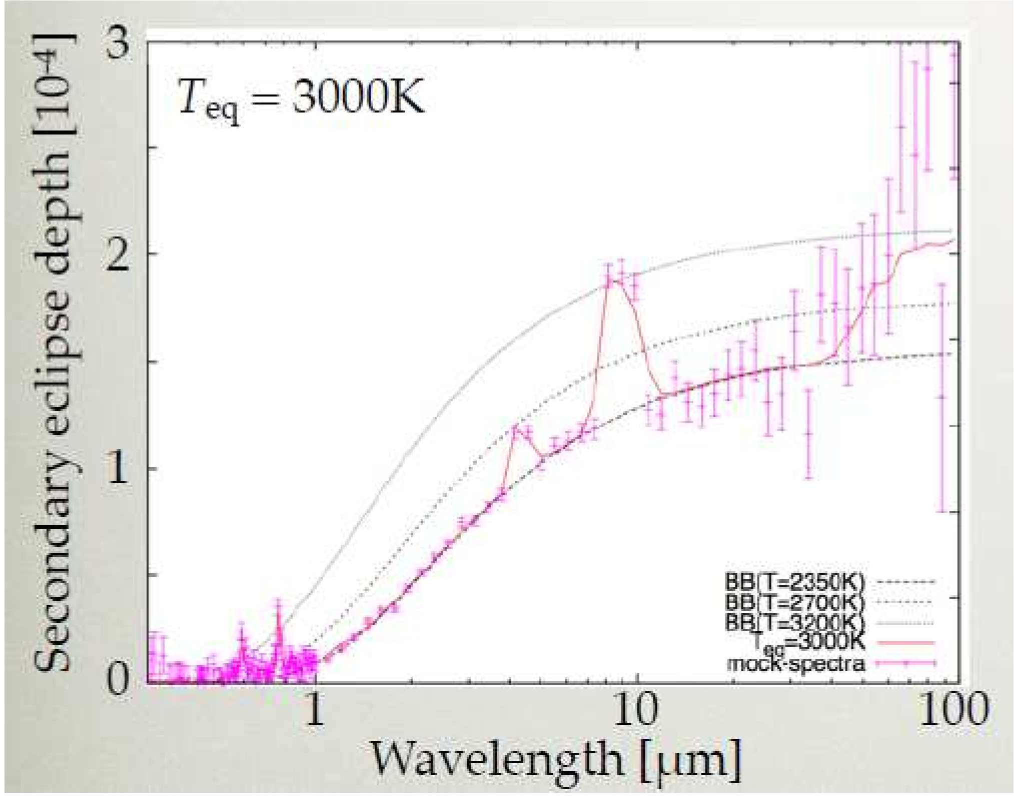
Transmission sprectrum : FLAT

→ clouds, Hazes

(L. Kreidberg et al. 2014)



SuperEarth with mineral atmosphere : Si0 band at 10 microns



Y. Ito et al ApJ 2015; talk here by M. Ikona

Phase curve of an exoplanet in the habitable zone of a M star

MIRI European Consortium

4 Yang, Cowan, & Abbot

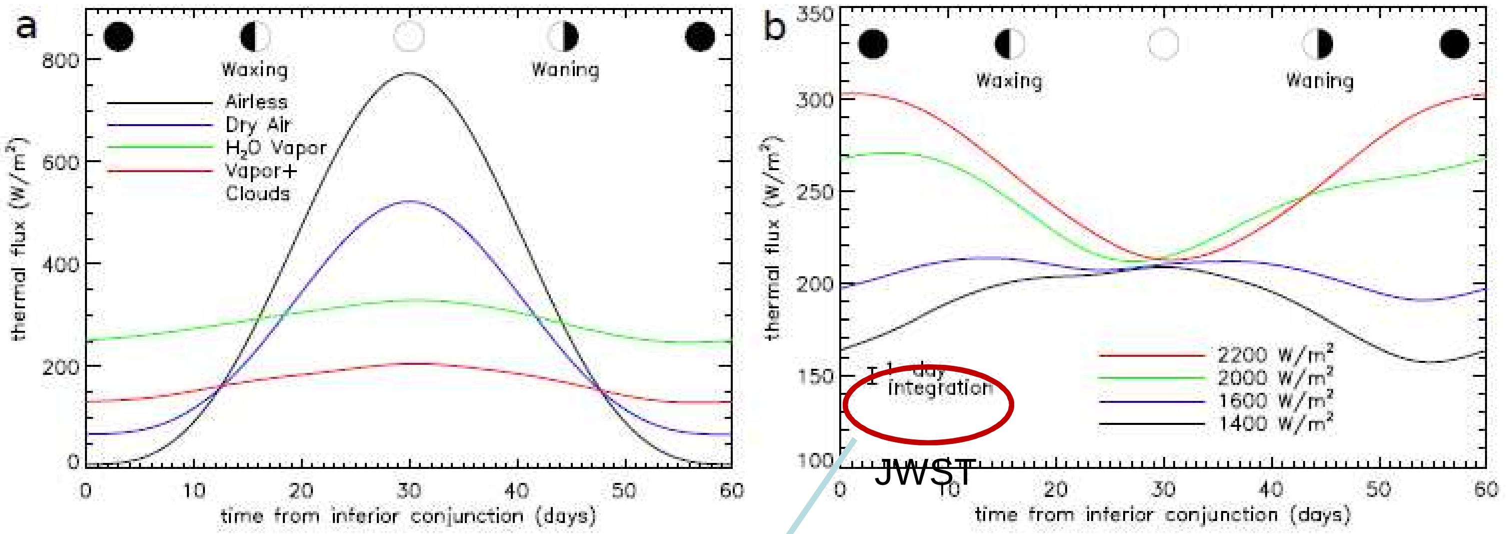


FIG. 3.— Thermal phase curves of tidally locked planets. (a) phase curves for different atmospheres with stellar flux fixed at 1200 W m^{-2}: airless, dry-air, water vapor, and water vapor plus clouds, (**b**) phase curves for a full atmosphere including water vapor and clouds for different stellar fluxes: 1400, 1600, 2000 and 2200 W m^{-2}. The error bar in (b) is the expected precision of the James Webb Space Telescope for observations of a nearby super-Earth. The surface albedo for the airless and dry-air cases is 0.2. The orbital period is 60 Earth-days.

1ppm : very challenging; systematics, stellar variability

Prediction is fine

but a key lesson at this conference for me is:

Explore

search for anomalies !

MIRI will take its share!!!

Transiting exoplanets: Down to super Earth + BD

MIRI European Consortium

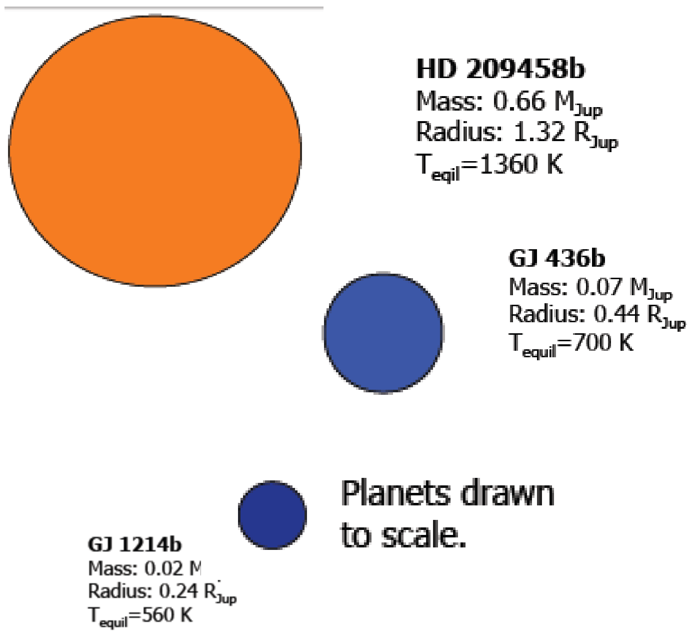
Brown dwarfs

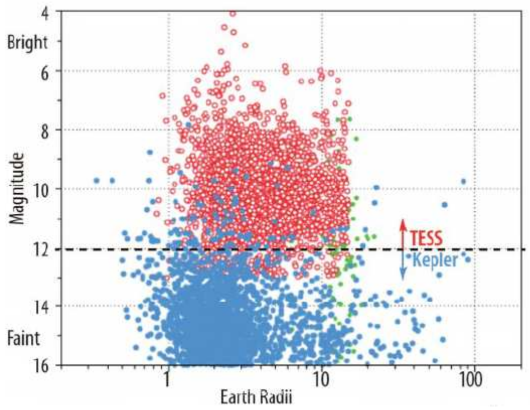
Giant planet

warm Neptune---mass planet (e.g. GJ436 b)

sub--Neptune mass planet (e.g. GJ1214 b)

small planets yet to be discovered (TESS)

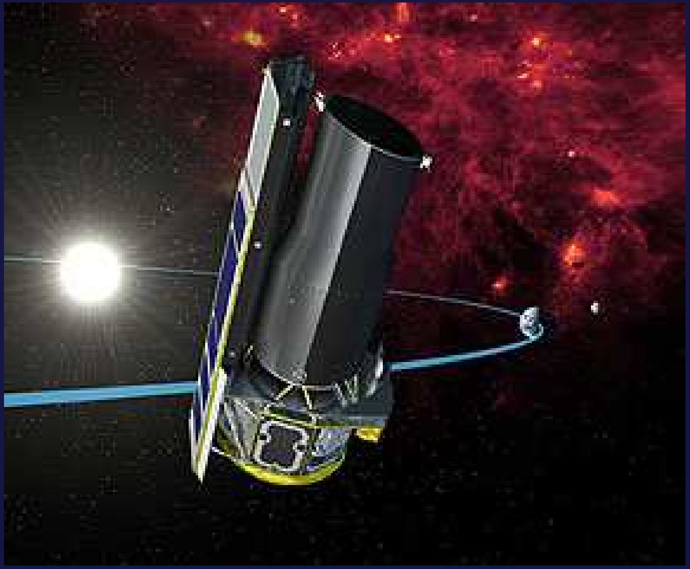




Ricker et al. 2014

Not really optimized for exo-planets (conceived a long time ago);
but telescope better than Spitzer (for example good stability at L2);
adaptations made possible at the level of instruments

From Spitzer



Telescope size : 85 cm

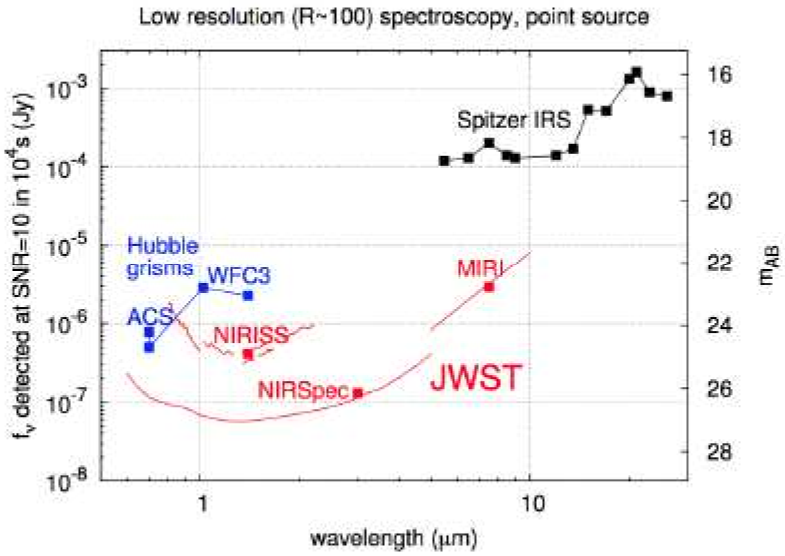
Amazing Photometric precision
(about 10^{-4})

S x 50

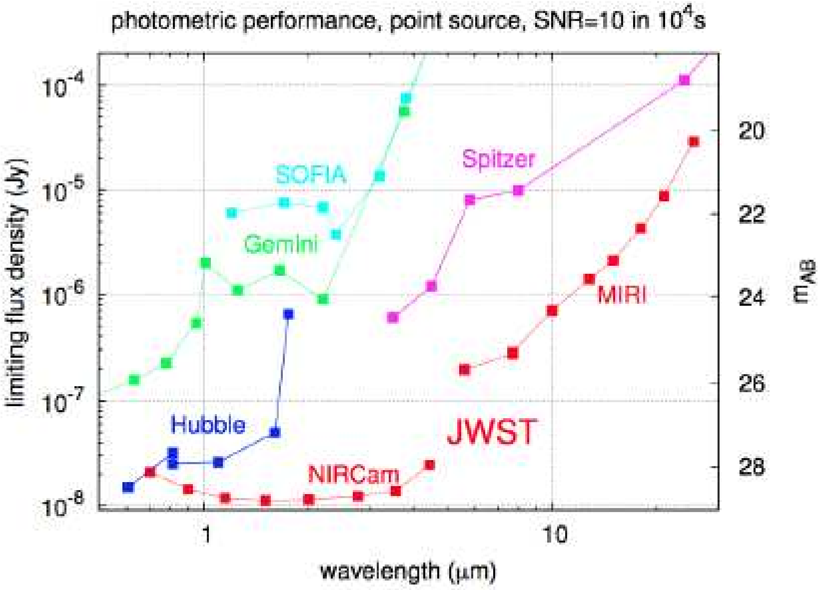
To JWST

Telescope size 660 cm

At the same photometric
from photometry (R=2) to spectroscopy
Need enhanced photometric precision



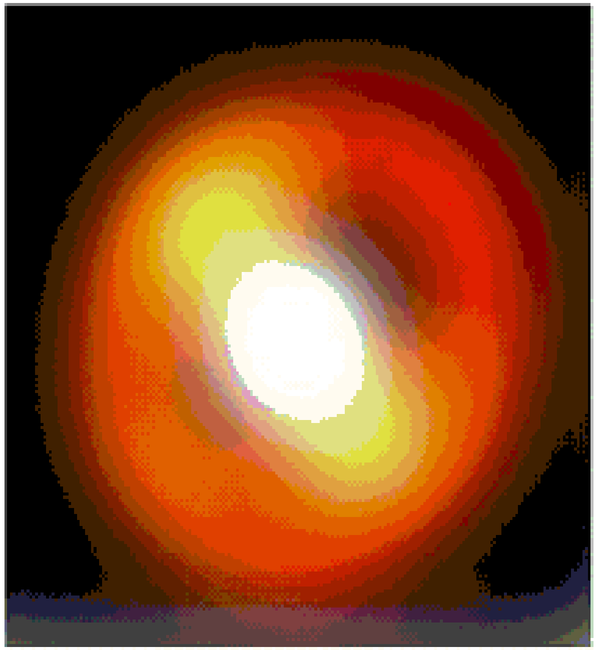
Low resolution (R~100) spectroscopy, point source



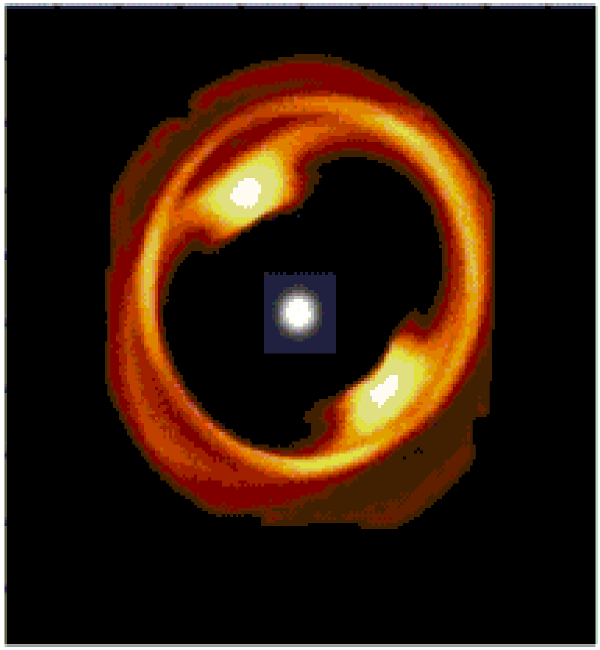
photometric performance, point source, SNR=10 in 10^4s

www.stci.edu/jwst/science/sensitivity

A huge increase in angular resolution



Vega disk from SIRTF
(simulated)



Vega disk from MIRI/JWST
(simulated)

George Rieke

Direct imaging thanks to coronographic

MIRI European Consortium

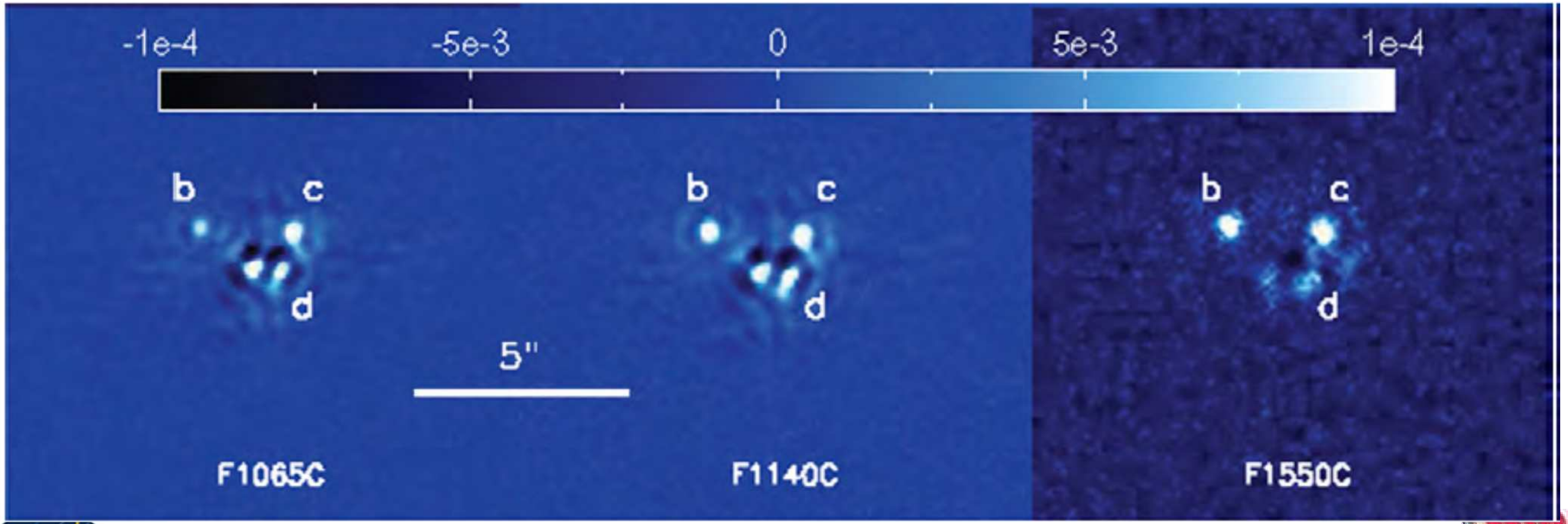
Exoplanets detected by direct imaging are of a different type than exoplanets from transit: giant, young

→ still cooling

→ Luminosity can constrain the planet formation theory

But model degenerescence

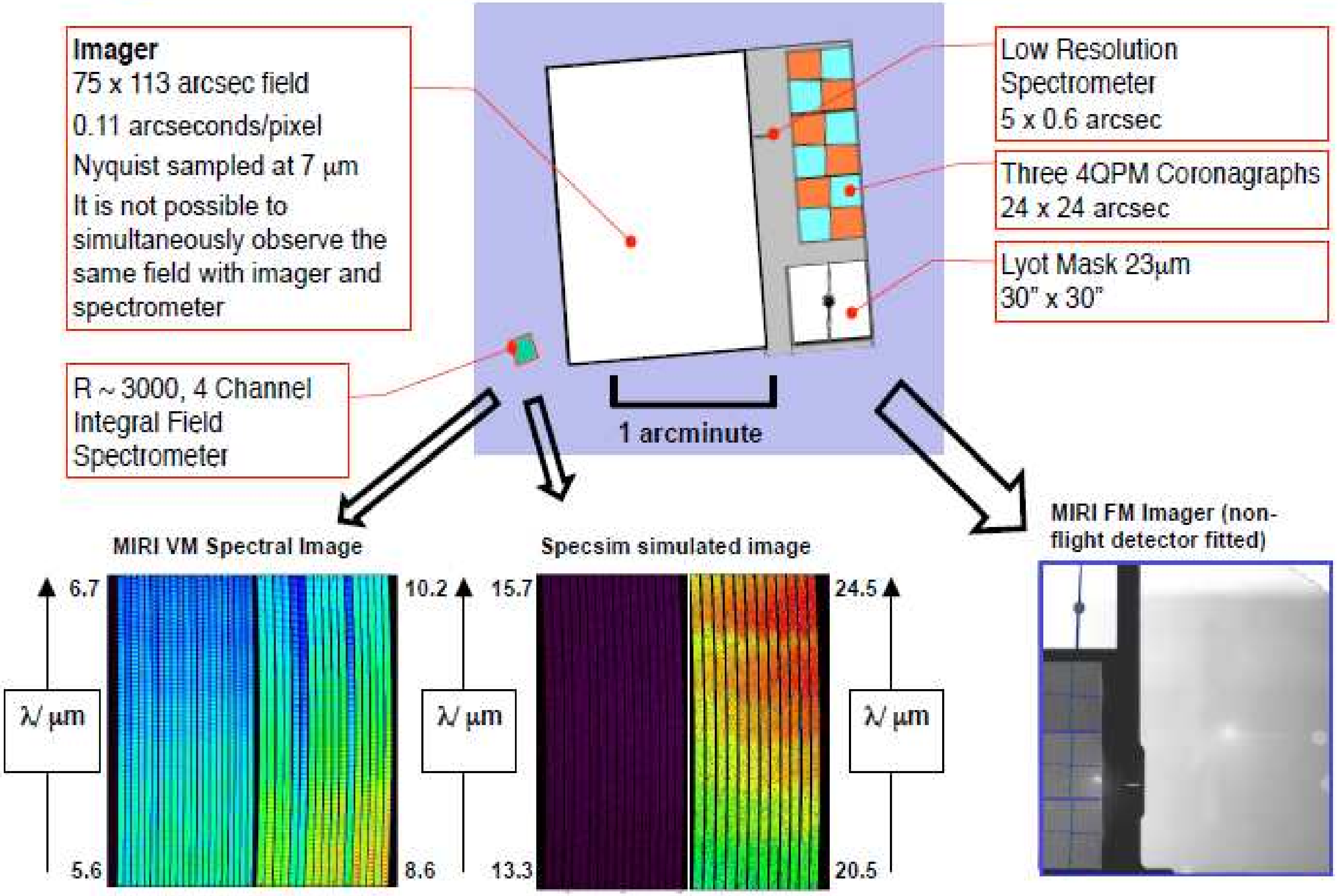
→ further constraint from atmospheric composition



Simulated MIRI images of HD 8799 system

A. Boccaletti et al., PASP in press

The MIRI Focal Planes (Entrance + Detector)



Imager
75 x 113 arcsec field
0.11 arcseconds/pixel
Nyquist sampled at 7 µm
It is not possible to simultaneously observe the same field with imager and spectrometer

R ~ 3000, 4 Channel Integral Field Spectrometer

Low Resolution Spectrometer
5 x 0.6 arcsec

Three 4QPM Coronagraphs
24 x 24 arcsec

Lyot Mask 23µm
30" x 30"

Gillian Wright et al.

All about MIRI

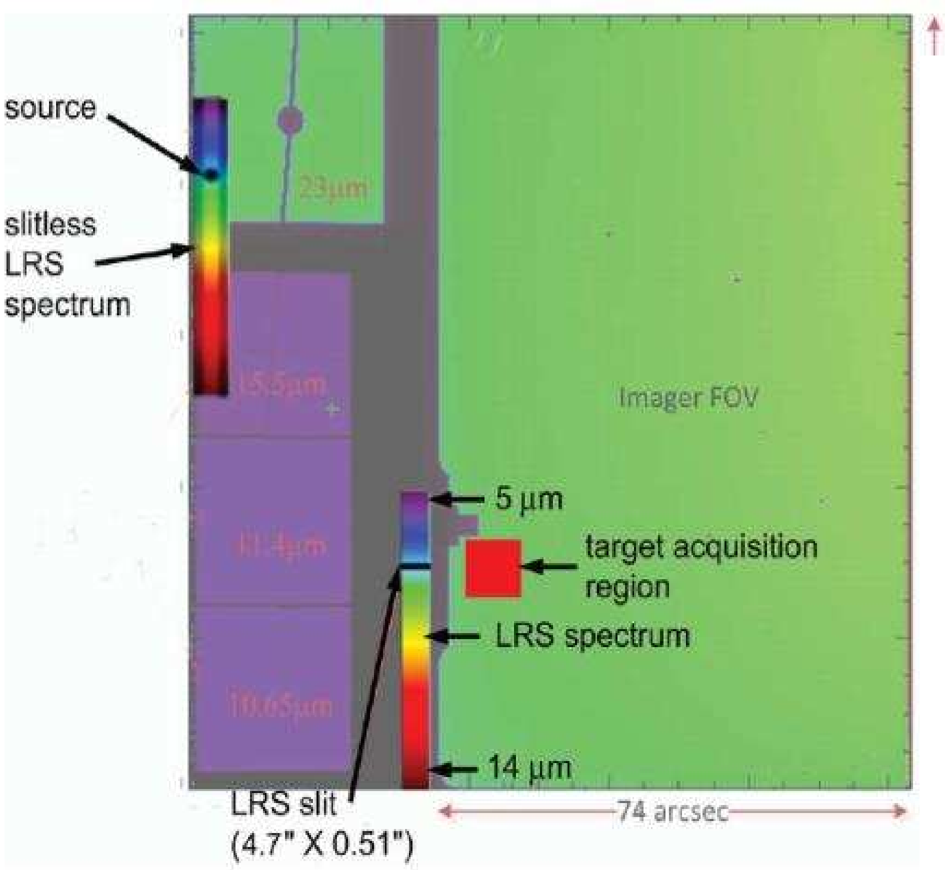
10 papers about MIRI in PASP 2015 in press

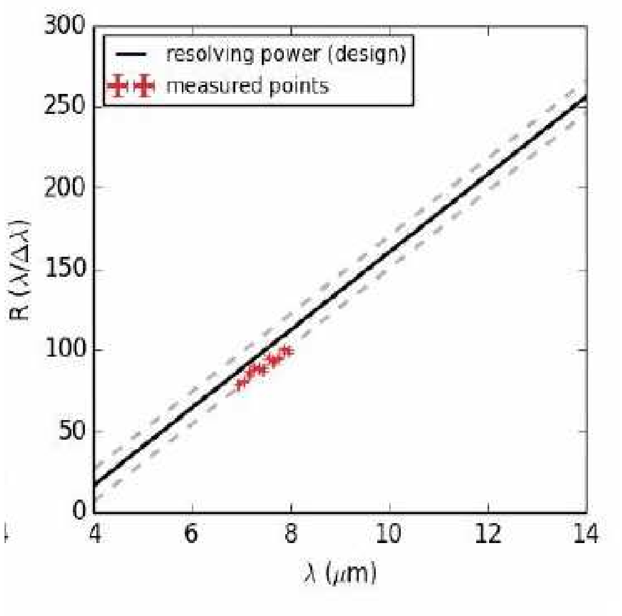
The Mid-Infrared Instrument for the James Webb SpaceTelescope

I: Introduction, G. H. Rieke, G. S. Wright, T. Boker et al.
II: Design and Build, G. S. Wright , D. Wright, G. B. Goodson, et al.
III: MIRIM, the MIRI Imager, P. Bouchet, M. Gacia Marin, P.O. Lagage et al.
IV: The Low Resolution Spectrometer, S. Kendrew, S. Scheithauer, P. Bouchet et al.
V: Predicted Performance of the MIRI Coronagraphs A. Boccaletti, P.O. Lagage, P. Baudoz et al.
VI:The Medium Resolution Spectrometer, Martyn Wells, J.-W. Pel, A. Glasse et al.
VII: The MIRI Detectors, G. H. Rieke, M. E. Ressler, J. E. Morrison et al.
VIII: The MIRI Focal Plane System, M. E. Ressler, K. G. Sukhatme, B. R. Franklin et al.
IX: Predicted Sensitivity, A. Glasse, G. H. Rieke, E. Bauwens et al.
X: Operations and Data Reduction, K. D. Gordon, C. H. Chen, R. E. Anderson et al.

A special mode added for transiting exoplanets

MIRI European Consortium





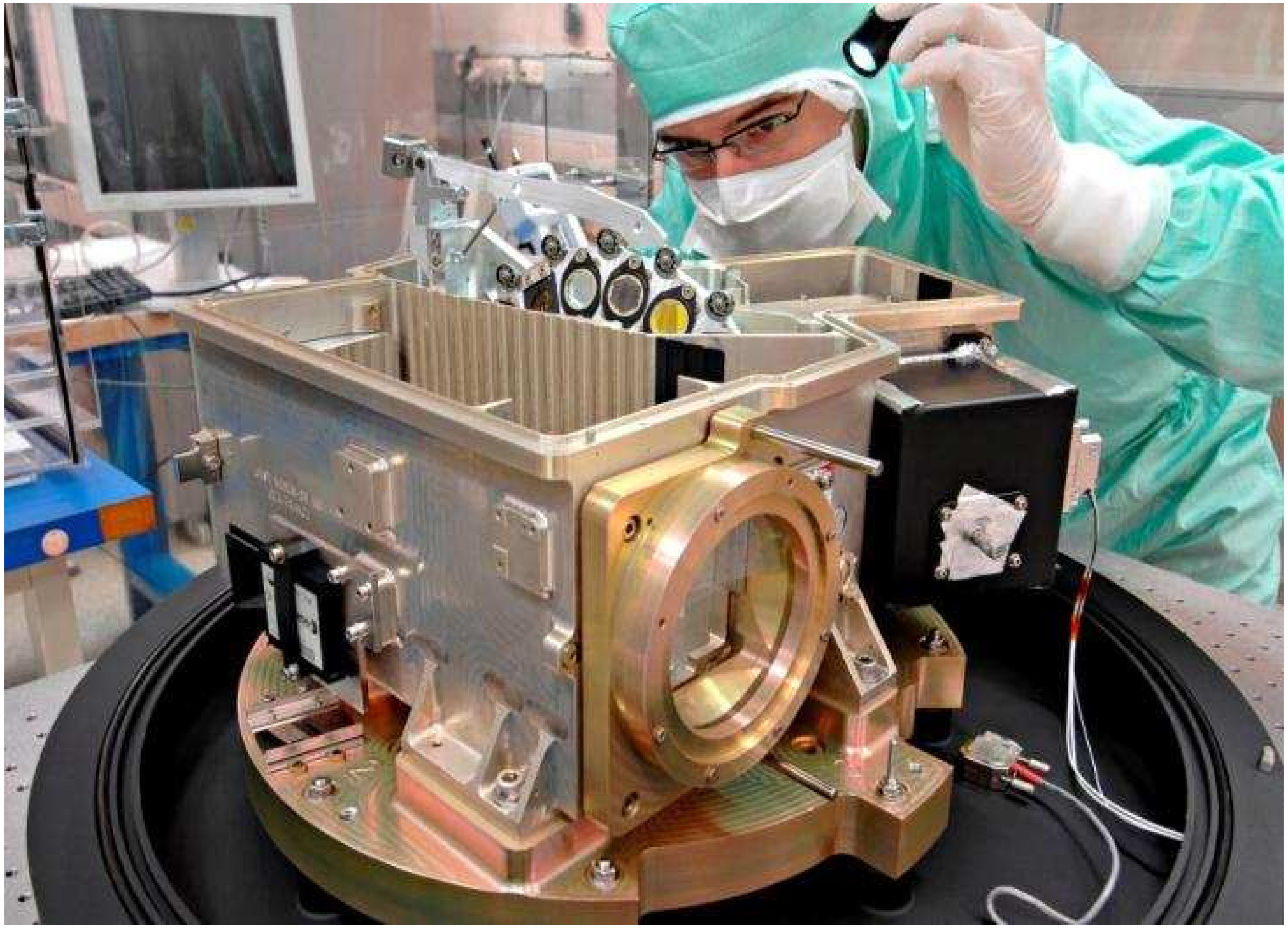
Telescope jitter 7 mas (1sigma) very low, but slitless needed

In addition only part of the array read (68x416)

→saturation:K m = 5.5 - 6

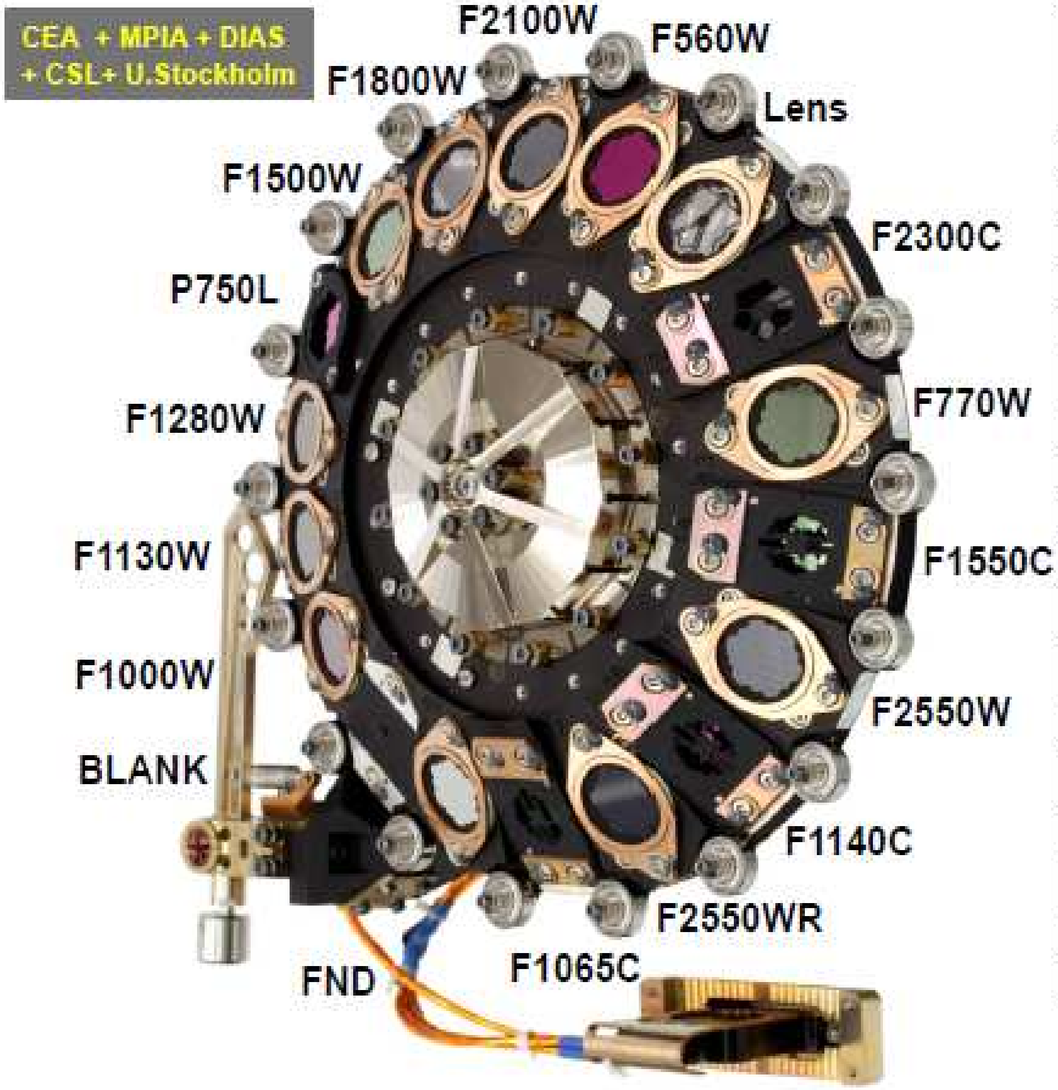
The MIRI imager in integration at Saclay

MIRI European Consortium



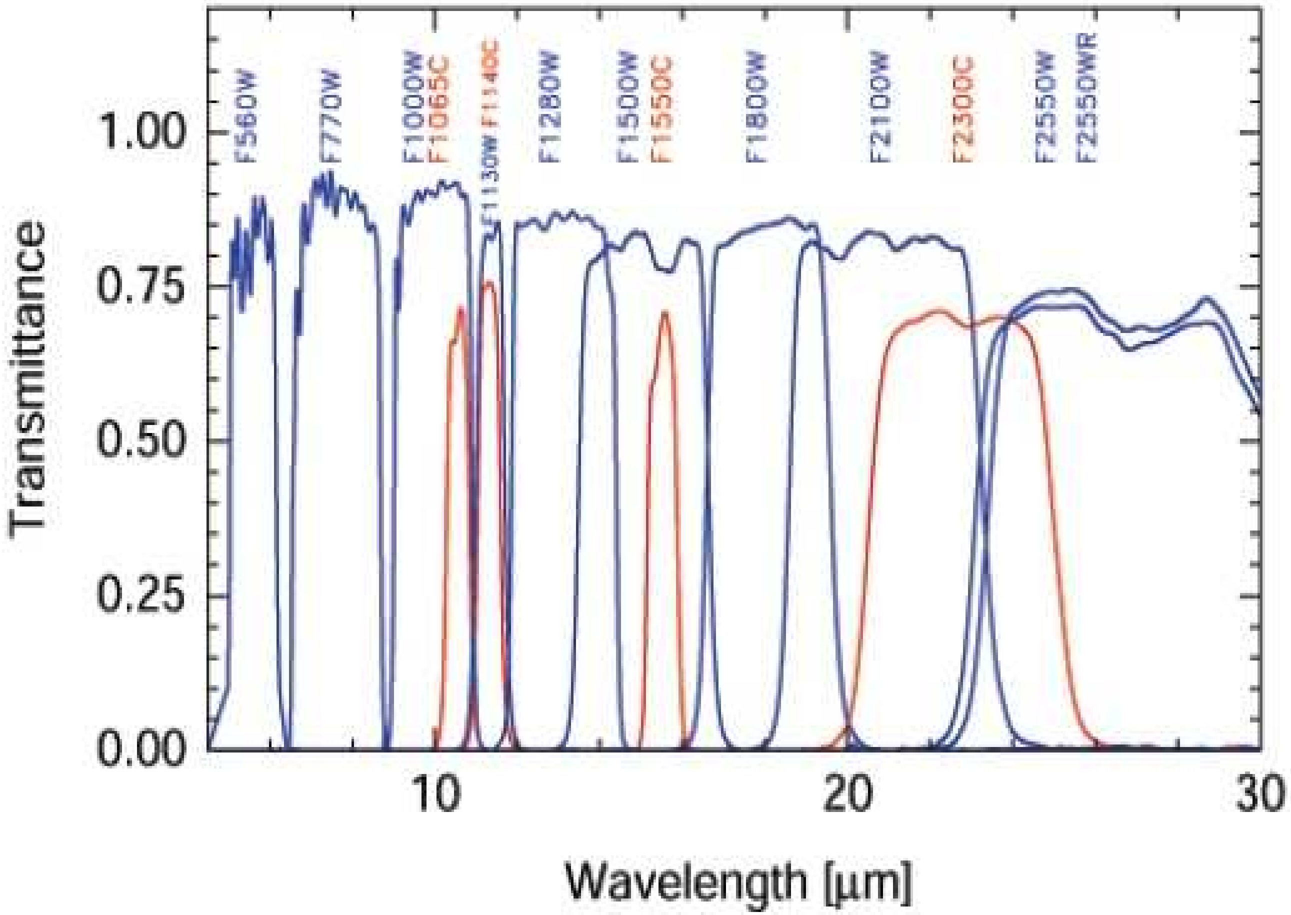
Miri imager wheel

MIRI European Consortium

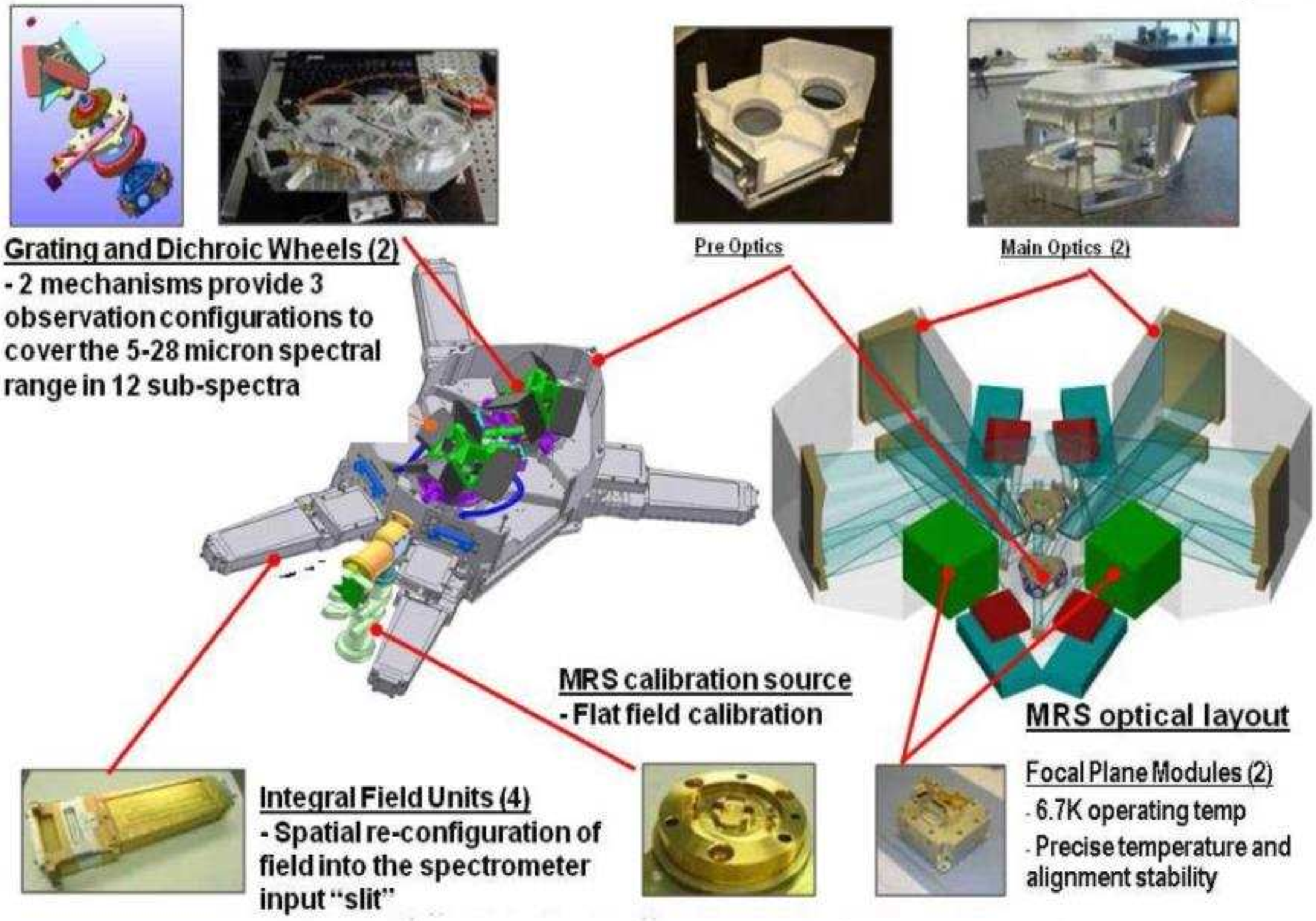


Filter name (and wavelength)	Pass band Δλ (μm)	Function
F560W	1.2	Imaging
F770W	2.2	
F1000W	2.0	
F1130W	0.7	
F1280W	2.4	
F1500W	3.0	
F1800W	3.0	
F2100W	5.0	
F2550W	4.0	
F2550WR	4.0	
P750L	5	R ~ 100 Spectroscopy
F1065C	0.53	Coronagraphy
F1140C	0.57	
F1550C	0.78	
F2300C	4.6	
FND	10	Target Acquisition
FLENS	N/A	Alignment
BLANK	N/A	Calibration

MIRI Imager Filters



The MIRI Medium résolution spectrometer



Grating and Dichroic Wheels (2)
- 2 mechanisms provide 3 observation configurations to cover the 5-28 micron spectral range in 12 sub-spectra

Pre Optics

Main Optics (2)

MRS calibration source
- Flat field calibration

MRS optical layout

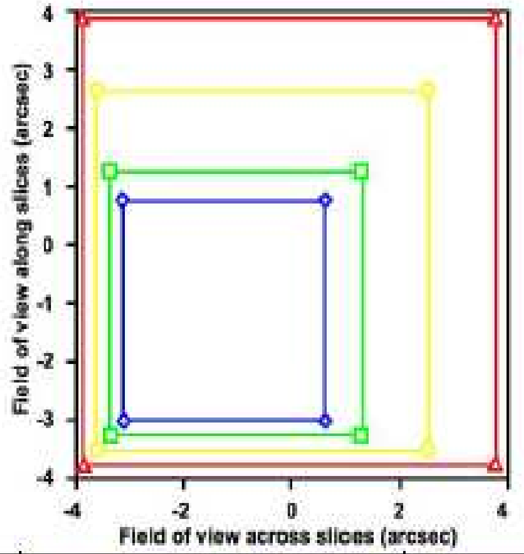
Integral Field Units (4)
- Spatial re-configuration of field into the spectrometer input "slit"

Focal Plane Modules (2)
- 6.7K operating temp
- Precise temperature and alignment stability

Martyn Wells, J.-W. Pel, A. Glasse et al.: **The Mid-Infrared Instrument for the James Webb SpaceTelescope VI:The Medium Resolution Spectrometer, PASP, in press**

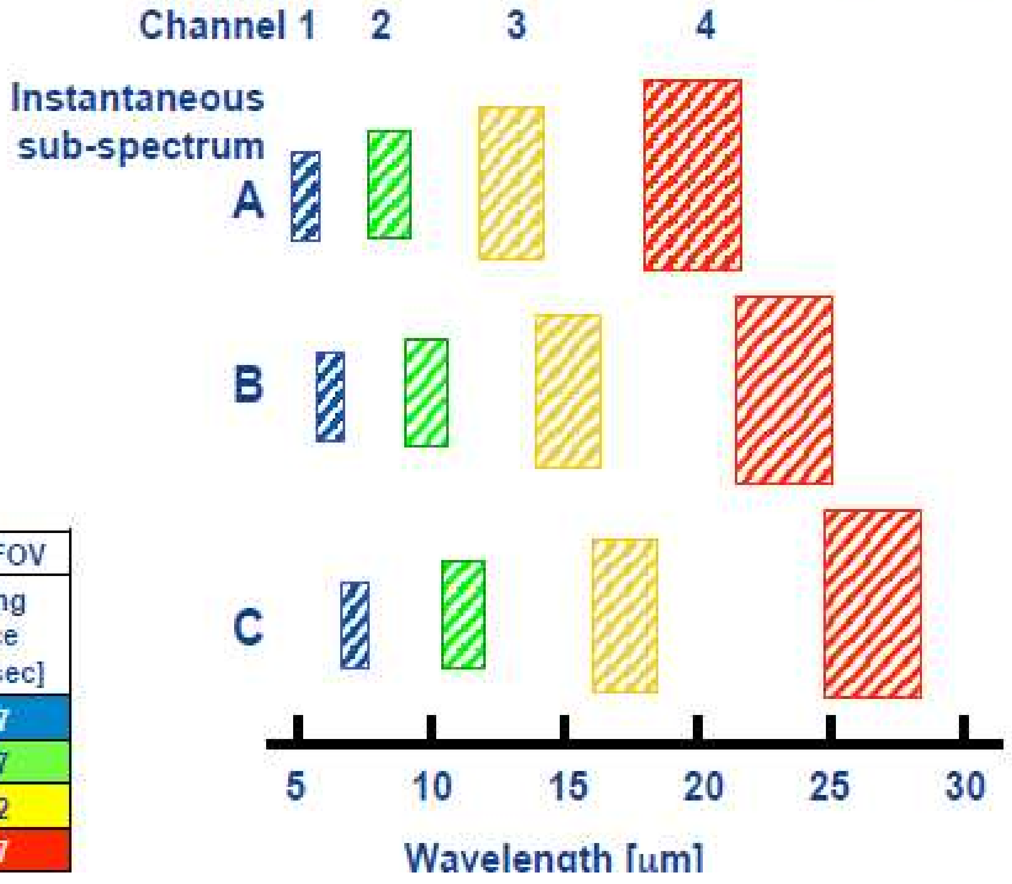
MIRI Medium Resolution Spectrometer

- 4 Spectral Channels with concentric fields of view



Channel Name	Spatial sample dimensions		Instantaneous FOV	
	Across slice (Slice width) [arcsec]	Along slice (Pixel) [arcsec]	Across slice [arcsec]	Along slice [arcsec]
1	0.18	0.20	3.7 (21)	3.7
2	0.28	0.20	4.5 (17)	4.7
3	0.39	0.25	6.1 (16)	6.2
4	0.64	0.27	7.9 (12)	7.7

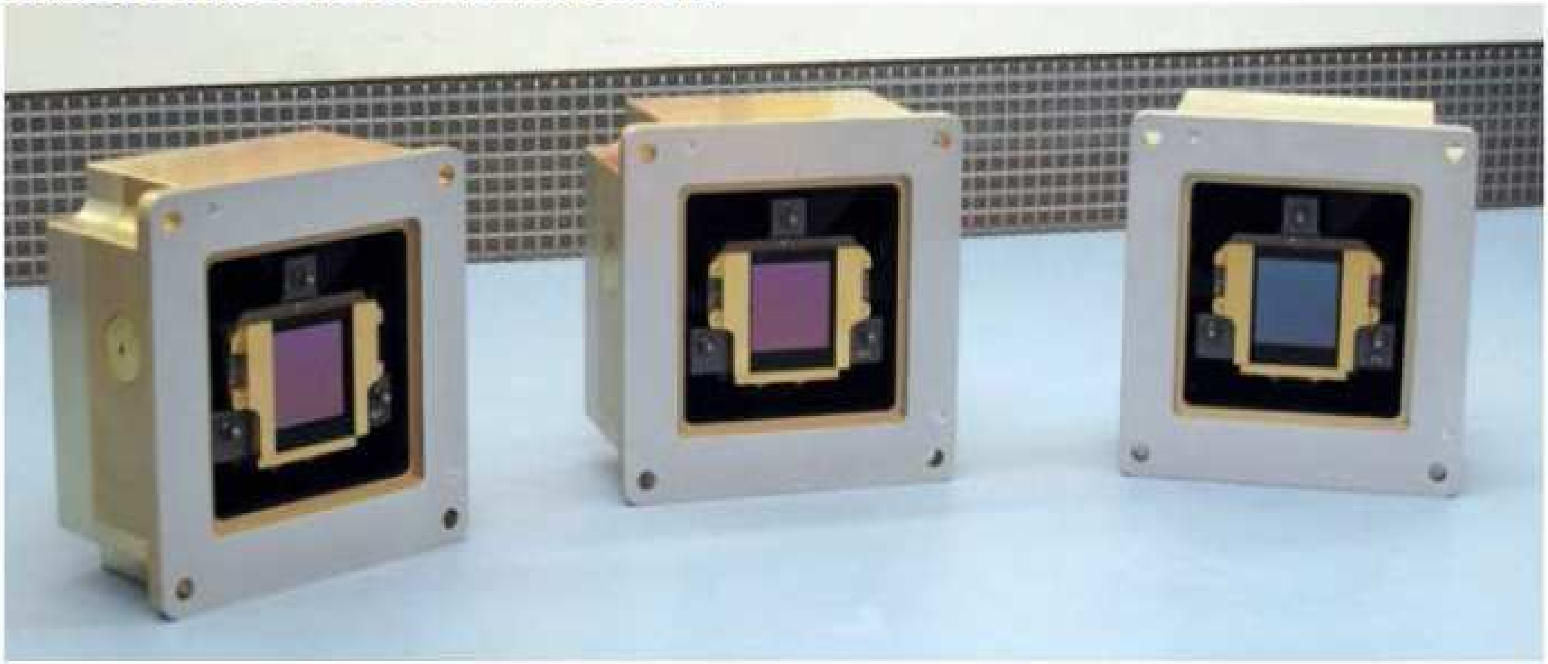
- 3 mechanism selected sub-spectra per channel with dedicated dichroic and gratings



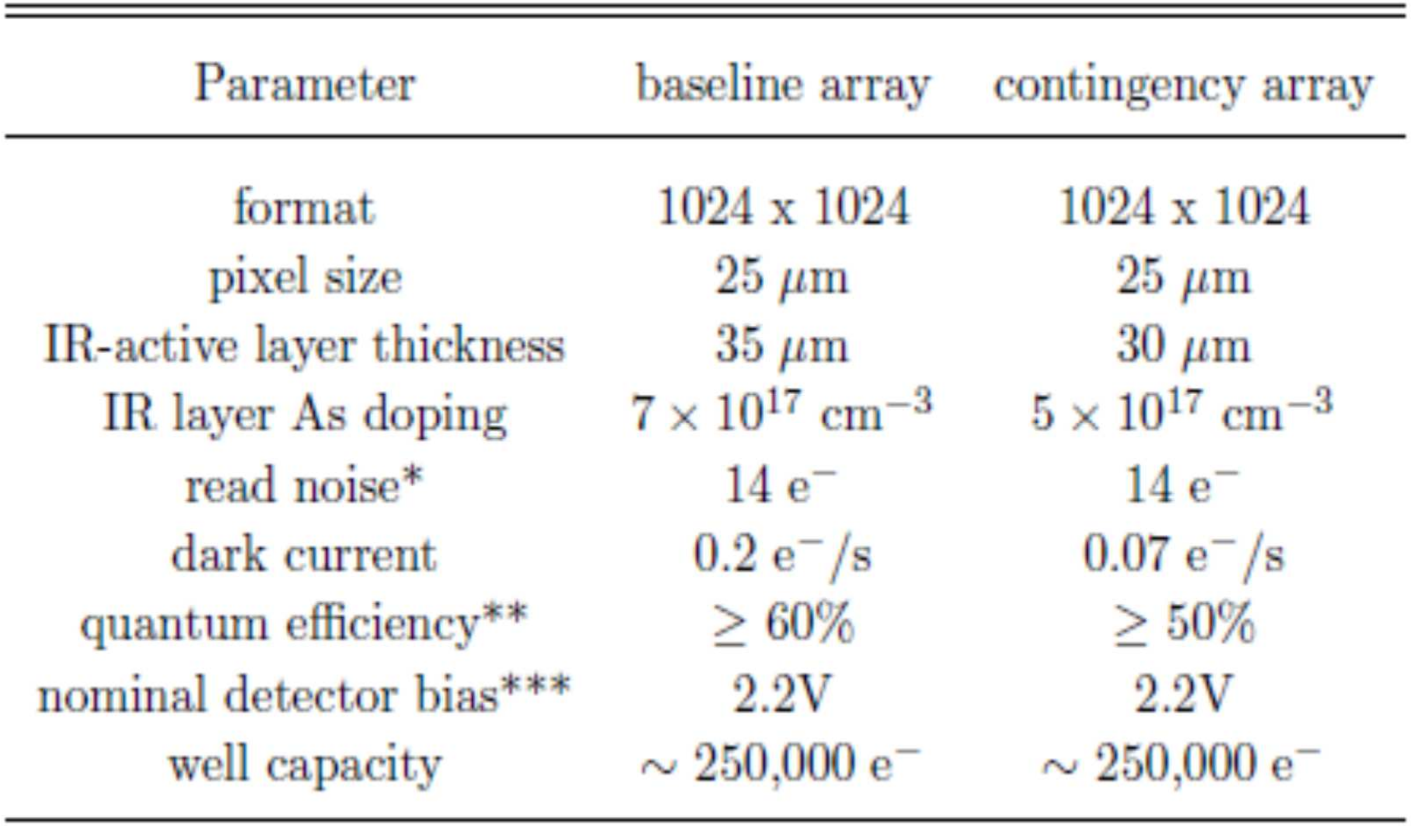
Martyn Wells, J.-W. Pel, A. Glasse et al.: **The Mid-Infrared Instrument for the James Webb SpaceTelescope VI:The Medium Resolution Spectrometer,** PASP, in press

The MIRI Focal Plane Modules

The MIRI focal planes were produced by Raytheon Vision Systems (RVS) for JPL, where they have been mounted into focal plane modules that can be bolted to the OM. Each detector array is 1024 X 1024 pixels of Si:As IBC devices. The FPMs provide shielding and thermal isolation to allow annealing.



M. E. Ressler, K. G. Sukhatme, B. R. Franklin et al. Martyn Wells, J.-W. Pel, A. Glasse et al.: **The Mid-Infrared Instrument for the James Webb SpaceTelescope VI: VIII: The MIRI Focal Plane System,** PASP, in press



Parameter	baseline array	contingency array
format	1024 x 1024	1024 x 1024
pixel size	25 μm	25 μm
IR-active layer thickness	35 μm	30 μm
IR layer As doping	7×10^{17} cm^{-3}	5×10^{17} cm^{-3}
read noise*	14 e^{-}	14 e^{-}
dark current	0.2 e^{-}/s	0.07 e^{-}/s
quantum efficiency**	$\geq$ 60%	$\geq$ 50%
nominal detector bias***	2.2V	2.2V
well capacity	$\sim$ 250,000 e^{-}	$\sim$ 250,000 e^{-}

M. E. Ressler, K. G. Sukhatme, B. R. Franklin et al. Martyn Wells, J.-W. Pel, A. Glasse et al.: **The Mid-Infrared Instrument for the James Webb SpaceTelescope VI: VIII: The MIRI Focal Plane System,** PASP, in press

Difficult observations

Down to 10 ppm (or more) → photometry stability

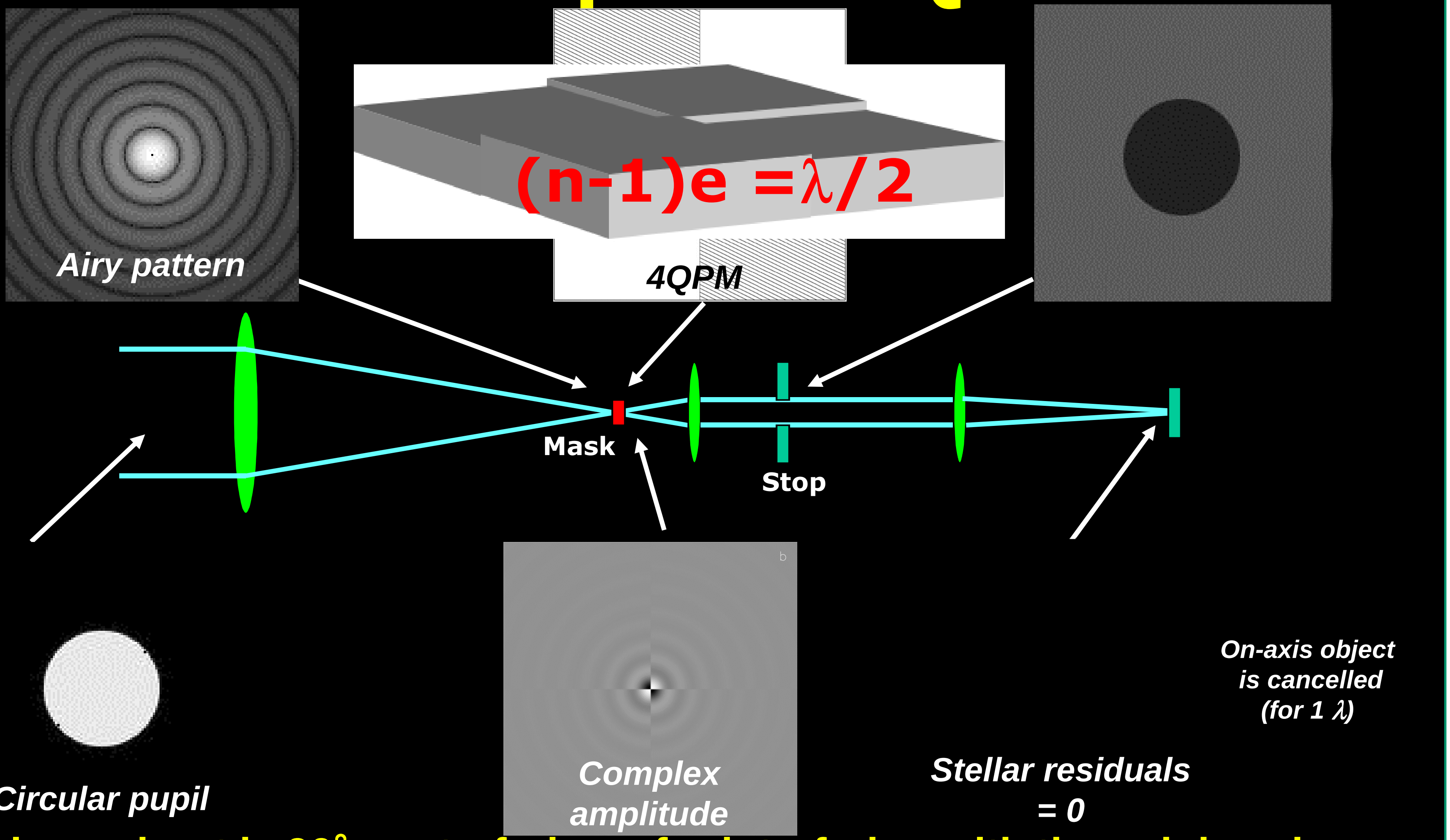
Can be optimistic as JWST should be more stable than HST and SPITZER (cf M. Clampin)

In addition, a lot of work on characterization/tests at the instrument level
(especially detectors at JPL, M. Ressler et al.)

Delay in the launch has helped!

Coronography
Principle of 4QPM

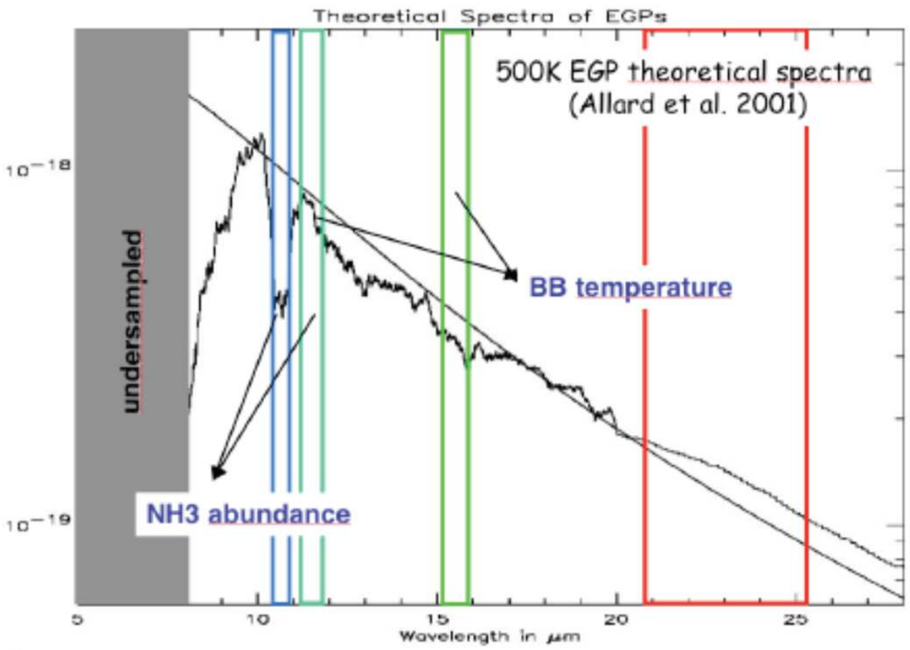
(LESIA)



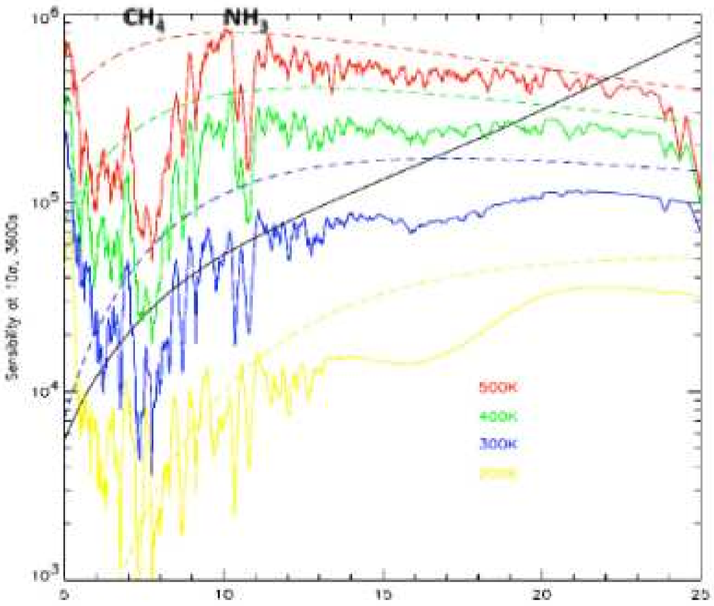
Each quadrant is 90° out-of-phase for interfering with the neighouring one ➔full attenuation of the central star which allows to observe the extremely close surrounding of the star (a fraction of the diffraction pattern).

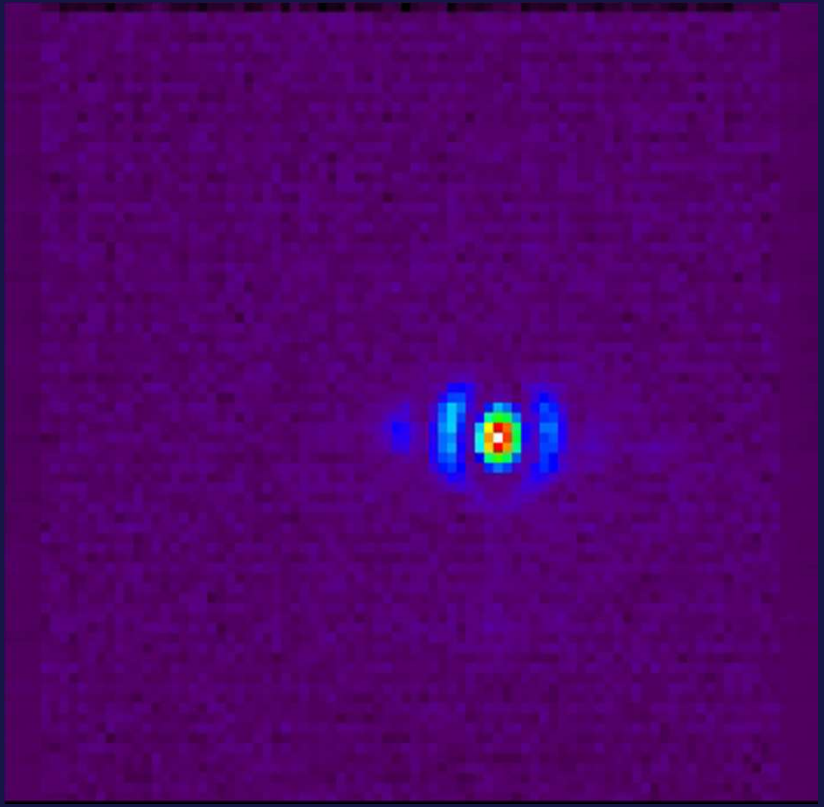
Chromatic → choice of 3 wavelengths

The observations can be at three wavelengths (10.65, 11.4 and 15.5 microns), which have been chosen to detect the NH3 feature at 10.65 microns, which can probe the temperature of the object.



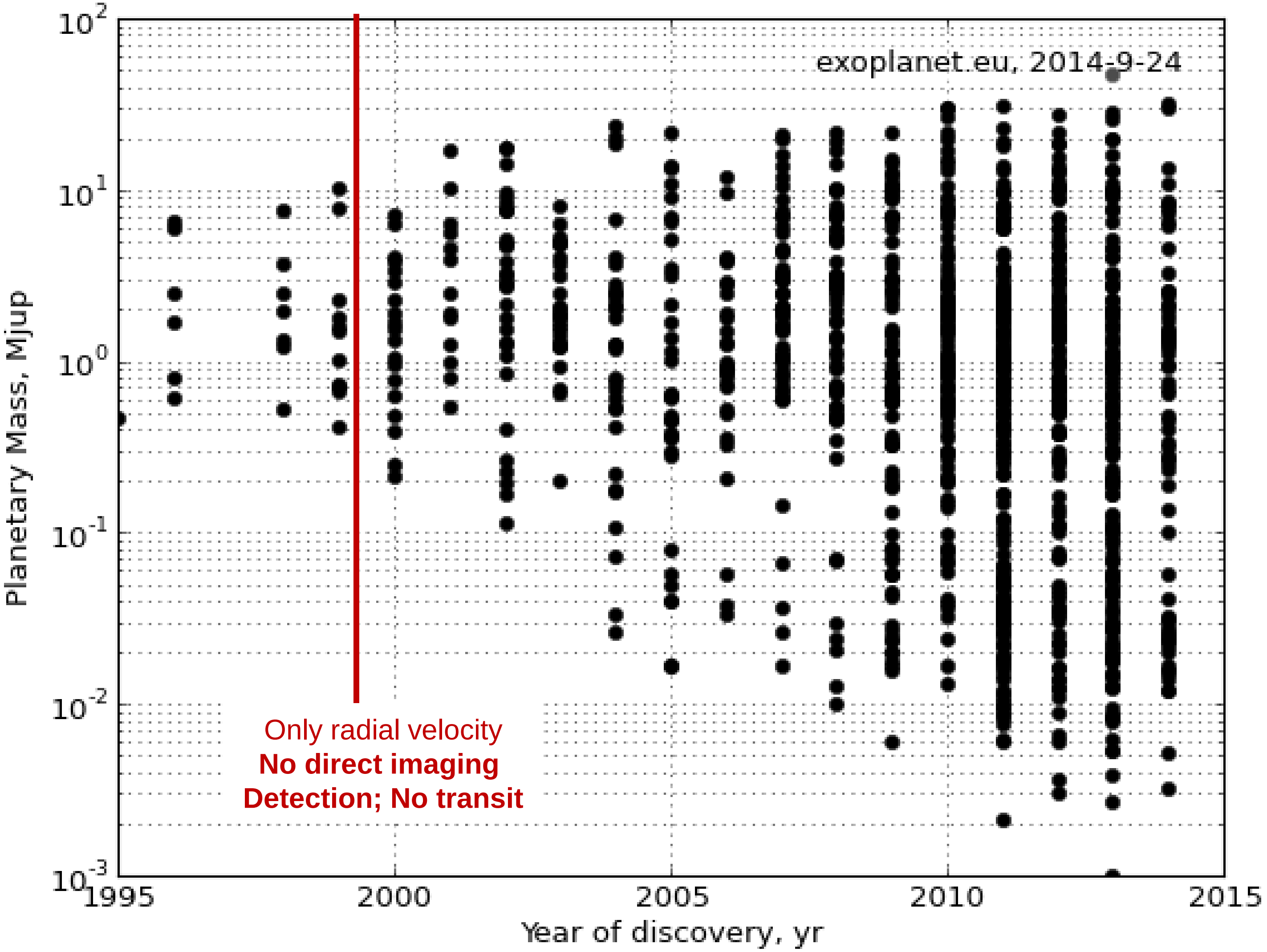
NH3 → Temperature





When we started MIRI, last century …

MIRI European Consortium



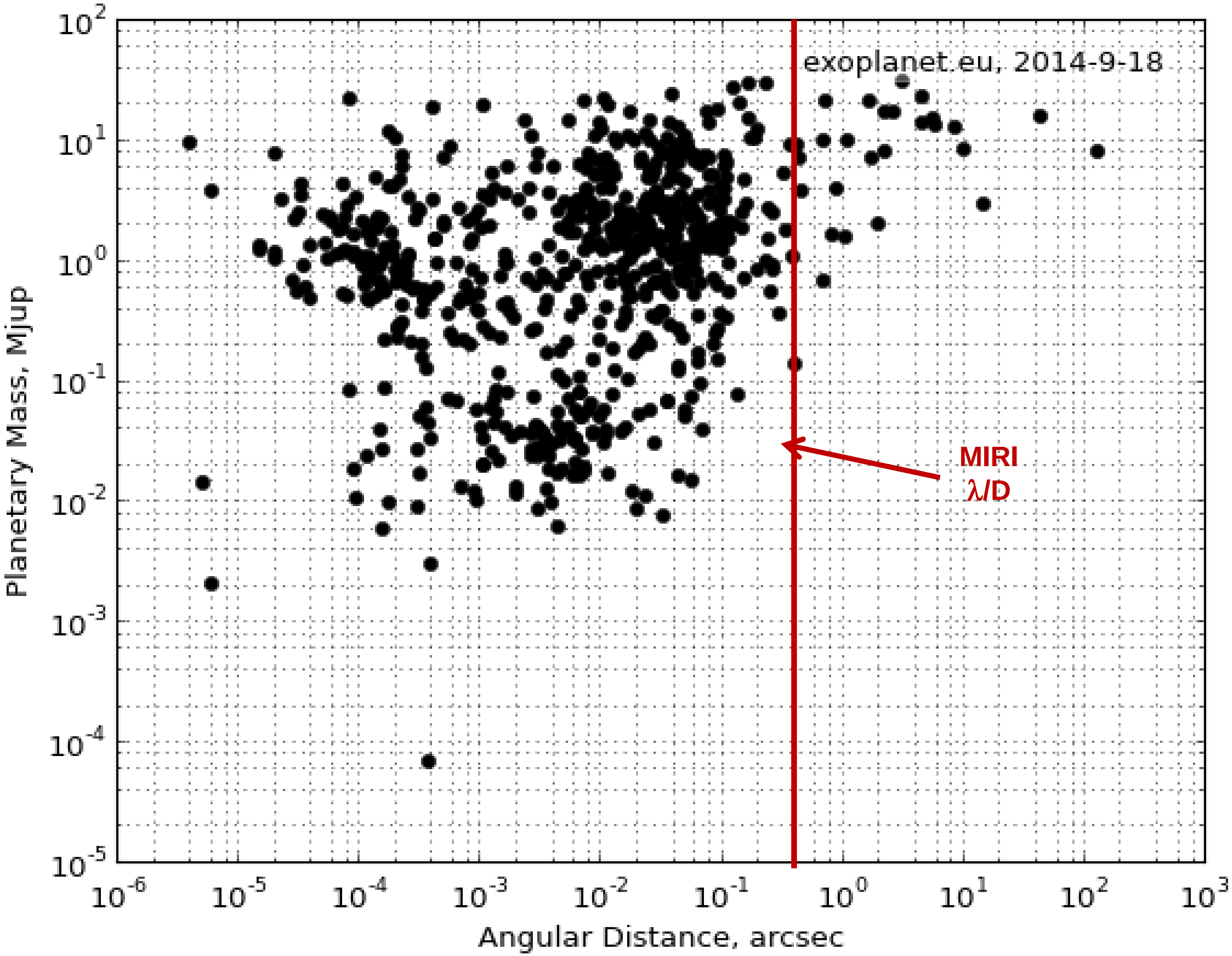
Only radial velocity

No direct imaging

Detection; No transit

Planets studied by direct imaging: today

MIRI European Consortium



MIRI
λ/D

List of sources for direct imaging

# name	mass	radius	semi_major_axis	angular_distance (arcsec)	temp_measured	temp_uncert	log_g	molecules
1RXS 1609 b	14	1,7	330	2,275862	1800	200	4	H2O, CO, K
2M 0122-2439 b	2	1	52	1,5	1600	100	4,5	
2M 0219-3925	13,9	1,44	156	3,96	1683	43	4,24	
2M1207 b	4	1,5	46	0,877863	1000	null	4	
AB Pic b	13,5	1,22	275	5,813953	2000	200	4	
CT Cha b	19	2,2	440	2,666667	2500	100	3,5	
FW Tau (AB) b	10	0,21	330	2,3	2000	100	null	
Fomalhaut b	3	1,2	115	14,92731	400	50	null	
GJ 504 b	4	null	43,5	2,48 en moyenne	510	30	3,9	CH4
GJ 758 b	35	null	44,8	3,516129	600	100	4,5	CH4
GQ Lup b	from 8 to 60	3	103	0,735714	2400	100	4	
HD 106906 b	11	null	654	7,71	1800	100	intermediate-gravity L2.5 ± 1	
HD 95086 b	5	1,3	61,5	0.6	1050	450	3,3	
HR 8799 b	7	1,2	68	1,725888	900	null	4	CH4, H2O, CO
HR 8799 c	10	1,3	42,9	1,088832	1000	null	4	
HR 8799 d	10	1,2	27	0,685279	1000	null	4	
HR 8799 e	9	null	14,5	0,36802	1000	null	4	
PZ Tel b	21	null	20	0,3	2500	130	3,5	
ROXs 12 b	16	null	210	1,7	null	null	null	
ROXs 42B (AB) b	10	2,5	140	1,1	2200	400	4	CO, H2O, K
VHS 1256-1257 b	11,2	null	102	8,06	880	140	4,24	
beta Pic b	7	1,76	9,04	0,440415	1550	150	3,5	H
kappa And b	14	1,2	55	1,058	1900	150	4,5	
SCR 1845 b	45	0,7	4,5	1,168831	1000	100	5	
2M 0103(AB) b	13		84					

From exoplanet encyclopedia

Not so many so far about 20 targets

More to come from Sphere, GPI?

A few as outliers : like GJ504b
Temperature: 500 K
Mass: 4 Jup masses
Far enough (2.5 arcsec)
to make direct MRS observations

Some with masses > 13 Jup mass

Link with sub-stellar objects

Bridge between stars and exoplanets (cf Hans talk)

improve the theoretical models,
meteorology in their atmospheres,
characterization of the properties of proto-brown dwarfs.

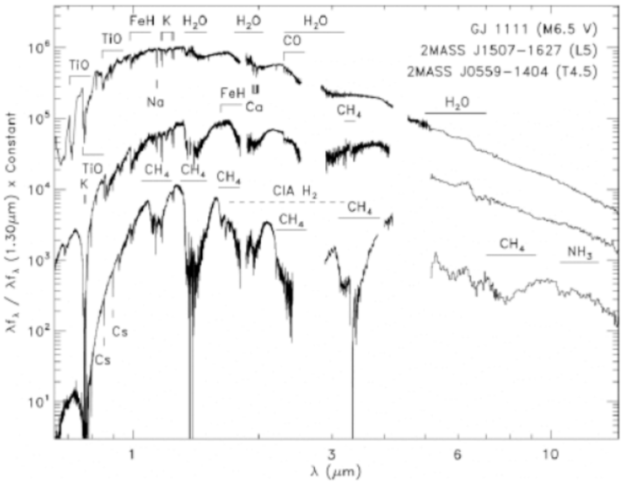


Figure 3: The 0.65-14.5μm spectra of GJ 1111 (M6.5 V), 2MASS J1507- 1627 (L5), and 2MASS J0559_1404 (T4.5). The red optical spectra are from Kirkpatrick et al. (1991), Reid et al. (2000), and Burgasser et al. (2003), and the near-infrared spectra are from Cushing et al. (2005) and Rayner et al. (2006). The spectra have been normalized to unity at 1.3 μm and multiplied by constants. The CIAH$_2$ absorption is indicated as a dashed line because it shows no distinct spectral features but rather a broad, smooth absorption (from Cushing et al., 2006).

JWST Time devoted to exoplanet ?

MIRI European GTO exoplanets about ¼ of the times : 100-110 hours

Team
Olivier Absil; David Barrado; Anthony Boccaletti; Jeroen Bouwman; Leen Decin; Daniel Dicken; René Gastaud; Alistair Glasse; Adrian Glauser; Manuel Guedel; Tomas Henning; Inga Kamp; Oliver Krause; Fred Lahuis; Pierre-Olivier Lagage (coordinator) Migo Mueller; Cyrine Nehme; Goran Olofsson; Eric Pantin ; John Pye; Daniel Rouan; Pierre Royer; Silvia Scheithauer; Bart Vandenbussche; Helen Walker; Rens Waters (co-coordinator)

In close coordination with Tom Greene (US)

Collaboration in progress with other GTO holders

GTO time for JWST : about 4000 hours

¼ → typically 1000 GTO hours of JWST for exoplanet

JWST Time devoted to exoplanet ?

More time for exoplanets?

Highly competitive

« We should be organized to compete with well organized communities,
such as cosmologists, in order to get our share (1.25 (+ 1.25) years) »
Chas Beichman

Not do what can be done more efficiently with a small mission such as Ariel (1.95 – 7.8 microns) (see G. Tinetti talk)

→ Spend a large amount of time on low mass temperate exoplanets,
if first observations confirm the feasability
(Cowan et al. 2015)

In any case MIRI observations unique!