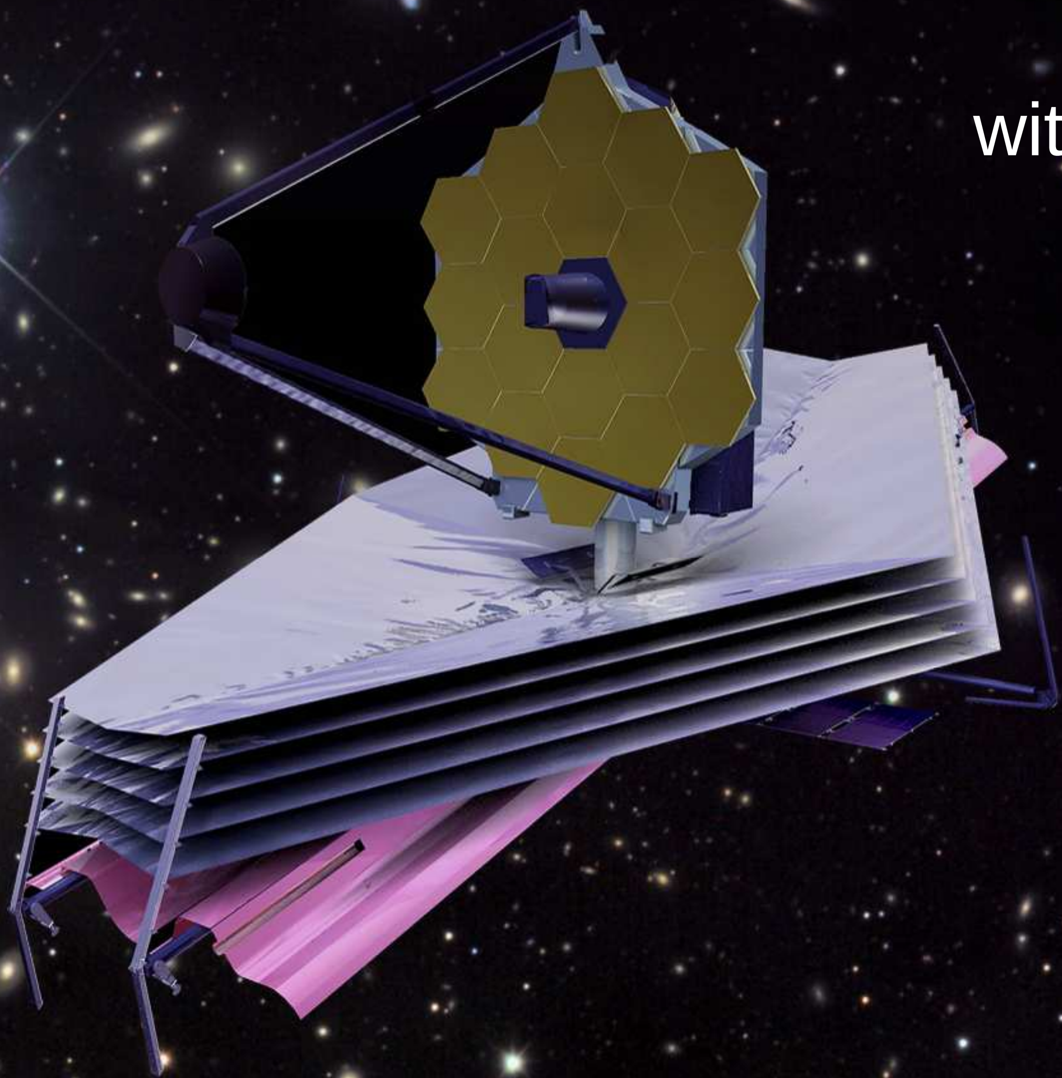
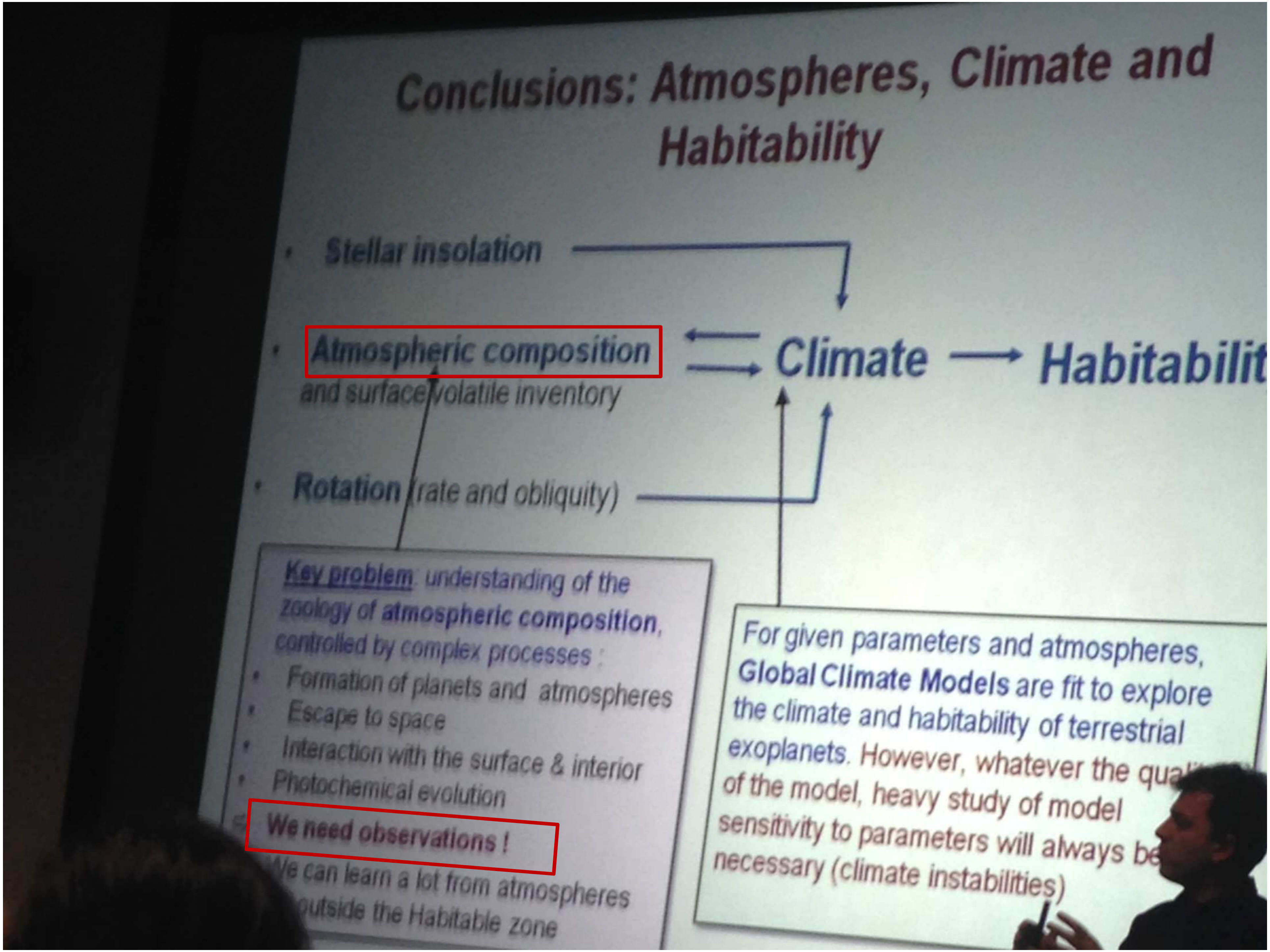
Exoplanet characterisation with the JWST

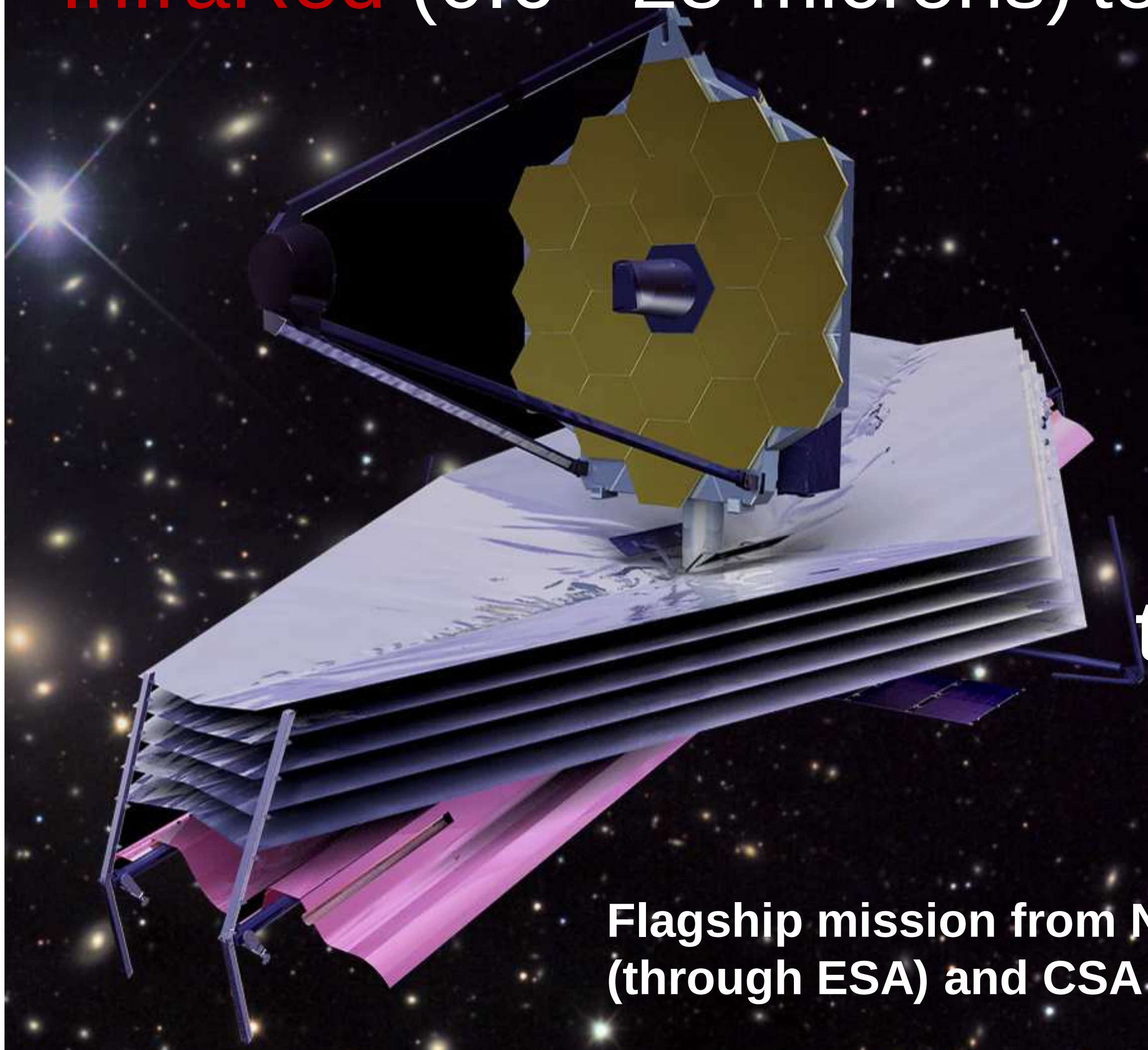
and particularly with the MIRI Instrument



P.-O. Lagage
AIM, CEA Saclay
MIRI Eurpean Consortium


Conclusions: Atmospheres, Climate and Habitability
Stellar insolation
Atmospheric composition and surface volatile inventory
Climate
Habitabilit
Rotation (rate and obliquity)
Key problem: understanding of the zoology of atmospheric composition, controlled by complex processes :
Formation of planets and atmospheres
Escape to space
Interaction with the surface & interior
Photochemical evolution
We need observations !
We can learn a lot from atmospheres outside the Habitable zone
For given parameters and atmospheres, Global Climate Models are fit to explore the climate and habitability of terrestrial exoplanets. However, whatever the qua
of the model, heavy study of model sensitivity to parameters will always be
necessary (climate instabilities)

The James Webb Space Telescope : a 6.5 meter InfraRed (0.6[1] -28 microns) telescope in Space[2]



To be launched by an Ariane rocket in **2018**

to be in operation for 5 to 10 years

Flagship mission from NASA with participation of Europe (through ESA) and CSA

[1] diffraction limited at 2 microns

[2] for example M. Clampin, SPIE talk June 2014 (YouTube)

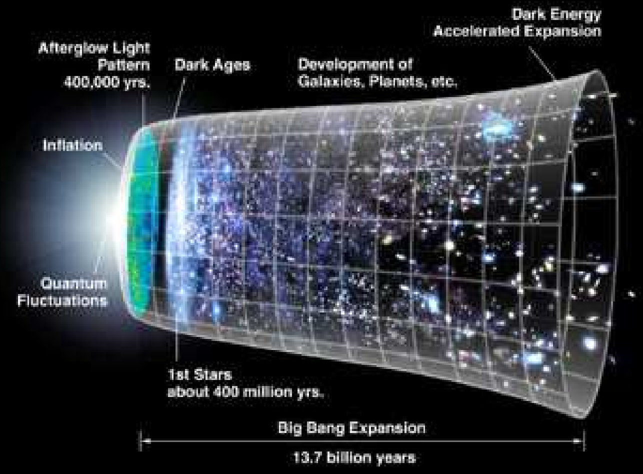
What JWST is NOT for exoplanets:

It is NOT a mission dedicated to exoplanets.

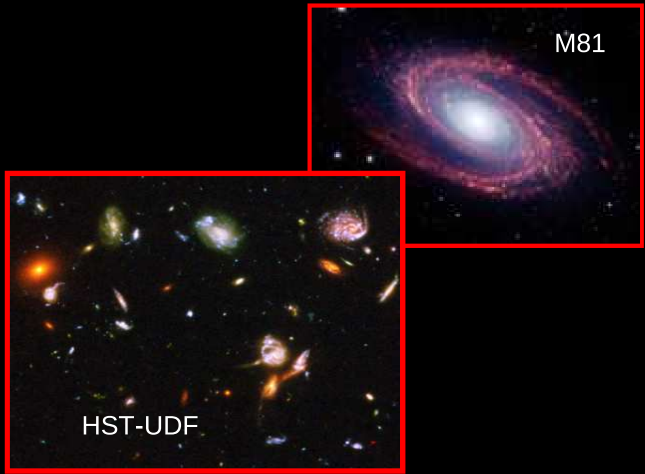
It is an observatory with competition between themes

« To get his share » (1/4 of the time) the exoplanet community has to be well organized because competitive communities are used to be !

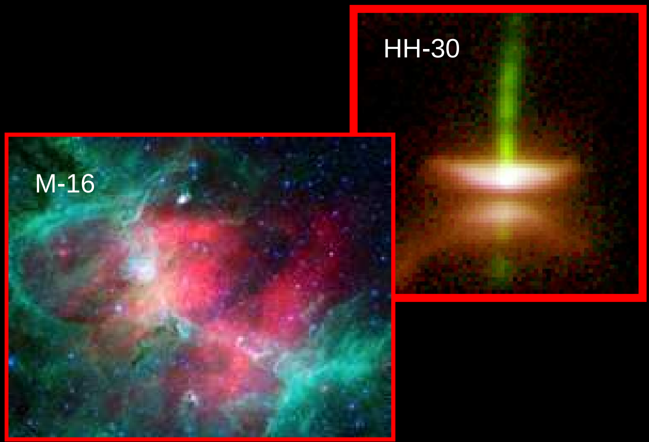
JWST Science Themes



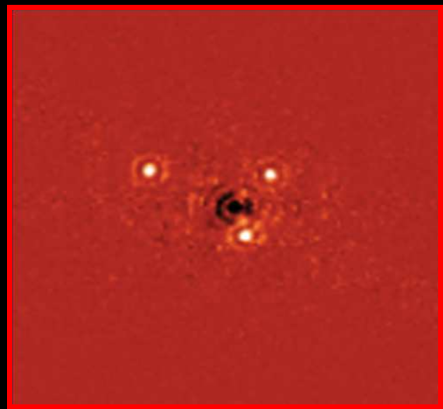
First Light and Re-Ionization



Assembly of Galaxies



Birth of stars and
proto-planetary systems



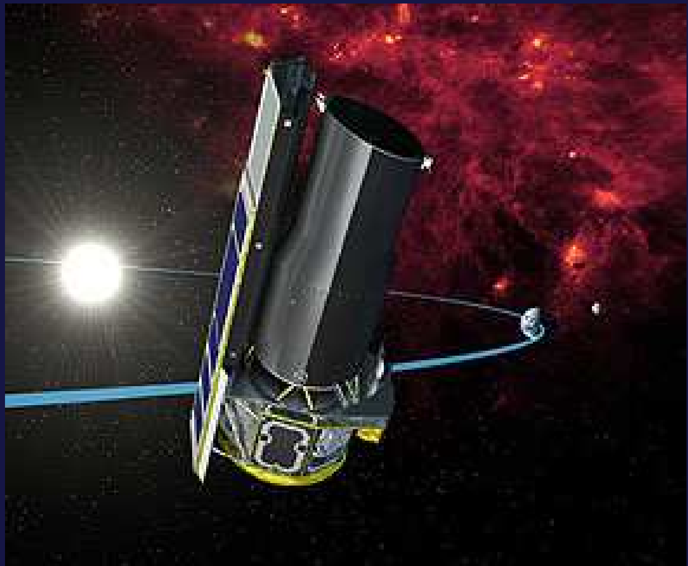
Planetary systems and the
origin of life

Four instruments built and delivered to NASA (Goddard Spa

NIRIS: Near-IR Imager and Slitless Spectrograph (0.6-5 μm)
NIRCAM: Near-IR CAMera (1-5 μm)
NIRSPEC: Near-IR SPECtrometer (1-5 μm)
MIRI: Mid-IR Instrument (5-28 μm)

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

What JWST will not do for exoplanets?

MIRI European Consortium

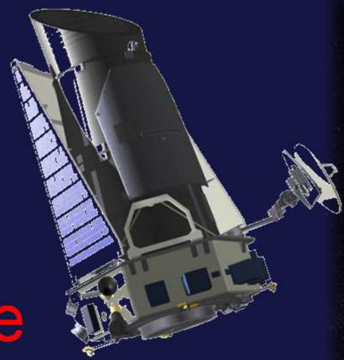
The main purpose of JWST is NOT to detect exoplanets[1]

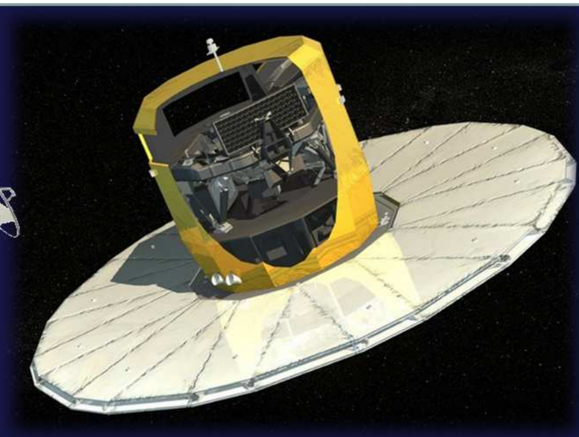
Already nearly 2000 exoplanets known and many missions → more to come:
especially super-Earths in the habitable zone of M stars, which are lacking as targets for JWST

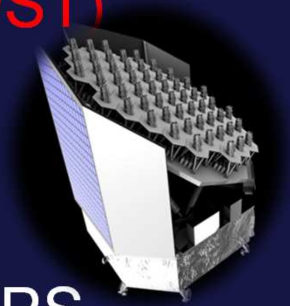
[1] a niche exists to detect, by direct imaging, exoplanets around M star, with masses down to neptune mass

In space

- Kepler-2
- GAIA
- TESS (specially conceived to provide targets to JWST)
- Cheops
- PLATO







On ground

- HARPS/HARPS North
- HAT-NET
- Super-WASP
- Carmenes
- M-Earth
- NGTS
- APACHE
- Spirou
- MASCARA

What JWST will do for exoplanets?

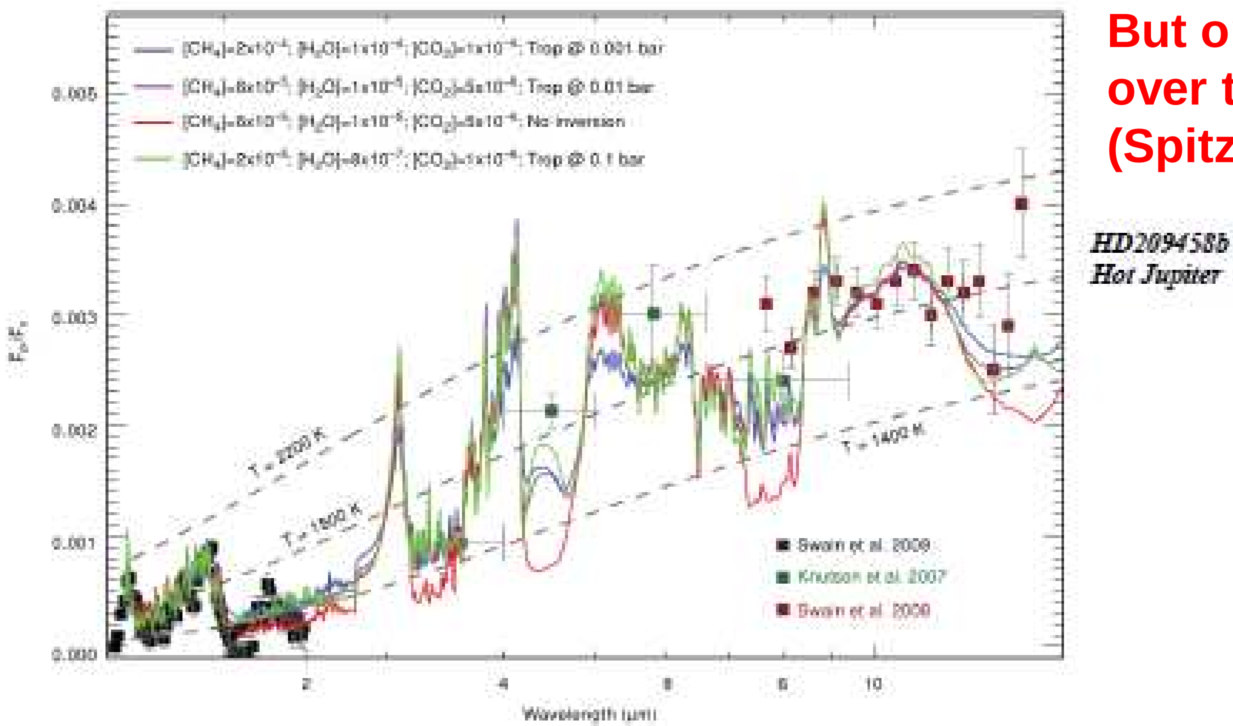
Focus will be on the characterization of known exoplanets,

essentially observing their atmosphere through photometric or spectro-photometric observations

State of the art

MIRI European Consortium

More and more information in the short wavelength range (HST; ground-based)



From Swain et al., ApJ 2009.

But only two exoplanet spectra over the visible to mid-IR range (Spitzer) (hot Jupiter)

→

An avenue for MIRI (5-28 microns)

Why to obtain such spectra:

MIRI European Consortium

1) To retrieve the composition of the atmosphere to:

→ **further constrain the internal structure of the exoplanet**

A way to break the degenerescence of models of the internal structure of exoplanets when only the mean density is known.

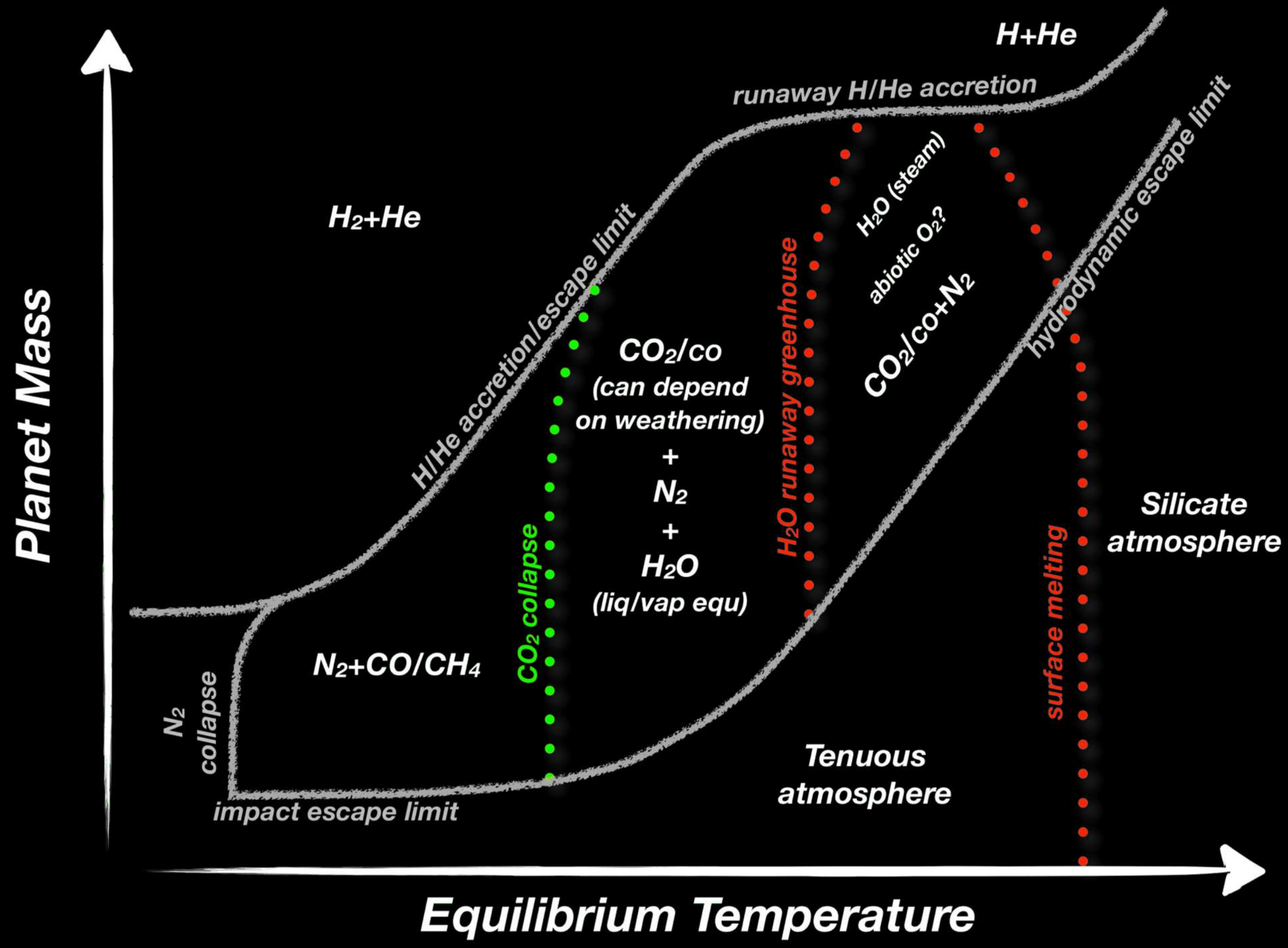
→ **constrain the exoplanet formation history**

Determination of the C/O abundance ratios of planets, and what does this reveal about their formation history?

→ **study the habitability of a planet**

(cf F. Forget talk this morning)

Models for example terrestrial atmospheres (Forget and Lecomte 2013)



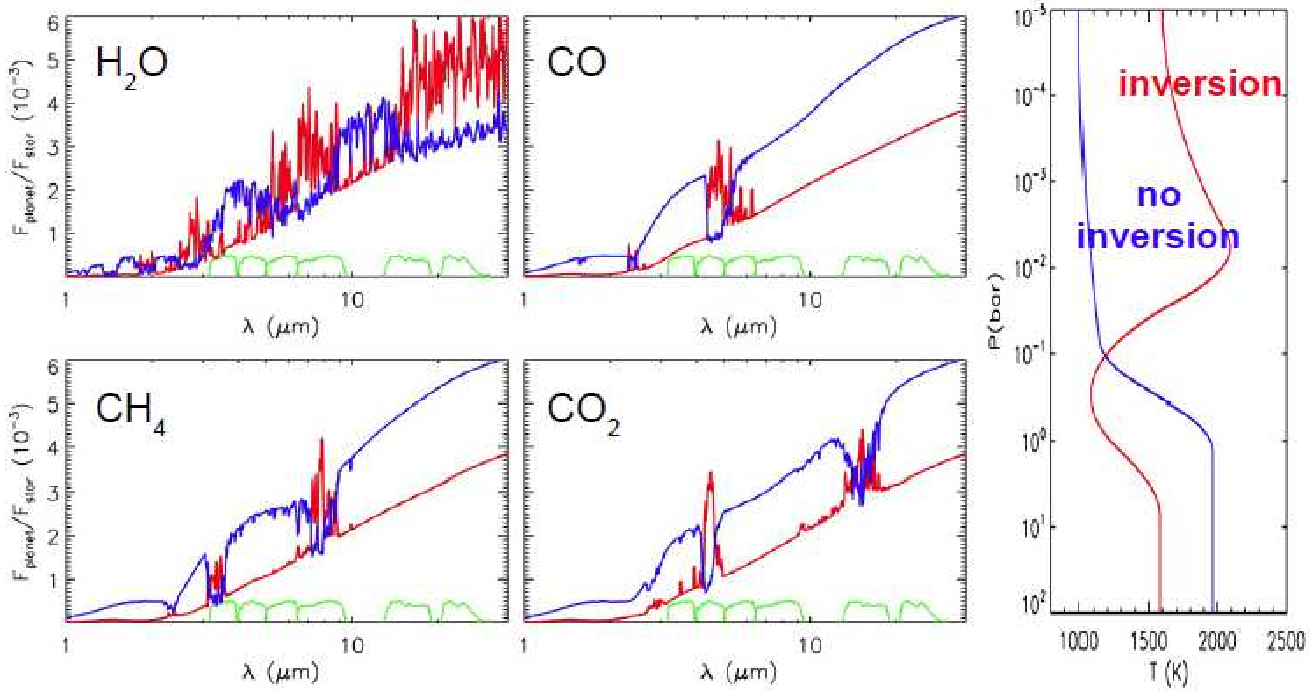
Why to obtain such spectra:

MIRI European Consortium

2) To study the atmosphere itself

Temperature/pressure profiles in atmospheres.

Origin of high altitude temperature inversions?



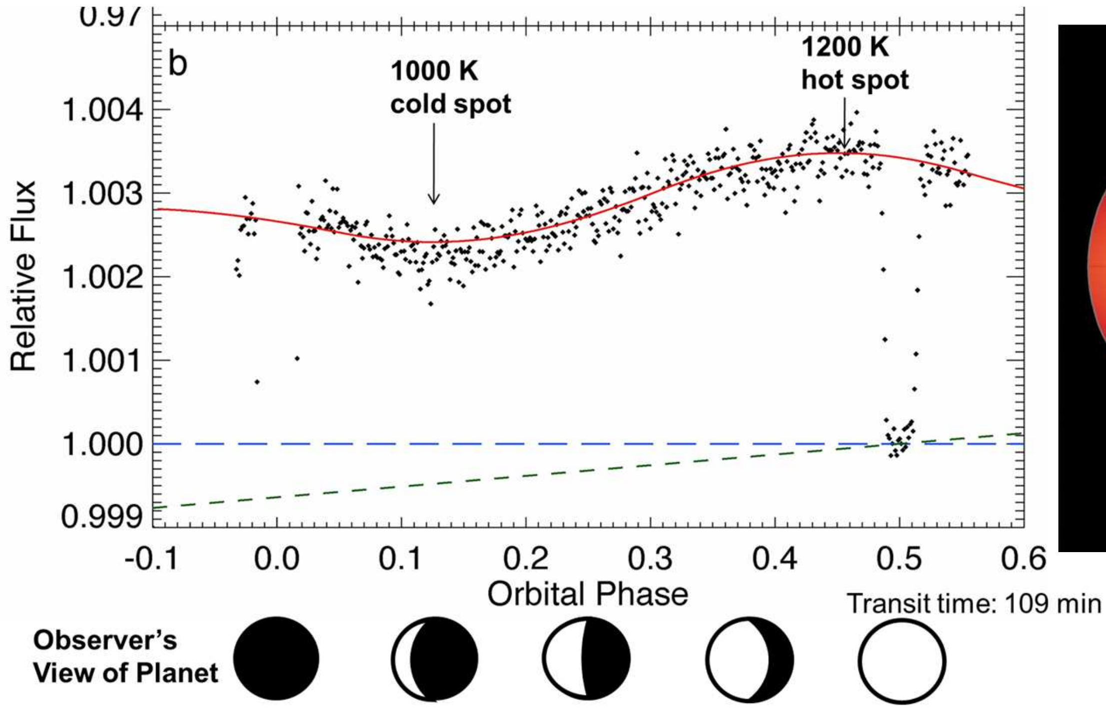
Madhusudhan+Seager-2010

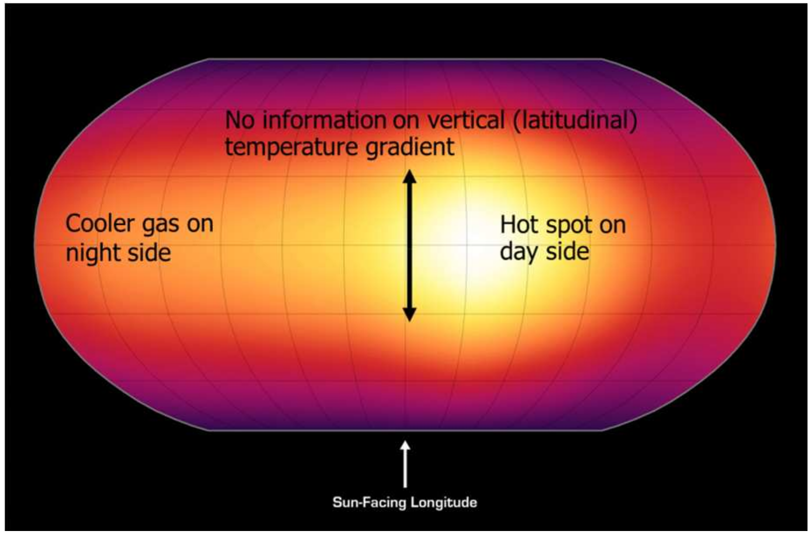
Why to obtain such spectra:

MIRI European Consortium

Atmosphere dynamics, climate (weather)

1D morphology information from Phase curves





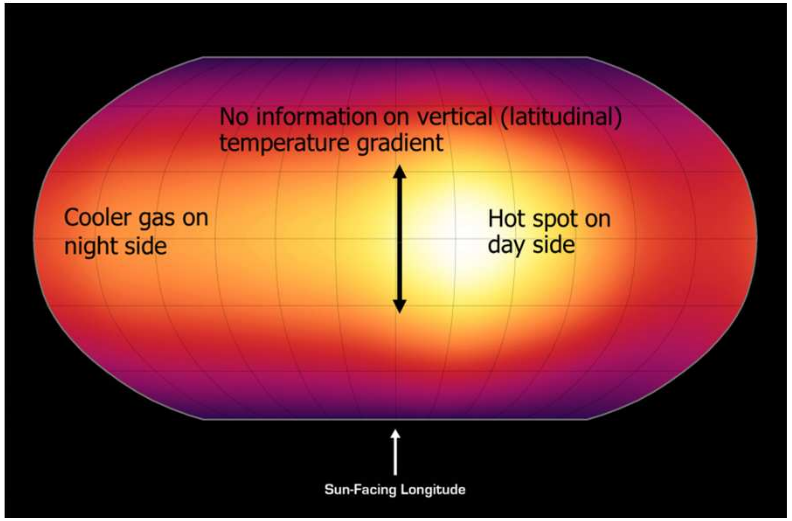
Phase curve for HD 189733b observed
at 8 µm with *Spitzer* (Knutson et al. 2007)

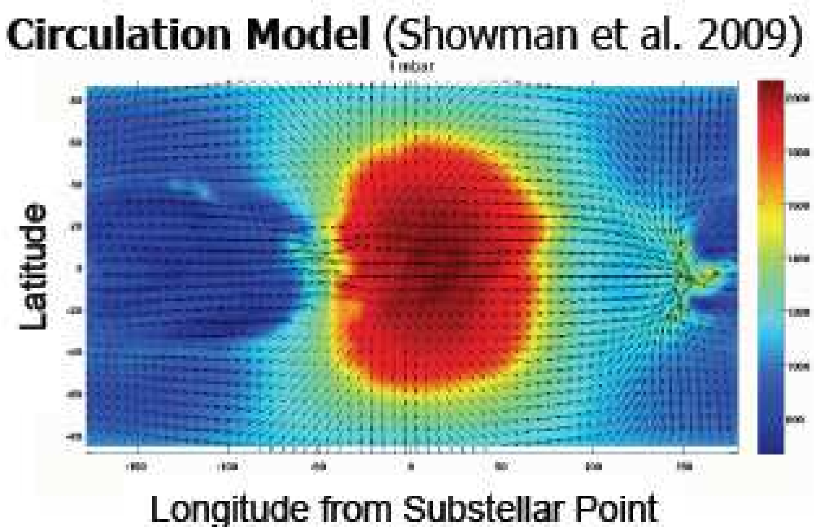
Why to obtain such spectra:

Atmosphere dynamics, climate (weather)

1D morphology information from Phase curves :

Testing circulation models





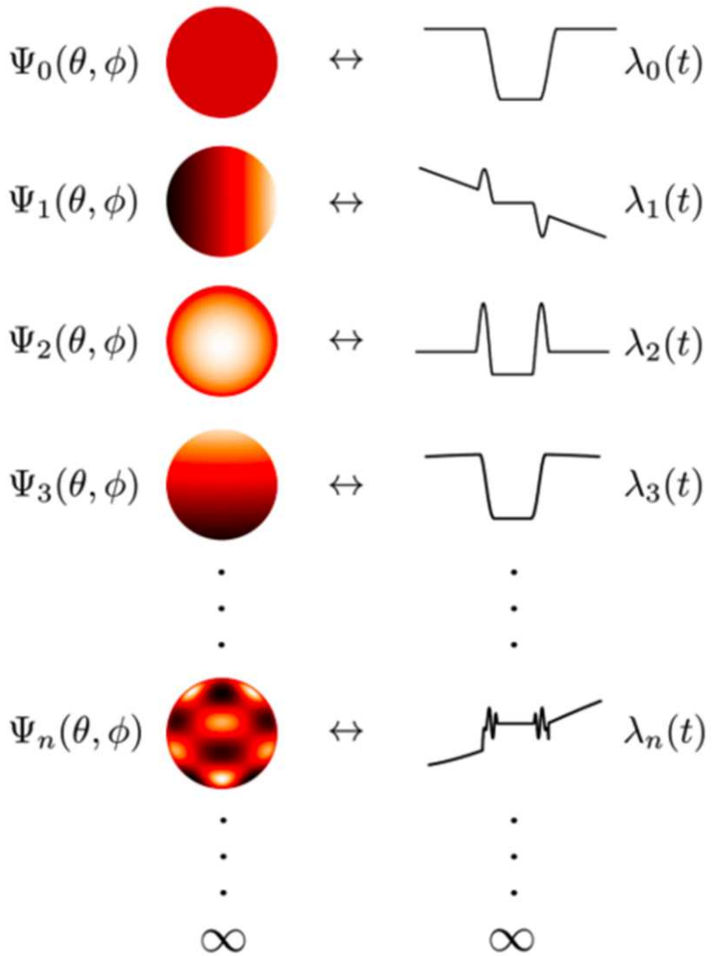
Why to obtain such spectra:

MIRI European Consortium

Atmosphere dynamics, climate (weather) :

2D maps possible from ingress, egress precise measurements,

High S/N → **JWST**

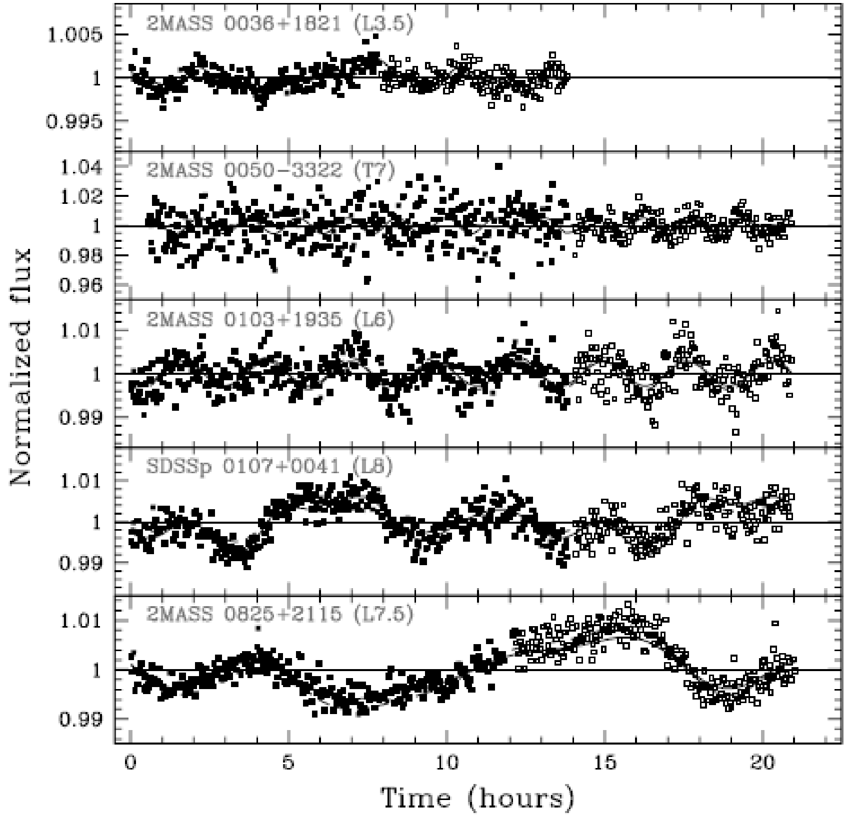


Majeau, Agol, & Cowan (2012)

Variability (observed at the level of 1% for brown dwarf)

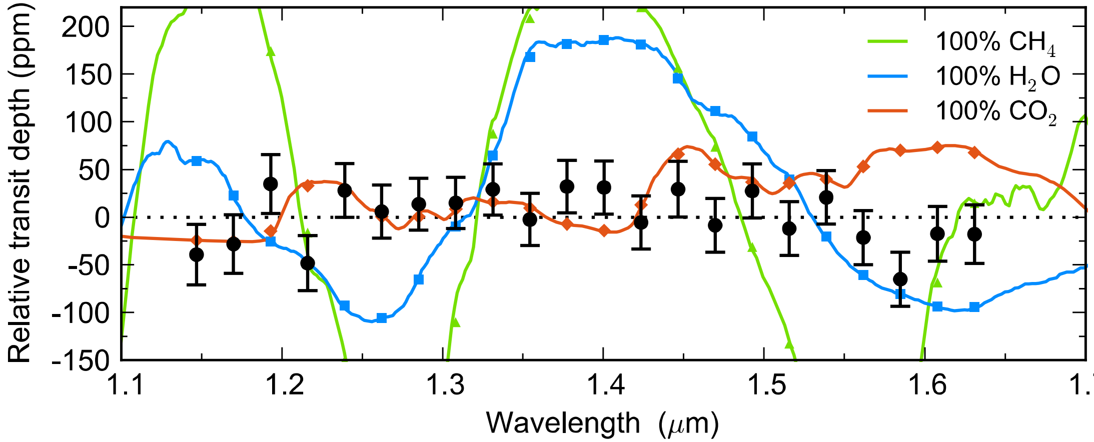
but what about exoplanets?

High S/N needed → **JWST**



S.A. Metchev et al. 2014

GJ 1214b HST transit observations
transit depth uncertainty: 30 ppm
$R_* = 0.2\ R_{sun}$
H = 9.1



Kreidberg et al. 2014

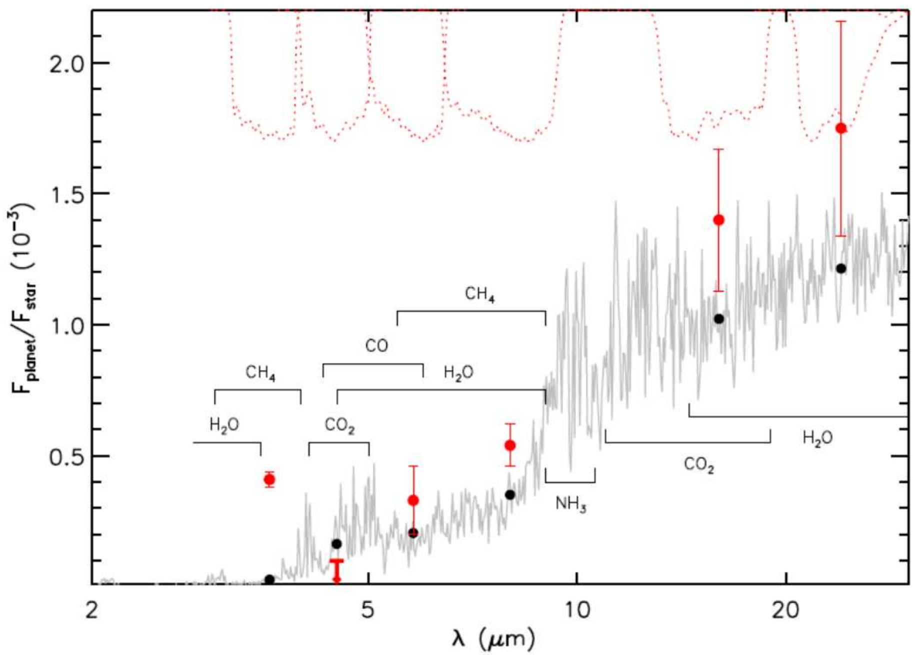
Clouds watch out the features!

MIRI specifities

MIRI European Consortium

MIRI best suited to detect “cool” object. The wavelength range of MIRI (5 – 28.5 microns) corresponds to the peak emission of a blackbody with temperature ranging from 600 K to about 100 K.

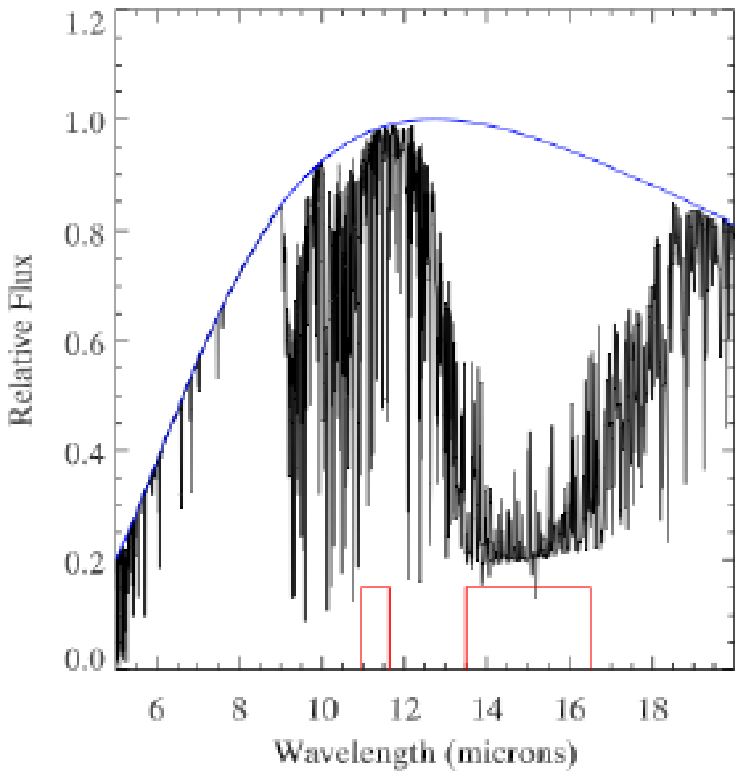
It contains signatures from most of the major molecular species; note that NH3 has its strongest resonance in the mid-IR; and it is an excellent “thermometer”. Broad CO_2 at 15 µm.



From Madhusudhan & Seager 2010.

MIRI detection of CO2 in super-Earth

MIRI European Consortium

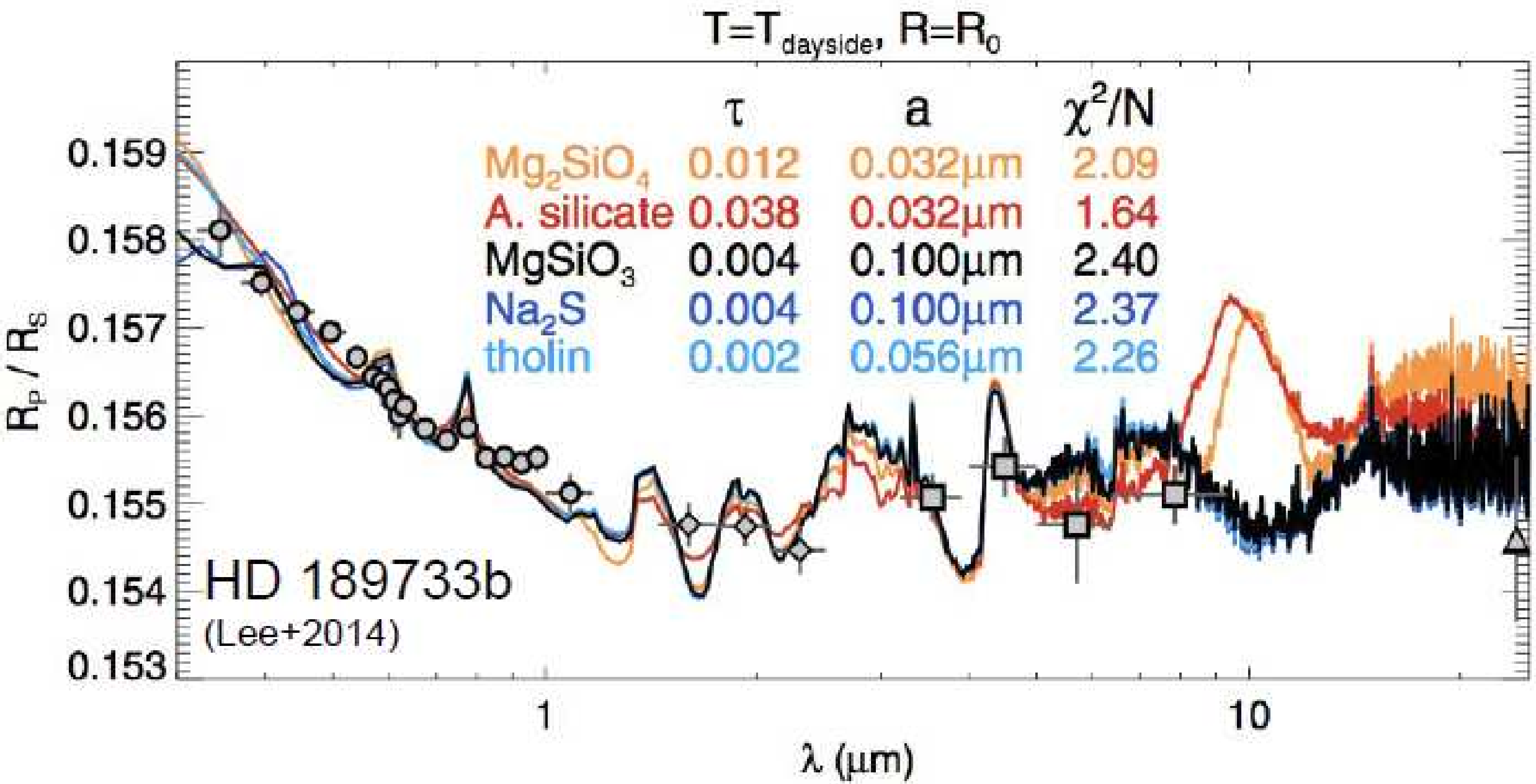


Deming et al. (2009) showing Miller-Ricci (2009) Super-Earth Emission spectrum and MIRI filters

- 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

MIRI and the composition of Haze

MIRI European Consortium



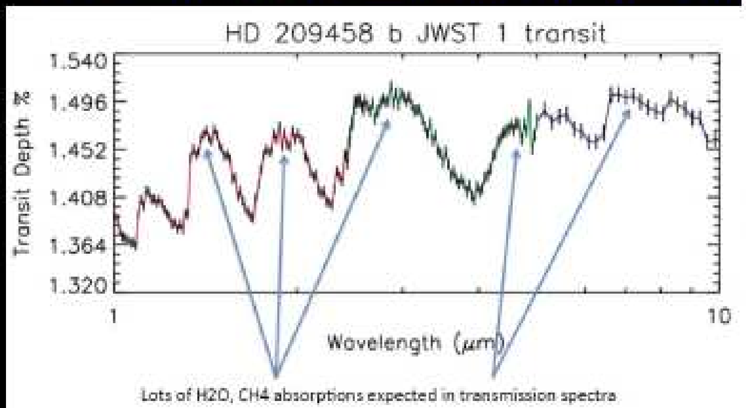
MIRI can complete near-IR spectra

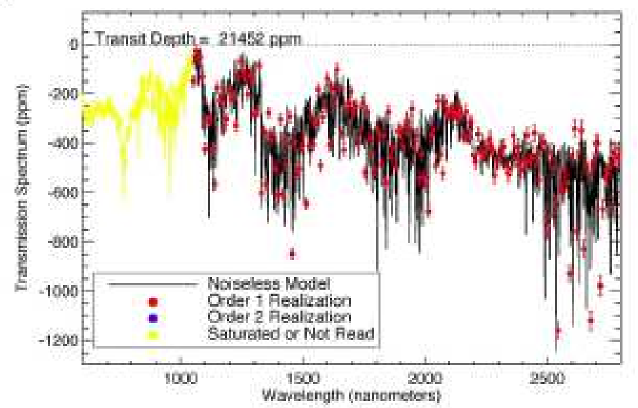
MIRI European Consortium

From C. Beichman, Heidelberg exoplanet Conf. Sep 2014

Continuous λ-Coverage with Multiple Transits

- Typical 2-4 hr transit requires 6-12 hours of observing (equal time before/after transit)
- NIRISS 0.6 – 2.5 µm @ R ~ 700
- NIRCam grisms/NIRSpec grating: 2.4 – 5 µm @ R ~ 1000 – 2700
- Fainter stars (J>11) can use NIRSpec prism (1-5 µm; R~30-100)
- MIRI LRS 5 – 12 µm @ R ~ 100
- Approx 25 hr/transit or eclipse for full coverage (4 modes)
- PASP + http://nexsci.caltech.edu/committees/JWST/agenda.shtml

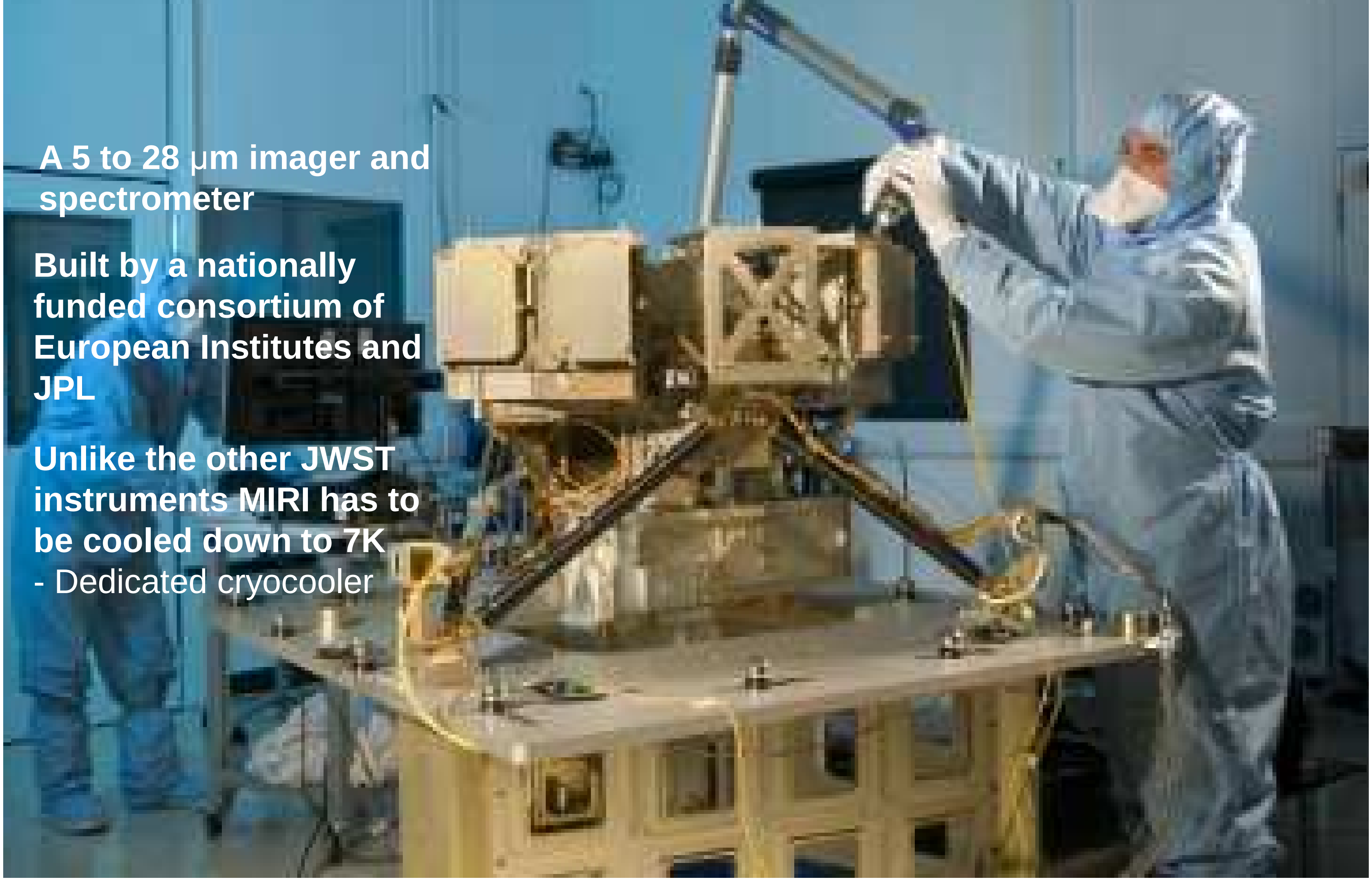




A few words about the instrument

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

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



A 5 to 28 µm imager and spectrometer

Built by a nationally funded consortium of European Institutes and JPL

Unlike the other JWST instruments MIRI has to be cooled down to 7K
- Dedicated cryocooler

The MIRI European Consortium

MIRI European Consortium

UK-ATC — Principal Investigator; Optical Engineering; Spectrometer Pre-Optics (SPO); Calibration Sources
Astrium Ltd — Consortium Management; PA Coordination; System Engineering
U. of Leicester — Mechanical Engineering; Primary Structure; MGSE
RAL — Thermal Engineering & Hardware; Optical Bench Assembly AIV

E-CoPI

Tom Ray
DIAS — Filters

Christoffel Waelkens
CSL — Input, Optics & Calibration (IOC); Instrument Control Electronics (ICE); Imager Mirrors
U. of Leuven — EGSE Software Support

CEA — Imager
LESIA/LAM — Coronagraph
Pierre-Olivier Lagage

INTA — MIRI Telescope Simulator (MTS)
Luis Colina

U. of Stockholm — Filters and Dichroics
Kay Justannont

DSRI — Hexapod
Ulrik Noorgard Neilsen

NOVA-ASTRON — Spectrometer Main Optics (SMO)
U. Leiden — Spectroscopy Analysis
Ewine van Dishoeck

MPIA Heidelberg — Electrical Engineering; Cryo Mechanisms
U. of Köln — Low Resolution Spectrometer; Double Prism
Thomas Henning

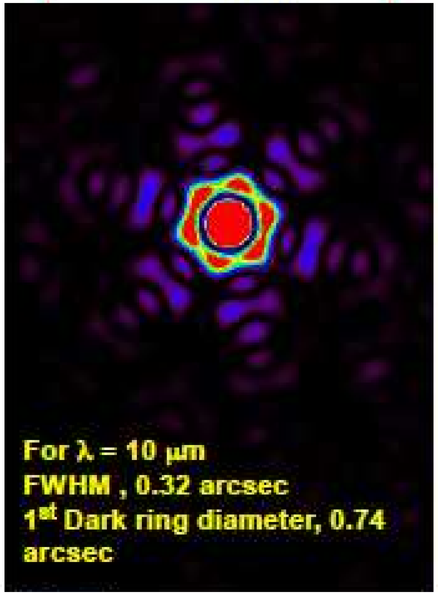
PSI — Contamination Control Cover; Cryo Harness
Manuel Guedel

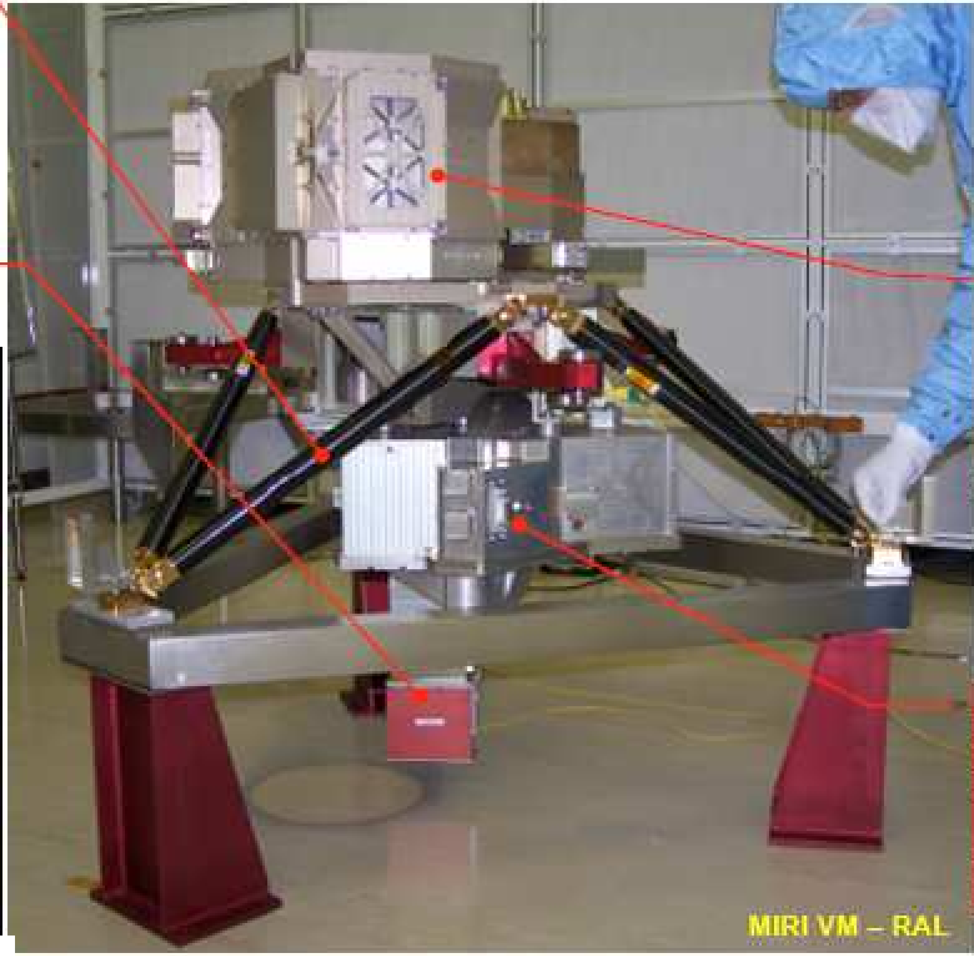
NASA/GSFC — JWST Project Office; Spacecraft; Integrated Science Instrument Module (ISIM)
JPL — Detector System; Flight Software; Cryo-Cooler
Univ Arizona — Quick-look pipeline
Mike Ressler

ESA/ESTEC — JWST Project Office; Prodex Office

A carbon fibre truss Isolates 7 K MIRI optics from the 40 K telescope

Light enters from the JWST telescope

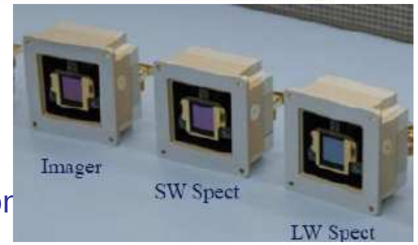




A 10 x 10 arcsec field passes through the deck Into the R ~ 3000, 4 channel Integral field spectrometer
2 detectors
2 channels per detector

A 115 x 115 arcsec region of the focal plane is directed into the imager
10 bandpass filters
4 coronagraphs
R ~ 100 slit spectrometer.

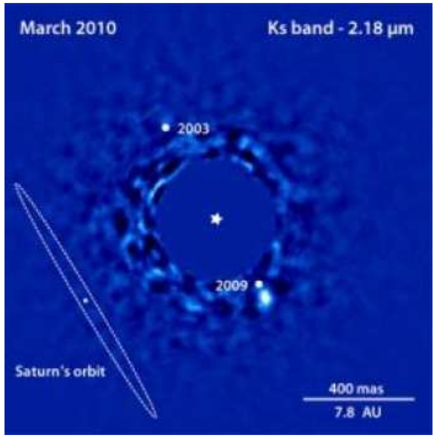
Three 1024 x 1024 Si As arrays



Ten papers about MIRI submitted to PASP

1) Introduction
2) Design and Build - an overview of MIRI
3) The imager
4) The Low Resolution Spectrometer
5) Coronagraphs
6) The Medium Resolution Spactrometer
7) Detector – theory
8) The focal plane system
9) Sensitivity/saturation projections
10) Operations, data analysis

Since the begining of the MIRI design, the exoplanet aspect has been taken into account, but for imaging

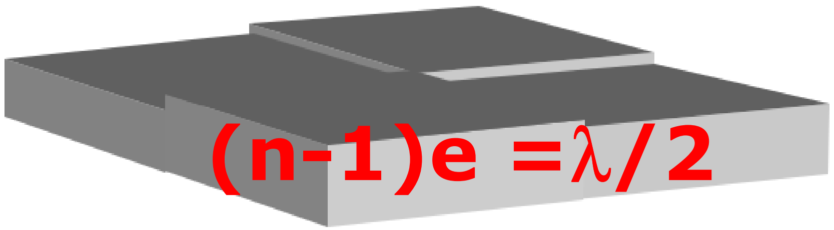


Beta-Pictoris A-M Lagrange et al.

by introducing a coronagraph mode

And by using a « sophisticated mask » : the 4 quadrant phase mask

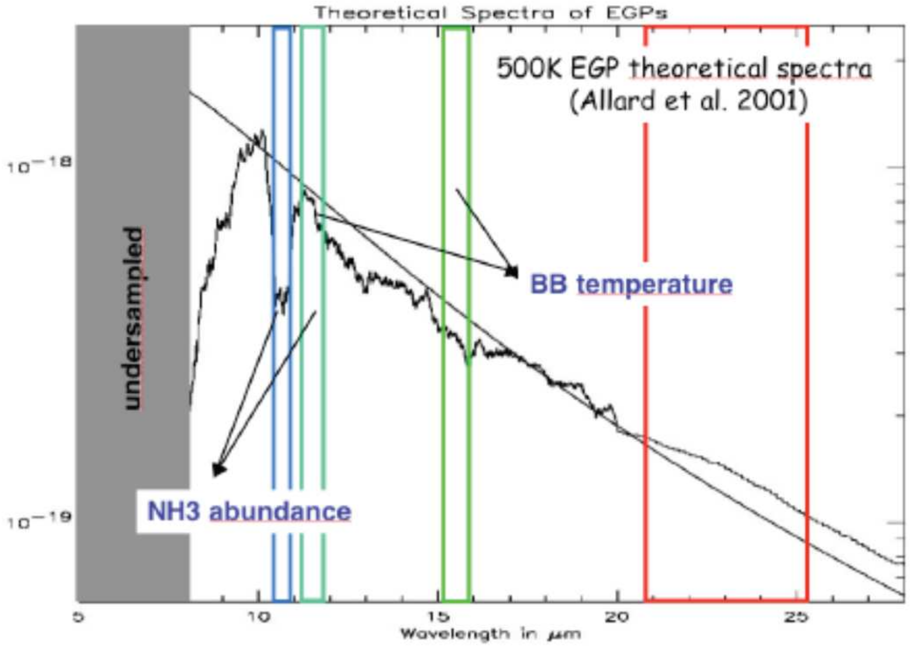
→ **small working angle** **(λ/D : 0.4 arcs at 10 µm)**



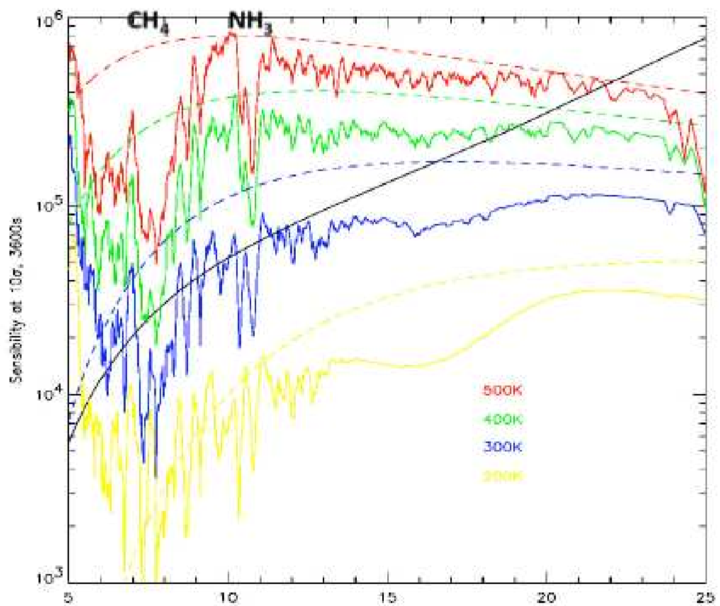
$$(n-1)e = \lambda/2$$

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

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.

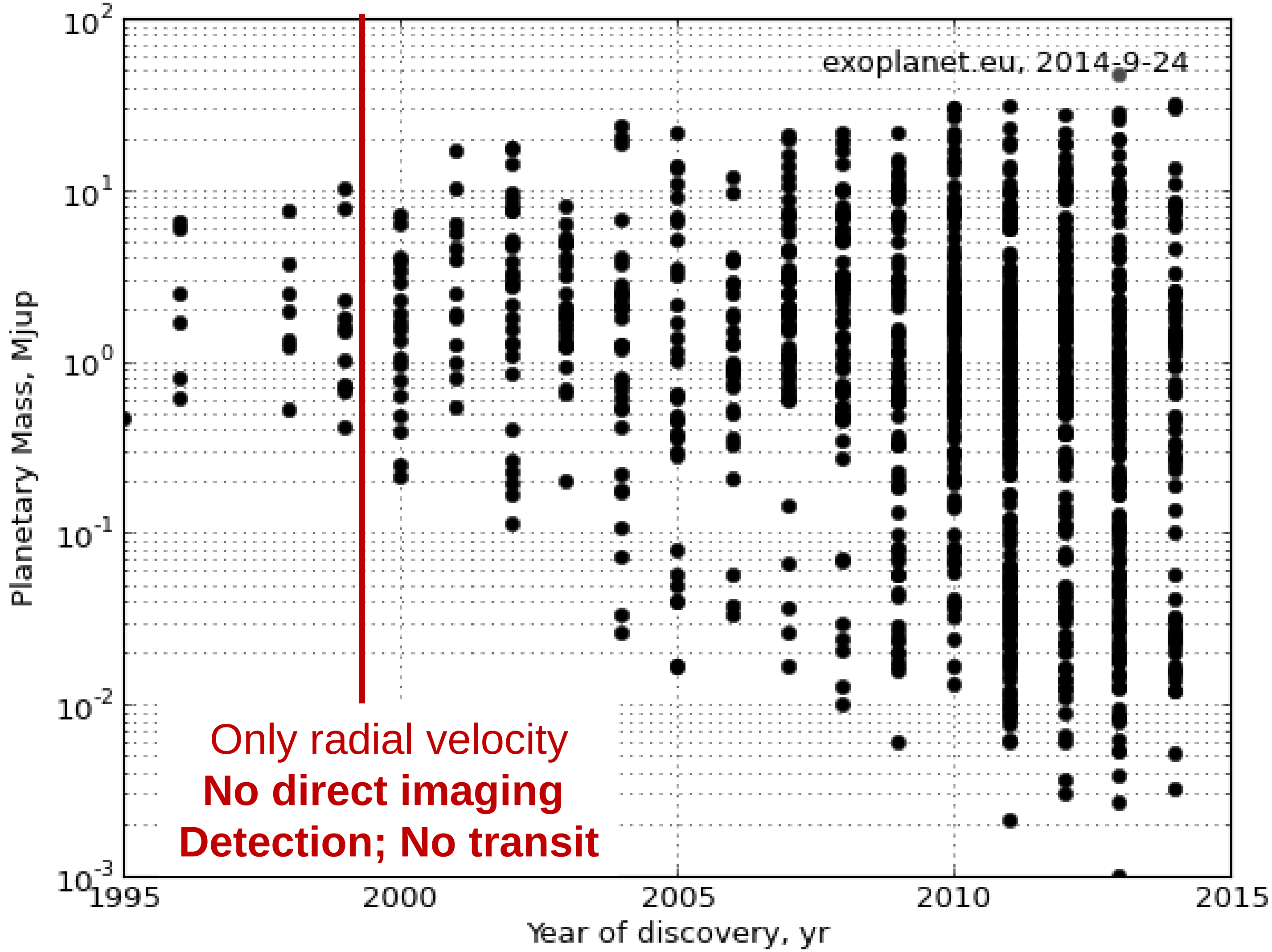


NH3 → Temperature



When we started MIRI, last century …

MIRI European Consortium



A coronagraph mode in the requirements

MIRI European Consortium

MIRI on JWST →

high sensitivities
(1000 times better than from ground)
good angular resolution

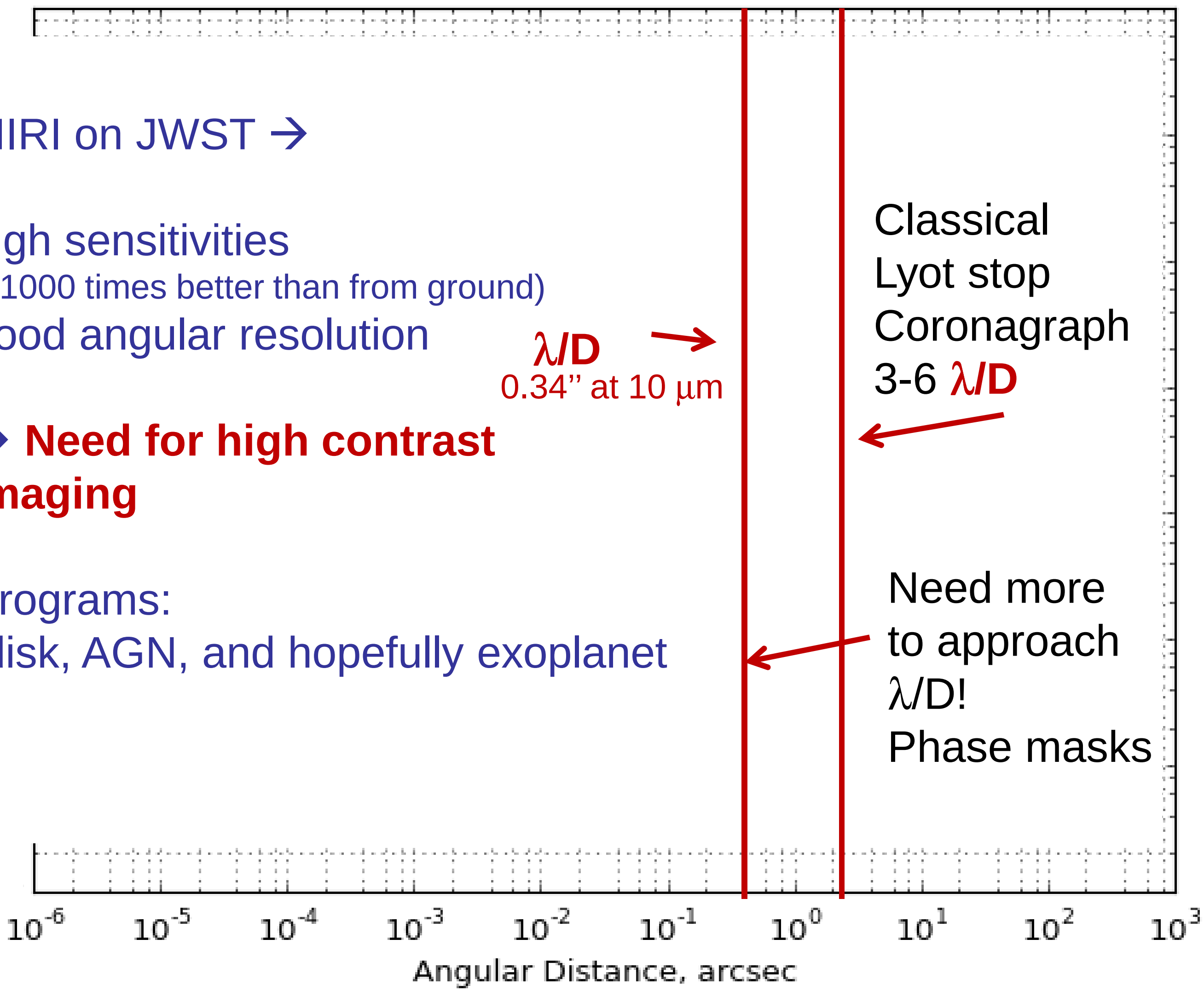
λ/D →
0.34'' at 10 µm

→ **Need for high contrast Imaging**

Programs:
disk, AGN, and hopefully exoplanet

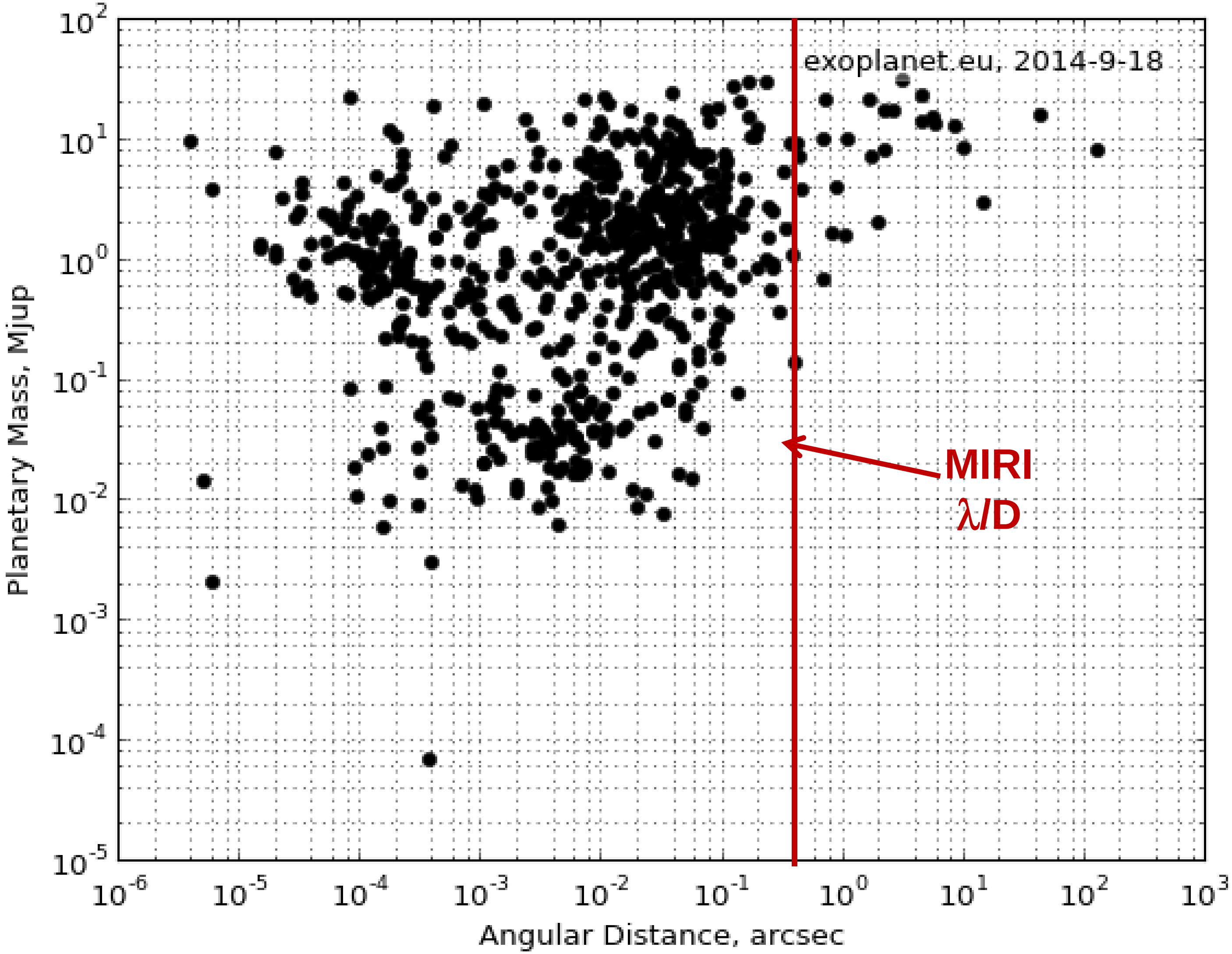
Classical Lyot stop Coronagraph 3-6 λ/D

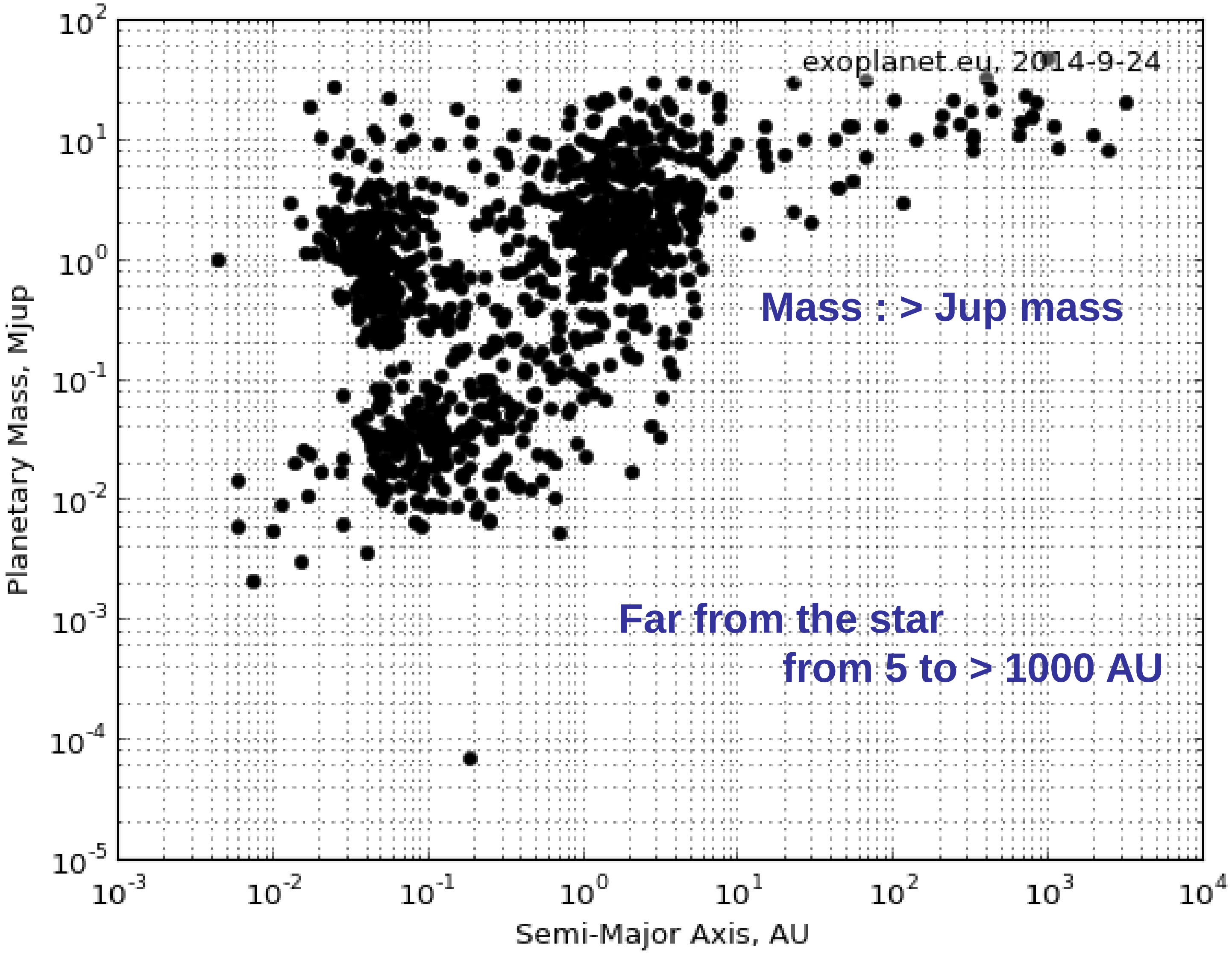
Need more to approach λ/D!
Phase masks



Planets studied by direct imaging: today

MIRI European Consortium




exoplanet.eu, 2014-9-24
Mass : > Jup mass
Far from the star
from 5 to > 1000 AU
Planetary Mass, Mjup
Semi-Major Axis, AU
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

Different type of exoplanets than those in transit

younger

→ still cooling

→ Luminosity can constrain the planet formation theory

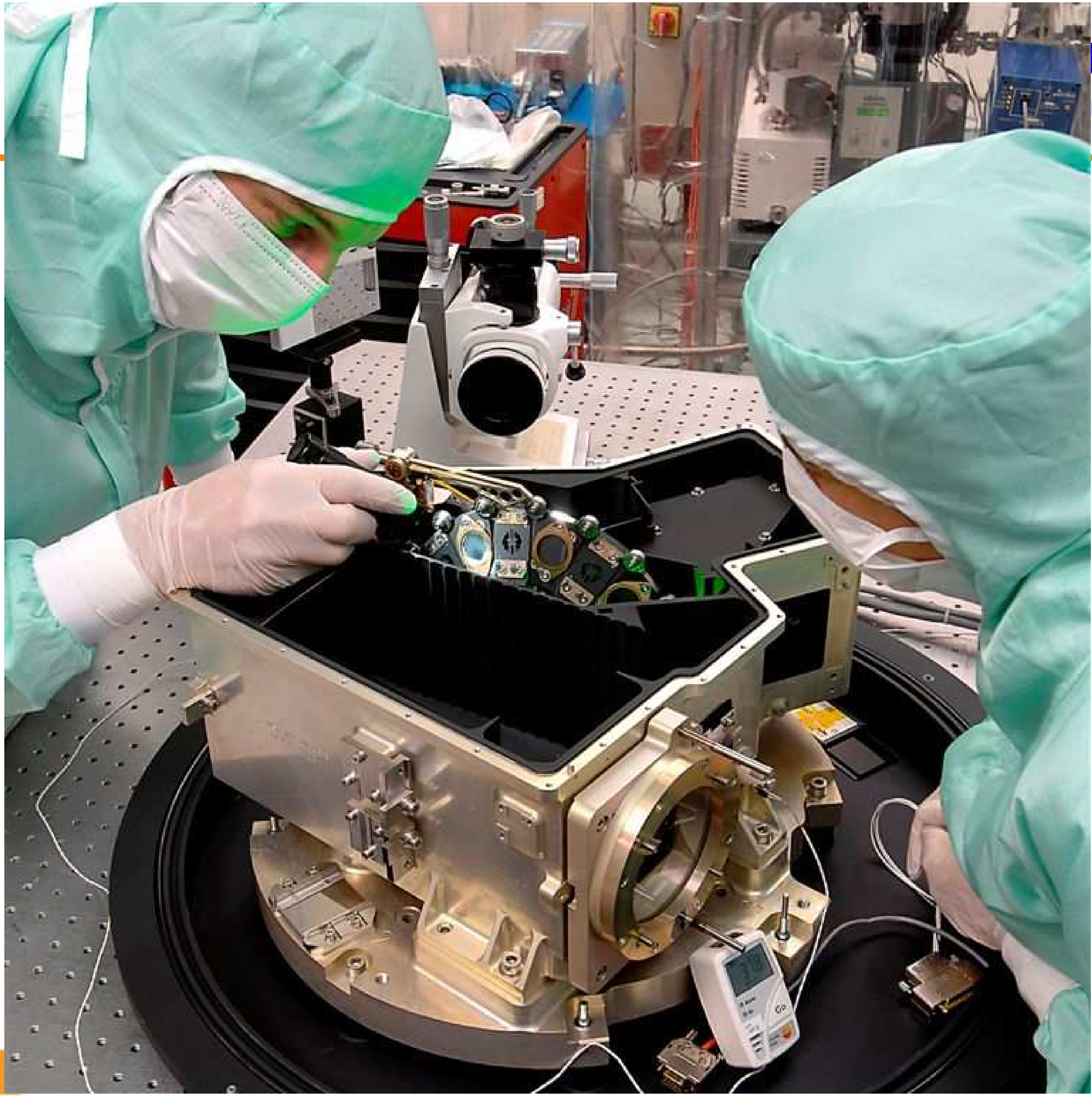
But model degenerescence

→ further constraint from atmospheric composition

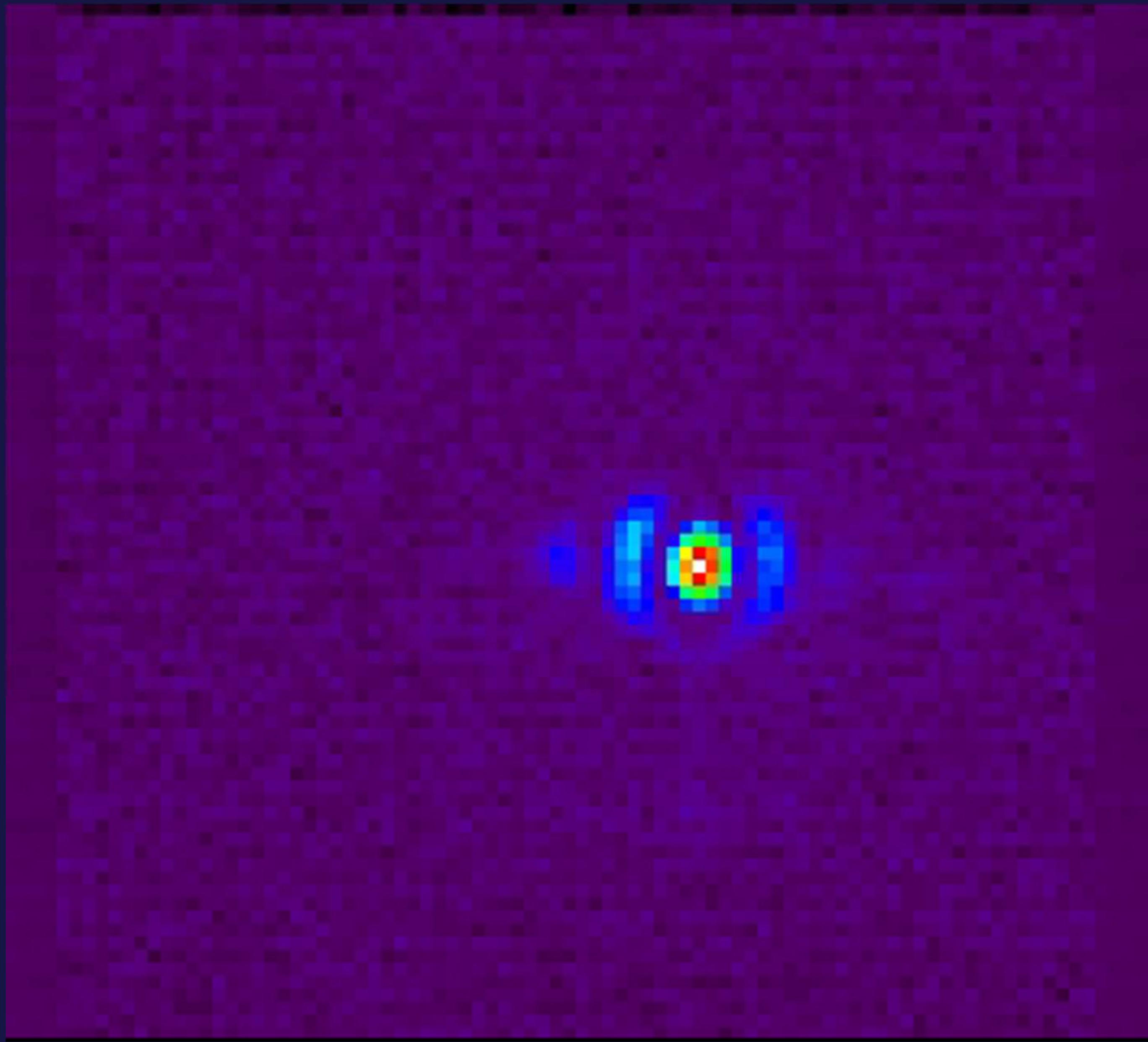
Atmospheric studies by themselves (variability, clouds, …)

→ monitoring

Note further away from their star → « uncontaminated" by the physical effects related to the extreme proximity to the host star (high irradiation, tidal effect...))

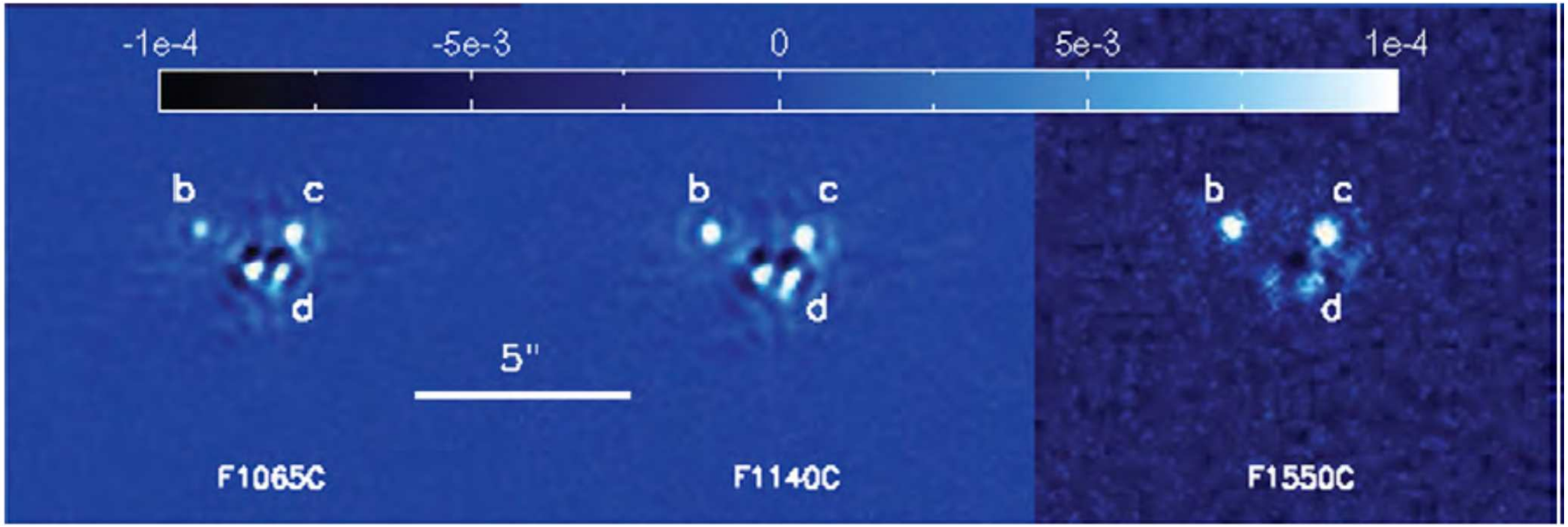


Test bench set up at Saclay



Development of a simulator

MIRI European Consortium



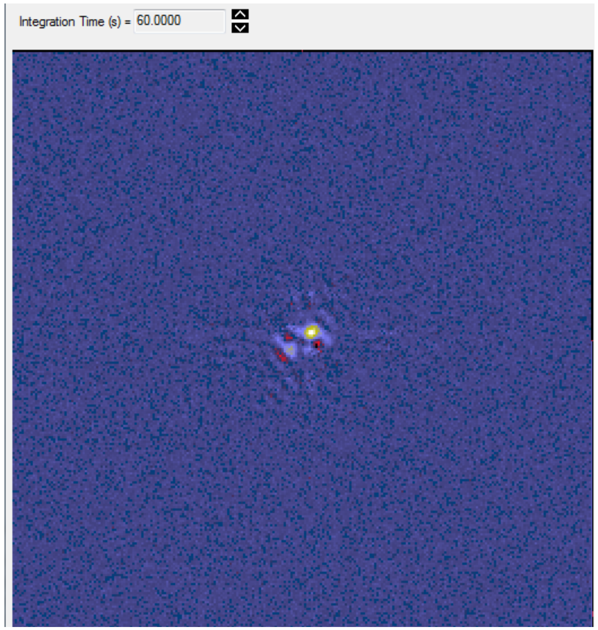
Simulations of HP 8799 exoplanets

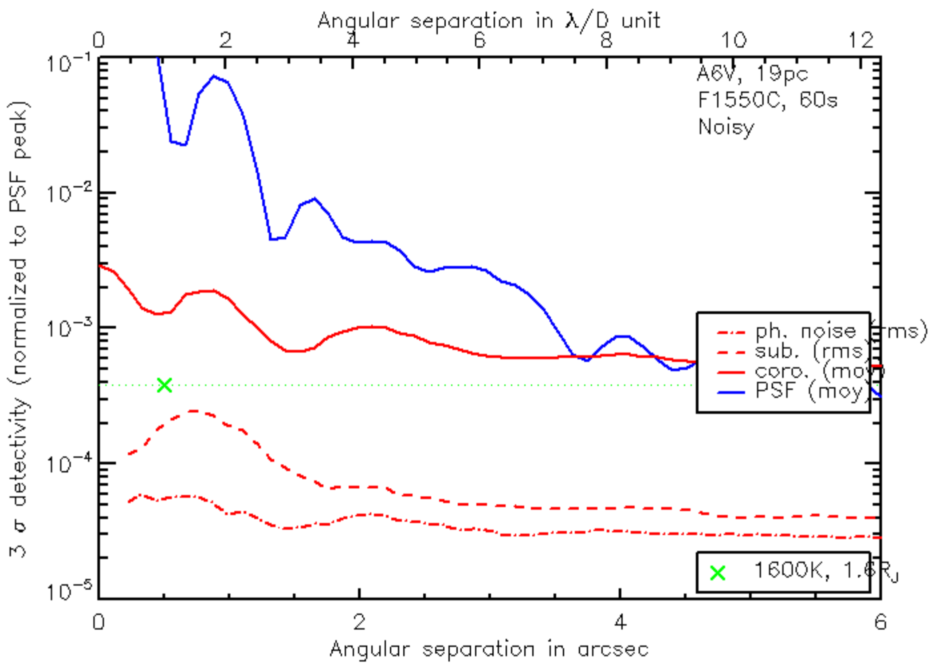
A. Boccaletti et al., Adv. Spc. Res., 36, 1099

Simulations of β-Pic b observations

MIRI **very sensitive** : two to three orders of magnitude more sensitive than actual ground-based instruments

The planet is detected in **about 1 minute**!





Attention: dust disk might dominate

Advantage : observing the system : star, planet, dust disk

may be detection of other planets

Possible thanks to the JWST excellent low jitter : 7 mas

Excellent pointing to center the star on the corono

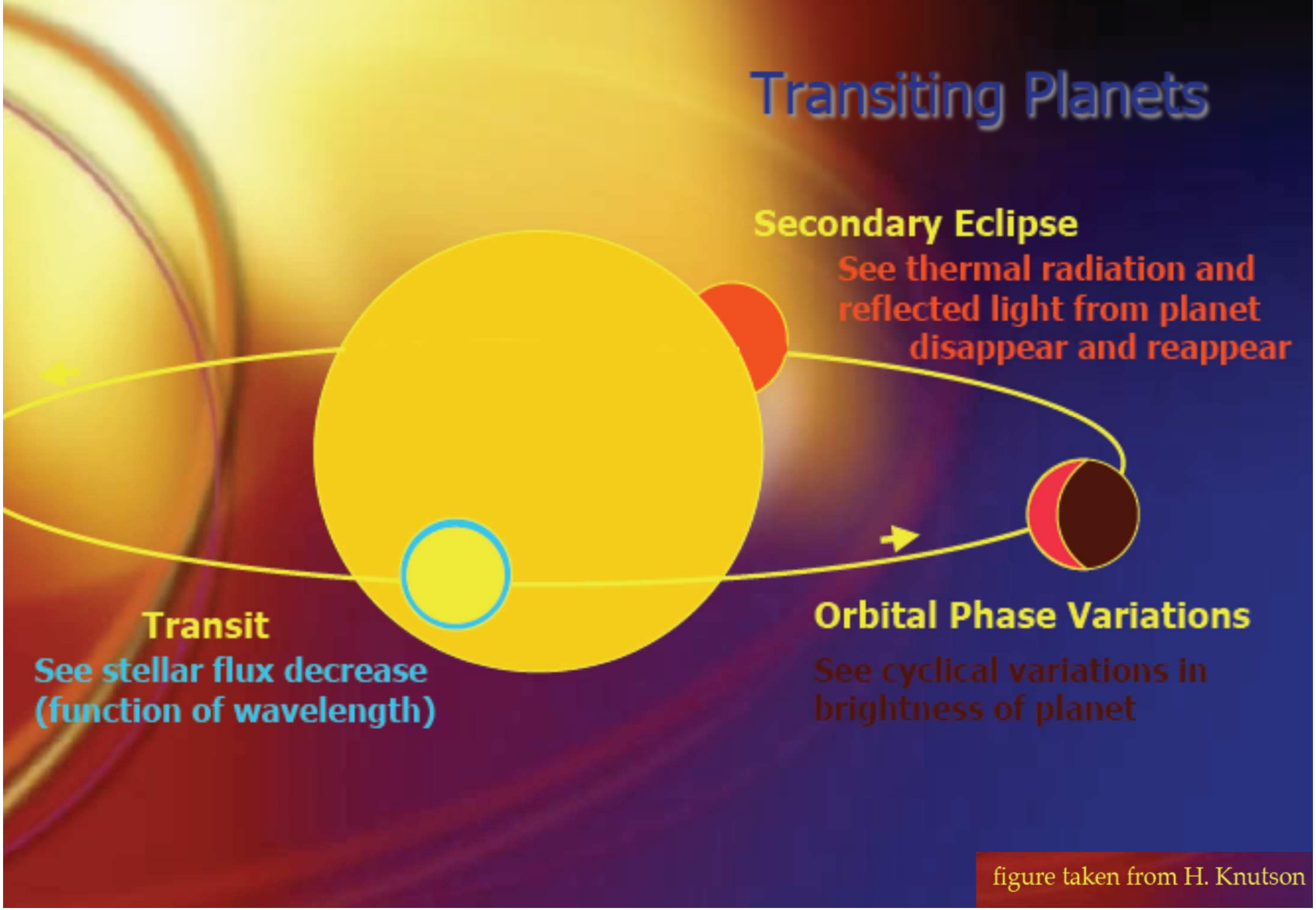
…

MIRI observations will pioneer the field.

Indeed no observation above 5 μm has ever been done on these objects. Spitzer suffers from a lack of angular resolution and ground-based observations have been limited to wavelengths shorter than 5 μm, by lack of sensitivity.

→ Surprises are expected.

Transit

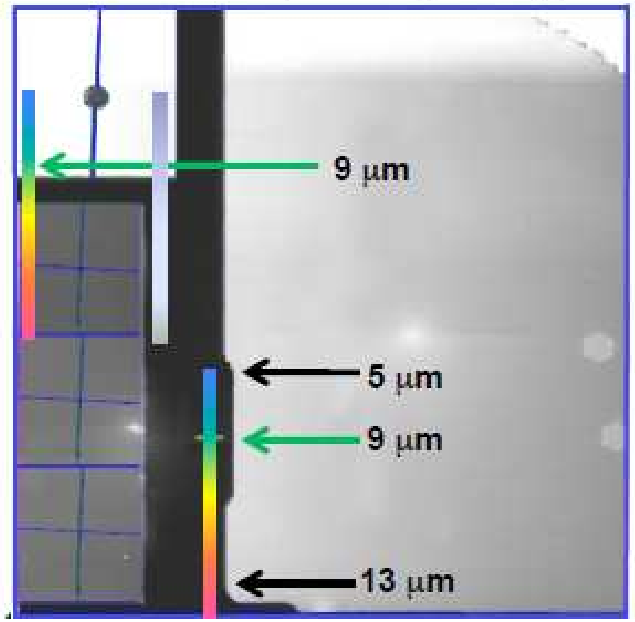

Transiting Planets
Secondary Eclipse
See thermal radiation and reflected light from planet disappear and reappear
Transit
See stellar flux decrease (function of wavelength)
Orbital Phase Variations
See cyclical variations in brightness of planet
figure taken from H. Knutson

MIRI initially not optimized for transit observation

MIRI European Consortium

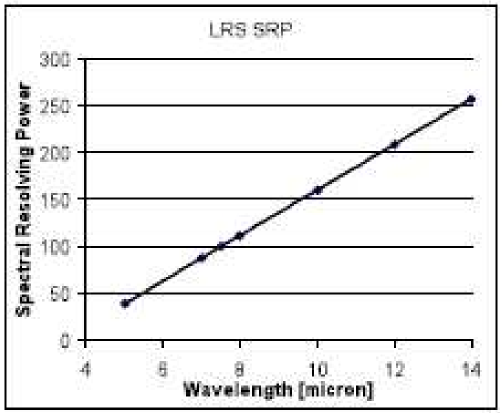
But new mode added : slitless observations; reading only a sub array → saturation K magnitude about 4-5

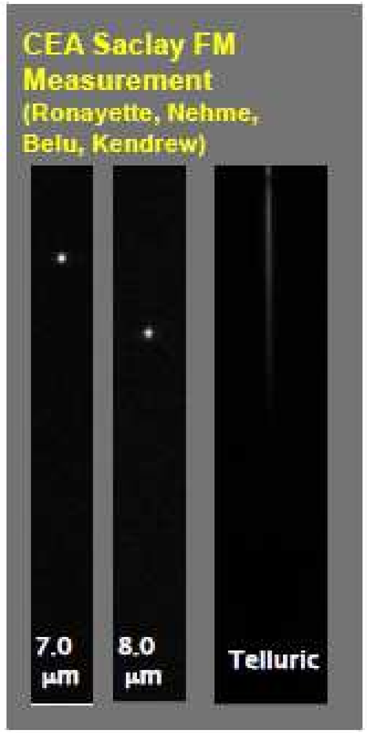
- **Slit and slitless locations**
  - Cusp at 5 μm in slitless spectra
  - Possible alternate slitless location (currently unsupported)



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

- **Spectral Resolving Power**





MIRI best suited to detect "cool" object. The wavelength range of MIRI (5 – 27 microns) corresponds to the peak emission of a blackbody with temperature ranging from 600 K to 165 K.

It contains signatures from most of the major molecular species; note that NH3 has its strongest resonance in the mid-IR; and it is an excellent "thermometer". broad CO_2 at 15 µm.

Better suited to study hazy atmospheres (HST has found be featureless spectra in the 1 – 2 µm range e.g. GJ 1214 b).

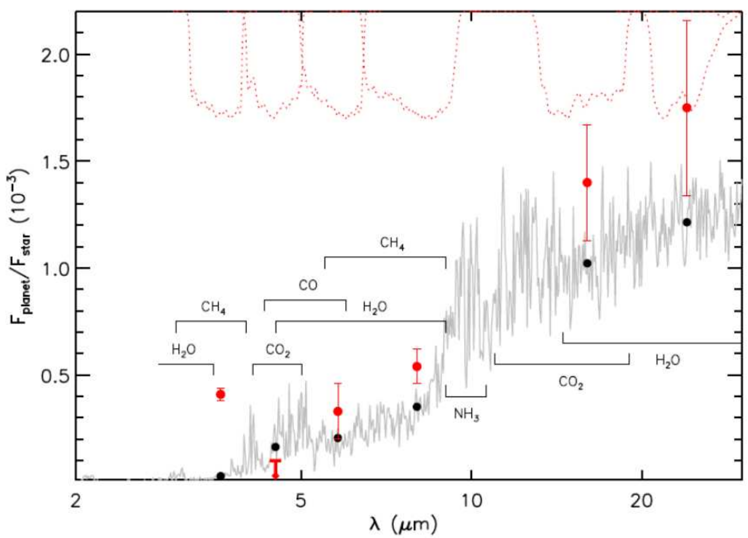


Figure *Molecular absorption features in Spitzer photometric bandpasses. The red dotted lines at the top show the six Spitzer bandpasses. The black lines show the extent of absorption features due to the corresponding molecules. The gray curve shows a hypothetical model spectrum of GJ 436b based on equilibrium chemistry, and the black filled circles show the corresponding integrated points in the Spitzer channels. The red filled circles with error bars show the observations of GJ 436b reported by Stevenson et al. (2010). From Madhusudhan & Seager 2010.*

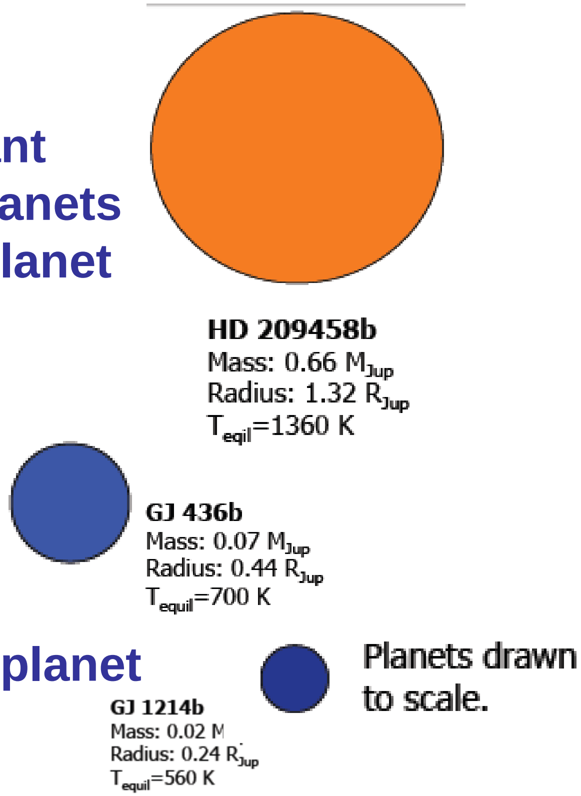
Observing plan

Final plan not decided, but it may include the following MIRI observations:

1. **LRS transmission and emission spectra of 2 or more well---studied gas giants**
2. **LRS emission or transmission spectra of other giant planets, including searching for NH3 in T < 1000 K planets**
3. **A partial phase curve of at least one warm or hot planet (mode TBD)**
4. **MRS emission spectrum of a giant planet**

5. **LRS spectrum of a warm Neptune---mass planet (GJ436 b: CH_4, photo---products)**

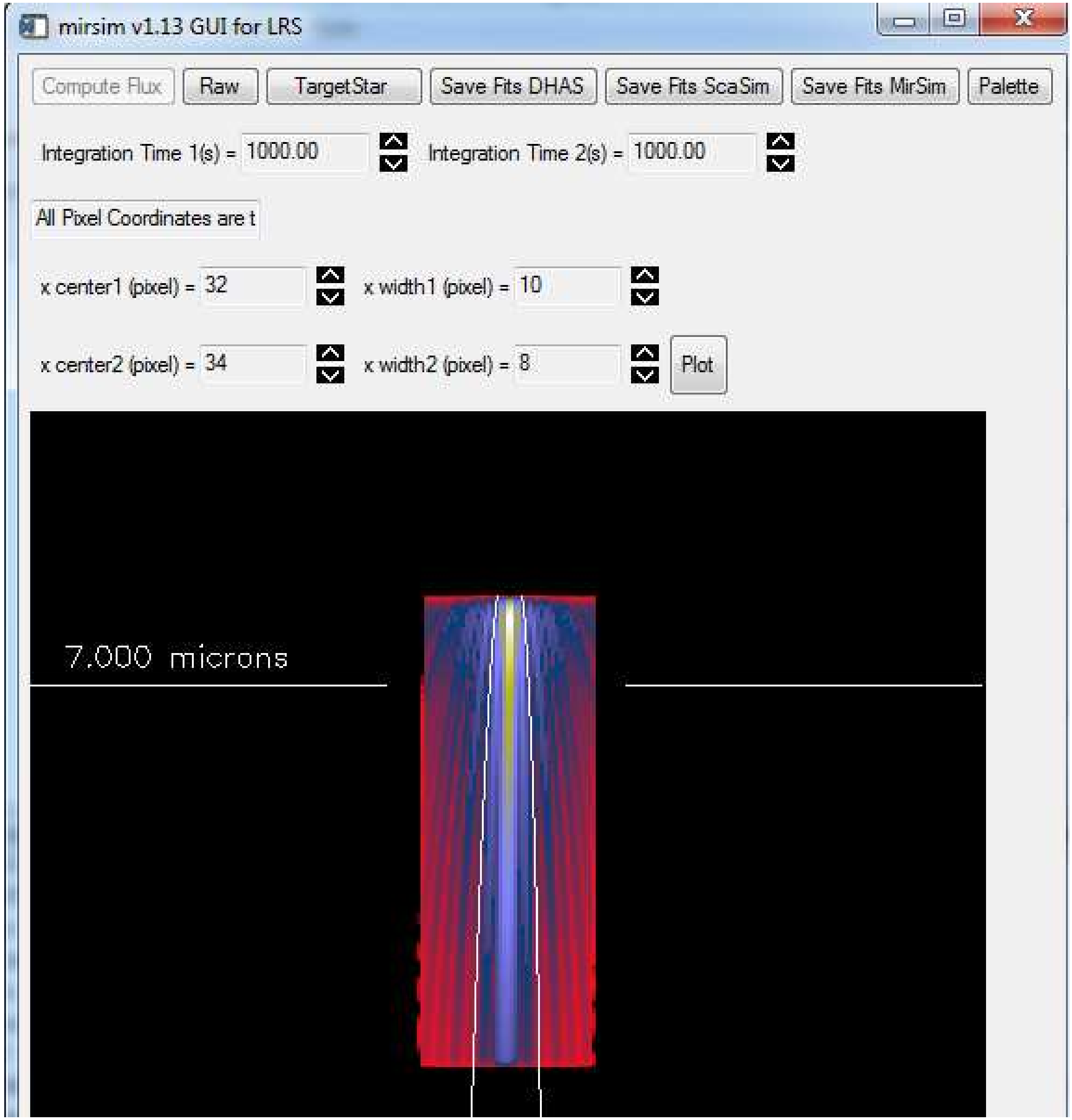
6. **LRS spectrum of at least one sub---Neptune mass planet (e.g., GJ1214 b)**



7. **Emission photometry or LRS spectra of yet to be discovered small planets**

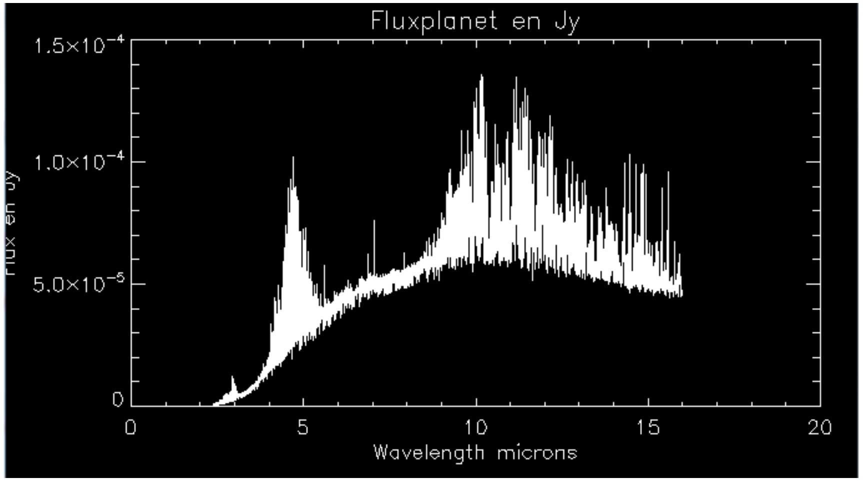
Development of a user friendly simulator

MIRI European Consortium

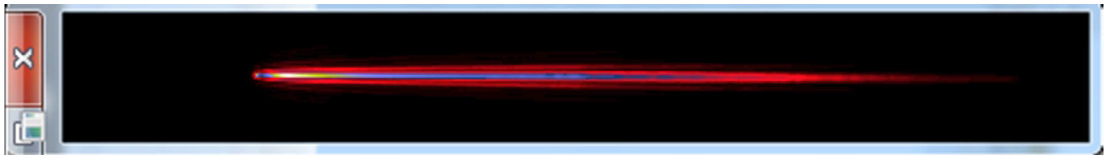


Development of a simulator

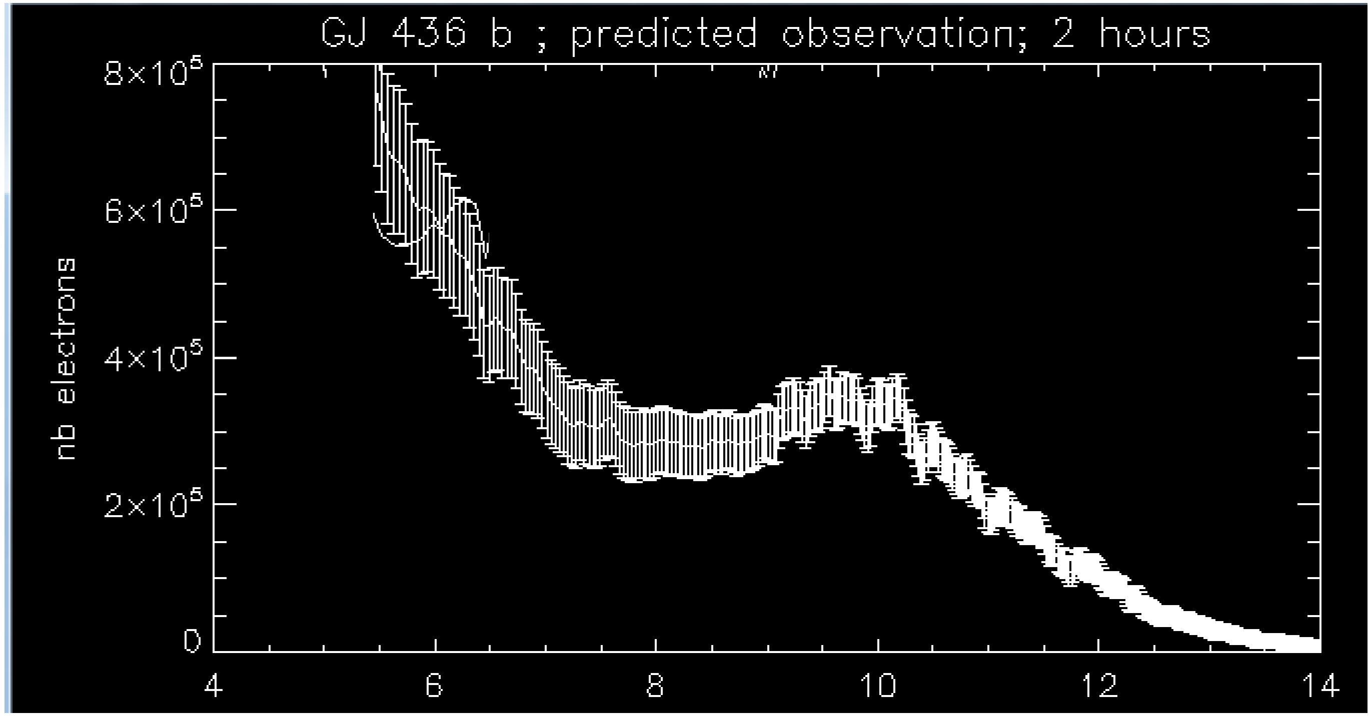
MIRI European Consortium



GJ436 Model from J. Fortney
Not so many models!



Simulated eclipse spectrum



Collaboration with Tom Greene

Still a lot of effects to be included in the simulator

Especially concerning the detectors (Latent, intrapixels…)
But also optics (franging)….

Exoplanet observations either direct imaging or from transit are challenging!

The delay of JWST is a chance to be better prepared

MIRI detector testing continues at JPL

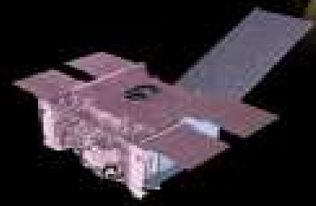
Better to be well prepared and organized as an exoplanet community

First Call for JWST observations probably in 2017

for an answer beginning 2018

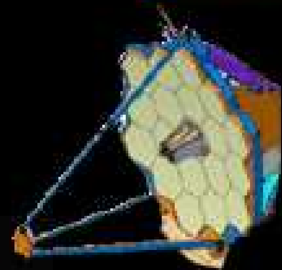
Project Milestones to Science Ops

- **2014: Manufacturing the spacecraft**



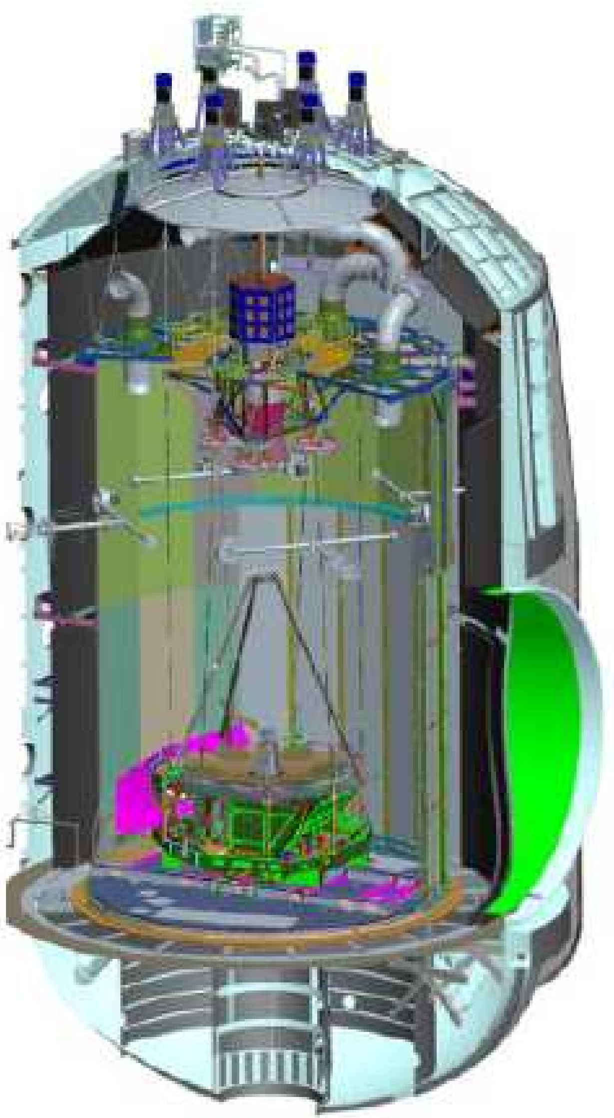
- **2015: Telescope Integration**

- **2016: Observatory assembly**



- **2017: Observatory Testing**


Refurbished JSC Chamber-A test facility
JWST
Clampin/GSFC

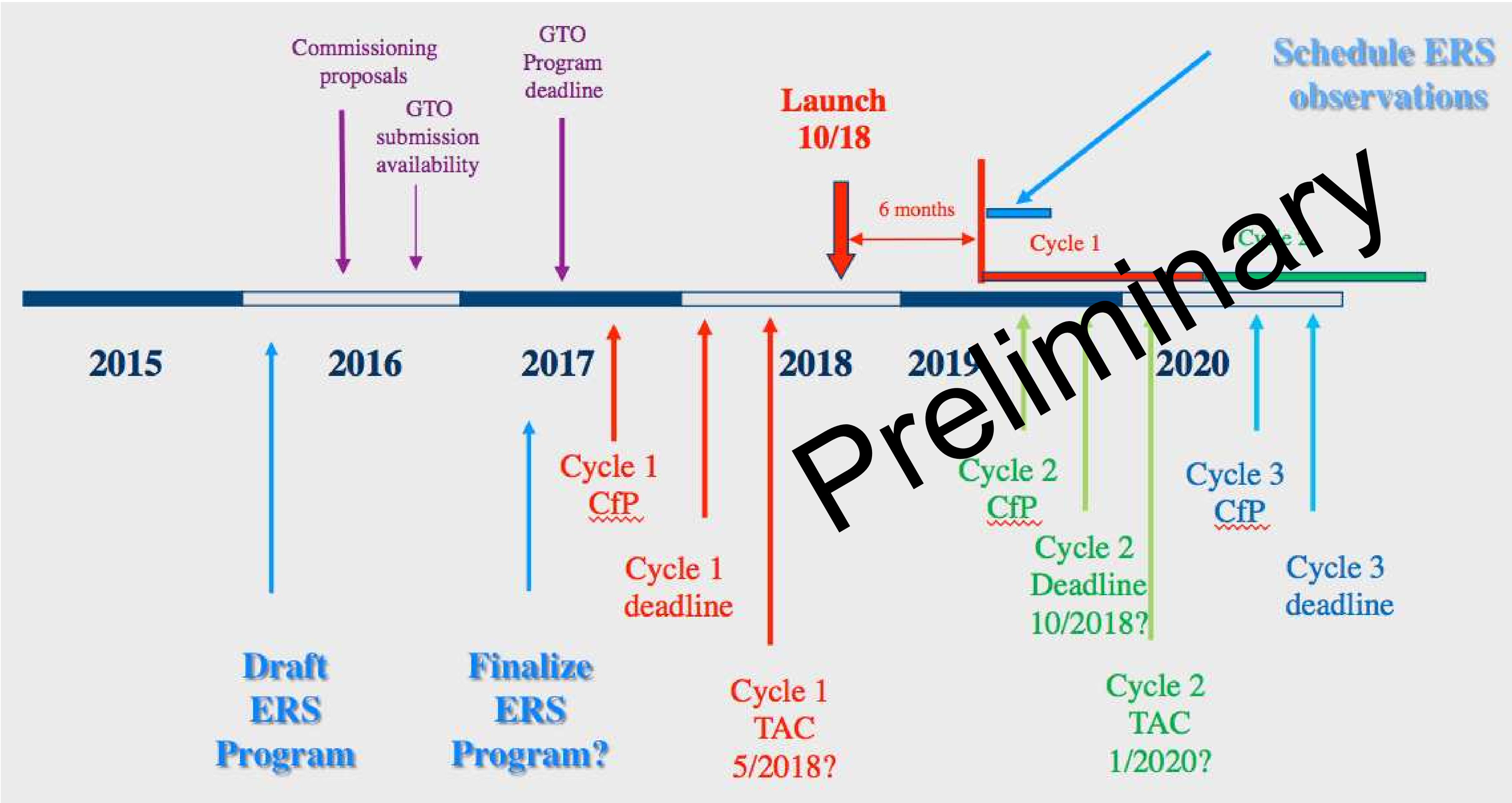


3 Separate Pathfinder Tests (2015-2016)
- Thermal
- 2 mirrors + Secondary
- 2 mirrors + Secondary & aft-optics

Flight OTIS Test - 1 cycle

Goals:
- Thermal verification
- Workmanship verification
- Alignment

JSC Chamber-A: Cryo-Optical Test Configuration


Commissioning proposals
GTO submission availability
GTO Program deadline
Launch 10/18
6 months
Schedule ERS observations
Cycle 1
Cycle 2
2015
2016
2017
2018
2019
2020
Draft ERS Program
Finalize ERS Program?
Cycle 1 CfP
Cycle 1 deadline
Cycle 1 TAC 5/2018?
Cycle 2 CfP
Cycle 2 Deadline 10/2018?
Cycle 2 TAC 1/2020?
Cycle 3 CfP
Cycle 3 deadline
Preliminary

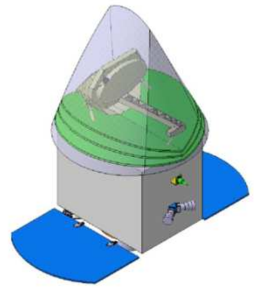
What JWST should NOT do:

MIRI European Consortium

Spent a large fraction of the exoplanet time on **bright hot planets**

Indeed a dedicated 1m telescope space mission in the 2-8 microns range is better suited for a statistical studies of 500-1000 such objects

This is the ARIEL project proposed to ESA in the M4 framework (an evolution of the M3 proposed Echo mission)



JWST should spent most of its time on a few relatively cool low mass planet

**Such observations are challenging
(down to 10 ppm, multiple transits to be co-added, detector stability, effect of stellar variability,…**

We will take advantage of time before launch to be well prepared!