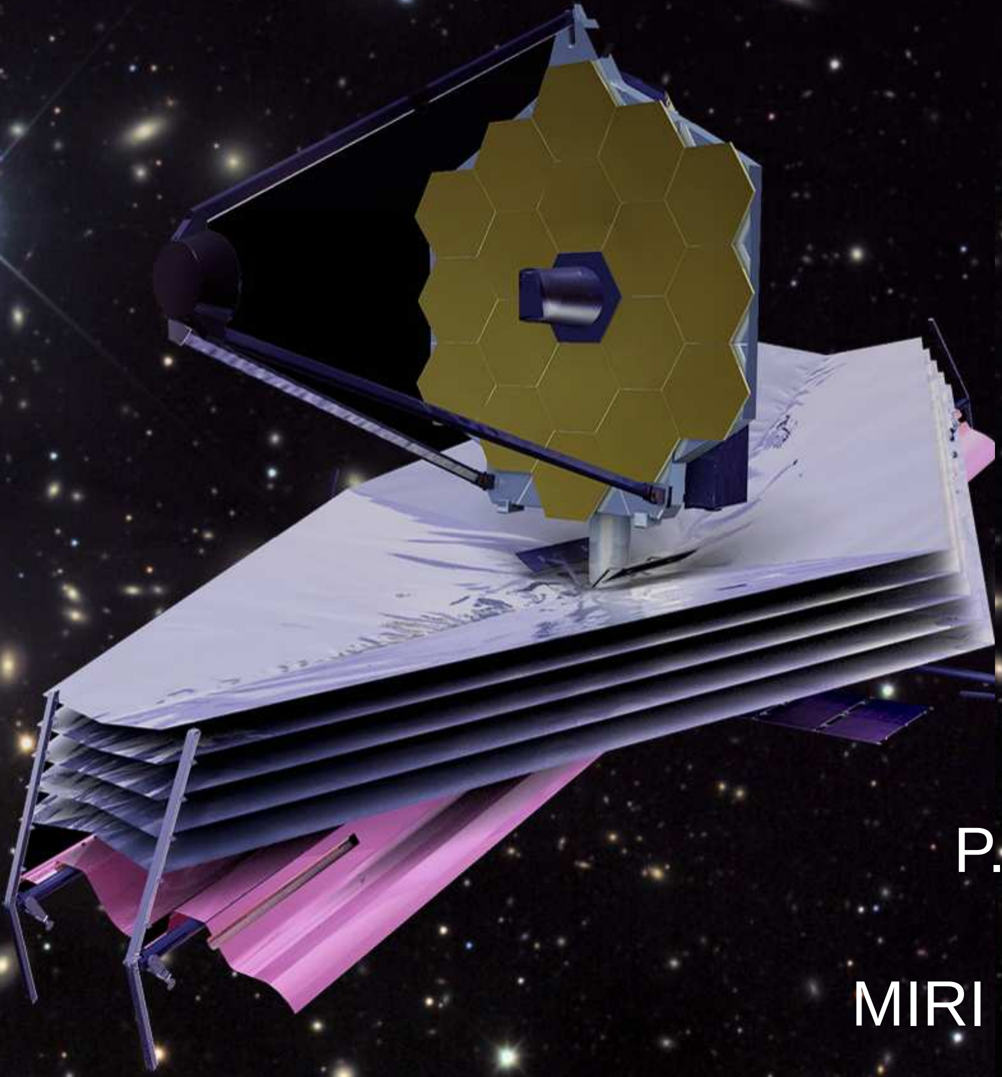
Exoplanet Atmospheres with MIRI



P.-O. Lagage (CEA – Saclay)
On behalf of
MIRI EC exoplanet working group

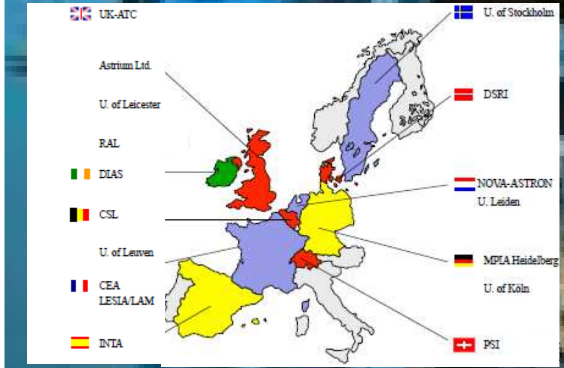
MIRI is a 50%-50% Europe-US share project

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

Exoplanet Atmosphere studies

MIRI European Consortium

To contrain internal structure of exoplanets,
To contrain exoplanet formation and migration
from spectroscopic observations → C/O ratio; metallicity …

To study the atmosphere of exo-planets by itself and test atmospheric models, circulation models, climate models in new regime

Atmosphere structure

Temperature/pressure profiles in atmospheres.
Origin of high altitude temperature inversions?

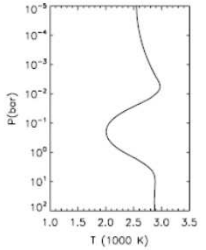
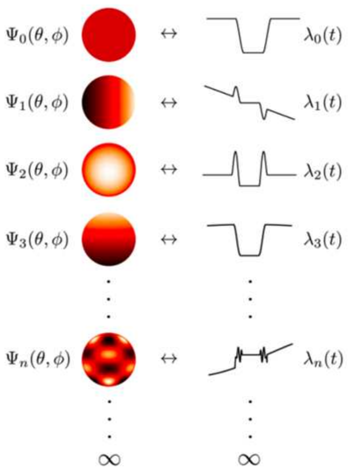


Figure 8. Temperature–pressure profile of HAT-P-7b corresponding to the atmosphere model shown in Figure 7, showing a temperature inversion.

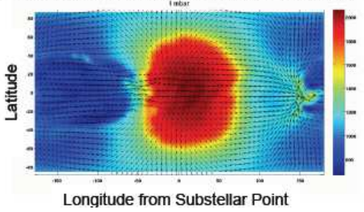


Majeau et al. 2014

Atmosphere dynamics, climate

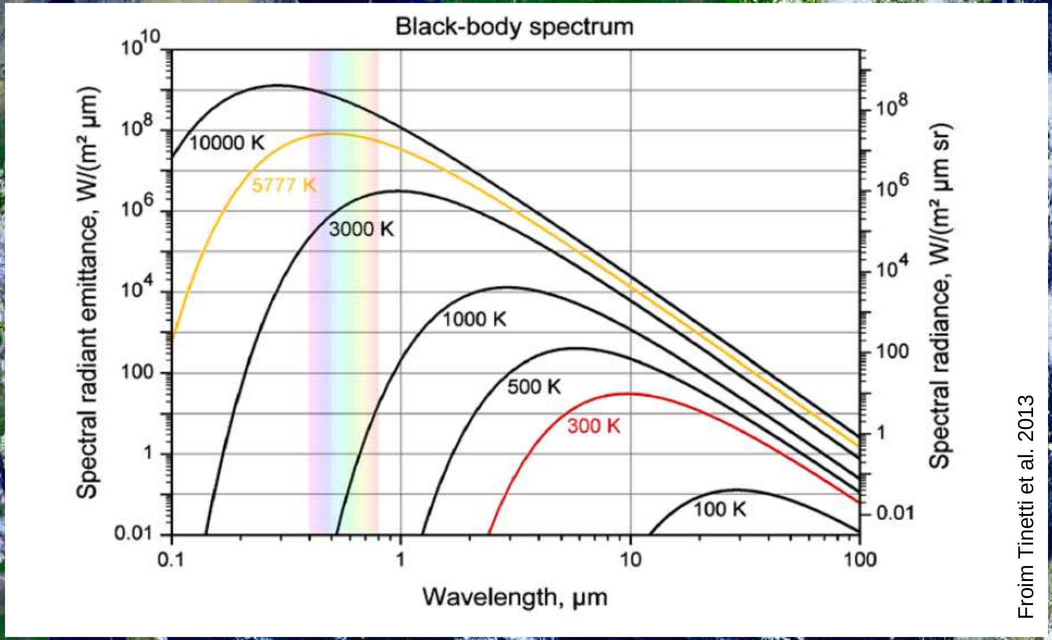
From phase curves,
from ingress, egress precise measurements → « 2D maps » possible;
Variability

3. Circulation Model (Showman et al. 2009)



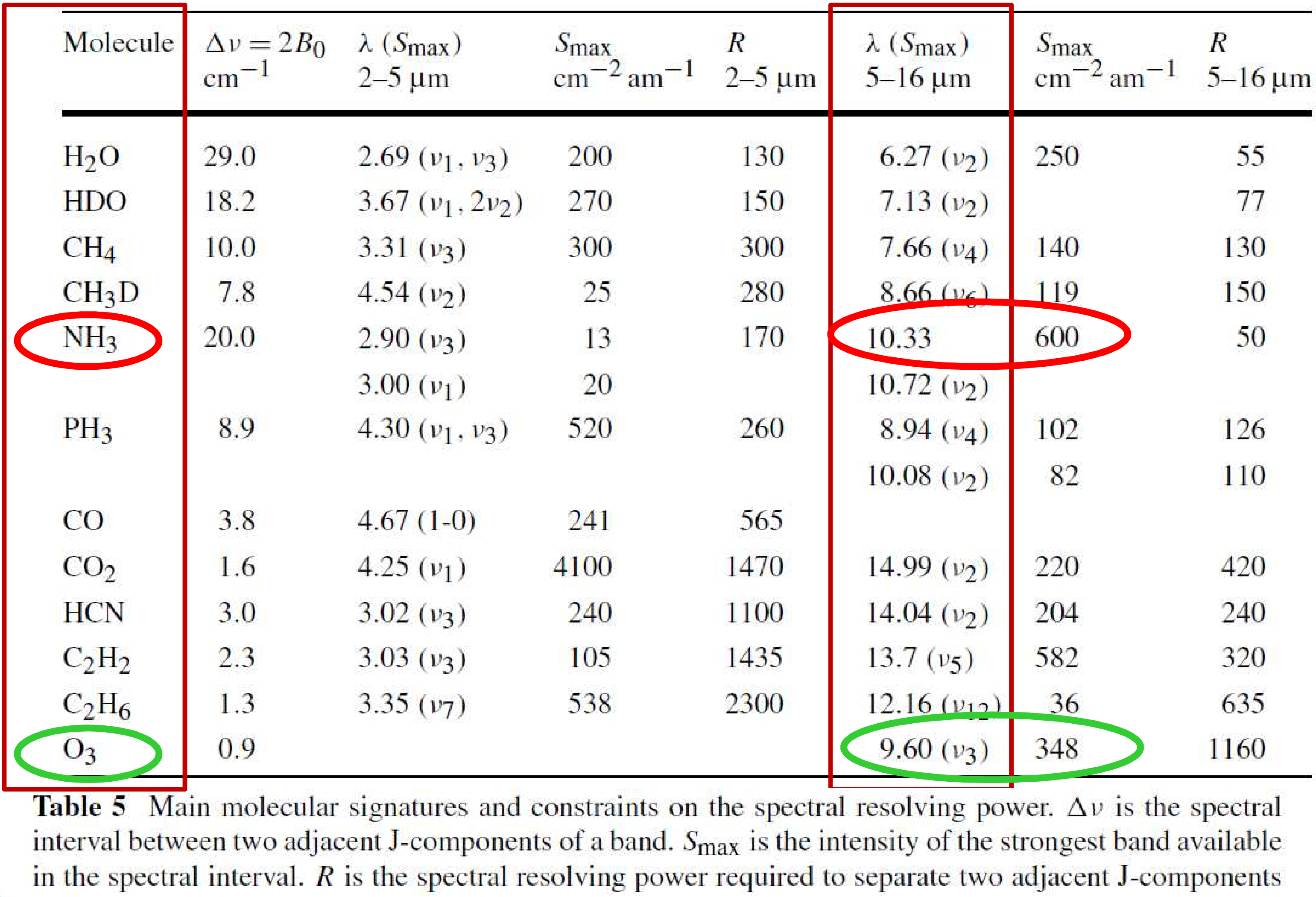
Pinpointing specificities MIRI can bring.

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

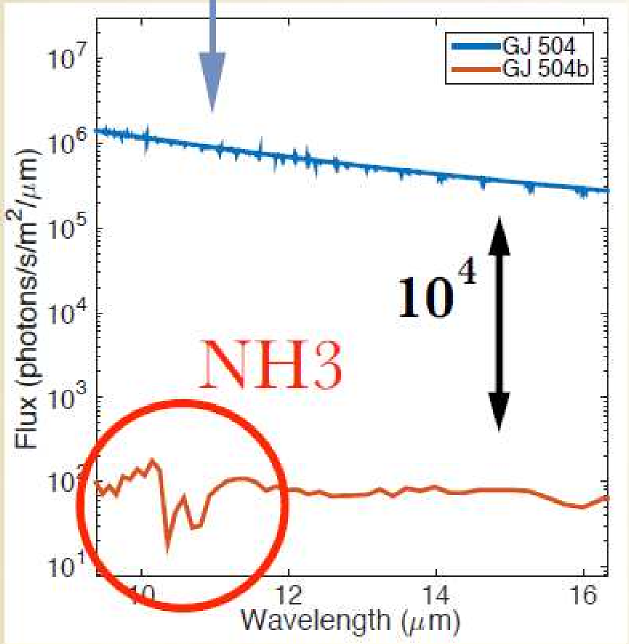
Table 5 Main molecular signatures and constraints on the spectral resolving power. $\Delta\nu$ is the spectral interval between two adjacent J-components of a band. S_{max} is the intensity of the strongest band available in the spectral interval. R is the spectral resolving power required to separate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

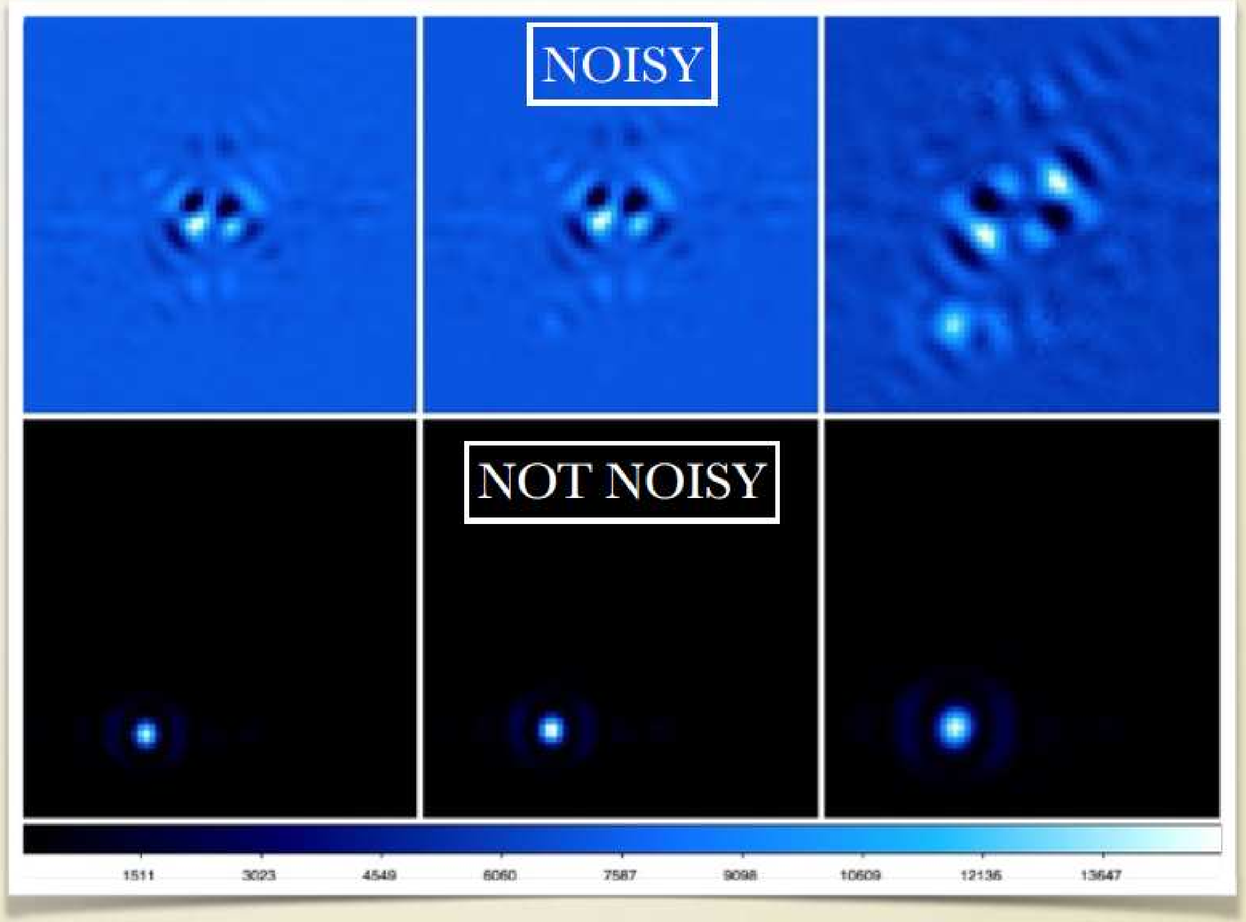
From Tinetti et al. AAR 2013

GJ 504b

Camilla Danielski's talk

PHOENIX





$M_P = 4\ M_J$

$R_P = \mathrm{NA}$

$T_P = 500\ \mathrm{K}$

$T_S = 6234\ \mathrm{K}$

$M_K = 4.033$

$d = 2''.48$

130nm rms; 2mmdefocus; 3% pupil shift; 0.5° pupil orientati
jitter 7 mas 1-sig; 5mas REF offset

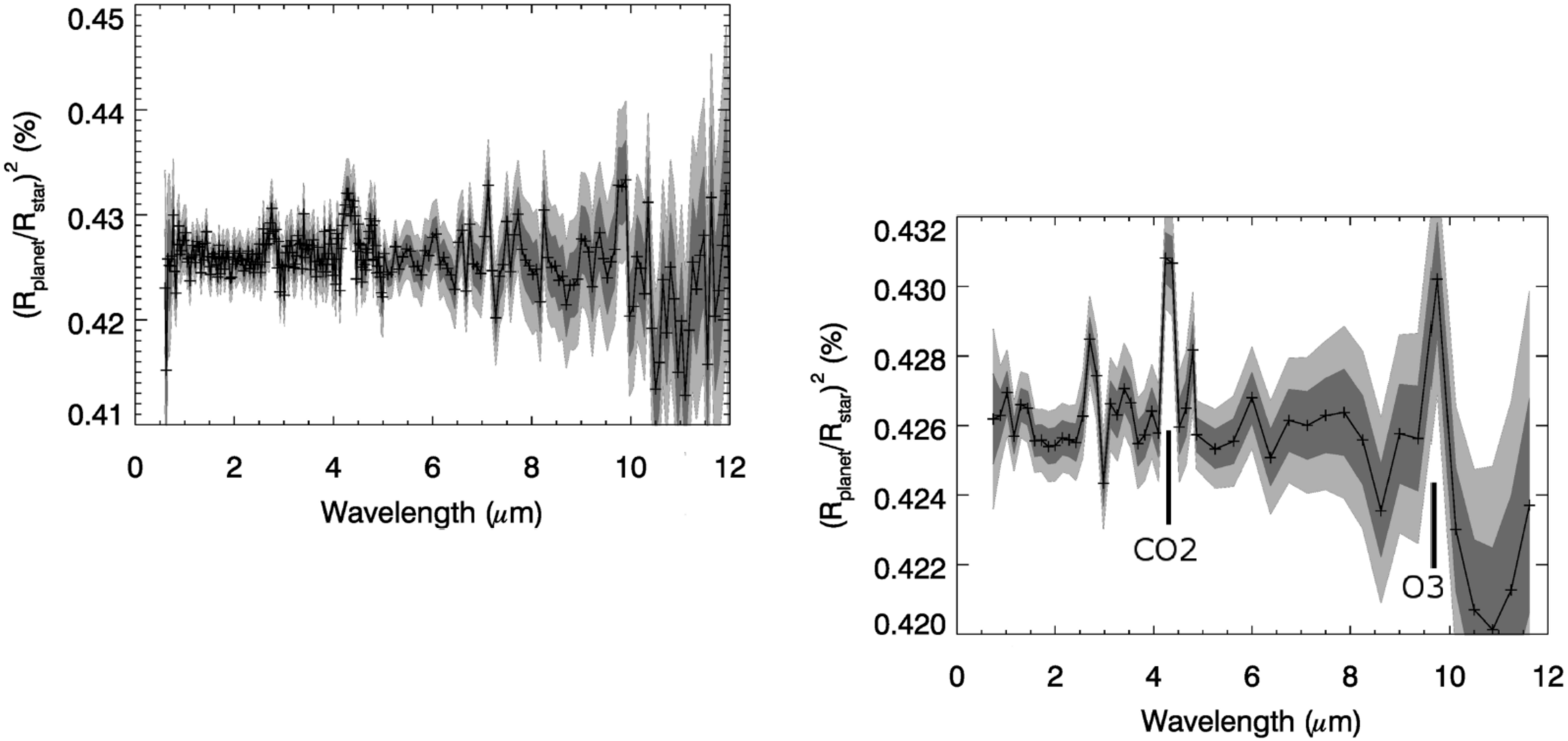
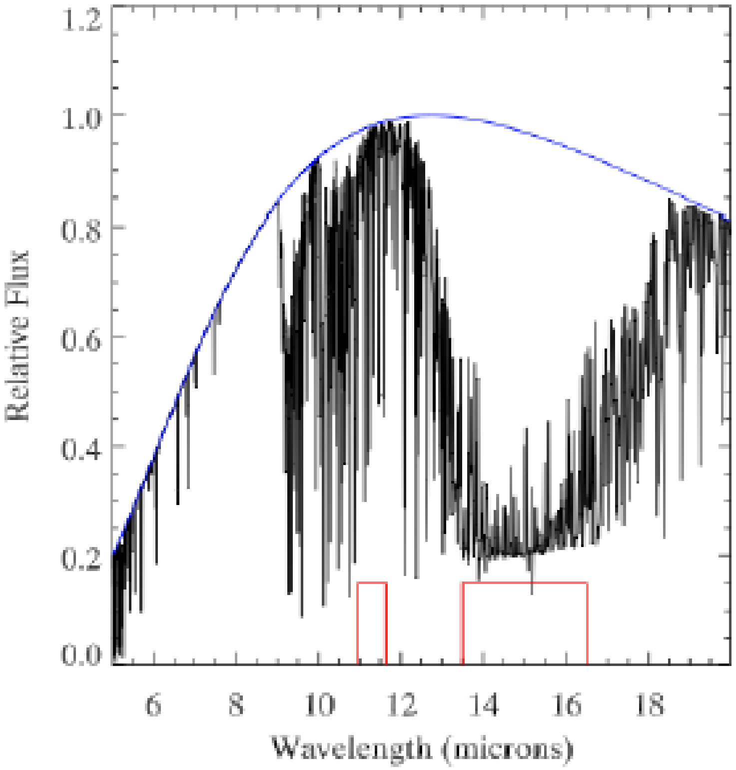


Figure 1. Spectra for 30 primary transits of an Earth orbiting an M dwarf at 10 pc. The spectrum on the right is binned up by a factor 5 to make the ozone band at 9.6 μm more obvious. The CO_2 band at 4.3 μm is also clearly visible. Dark/light grey shading indicates $1\sigma/2\sigma$ error bars.

Barstow et al. 2015

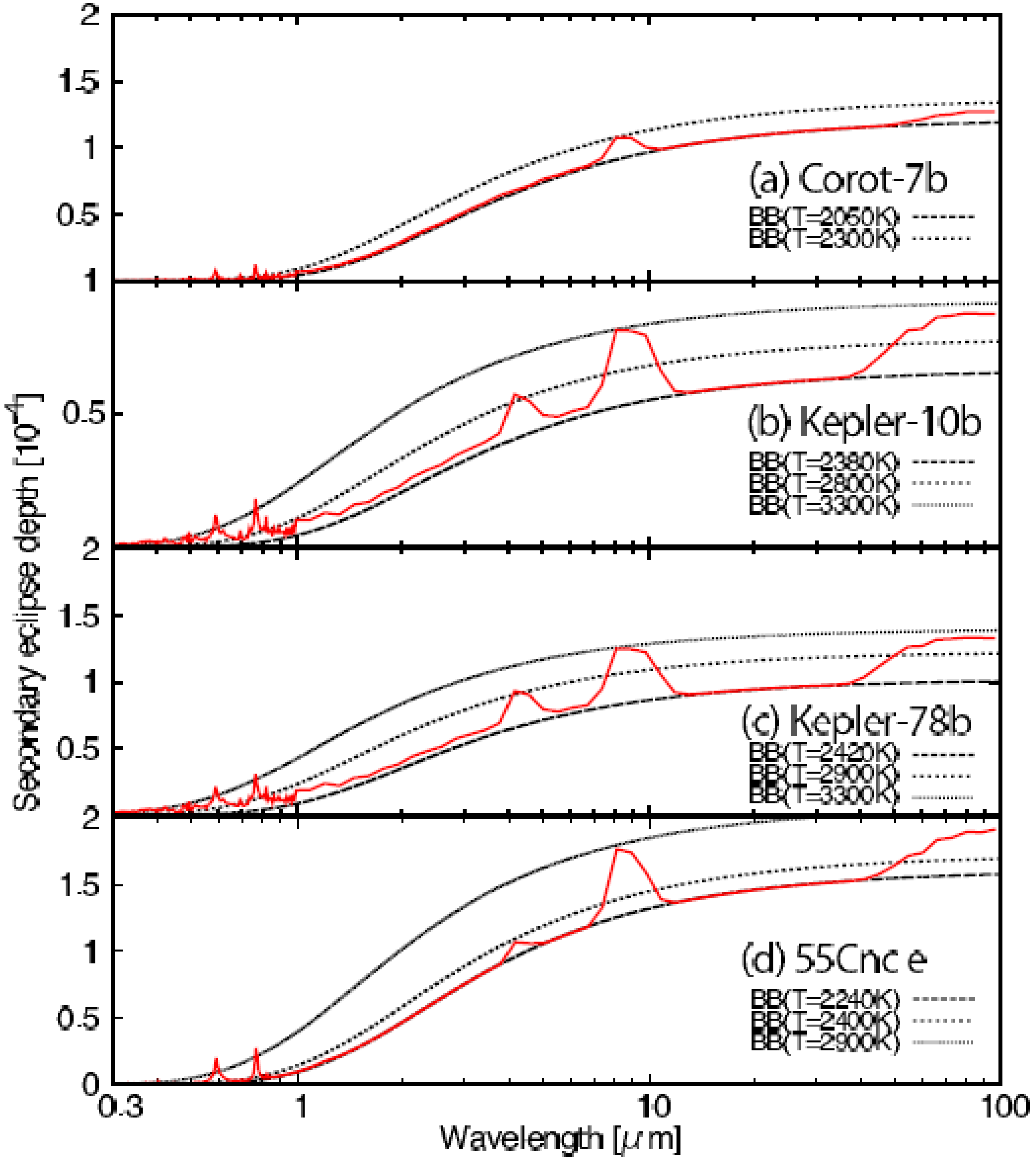
MIRI detection of CO_2 in Super-Earth emission?



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

SuperEarth with mineral atmosphere :
Si0 band at 10 microns



Y. Ito et al ApJ 2015

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

4 Yang, Cowan, & Abbot

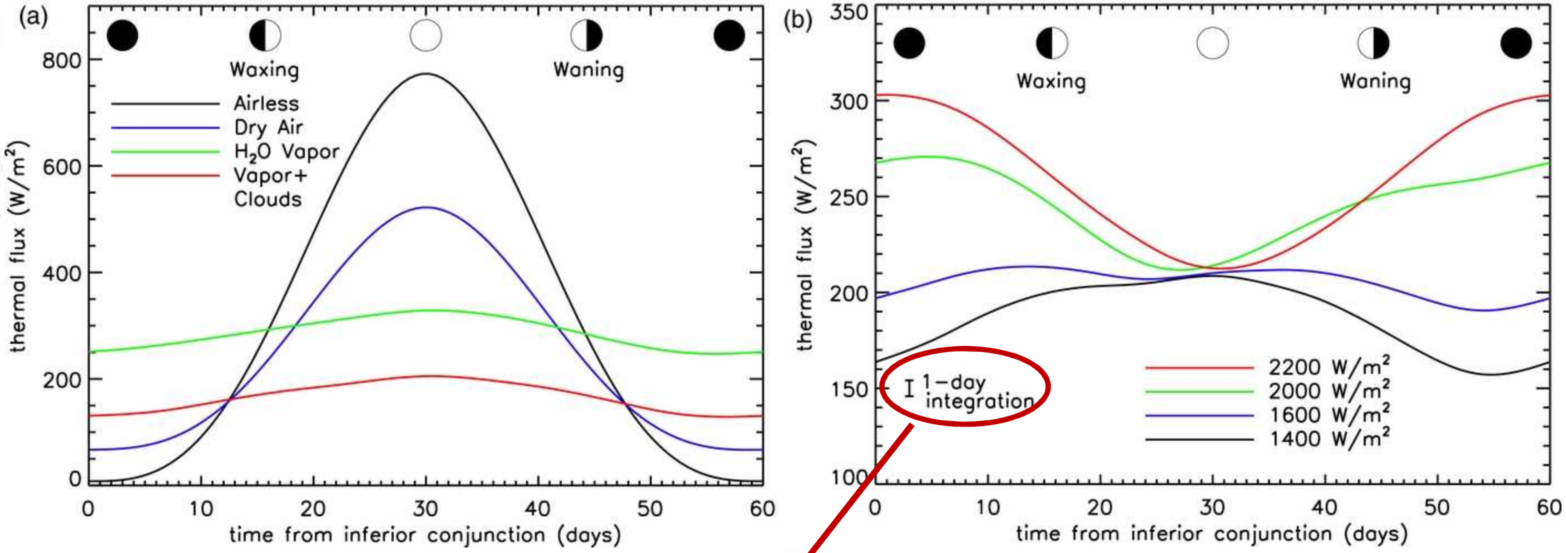
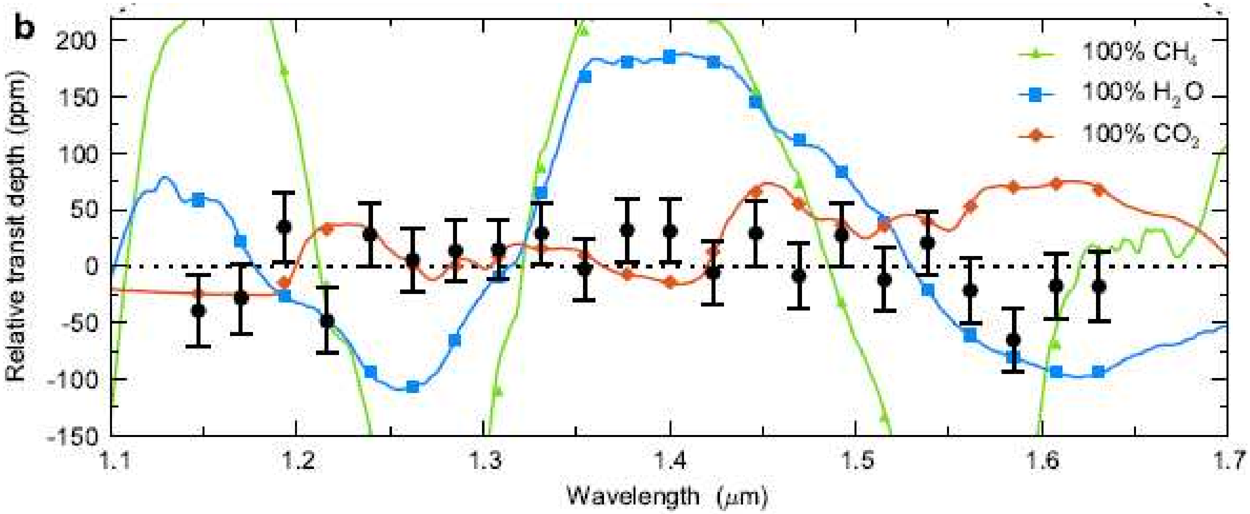


FIG. 3.— Thermal phase curves of tidally locked planets. (a) phase curves for different atmospheres with stellar flux fixed at 1200 W m^{-2}: airless, dry-air, water vapor, and water vapor plus clouds, (b) phase curves for a full atmosphere including water vapor and clouds for different stellar fluxes: 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.

1 ppm : very « challenging »; systematics, stellar variability

Dust features

MIRI European Consortium



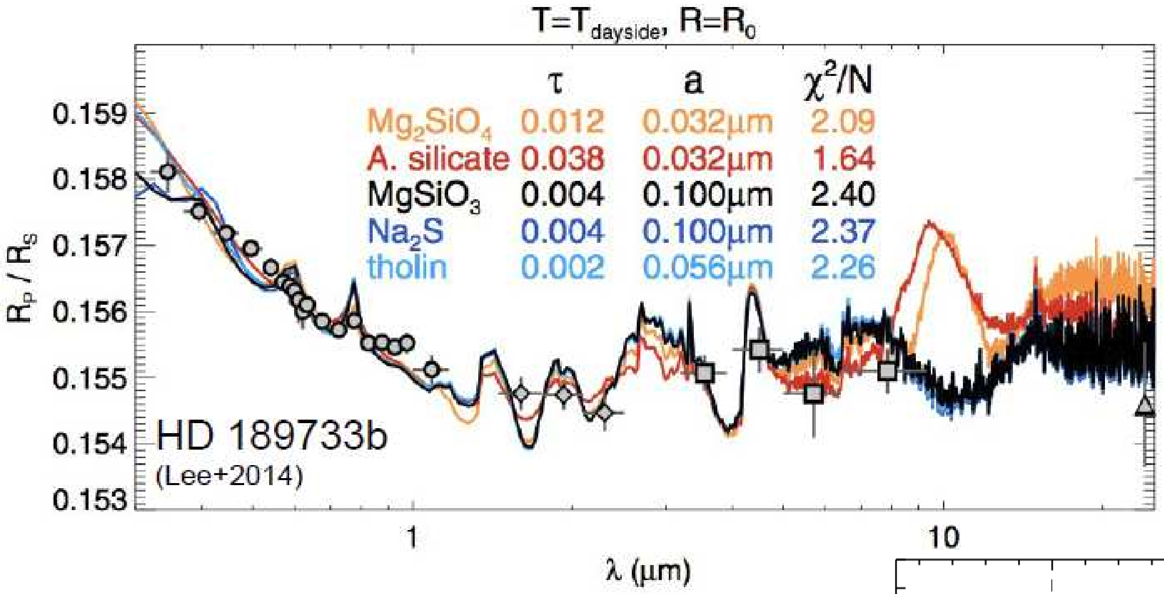
GJ1214b

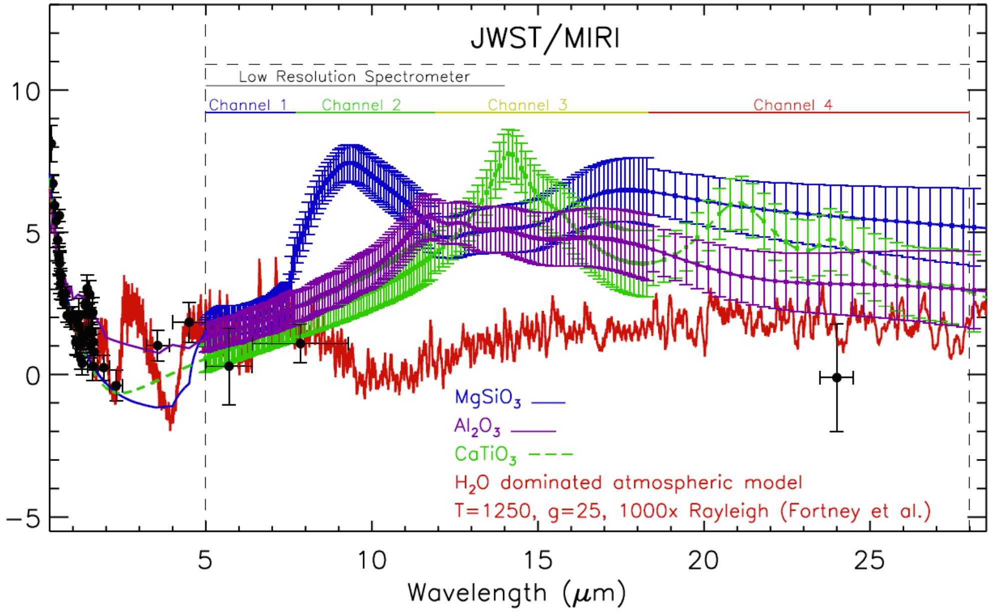
Transmission sprectrum : FLAT

→ clouds, Hazes

(L. Kreidberg et al. 2014)

A better transmission spectrum in the mid-IR needed





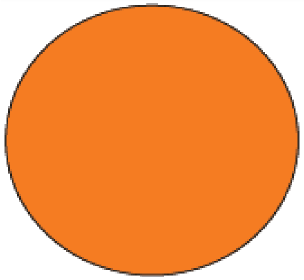
H. R. Wakeford and D. K. Sing: Transmission spectral properties of clouds for hot Jupiter exoplanets

Which kind of exoplanets to be observed with MIRI ?

Transiting exoplanets: Down to super Earth

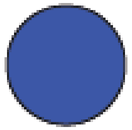
Giant planet

HD 209458b
Mass: 0.66 M_{Jup}
Radius: 1.32 R_{Jup}
T_{eqil}=1360 K



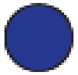
**warm Neptune---
mass planet**

GJ 436b
Mass: 0.07 M_{Jup}
Radius: 0.44 R_{Jup}
T_{equil}=700 K

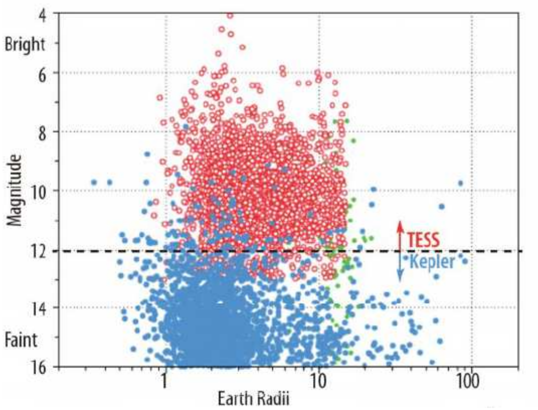


**sub-Neptune
mass planet**

GJ 1214b
Mass: 0.02 M_{Jup}
Radius: 0.24 R_{Jup}
T_{equil}=560 K

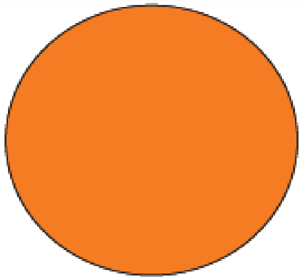


**small planets
yet to be discovered
(K2, TESS)**



Ricker et al. 2014

Direct imaged Giant Planets

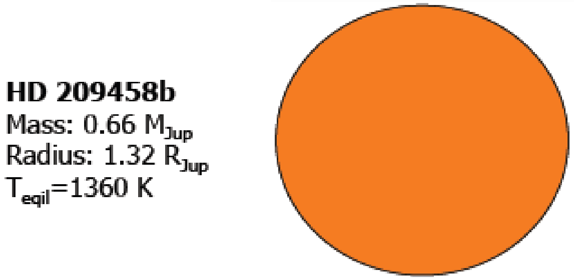


+ link with brown dwarfs

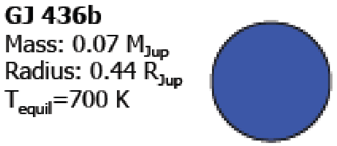
Which kind of exoplanets to be observed with MIRI ?

Transiting exoplanets: Down to super Earth

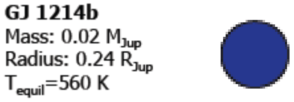
Giant planet



**warm Neptune---
mass planet**



**sub-Neptune
mass planet**



**small planets
yet to be discovered
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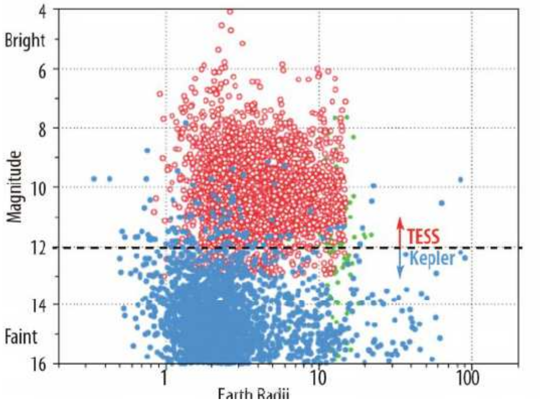


Ricker et al. 2014

Direct imaged Giant Planets

YOUNG!
(in the tens of Million years range)

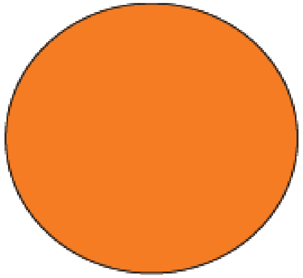
Which kind of exoplanets to be observed with MIRI ?

Transiting exoplanets: Down to super Earth

Direct imaged Giant Planets

Giant planet

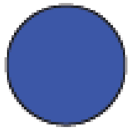
HD 209458b
Mass: 0.66 M_{Jup}
Radius: 1.32 R_{Jup}
T_{eqil}=1360 K



Highly irradiated by the star

warm Neptune---
mass planet

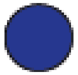
GJ 436b
Mass: 0.07 M_{Jup}
Radius: 0.44 R_{Jup}
T_{equil}=700 K



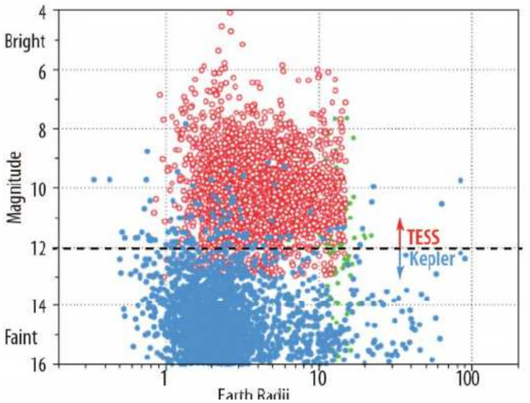
Far from the star
→ Irradiation can be neglected

sub-Neptune
mass planet

GJ 1214b
Mass: 0.02 M_{Jup}
Radius: 0.24 R_{Jup}
T_{equil}=560 K



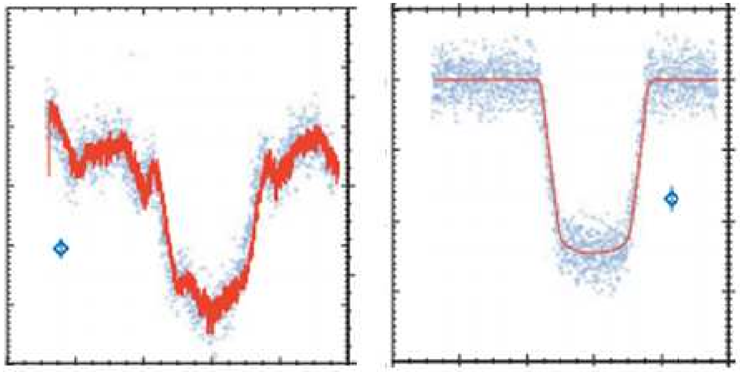
small planets
yet to be discovered
(K2, TESS)



Ricker et al. 2014

Another difference: the integration time

For transiting bright planets around bright stars, observing time not limited by the S/N needed but by transit time in order to correct from systematics



Spitzer observations; Left : uncorrected;
Right: after correction

For transit observations limited by star photon noise :

$$S/N \propto D\sqrt{t} \rightarrow D \propto \frac{S/N_{given}}{\sqrt{T_{transit}}}$$

TESS will bring the small size warm nearby exoplanets needed for JWST transit Observations (especially for MIRI), but will also bring a lot of targets which are in fact good targets for smaller Telescopes than JWST.

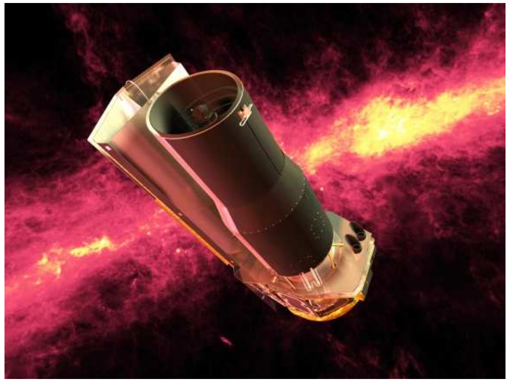
To have a large sample of exoplanet atmosphere (500) need a dedicated telescope like the ARIEL ESA mission selected for competitive phase A study (PI G. Tinetti)

Very little in the mid-IR so far !

Not by lack of interest but by lack of facilities

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

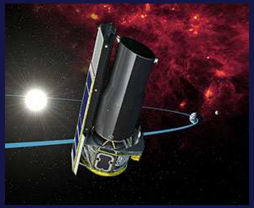
For transisting planets, spectra of only **2 giant** bright exoplanets :
HD 189733b, HD 209458 (cold Spitzer)



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

To JWST

From Spitzer



S x 50

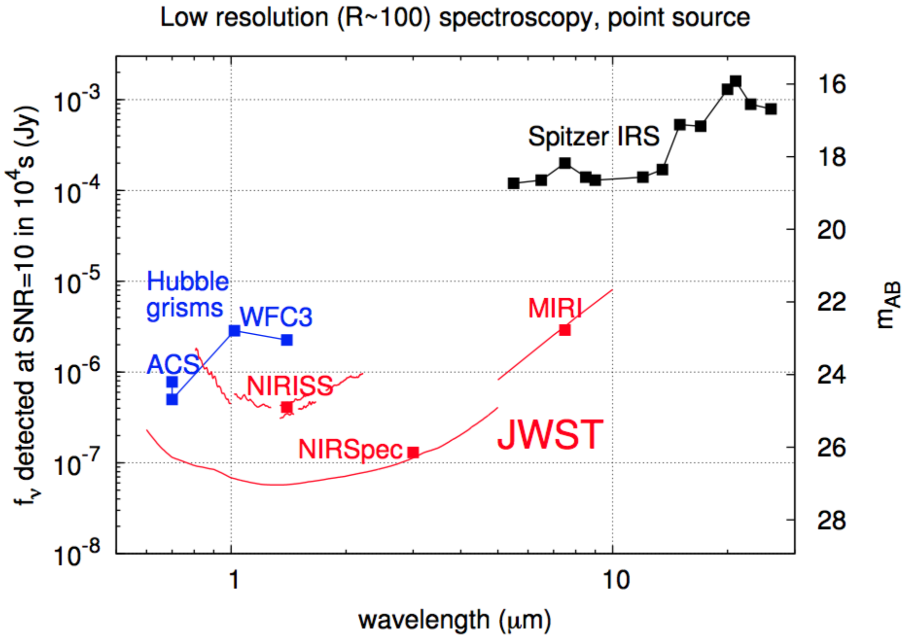
Telescope size : 85 cm

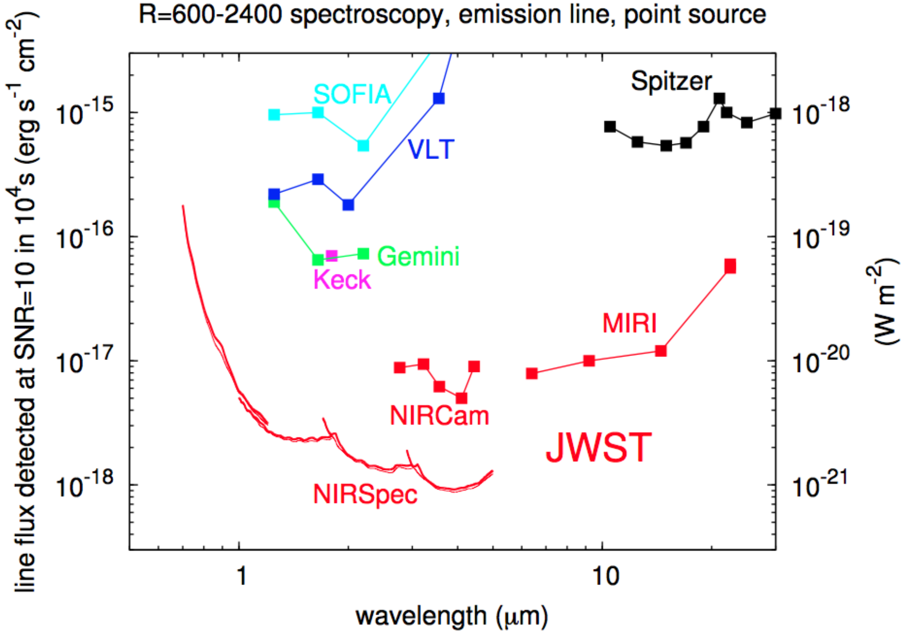
Amazing relative photometric precision
(better than 10^{-4}) for an observatory not
Conceived for exoplanets observations

Telescope size 660 cm

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

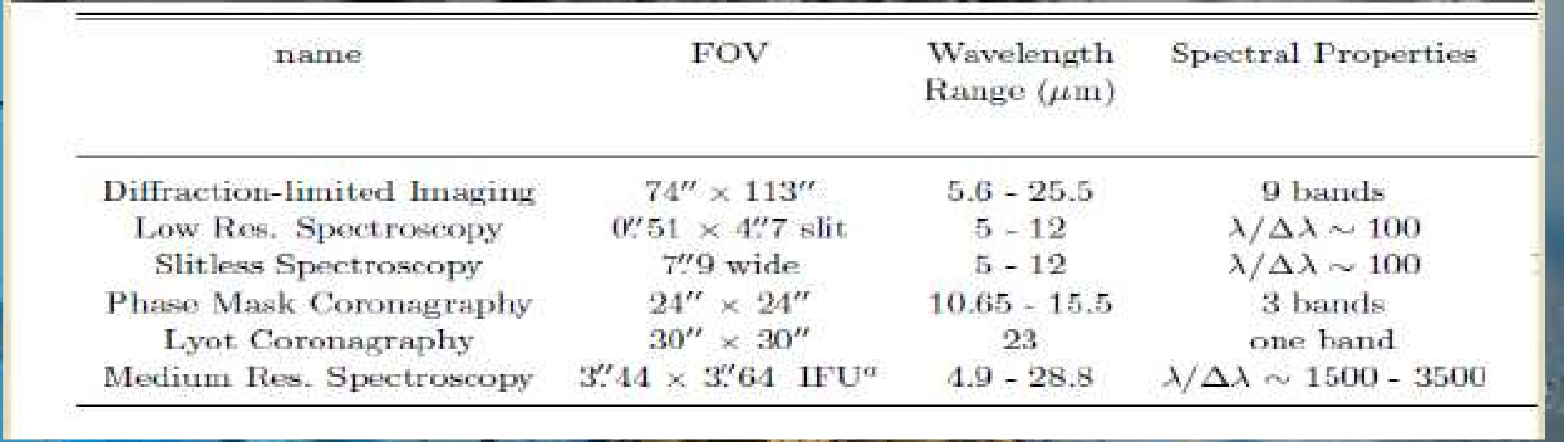
Sensibility





From www.stci.edu/jwst/science/sensitivity

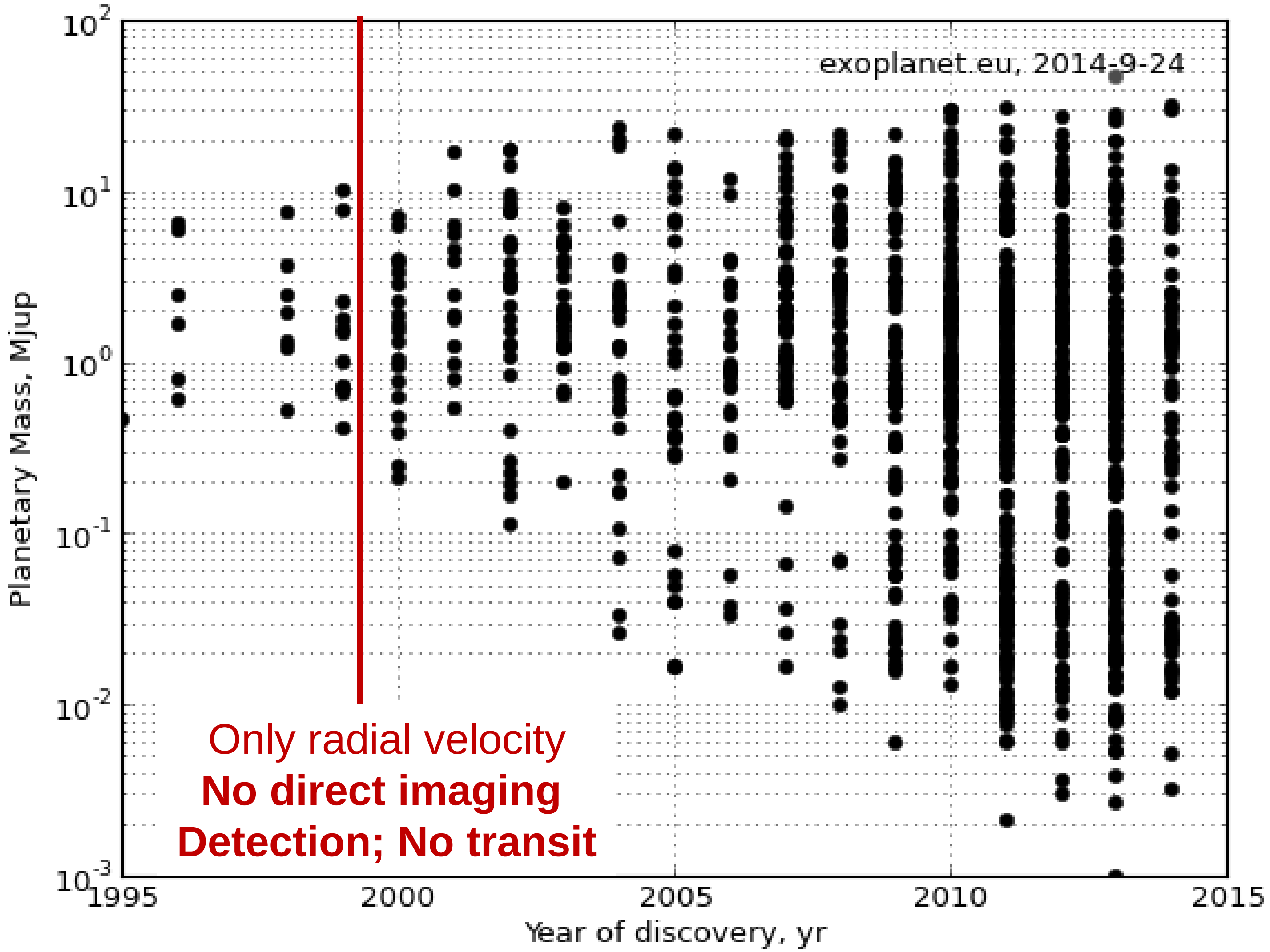
Observing modes



name	FOV	Wavelength Range (μm)	Spectral Properties
Diffraction-limited Imaging	74″ × 113″	5.6 - 25.5	9 bands
Low Res. Spectroscopy	0.″51 × 4.″7 slit	5 - 12	$\lambda/\Delta\lambda \sim 100$
Slitless Spectroscopy	7.″9 wide	5 - 12	$\lambda/\Delta\lambda \sim 100$
Phase Mask Coronagraphy	24″ × 24″	10.65 - 15.5	3 bands
Lyot Coronagraphy	30″ × 30″	23	one band
Medium Res. Spectroscopy	3.″44 × 3.″64 IFU[a]	4.9 - 28.8	$\lambda/\Delta\lambda \sim 1500 - 3500$

When we started MIRI, last century …

MIRI European Consortium



Only radial velocity

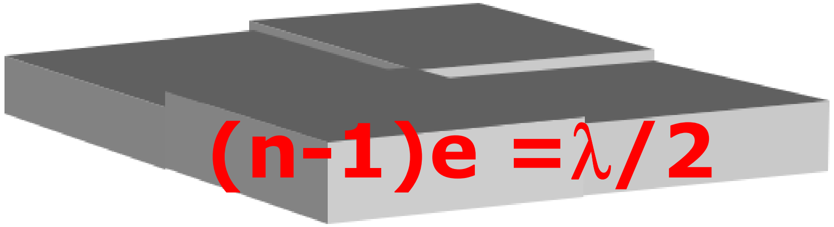
No direct imaging Detection; No transit

The best coronagraph we can use at that time :
4 quadrant phase mask

→ inner working angle down to lambda/D (0.3 arcsec)

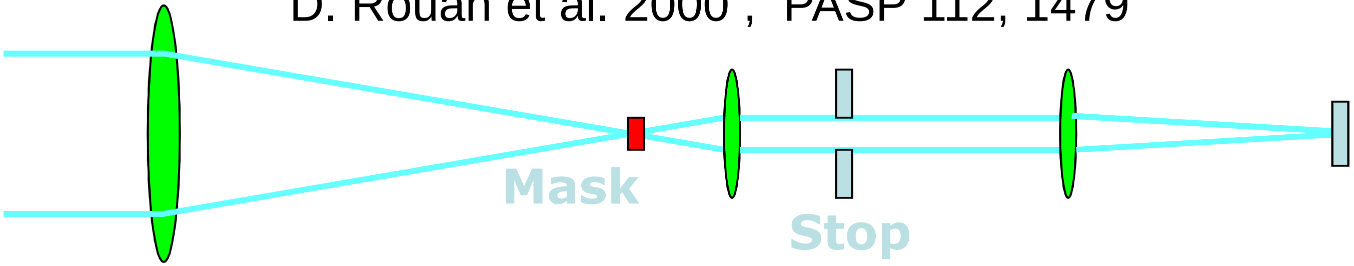
→ Similar as NIRCAM, at shorter wavelength

4 Quadrant Phase mask

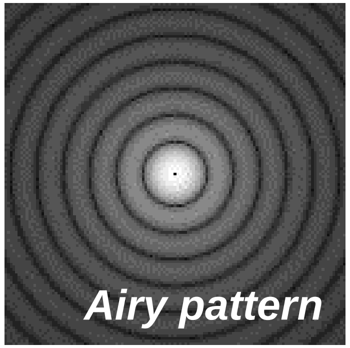


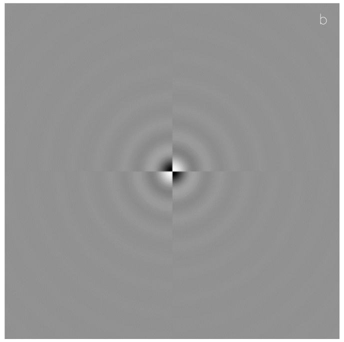
$(n-1)e = \lambda/2$

D. Rouan et al. 2000 , PASP 112, 1479

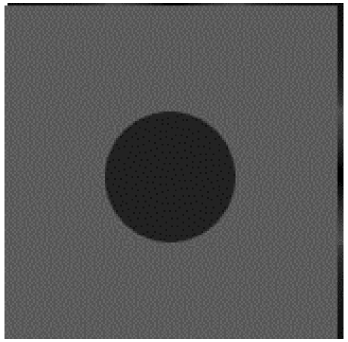


Each quadrant is 90° out-of- phase for interfering with the neighbouring one
➔full attenuation of the central star





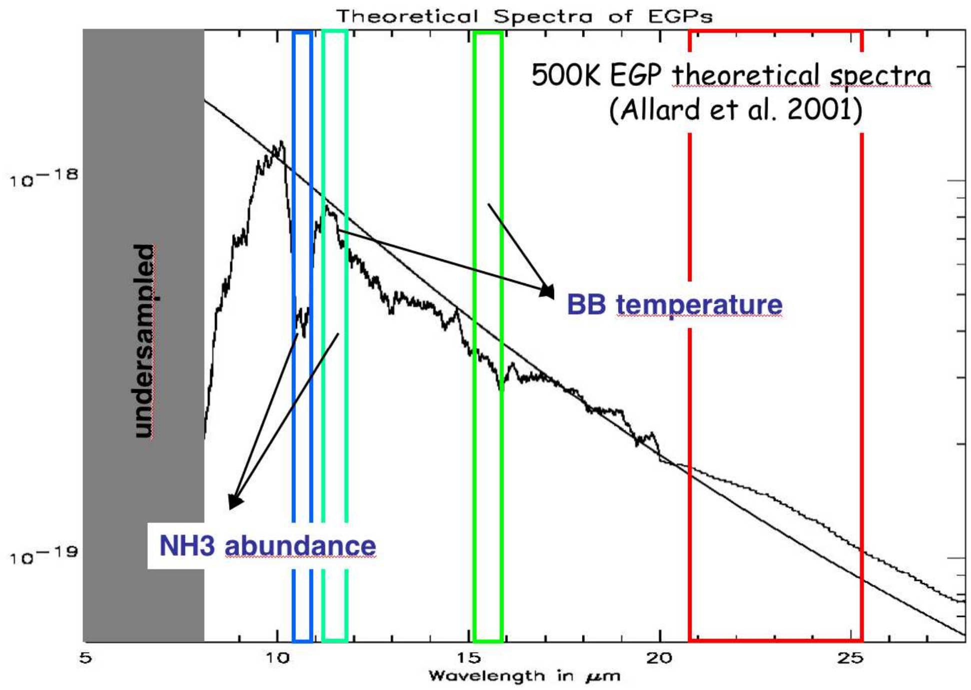
focal plan mask

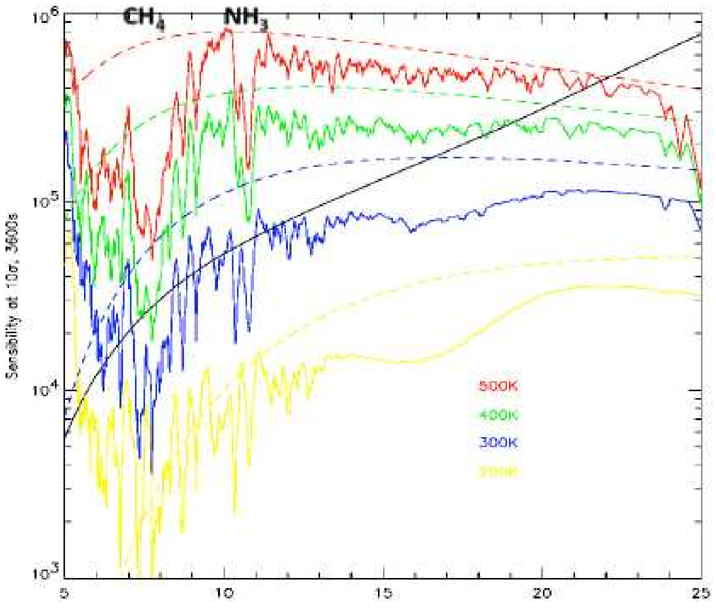


pupil mask

On-axis object is cancelled (for 1 λ)
Stellar residuals = 0

4 quadrant masks chromatic

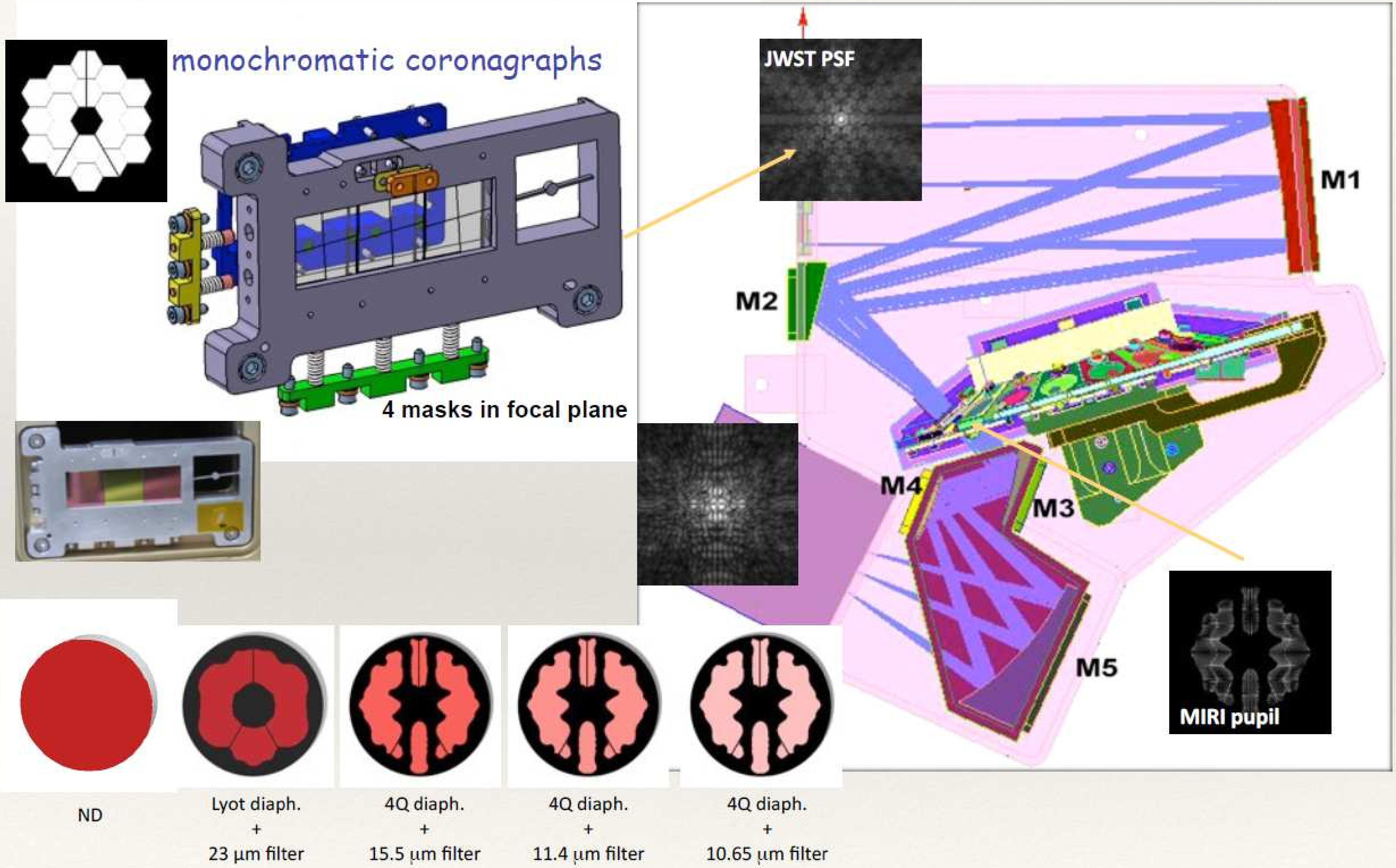




→3 phase masks with wavelength at 10,65, 11,4 and 15,5 μm

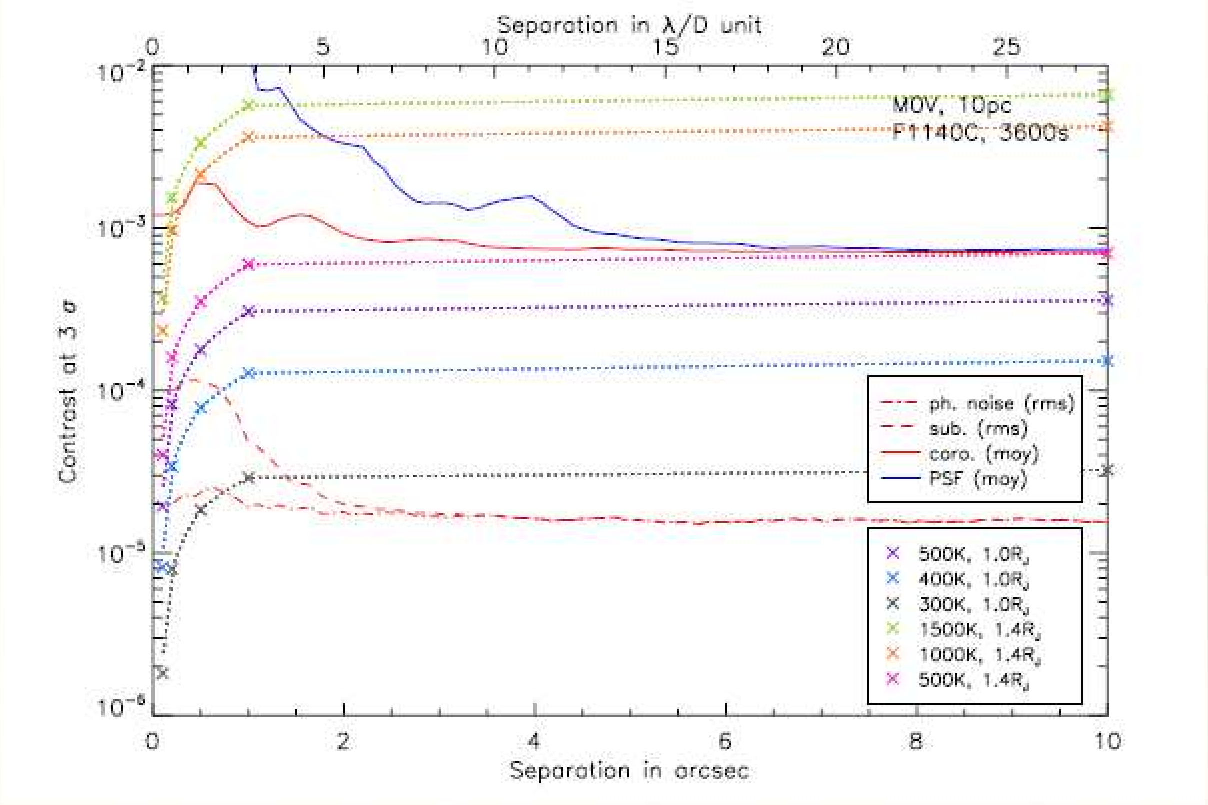
Plus Lyot coronagraph at 23 μm

MIRI coronagraph

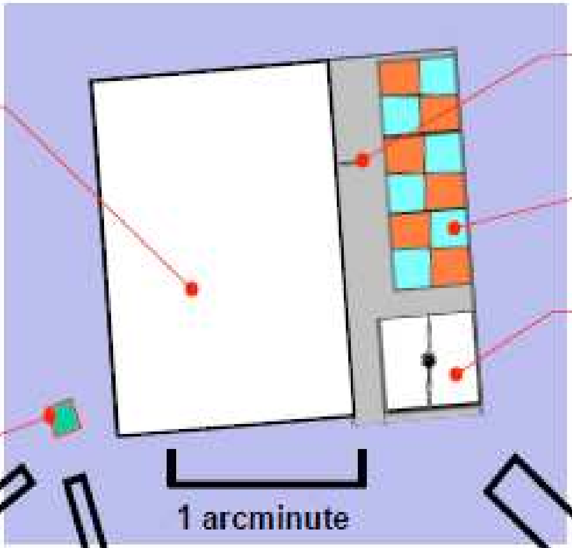


Filter name (and wavelength)	Pass band Δλ (μm)	Function
F560W	1.2	Imaging
F770W	2.2	
F1000W	2.0	
F1130W	0.7	
F1280W	2.4	
F1500W	3.0	
F1800W	3.0	
F2100W	5.0	
F2550W	4.0	
F2550WR	4.0	
P750L	5	R ~ 100 Spectroscopy
F1065C	0.53	Coronagraphy
F1140C	0.57	
F1550C	0.78	
F2300C	4.6	
FND	10	Target Acquisition
FLENS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

MIRI contrast



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

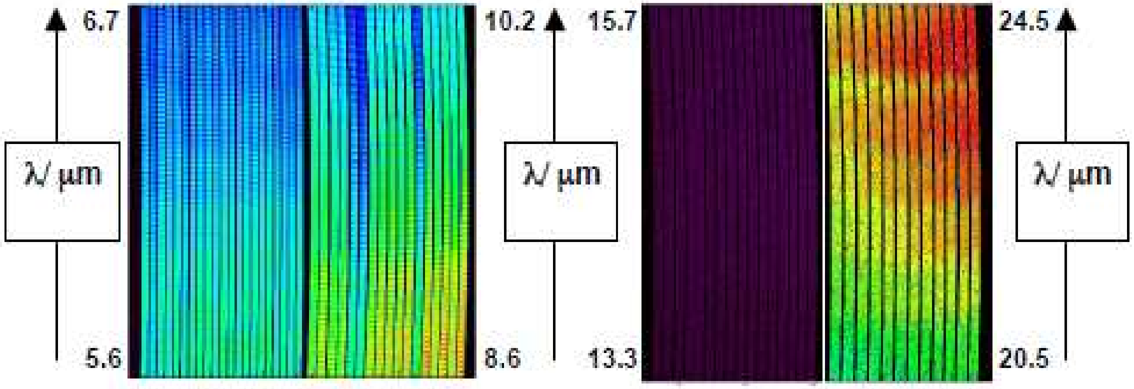
Low Resolution Spectrometer
5 x 0.6 arcsec

Three 4QPM Coronagraphs
24 x 24 arcsec

Lyot Mask 23µm
30" x 30"

MIRI VM Spectral Image

Specsim simulated image

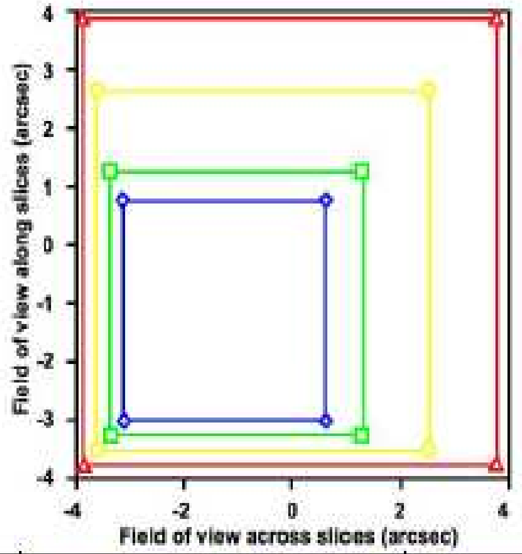


MIRI FM Imager (non-flight detector fitted)

Gillian Wright et al.

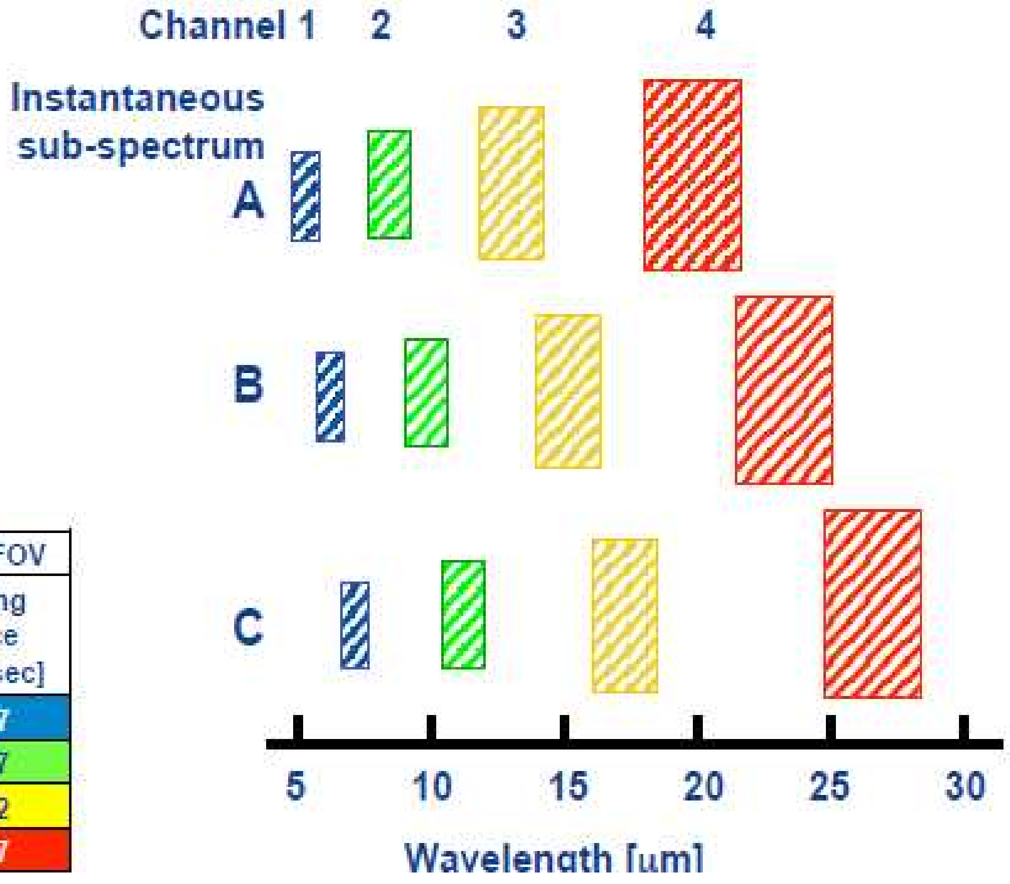
MIRI Medium Resolution Spectrometer

- 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



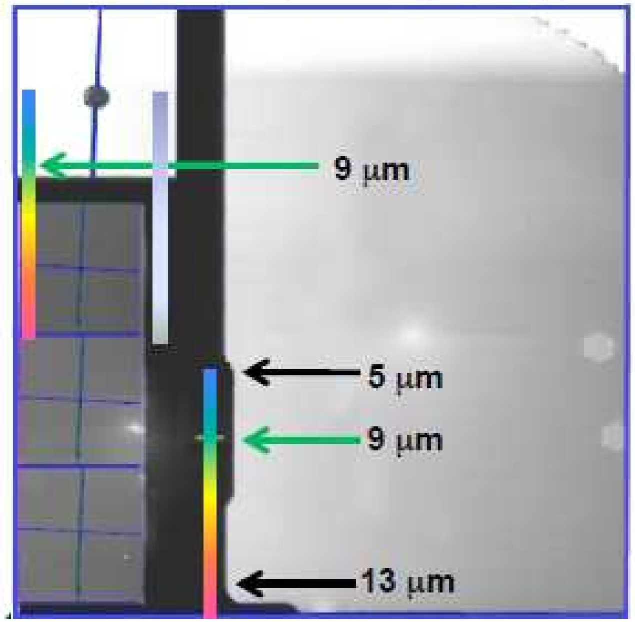
From Martyn Wells et al.: **The Mid-Infrared Instrument for the James Webb Space Telescope VI:The Medium Resolution Spectrometer,** PASP, in press

MIRI was not initially optimized for transit observation

New mode : slitless observations; reading only a sub array

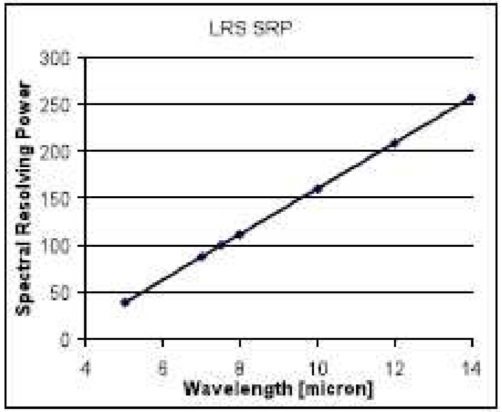
→ saturation K magnitude about 5

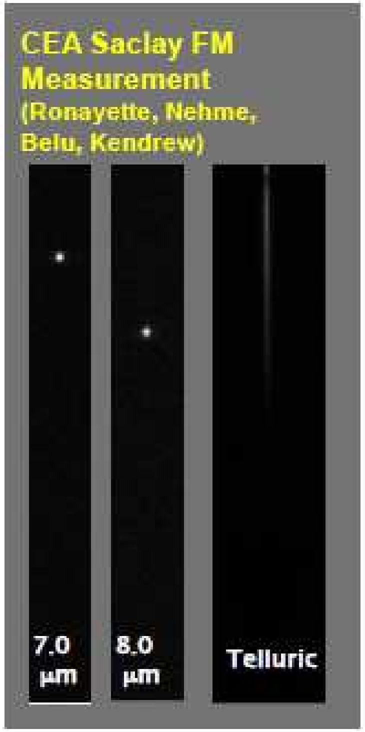
- **Slit and slitless locations**
  - Cusp at 5 μm in slitless spectra
  - Possible alternate slitless location (currently unsupported)



- **Continuum sensitivity**
  - ~3 microJansky 10 σ 10000 sec at 7.5 μm

- **Spectral Resolving Power**



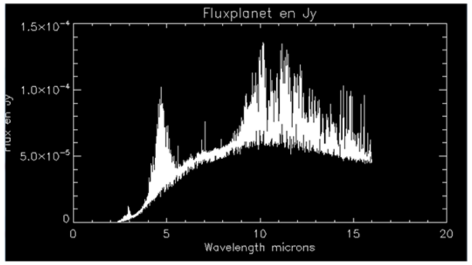


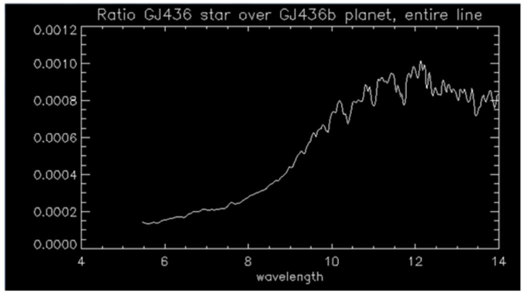
CEA Saclay FM Measurement

(Ronayette, Nehme, Belu, Kendrew)

SIMULATIONS

Results GJ436b



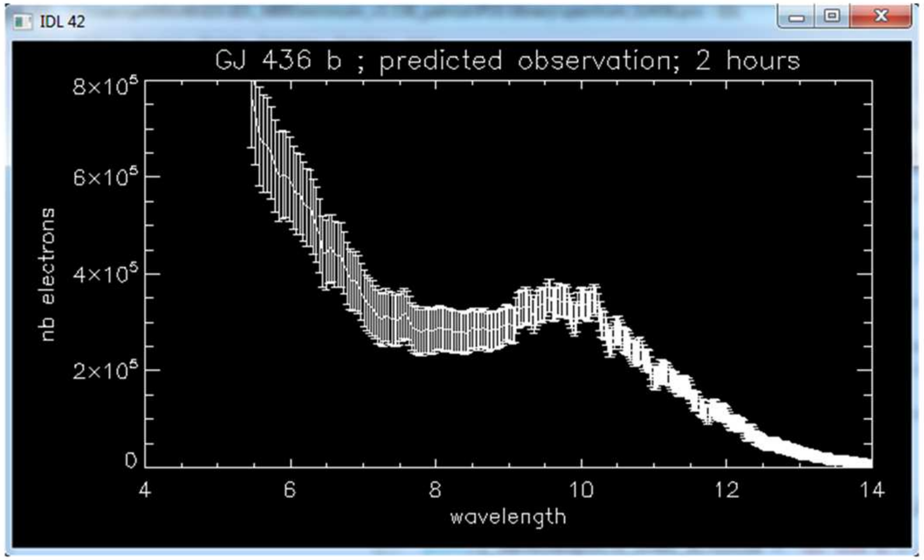


Gastaud et al. 2014

GJ436 Model from J. Fortney Not so many models!

In collaboration with Tom Greene

Simulated eclipse spectrum



Not so easy !

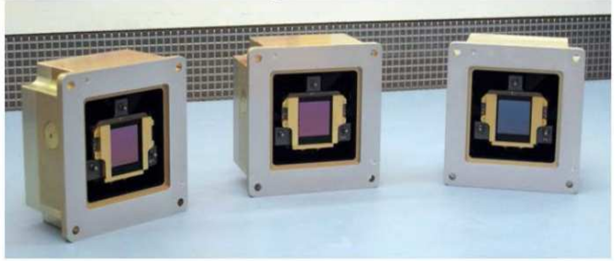
From models, everythink can seem possible and easy.

When you do hardware, you can realize it’s not so easy

Exoplanet observations are definitely difficult one

More characterisations of detectors at JPL (Mike Ressler et al.)

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.



Delay of JWST used positively!!!

M. Ressler et al. : “The Mid-Infrared Instrument for the JWST : VIII The MIRI Focal Plane System, PASP, 2015 in press

The most interesting will be the surprises !

**I am sure we will have some, expecially with MIRI,
which is really opening the field**

Then we should get our share of the JWST time

For more detailed information about MIRI capabilities:

Posters by :

Glasse et al

Garcia-Marin et al

And

PASP Volume 127, Issue 953 (2015) available at http://ircamera.as.arizona.edu/MIRI/index.htm (10 papers)

Thank you for your attention