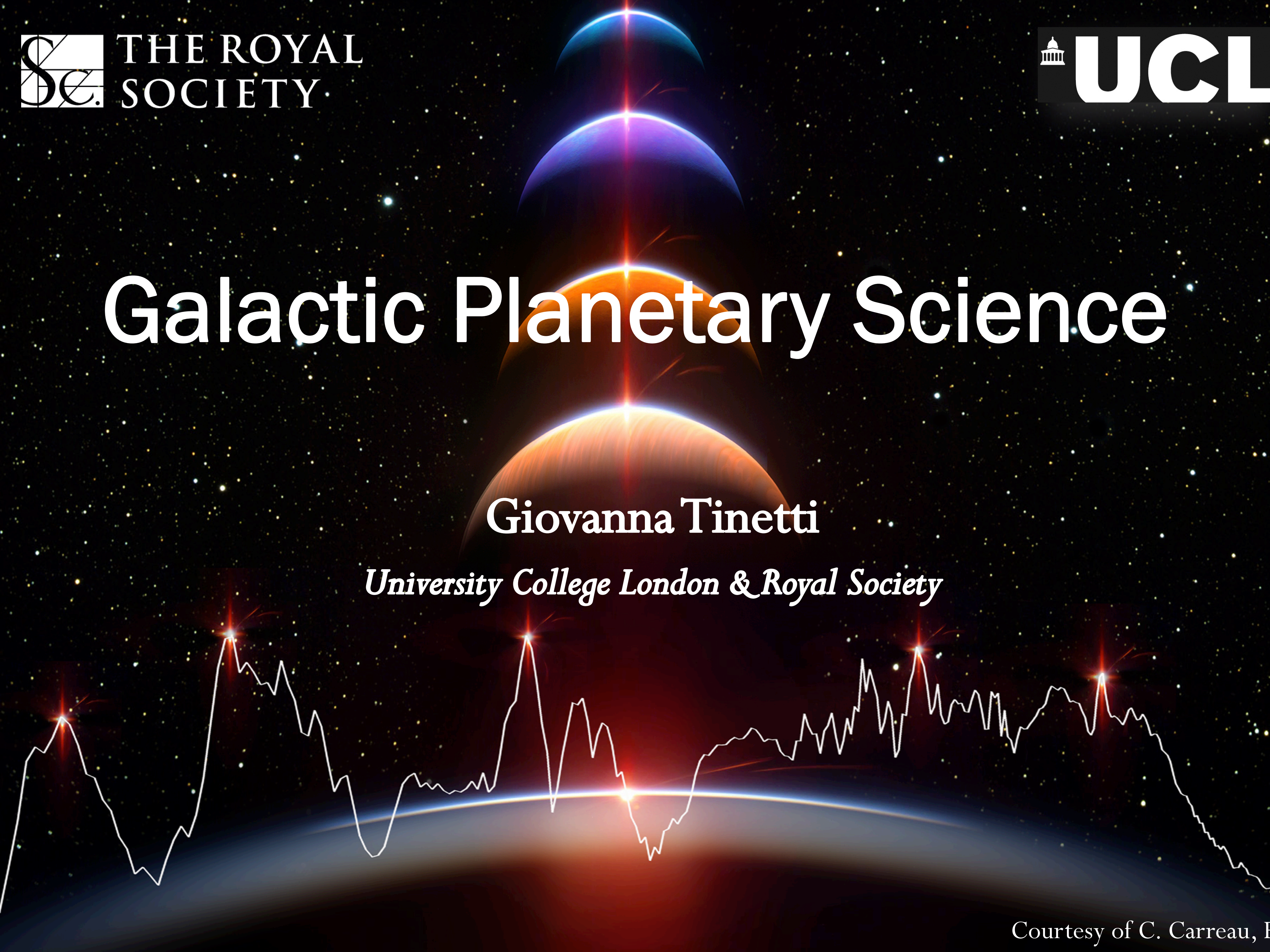
THE ROYAL SOCIETY

UCL



Galactic Planetary Science

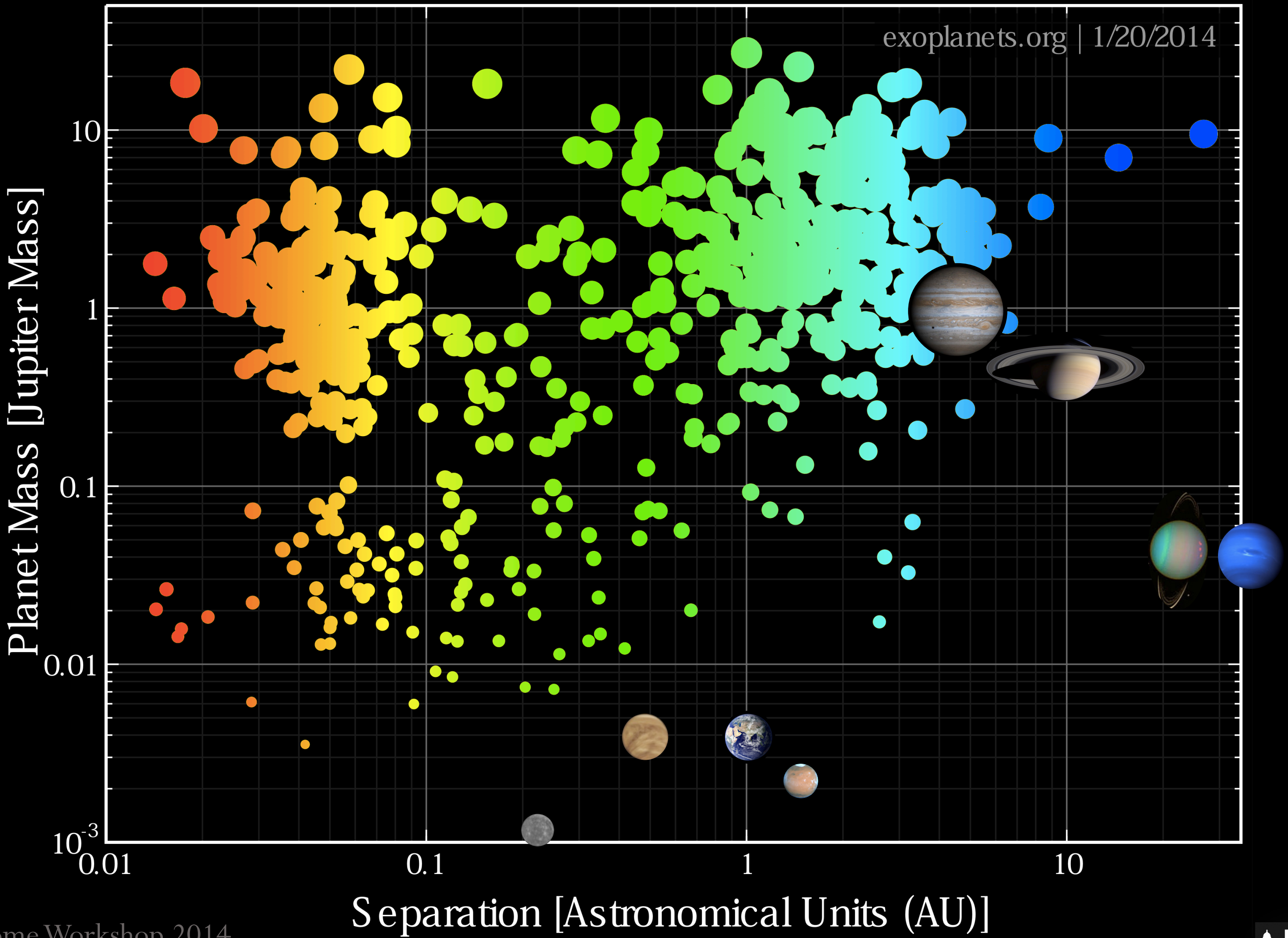
Giovanna Tinetti

University College London & Royal Society

Courtesy of C. Carreau,

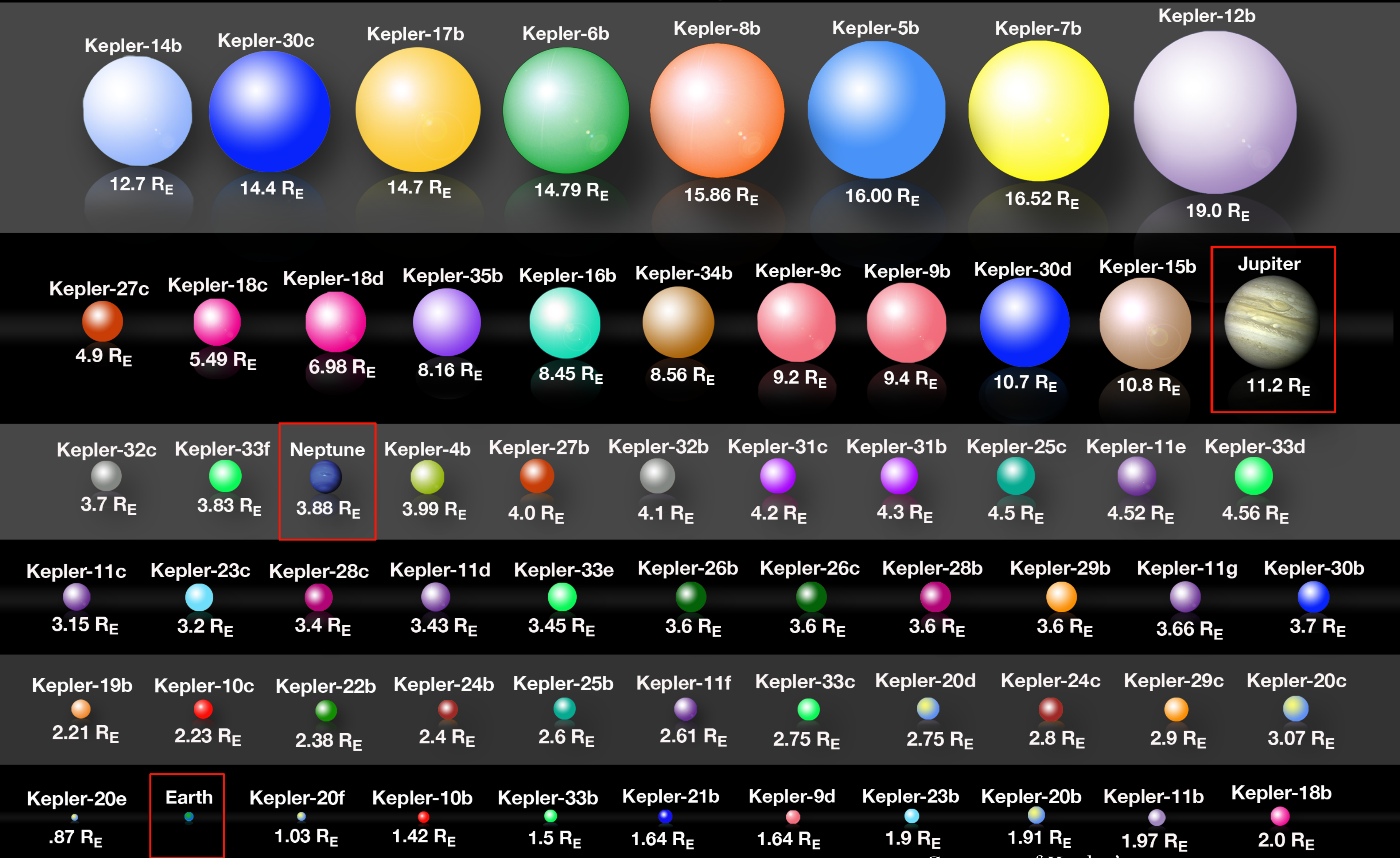
The Exoplanet Revolution

9 to 1000 in 20 years!



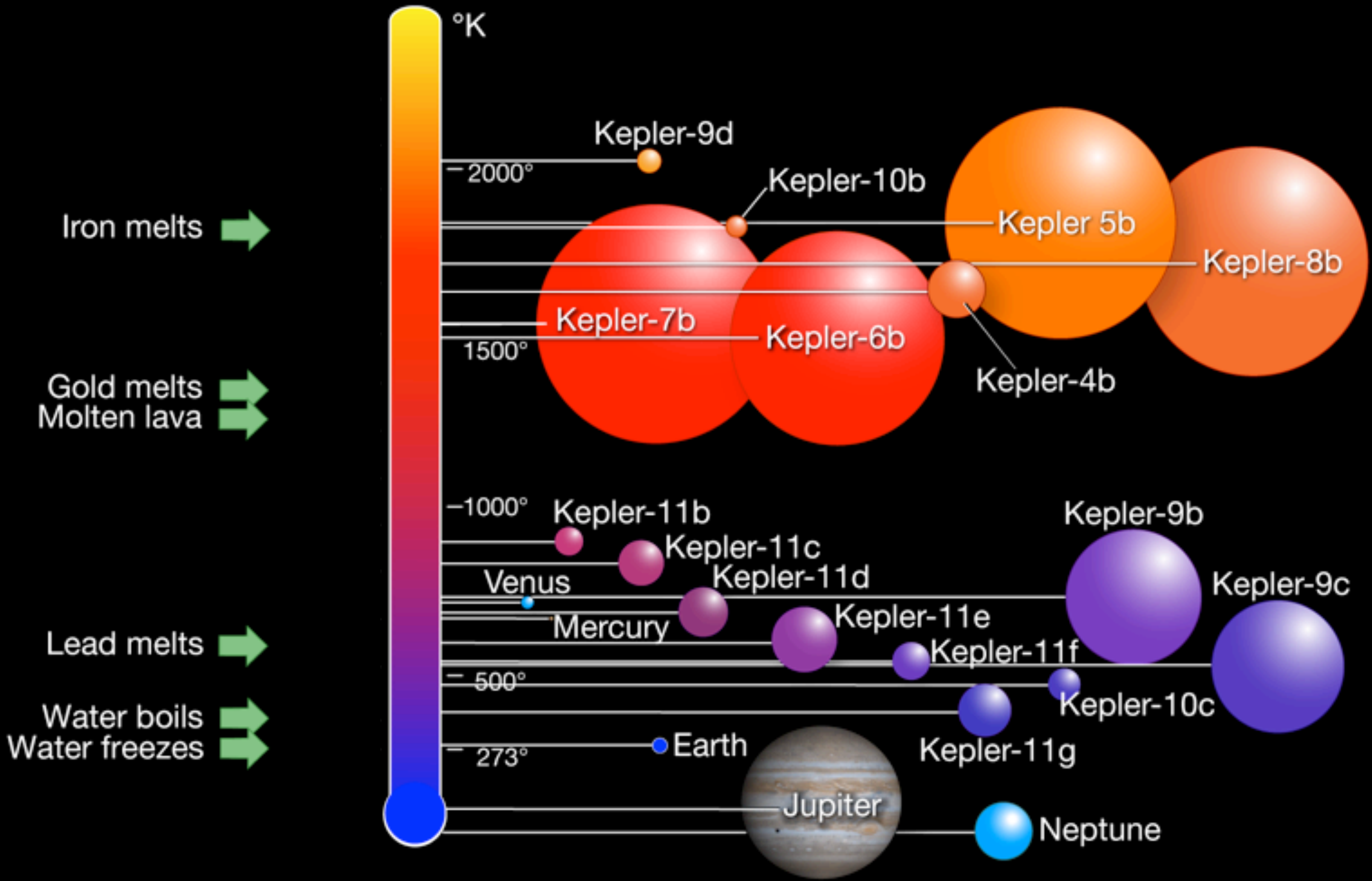
Kepler Planets

As of February 27, 2012



Courtesy of Kepler's team

Planet Temperature & Size



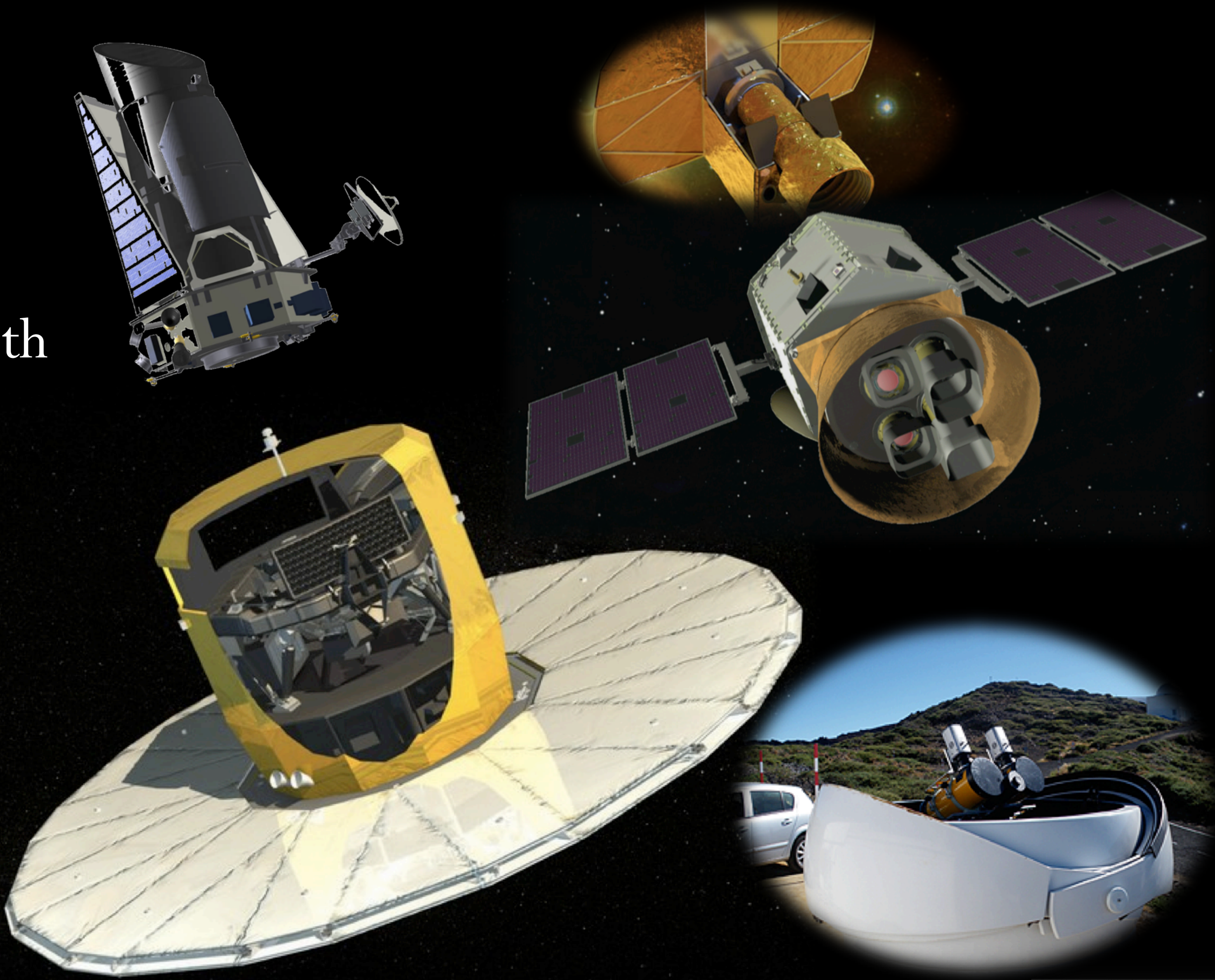
Courtesy of Kepler's team

UCL

GAIA + Transit & Radial Velocity surveys

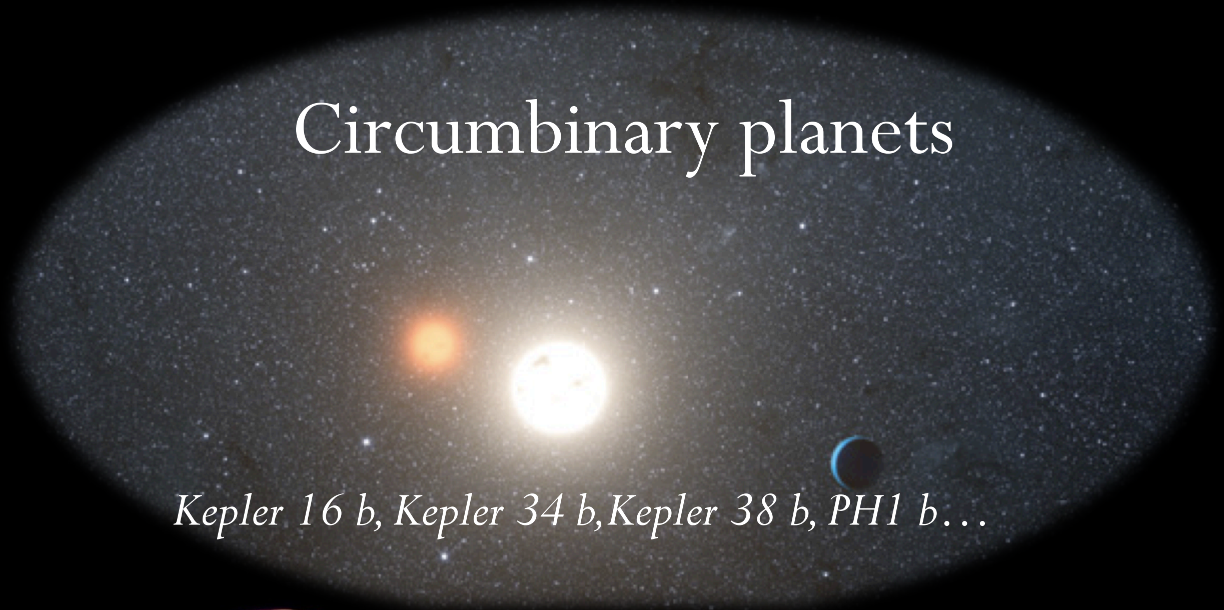
Several thousands new planets in the next decade

- GAIA
- Cheops
- TESS
- Kepler-2
- HARPS/HARPS North
- HAT-NET
- Super-WASP
- Carmenes
- M-Earth
- NGTS
- APACHE
- Spirou
- MASCARA



The Solar System is *not* representative

There is much more variety than the Sun's planets



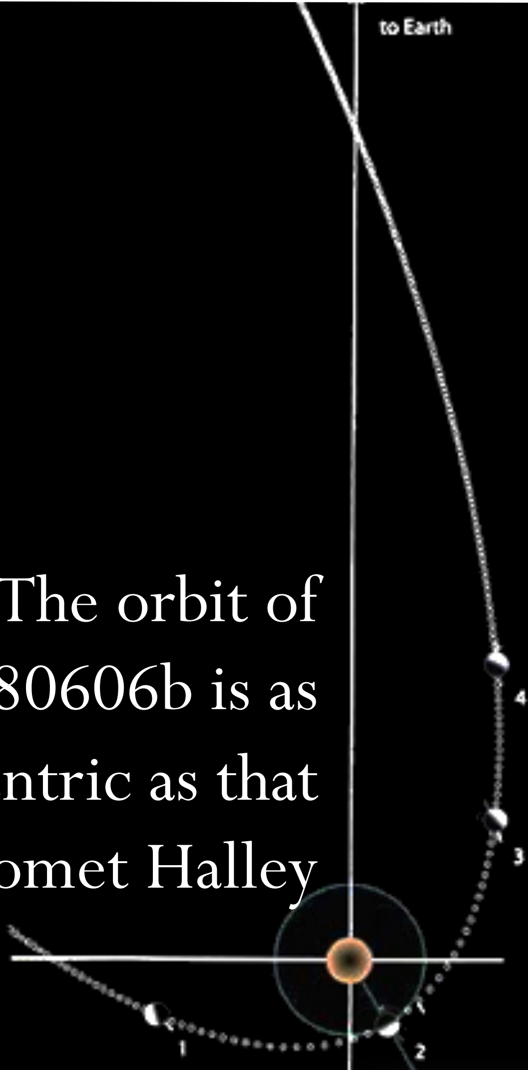
Circumbinary planets

Kepler 16 b, Kepler 34 b,Kepler 38 b, PH1 b…

"Lava planets"

T > 2500K

Corot 7b, Kepler 78b, 55 Cnc e, Kepler 10b….



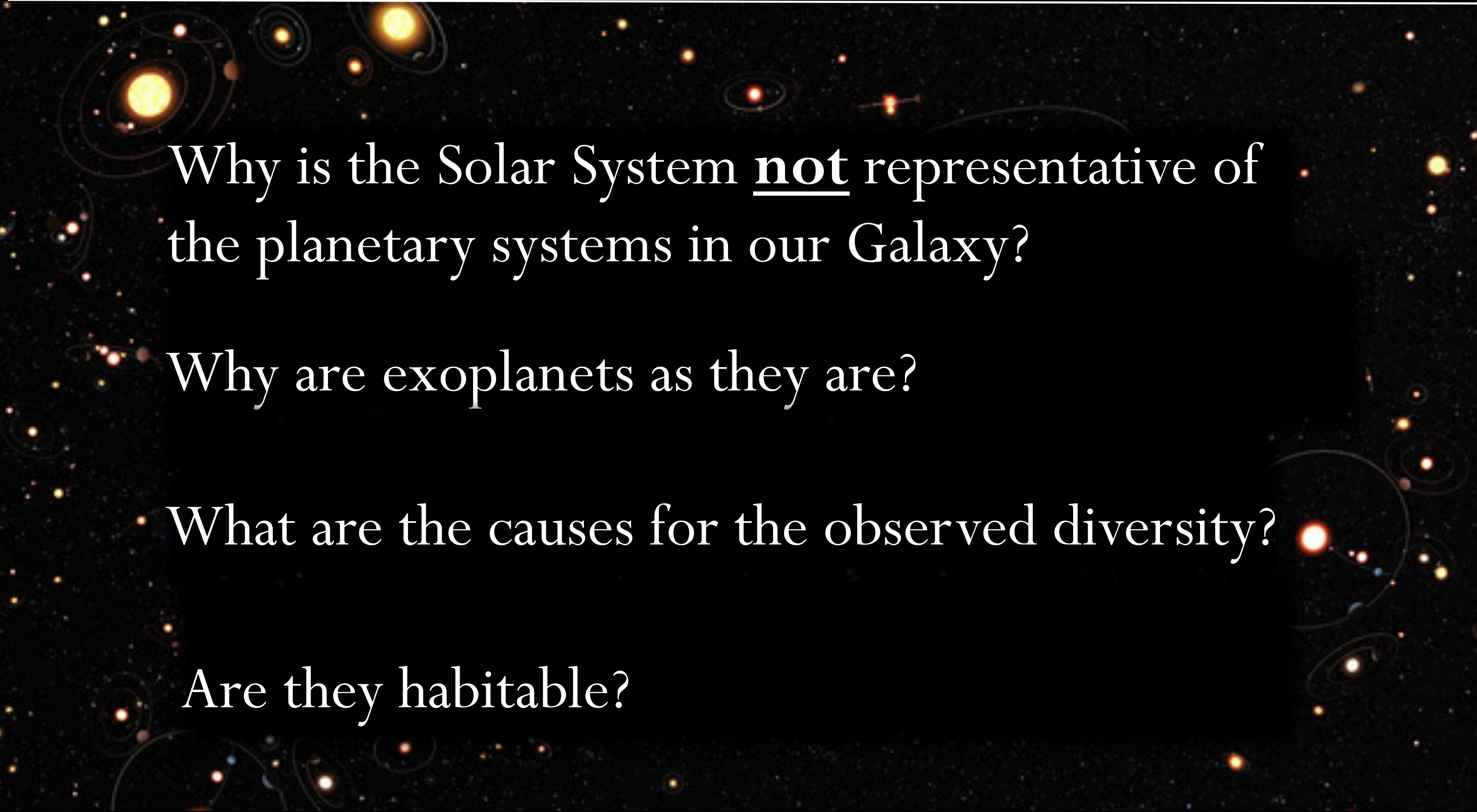
The orbit of HD80606b is as eccentric as that of comet Halley

The Solar System is *not* representative

There is much more variety than the Sun's planets

A key question of modern astrophysics is to understand why

Outstanding Science Questions



Why is the Solar System **not** representative of the planetary systems in our Galaxy?

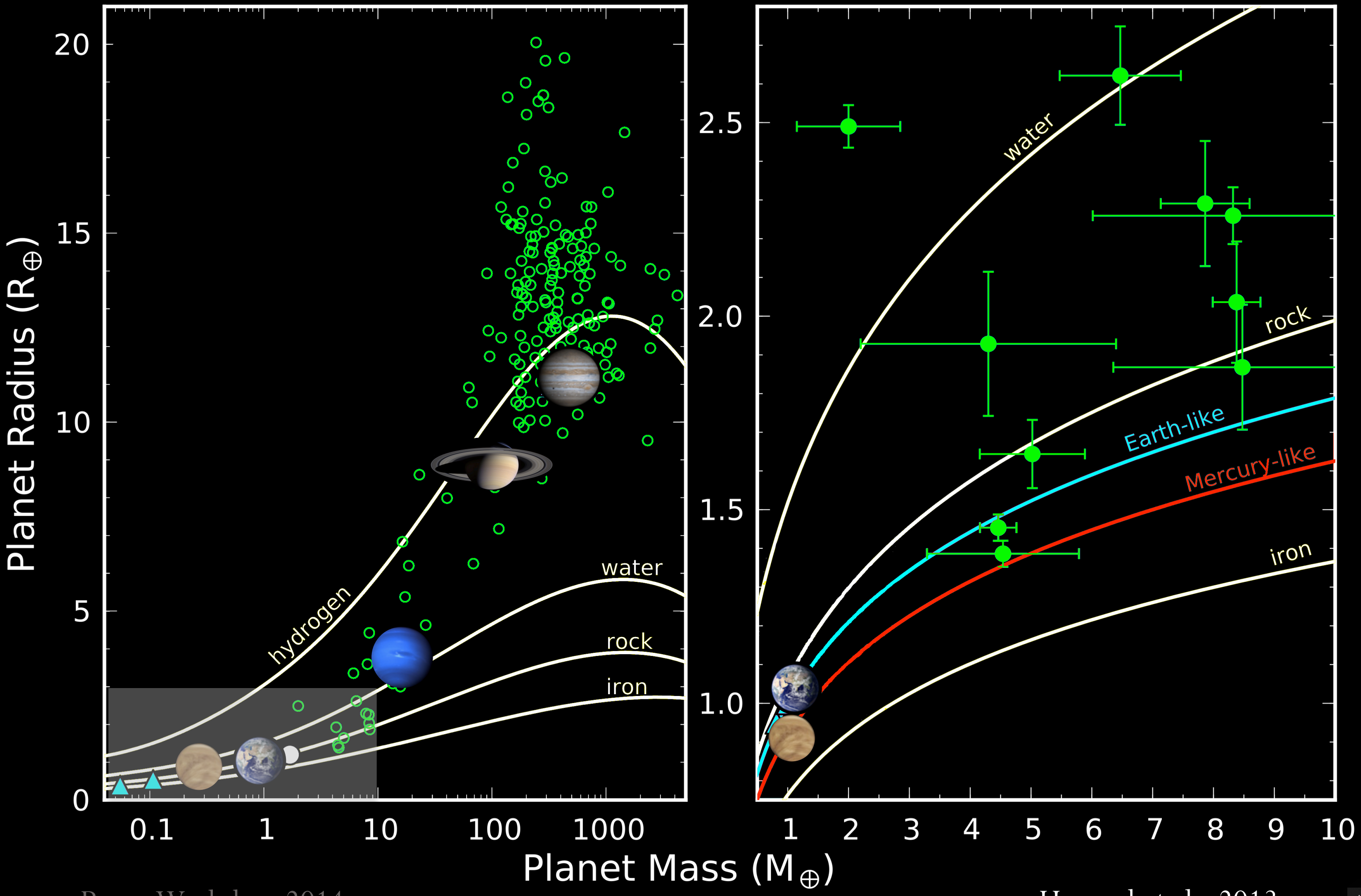
Why are exoplanets as they are?

What are the causes for the observed diversity?

Are they habitable?

Understanding the exoplanet diversity

Mass & radius tell only part of the story



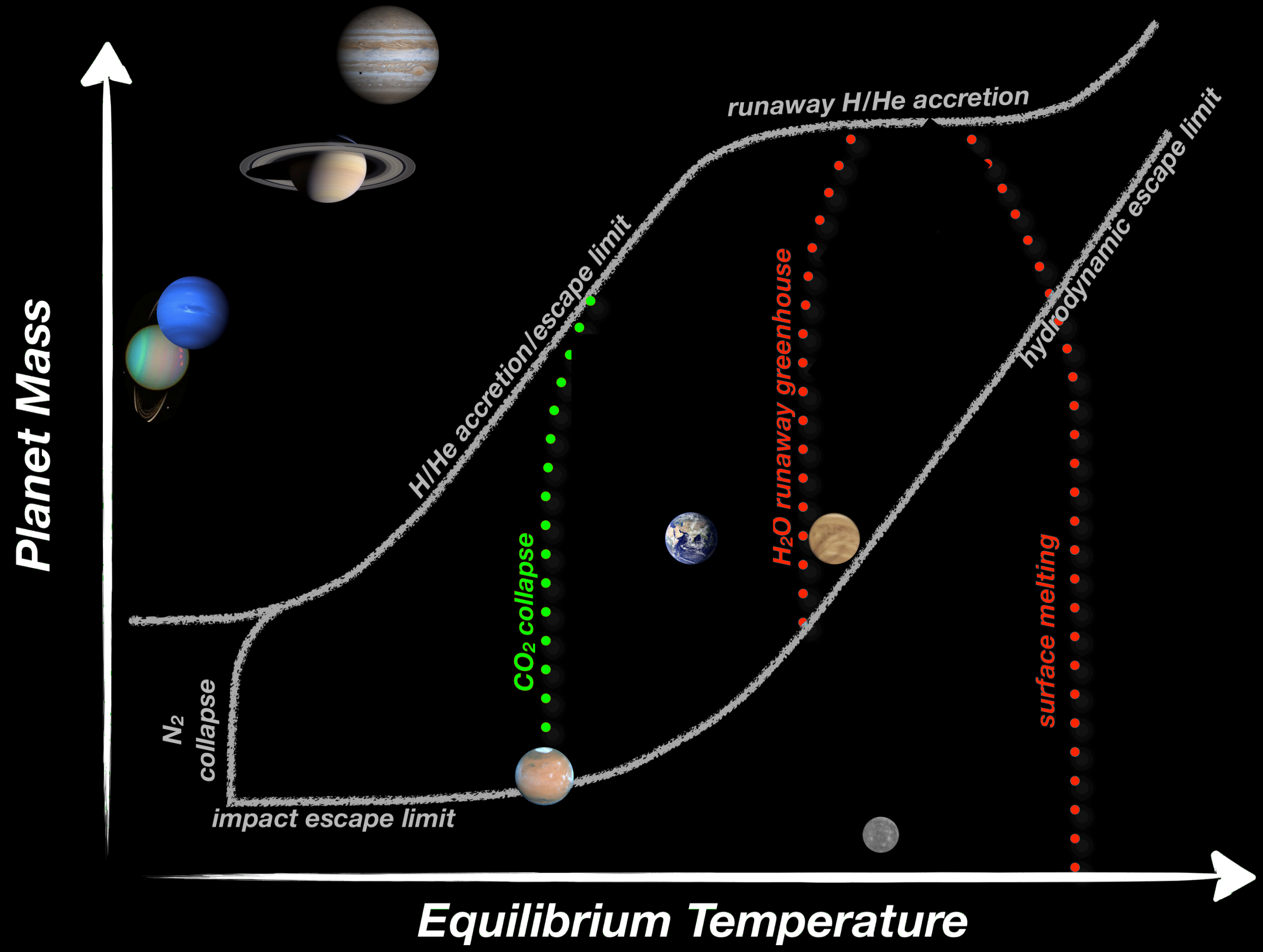
Howard et al., 2013

The gaseous envelope

Atmospheric composition is determined by many processes

Understanding exoplanet diversity

Predicted atmospheric composition of exoplanets

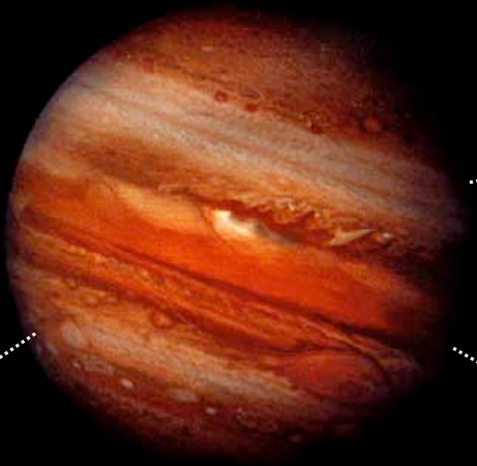


Rome Workshop 2014

Forget & Leconte, 2013

Gaseous planets

Key questions & observables



Energy budget

Albedo/thermal emission

Planet formation

Metal enrichment, C/O etc.

Planet evolution

Escape/Ions,H_3^+

Weather

Temporal variability/
Thermal structure

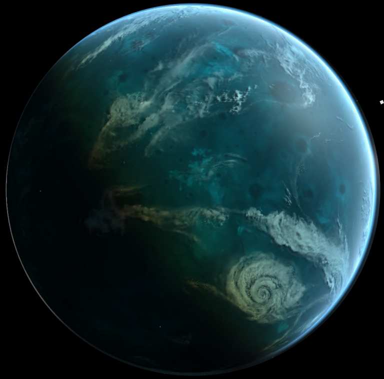
Planet-star interaction

Photochemistry+
Day/night variation

Tinetti, Encrenaz, Coustenis, 2013

Solid planets

Key questions & observables



Does the planet have an atmosphere?
Spectral observations

Habitable conditions?
Temperature?
Water? Biosignatures?

Primary or secondary atmosphere?
H_2 retained or not

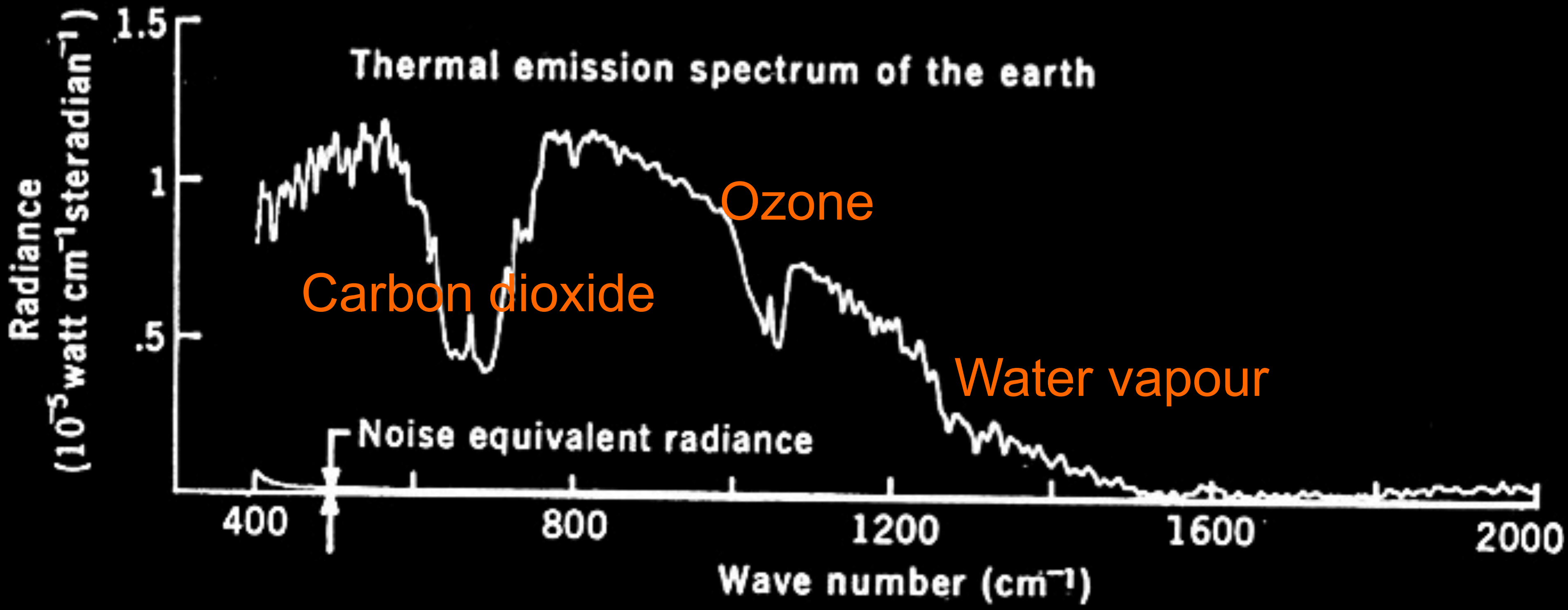
Main atmospheric component
Primary transit observations

Planet-star interaction
Photochemistry

Energy budget
Albedo/thermal emission

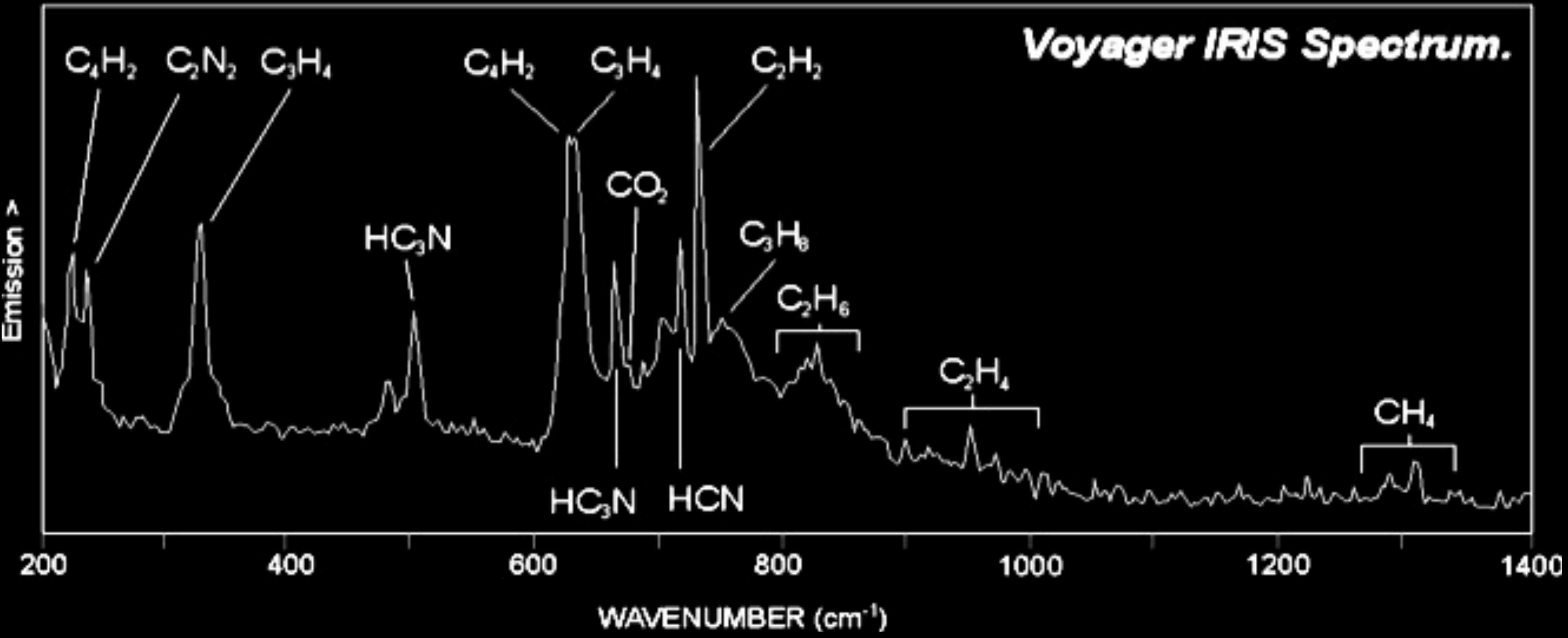
Tinetti, Encrenaz, Coustenis, 2013

1969 – Nimbus 3: *The Earth*



Hanel & Conrath, 1969

1980 – The outer solar system

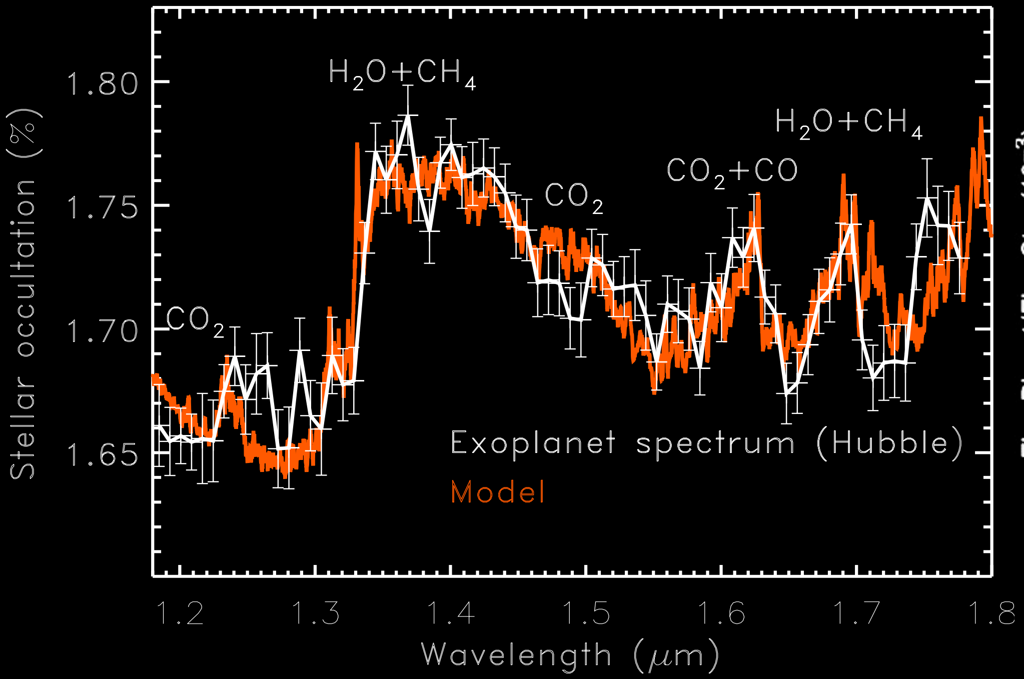


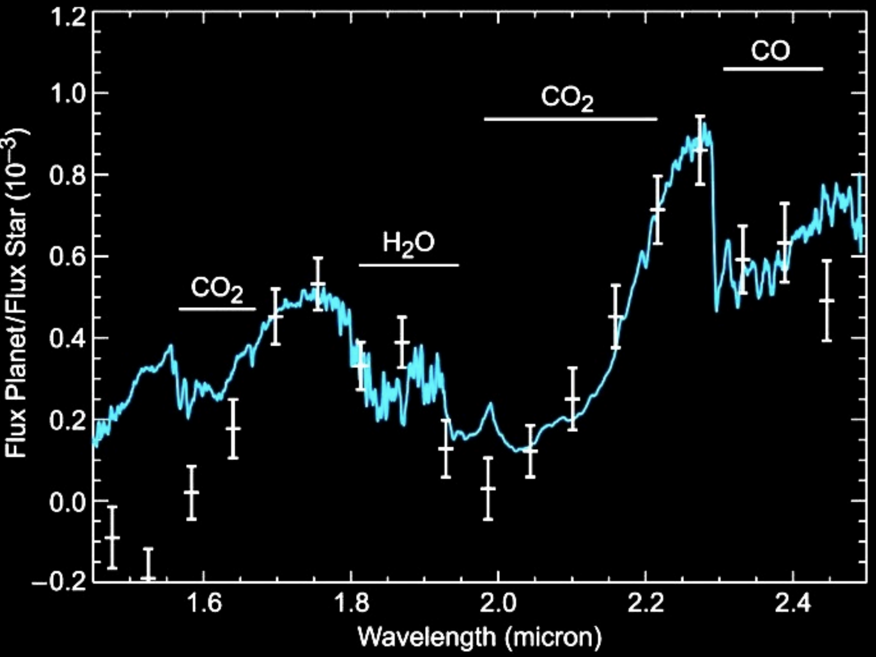
Samuelson et al., 1983

Pioneering work on Exo-Atmospheres

Transit spectra with Hubble, Spitzer, ground...

Hot-Jupiters, Temperatures ~ 1200 K

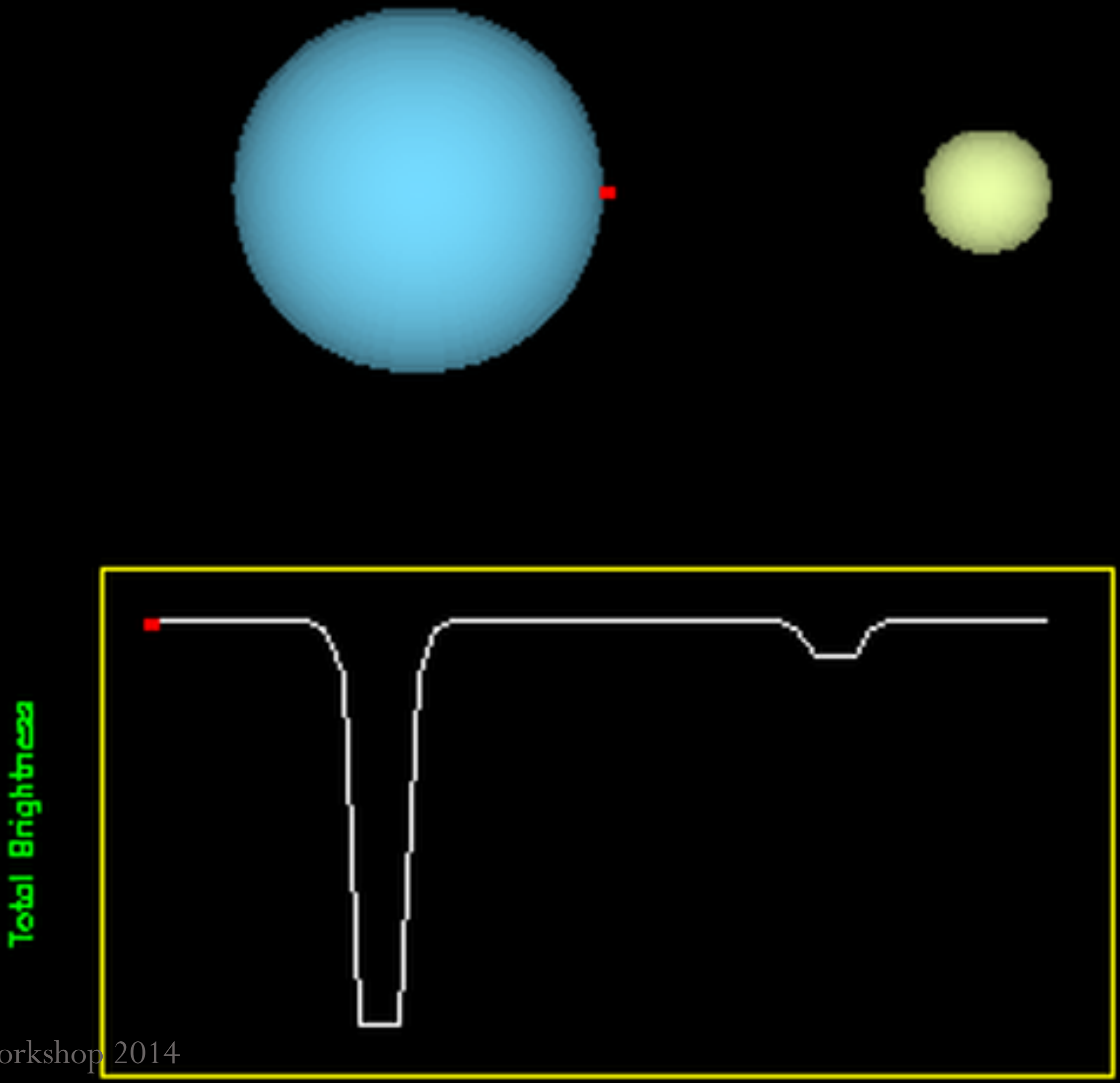




Tinetti et al, 2010; Swain et al., 2009

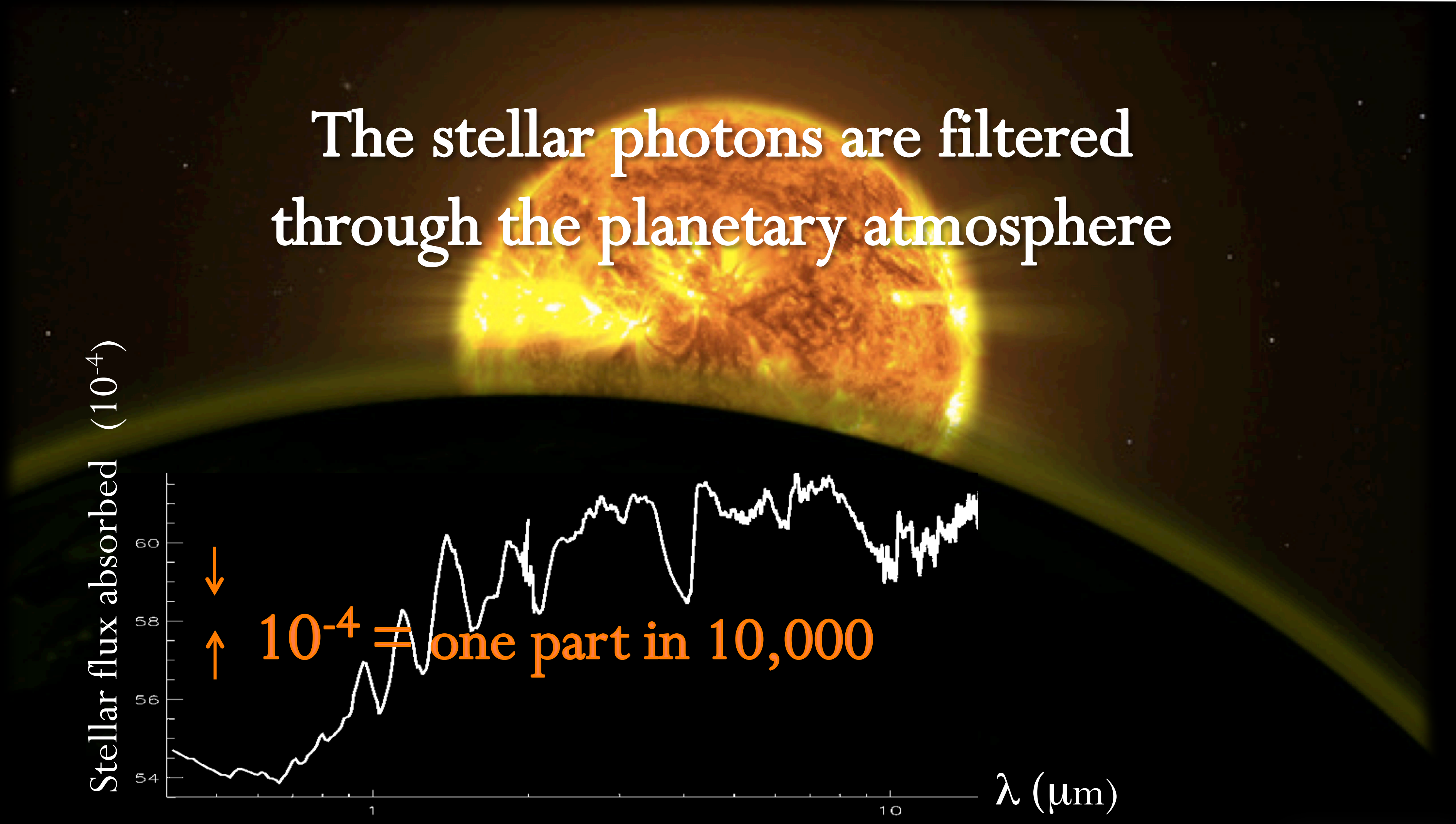
Transiting planets

Transits & eclipses



How to probe an exoplanet atmosphere

1: Transit spectroscopy

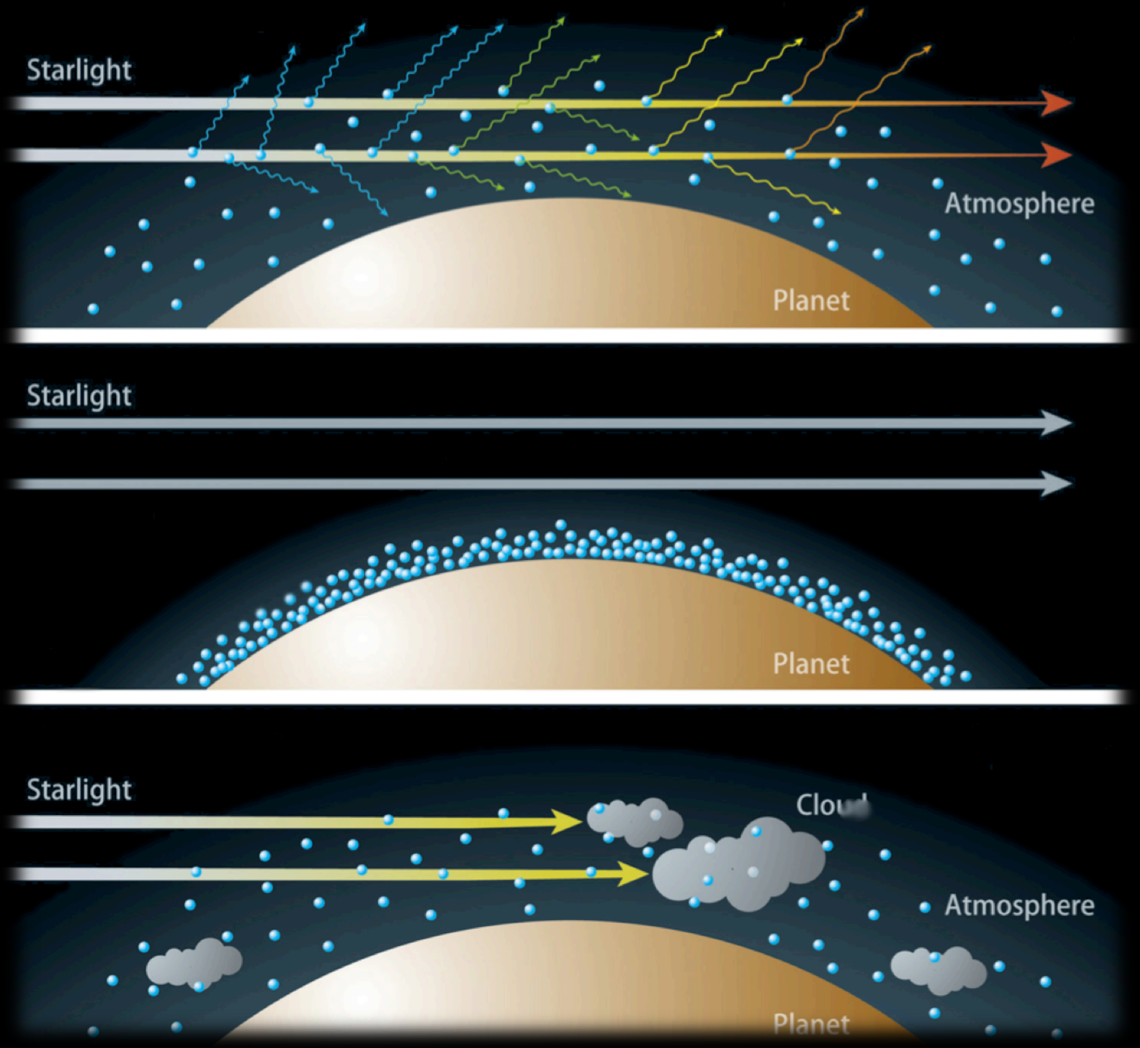


The stellar photons are filtered through the planetary atmosphere

10^{-4} = one part in 10,000

How to probe an exoplanet atmosphere

1: Transit spectroscopy



Scattering

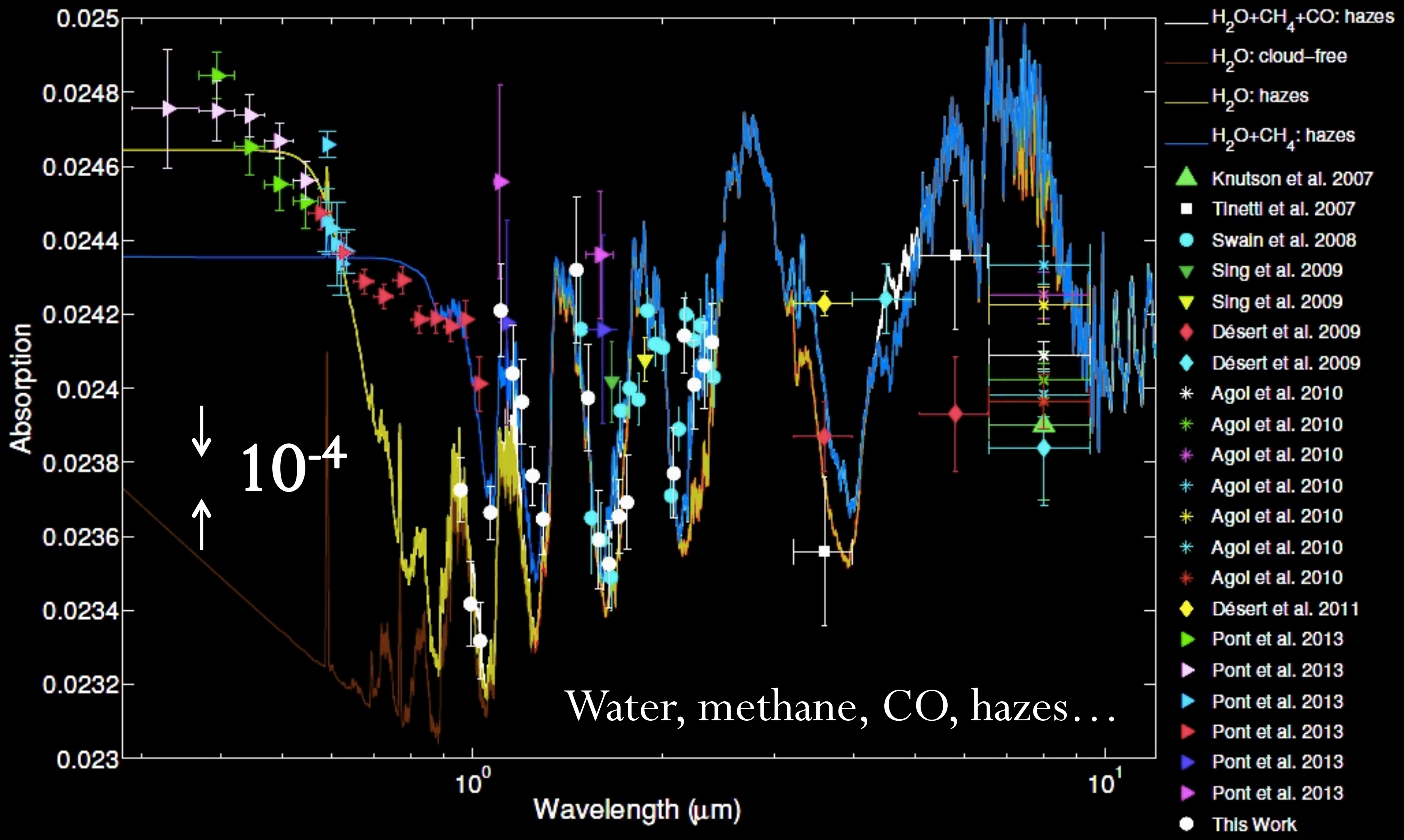
Scale height

Absorption

Credit: NAOJ

Hot-Jupiters: HD189733b

Transit spectra with Hubble, Spitzer, ground…



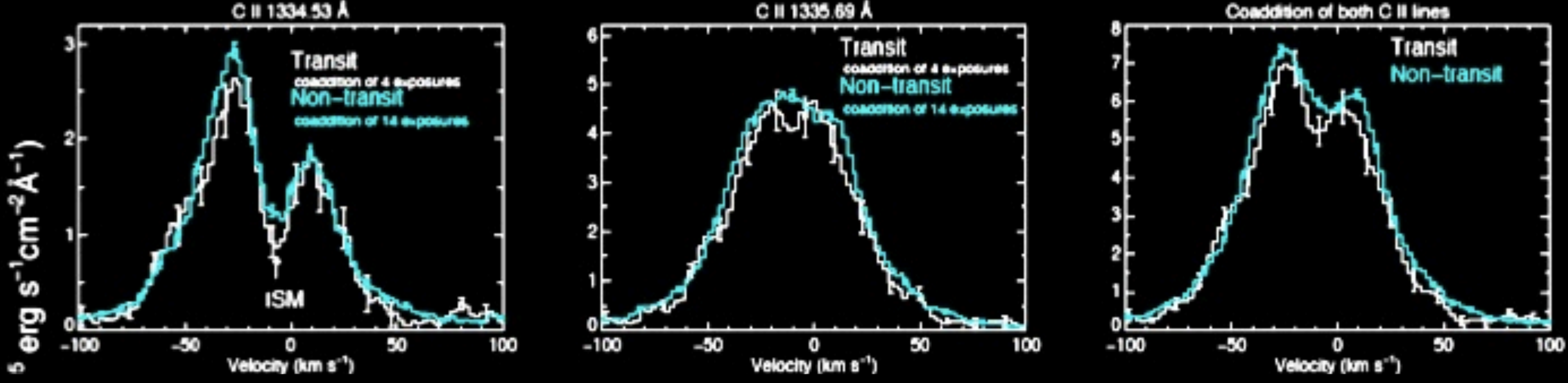
↓ 10^{-4} ↑

Water, methane, CO, hazes…

Danielski et al., 2014

Hot-Jupiters: HD209458b

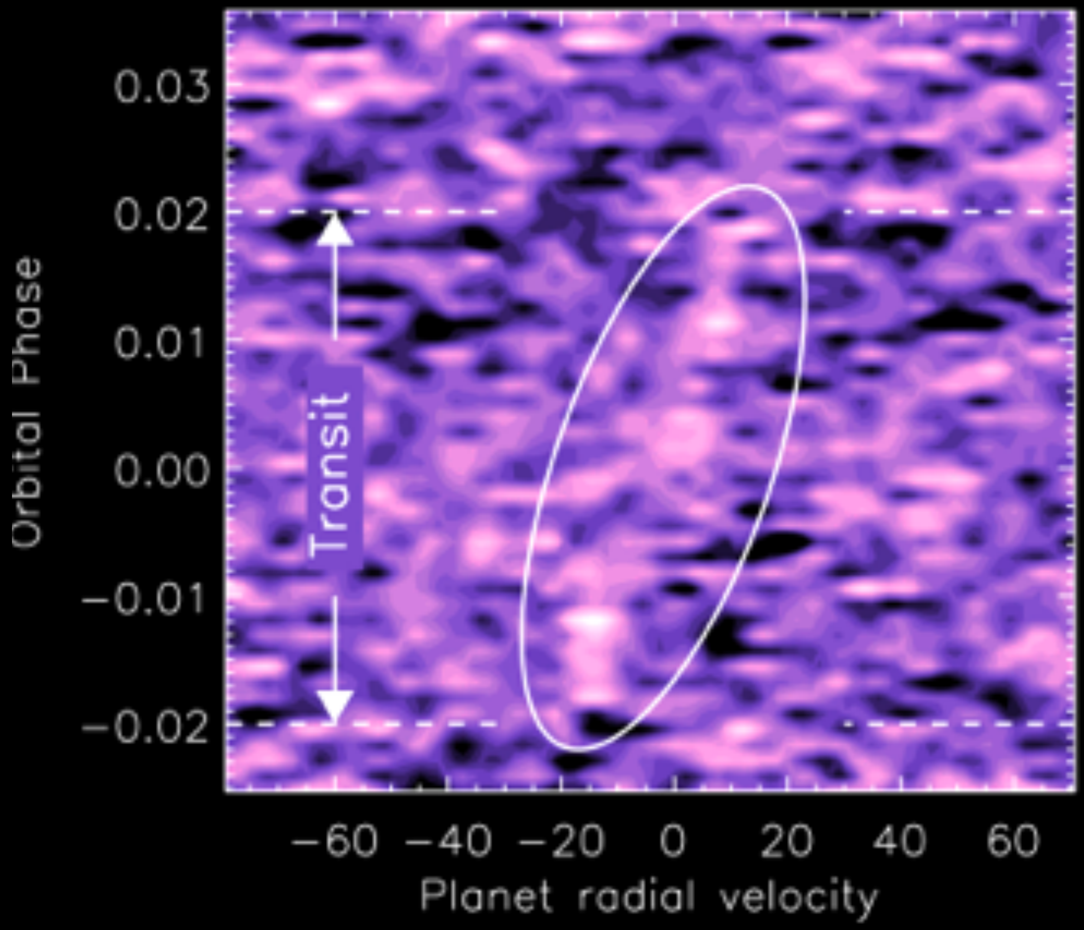
Hydrodynamic escape: UV spectroscopy



Linsky et al, 2010

Hot-Jupiters: HD209458b

Narrow band-high-resolution from the ground



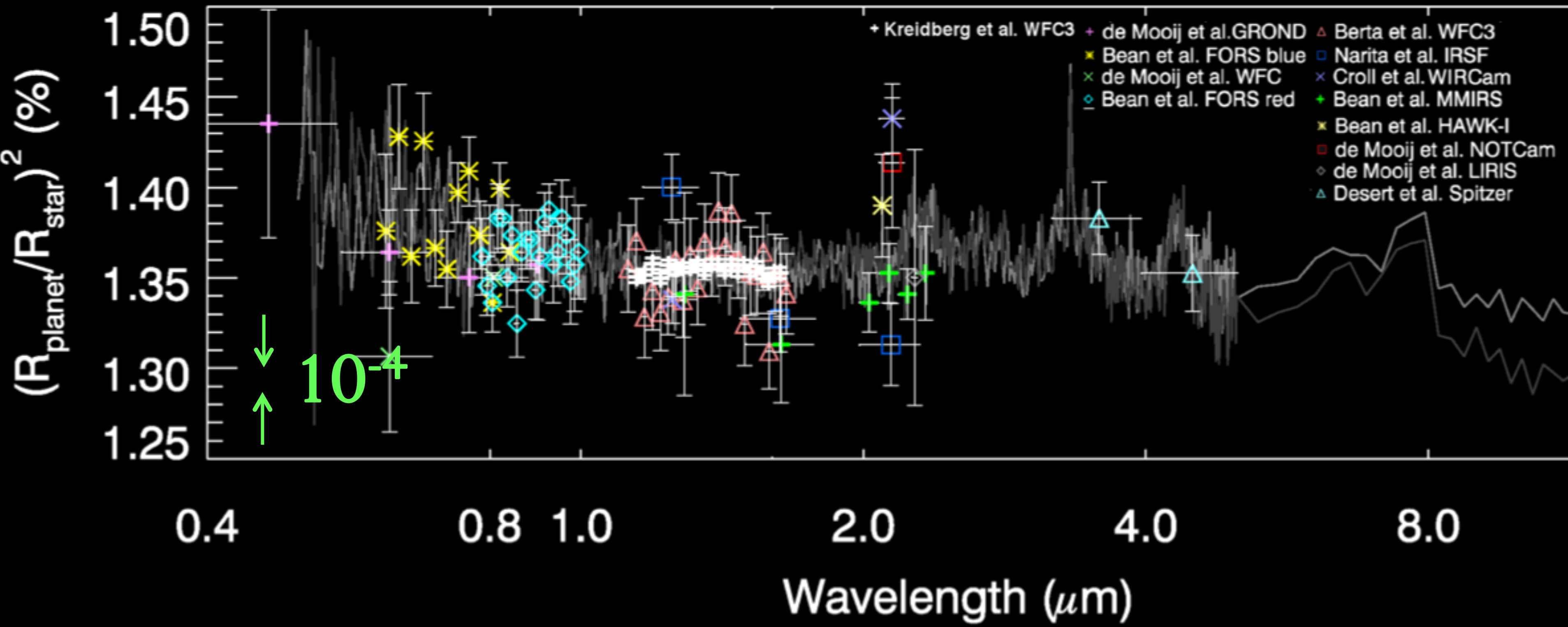
CO detection

Snellen et al., 2010

Warm super-Earths: GJ1214b

Transit spectra with Hubble, Spitzer, ground…

~6 M_E @ 450 K: Clouds? Water vapour?

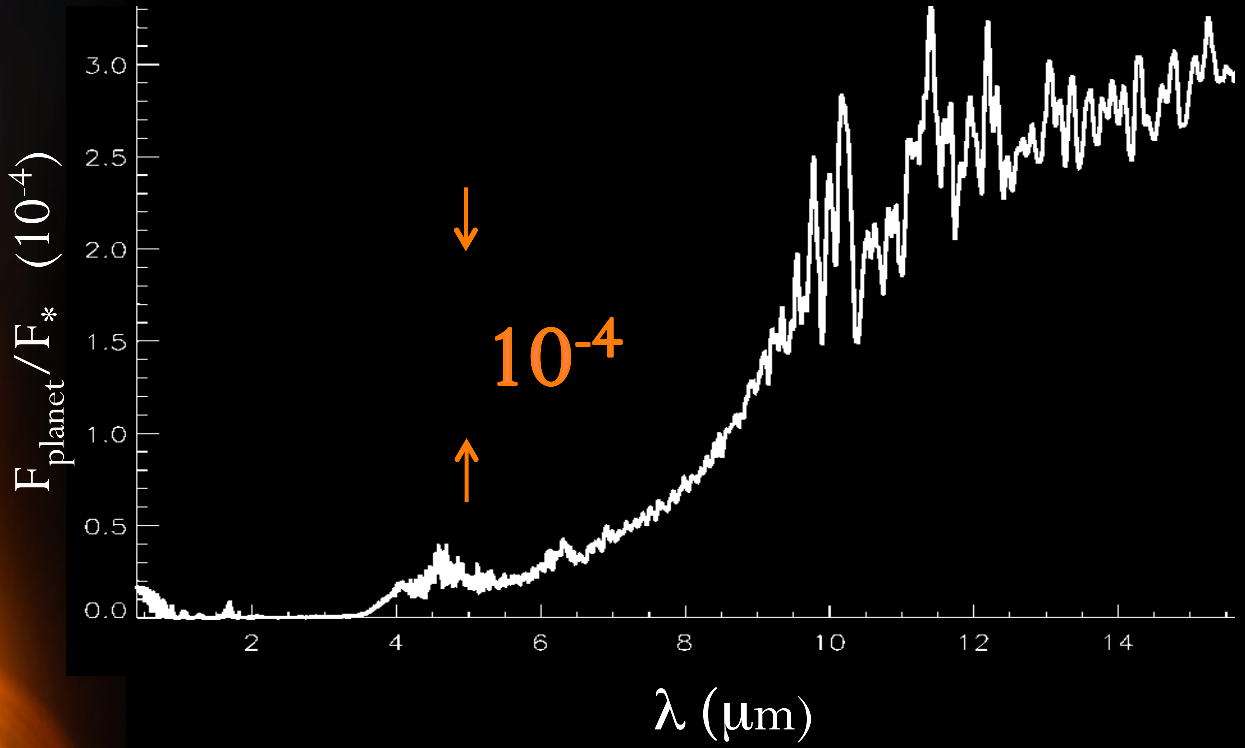


Barstow et al., 2014

How to probe an exoplanet atmosphere

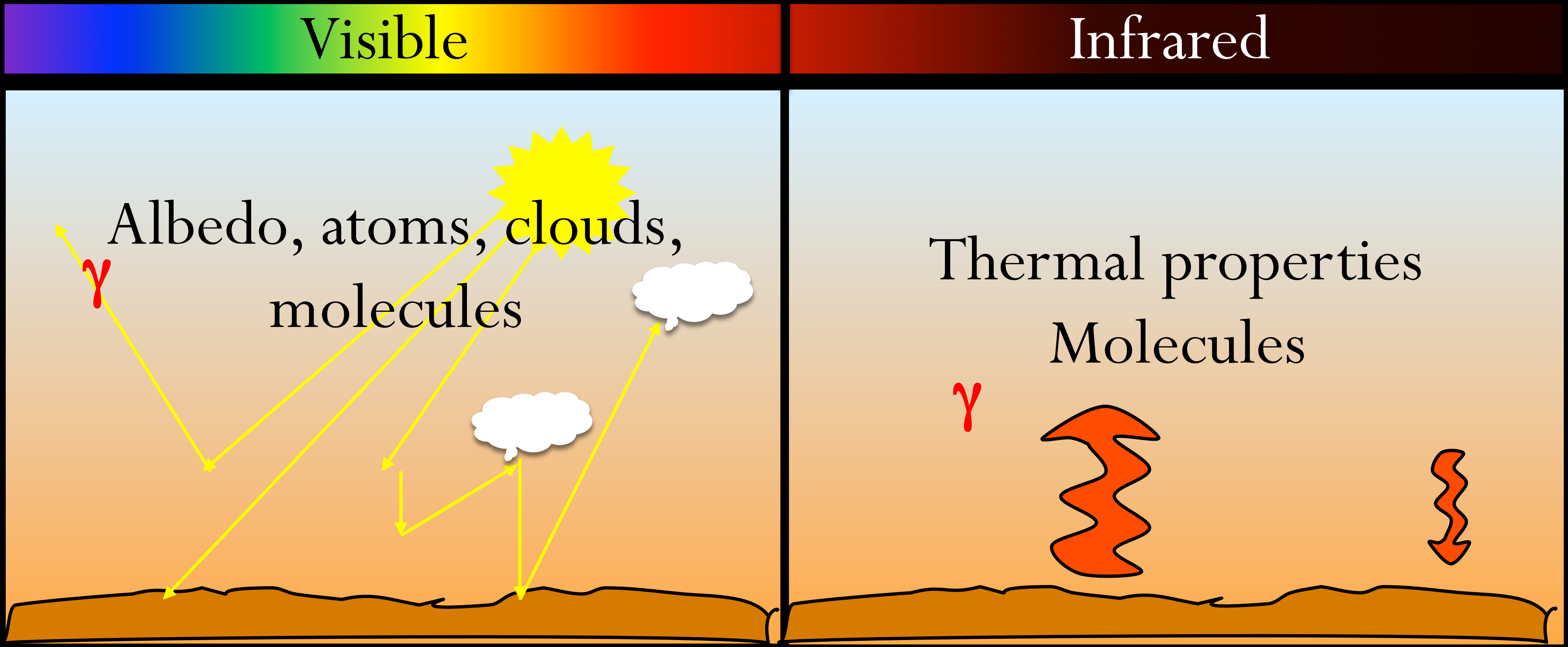
2: Eclipse spectroscopy

Using the planet ephemeris to separate the planet from the star



How to probe an exoplanet atmosphere

2: Eclipse spectroscopy



Visible

Albedo, atoms, clouds, molecules

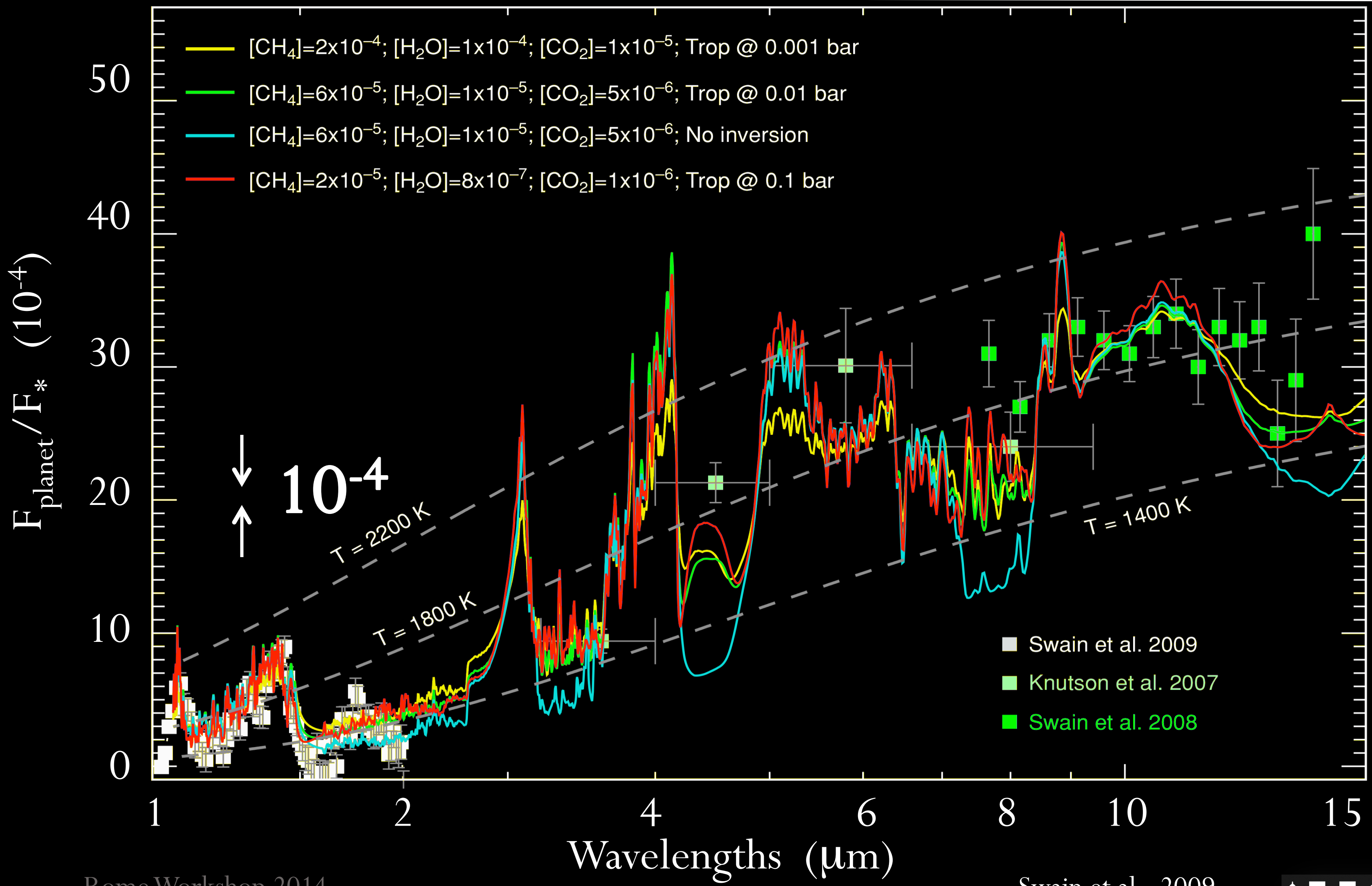
Infrared

Thermal properties

Molecules

Hot-Jupiters: HD209458b

Eclipse spectra with Hubble, Spitzer, ground...



Rome Workshop 2014

Swain et al., 2009

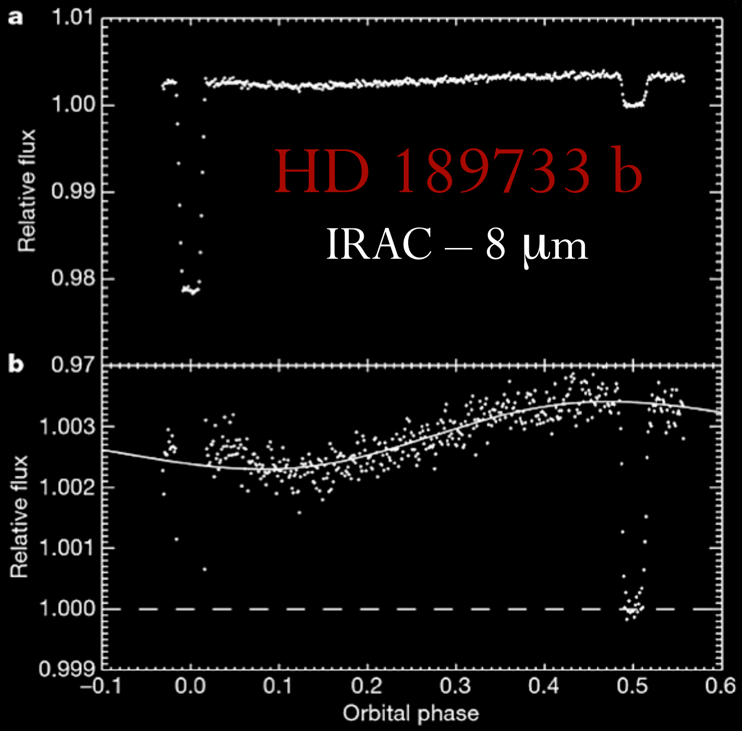
UCL

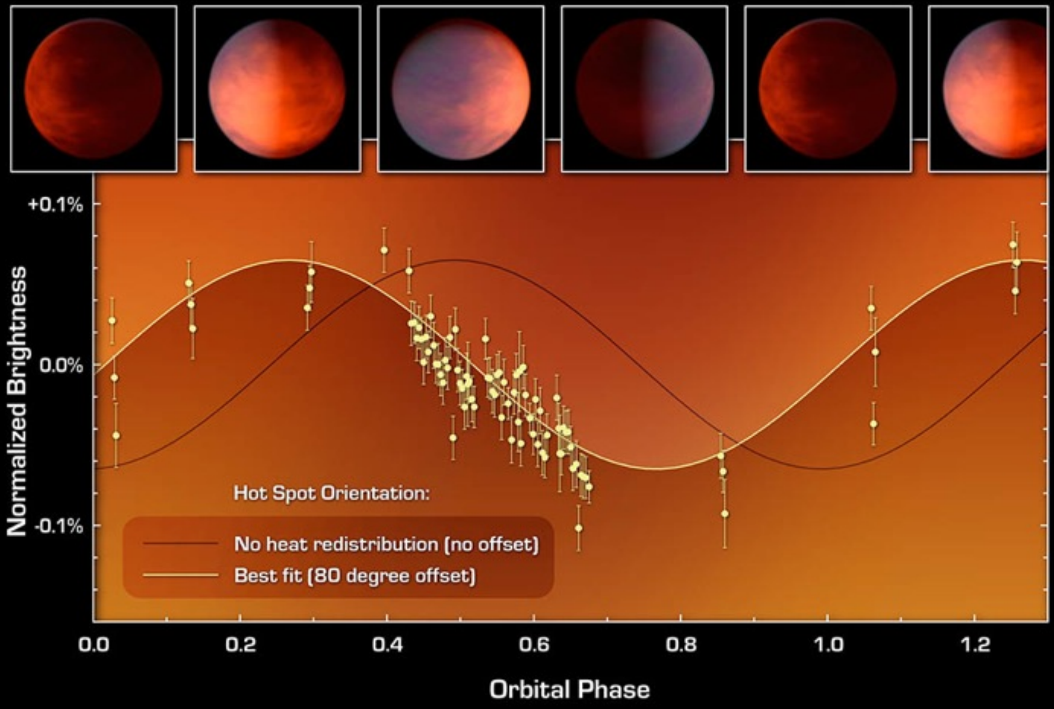
How to probe an exoplanet atmosphere

3: Phase-curves & eclipse mapping

Transiting

Non-transiting



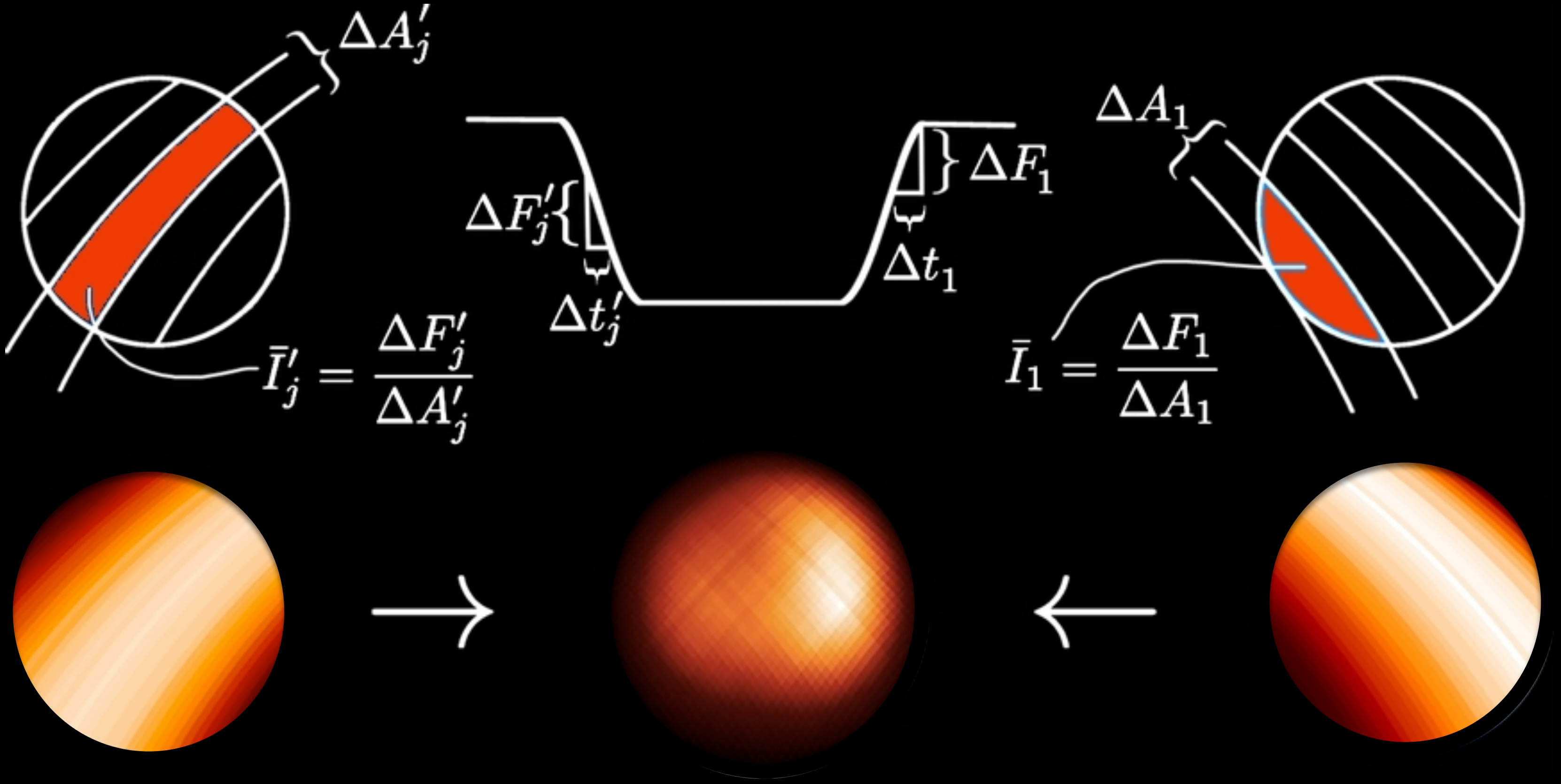


Rome Workshop 2014

Knutson et al., 2007; Crossfield et al., 2010

How to probe an exoplanet atmosphere

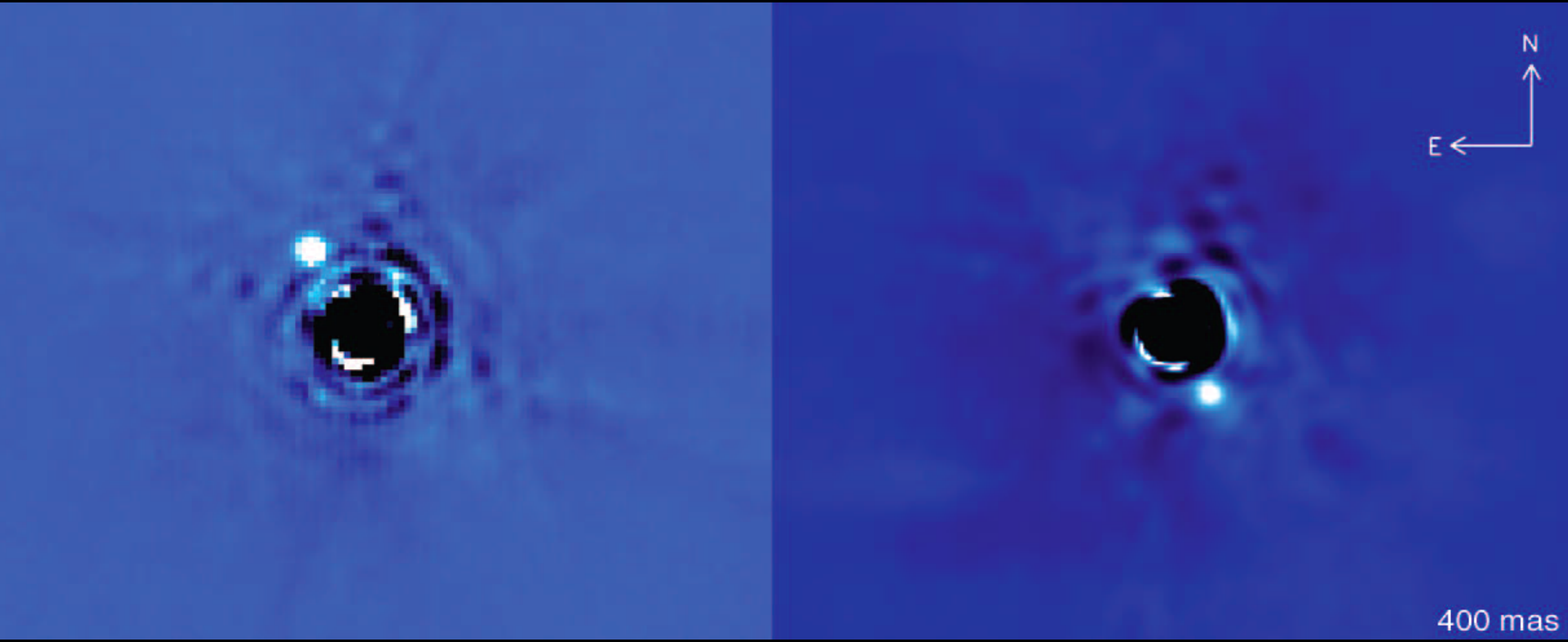
3: Phase-curves & eclipse mapping



Majeau et al., 2012

How to probe an exoplanet atmosphere

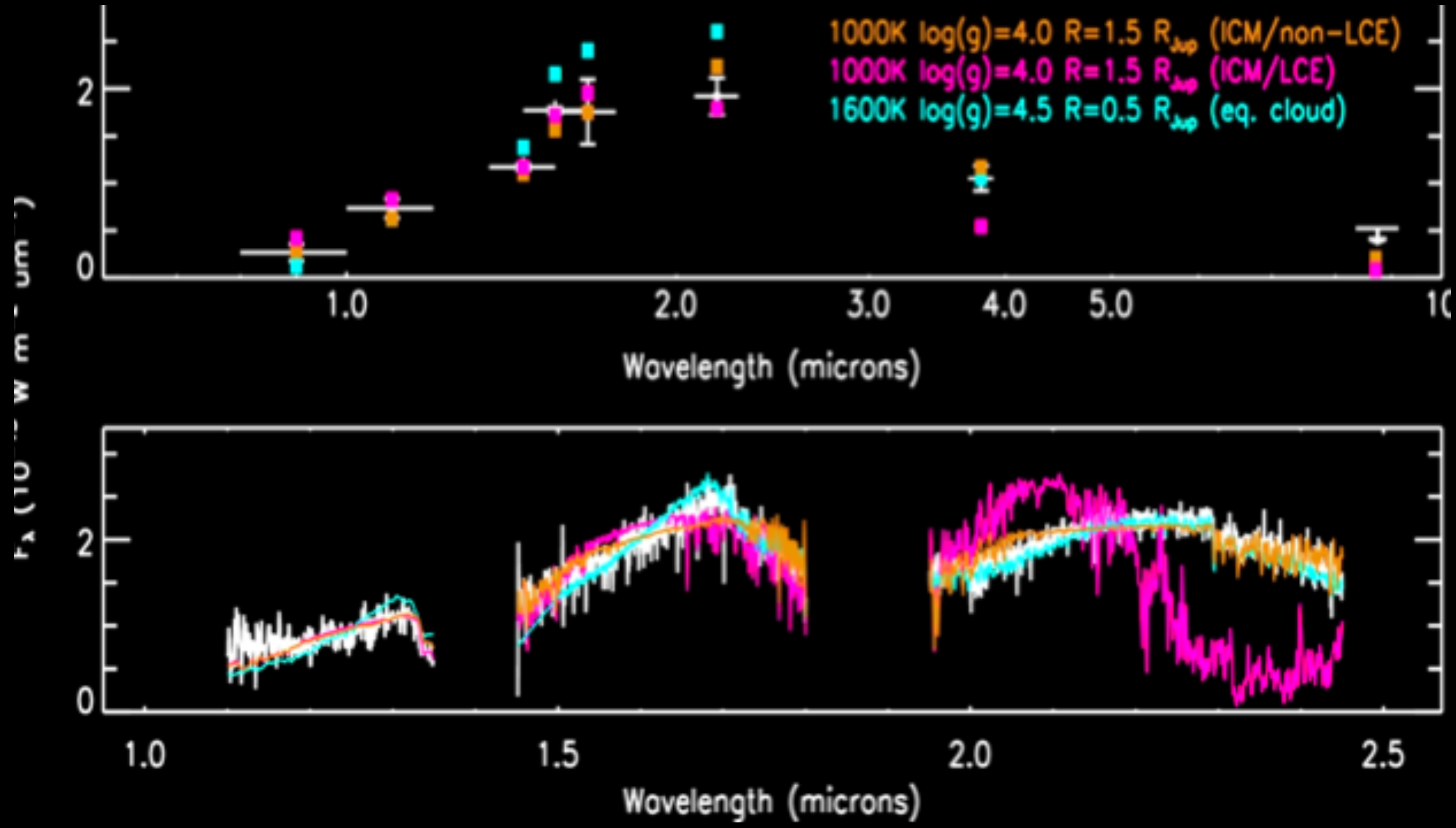
4: Direct imaging spectroscopy



Lagrange et al., 2010

How to probe an exoplanet atmosphere

4: Direct imaging spectroscopy: young-giants at large separation



Rome Workshop 2014

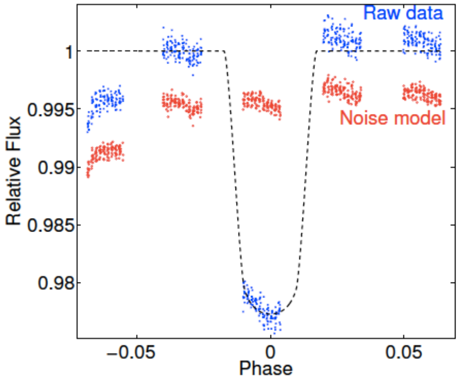
Barman et al., 2011

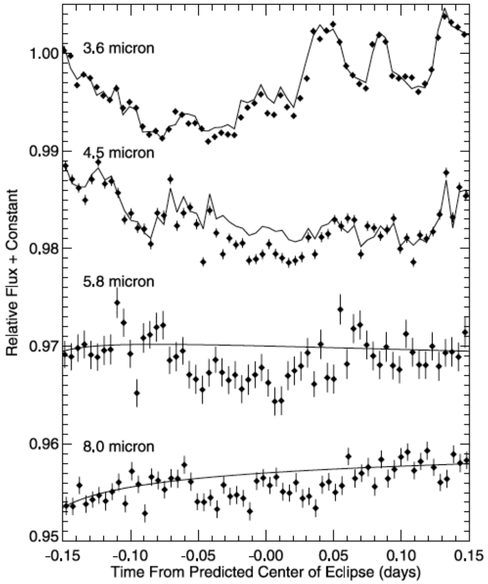
Issues with current observations

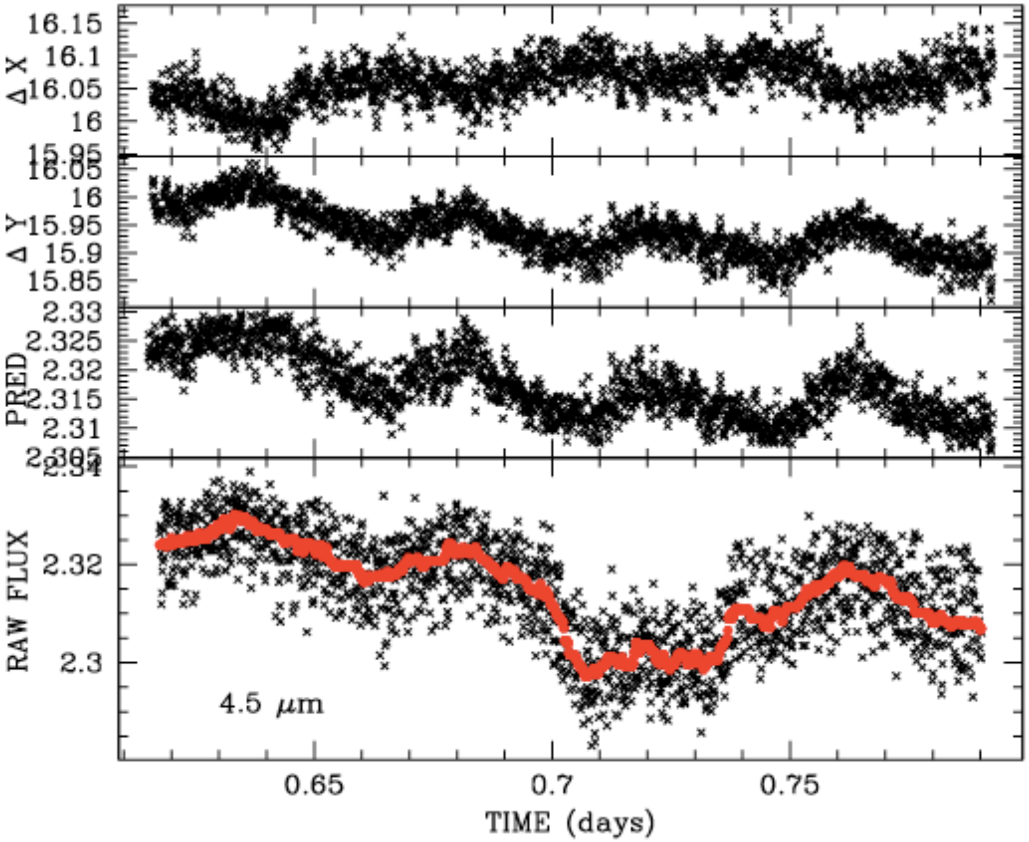
- We are dealing with low *Signal to Noise & Resolution* observations
- Data are sparse, not enough wavelength coverage
- Broad wavelength coverage is not simultaneous
- Absolute calibration at the level of 10^{-4} is **<u>not</u>** guaranteed
- Instrument systematics are difficult to disentangle from the signal
- Stellar activity is the largest source of astrophysical noise
- We need observations on a population of objects to draw conclusions

Instrument systematics

The best of worst of current instruments



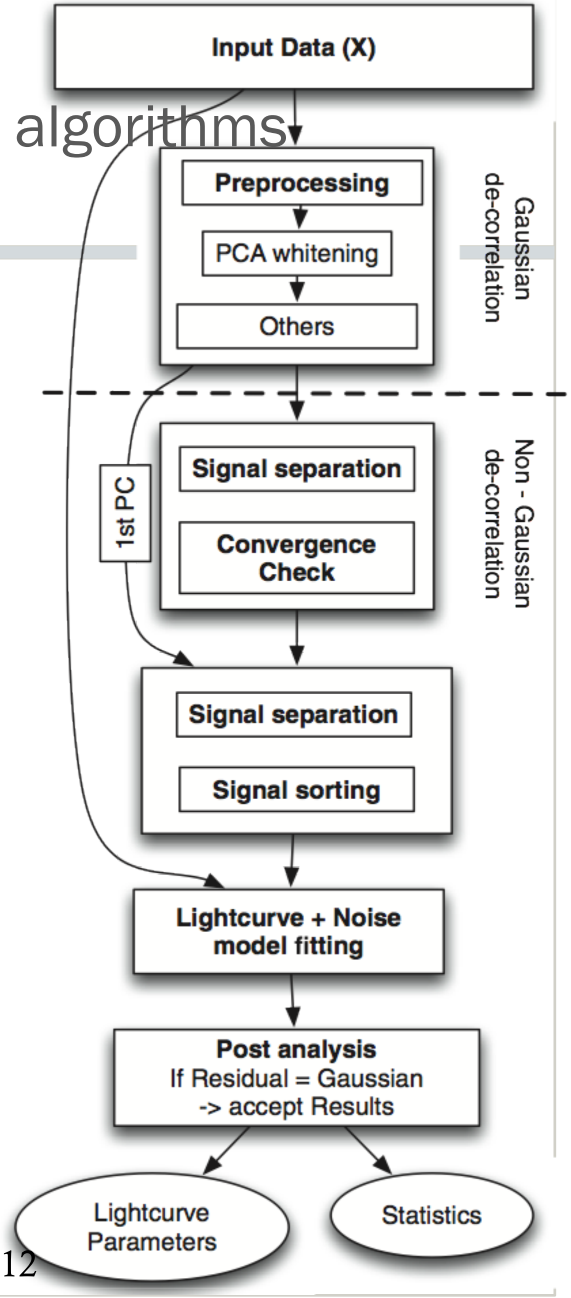




New techniques

Use of non-parametric machine learning algorithms

- De-correlating Gaussian statistics (1st and 2nd moments) -> PCA
- De-correlating non-Gaussian statistics (3rd and 4th moments) -> ICA
- Fit independent components amplitude to out-of-transit
- Build noise model
- Correct original data

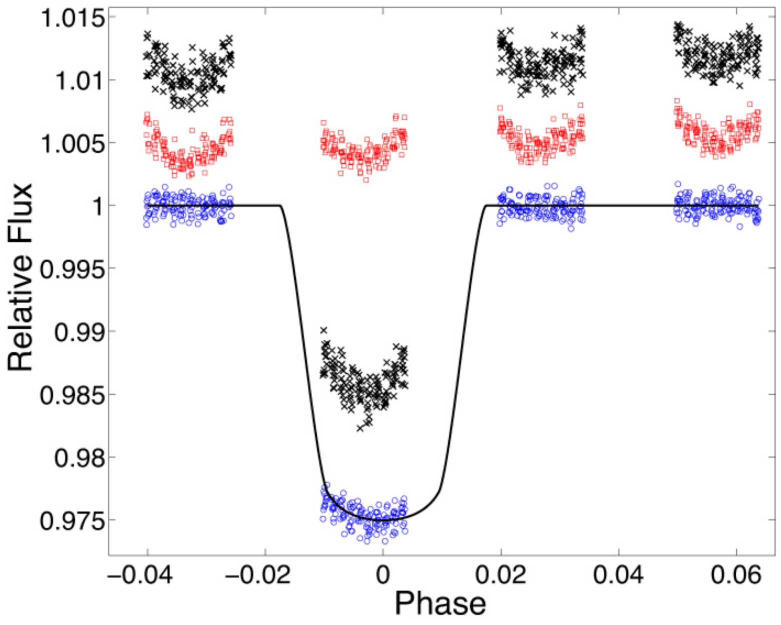


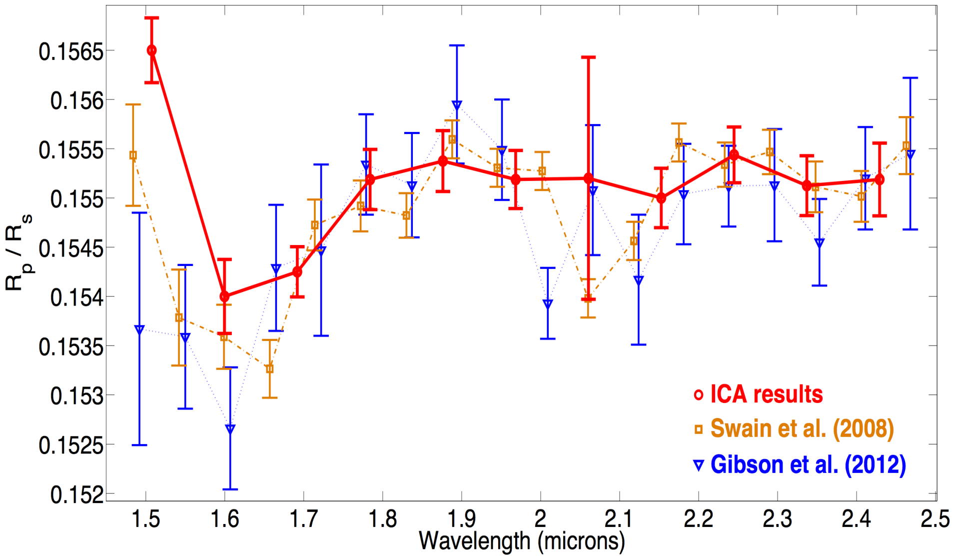
Waldmann, 2012

New techniques

Use of non-parametric machine learning algorithms

From raw data to spectra





Hubble-NICMOS raw data

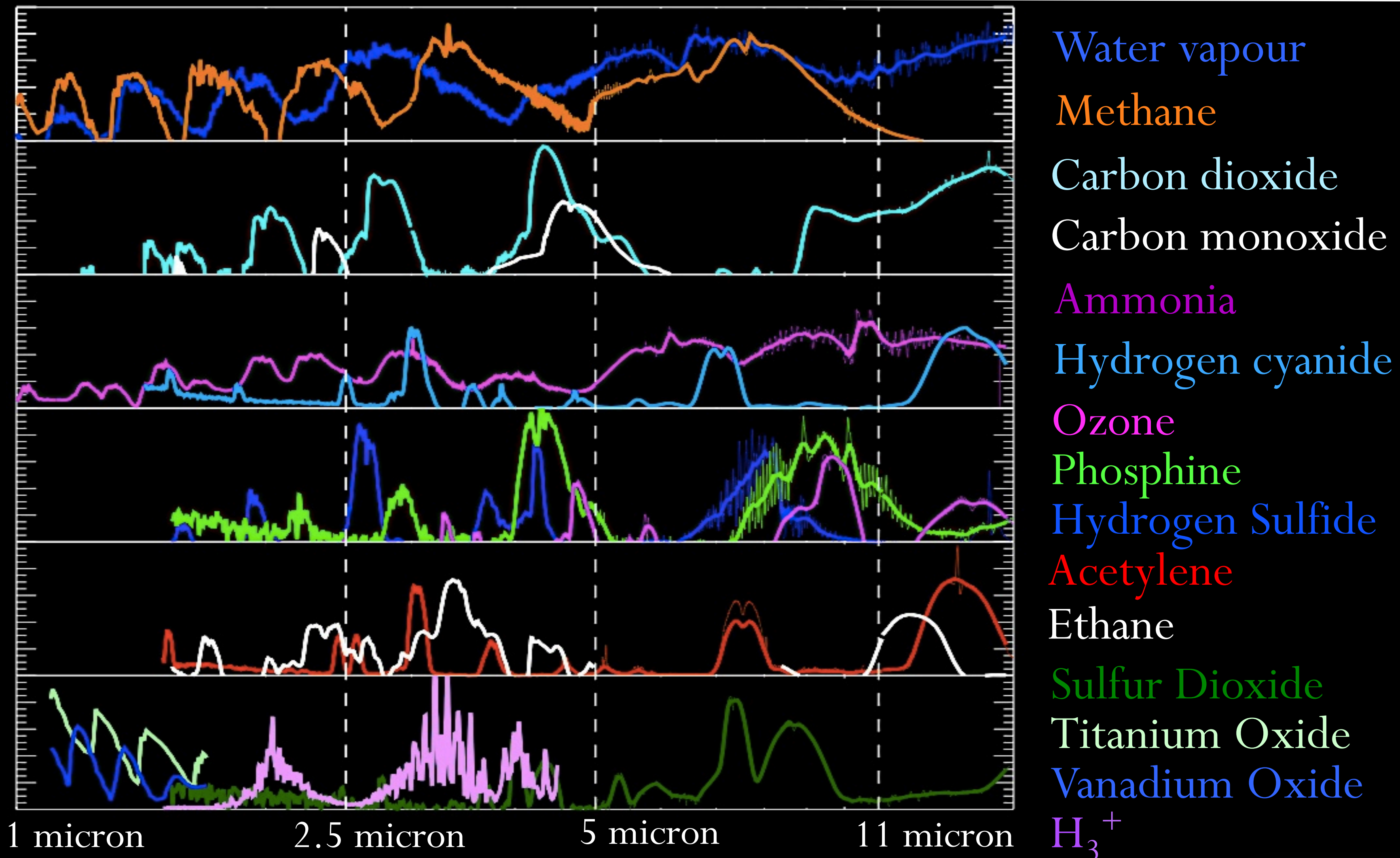
Extracted systematic noise

Detrended data

Waldmann, 2012, Wadmann et al., 2012, 2013

Broad wavelength coverage

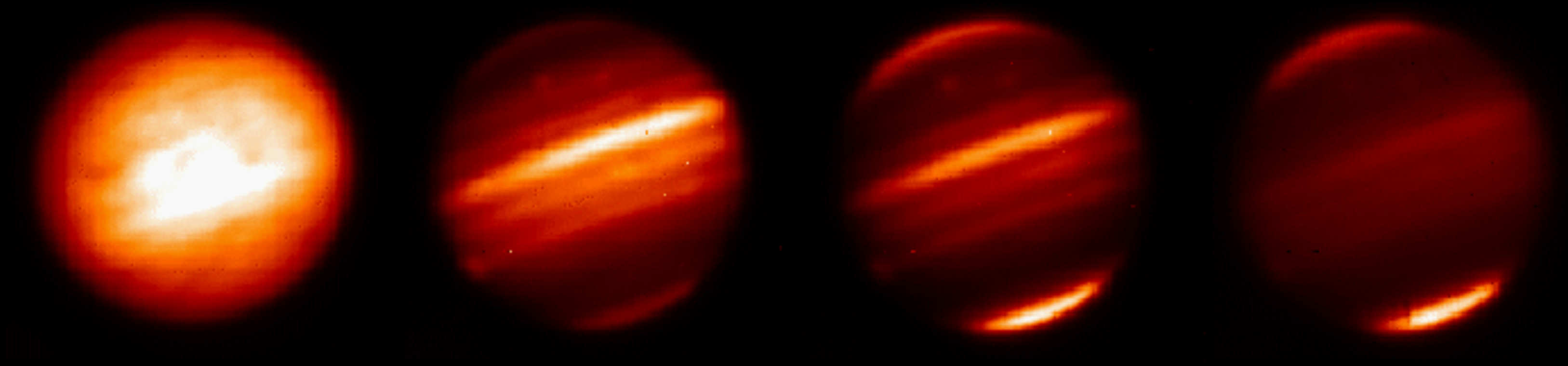
Redundancy for molecular detections



Tinetti, Encrenaz, Coustenis, 2013

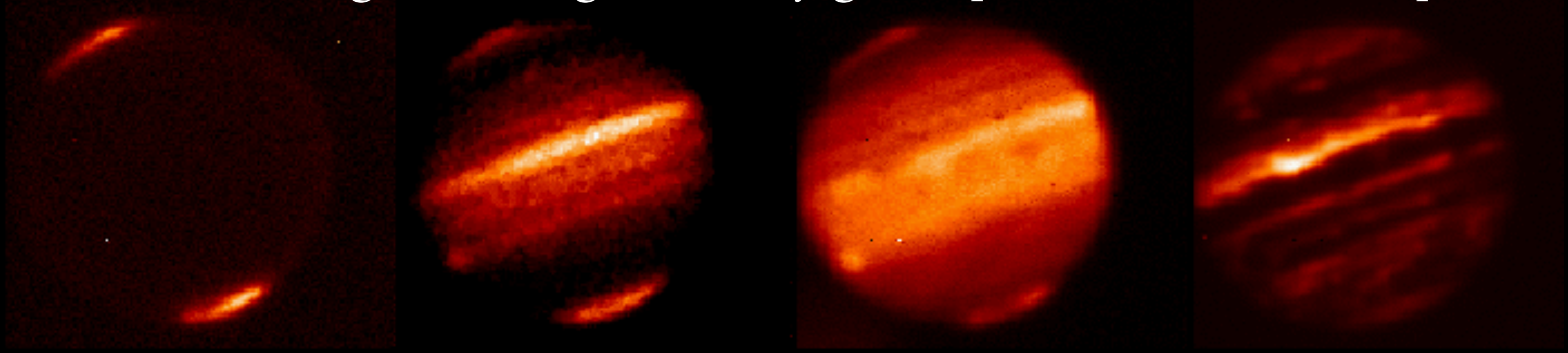
Broad wavelength coverage

Ensures understanding of the atmospheric complexity



1.60 µm 2.04 µm 2.10 µm 2.27 µm

Narrow wavelength coverage can only give a partial view – see Jupiter



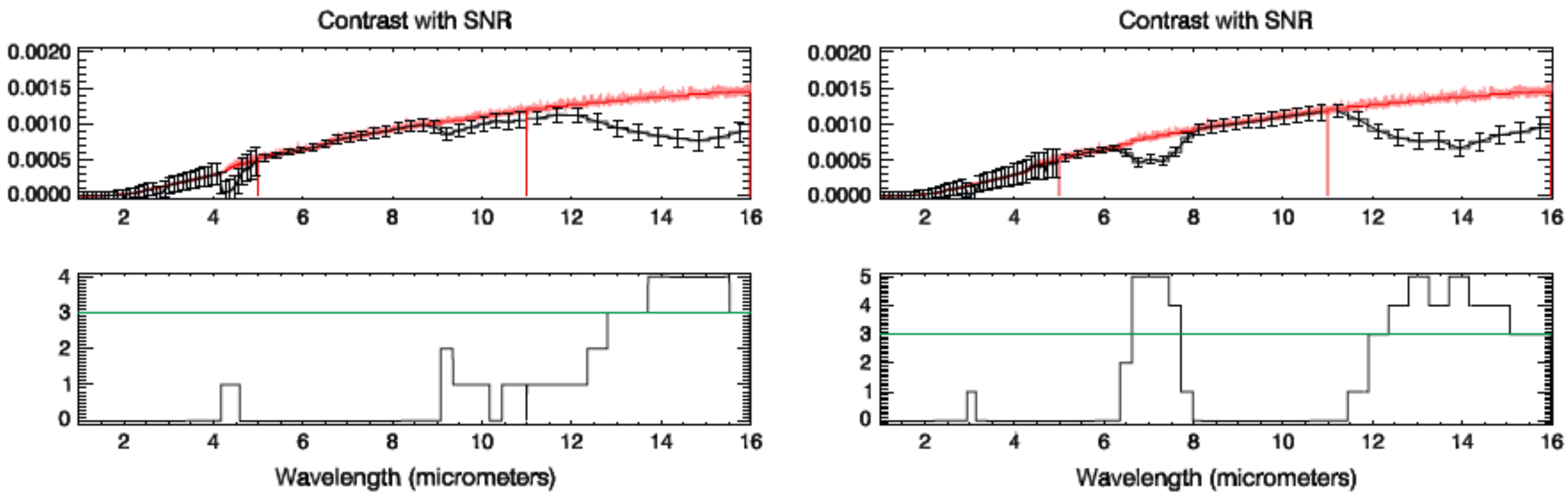
3.41 µm 3.80 µm 4.00 µm 5.05 µm

Courtesy of Kevin H. Baines, NASA IRTF

Optimal R and SNR

R ~ 300 λ < 5 μm & R ~ 30 λ > 5 μm

Warm Neptunes (CO2 & HCN, SNR=10)



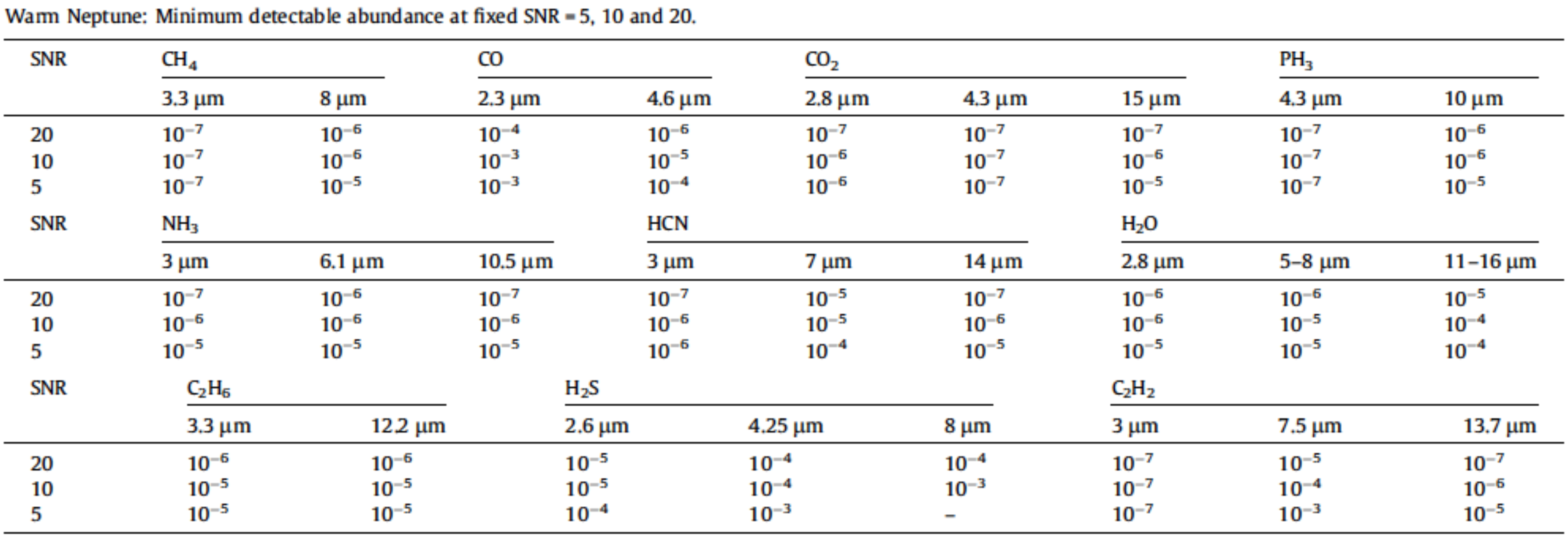
Rome Workshop 2014

Tessenyi et al., 2013

Optimal R and SNR

R ~ 300 λ < 5 μm & R ~ 30 λ > 5 μm

Warm Neptunes



Warm Neptune: Minimum detectable abundance at fixed SNR = 5, 10 and 20.

SNR	CH_4		CO		CO_2			PH_3	
	3.3 μm	8 μm	2.3 μm	4.6 μm	2.8 μm	4.3 μm	15 μm	4.3 μm	10 μm
20	10^{-7}	10^{-6}	10^{-4}	10^{-6}	10^{-7}	10^{-7}	10^{-7}	10^{-7}	10^{-6}
10	10^{-7}	10^{-6}	10^{-3}	10^{-5}	10^{-6}	10^{-7}	10^{-6}	10^{-7}	10^{-6}
5	10^{-7}	10^{-5}	10^{-3}	10^{-4}	10^{-6}	10^{-7}	10^{-5}	10^{-7}	10^{-5}
SNR	**NH_3**			**HCN**			**H_2O**		
	3 μm	6.1 μm	10.5 μm	3 μm	7 μm	14 μm	2.8 μm	5–8 μm	11–16 μm
20	10^{-7}	10^{-6}	10^{-7}	10^{-7}	10^{-5}	10^{-7}	10^{-6}	10^{-6}	10^{-5}
10	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-5}	10^{-6}	10^{-6}	10^{-5}	10^{-4}
5	10^{-5}	10^{-5}	10^{-5}	10^{-6}	10^{-4}	10^{-5}	10^{-5}	10^{-5}	10^{-4}

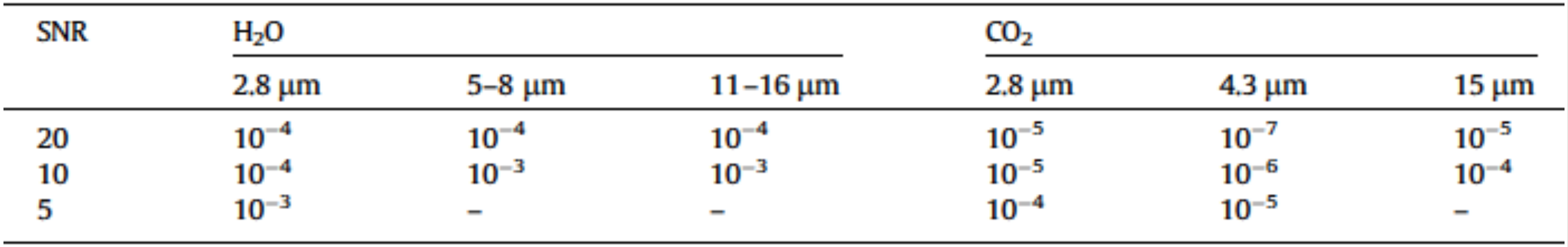
SNR	C_2H_6		H_2S			C_2H_2		
	3.3 μm	12.2 μm	2.6 μm	4.25 μm	8 μm	3 μm	7.5 μm	13.7 μm
20	10^{-6}	10^{-6}	10^{-5}	10^{-4}	10^{-4}	10^{-7}	10^{-5}	10^{-7}
10	10^{-5}	10^{-5}	10^{-5}	10^{-4}	10^{-3}	10^{-7}	10^{-4}	10^{-6}
5	10^{-5}	10^{-5}	10^{-4}	10^{-3}	–	10^{-7}	10^{-3}	10^{-5}

Tessenyi et al., 2013

Optimal R and SNR

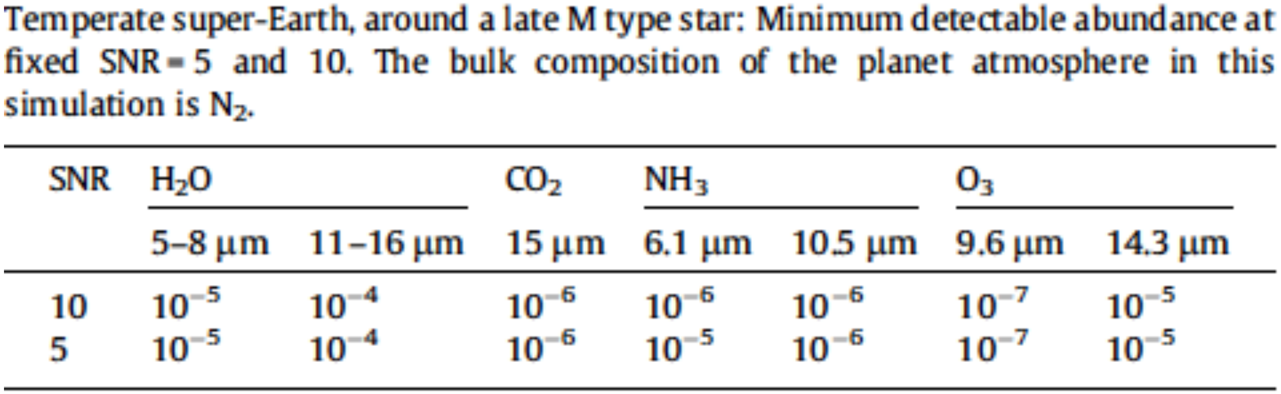
$R \sim 300\ \lambda < 5\ \mu m$ & $R \sim 30\ \lambda > 5\ \mu m$

Hot super-Earths



SNR	H_2O			CO_2		
	2.8 μm	5–8 μm	11–16 μm	2.8 μm	4.3 μm	15 μm
20	10^{-4}	10^{-4}	10^{-4}	10^{-5}	10^{-7}	10^{-5}
10	10^{-4}	10^{-3}	10^{-3}	10^{-5}	10^{-6}	10^{-4}
5	10^{-3}	–	–	10^{-4}	10^{-5}	–

Temperate super-Earths around M-stars



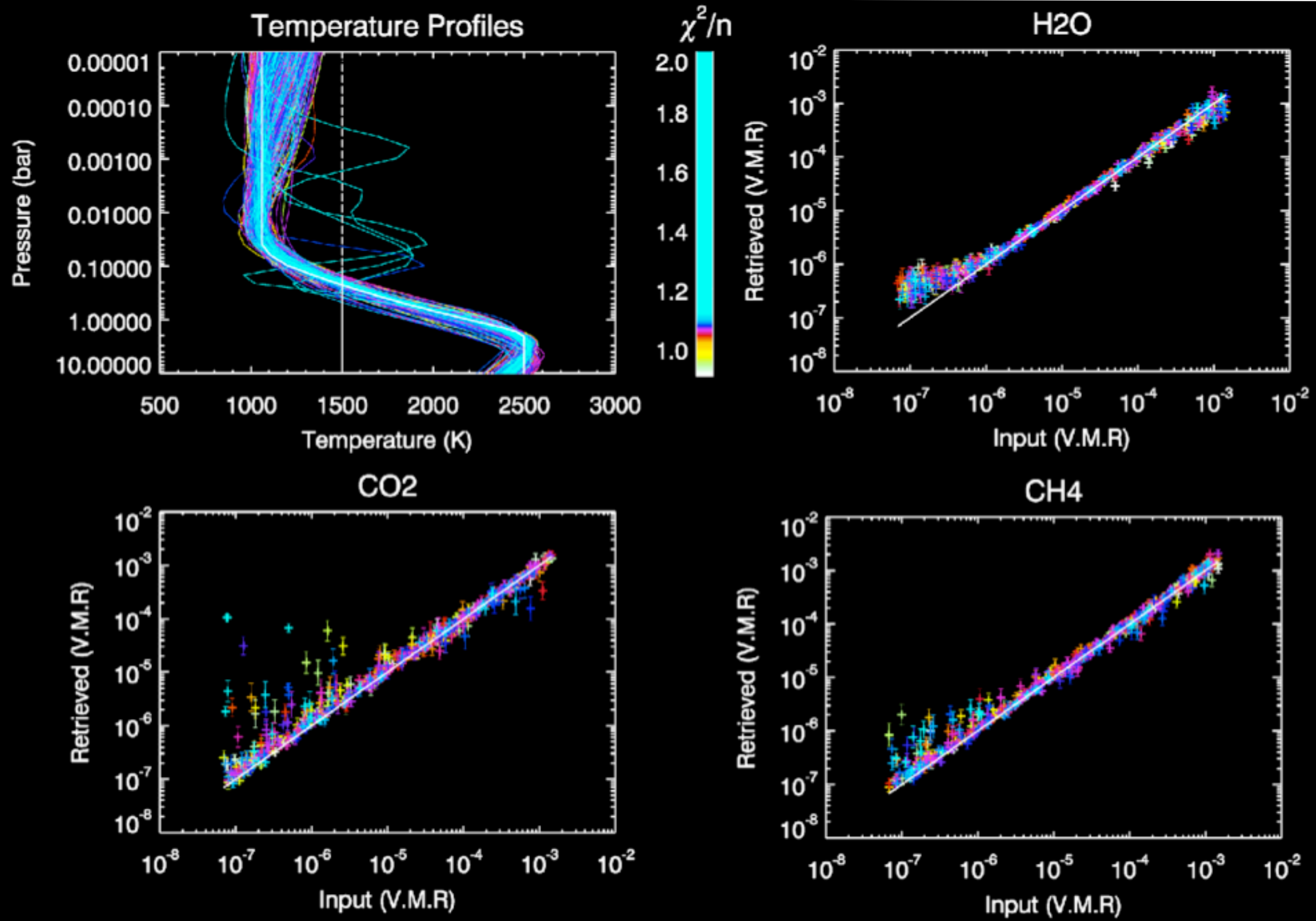
Temperate super-Earth, around a late M type star: Minimum detectable abundance at fixed SNR = 5 and 10. The bulk composition of the planet atmosphere in this simulation is N_2.

SNR	H_2O		CO_2	NH_3		O_3	
	5–8 μm	11–16 μm	15 μm	6.1 μm	10.5 μm	9.6 μm	14.3 μm
10	10^{-5}	10^{-4}	10^{-6}	10^{-6}	10^{-6}	10^{-7}	10^{-5}
5	10^{-5}	10^{-4}	10^{-6}	10^{-5}	10^{-6}	10^{-7}	10^{-5}

Tessenyi et al., 2013

Broad wavelength coverage

Spectral retrieval thermal structure & molecular abundances

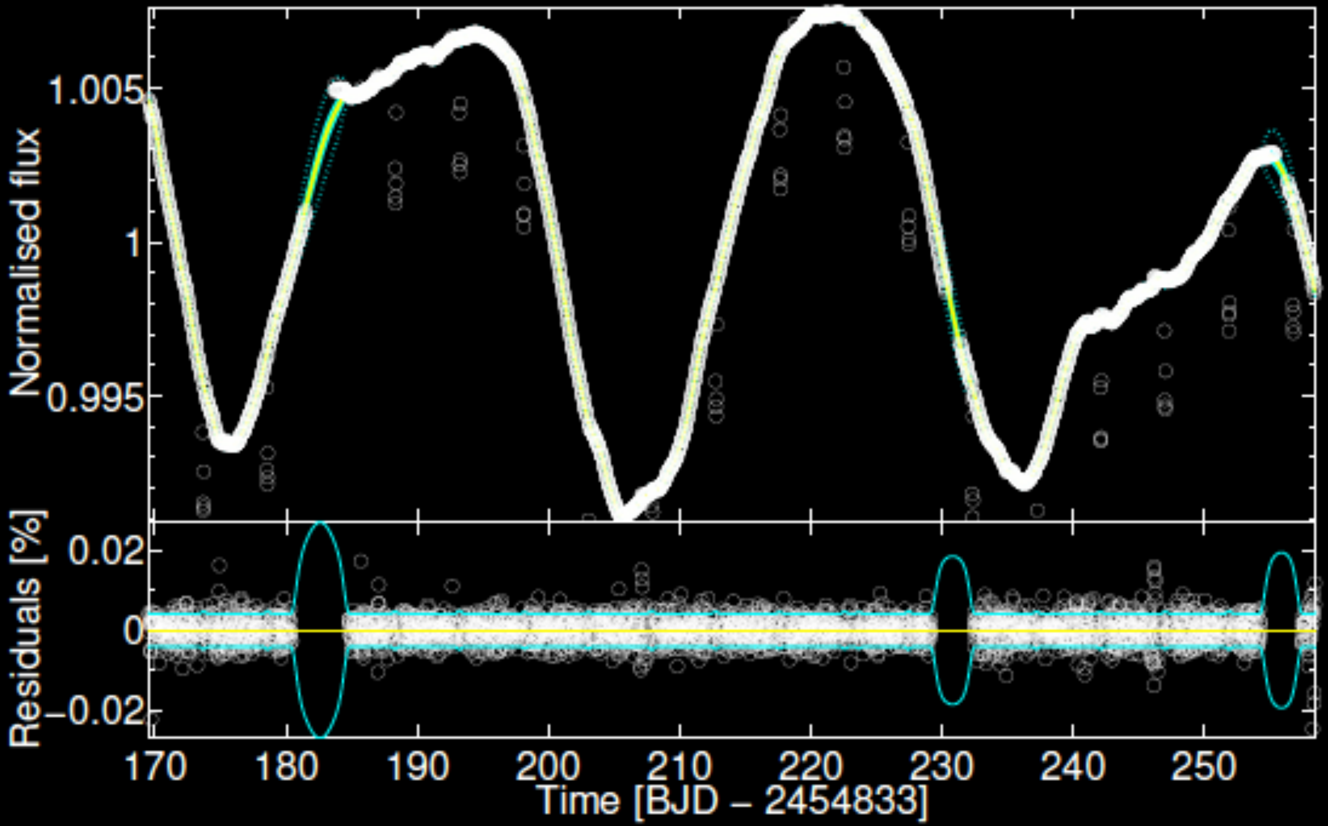


Barstow et al., 2012

Removing stellar activity

Gaussian processes & Independent Component Analysis

Kepler data: 90 days

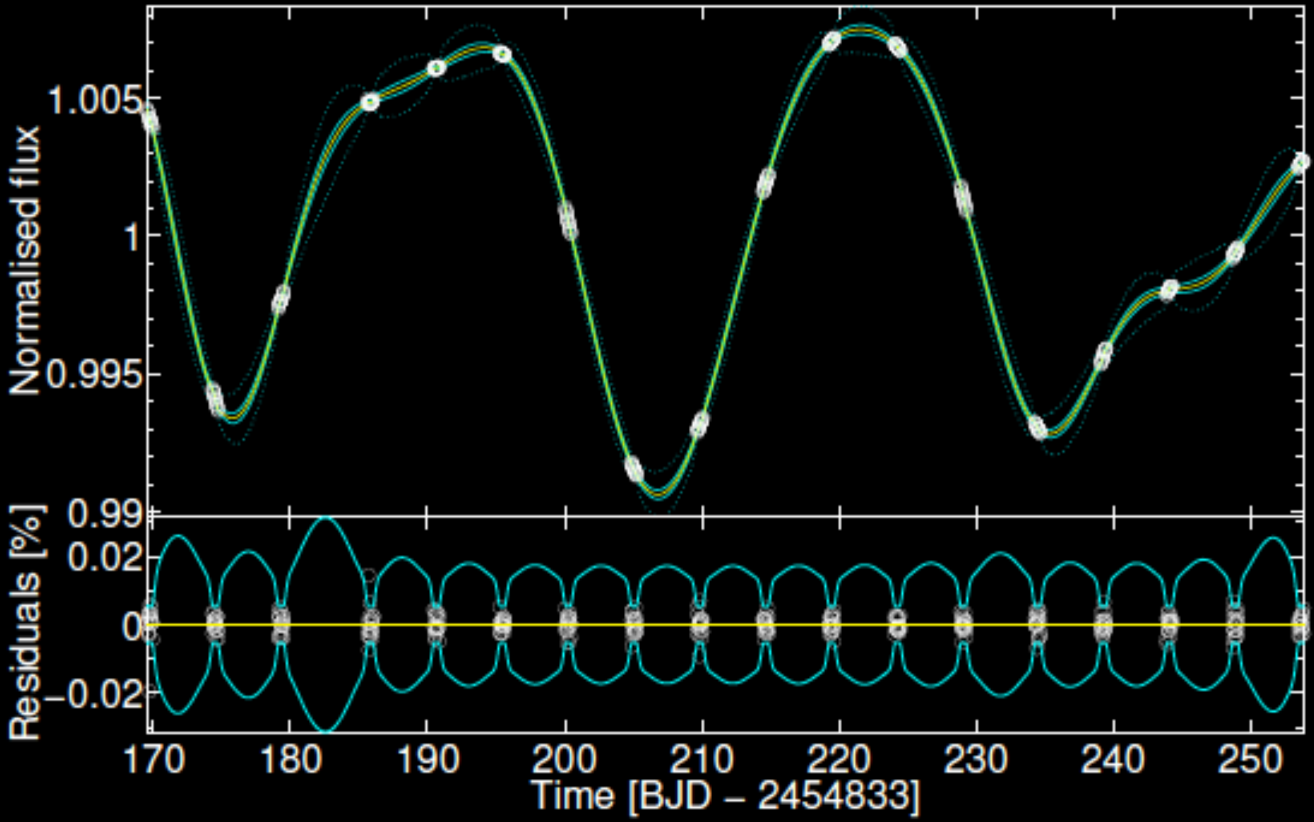


Danielski et al., 2014

Removing stellar activity

Gaussian processes & Independent Component Analysis

Kepler data: 10 hours every 5 days



Danielski et al., 2014

The future

More and better observations

HUBBLE

CoRoT

VLT

TESS

Cheops

SPICA

PLATO

Early years

The present

The golden future

2005

2020

Spitzer

Kepler

K2

GAIA

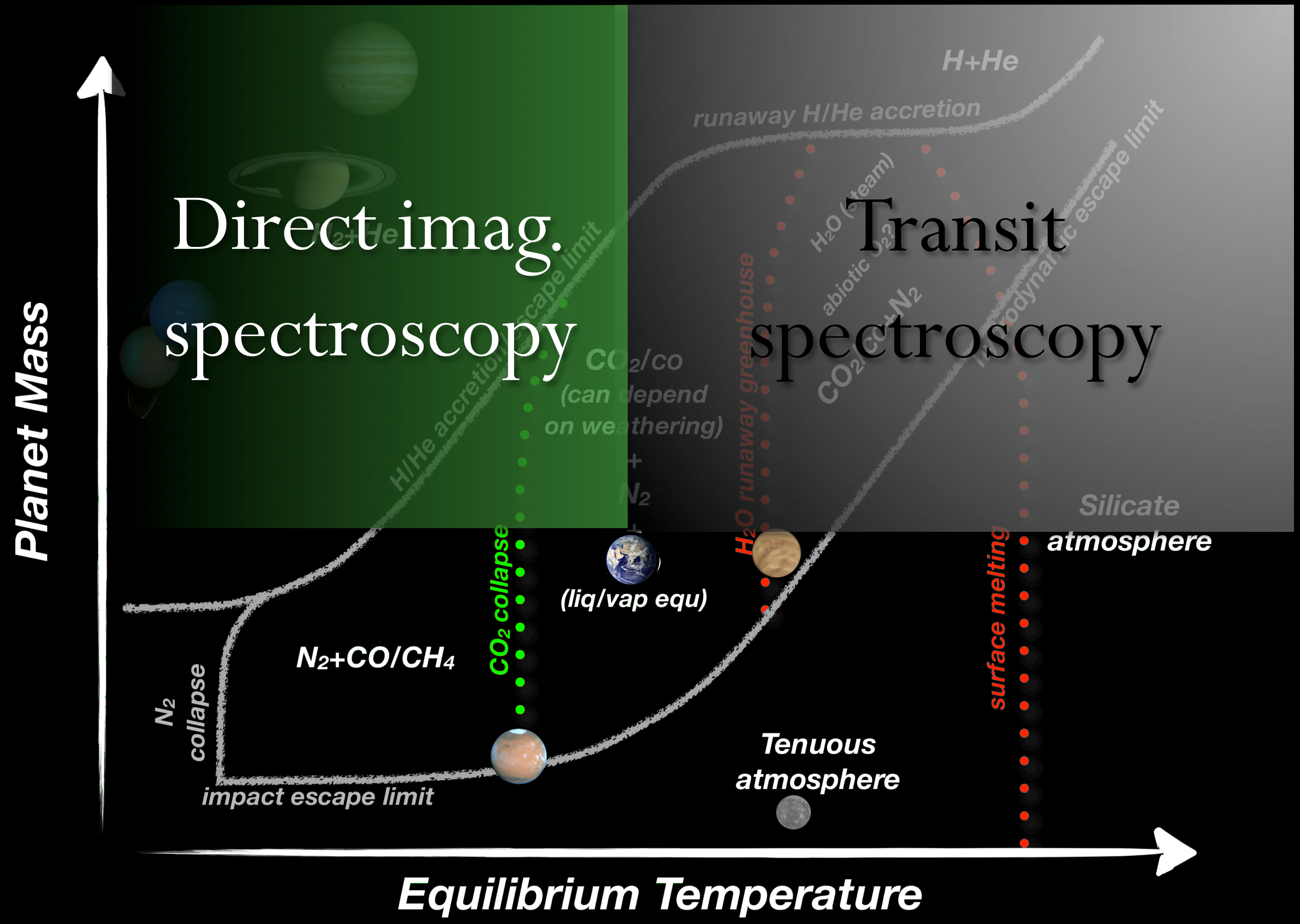
JWST

EChO

E-ELT

The future

Parameter space probed by different techniques



Forget & Leconte, 2013

Issues with current observations

- We are dealing with low SNR & R observations ✔ JWST, ELT
- Data are sparse, not enough wavelength coverage ✗
- Broad wavelength coverage is not simultaneous ✗
- Absolute calibration at the level of 10^{-4} is **not** guaranteed ✗
- Instrument systematics are difficult to disentangle from the signal ✗
- Stellar activity is the largest source of astrophysical noise ✗
- We need observations on a population of objects to draw conclusions ✗

EChO

Exoplanet Characterisation Observatory

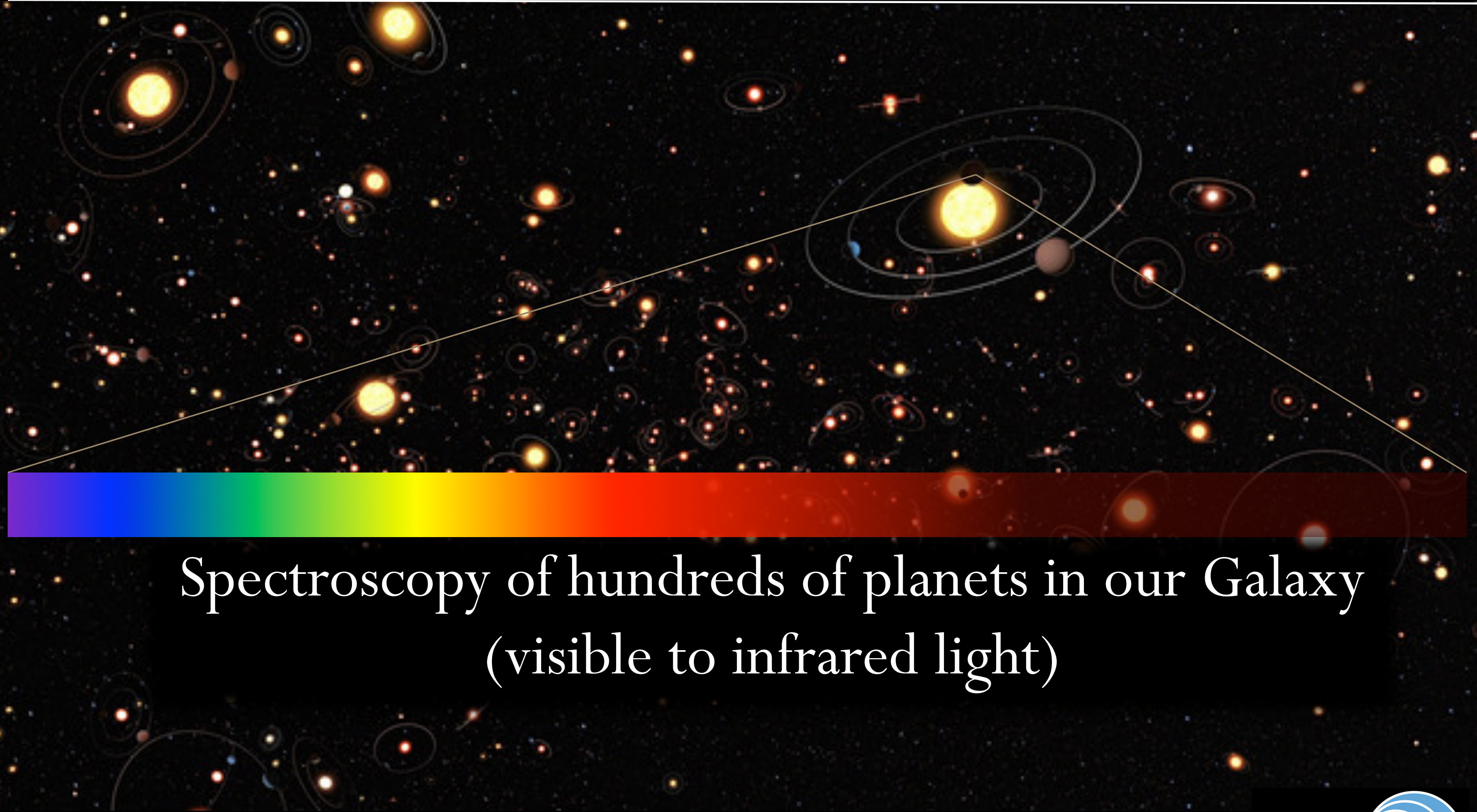
European Space Agency
M3 mission candidate

1m class telescope in space (L2)

Stability:
1 part in 10000 over 10 hours

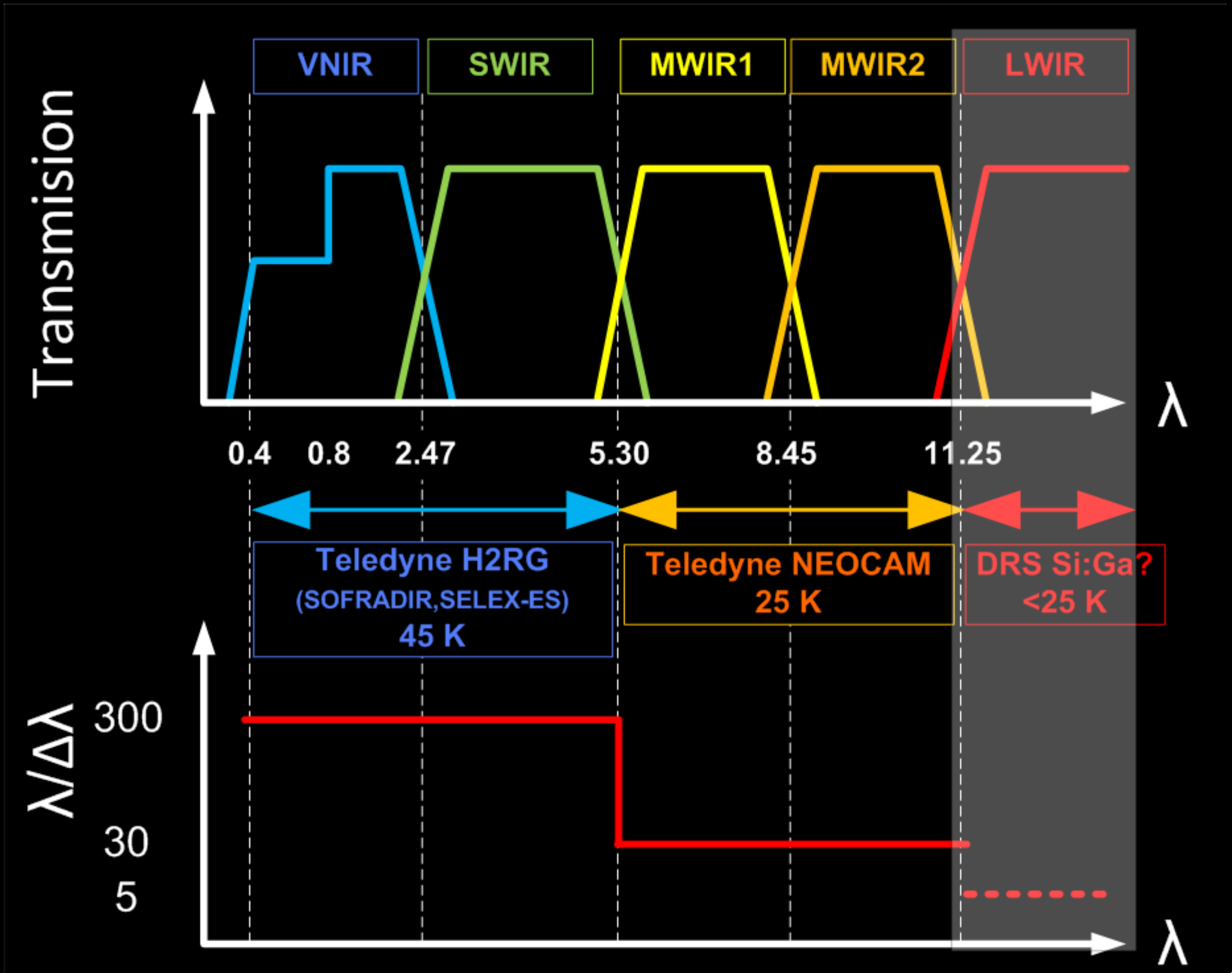
Remote exploration of exotic worlds

Beyond our Solar System



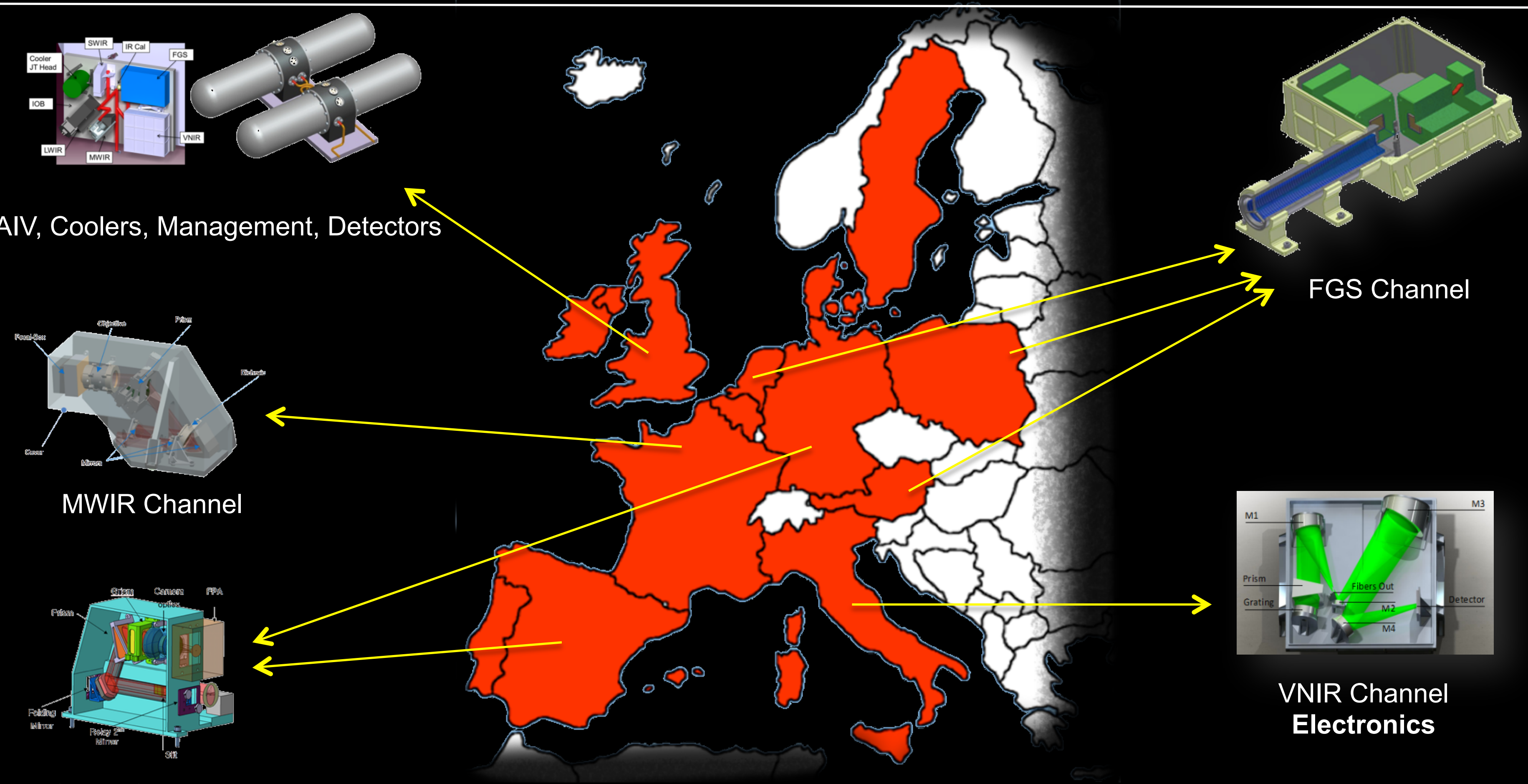
Spectroscopy of hundreds of planets in our Galaxy
(visible to infrared light)

Instrument Concept



Instrument Consortium

Large European consortium



AIV, Coolers, Management, Detectors

FGS Channel

MWIR Channel

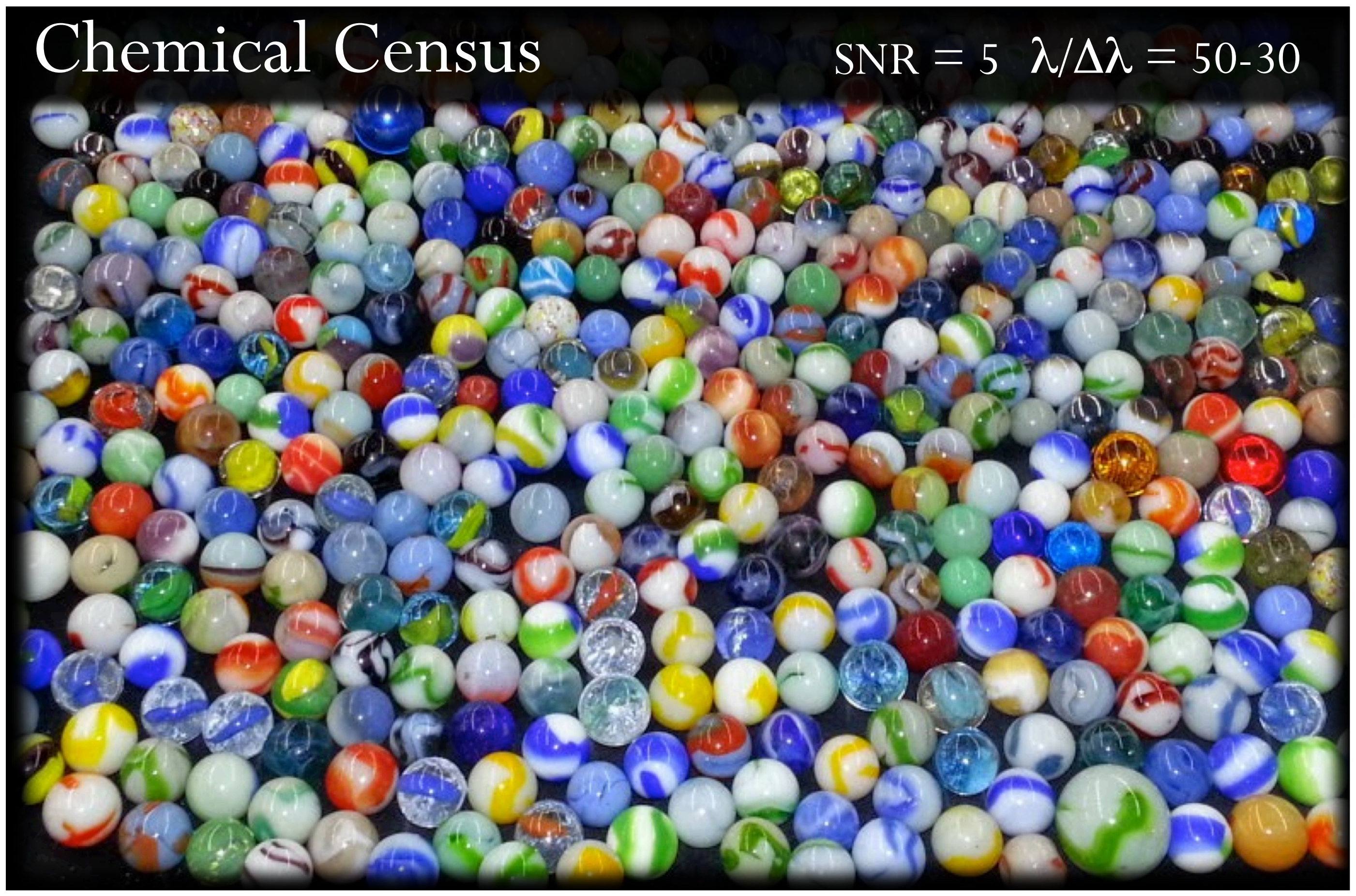
VNIR Channel
Electronics

SWIR Channel

NL, B, P, S, DK, IR providing components and AIV support
Instrument data centre contributions from all partners

EChO's 3 Surveys:

Study exoplanets as a population & individually



Chemical Census

SNR = 5 λ/Δλ = 50-30

EChO's 3 Surveys:

Study exoplanets as a population & individually

Chemical Census SNR = 5 λ/Δλ = 50-30

Origin SNR = 10 λ/Δλ = 100-30

EChO's 3 Surveys:

Study exoplanets as a population & individually

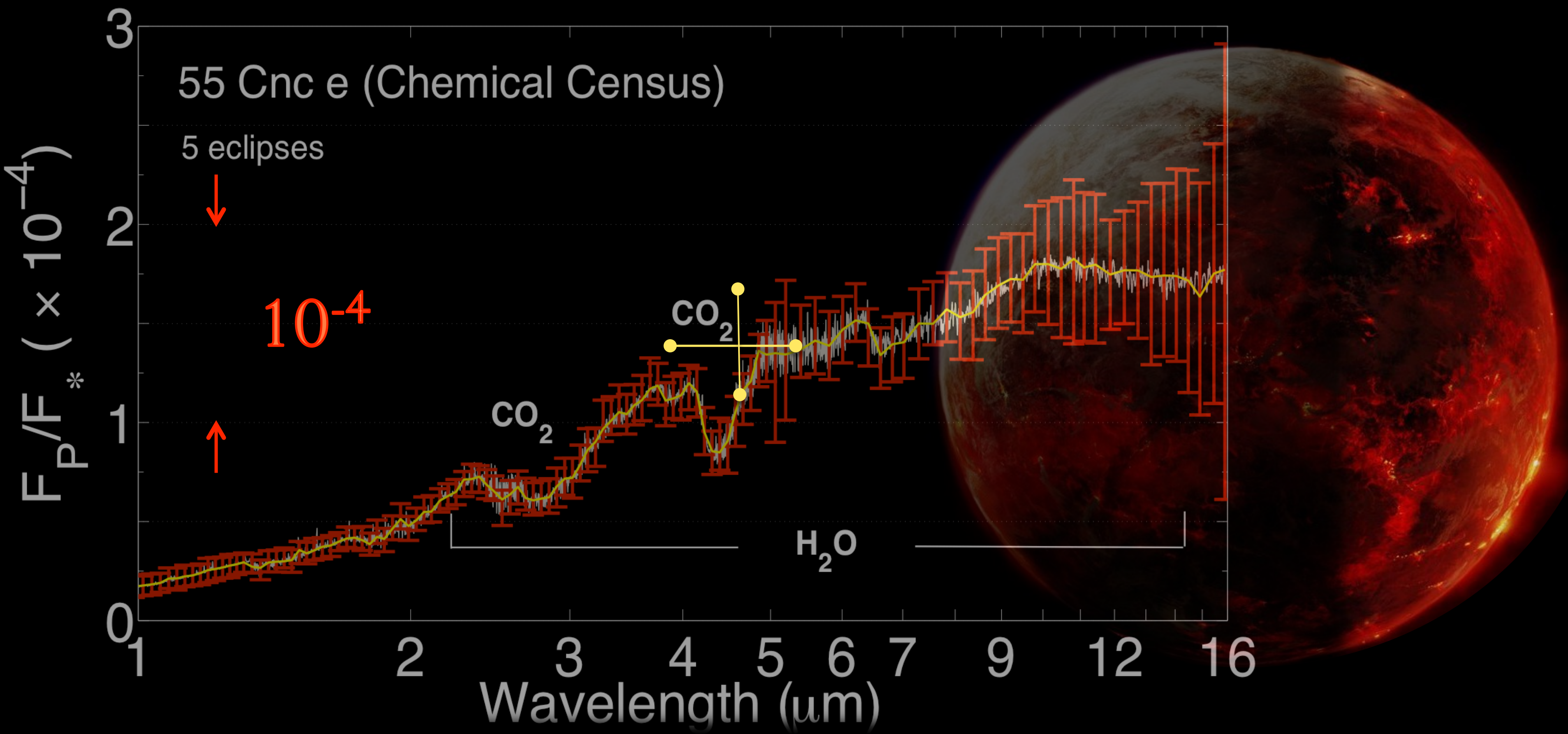
Chemical Census SNR = 5 $\lambda/\Delta\lambda$ = 50-30

Origin SNR = 10 $\lambda/\Delta\lambda$ = 100-30

Rosetta Stones SNR = 20 $\lambda/\Delta\lambda$ = 300-30

“Lava planet” 55-Cnc e

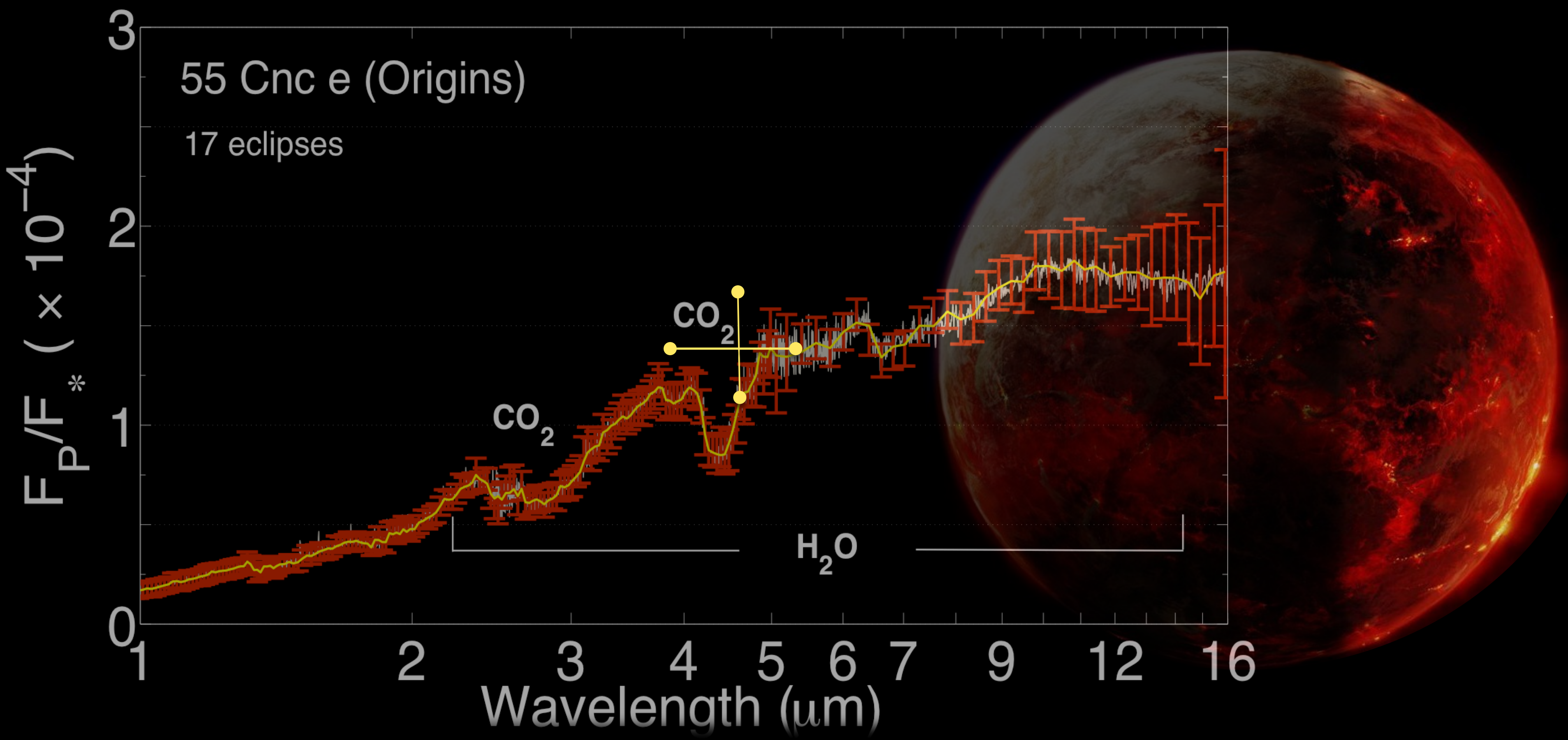
~ 5 Earth masses, T = 2500 K



Varley et al., 2014; Tessenyi et al., 2013

“Lava planet” 55-Cnc e

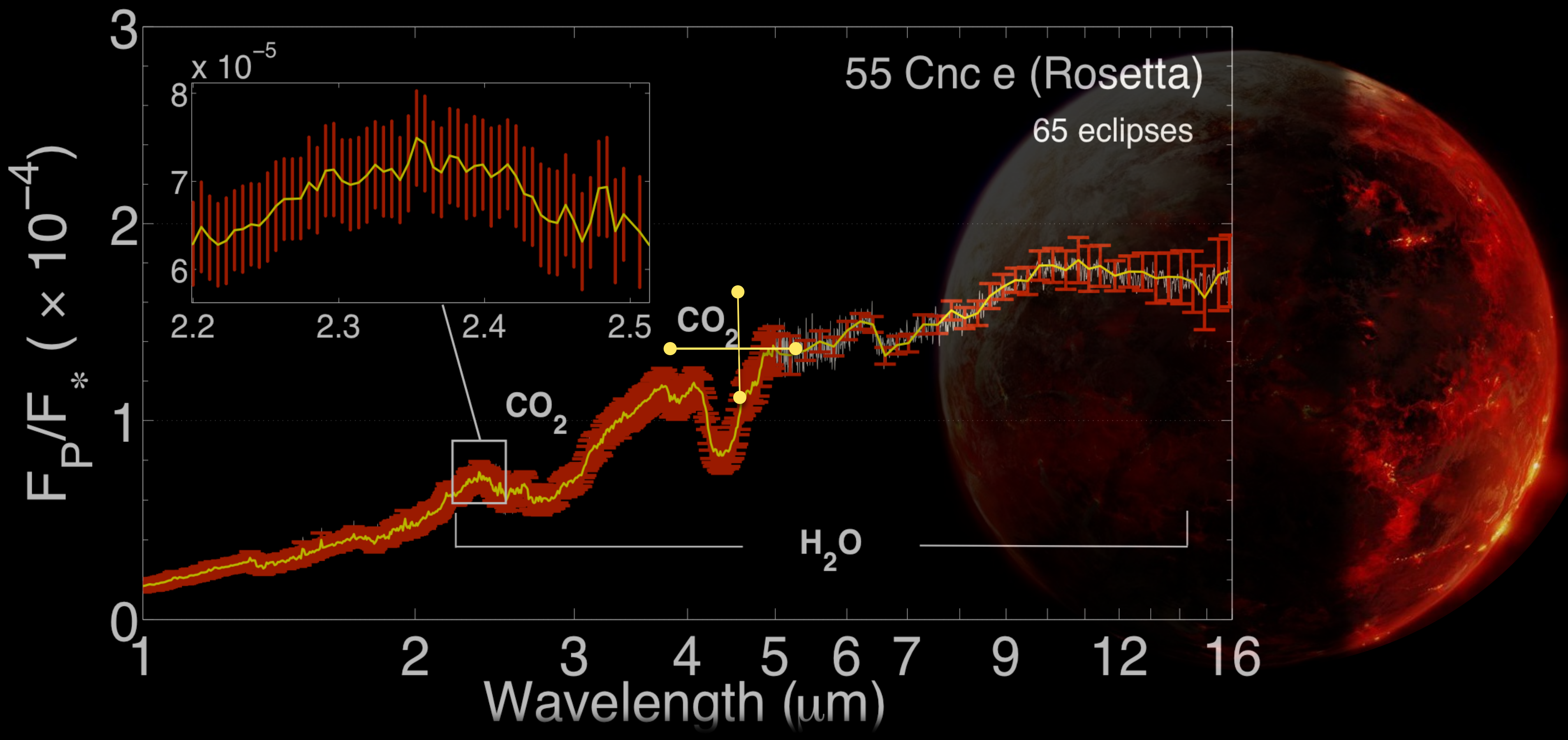
~ 5 Earth masses, T = 2500 K



Varley et al., 2014; Tessenyi et al., 2013

“Lava planet” 55-Cnc e

~ 5 Earth masses, T = 2500 K

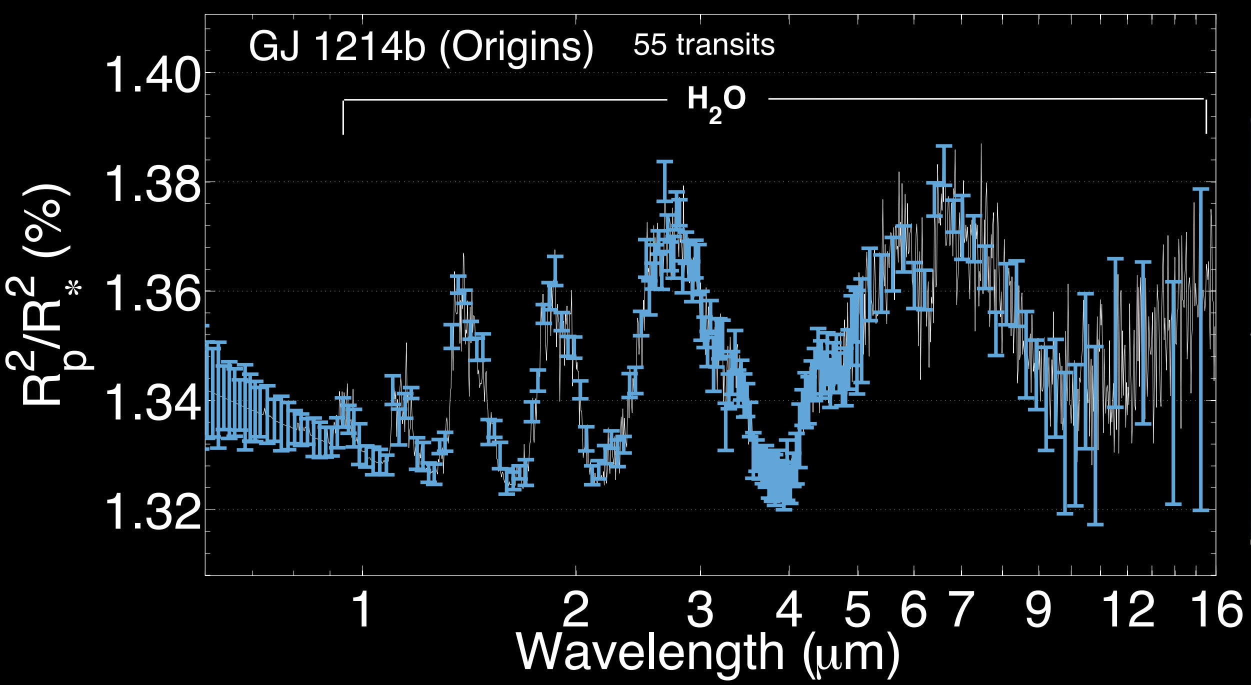


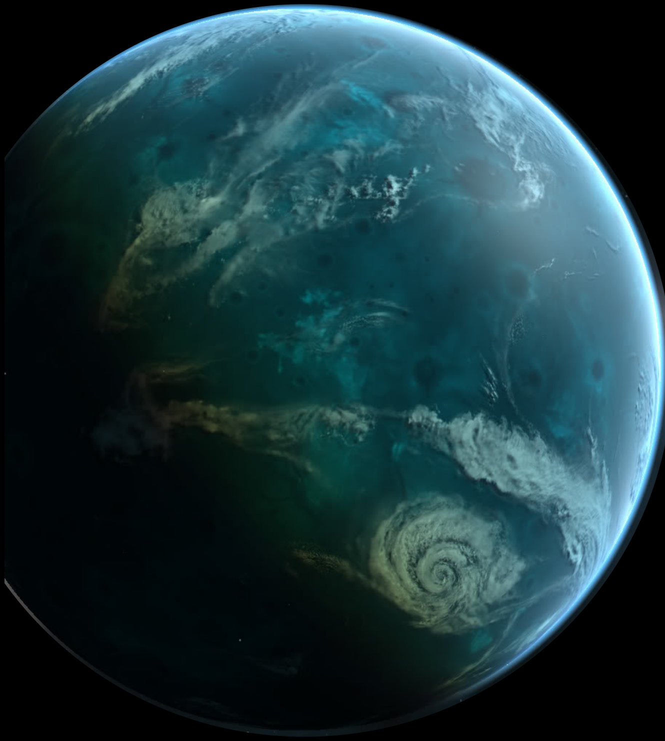
Varley et al., 2014; Tessenyi et al., 2013

EChO Performance

Unveiling the composition of Gj1214b

Clouds? Water vapour? ~50 EChO spectra and we will know it

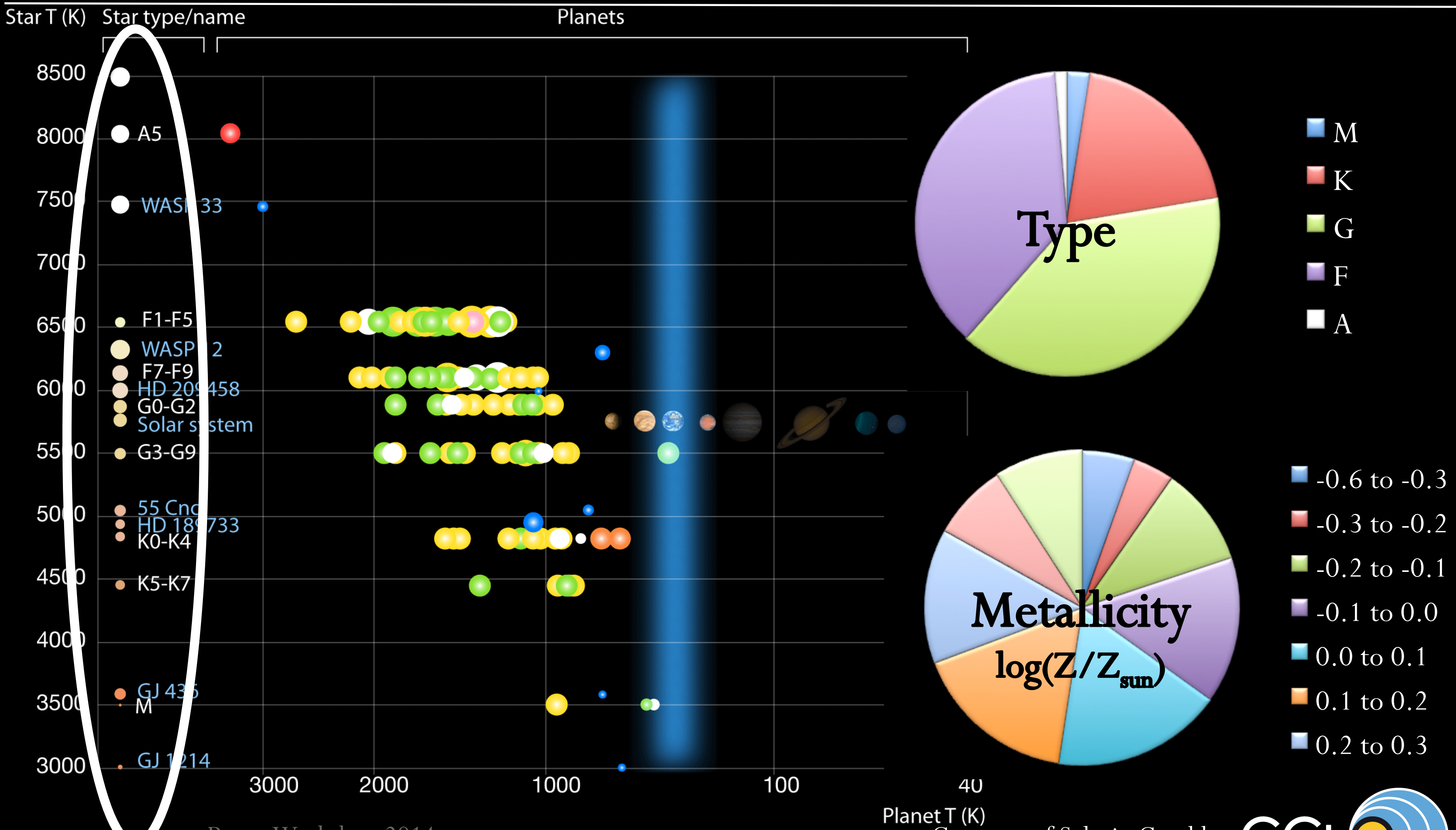




Varley et al, 2014

Known Planets observable by EChO

More than 160 today

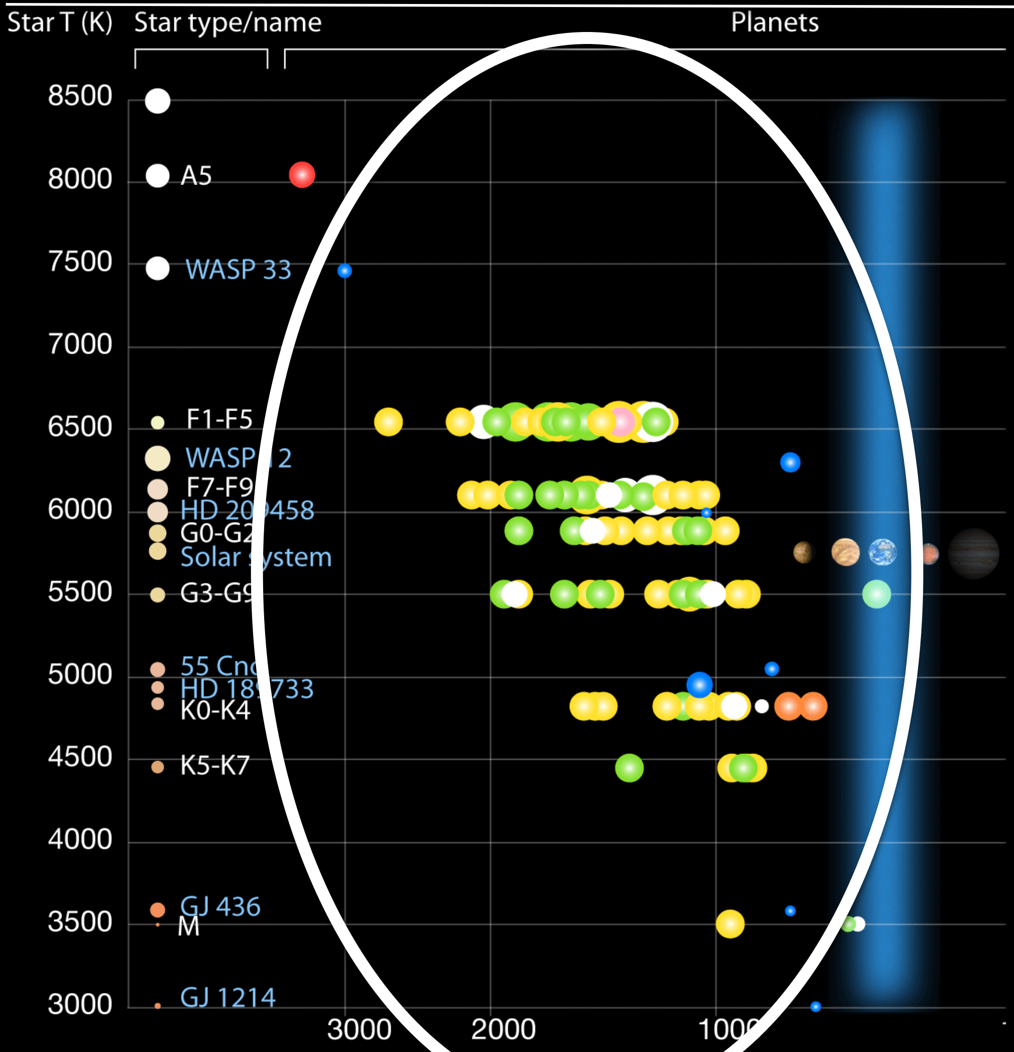


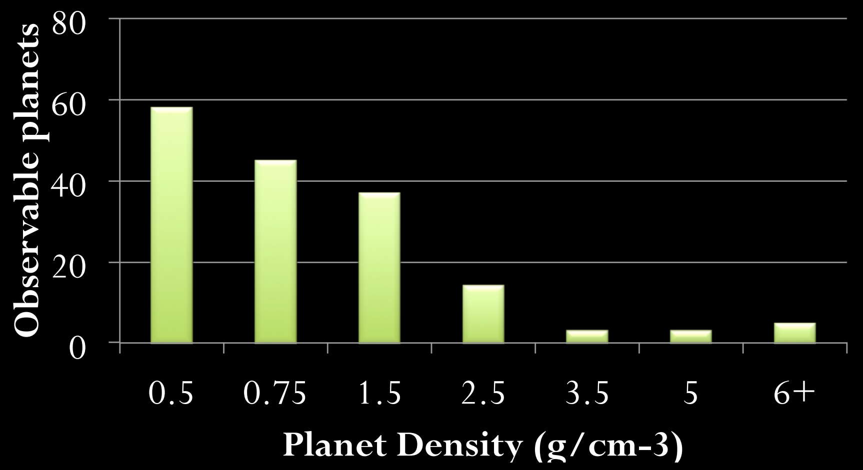
Rome Workshop 2014

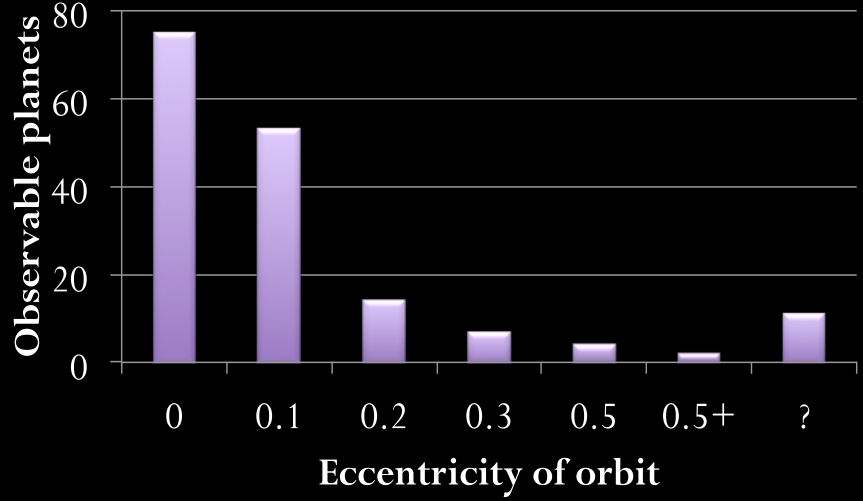
Courtesy of Sylvain Cnudde

Known Planets observable by EChO

More than 160 today

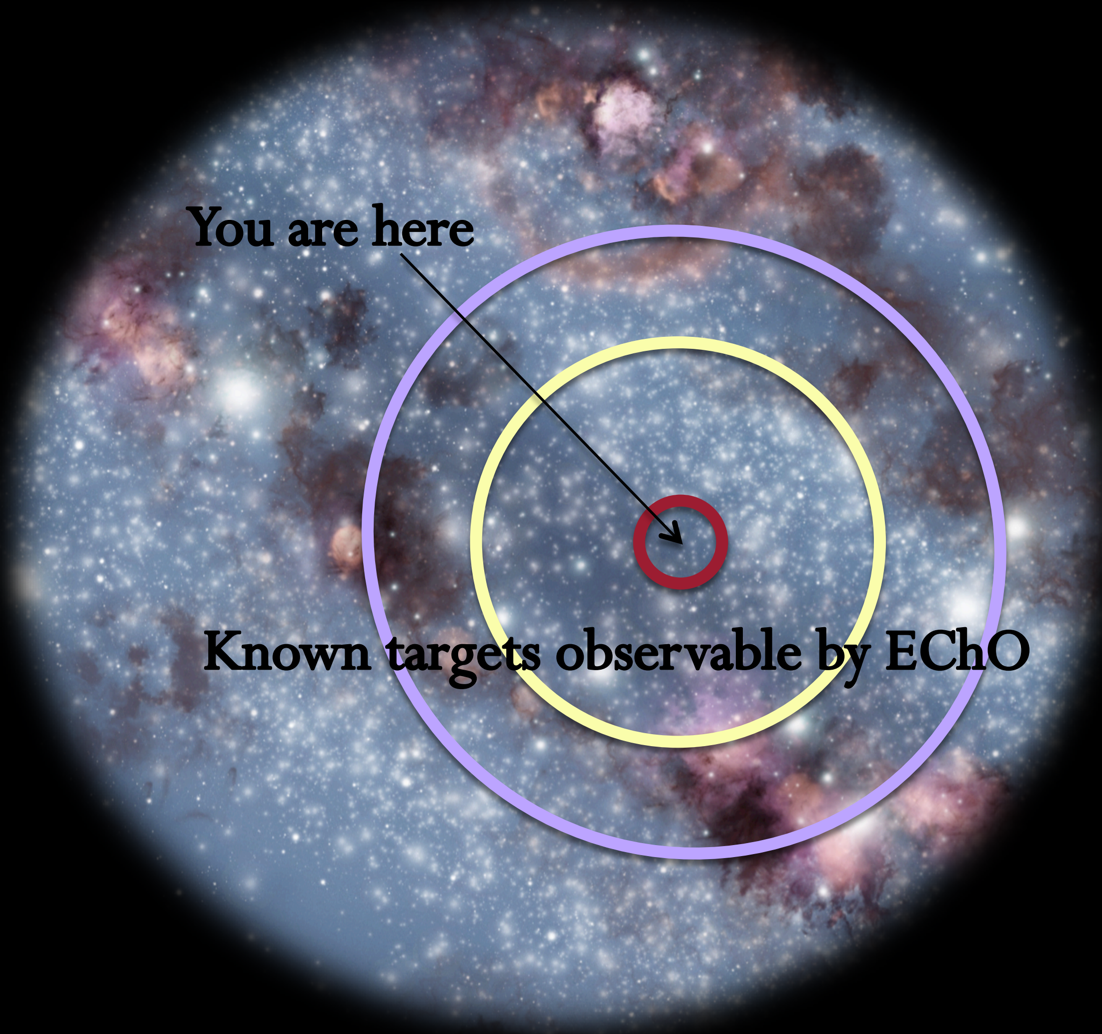






EChO *Chemical Census* survey

Chemical survey of planets in the Solar neighbourhood



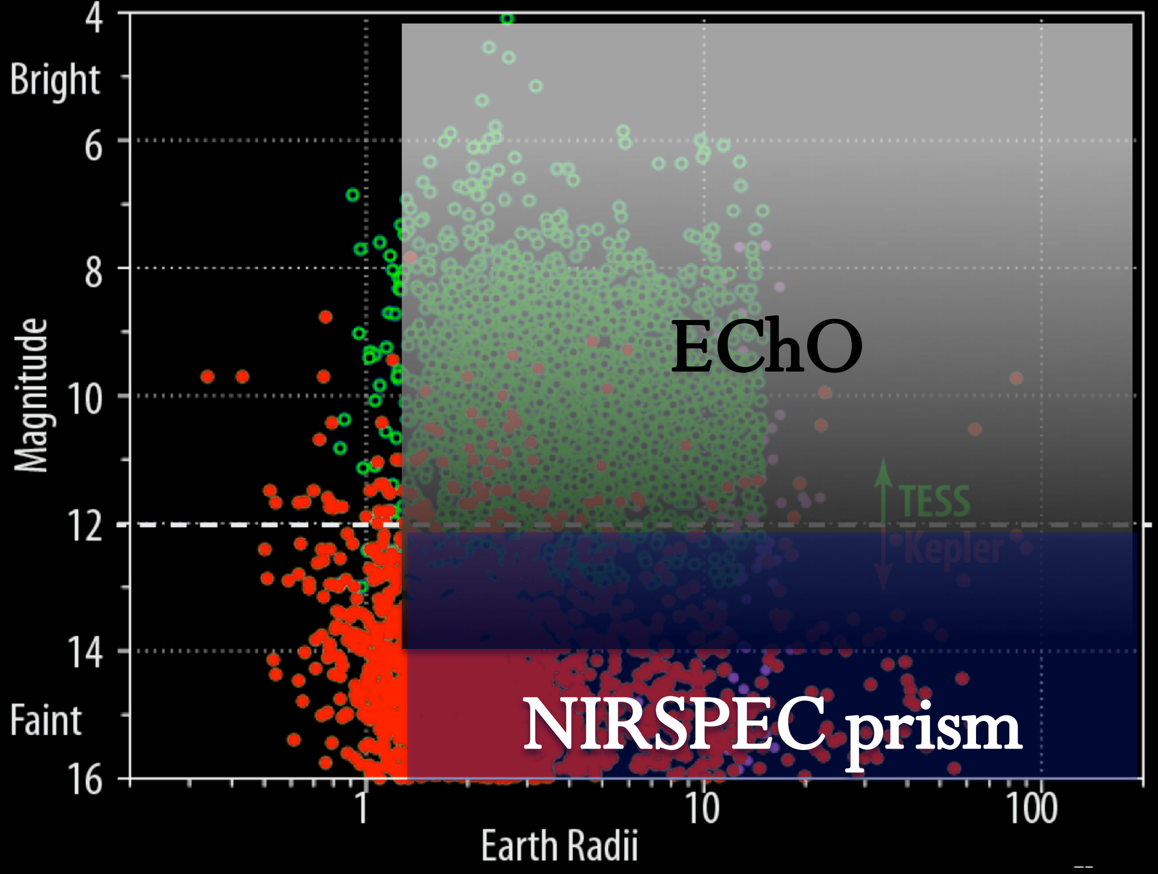
A-F stars ~1800 light-years

G-K stars ~1200 light-years

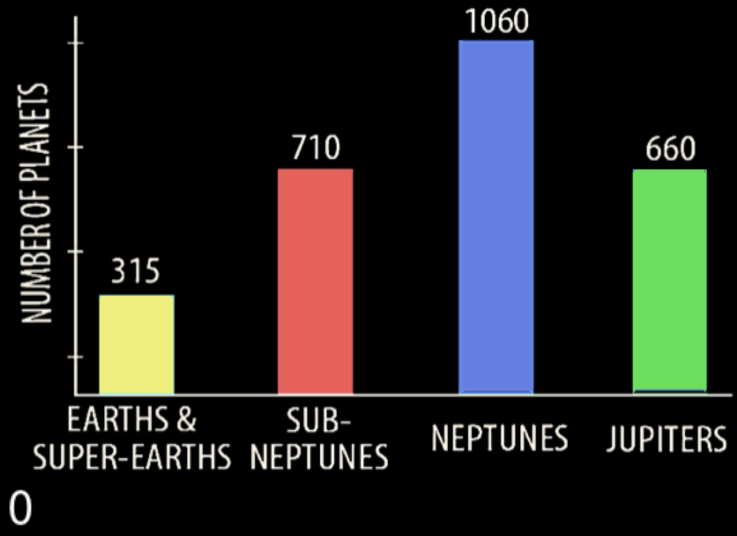
M stars ~ 150 light-years

Additional targets from NASA-TESS

Dedicated mission to detect transiting planets (2017)



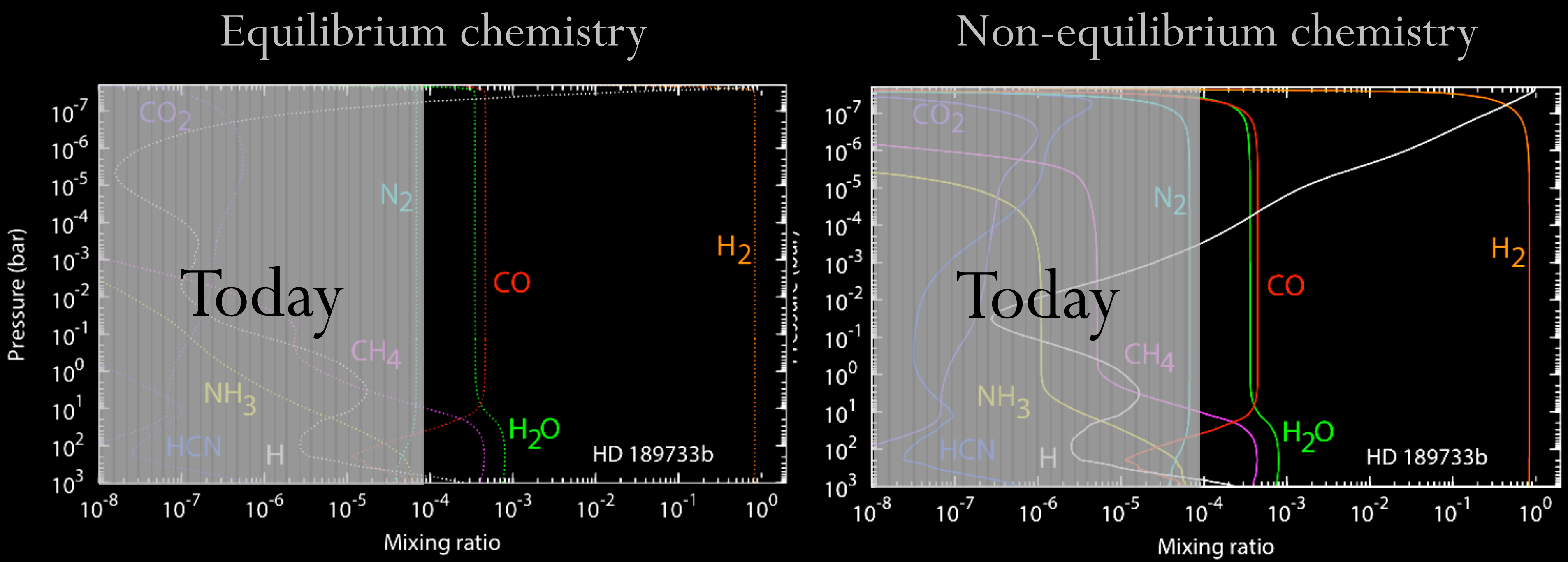
Transiting planets expected to be discovered by TESS



Courtesy of the TESS team

Current observations

Detecting only the most abundant molecules

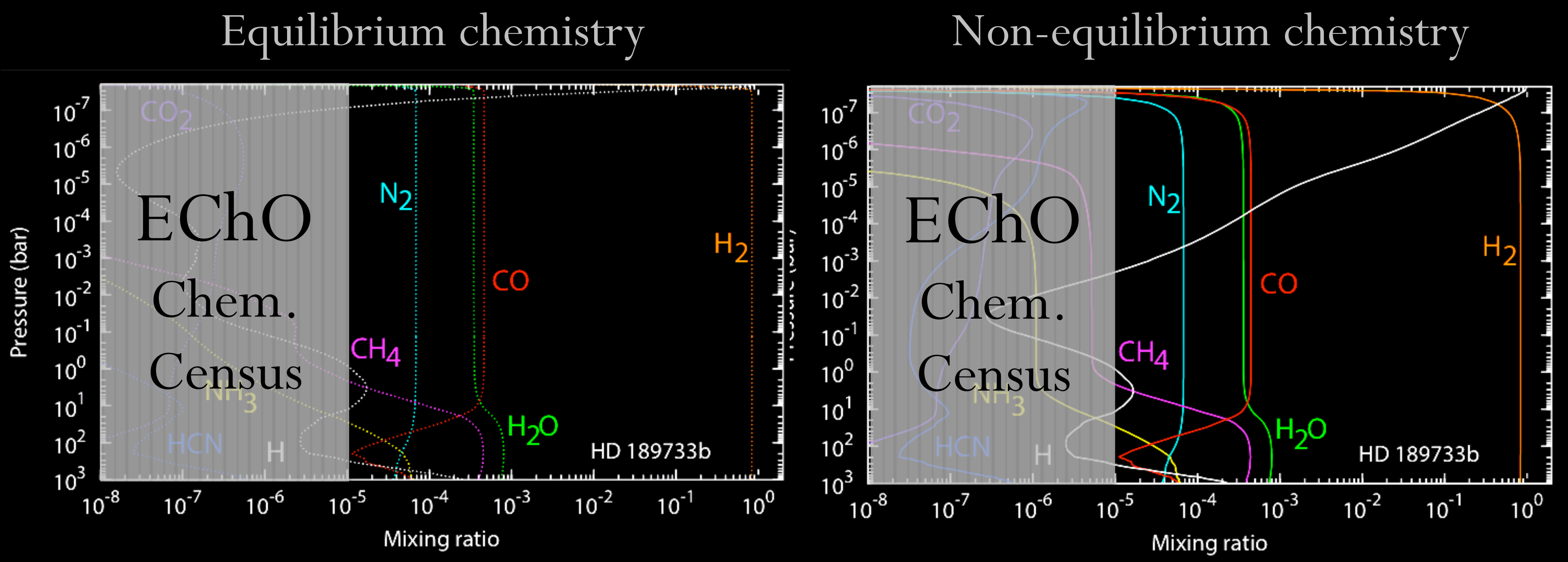


~ 10 planets

Venot et al., 2012

EChO *Chemical Census* survey

Detecting key molecules, mapping the chemical diversity



~ 150-300 planets

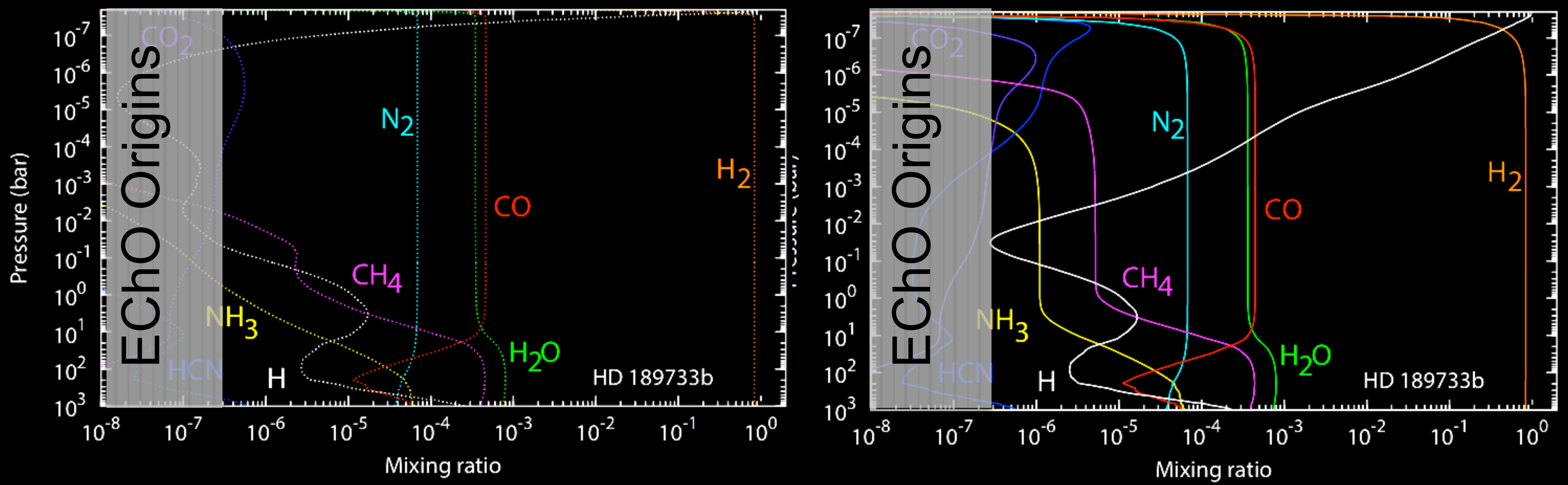
Venot et al., 2012

ECh0 *Origin* survey

Understanding the role of non-equilibrium chemistry

Equilibrium chemistry

Non-equilibrium chemistry

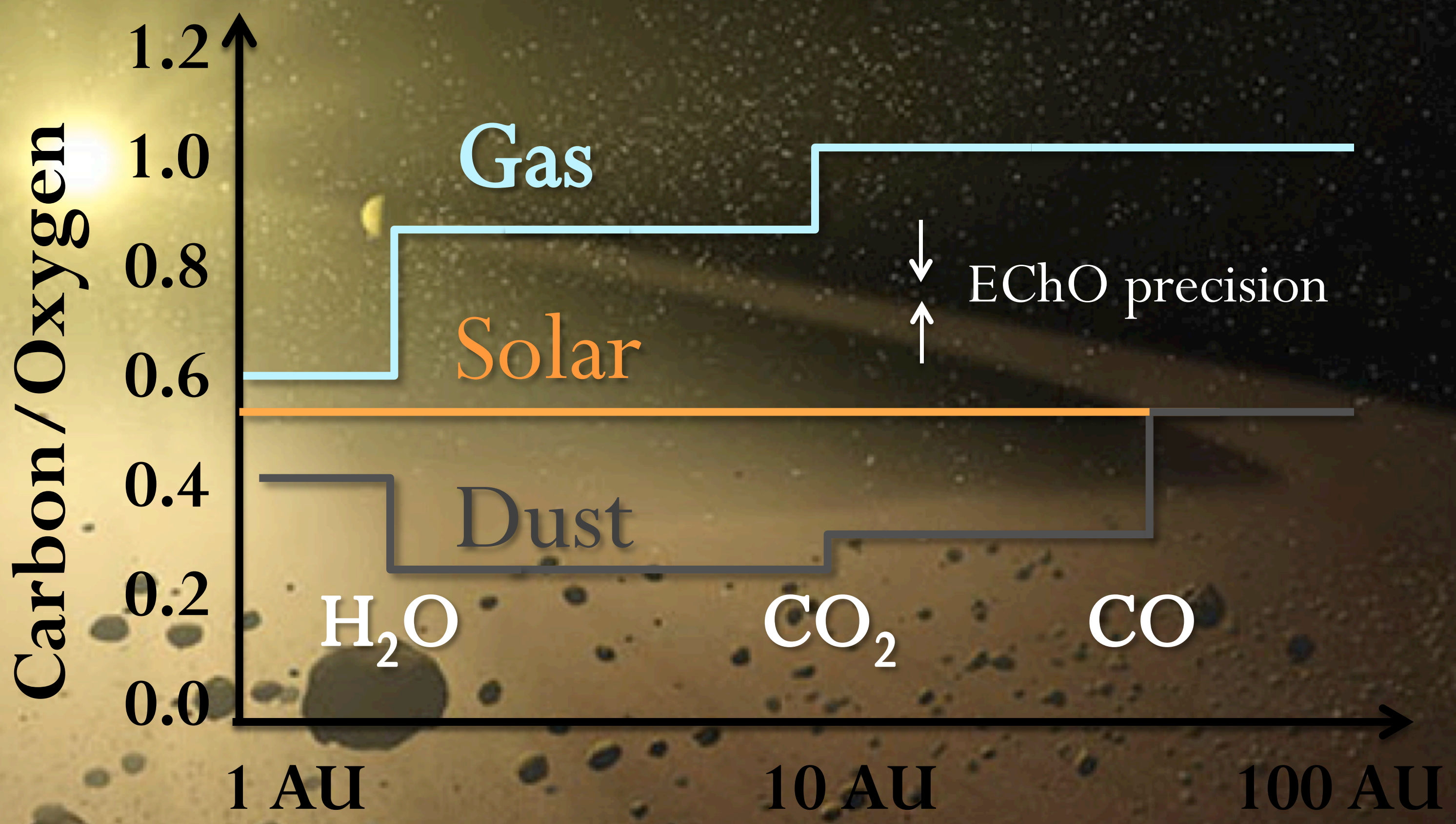


~ 50-100 planets

Venot et al., 2012

EChO *Origin* survey

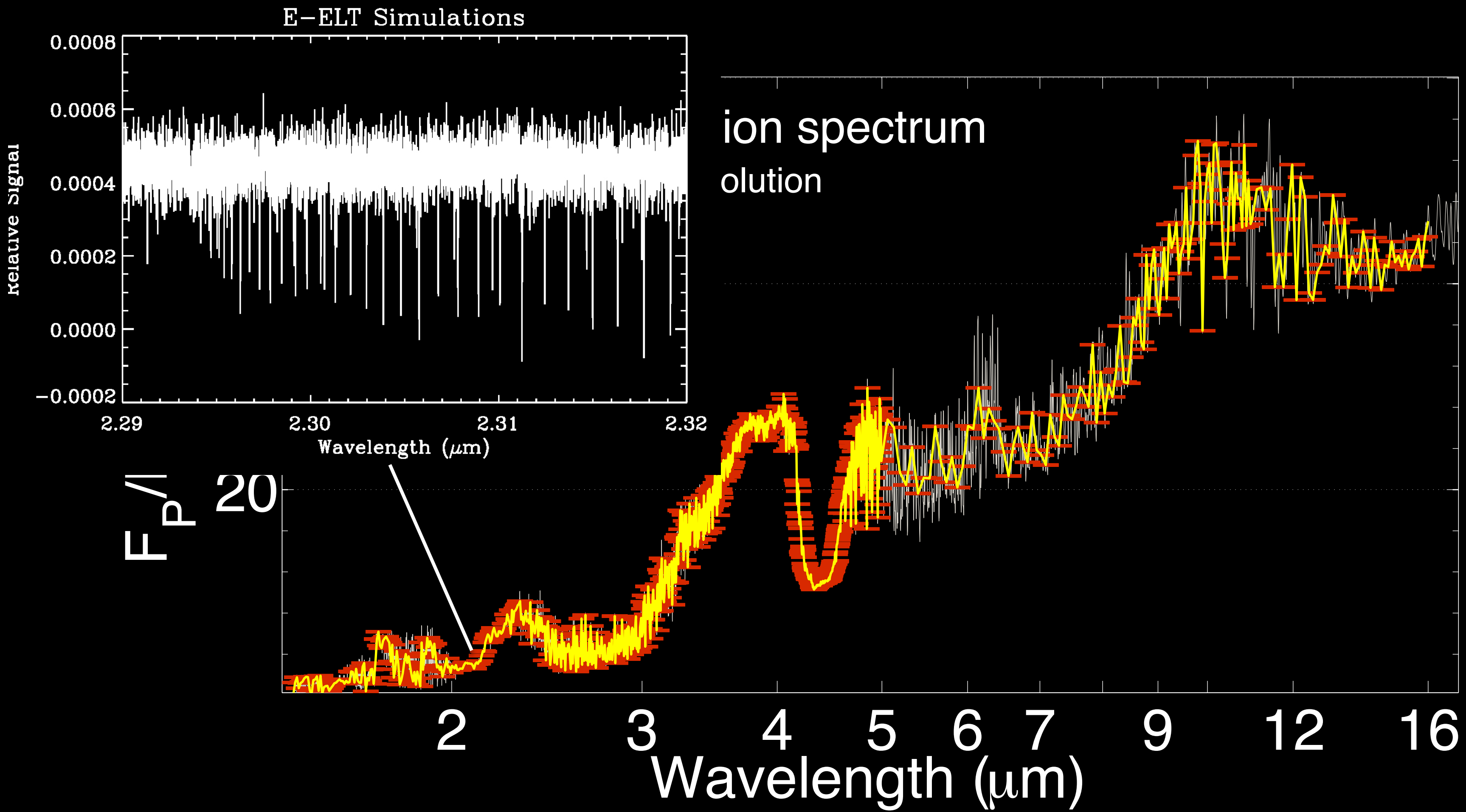
Understanding planet formation/migration processes



Obert et al., 2011; Nelson, Turrini, Barbieri 2014

EChO *Rosetta Stones* survey

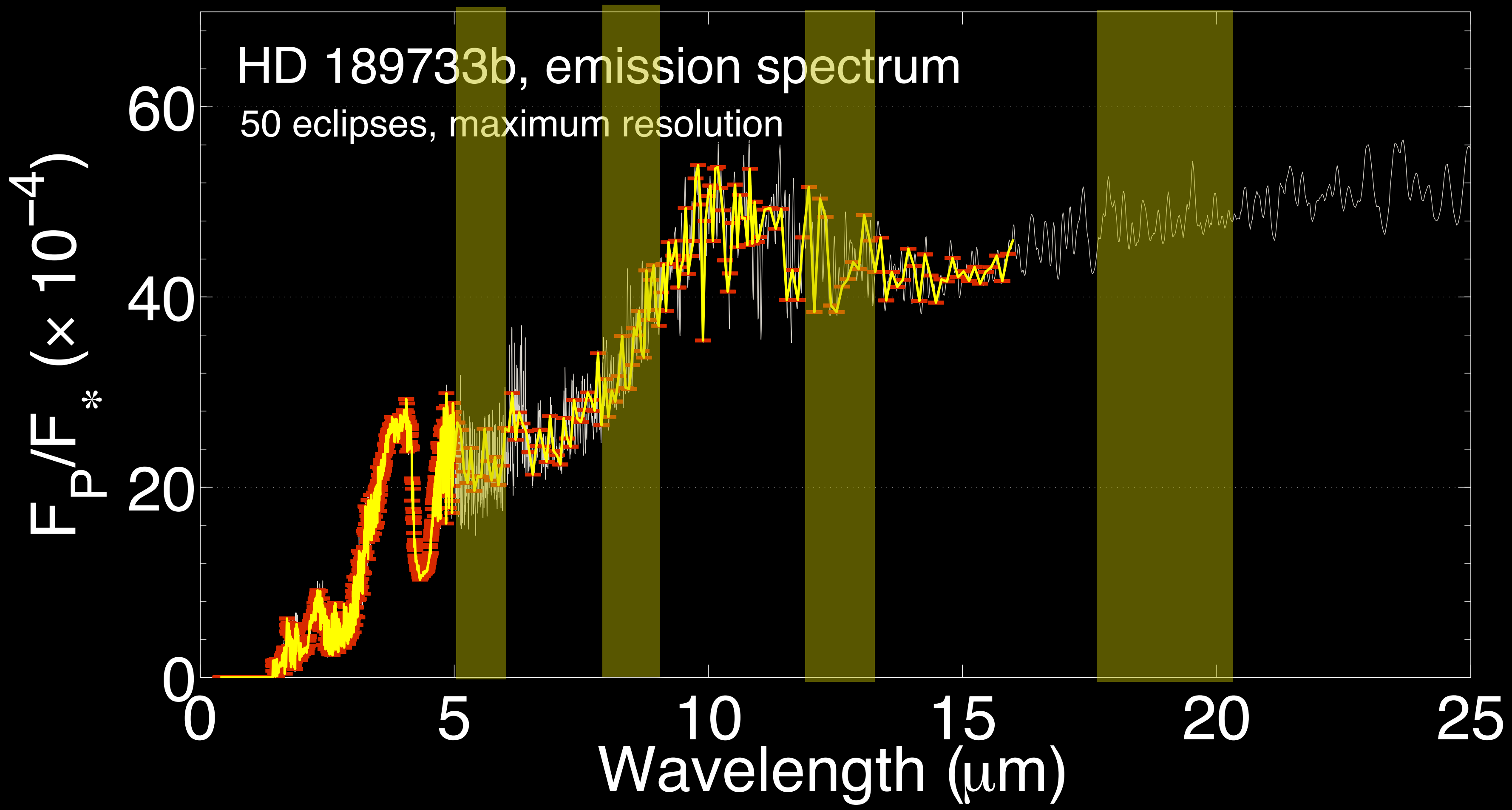
Benchmark cases to understand classes of planets



Varley et al, 2014

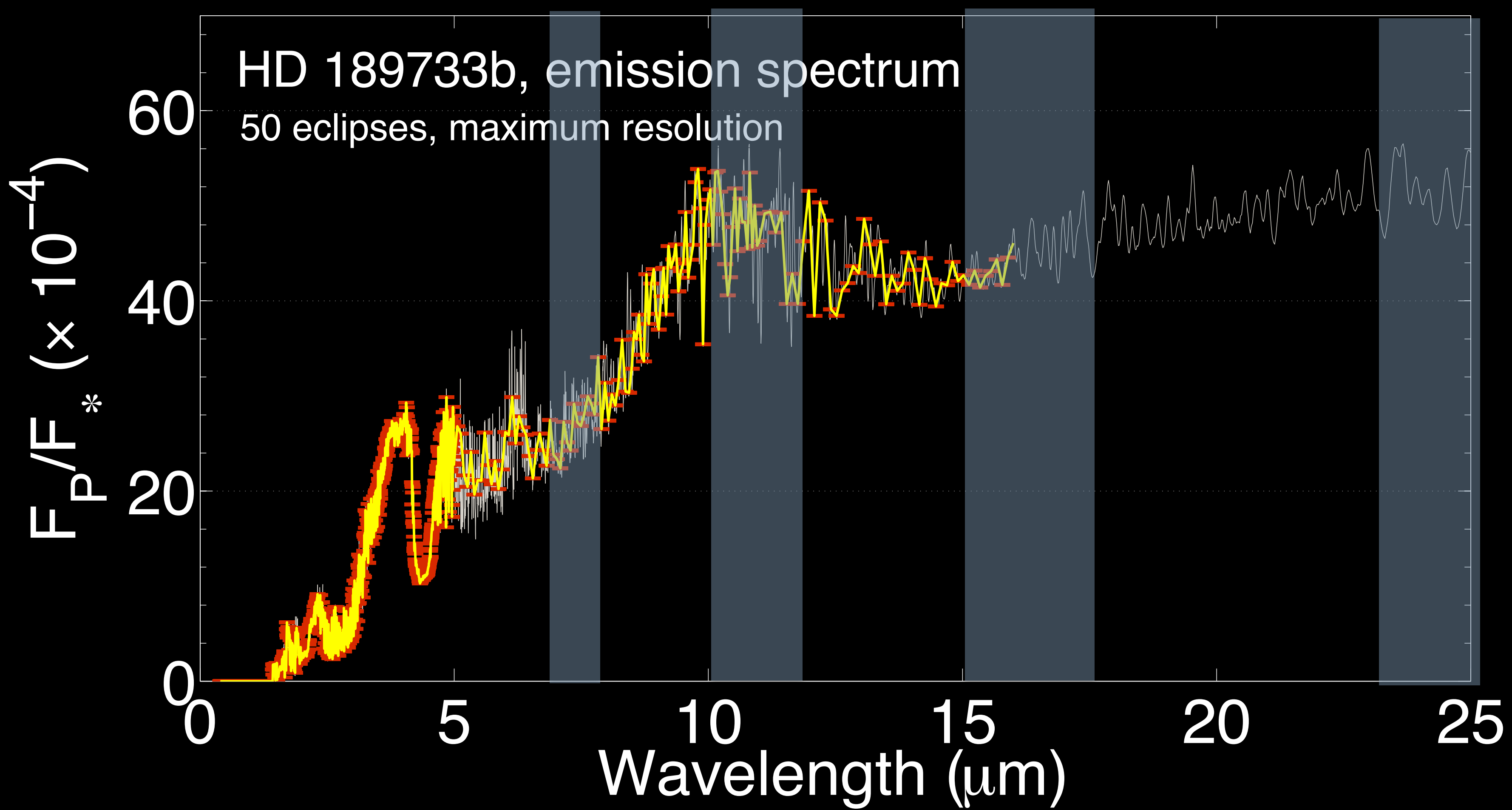
EChO *Rosetta Stones* survey

Synergy with MIRI Filters



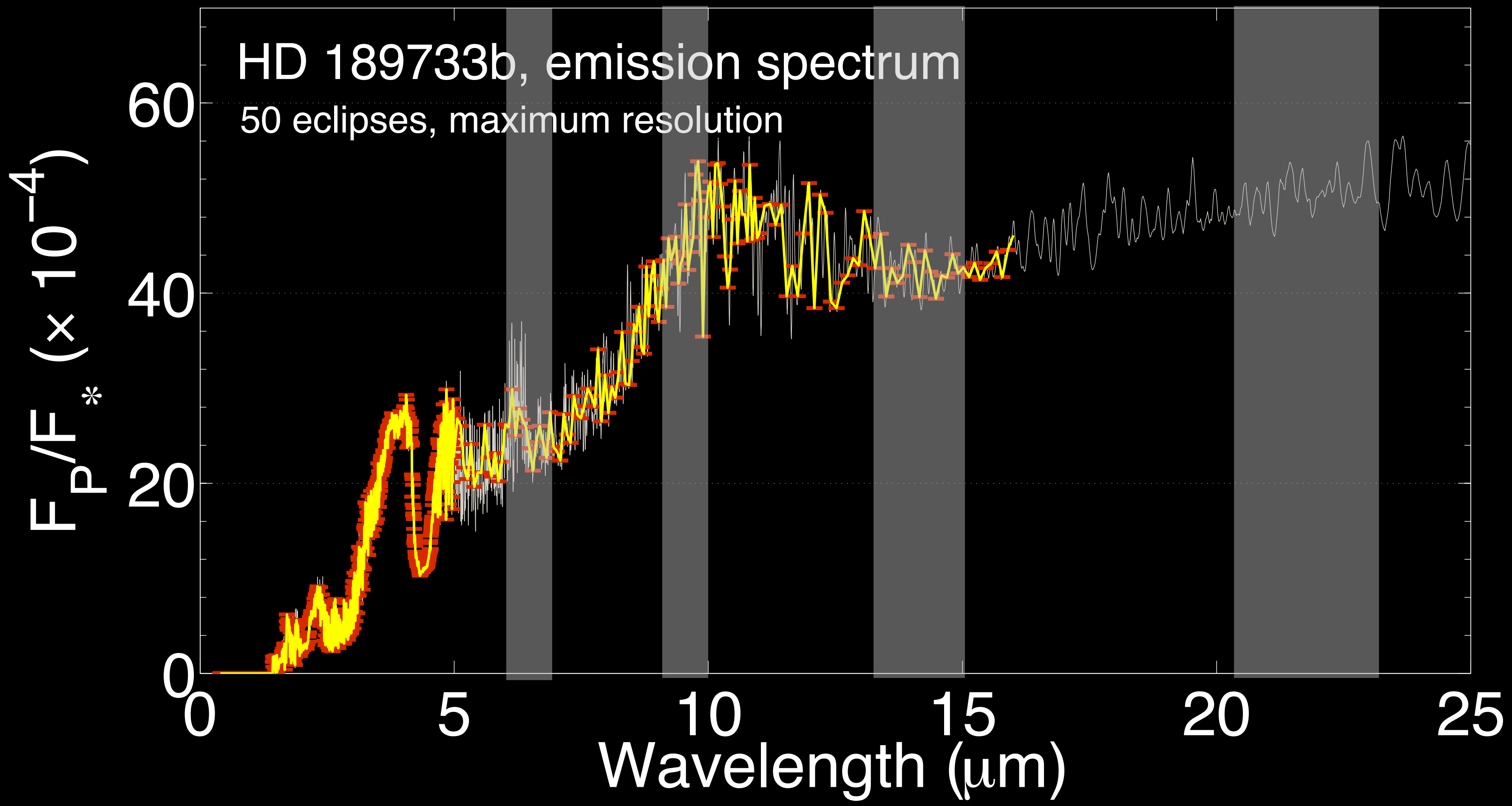
EChO *Rosetta Stones* survey

Synergy with MIRI Filters



EChO *Rosetta Stones* survey

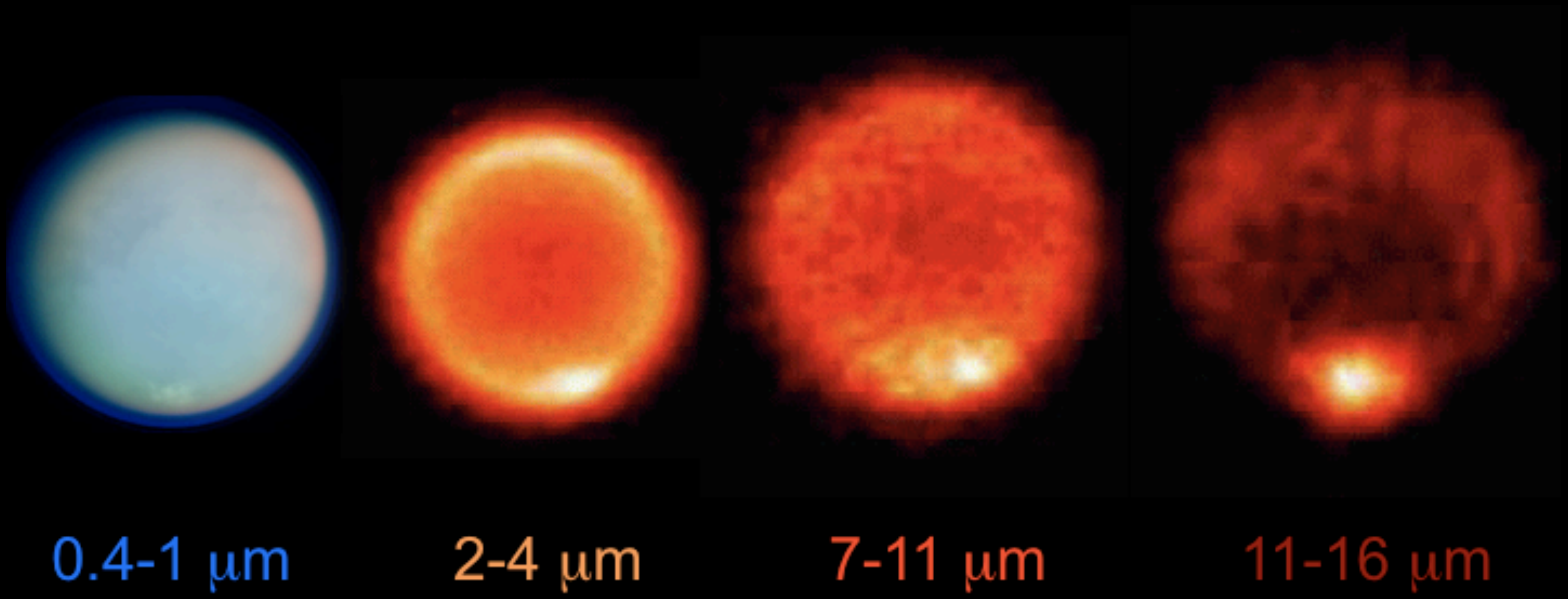
Synergy with MIRI Filters



EChO *Rosetta Stones* survey

2D images of the planet

Exploring spatial variability

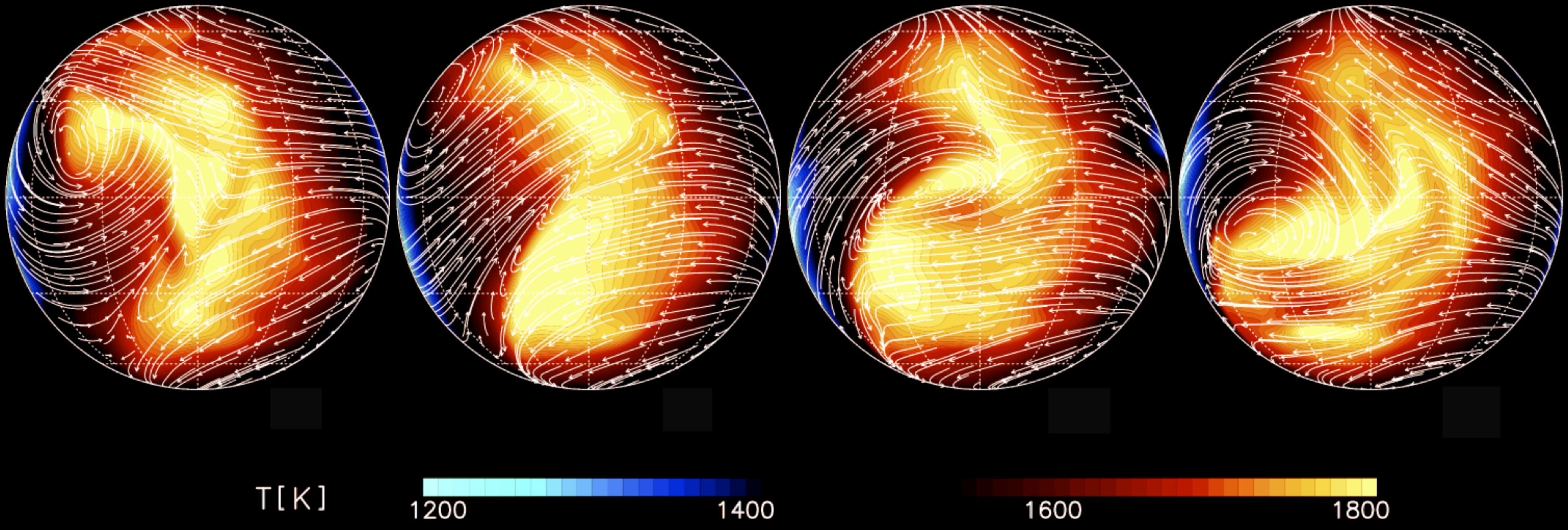


Majeau et al., 2014

EChO *Rosetta Stones* survey

Weather & temporal variability

Understanding the role of dynamics (repeating > 20 times)

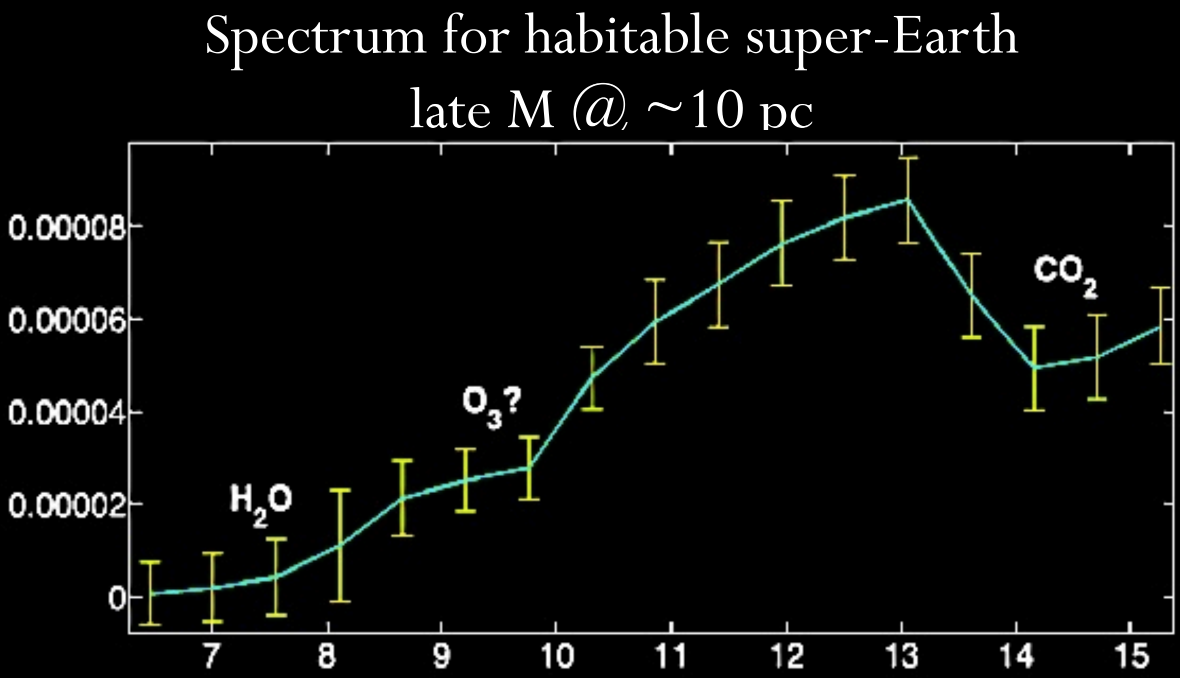


Thrastarson & Cho, 2012

Super-Earths around M-dwarfs:

Are they habitable?

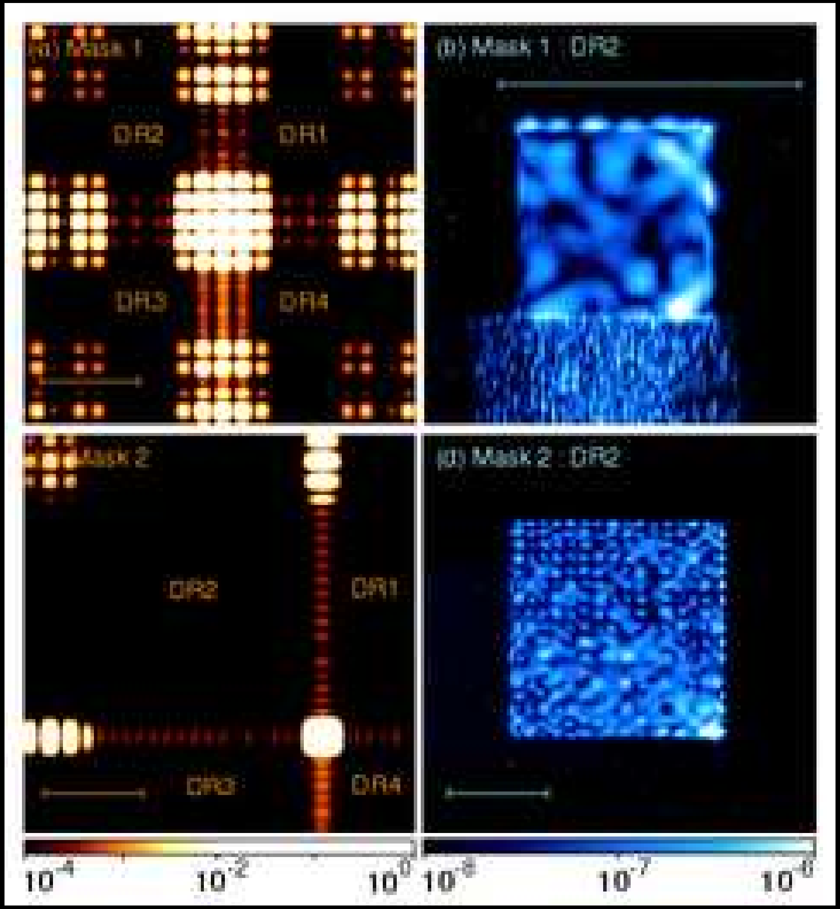
"Pack your suitcase? Super-Earth Gliese 581d is in the "Habitable Zone"


Spectrum for habitable super-Earth
late M @ ~10 pc

Tessenyi et al., 2012; Varley et al, 2014

Direct detection from space

Coronagraph & adaptive optics



Enya et al., 2010

Conclusions

- Solar System is no longer the paradigm!
- We now need to understand how planets form & evolve
- The way forward is to study the *atmospheric chemistry of exoplanets*
- Galactic planetary science has proven possible with current instrument
- If launched, EChO will deliver *transformational science:*
  - First broad survey of planetary atmospheres
  - Hundreds of planets spectroscopically observed
  - Molecular abundances 3 orders of magnitude lower than currently possible
  - Fourfold increase in the number of detected molecules Galactic planetary science has proven possible with current instrument
  - Are M-stars planets good environments for life?
- Direct Imaging mission should follow