Galactic planetary science

(Today & tomorrow)

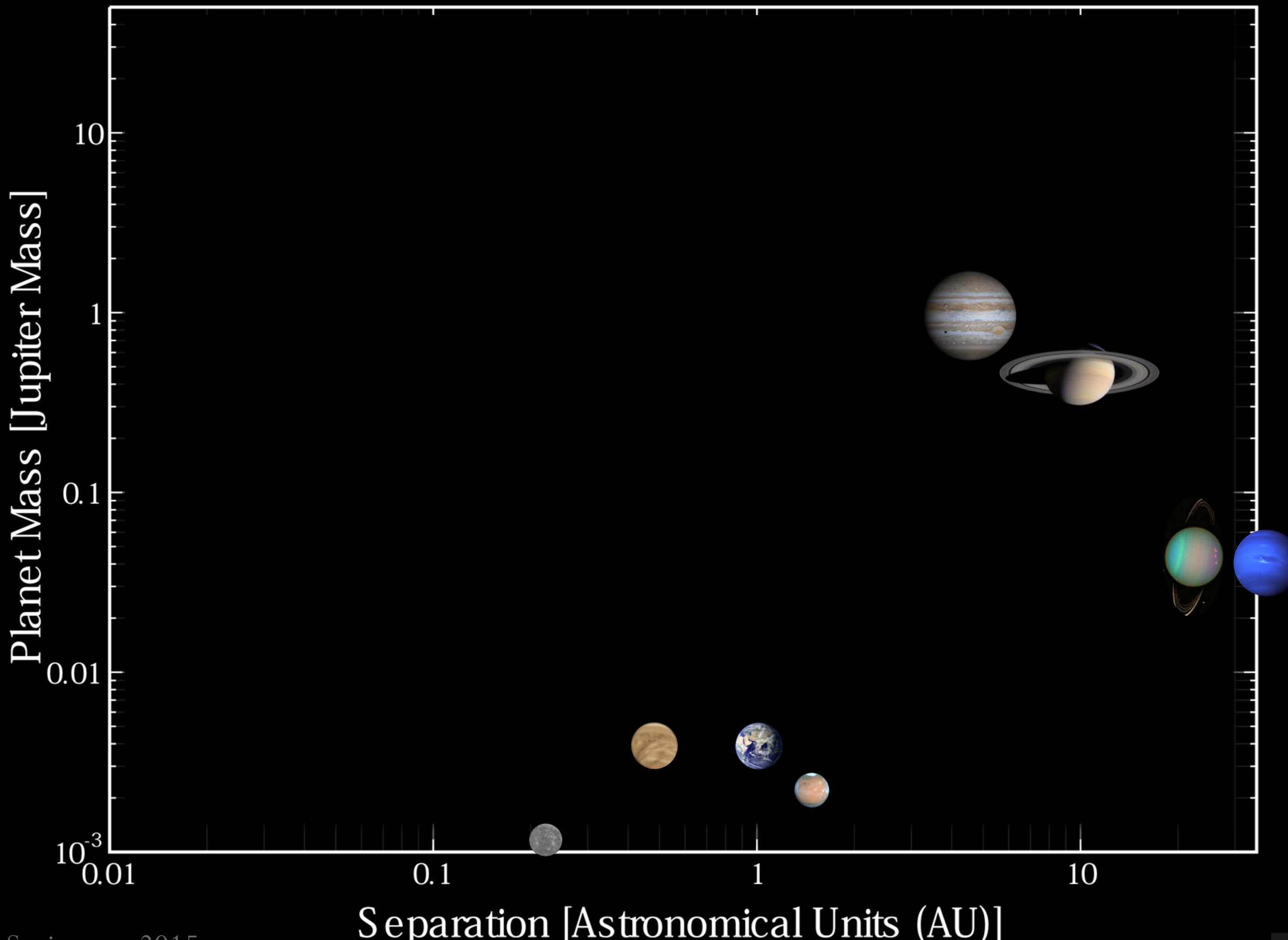
Giovanna Tinetti

University College London & Royal Society

La Sapienza – 2015

The Exoplanet Revolution

9 to 2000 in 20 years!



The Exoplanet Revolution

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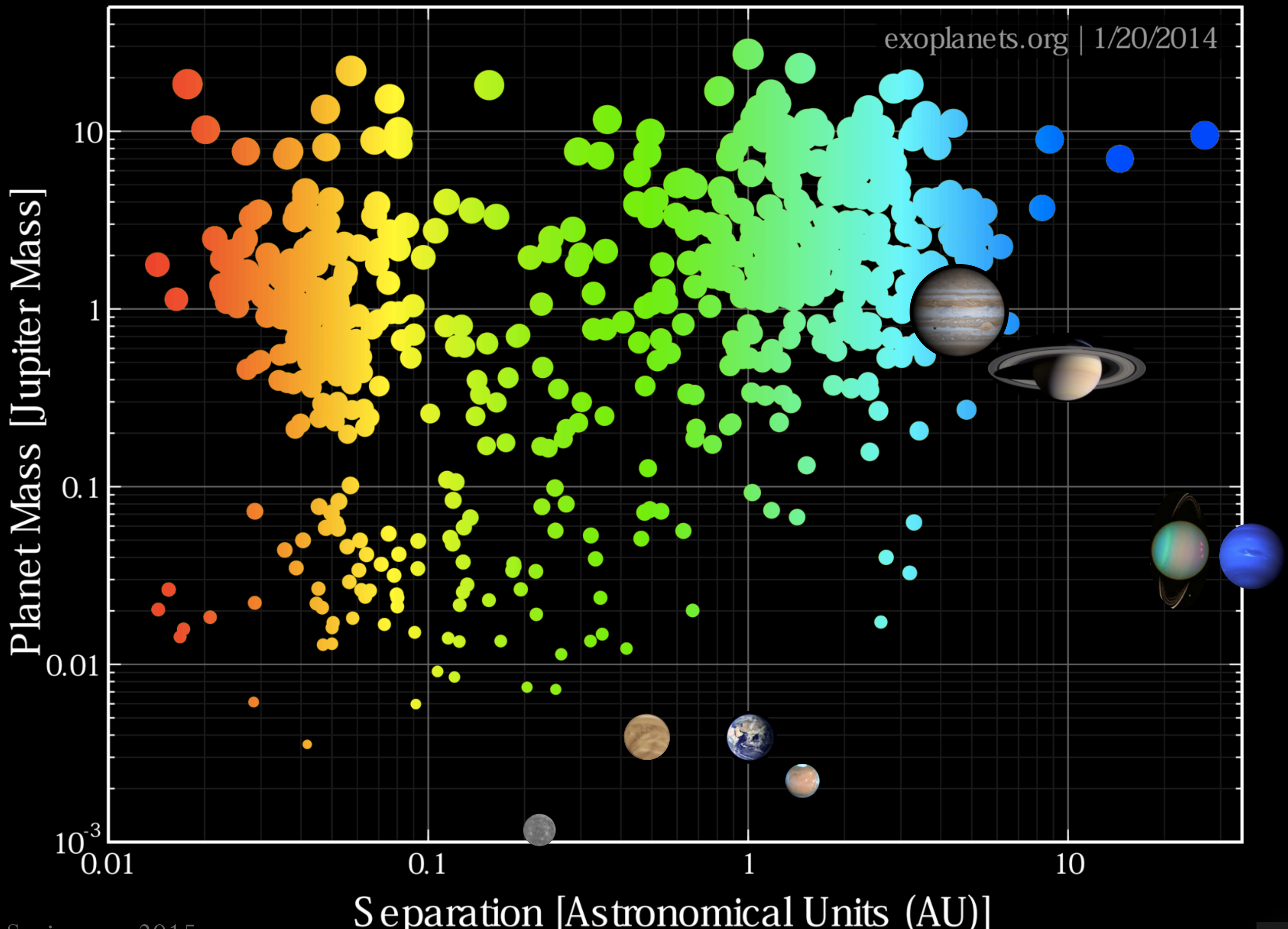

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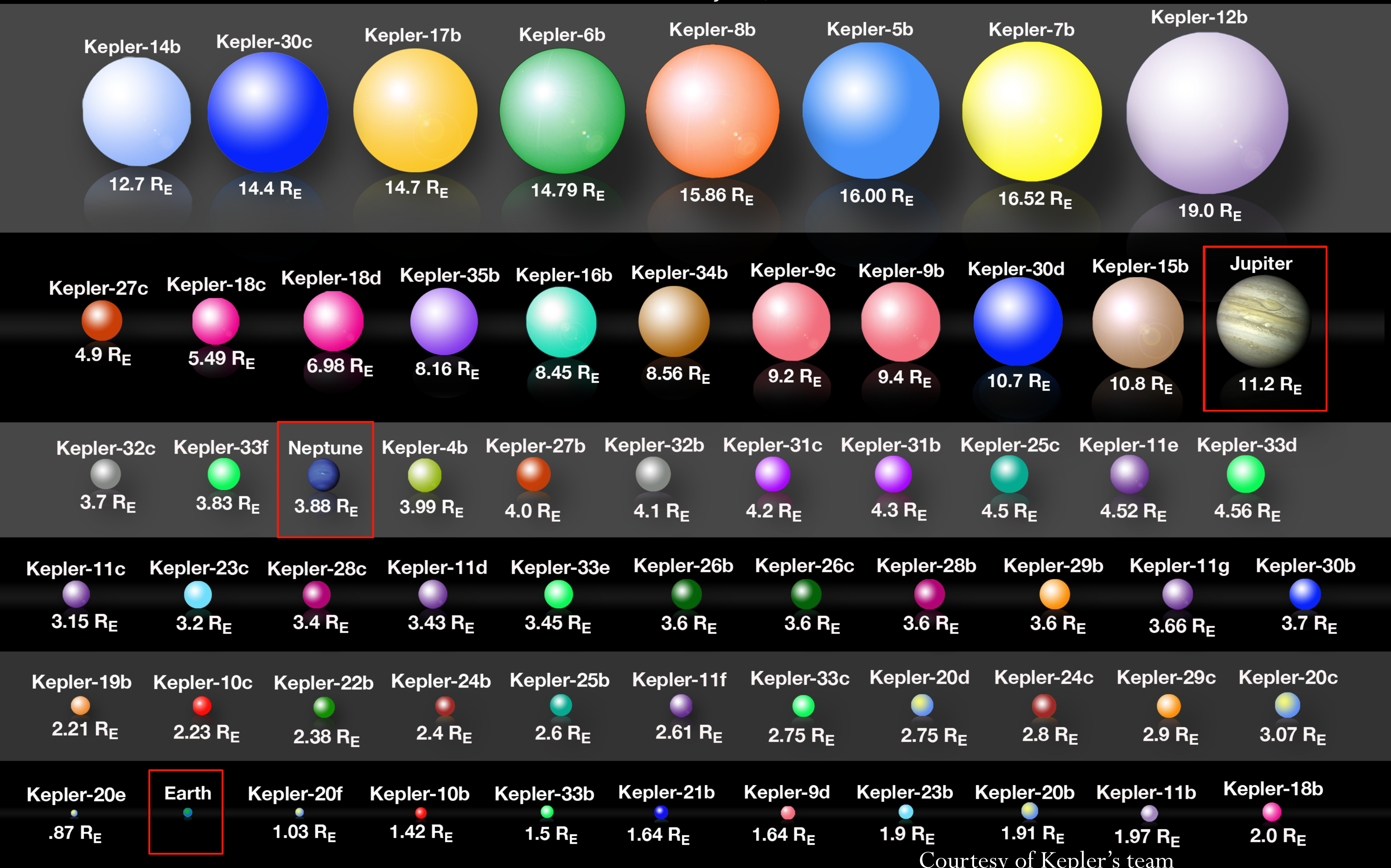
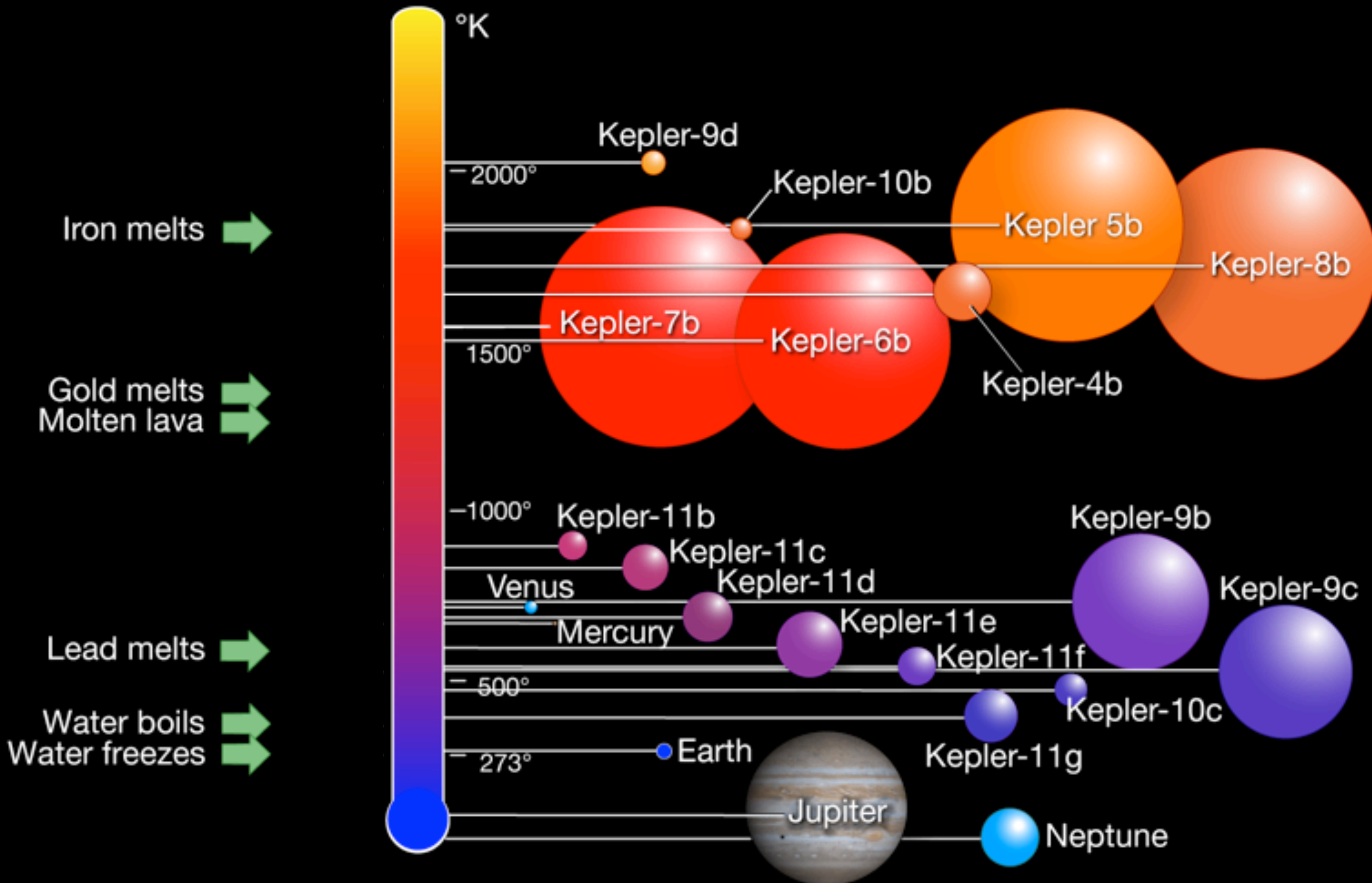
Kepler Planets

As of February 27, 2012



Courtesy of Kepler's team

Planet Temperature & Size

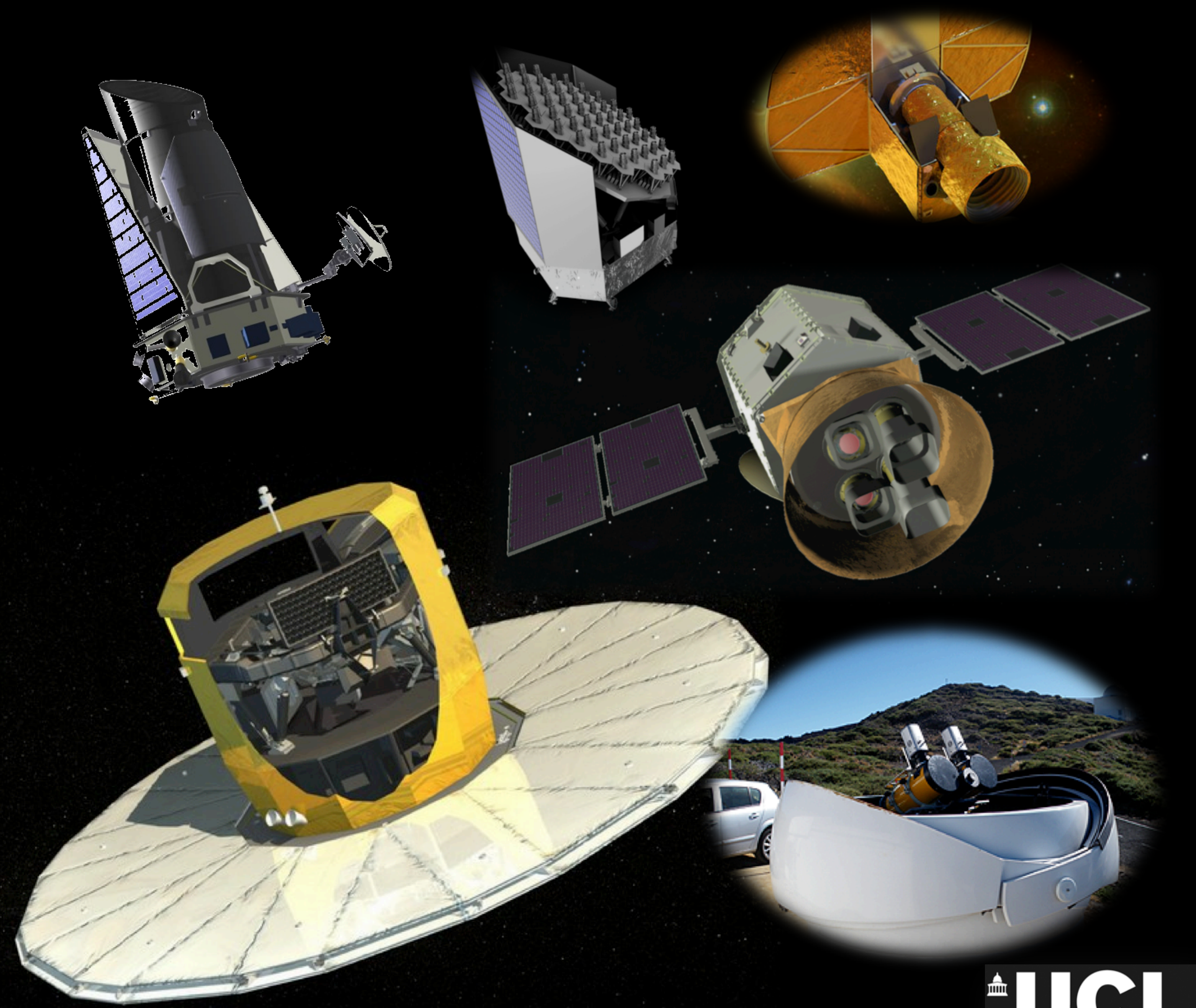


Courtesy of Kepler's team

Space missions & ground-based surveys

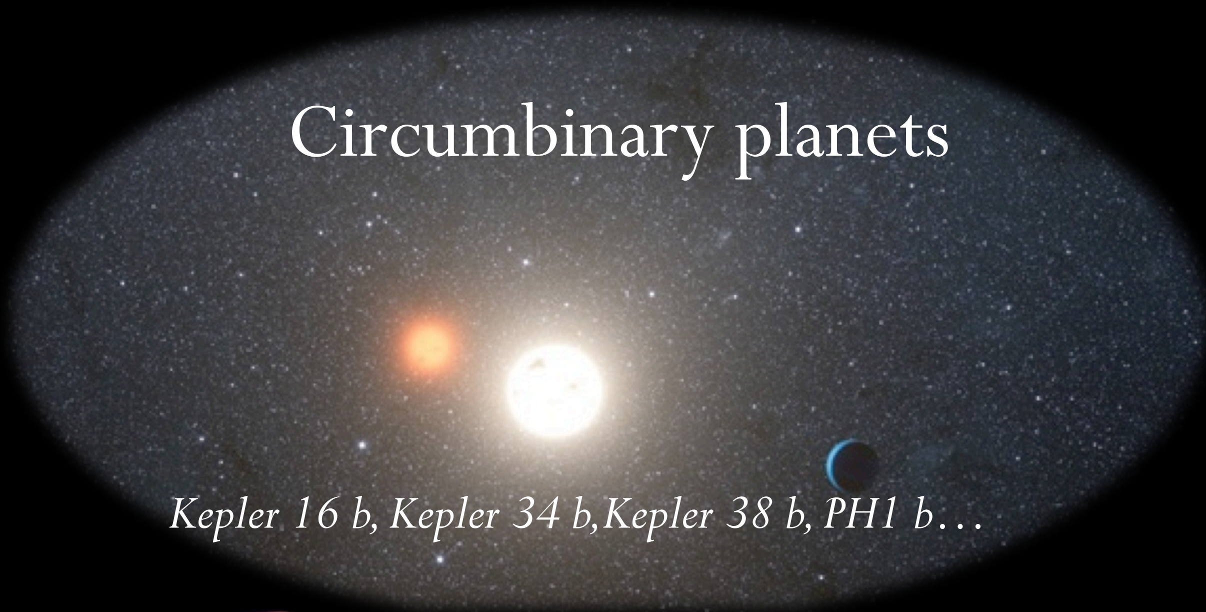
Several thousands new planets in the next decade

- Kepler-2
- GAIA
- Cheops
- TESS
- PLATO
- GPI
- VLT-SPHERE
- HARPS/HARPS No
- HAT-NET
- Super-WASP
- Carmenes
- M-Earth
- NGTS
- APACHE



The Solar System is *not* representative

There is much more variety than the Sun's planets



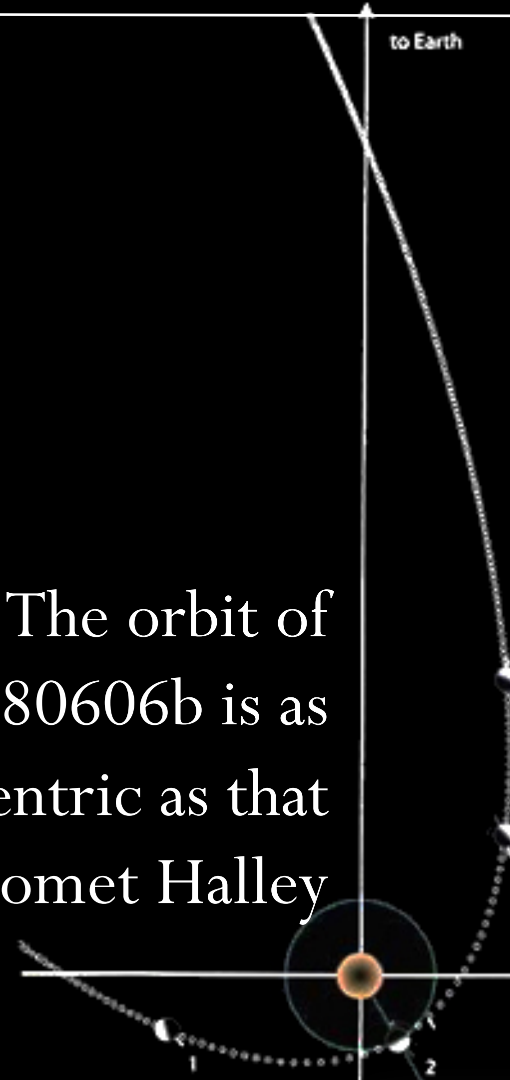
Circumbinary planets

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



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The Solar System is *not* representative

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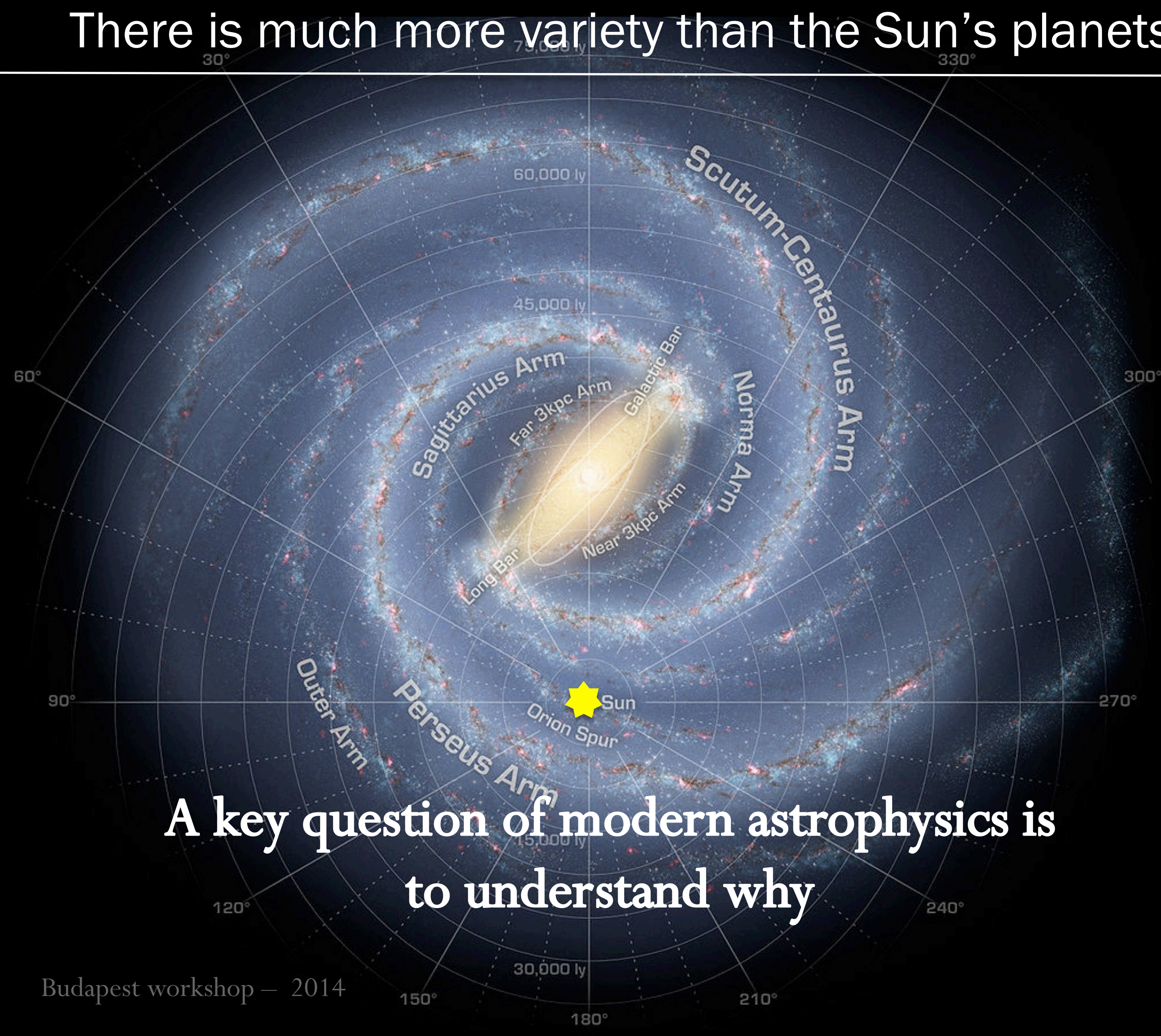


A key question of modern astrophysics is to understand why

Outstanding Science Questions

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

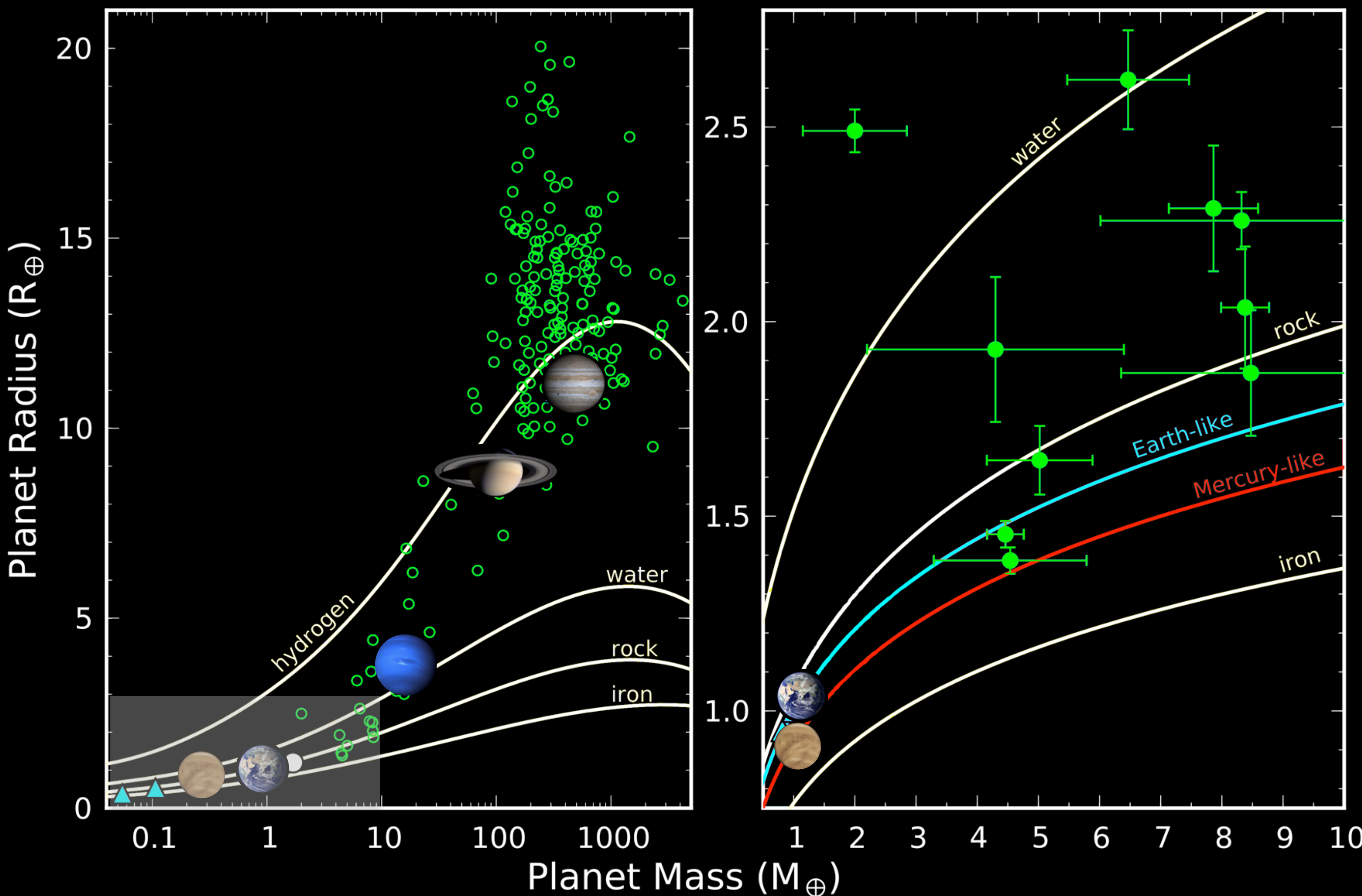
Why are exoplanets as they are?

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

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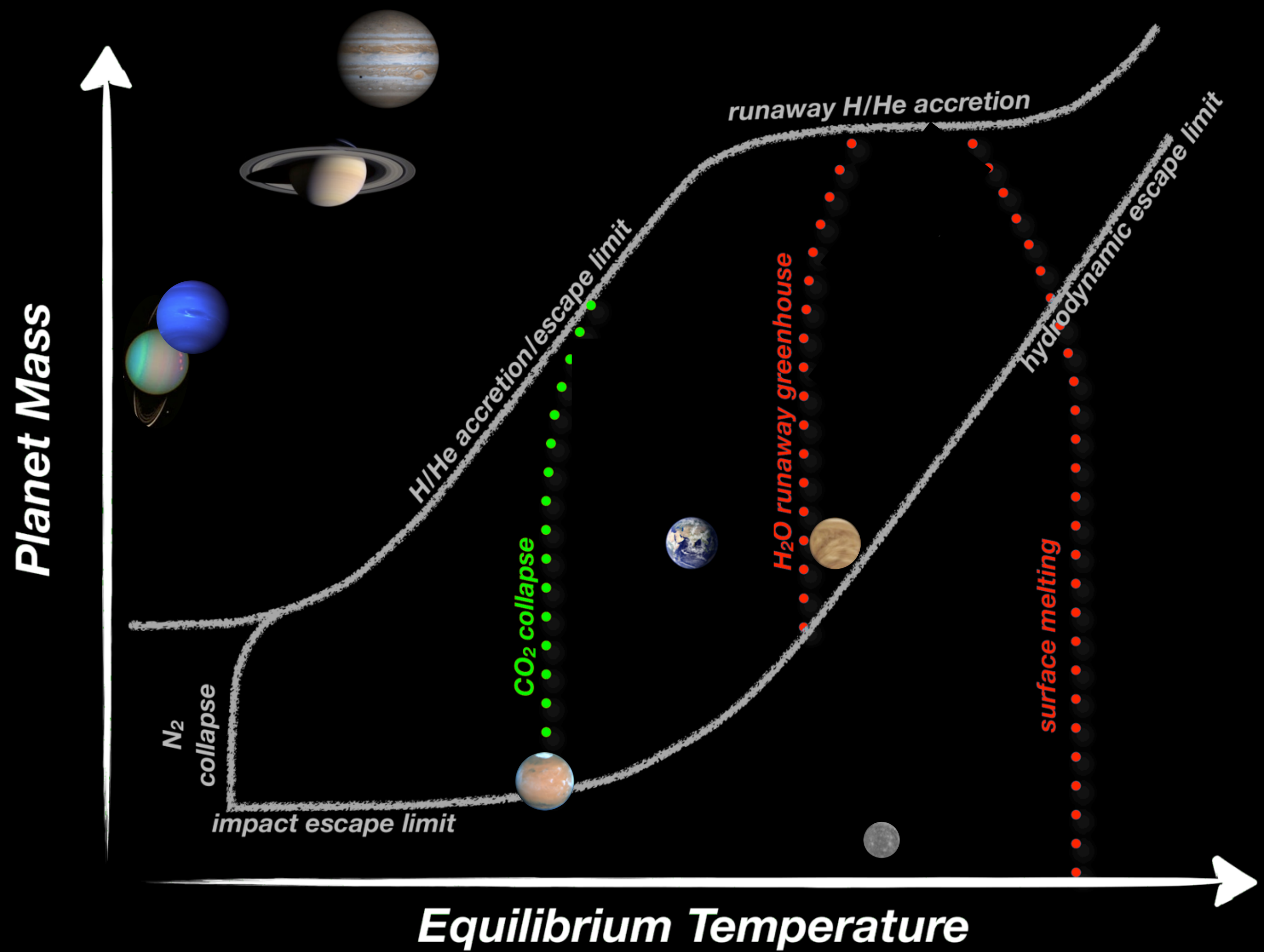
Understanding exoplanet diversity

Predicted atmospheric composition of exoplanets



Forget & Leconte, 2013

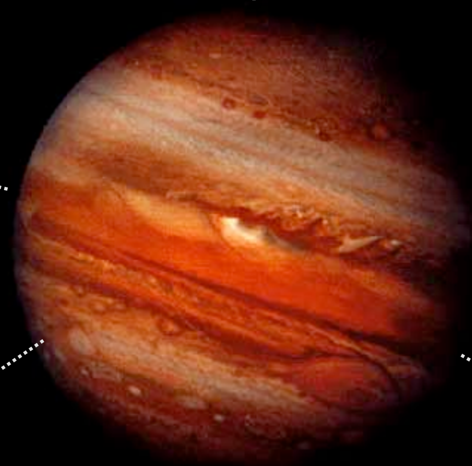
Gaseous planets

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

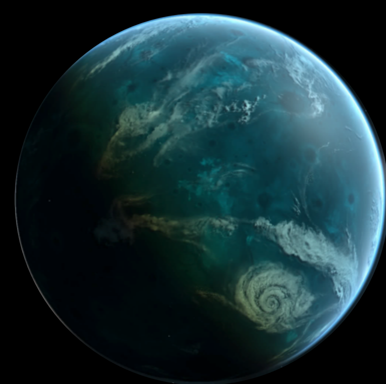
Solid planets

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

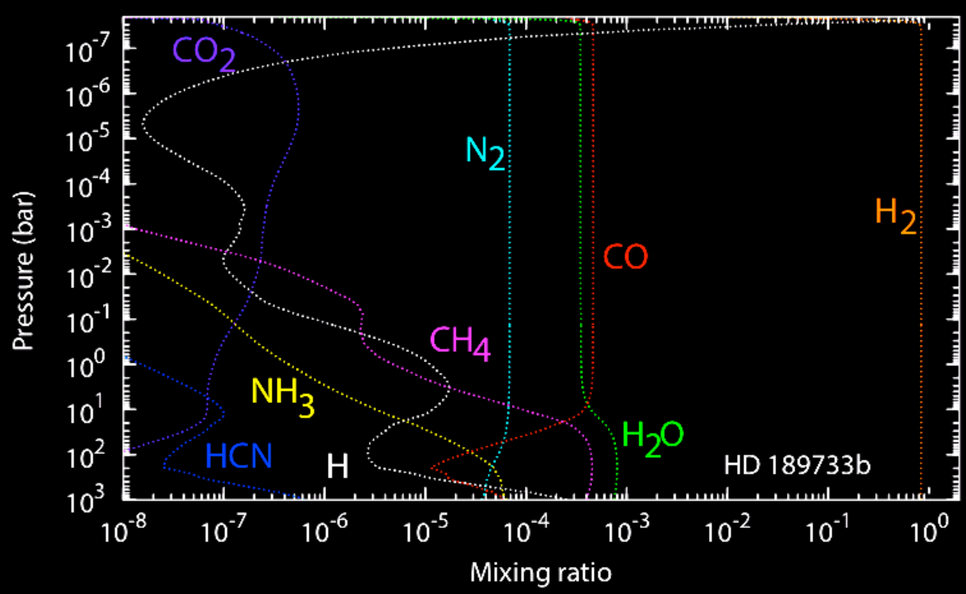
Planet-star interaction
Photochemistry

Energy budget
Albedo/thermal emission

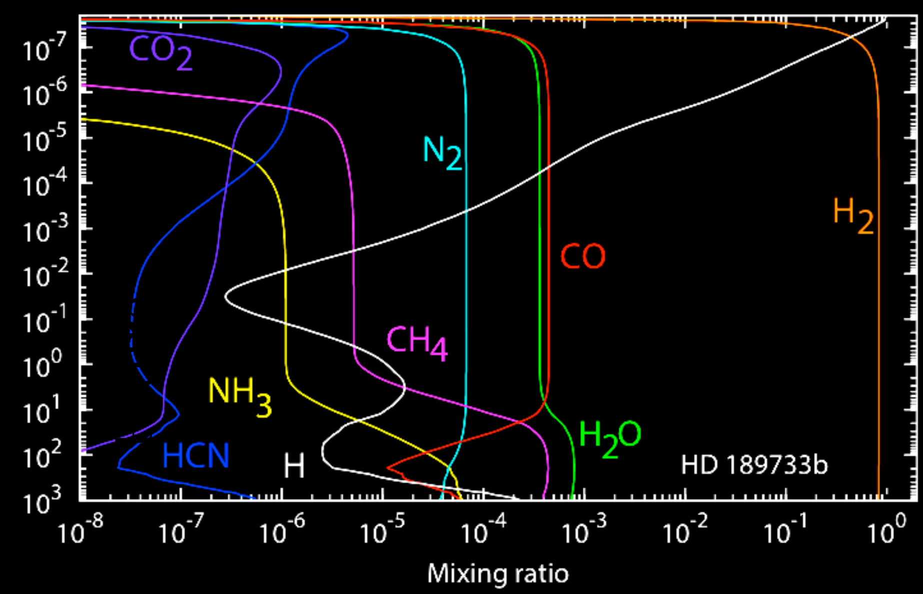
Planets' chemistry

Vertical/horizontal profiles

Equilibrium chemistry



Non-equilibrium chemistry

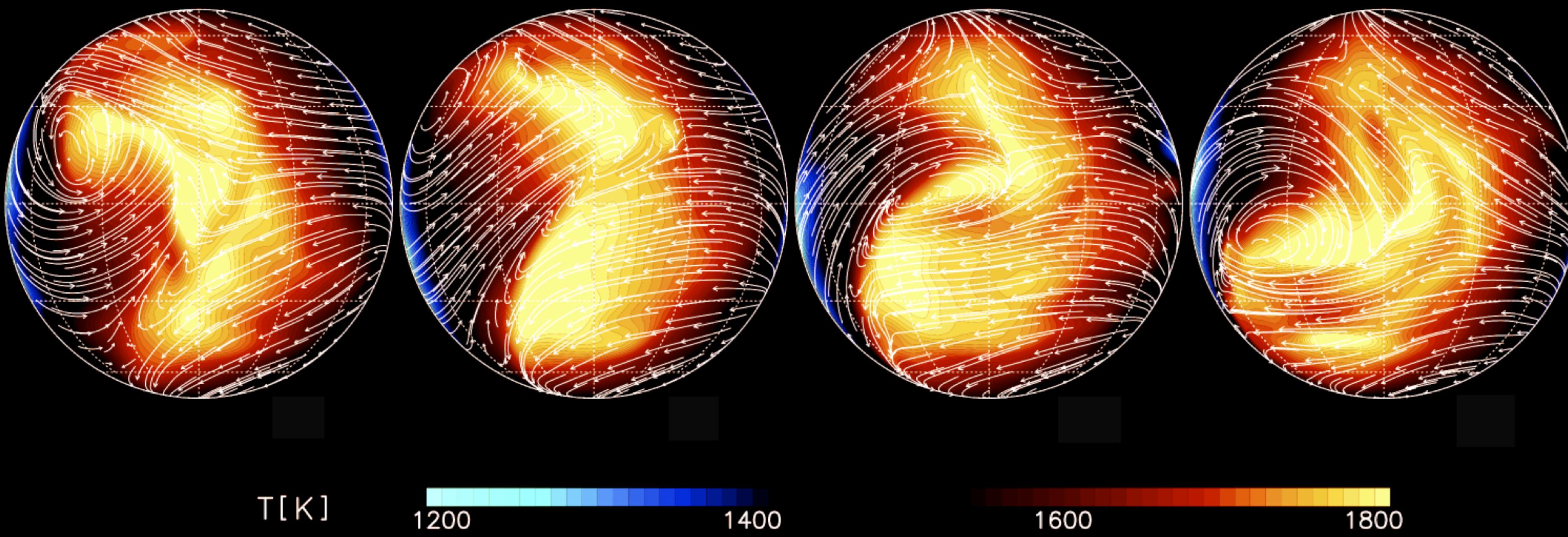


Venot et al., 2012

Planets' climate

Weather & temporal variability

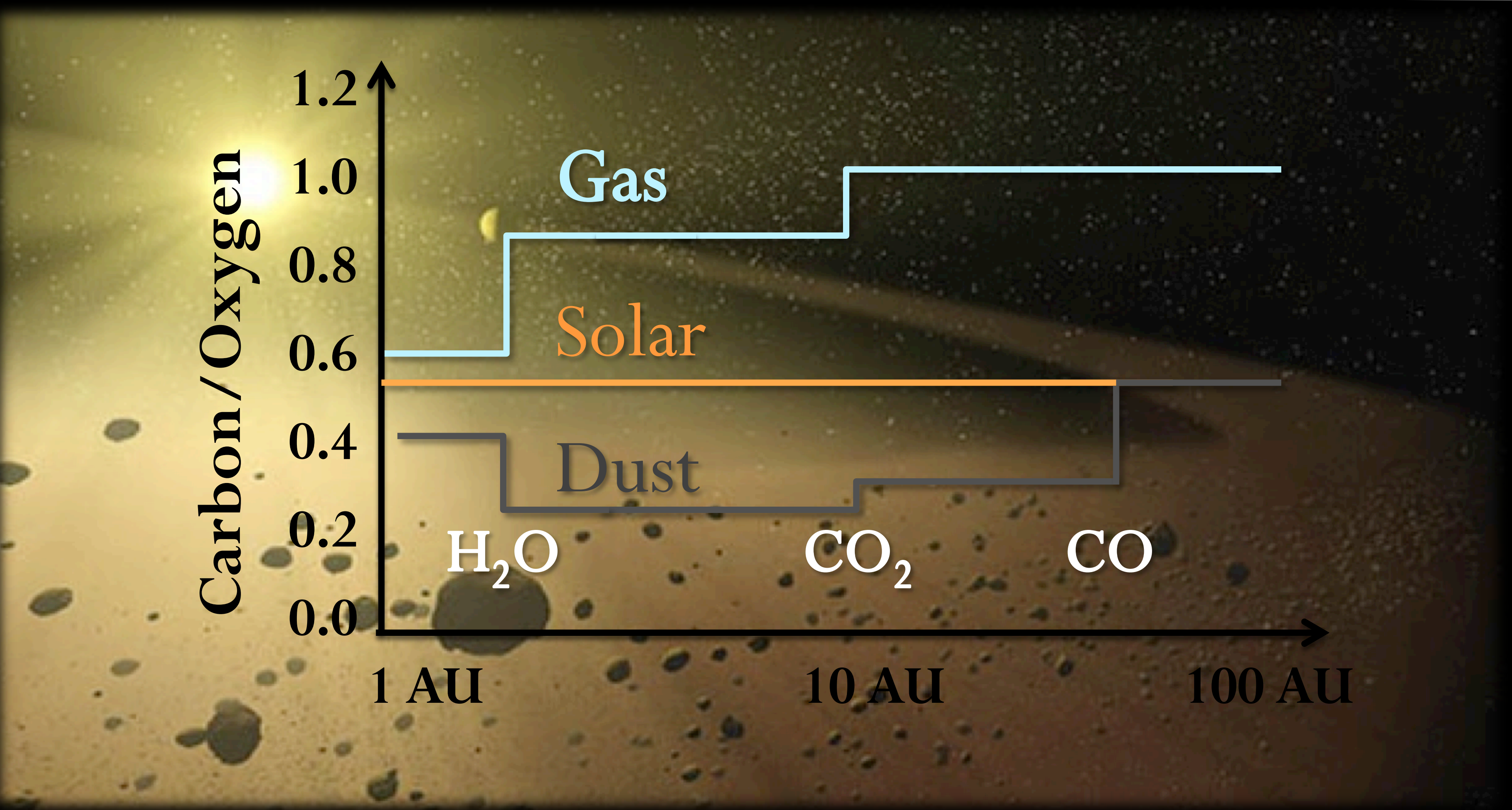
Understanding the role of dynamics



Thrastarson & Cho, 2012

Relative elemental abundances

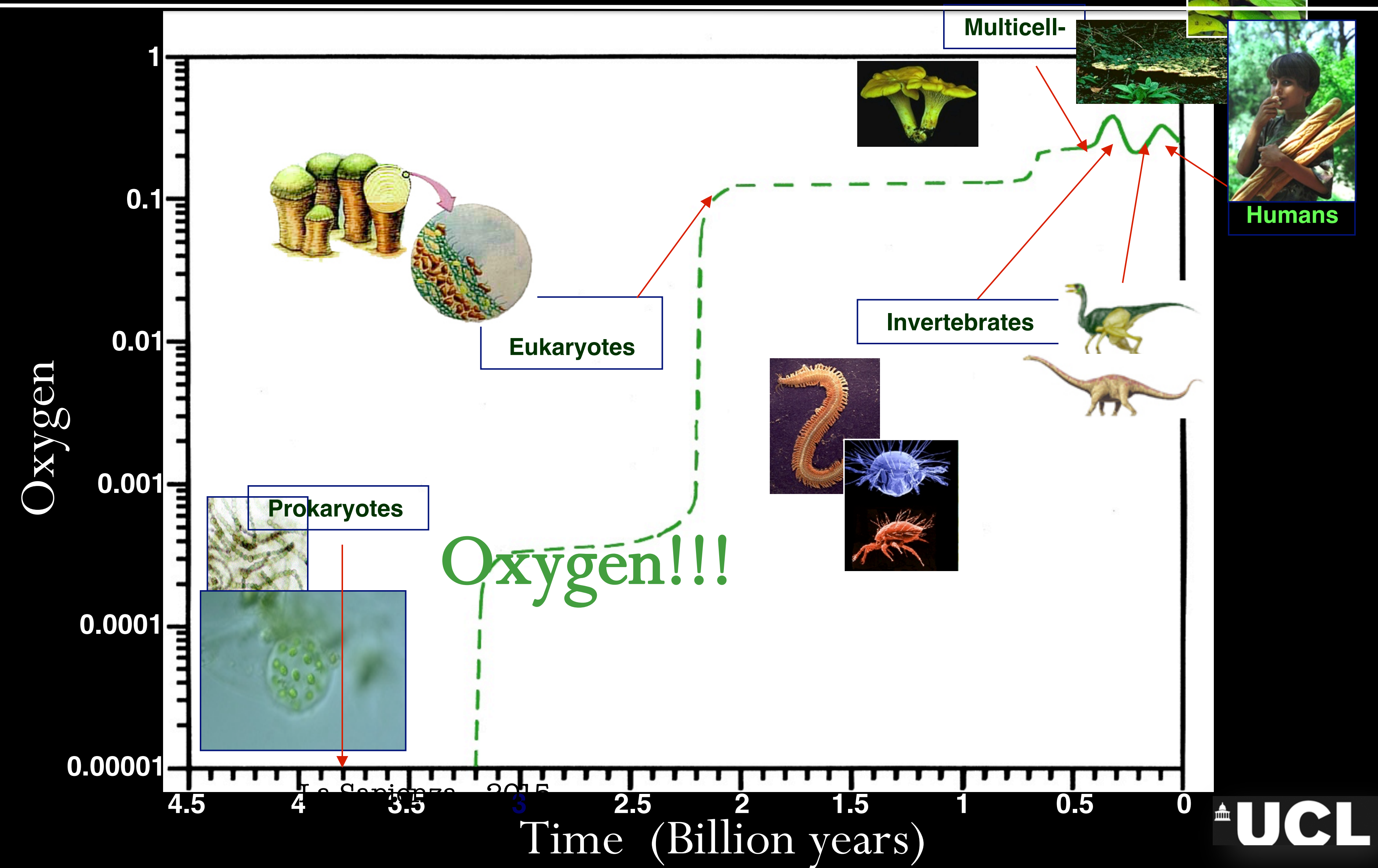
Understanding planet formation/migration)



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

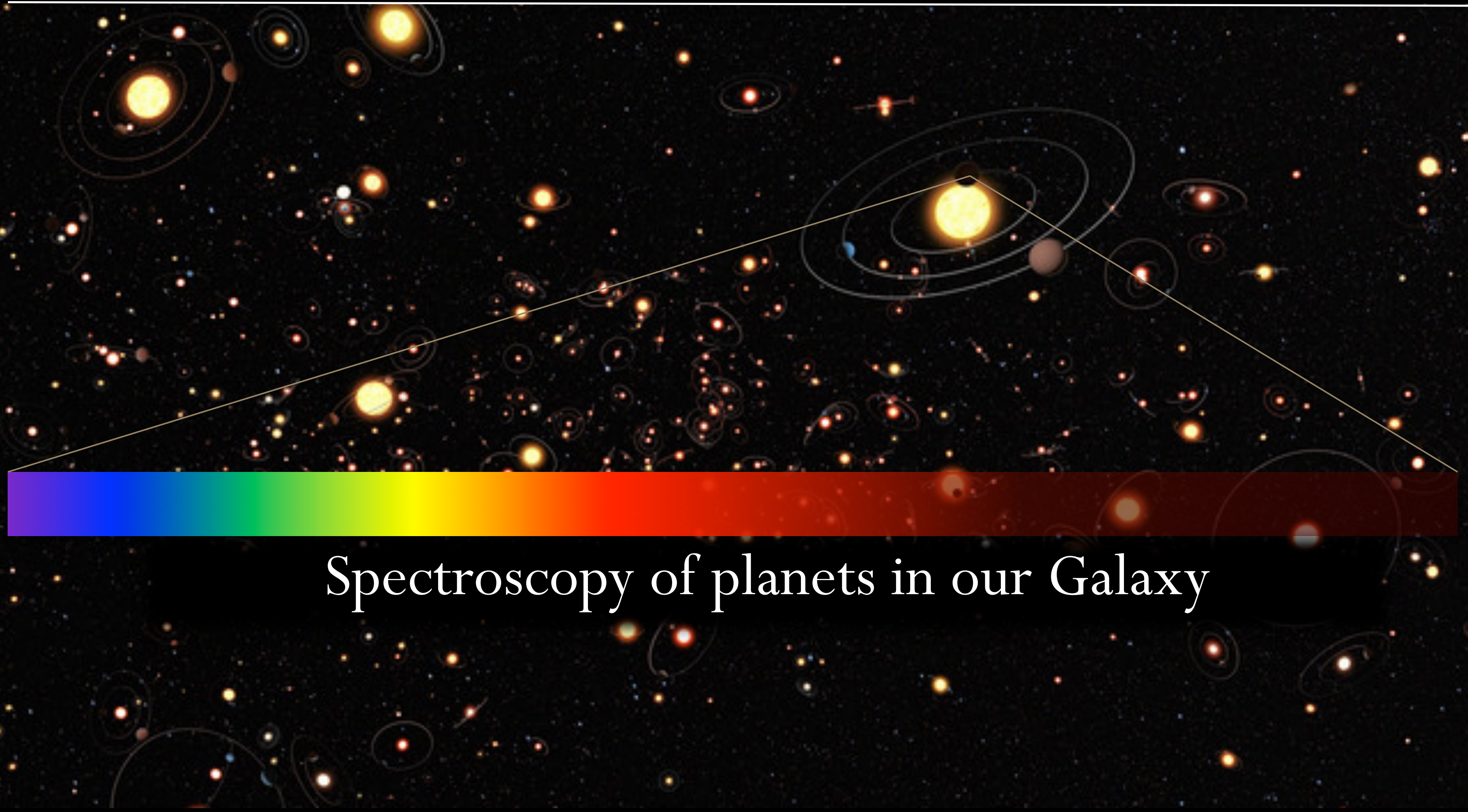
Life & Oxygen

Complexity & oxygen grows together

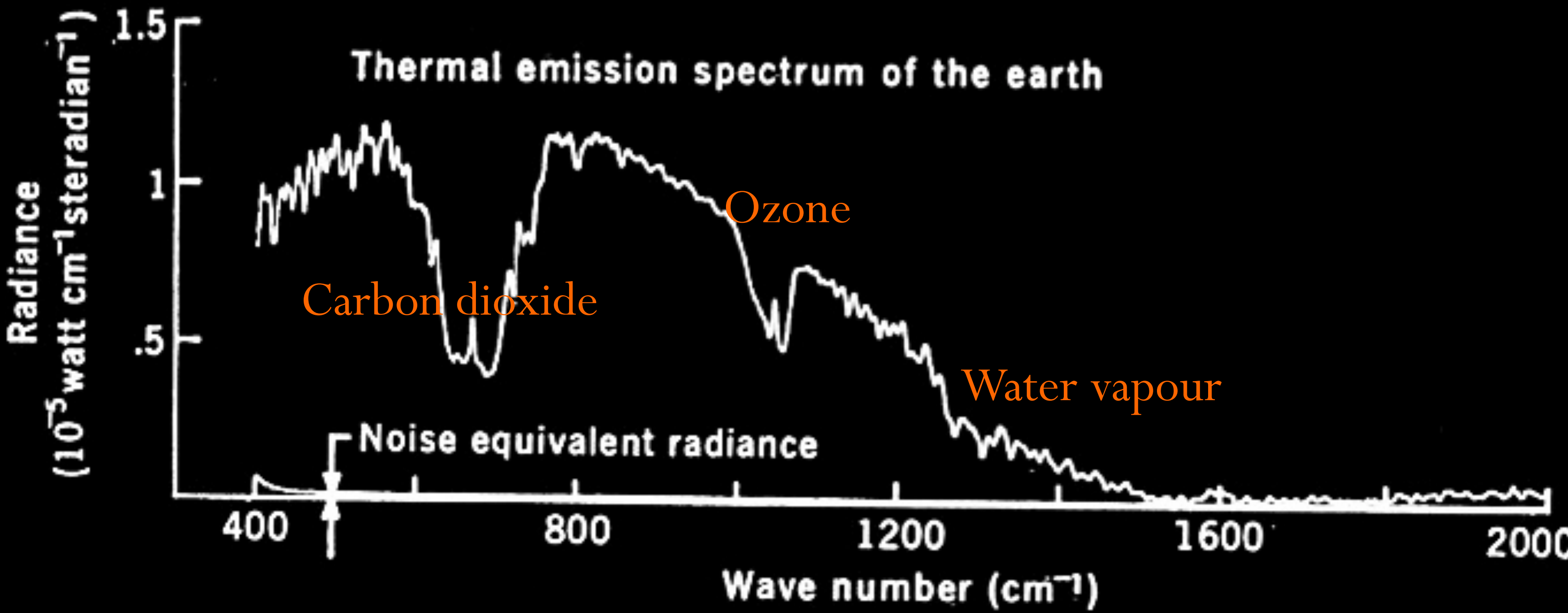


Remote exploration of exotic worlds

Beyond our Solar System

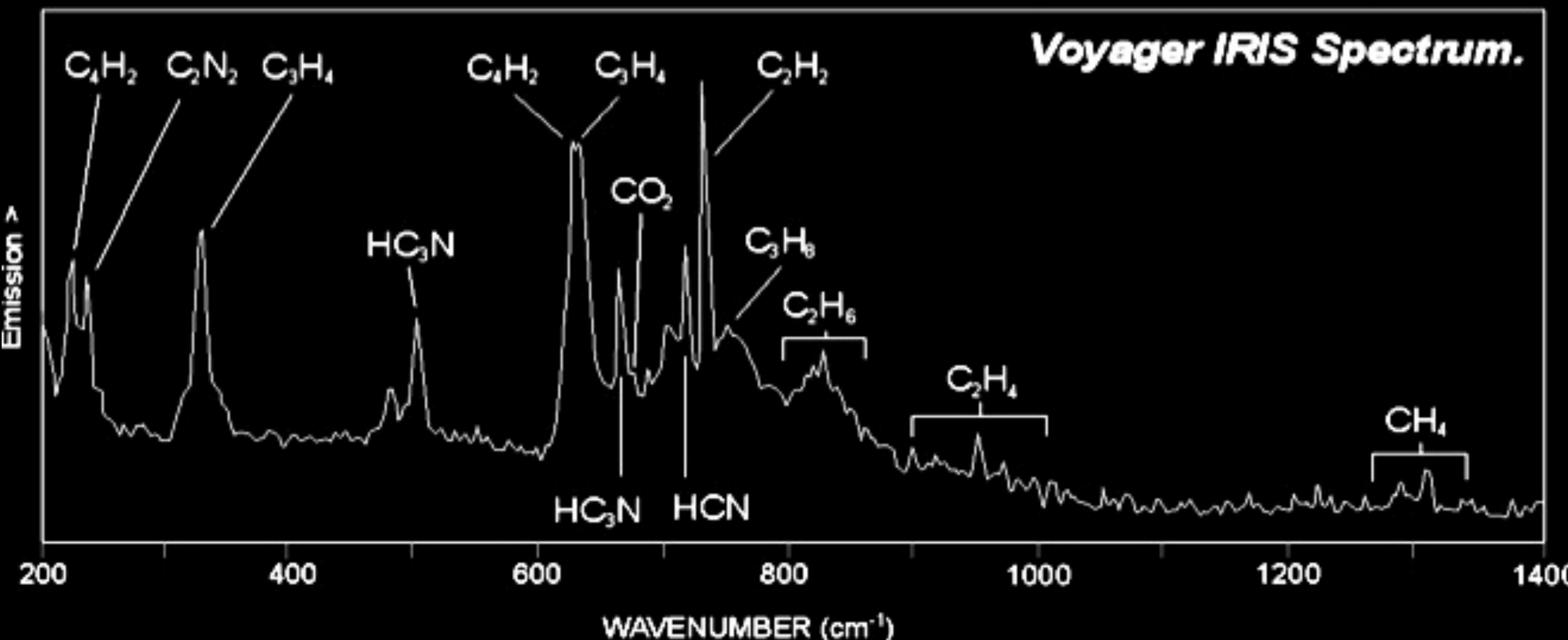


1969 – Nimbus 3: *The Earth*



Hanel & Conrath, 1969

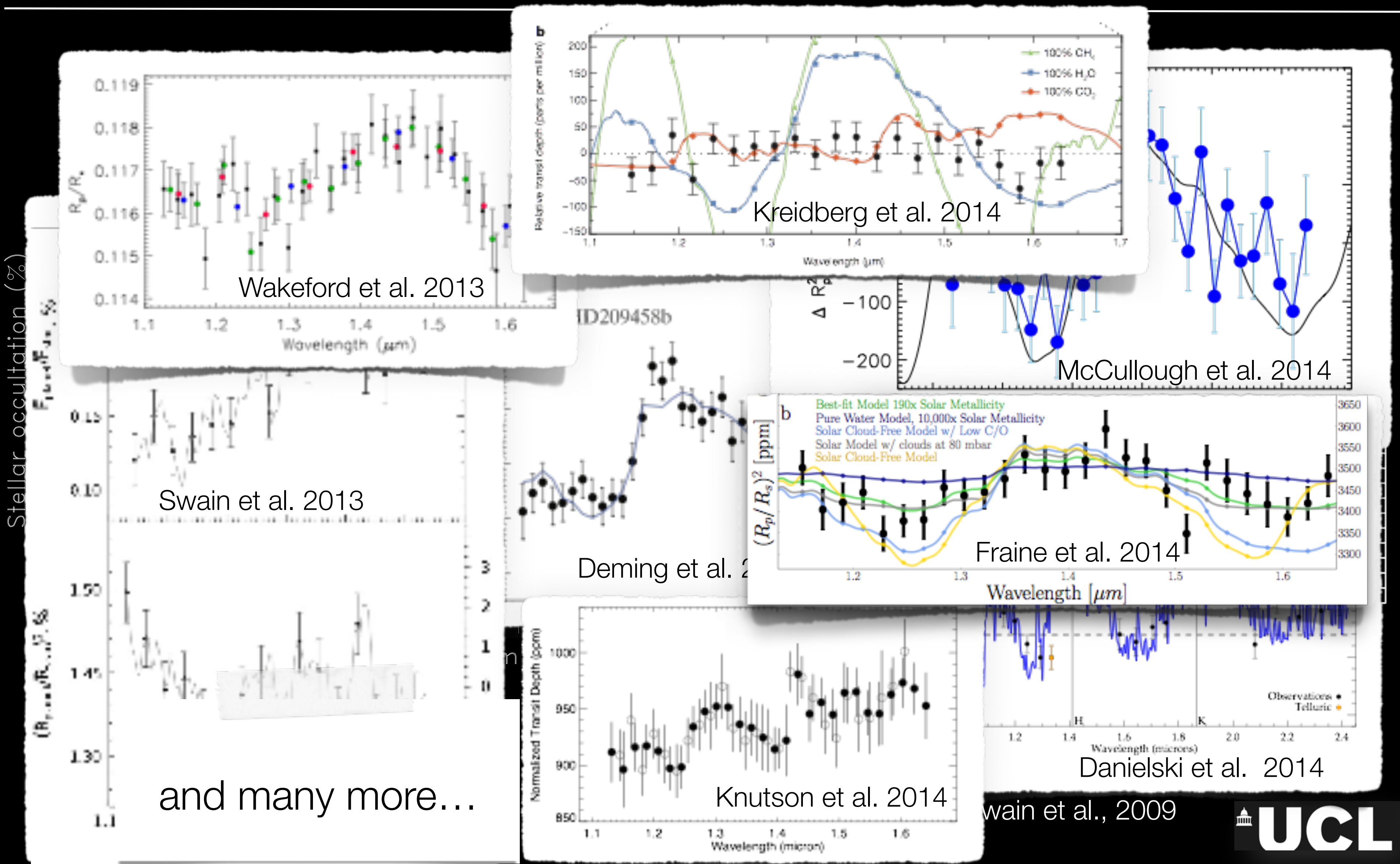
1980 – The outer solar system



Samuelson et al., 1983

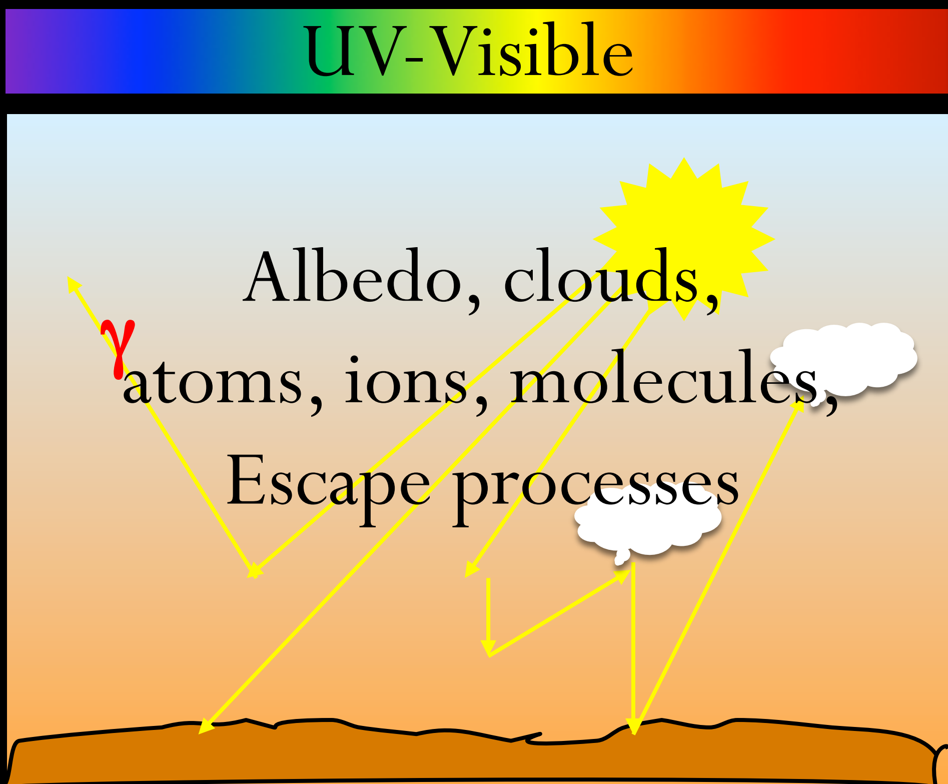
Pioneering work on Exo-Atmospheres

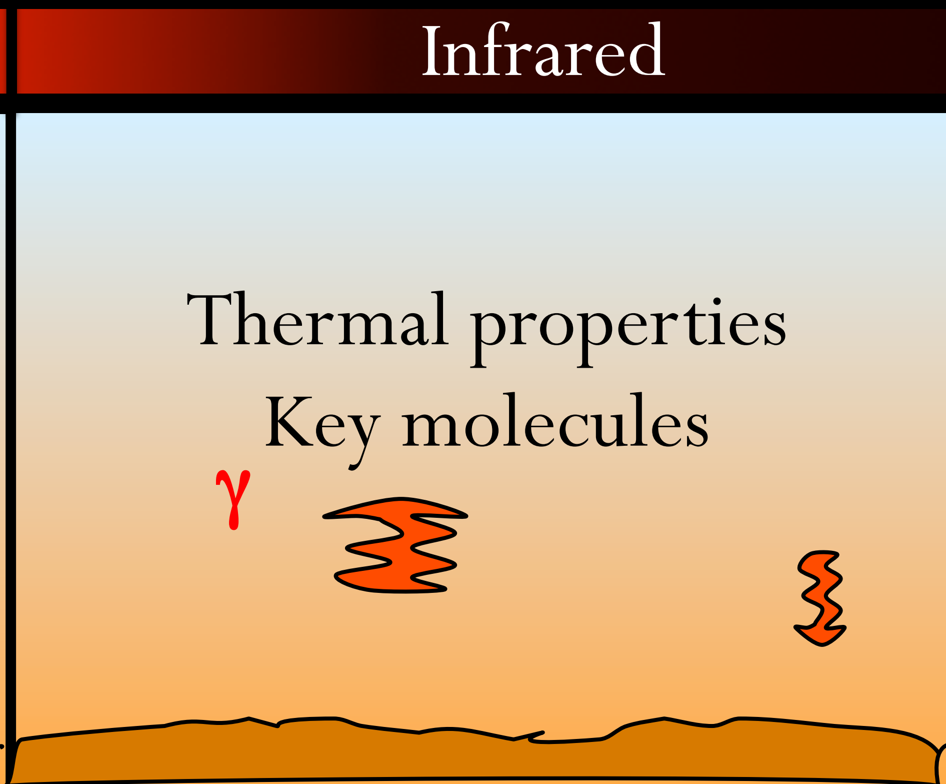
Transit spectra with Hubble, Spitzer, ground…



How to probe an exoplanet atmosphere

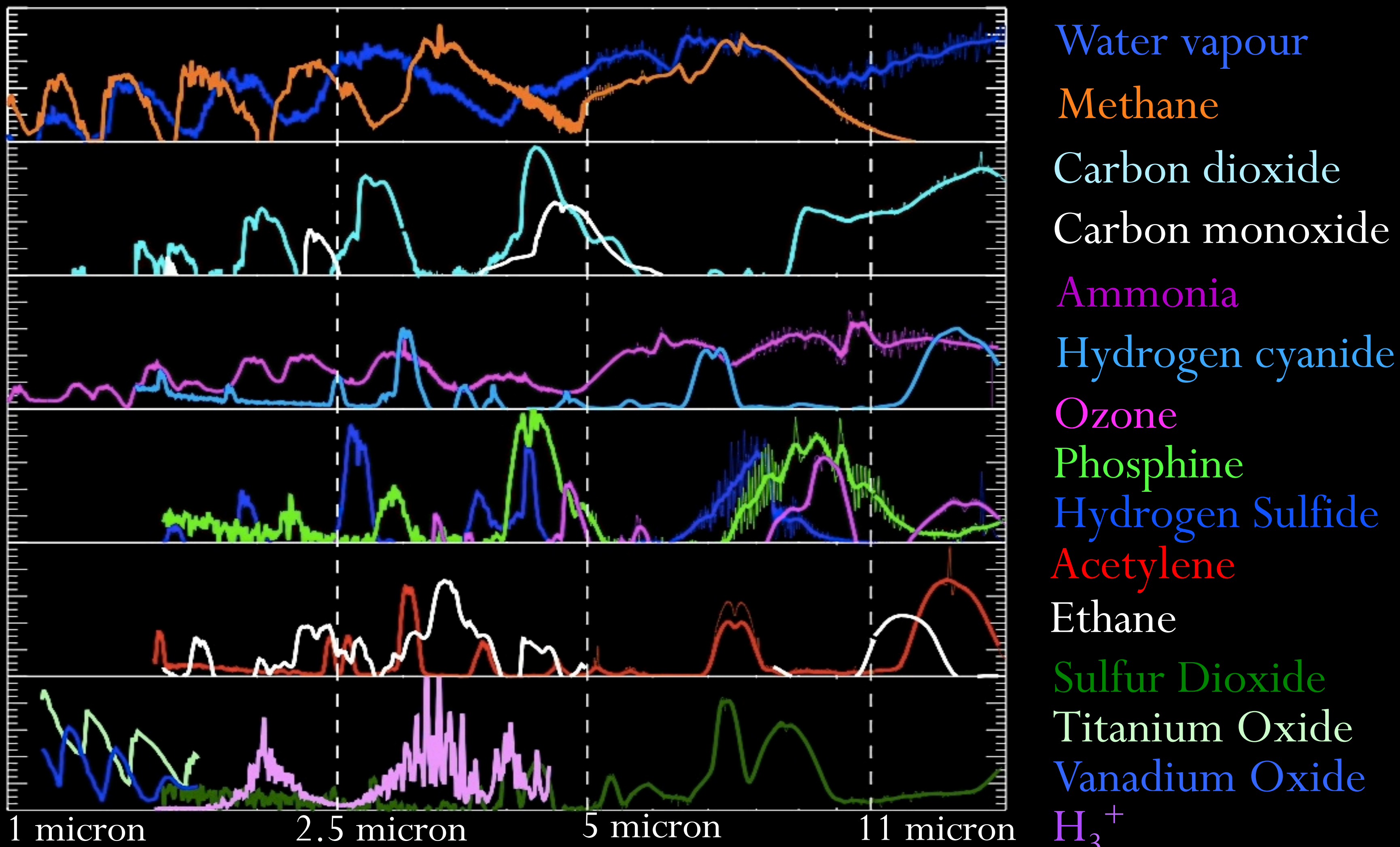
Spectral region is critical





Key molecular signatures

Infrared – rotational & vibrational bands



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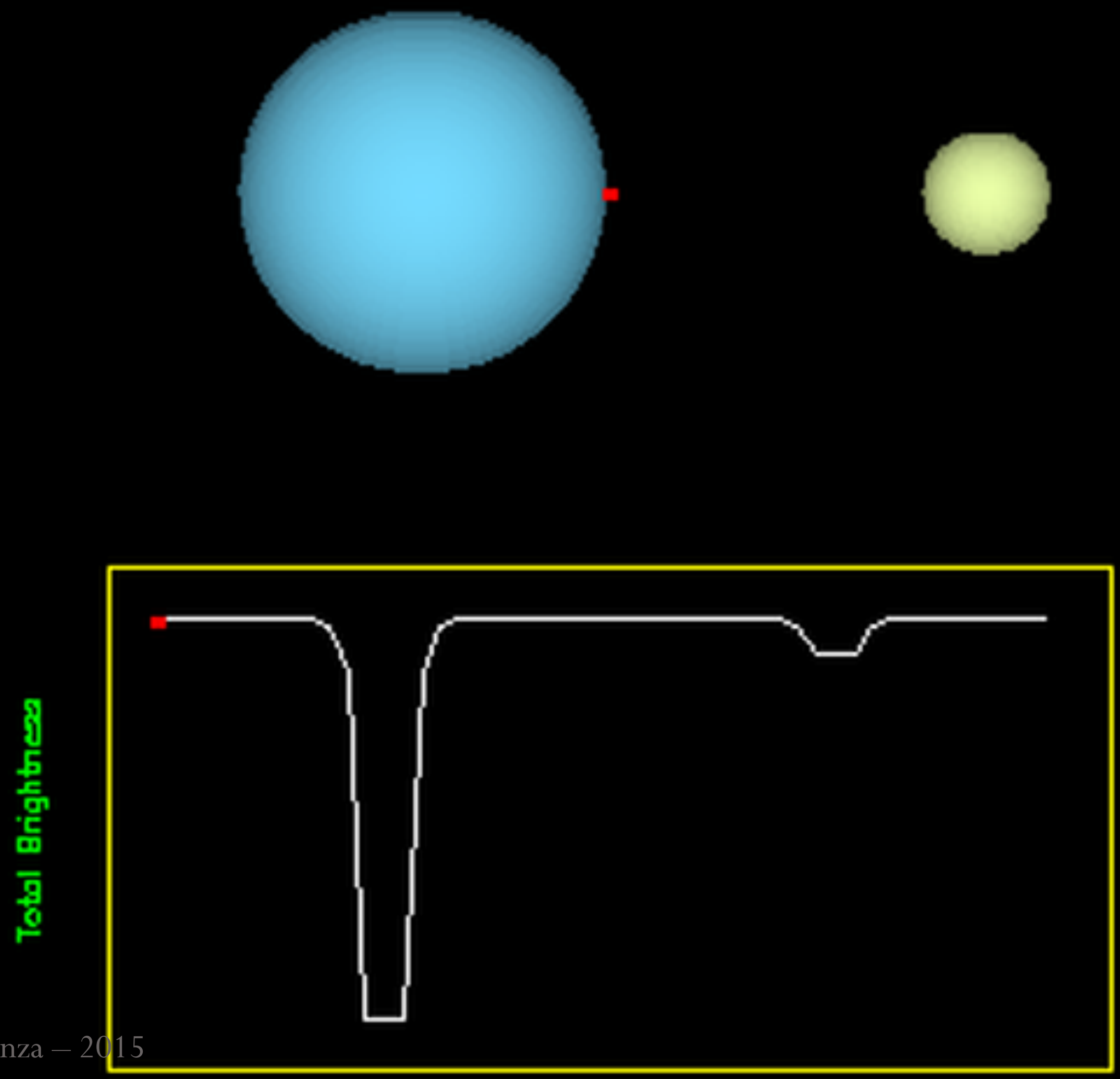
Tinetti, Encrenaz, Coustenis, 2013

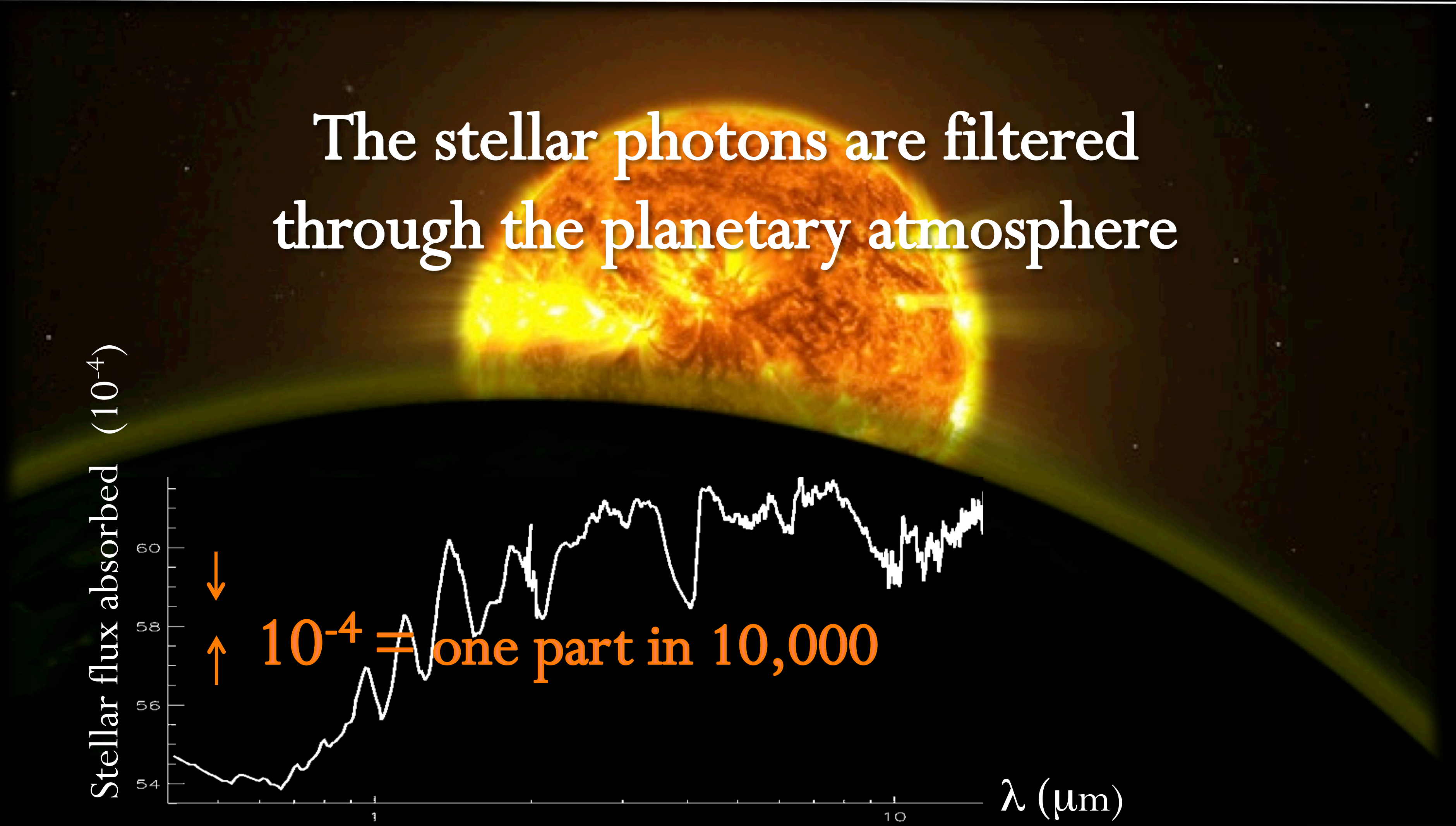
Transiting planets

Transits & eclipses



How to probe an exoplanet atmosphere

1: Transit spectroscopy



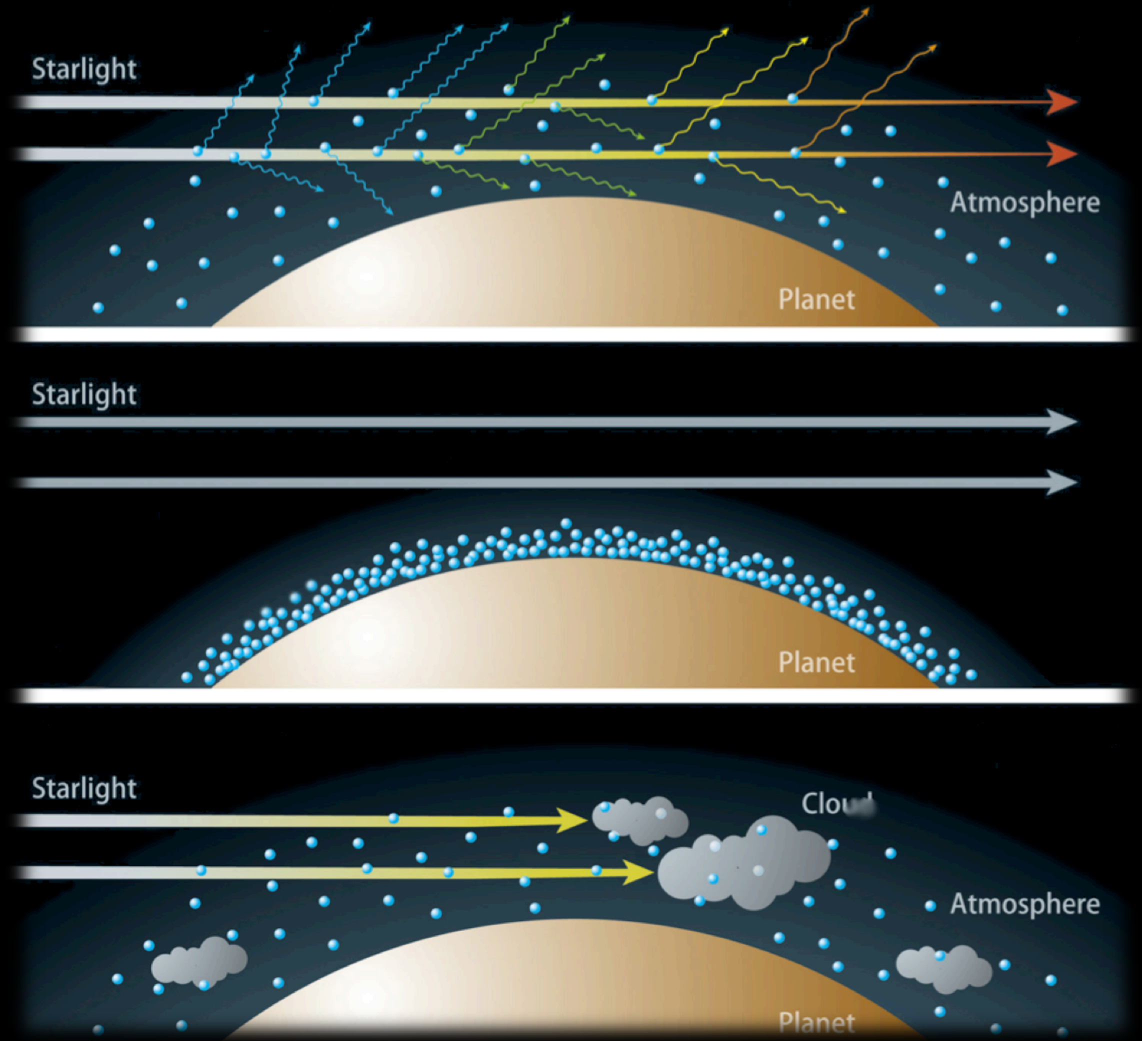
How to probe an exoplanet atmosphere

1: Transit spectroscopy

Scattering

Scale height

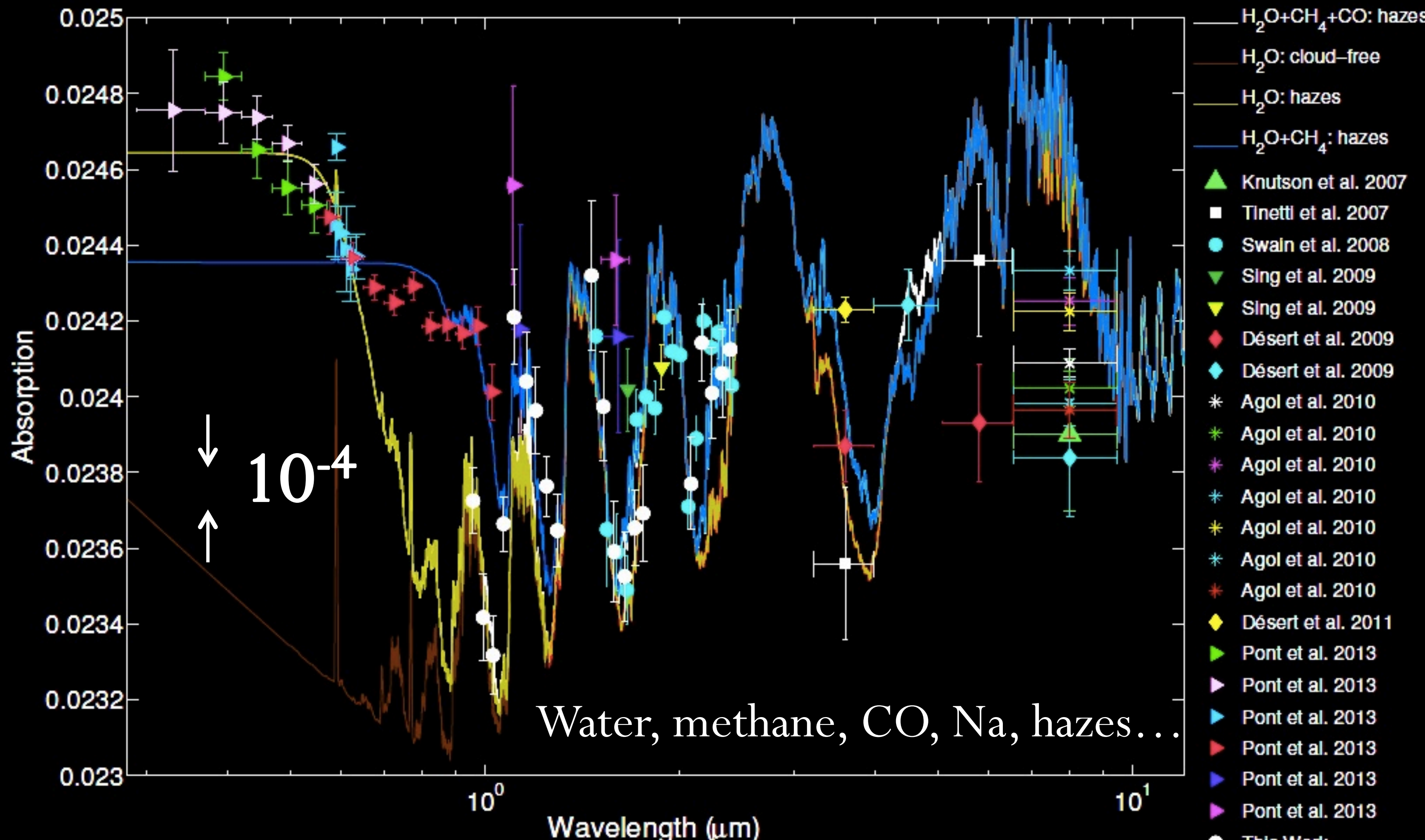
Absorption



Credit: NAOJ

Hot-Jupiters: HD189733b

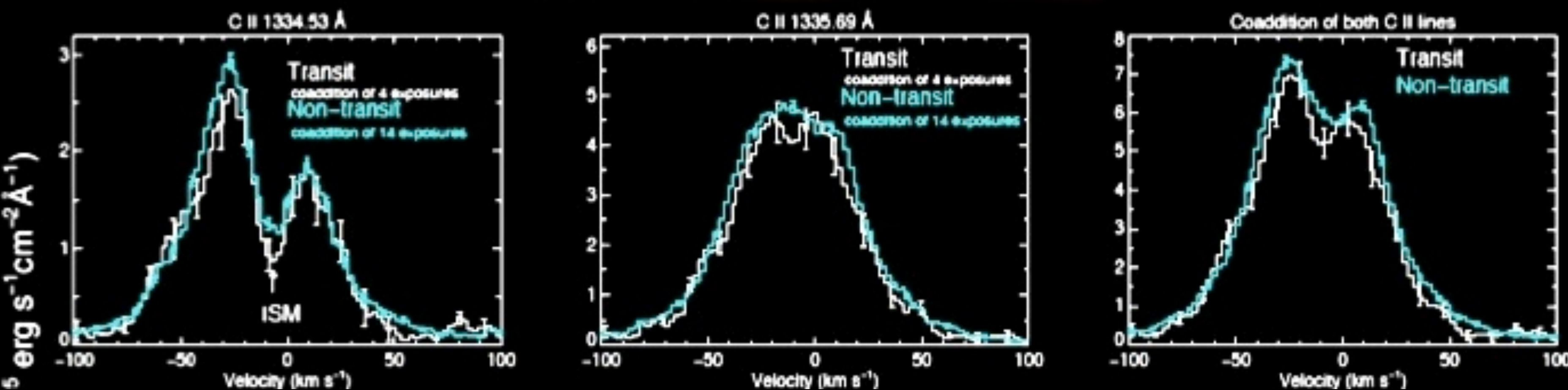
Transit spectra with Hubble, Spitzer, ground…



Danielski et al., 2014

Hot-Jupiters: HD209458b

Hydrodynamic escape: UV spectroscopy



Linsky et al, 2010

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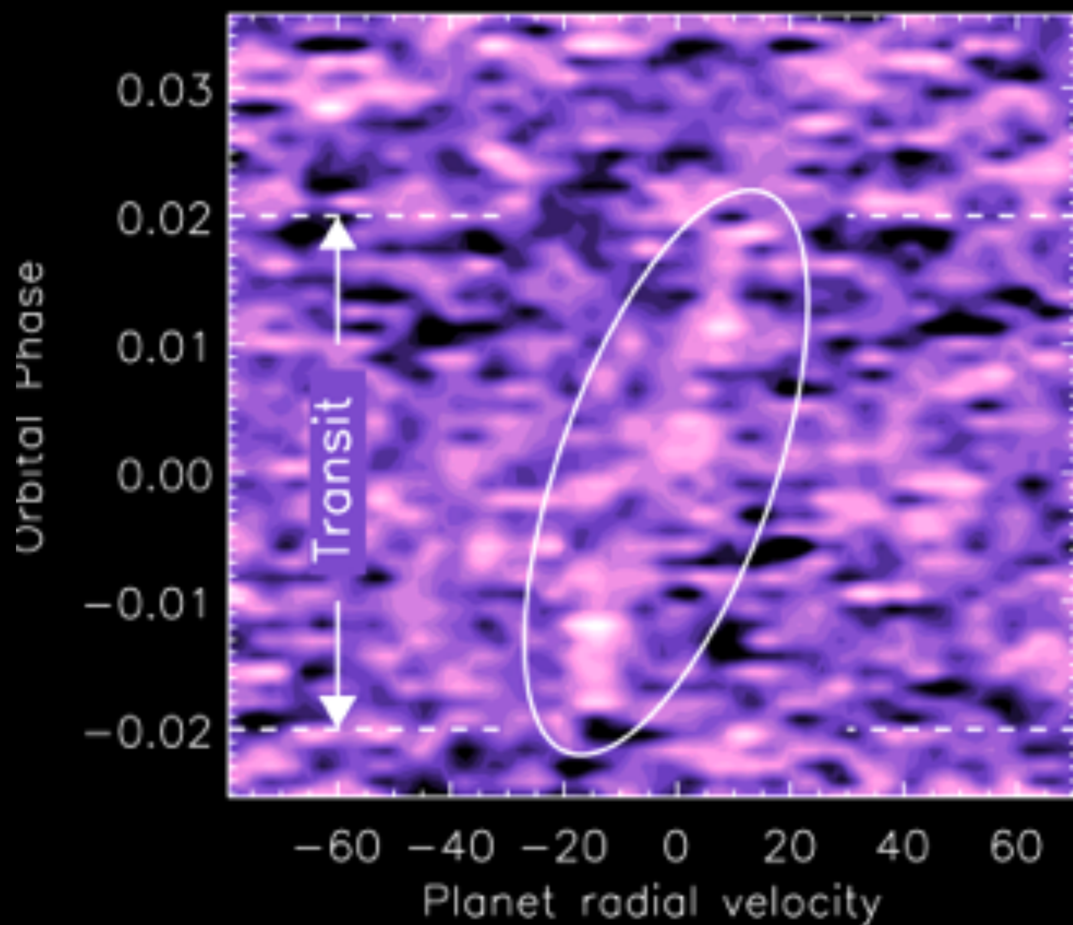
Hot-Jupiters: HD209458b

Narrow band-high-resolution from the ground



CO detection

Snellen et al., 2010

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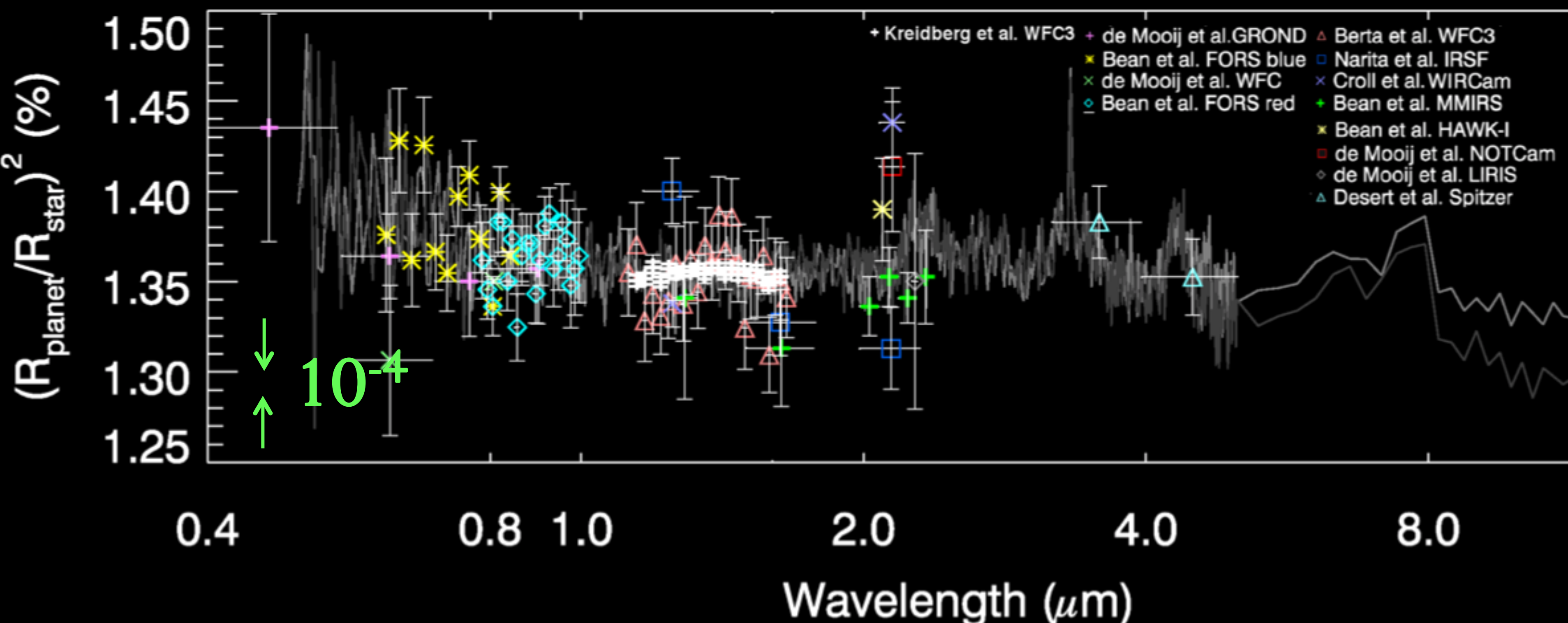
Warm super-Earths: GJ1214b

Transit spectra with Hubble, Spitzer, ground…

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



Barstow et al., 2014

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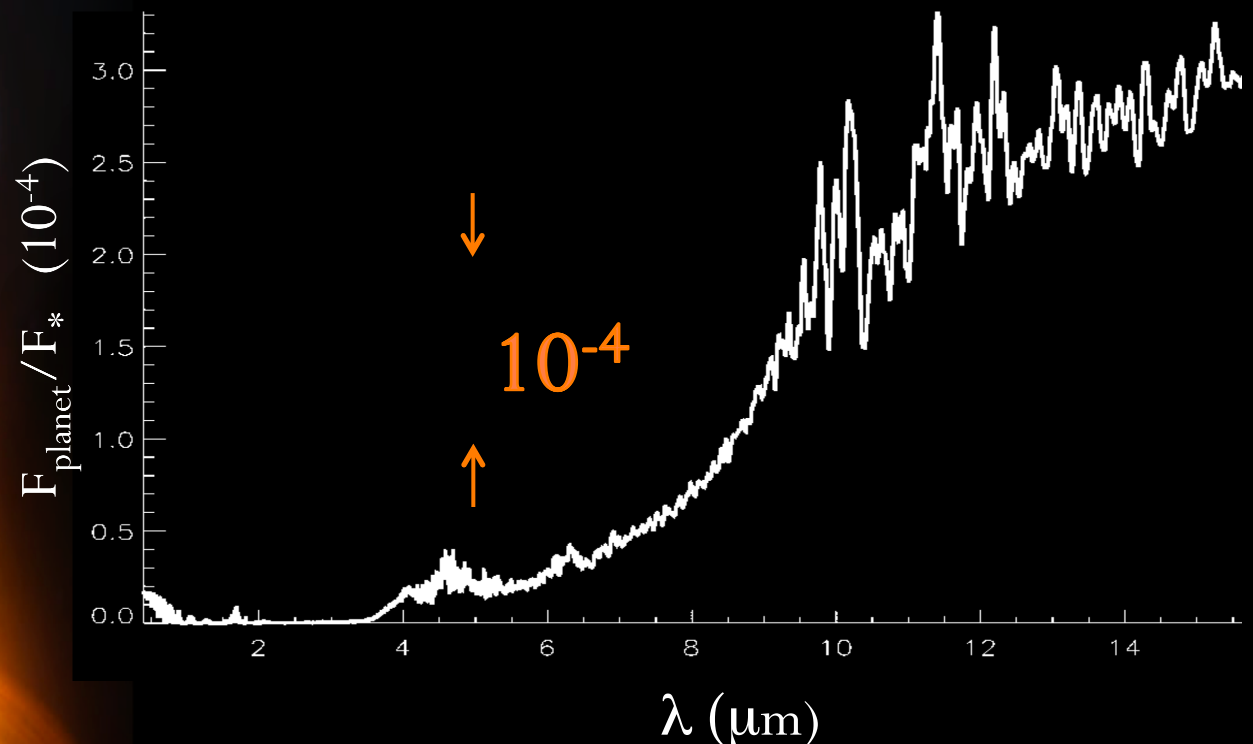
How to probe an exoplanet atmosphere

2: Eclipse spectroscopy

Using the planet ephemeris to separate the planet from the star



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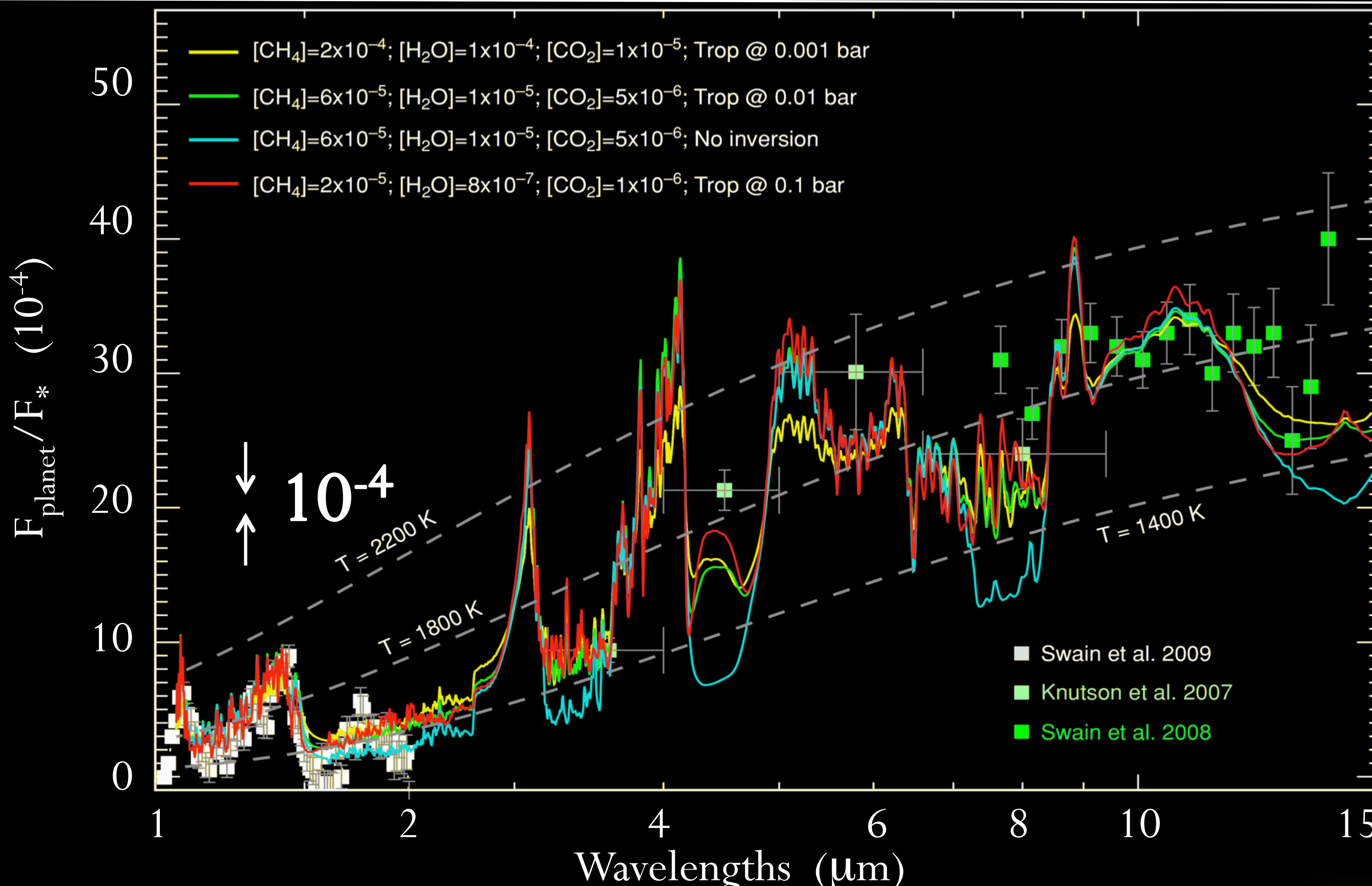
Hot-Jupiters: HD209458b

Eclipse spectra with Hubble, Spitzer, ground…



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Swain et al., 2009

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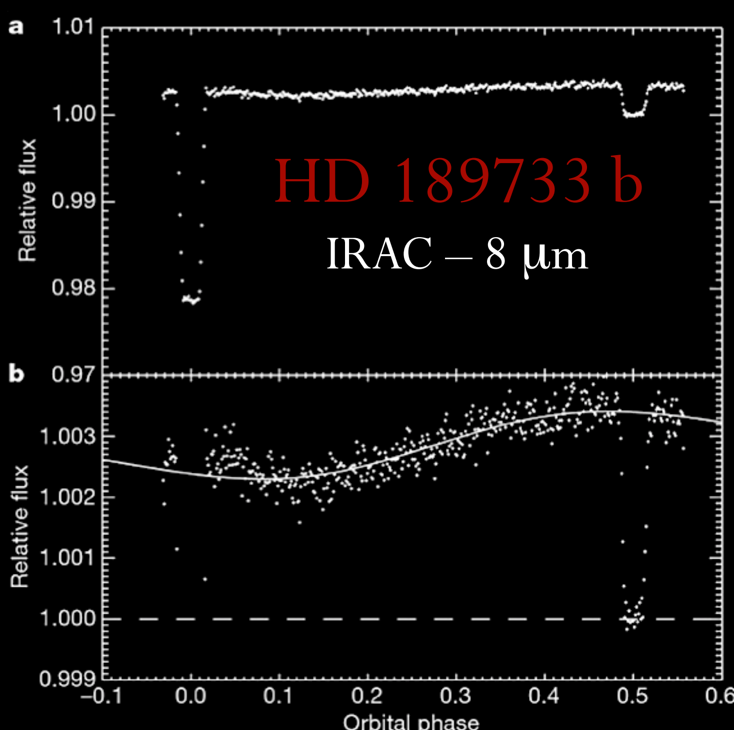
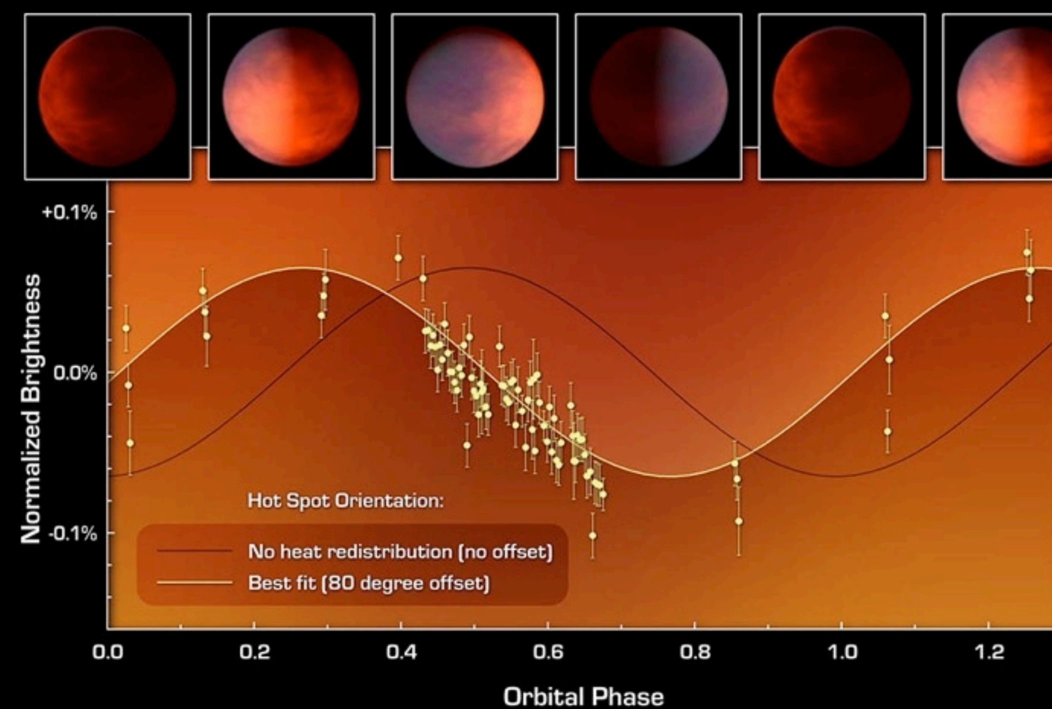
How to probe an exoplanet atmosphere

3: Phase-curves & eclipse mapping

Transiting



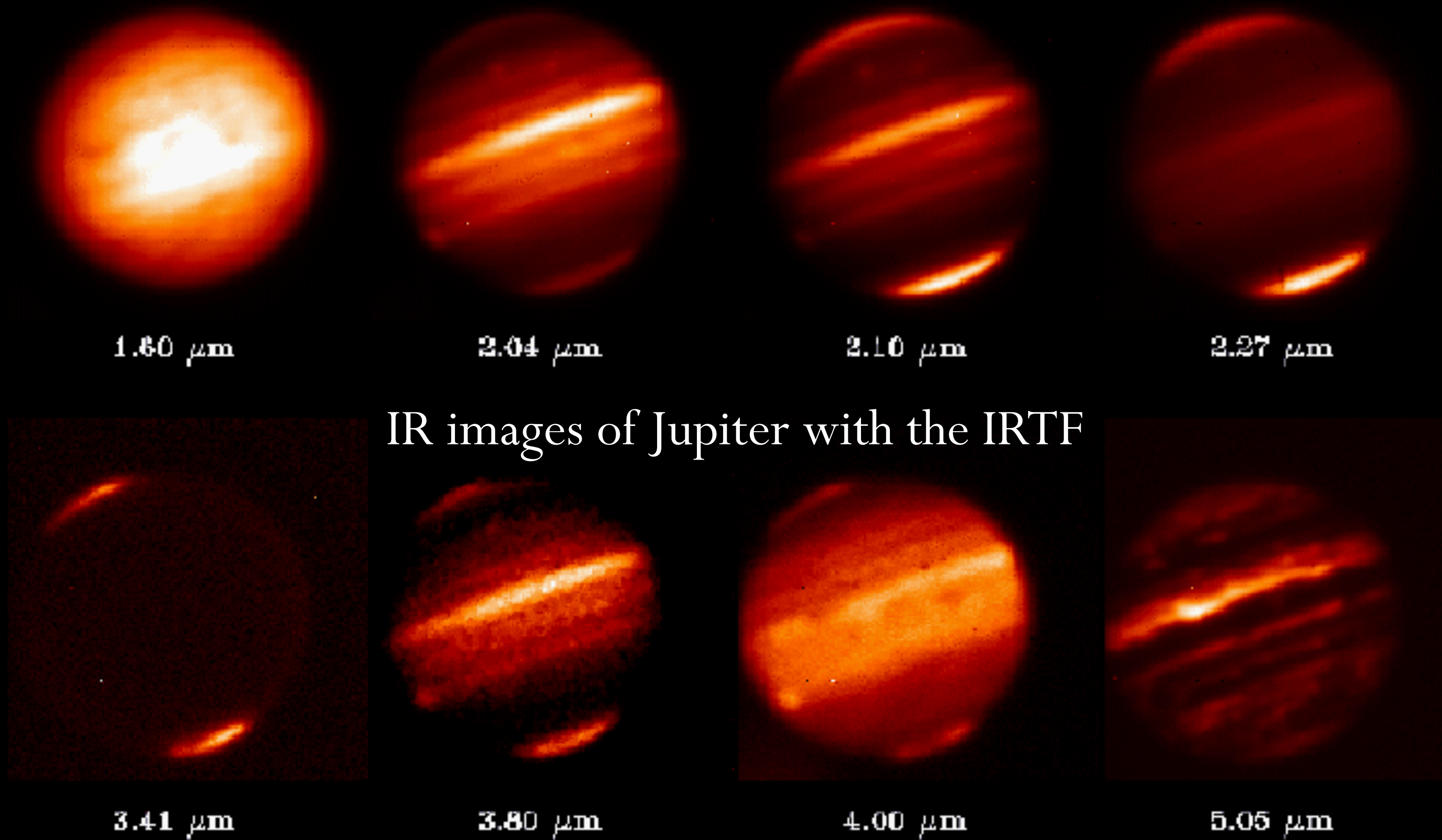
Non-transiting



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

How to probe an exoplanet atmosphere

3: Phase-curves & eclipse mapping

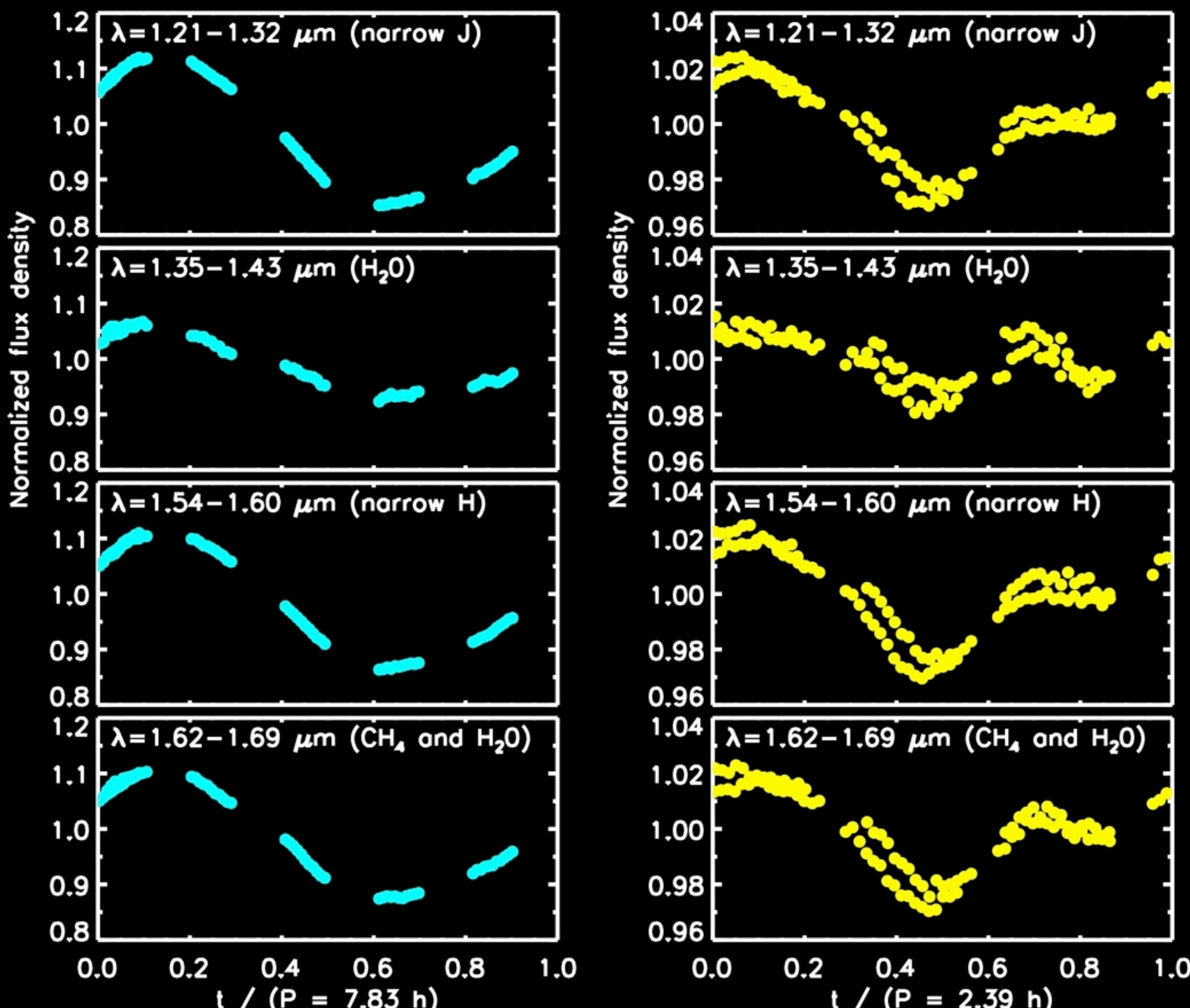


IR images of Jupiter with the IRTF

Majeau et al., 2012

How to probe an exoplanet atmosphere

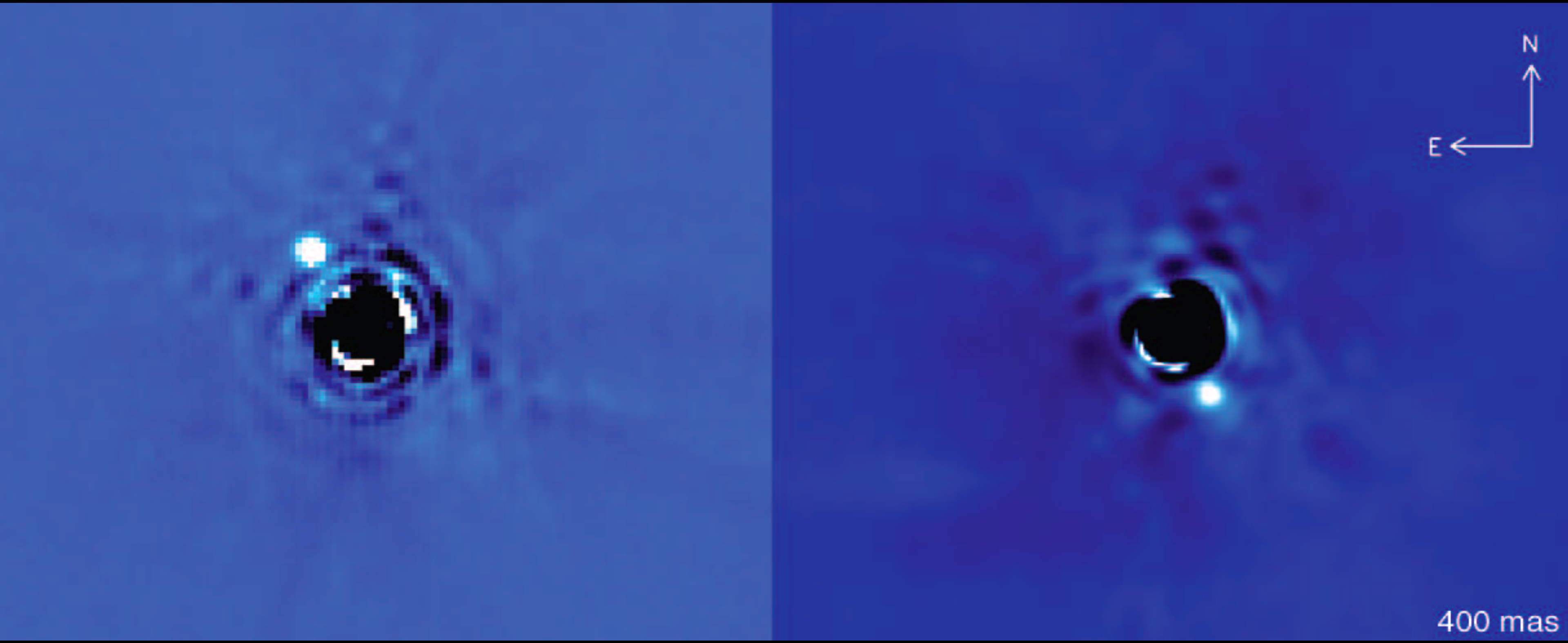
4: Temporal variability (Weather)



Apai et al., 2013

How to probe an exoplanet atmosphere

5: Direct imaging spectroscopy



Lagrange et al., 2010

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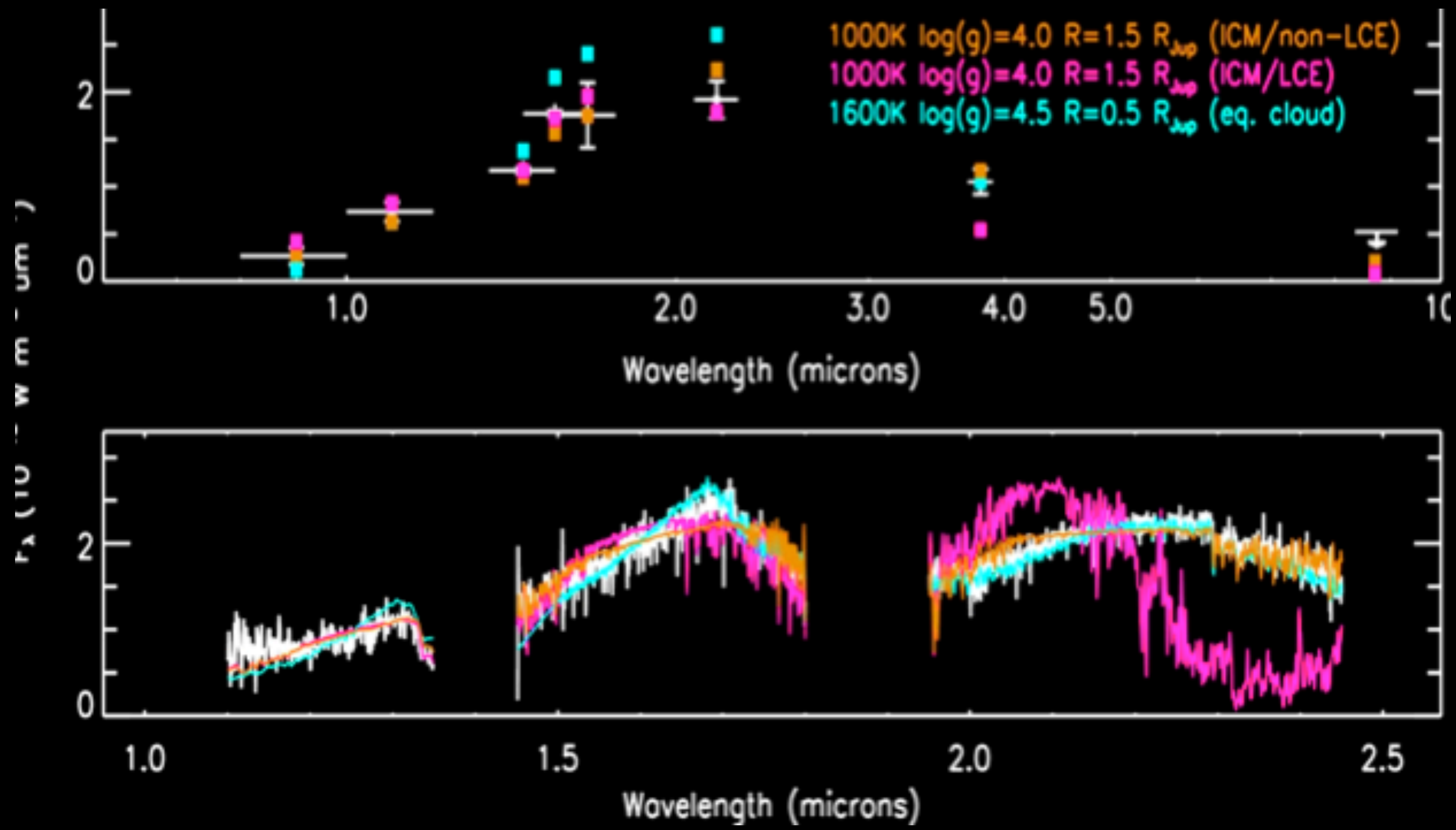
How to probe an exoplanet atmosphere

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



Barman et al., 2011

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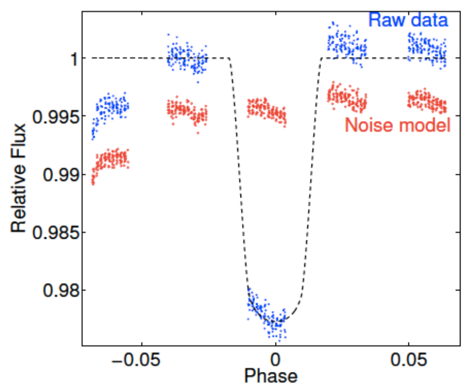
Issues with current observations

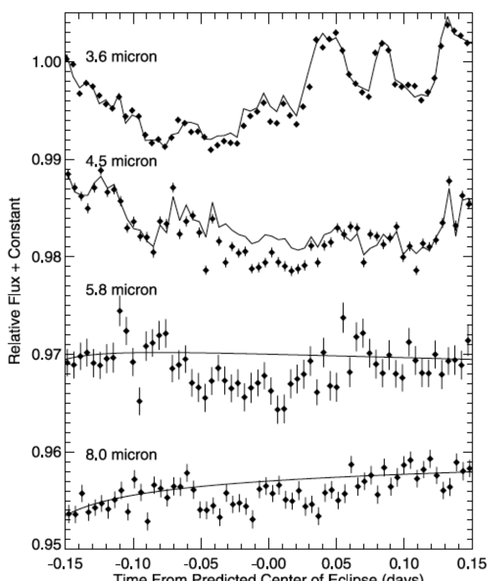
- We are dealing with low *Signal to Noise & Resolution* observations
- Data are sparse, not enough wavelength coverage
- Broad wavelength coverage is not simultaneous
- Absolute calibration at the level of 10^{-4} is **not** guaranteed
- Instrument systematics are difficult to disentangle from the signal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

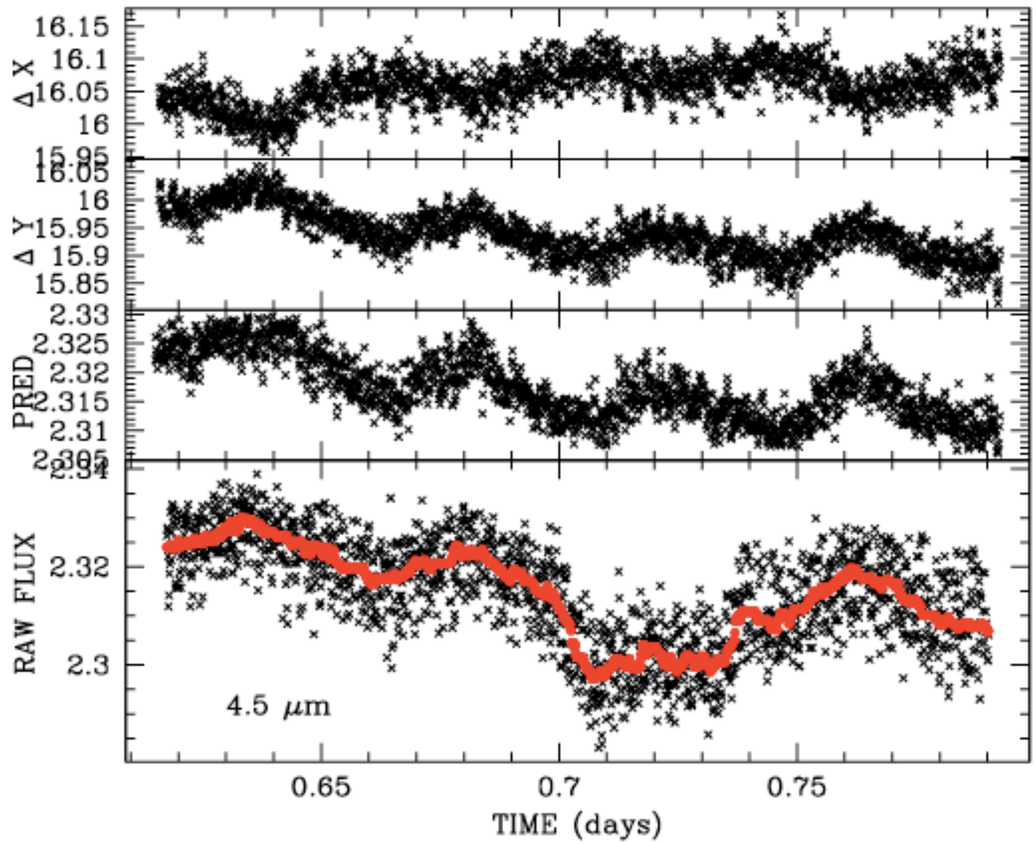
Tinetti, 2014

Instrument systematics

The best of worst of current instruments

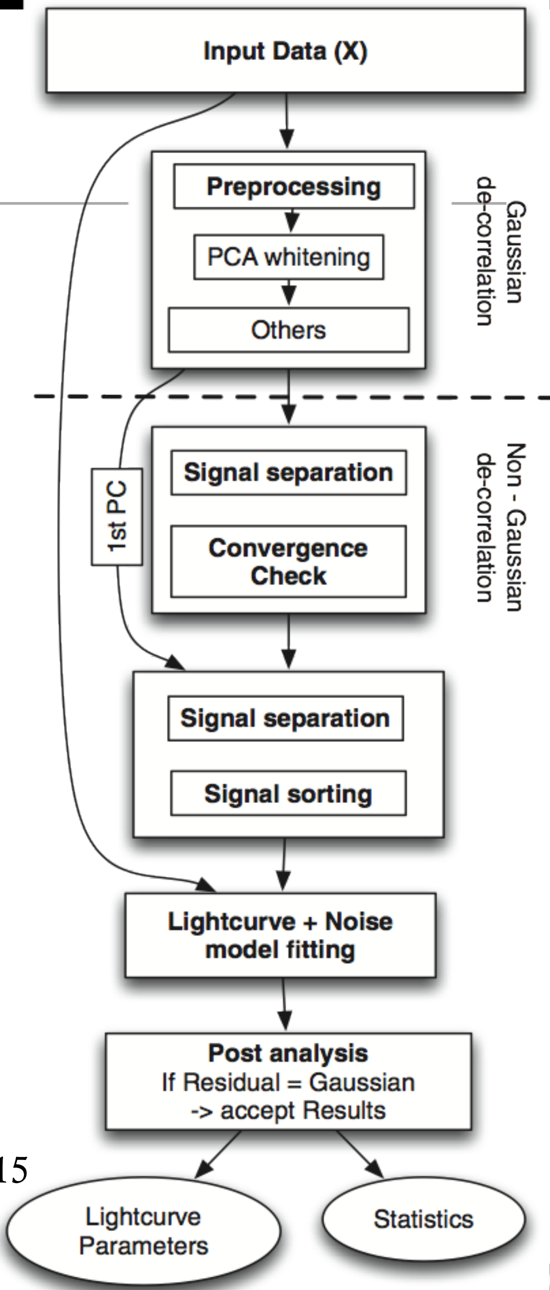






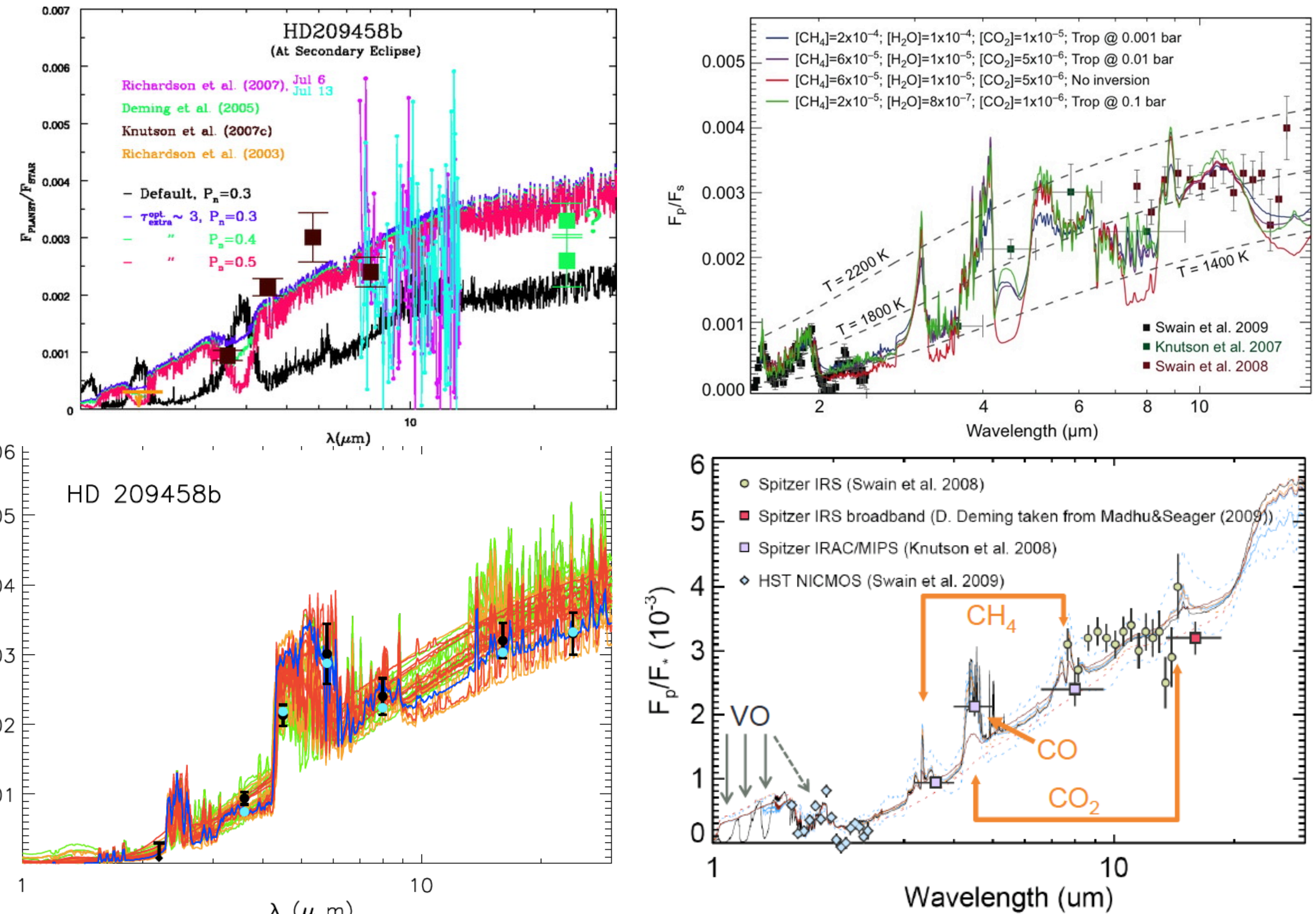
Instrument systematics

- 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, 2013, 2014; Morello et al., 2014, 2015

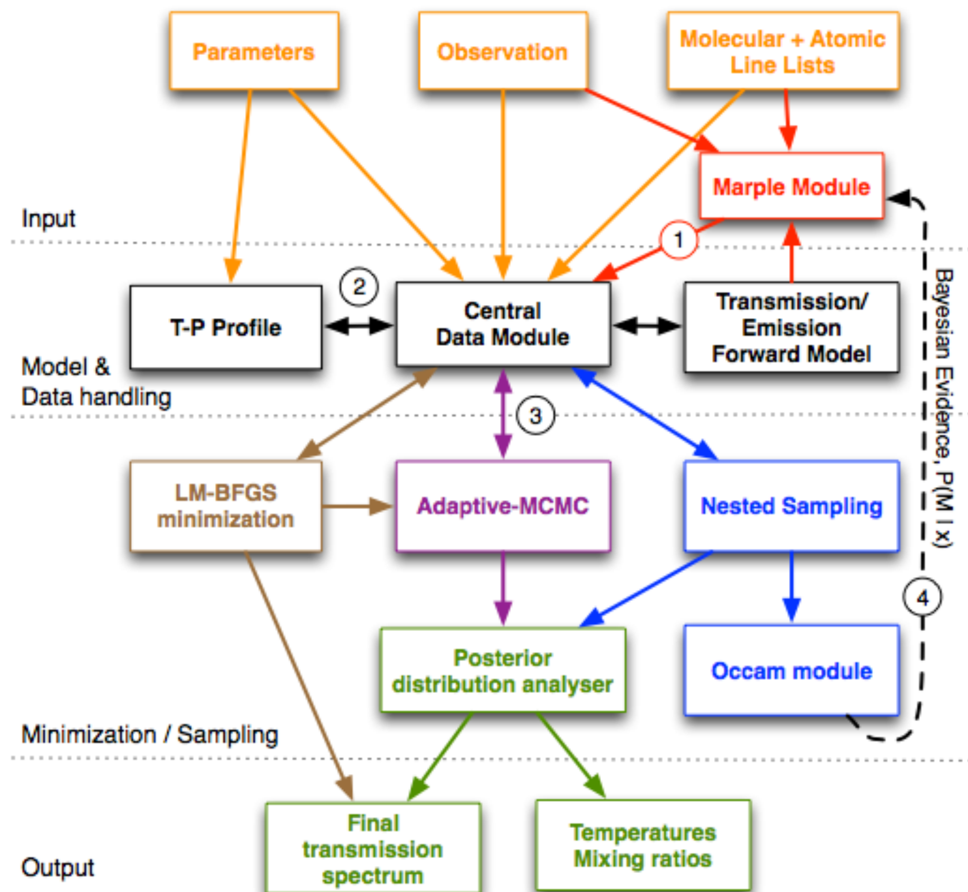
Spectral retrieval:
how to handle the degeneracy of interpretation

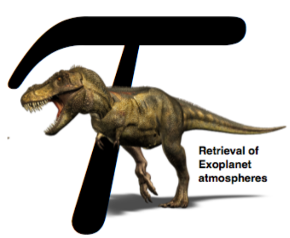


Burrows et al. 2007; Swain *et al.*, 2009; Madhu & Seager; Lee, Fletcher, Irwin, 2012;

Tau-Rex: the next generation of spectral retrieval

- **Fully Bayesian Retrieval**
  - MCMC
  - Nested Sampling
- **Custom made opacity line-lists** from the ExoMol project
- Prior composition selection through **pattern recognition software**
- **Full parallelisation for cluster computing**





arXiv:1409.2312

Waldmann et al., ApJ, 2015

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The Marple Module

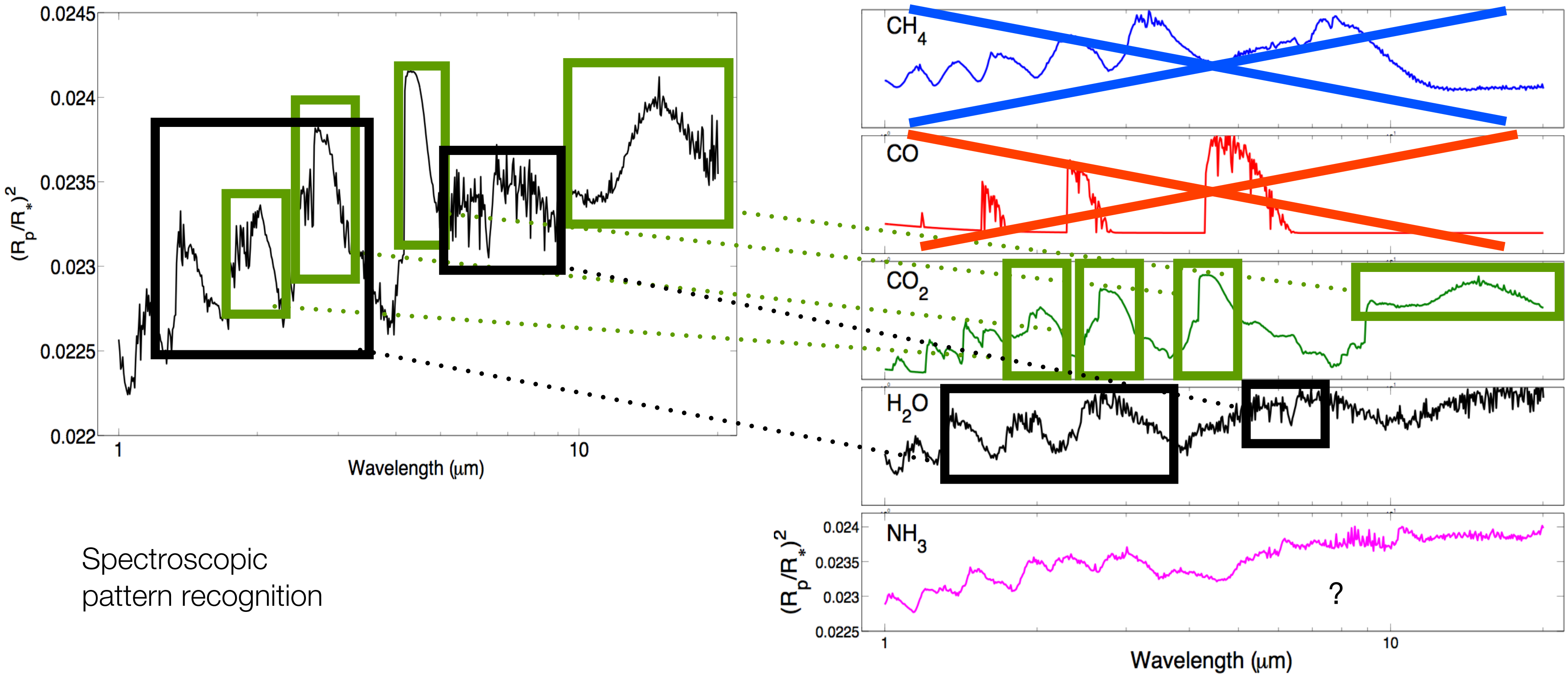
- Constrain prior space by finding most likely absorbers.
- Custom built pattern recognition
- Based on ‘eigenface’ facial recognition

arXiv:1409.2312

The Marple Module - Constraining the prior space

Observed Spectrum

Individual molecules



Spectroscopic
pattern recognition

arXiv:1409.2312

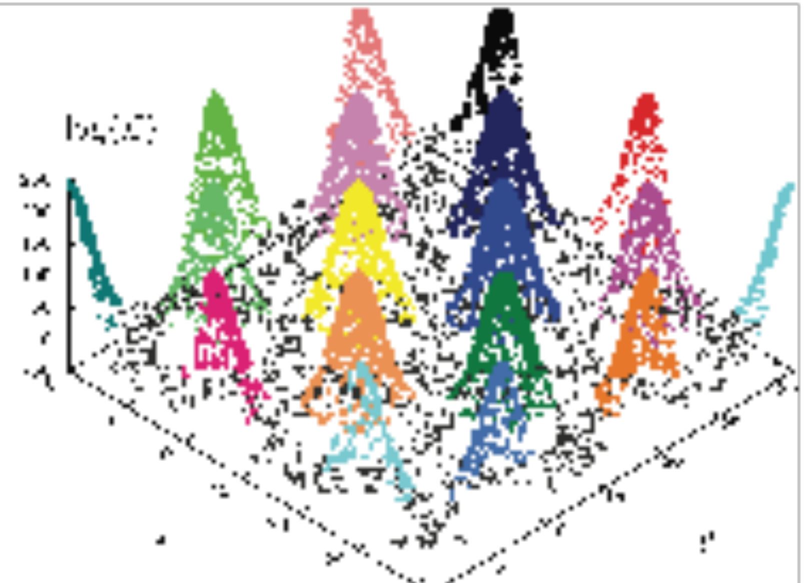
Waldmann et al., ApJ, 2015

The Occam module - Bayesian Model Selection

Bayesian Evidence

$$E = \int P(\boldsymbol{\theta}|\mathcal{M})P(\mathbf{x}|\boldsymbol{\theta},\mathcal{M})\mathrm{d}\boldsymbol{\theta}$$

- Using MCMC and Nested Sampling
- Fully map the likelihood space
- Global model selection
  (Bayesian Evidence)
- Nested model selection
  (Savage Dickey Ratio)



Feroz et al. 2009

Waldmann et al., ApJ, 2015

arXiv:1409.2312

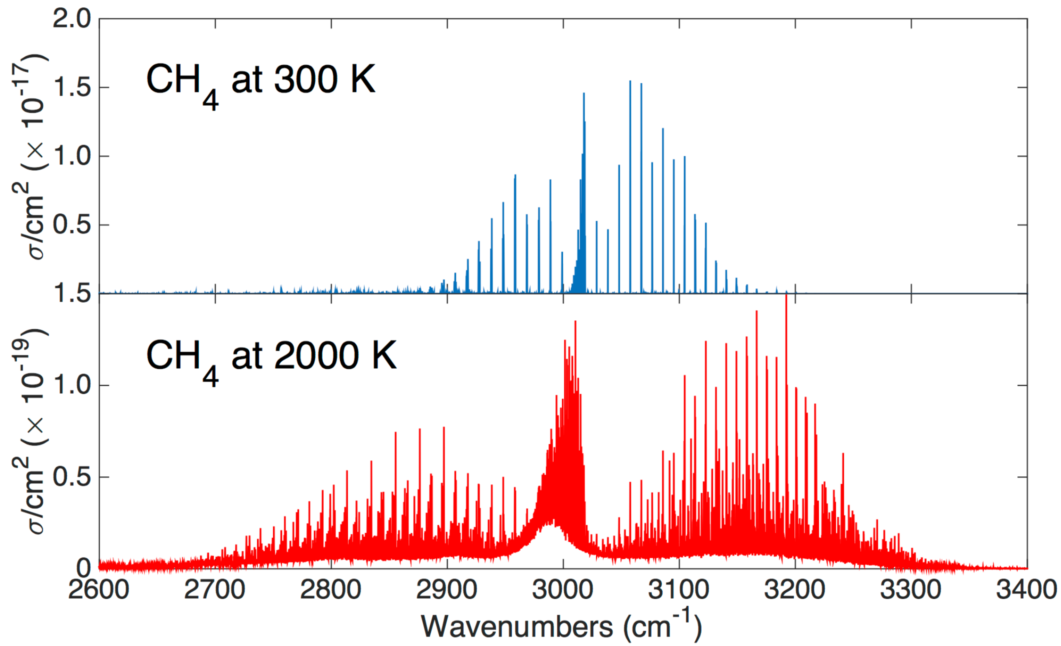
Custom built line lists

High temperature ExoMol line-lists

Line-by-line forward model

Non-linearly sampled for optimal computation

Exact line broadening



Waldmann et al., ApJ, 2015

arXiv:1409.2312

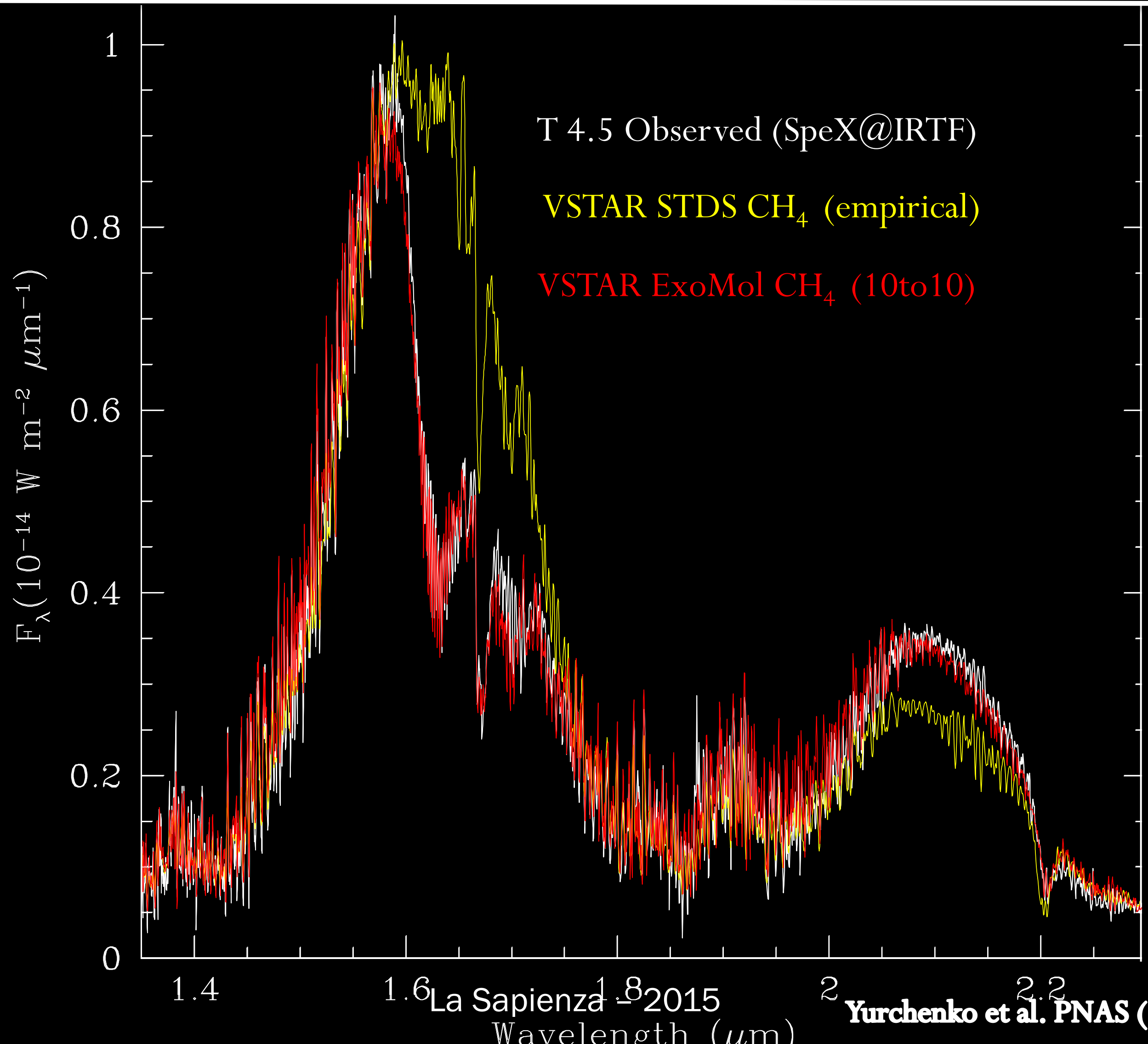
Molecular line lists for exoplanets & other atmospheres

H_2										Already available
LiH	OH				BeH	H_2S	KCl	HCN	HNC	
HeH^+	NO		HCl	CH_4	NaCl	SiO	MgH	CH	CN	
H_3^+	O_3	CO_2	HDO	H_2O	NH_3	CaH		CO	CO_2	
H_2D^+	O_2	HOOH	HNO_3		VO	FeH	AlH	C_3	C_2H_2	To-Do
	SO_3	H_2CO	PH_3	CH_3D	YO	AlO			C_2H_4	
	P_2H_2	SO	HF	SO_2	NiH	TiH	SiH	CH_3Cl	C_2H_6	
		PN	NaH	H_2S	CrH			ScH	C_3H_8	
				SH	C_2		TiO			

Yurchenko & Tennyson, (2014)

10^{10} to fit T dwarf spectrum

2MASS 0559-14



Yurchenko et al. PNAS (2014)

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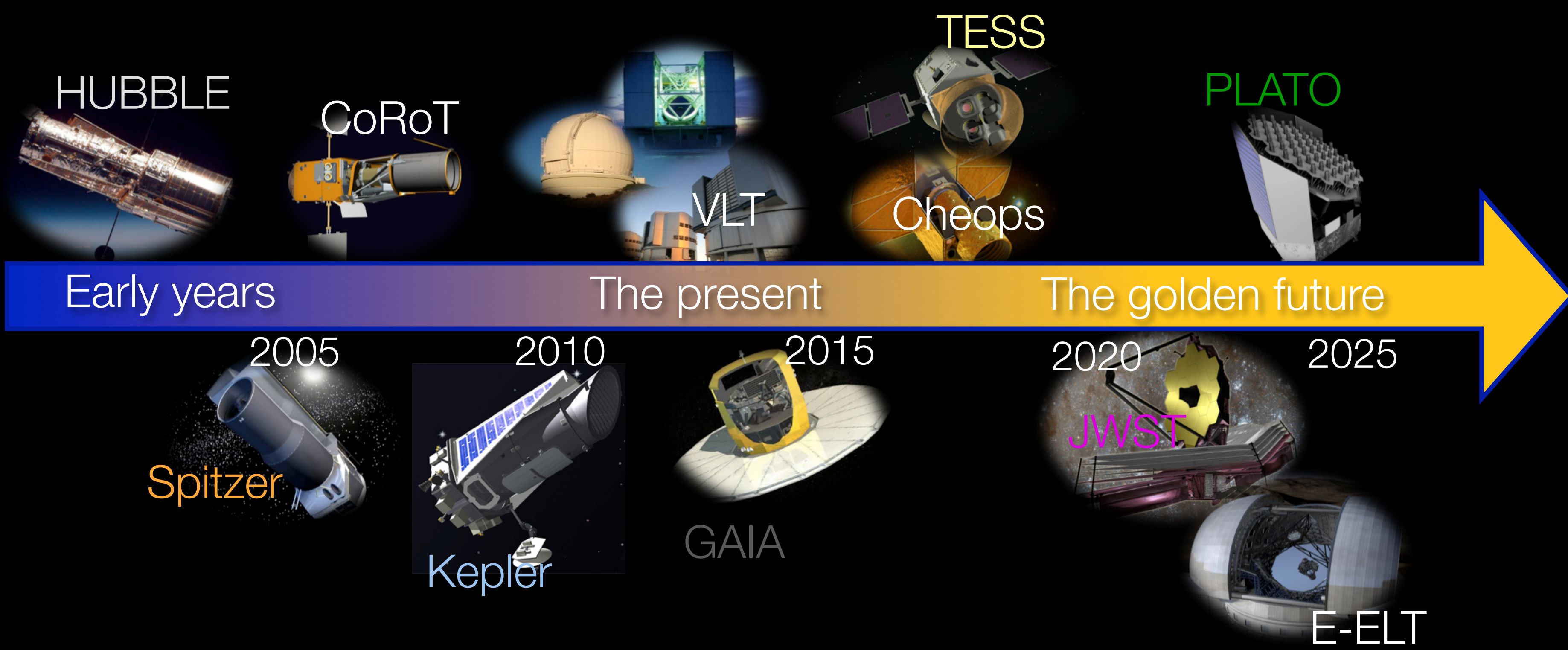
The future

More and better observations



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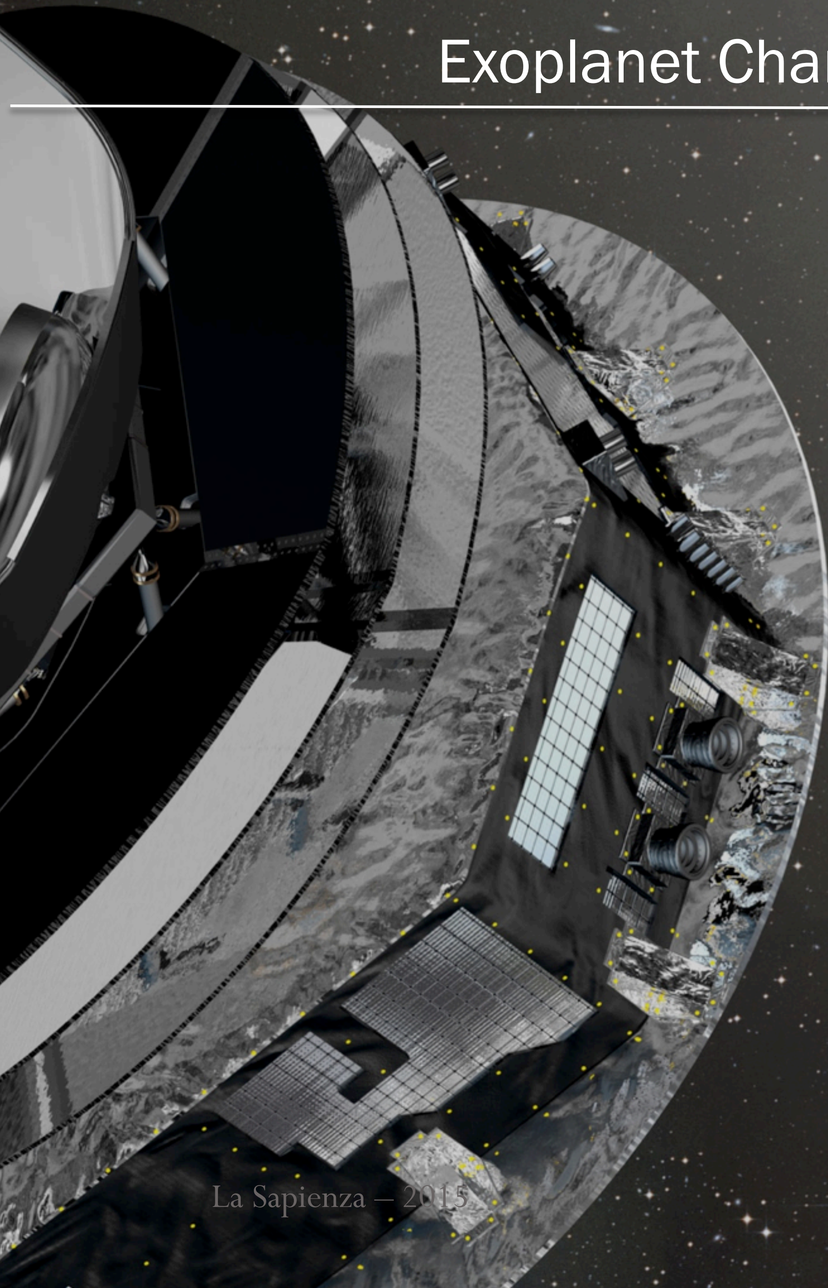
EChO

Exoplanet Characterisation Observatory



European Space Agency
M3 mission candidate

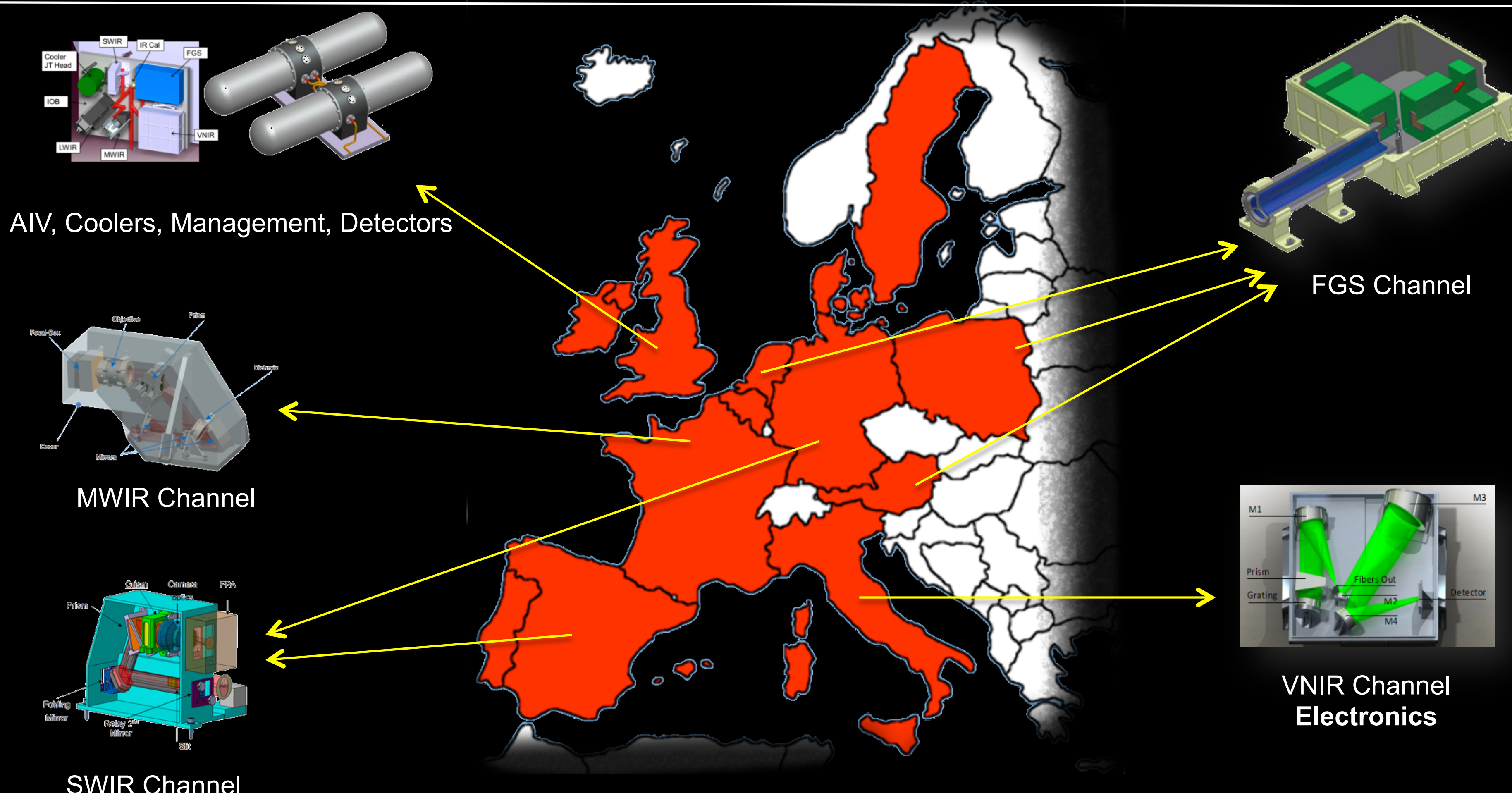
1m class telescope in space (L2)

Stability:
1 part in 10000 over 10 hours

Spectral range:
0.5-11 (16) micron

Instrument Consortium

Large European consortium

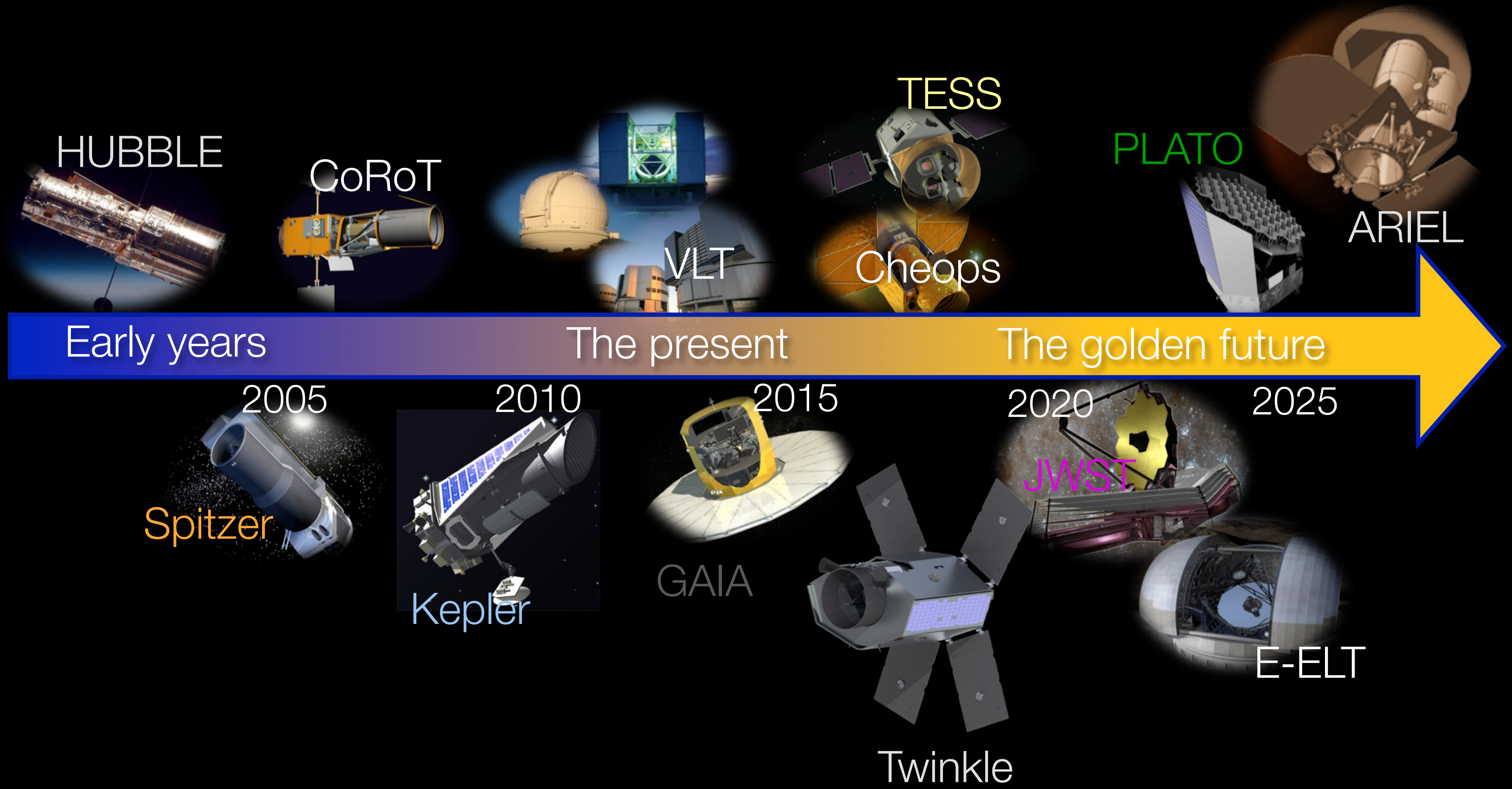


NL, B, P, S, DK, IR providing components and AIV support

Instrument data centre contributions from all partners

The future

More and better observations



ARIEL

The Atmospheric Remote-Sensing Infrared Exoplanet Large-survey

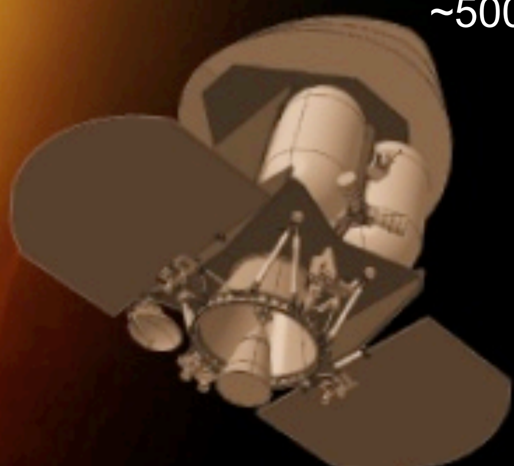
ESA-M4 mission candidate
(launch 2025)

1m class telescope in space (L2)

Stability:
1 part in 10000 over 10 hours

Spectral range:
0.5-8 micron

~500 Exoplanet atmospheres



The ARIEL team

ESA ARIEL Project Manager

ESA ARIEL Project Scientist

ESA ARIEL Payload Manager

ESA ARIEL Project Team

ARIEL Science Team

ARIEL European Steering Committee

Consortium Central Leadership

- Consortium Project Manager / UK NPM **Paul Eccleston** RAL Space
- Calibration Scientist **Marc Ollivier** IAS
- Instrument Scientist **Emanuele Pace** Uni di Firenze
- Payload Scientist **Enzo Pascale** Cardiff University
- Consortium PI **Giovanna Tinetti** UCL

National Project Managers

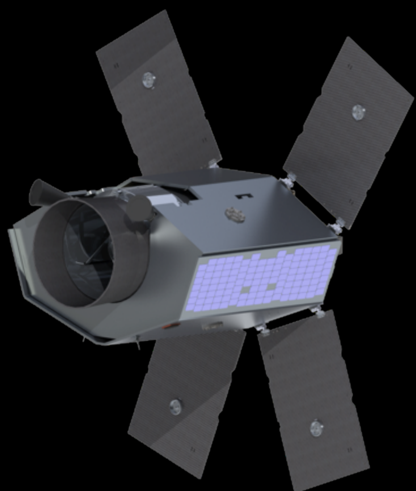
- France NPM **Jean-Michel Reess** OPM - Lesia
- Italy NPM **Emanuele Pace** Uni di Firenze
- Spain NPM **Pep Colomé** CSIC - ICE
- Netherlands NPM **Rien van der Linden** SRON
- Poland NPM **Miroslaw Rataj** SRC Warsaw
- Germany NPM **Mirim Rengel** MPS
- Austria NPM **Roland Ottensamer** Uni of Vienna
- Belgium NPM **Etienne Renotte** CSL
- Ireland NPM **Ruyman Azzollini** DIAS

Consortium National Leads

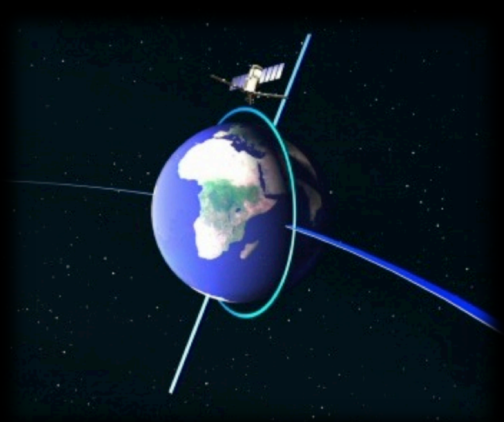
- Italy Co-PI **Giusi Micela** INAF - Palermo
- France Co-PI **Jean-Philippe Beaulieu** CNRS IAP
- UK co-I **Bruce Swinyard** UCL / RAL Space
- Spain co-I **Ignasi Ribas** CSIC - ICE
- Germany co-I **Paul Hartogh** MPS
- Netherlands co-I **Frank Helmich** SRON
- Austria co-I **Manuel Güdel** Uni of Vienna
- Poland co-I **Miroslaw Rataj** SRC Warsaw
- Ireland co-I **Tom Ray** DIAS
- Belgium co-I **Bart Vandenbussche** Uni de Leuven
- Portugal co-I **David Luz** Uni de Lisboa

TWINKLE

A British Mission to Explore Faraway Worlds



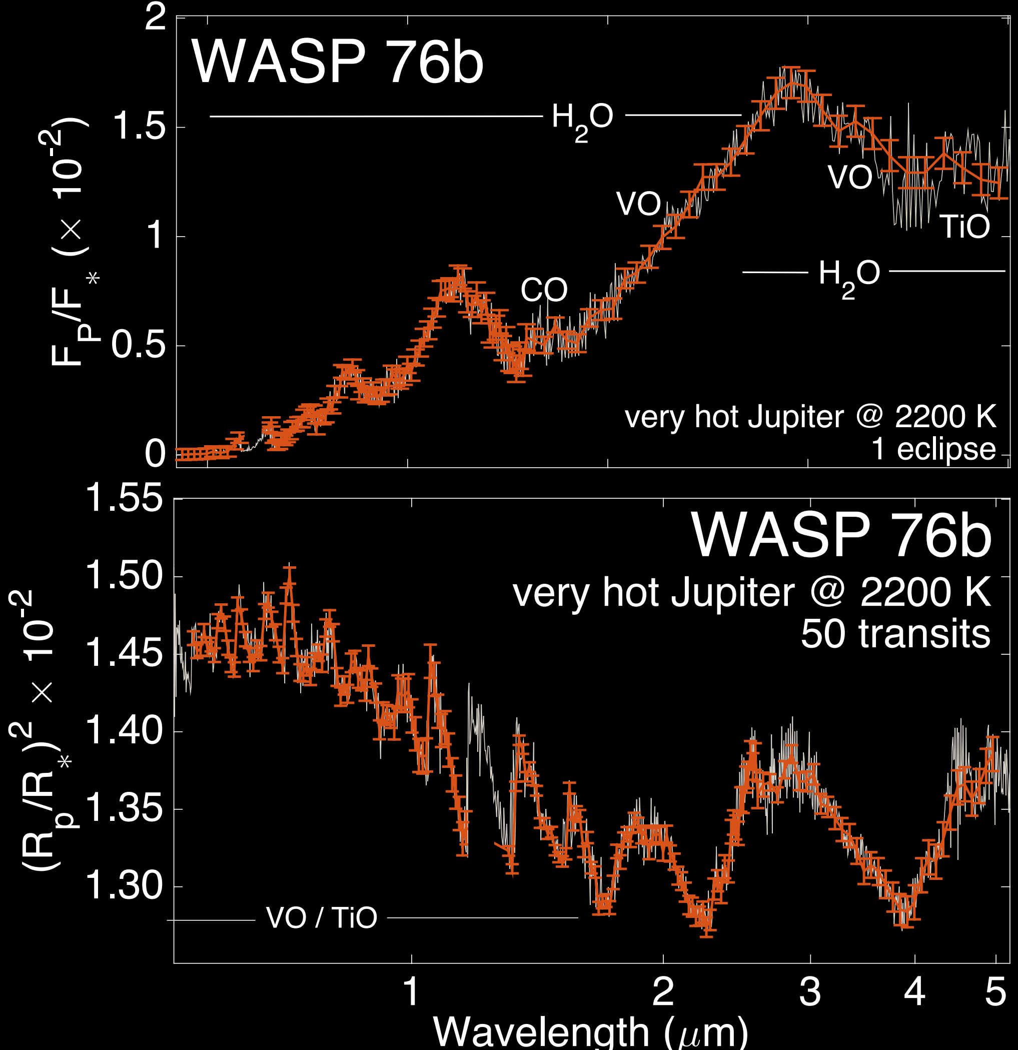
- Cost-effective (small, fast & cheap)
  - 50cm Primary mirror in low-Earth orbit
  - To be launched and function <5 years from now
  - Cost: <10% of ESA M-class mission
- High-visibility inspirational science
  - spectra of 100's of known exoplanets (0.5-5 μm)

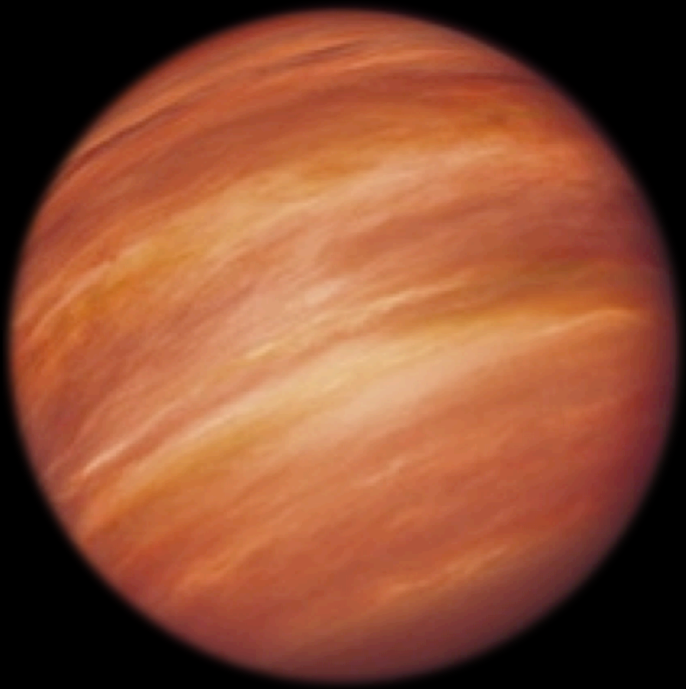


- SSTL-300 platform
  - ~700 km altitude Low Earth Orbit
  - ~100 min orbit
  - Sun-synchronous orbit constantly pointing away from Sun
- Launch managed by SSTL
- Off-the shelf components
- 3 year guaranteed lifetime (Goal: 7)

WASP-76b

Hot-Jupiter @ T~ 2200 K (simulations with Twinkle-sim)



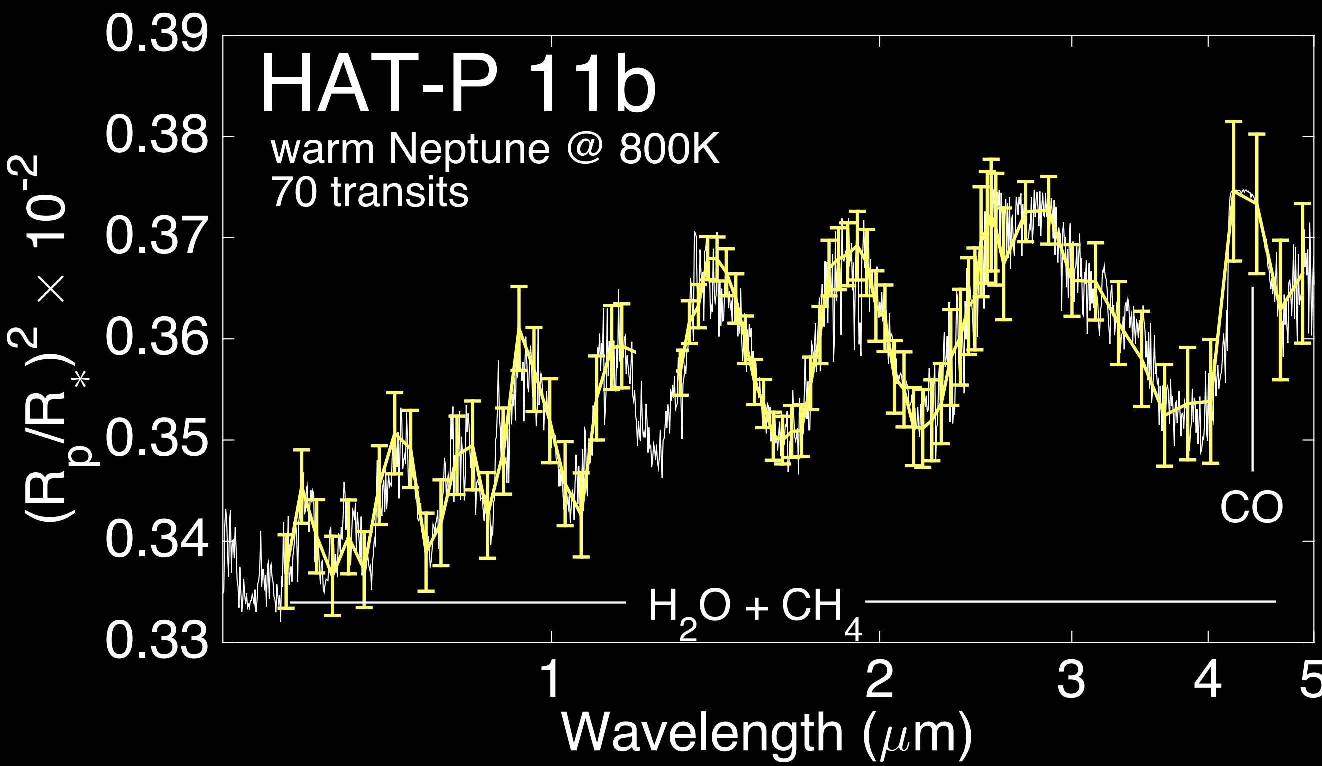


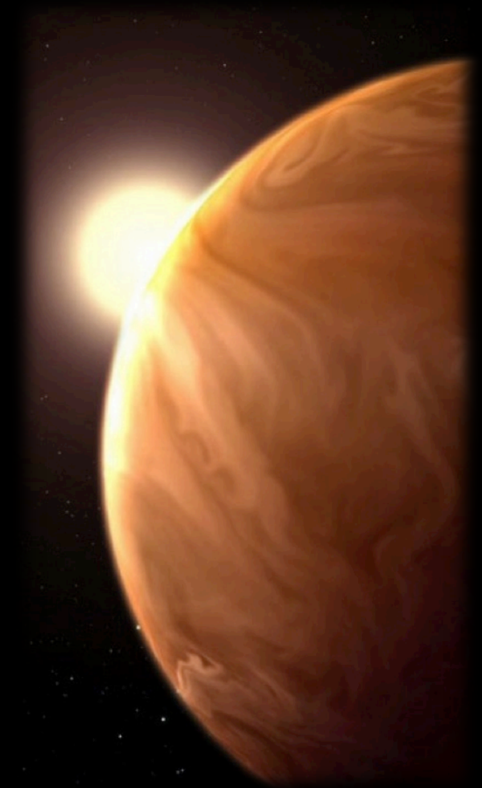
Waldmann & Pascale, 2015

UCL

HAT-P 11b

Warm Neptune @ T~800K (simulations with Twinkle-sim)

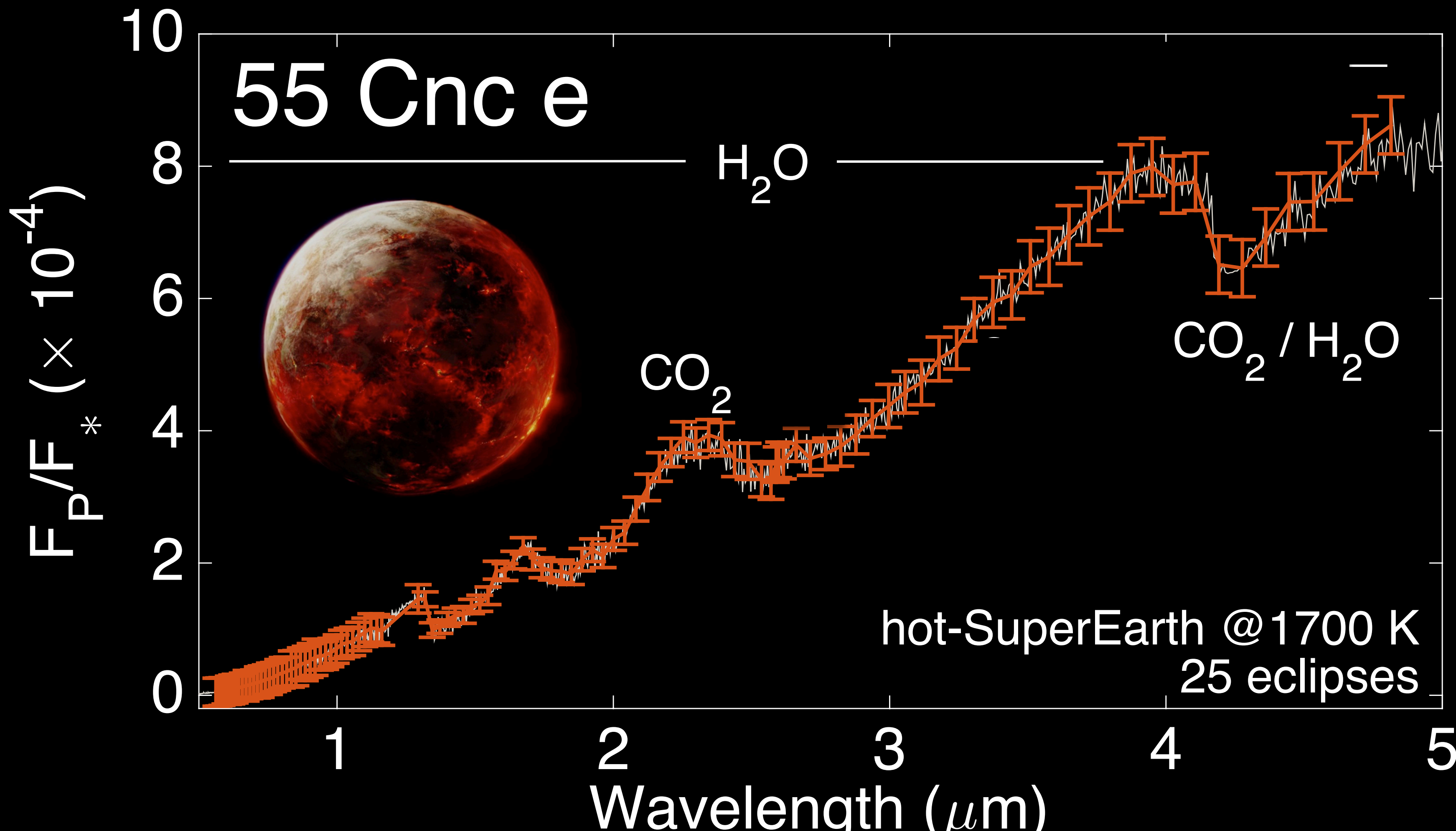




Waldmann & Pascale, 2015

55-Cnc e

Hot super-Earth @ T = 2500 K (*Lava planet*)



Waldmann & Pascale, 2015

Conclusions

- Thousands of planets known and we know very little about them!
- 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, a dedicated instrument for exoplanet spectroscopy from space would deliver *transformational science.*
- More thorough and statistically objective data- analysis is needed
- Better line-lists, especially at high T needed to interpret the spectra

Volete saperne di più?

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