EChO

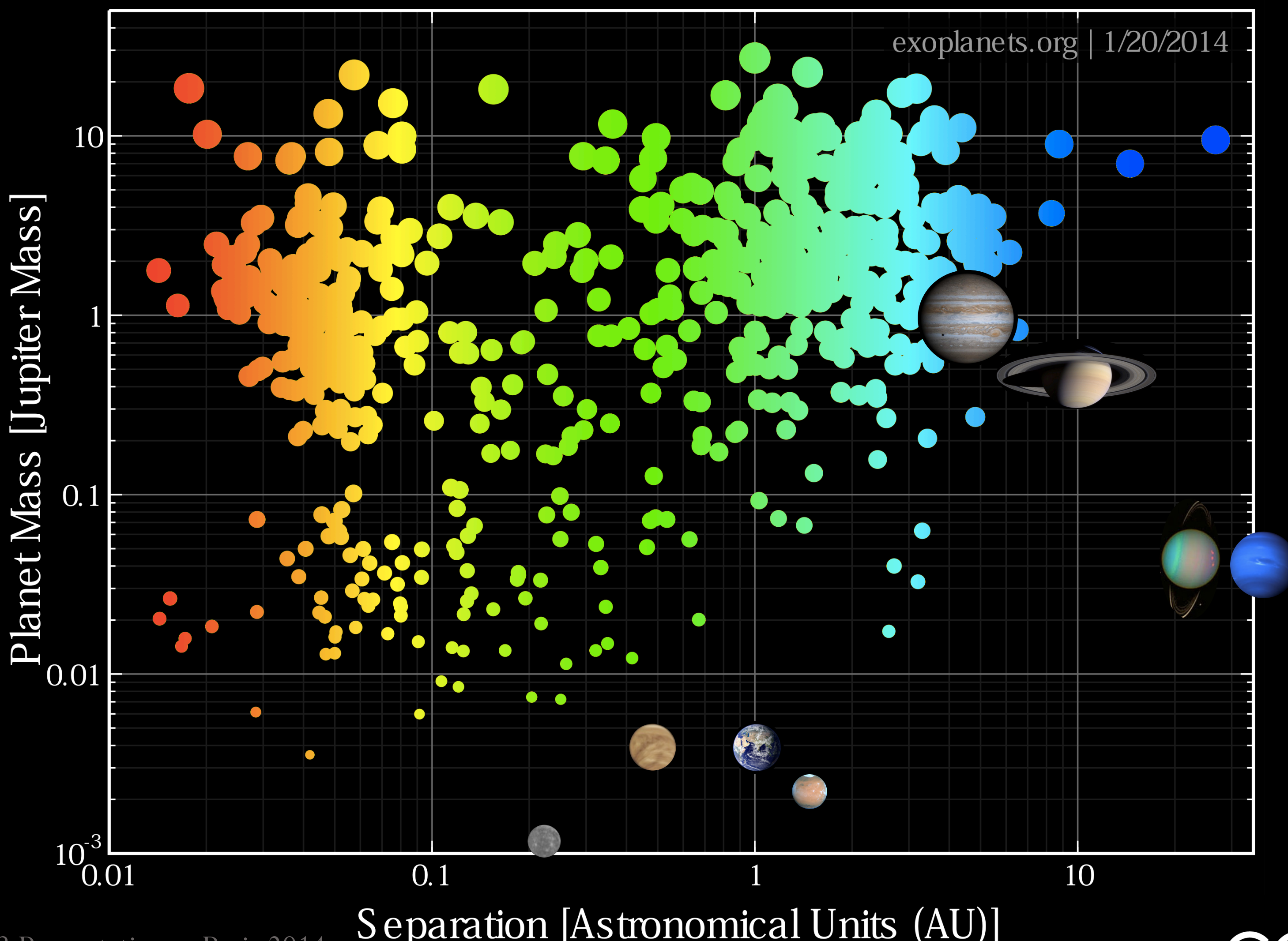
Exoplanet Characterisation Observatory

G. Tinetti & B. Swinyard

on behalf of EChO SST & EChO Consortium

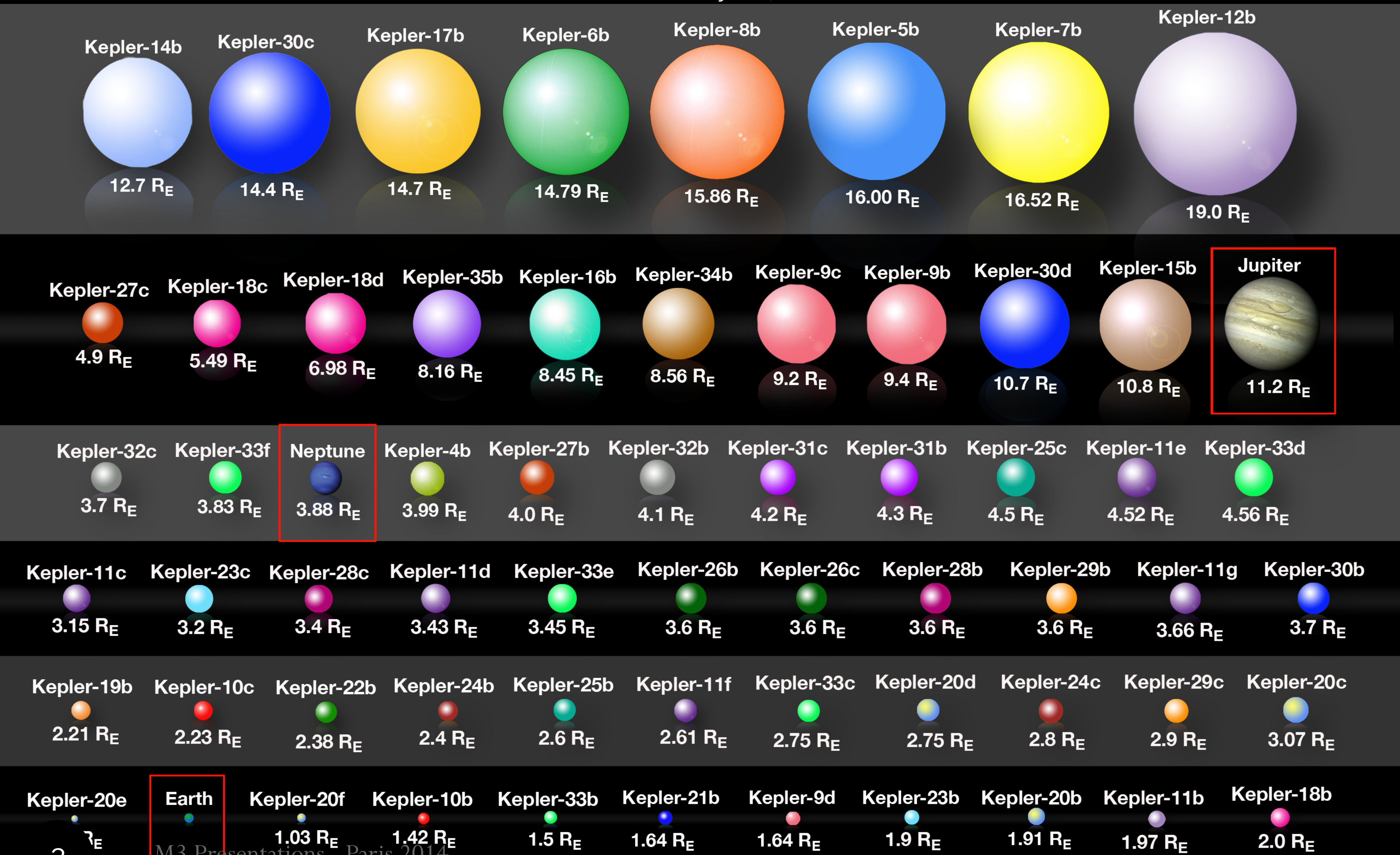
The Exoplanet Revolution

9 to 1000 in 20 years!



Kepler Planets

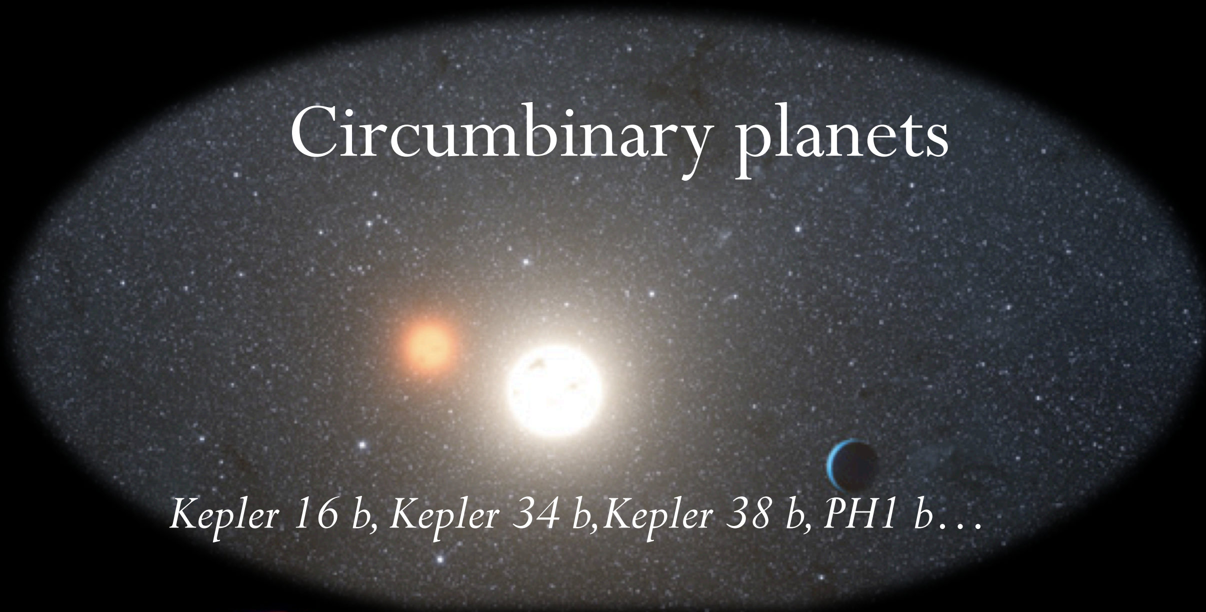
As of February 27, 2012



Courtesy of Kepler's team

The Solar System is *not* representative

There is much more variety than the Sun's planets



Circumbinary planets

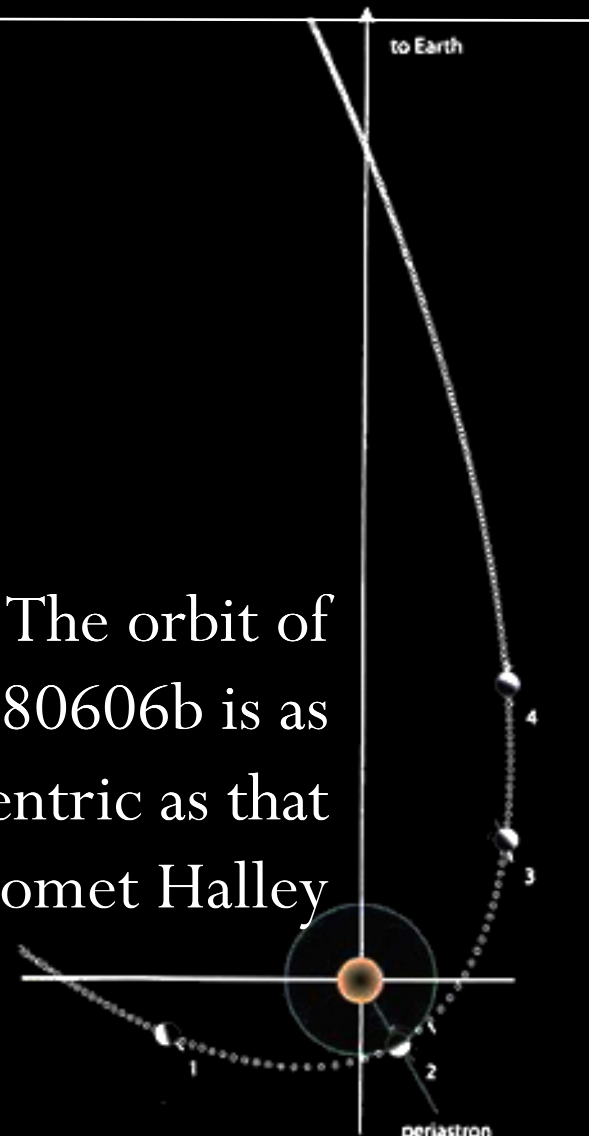
Kepler 16 b, Kepler 34 b,Kepler 38 b, PH1 b…

"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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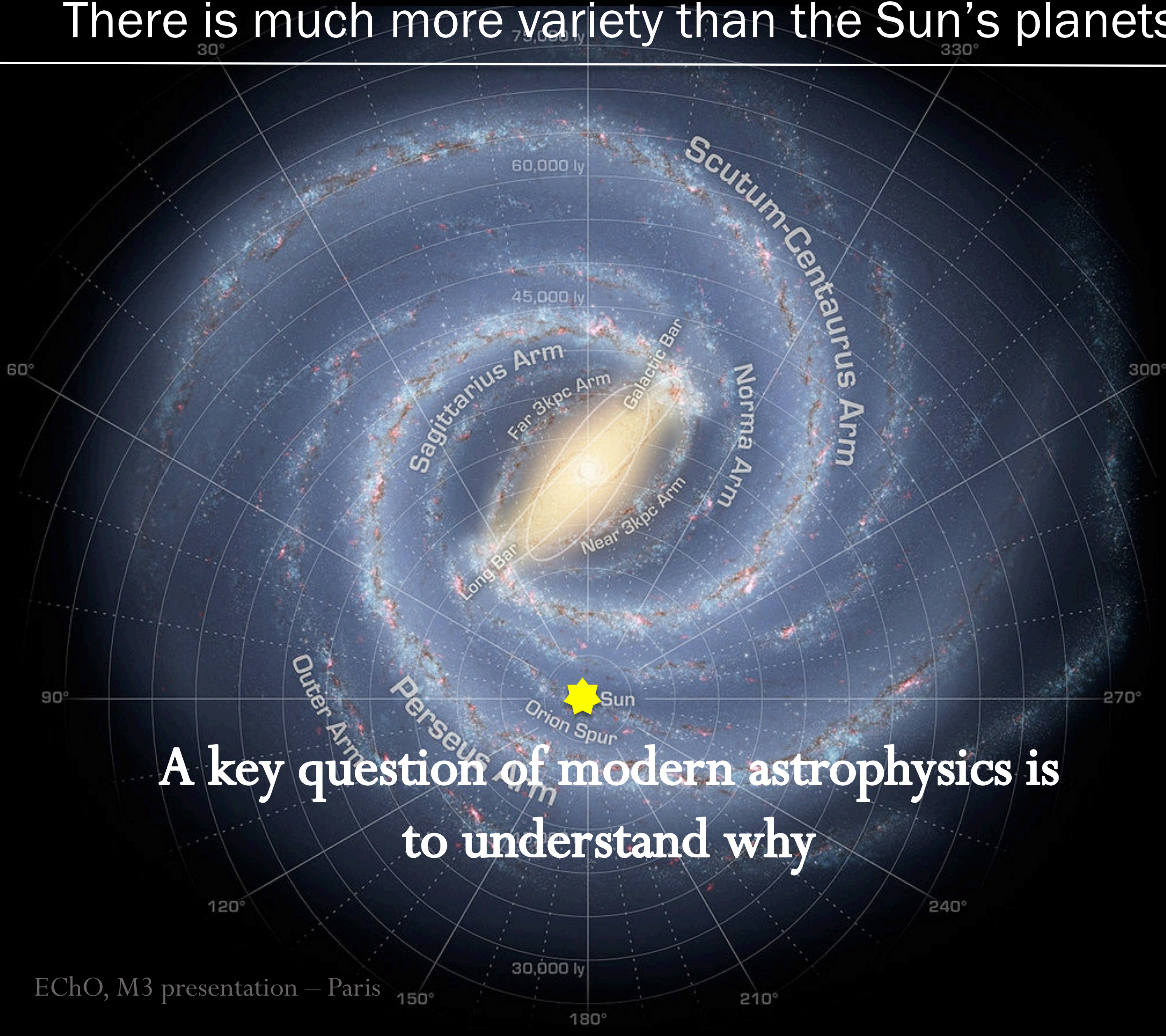


A key question of modern astrophysics is to understand why

Outstanding Science Questions

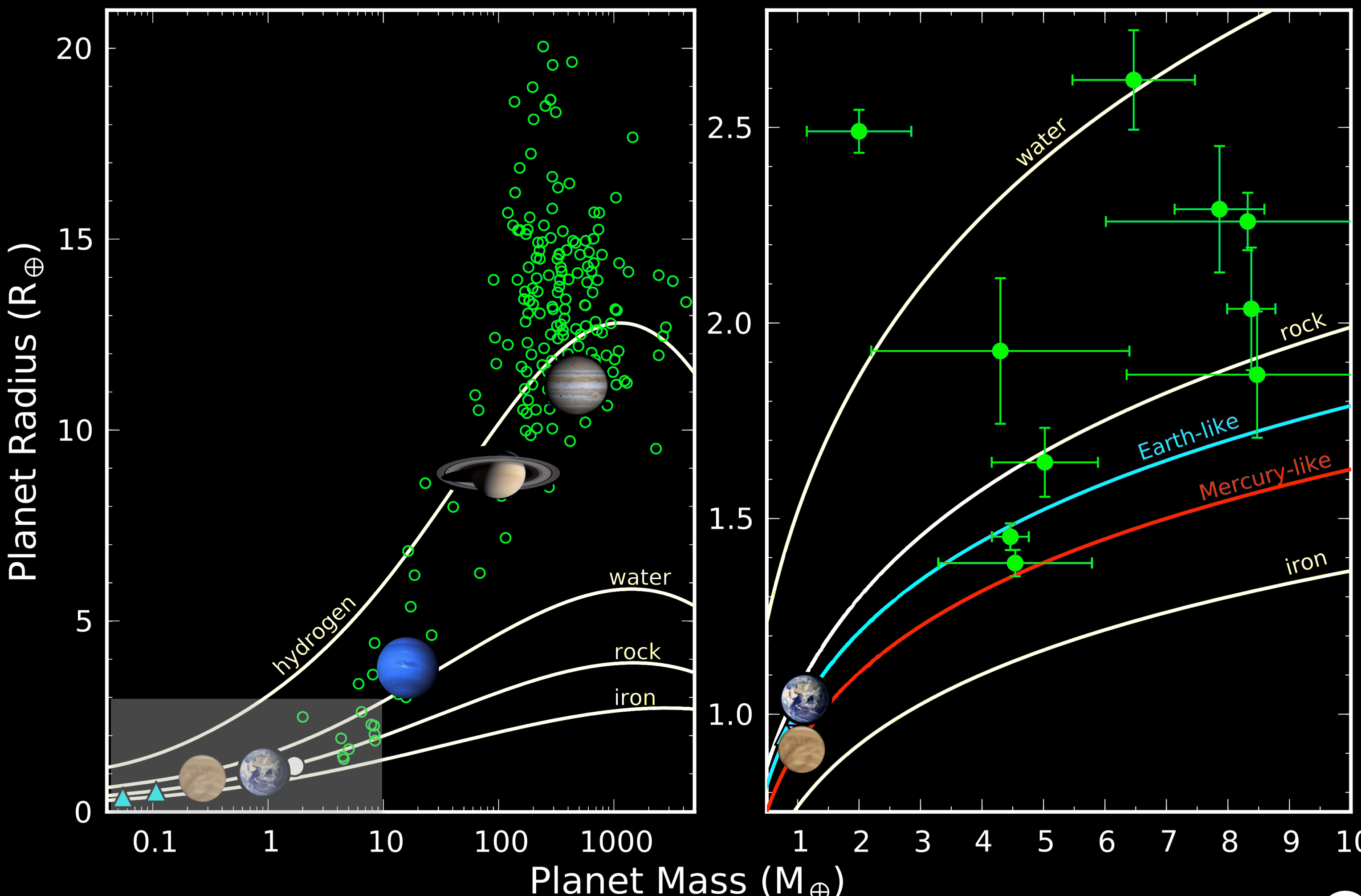
Why is the Solar System **not** representative of the planetary systems in our Galaxy?

Why are exoplanets as they are?

What are the causes for the observed diversity?

Understanding the exoplanet diversity

Mass & radius tell only part of the story



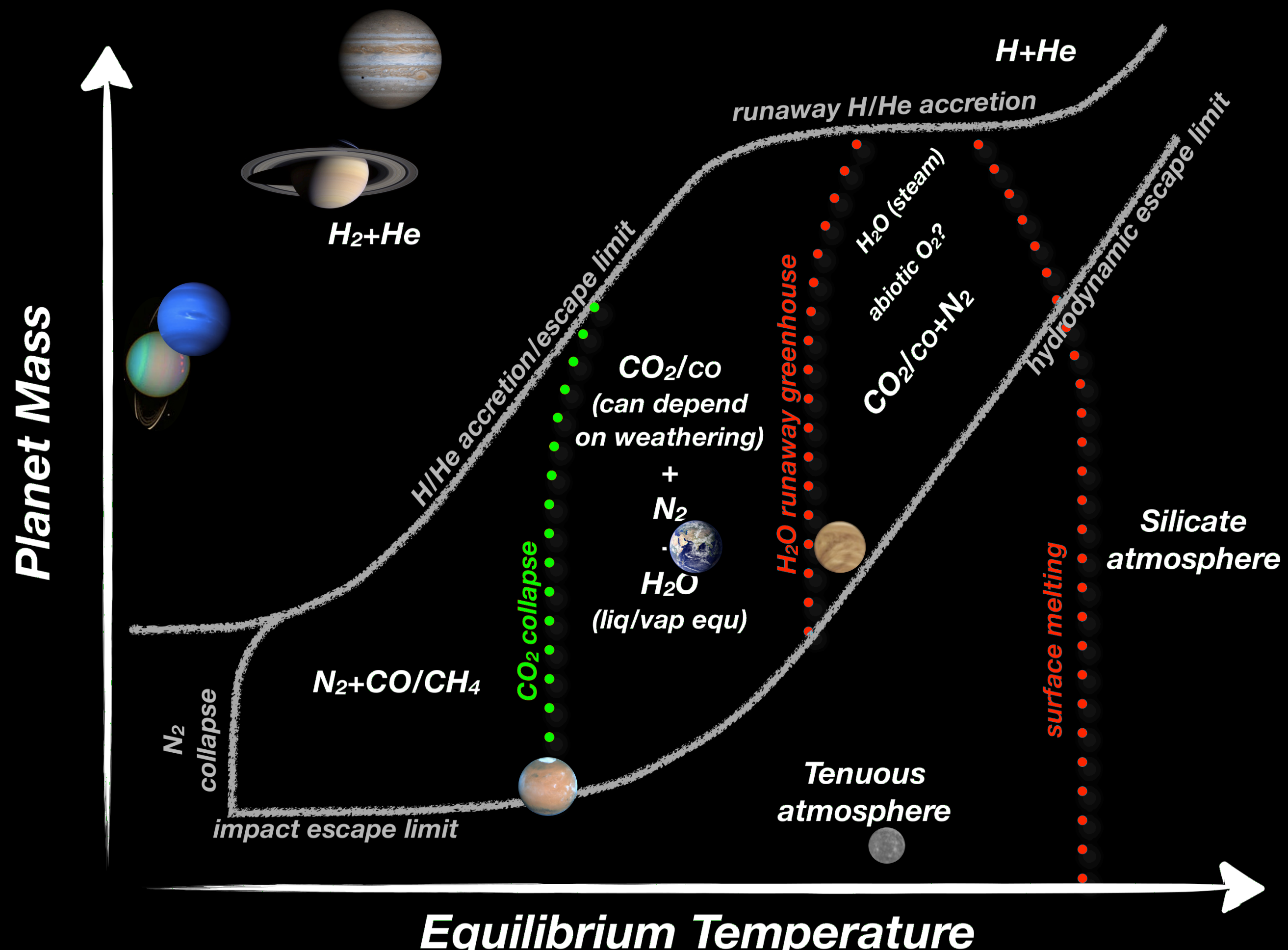
Howard et al., 2013

The gaseous envelope

Atmospheric composition is determined by many processes

Understanding exoplanet diversity

Predicted atmospheric composition of exoplanets



Forget & Leconte, 2013

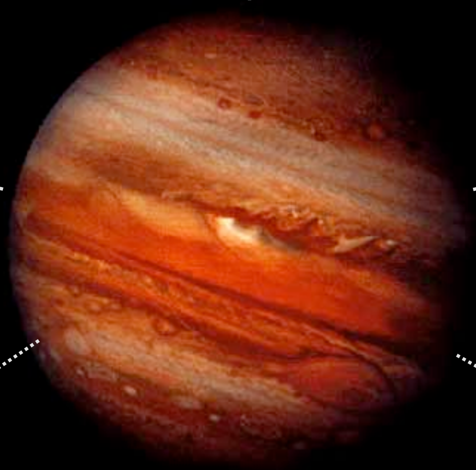
Gaseous planets

Key questions & observables

Energy budget
Albedo/thermal emission

Planet formation
Metal enrichment, C/O etc.

Planet evolution
Escape/H_3^+



Weather
Temporal variability/
Thermal structure

Planet-star interaction
Photochemistry+
Day/night variation

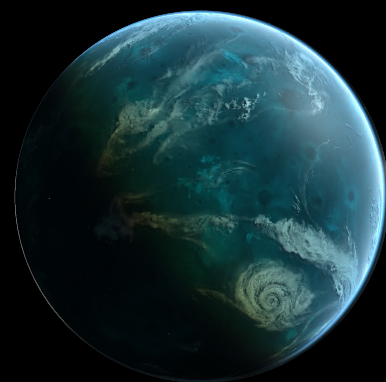
Solid planets

Key questions & observables

Does the planet have an atmosphere?
Spectral observations

Habitable conditions?
Temperature? H_2O?

Primary or secondary atmosphere?
H_2 retained or not



Main atmospheric component
Primary transit observations

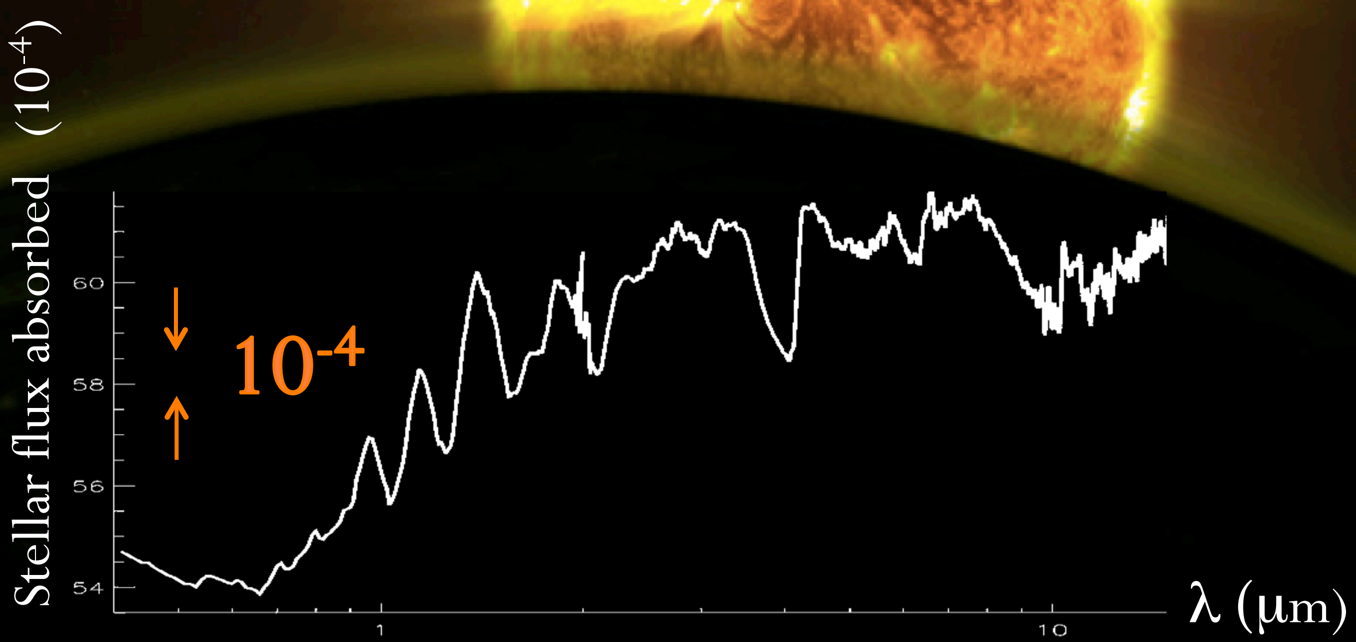
Planet-star interaction
Photochemistry

Energy budget
Albedo/thermal emission

How to probe an exoplanet atmosphere

1: Transit spectroscopy

The stellar photons are filtered through the planetary atmosphere



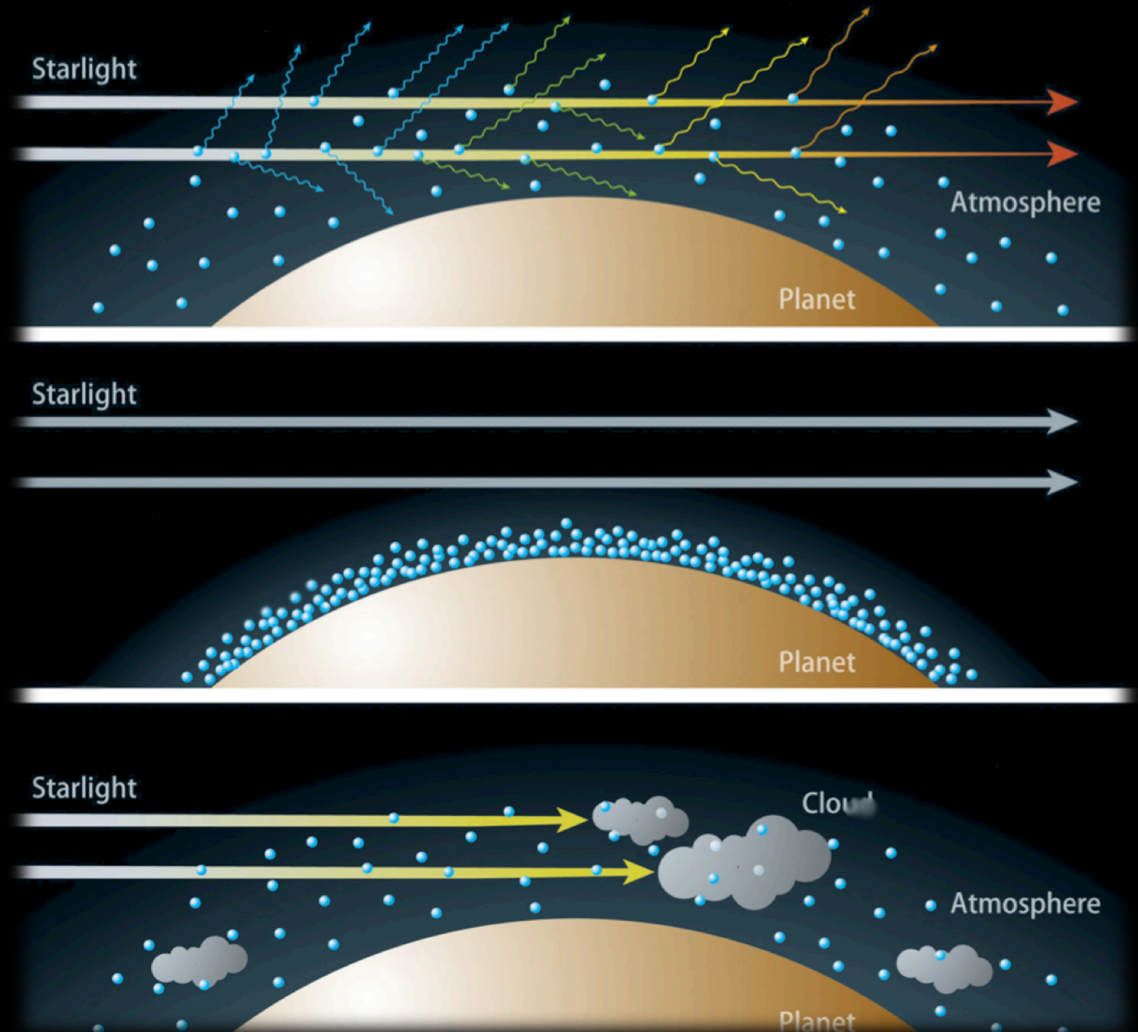
How to probe an exoplanet atmosphere

1: Transit spectroscopy

Scattering

Scale height

Absorption

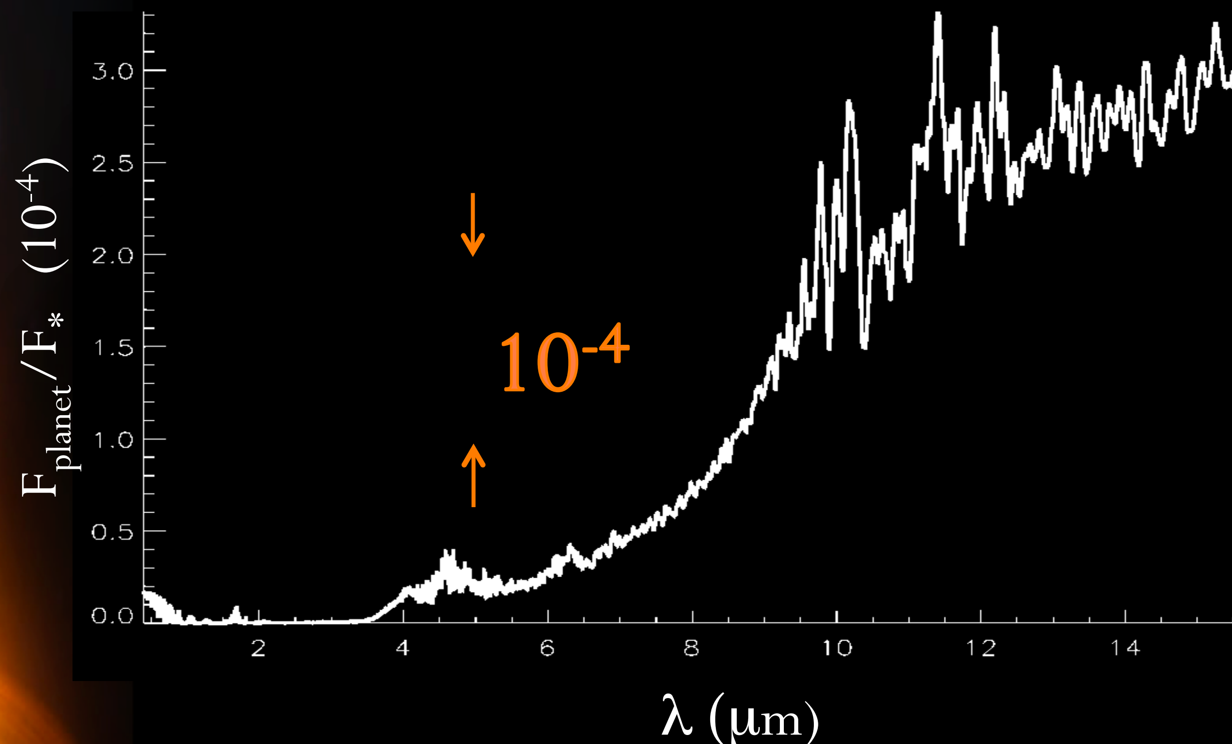


Credit: NAOJ

How to probe an exoplanet atmosphere

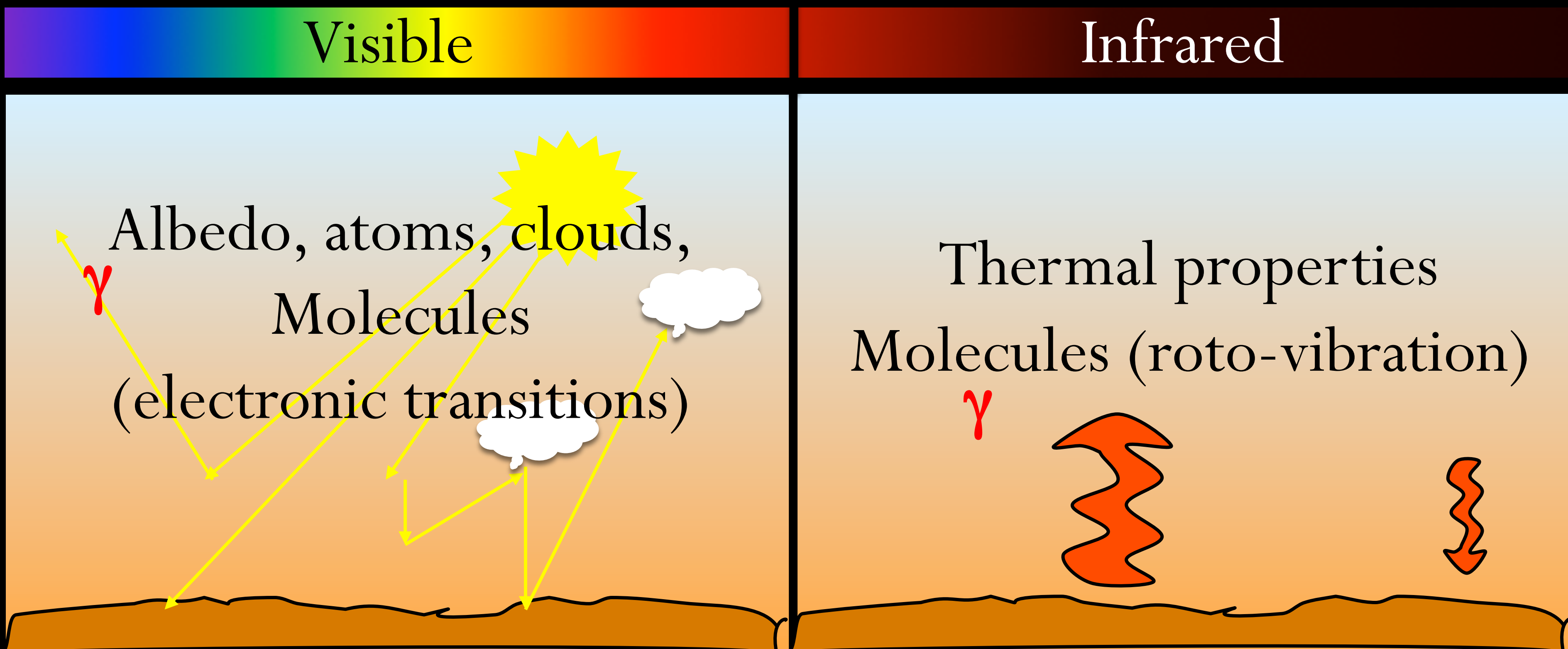
2: Eclipse spectroscopy

Using the planet ephemeris to separate the planet from the star



How to probe an exoplanet atmosphere

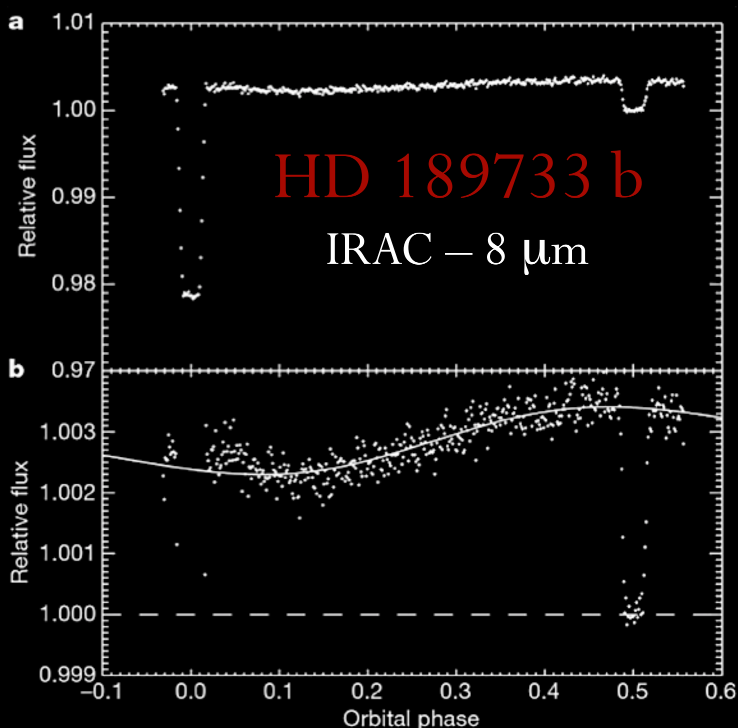
2: Eclipse spectroscopy



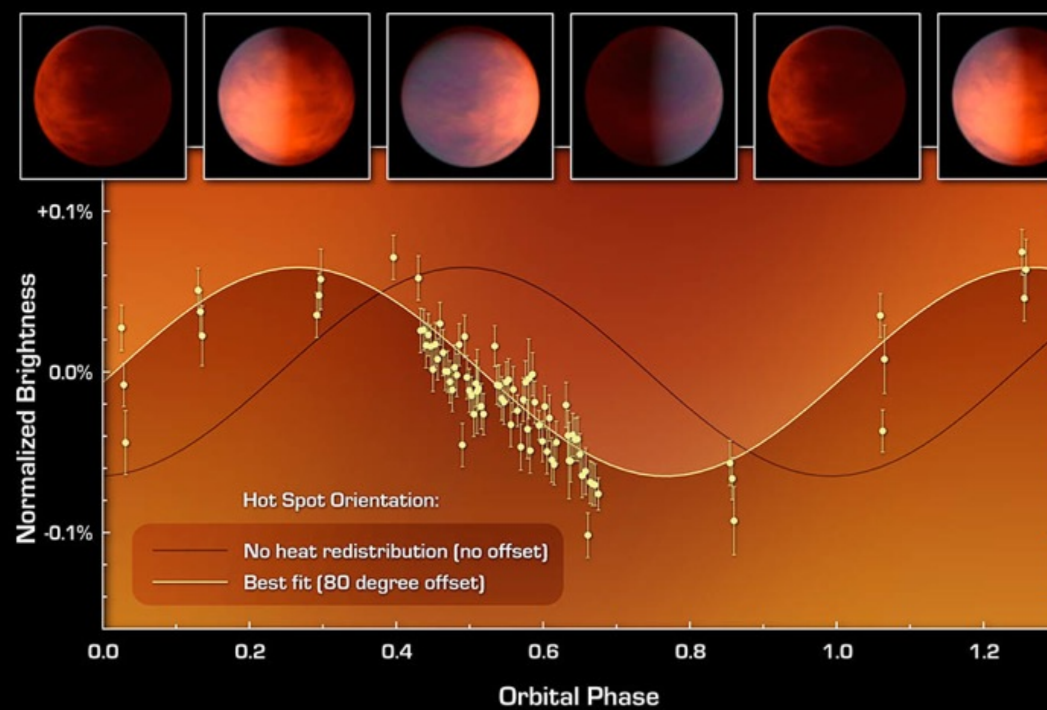
How to probe an exoplanet atmosphere

3: Phase-curves

Transiting



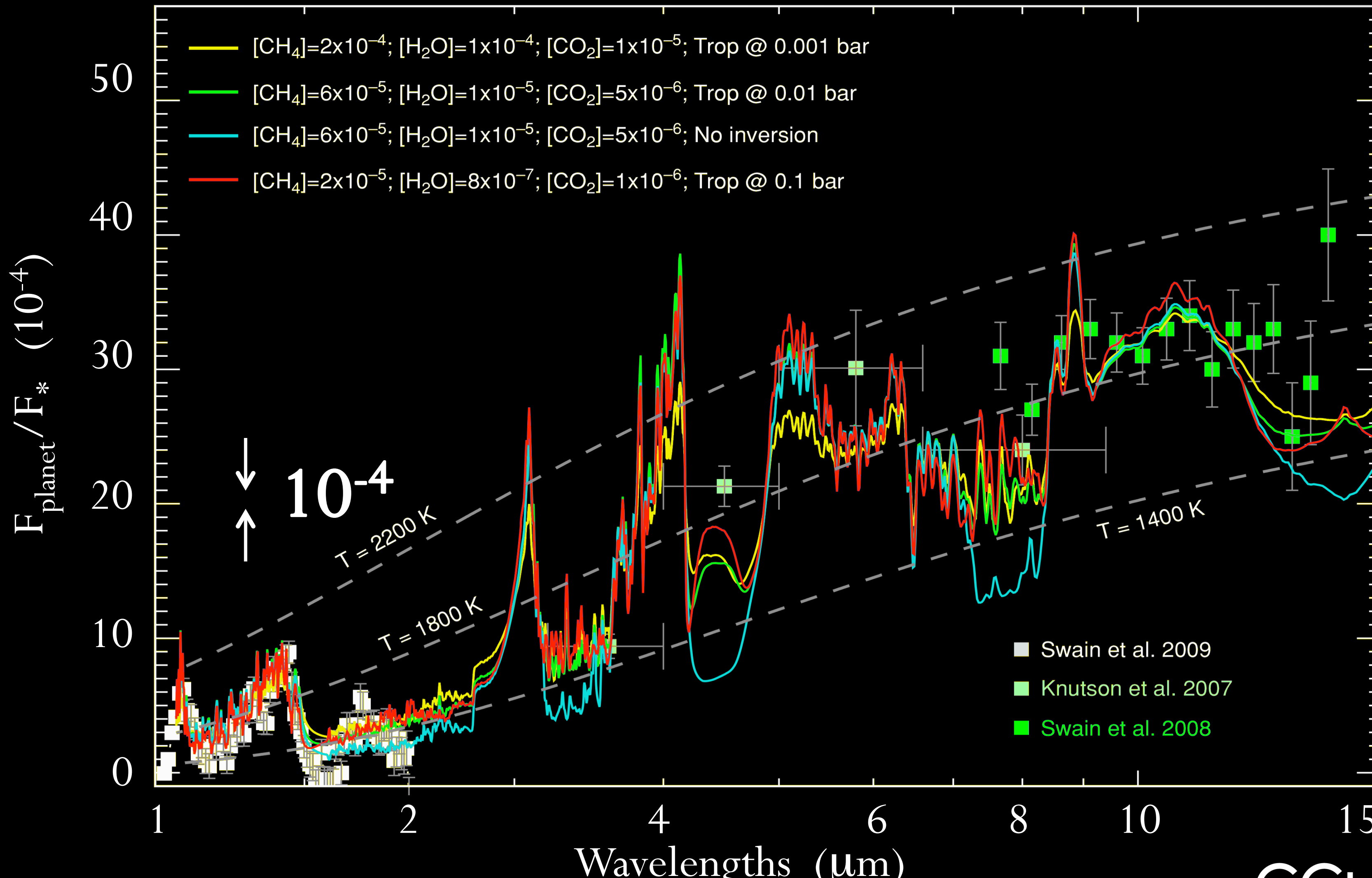
Non-transiting



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

Pioneering work on Exo-Atmospheres

Transit spectra with Hubble, Spitzer, ground…



Swain et al., 2009

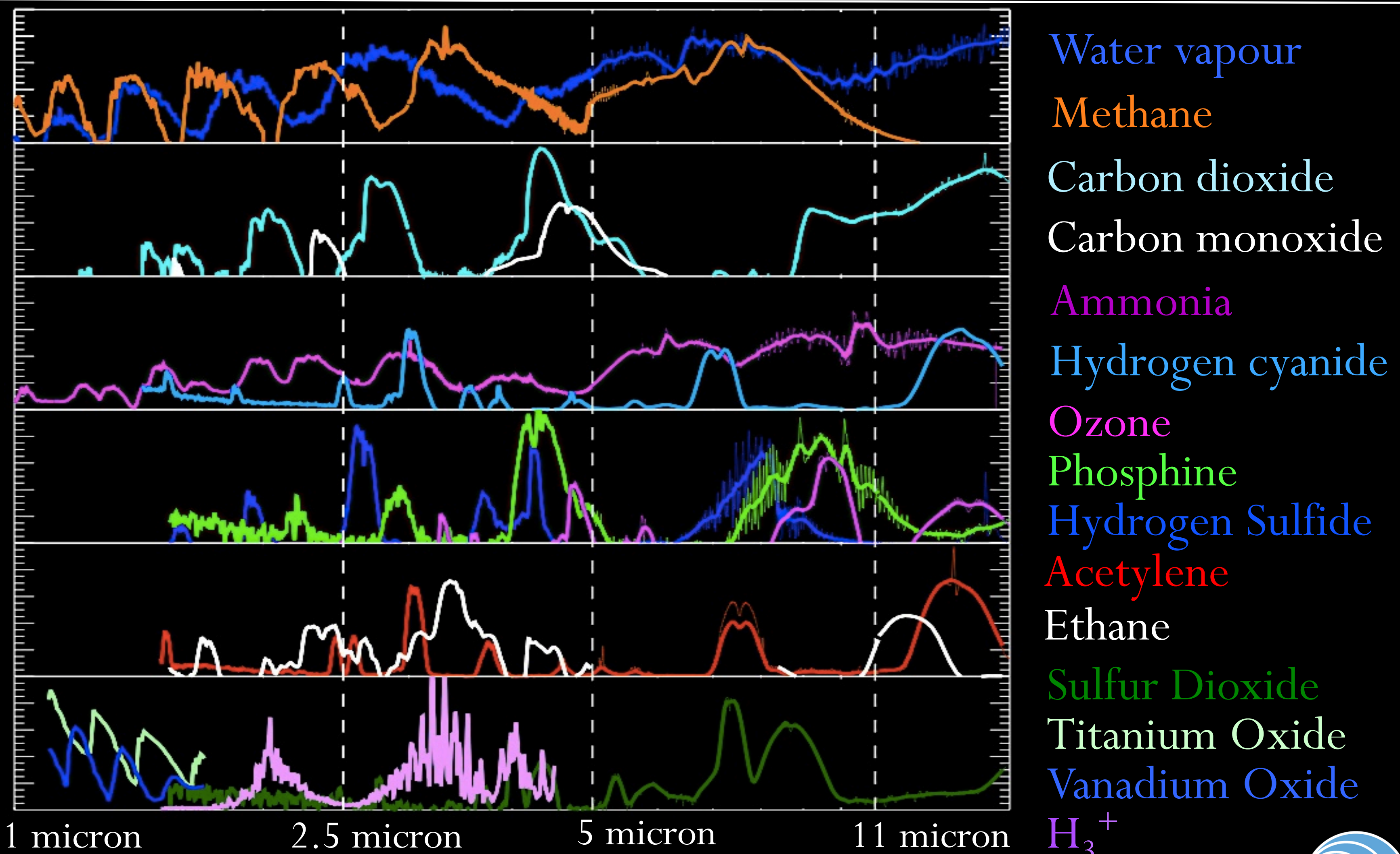
Issues with current observations

- 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 ✗

We need a dedicated mission from space!

Broad wavelength coverage

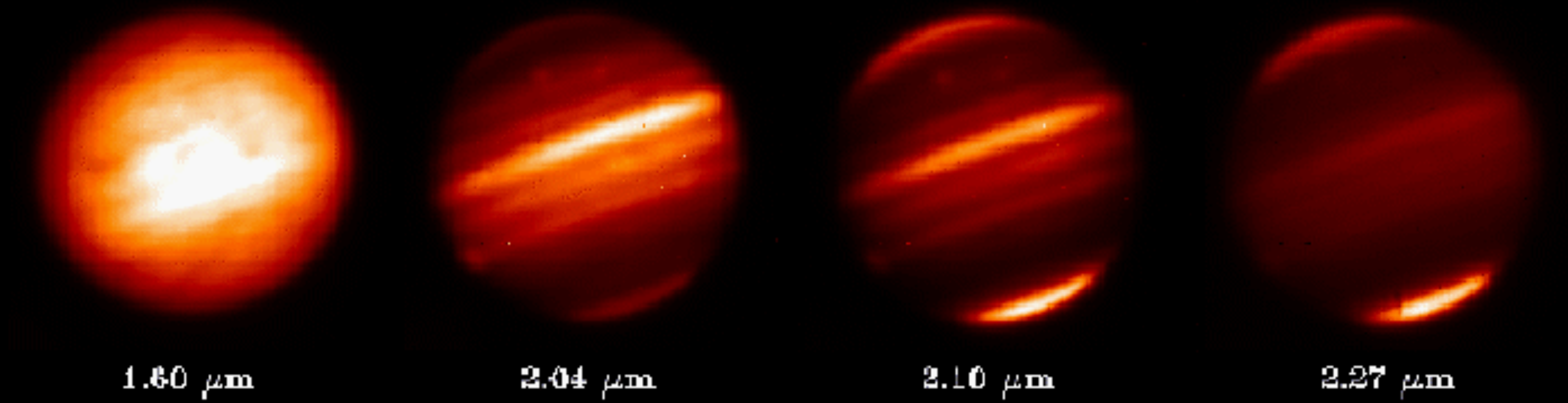
Redundancy for molecular detections



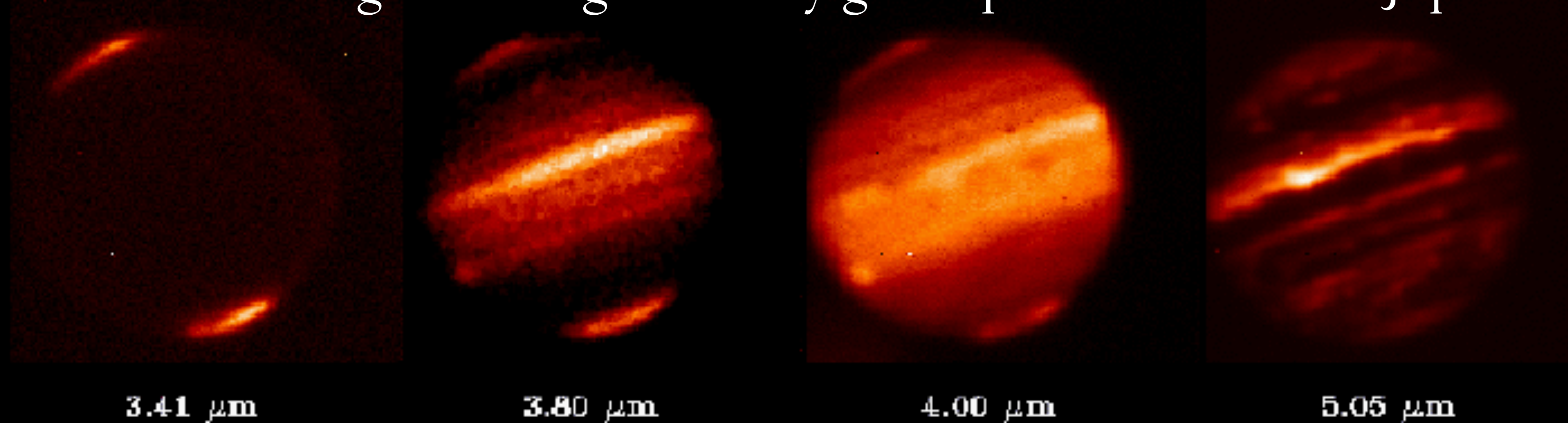
Tinetti, Encrenaz, Coustenis, 2013

Broad wavelength coverage

Ensures understanding of the atmospheric complexity



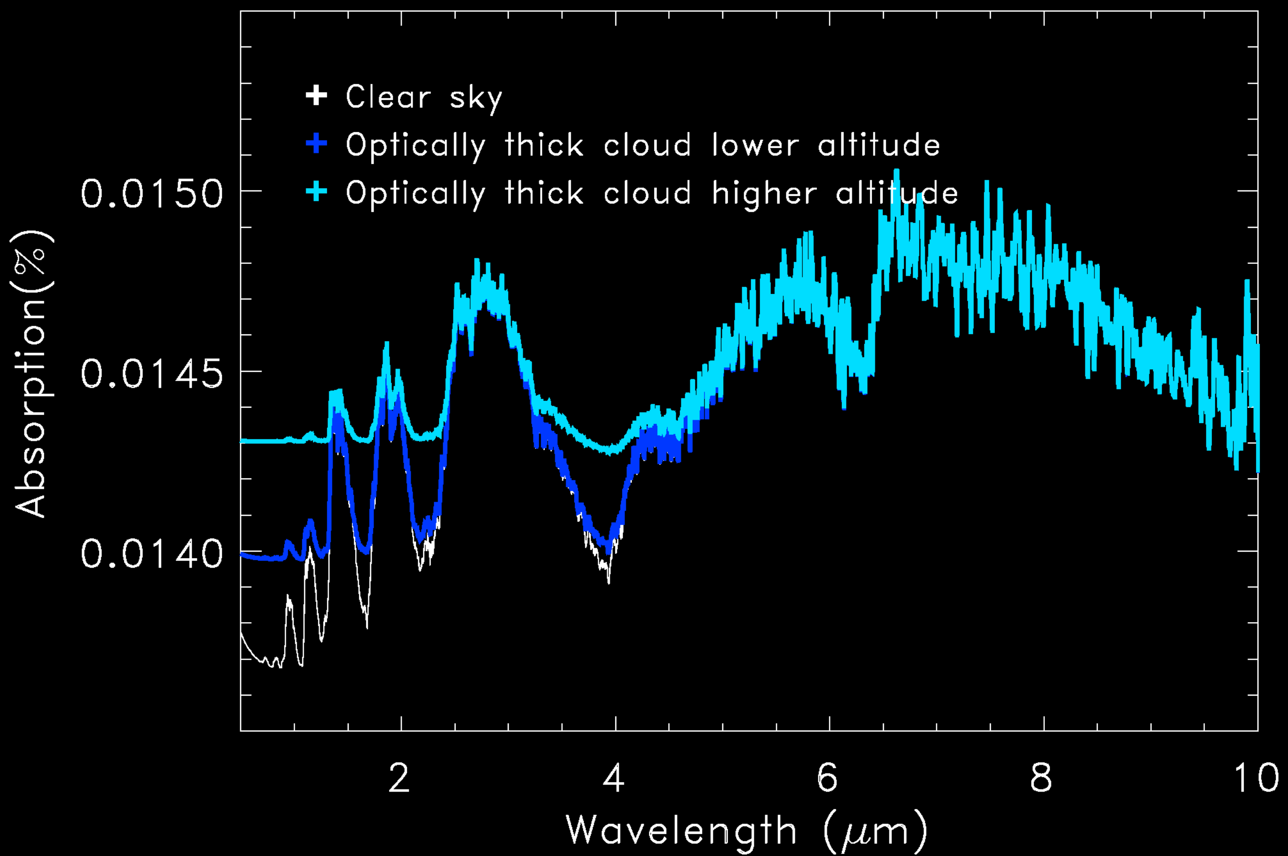
Narrow wavelength coverage can only give a partial view – see Jupiter



Courtesy of Kevin H. Baines, NASA IRTF

Broad wavelength coverage

Ensures understanding of the atmospheric complexity

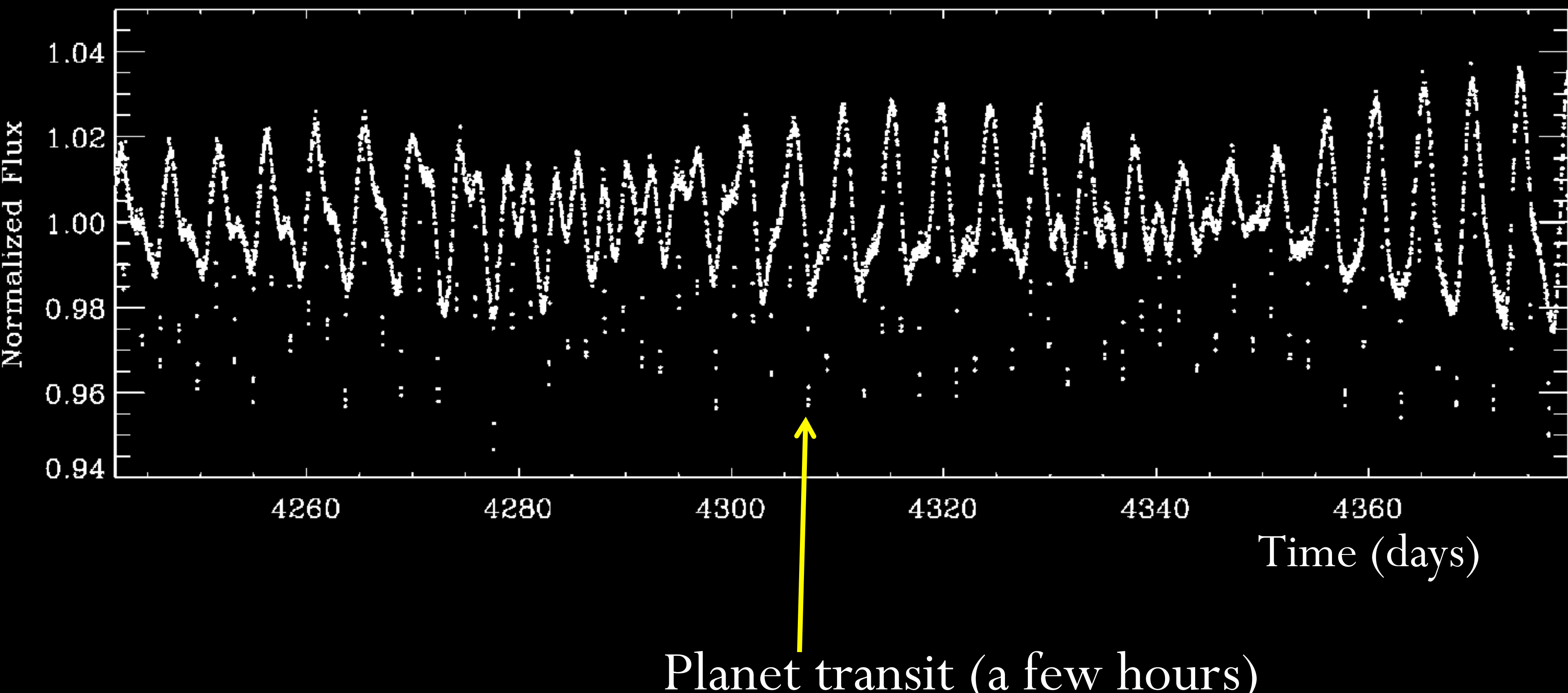


Narrow wavelength coverage can only give a partial view – see cloudy spectra

Broad-wavelength simultaneous coverage

Best antidote to stellar activity

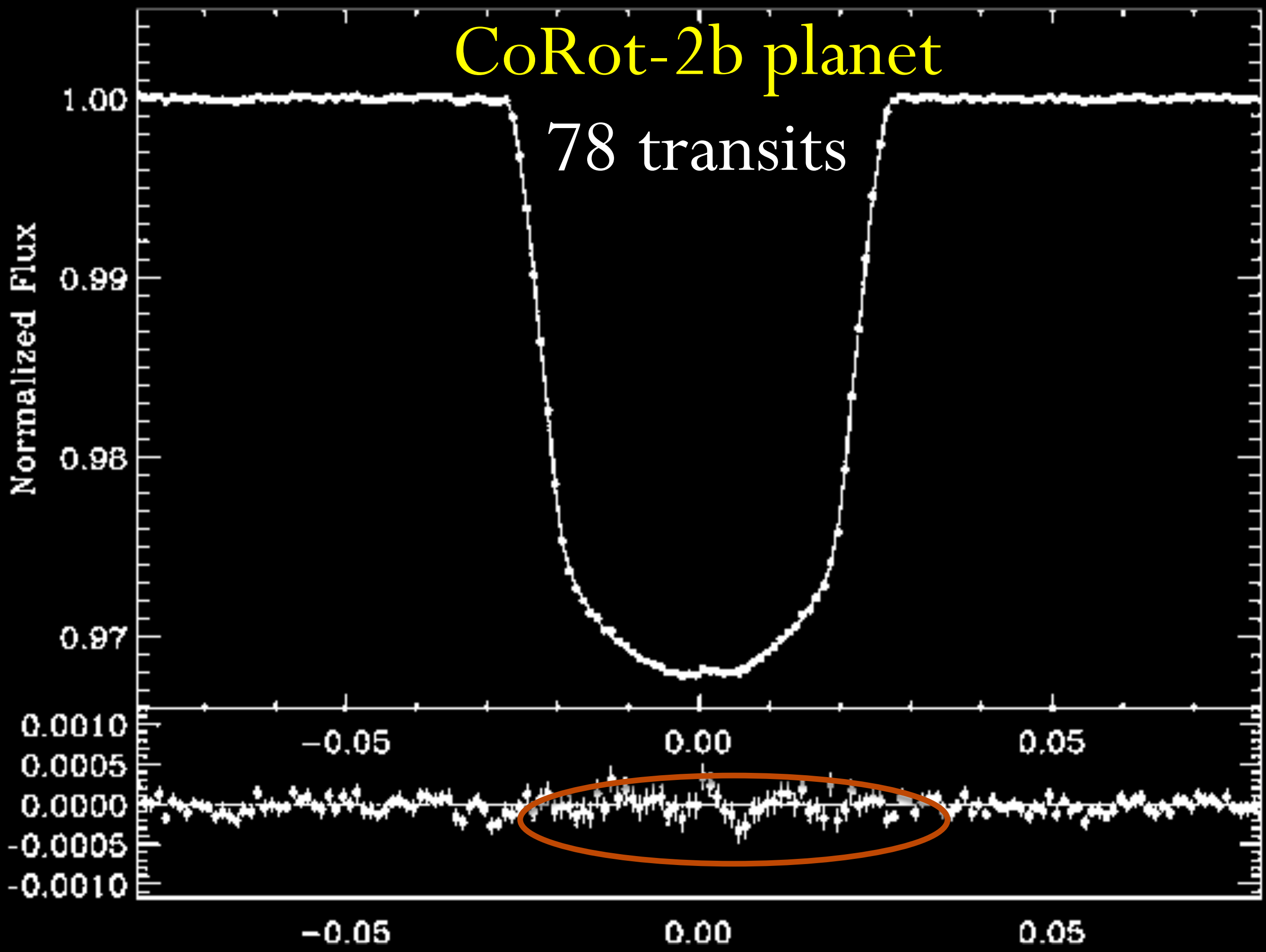
CoRot-2 star – Normalised Flux



Alonso et al., 2008

Broad-wavelength simultaneous coverage

Best antidote to stellar activity



Alonso et al., 2008

Broad-wavelength simultaneous coverage

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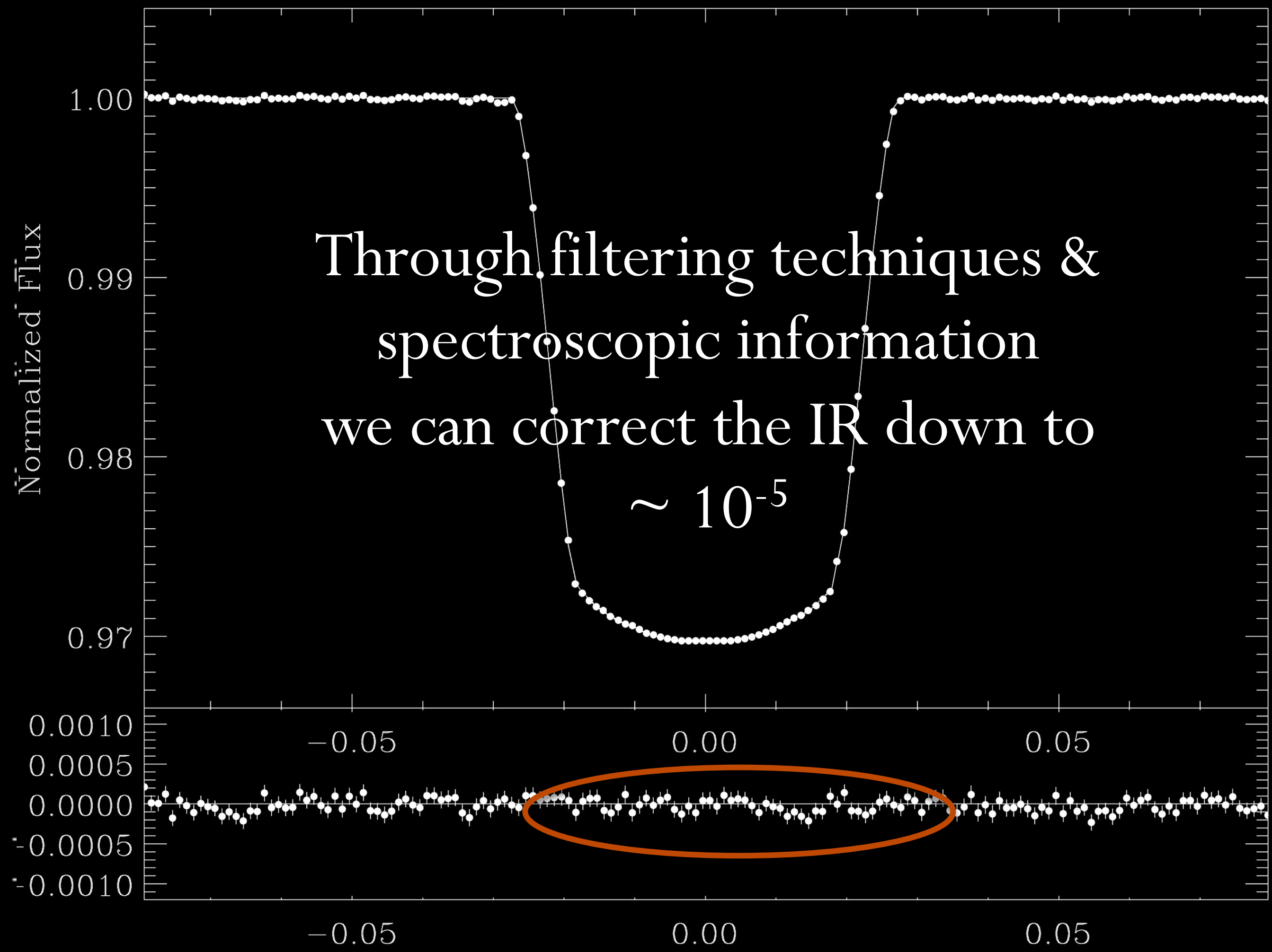


Through filtering techniques & spectroscopic information we can correct the IR down to ~ 10^{-5}

Ribas, Micela, ESA Tech Note; Waldmann, 2012; Danielski et al., 2014

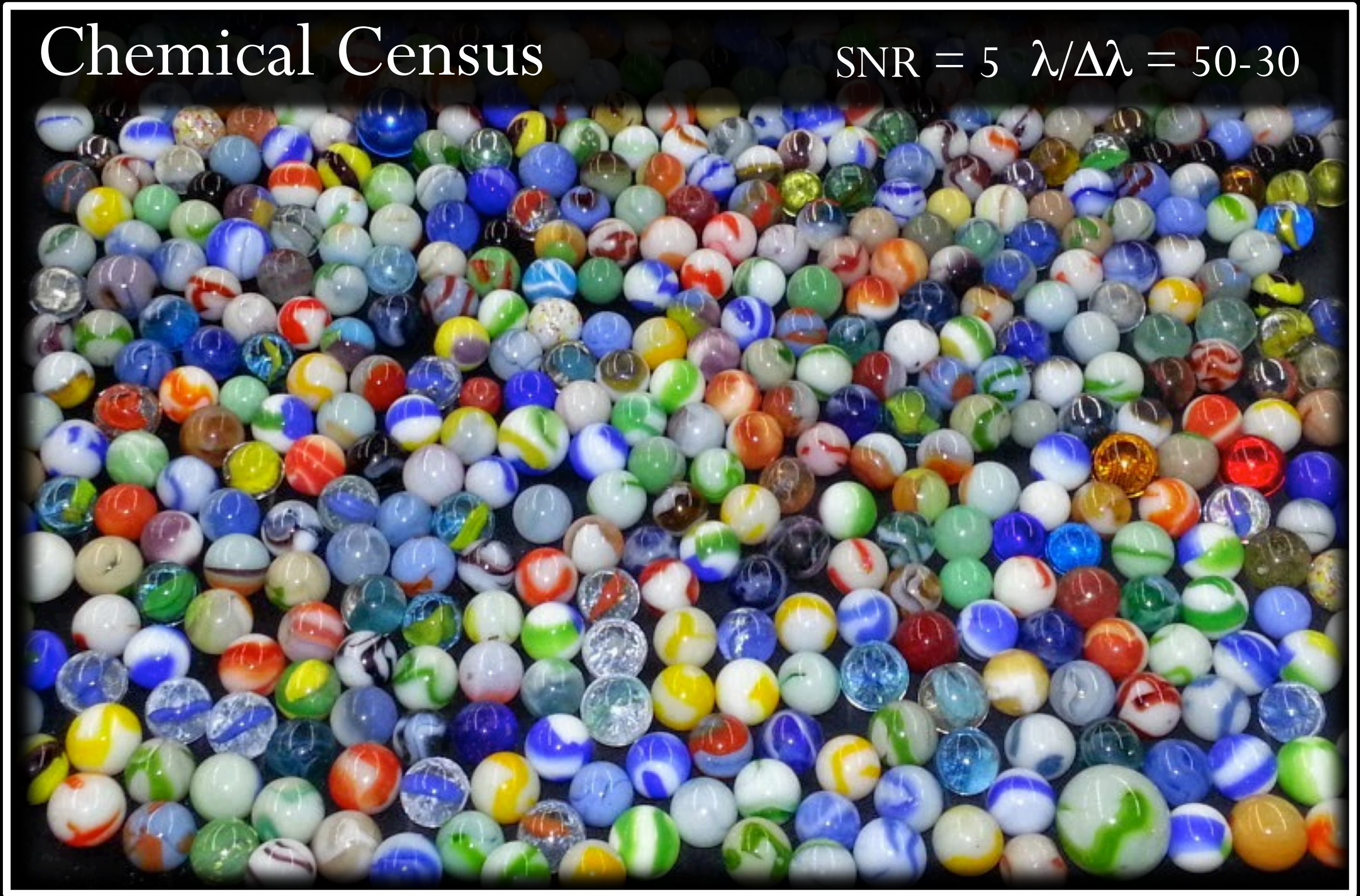
EChO's 3 Surveys:

Study exoplanets as a population & individually

- Chemical Census (survey)
  - Explore exoplanet chemical diversity (150-300 planets)
- Origin (deep survey)
  - Understand the origin of exoplanet diversity (50-100 planets)
- Rosetta Stones (ultra deep survey)
  - Weather, 2D-3D Maps, Benchmark cases (10-20 planets)

EChO's 3 Surveys:

Study exoplanets as a population & individually



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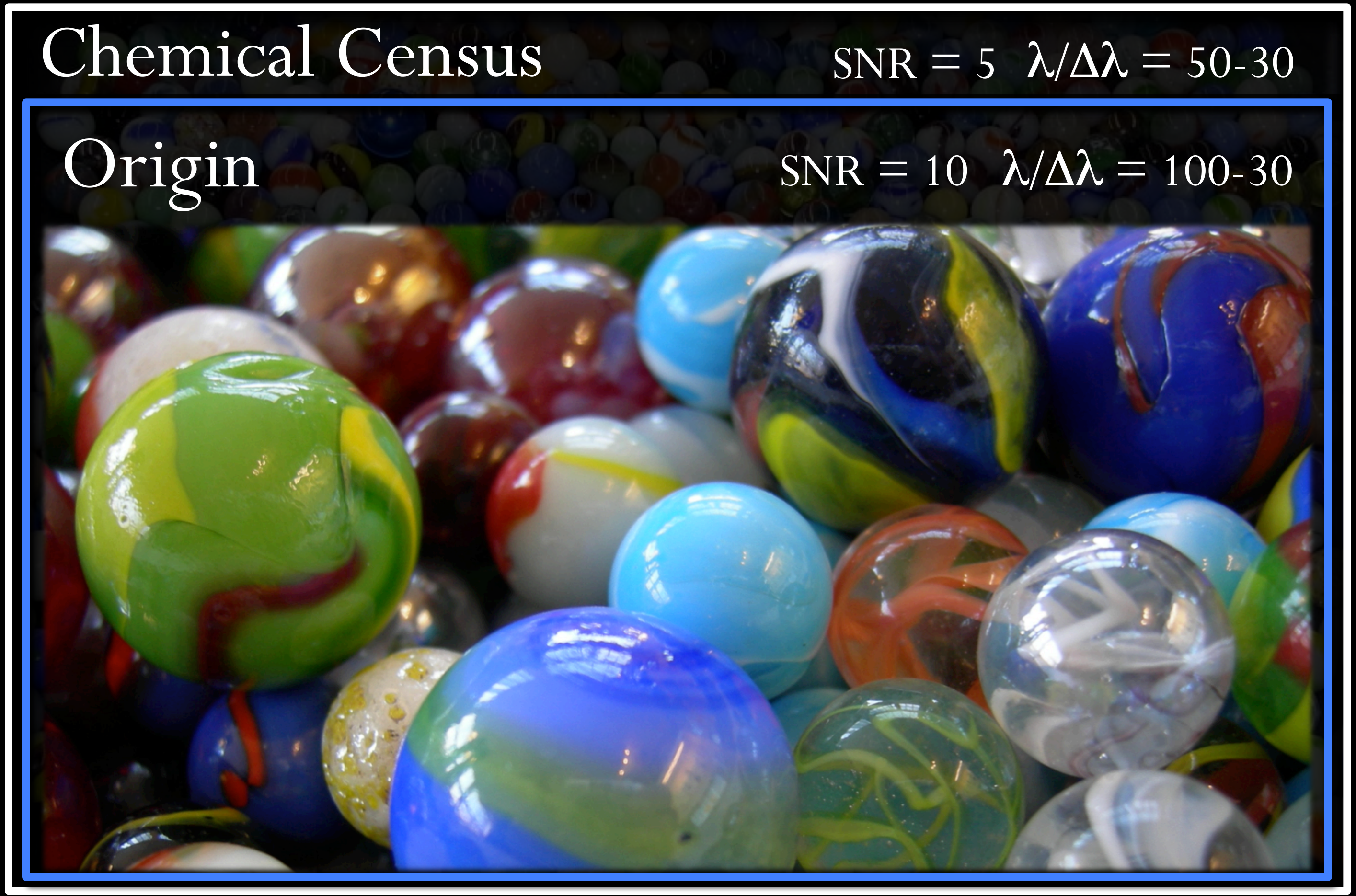


EChO's 3 Surveys:

Study exoplanets as a population & individually

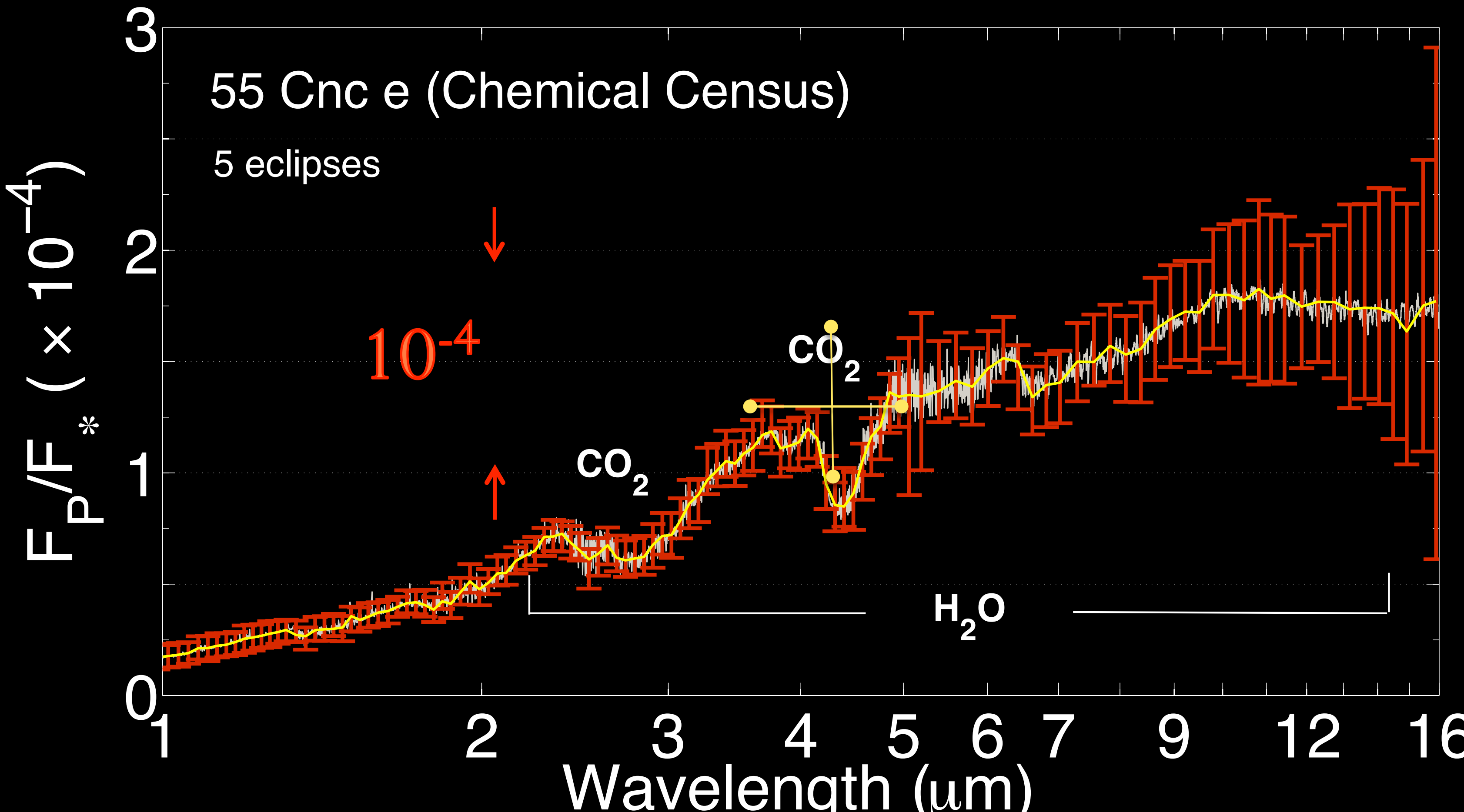
Chemical Census SNR = 5 $\lambda/\Delta\lambda$ = 50-30

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

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

Optimal SNR & λ/Δλ for each survey

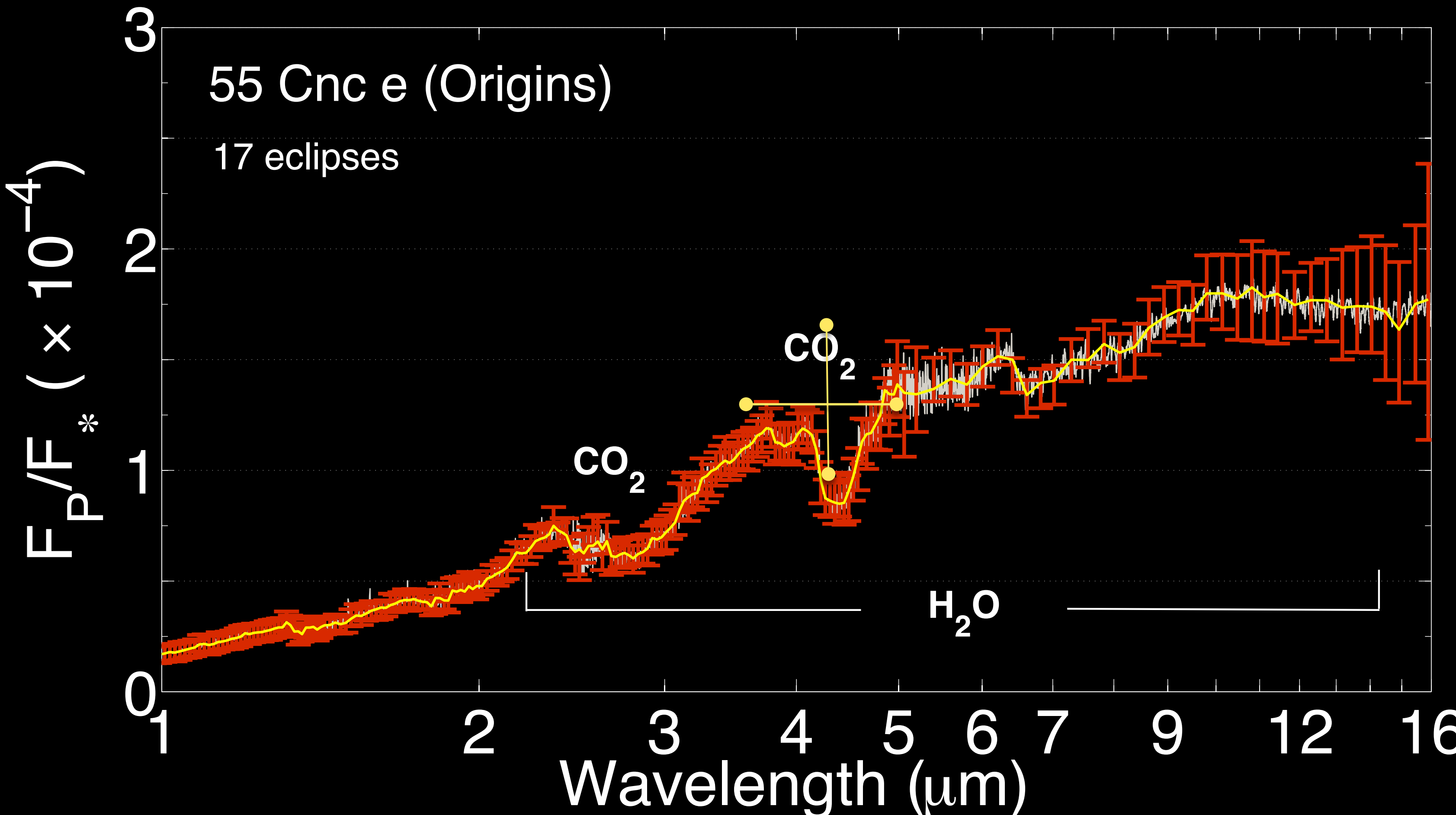
Chemical Census: SNR =5, λ/Δλ= 30-50



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

Optimal SNR & $\lambda/\Delta\lambda$ for each survey

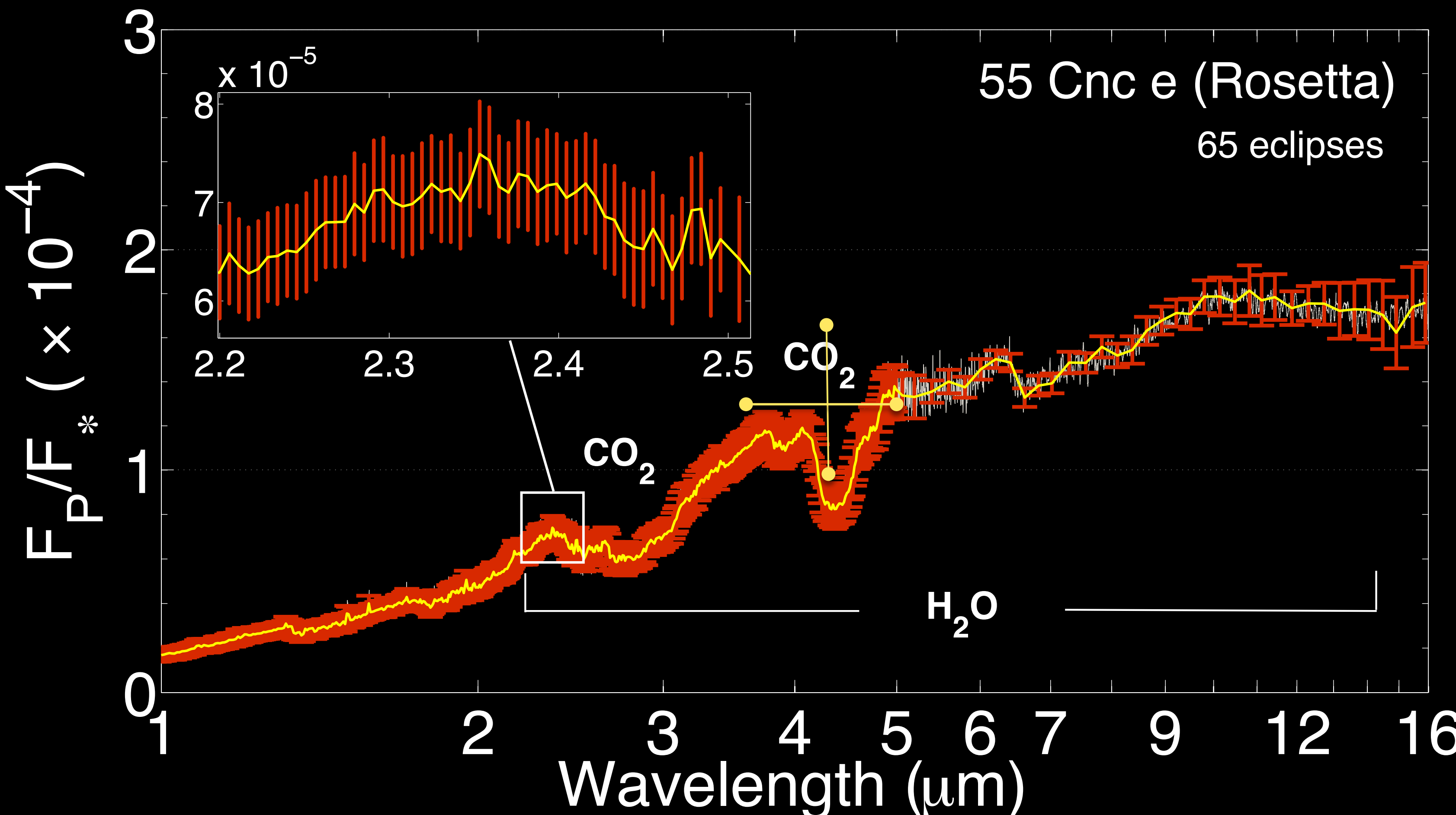
Origin: SNR =10, $\lambda/\Delta\lambda$= 30-100



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

Optimal SNR & λ/Δλ for each survey

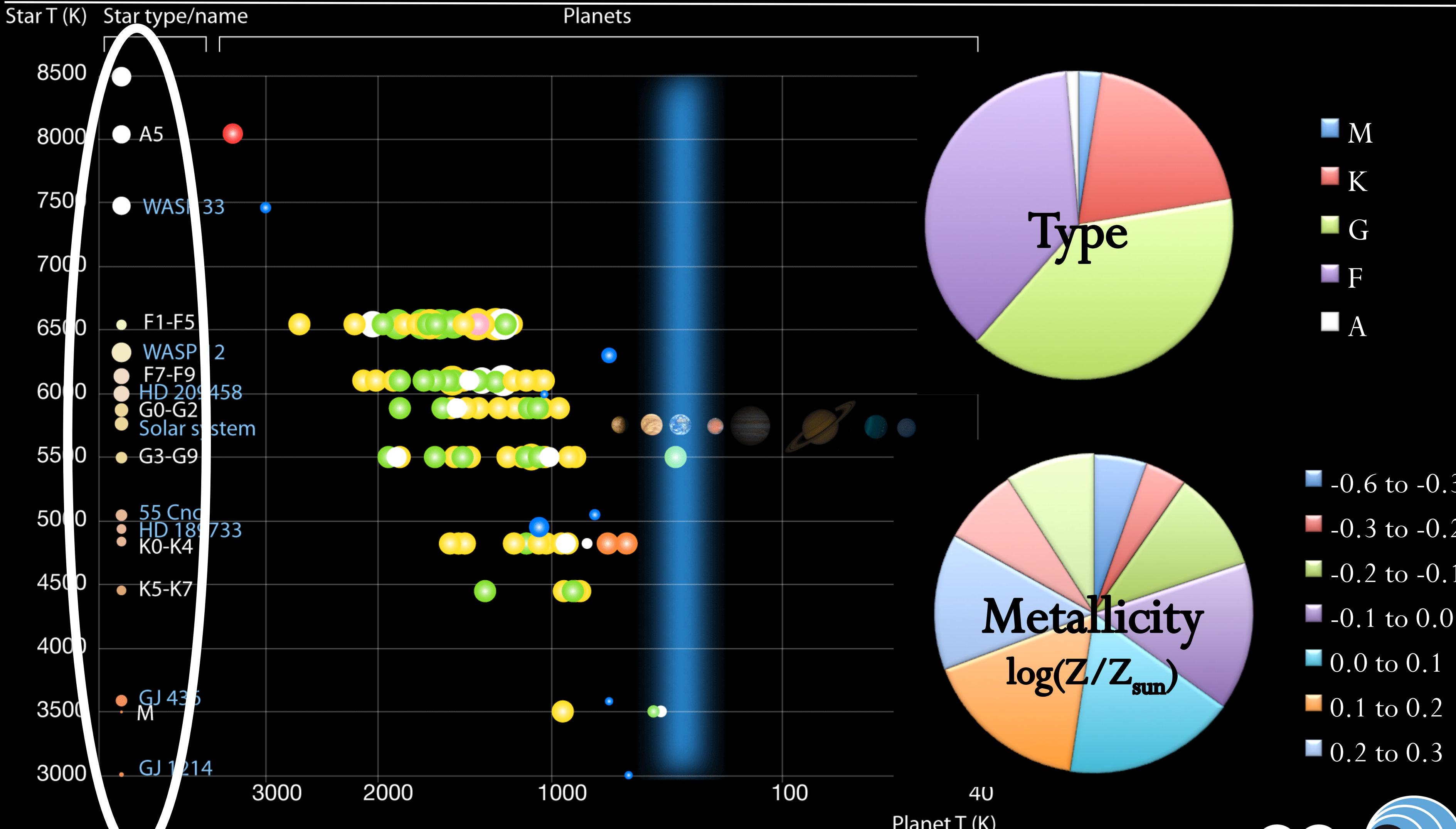
Rosetta Stones: SNR =20, λ/Δλ= 30-300



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

Known Planets observable by EChO

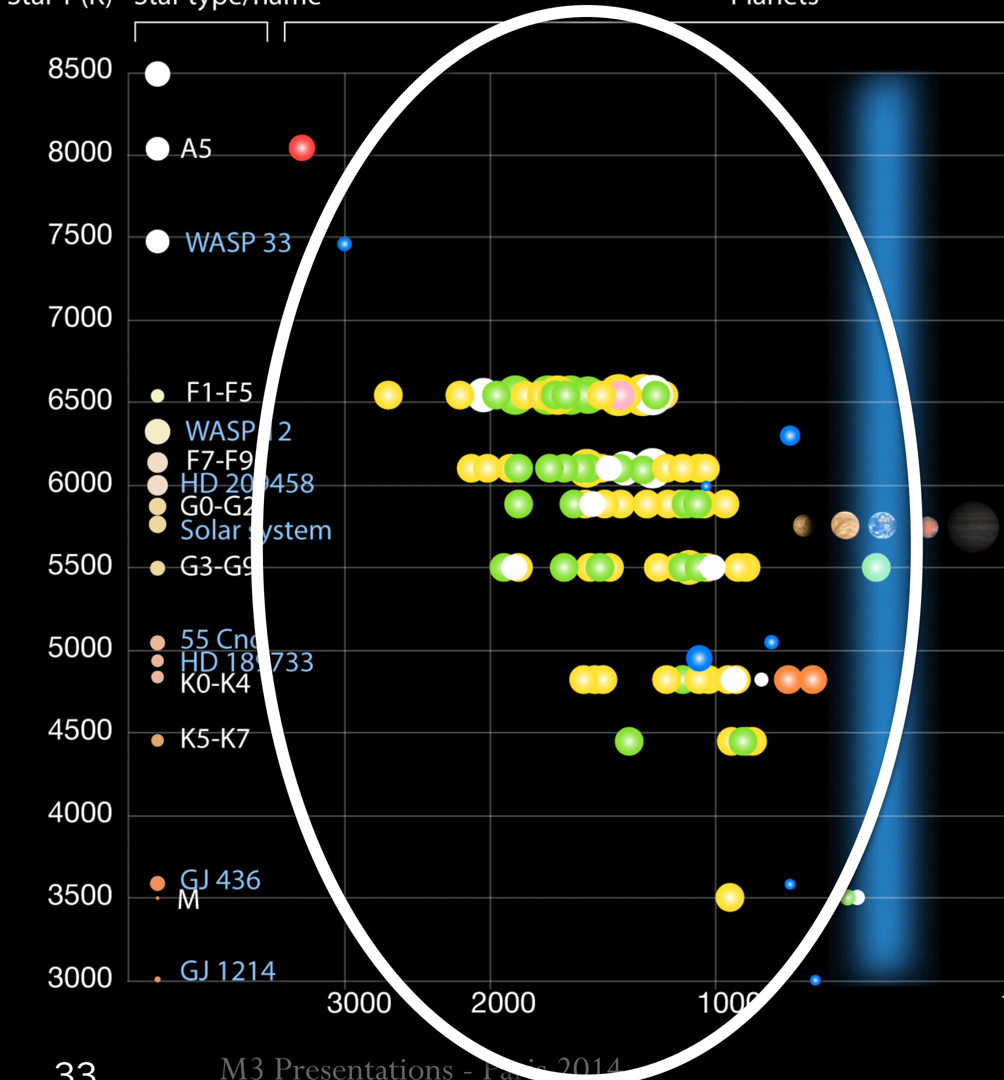
More than 160 today

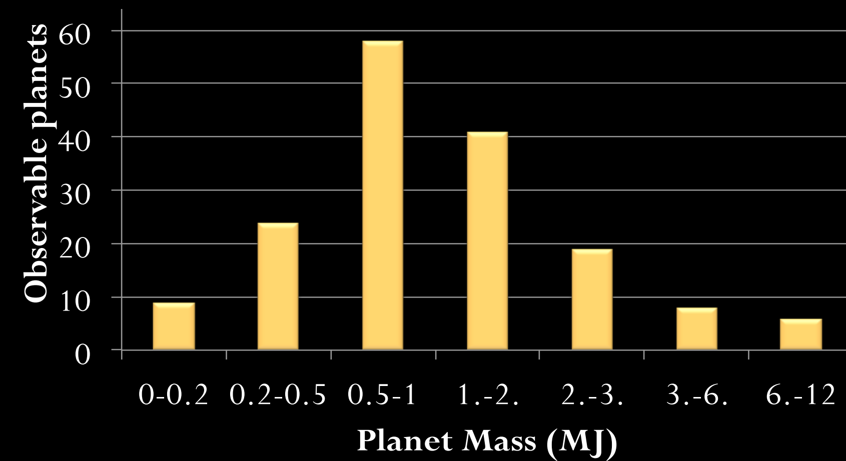


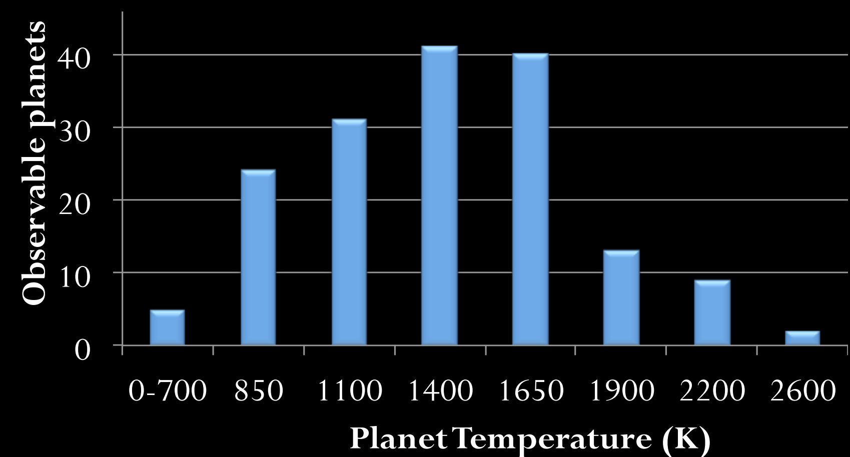
Courtesy of Sylvain Cnudde

Known Planets observable by EChO

More than 160 today







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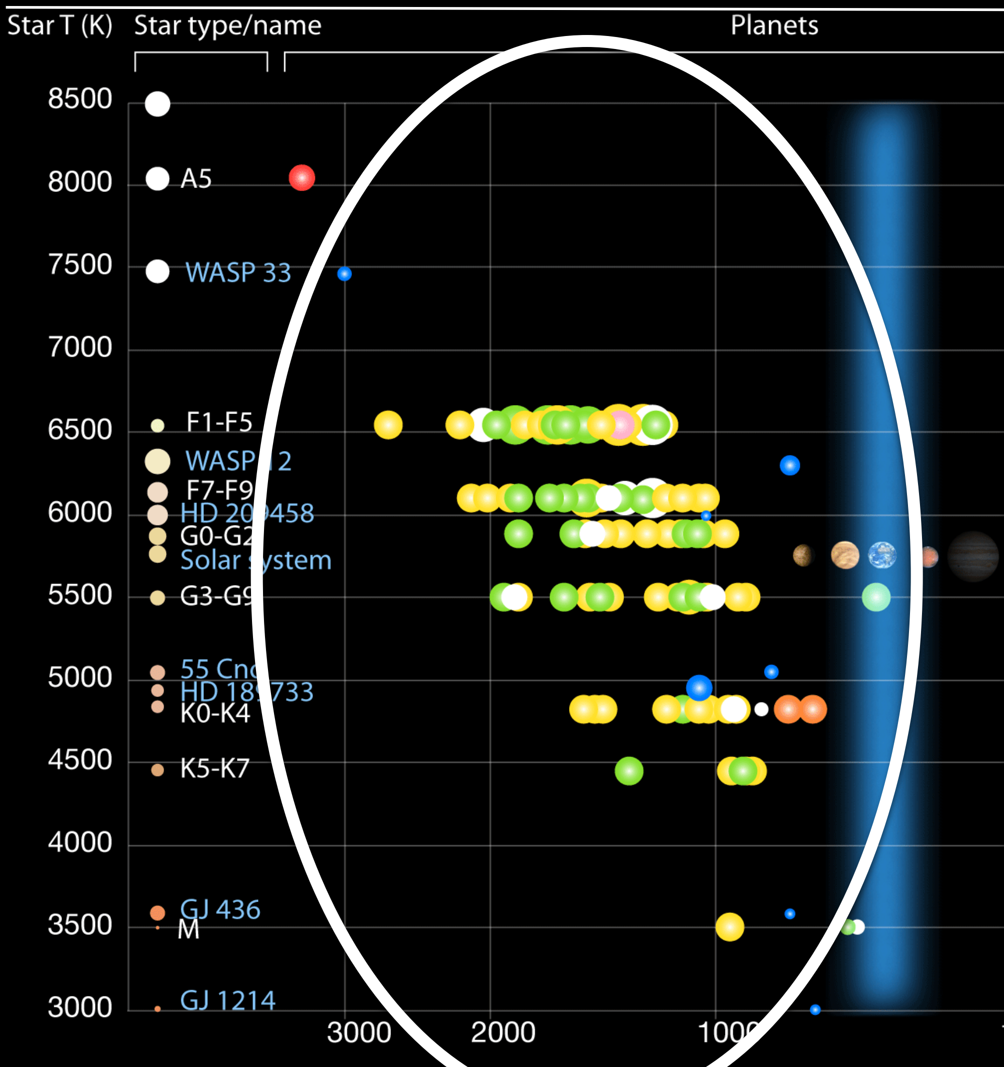
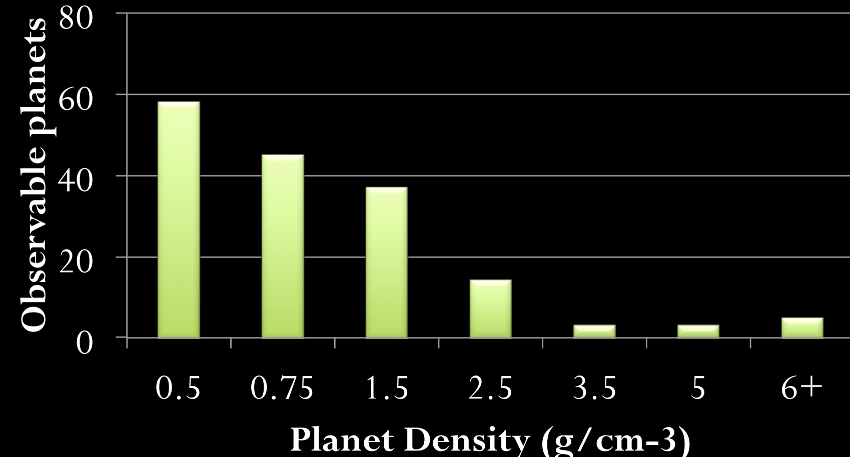
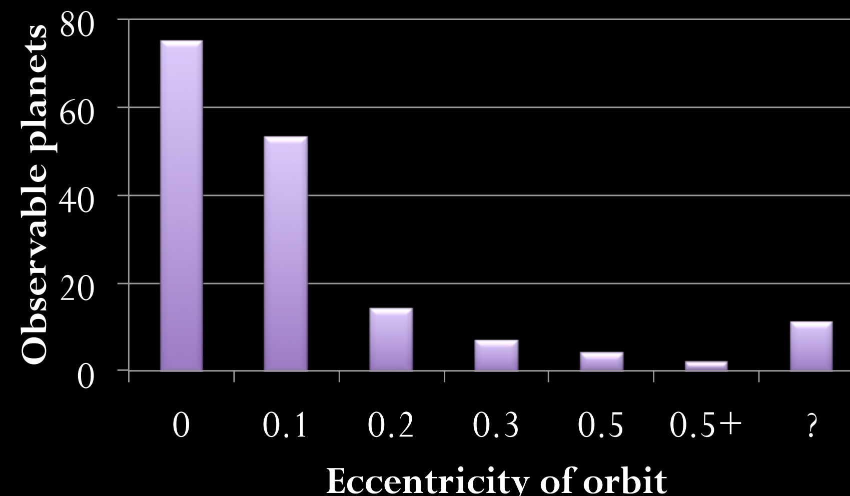






EChO *Chemical Census* survey

Chemical survey of planets in the Solar neighbourhood

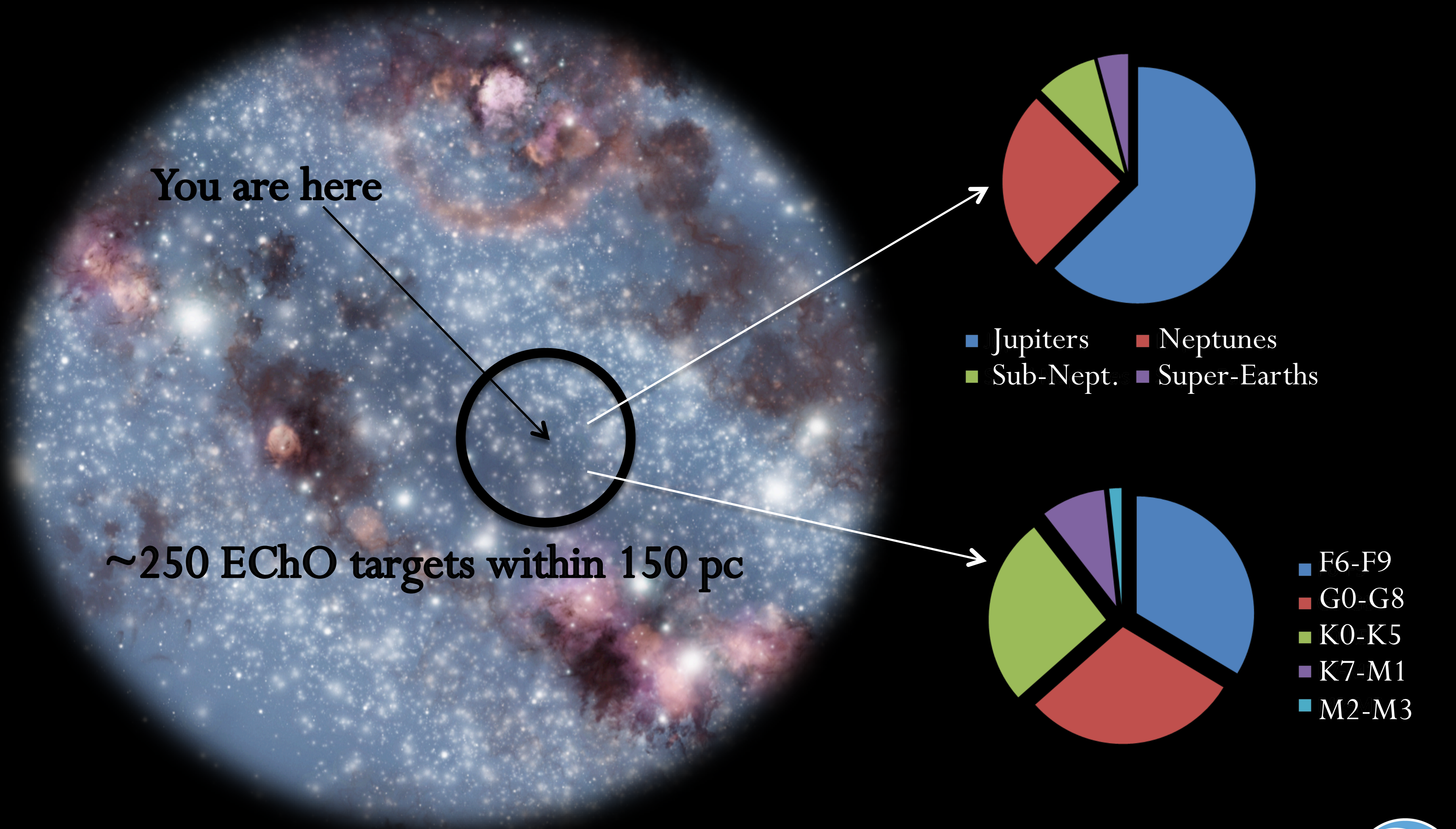
A-F stars ~ 600 pc

G-K stars ~ 400 pc

M stars ~ 50 pc

EChO *Chemical Census* survey

Chemical survey of planets in the Solar neighbourhood

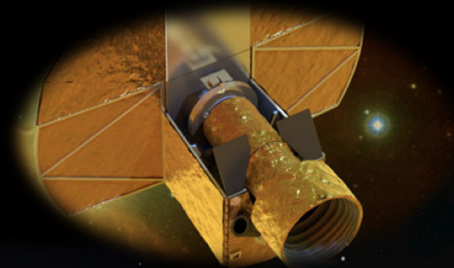


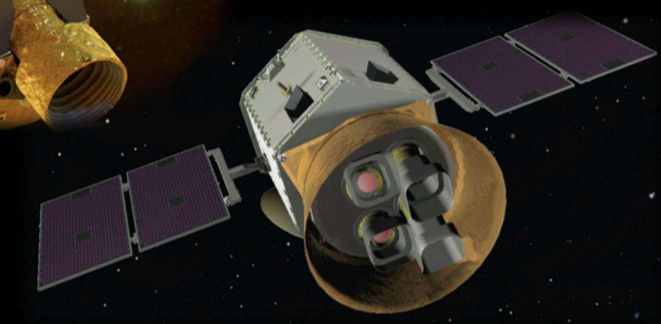
Ribas & Lovis, 2014

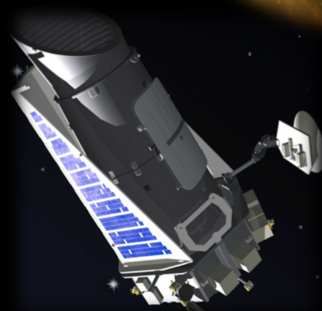
GAIA + Transit & RV surveys

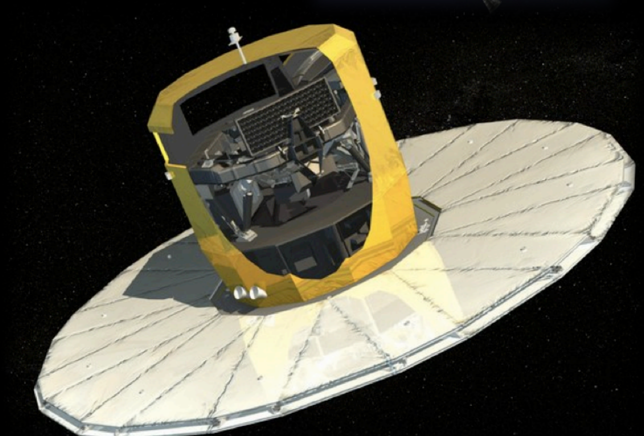
Additional targets for EChO & better stellar parameters

- GAIA
- Cheops
- TESS
- Kepler2
- HARPS/HARPS North
- HAT-NET
- Super-WASP
- Carmenes
- M-Earth
- NGTS
- APACHE
- Spirou
- MASCARA



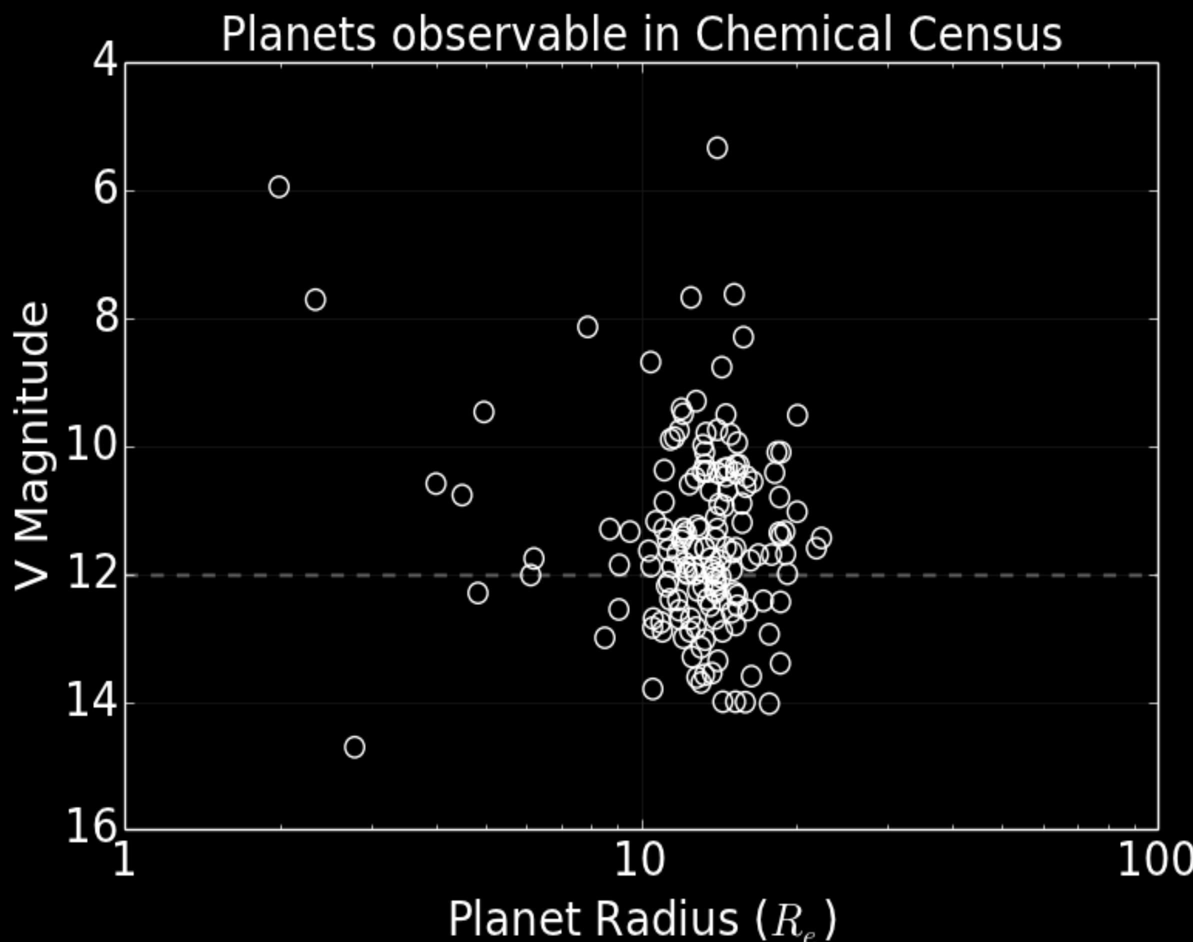






Additional targets from NASA-TESS

Dedicated mission to detect transiting planets (2017)



Current known planets observable by EChO

Varley et al., 2014

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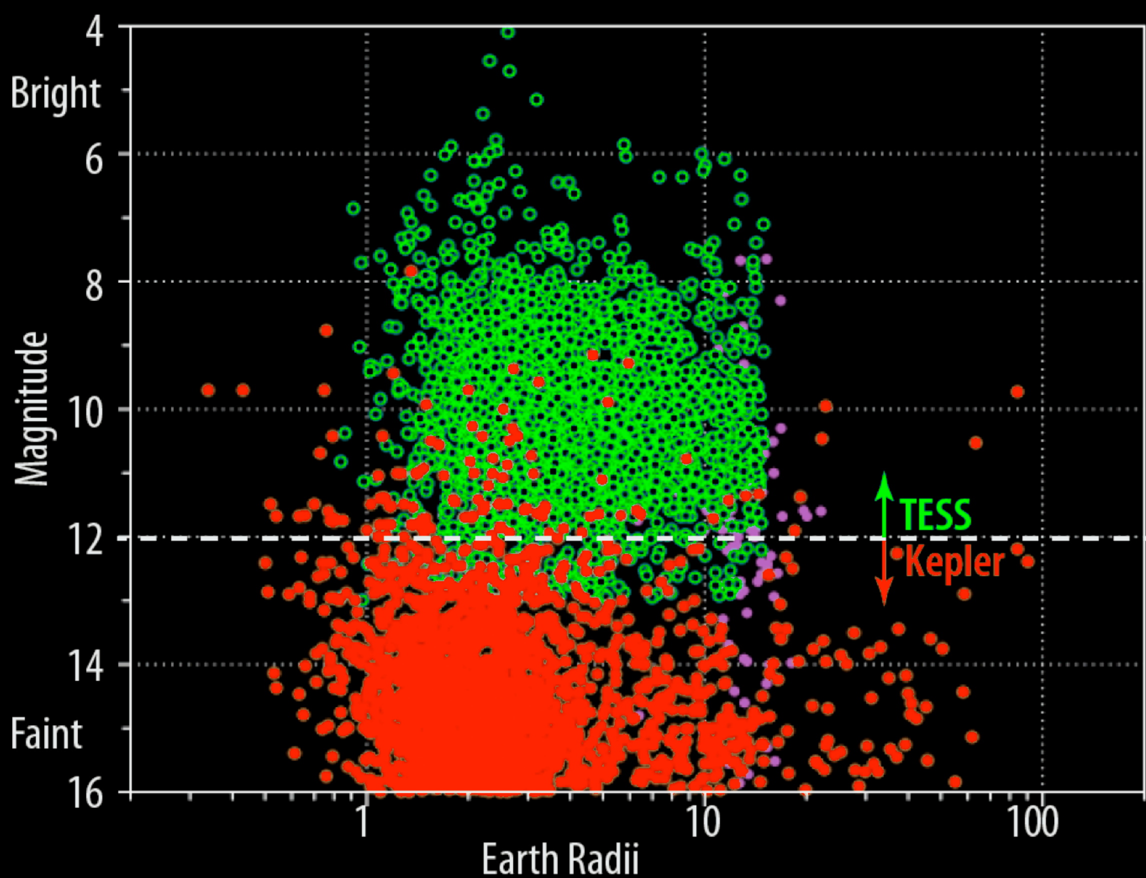
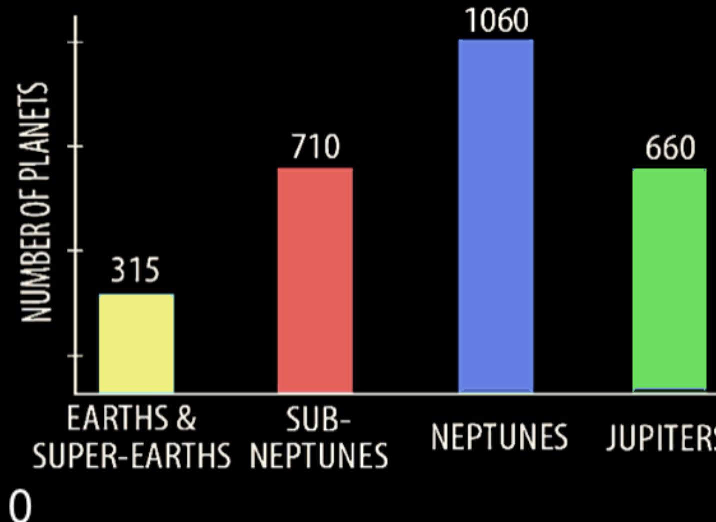


Transiting planets expected to be discovered by TESS



Courtesy of the TESS team

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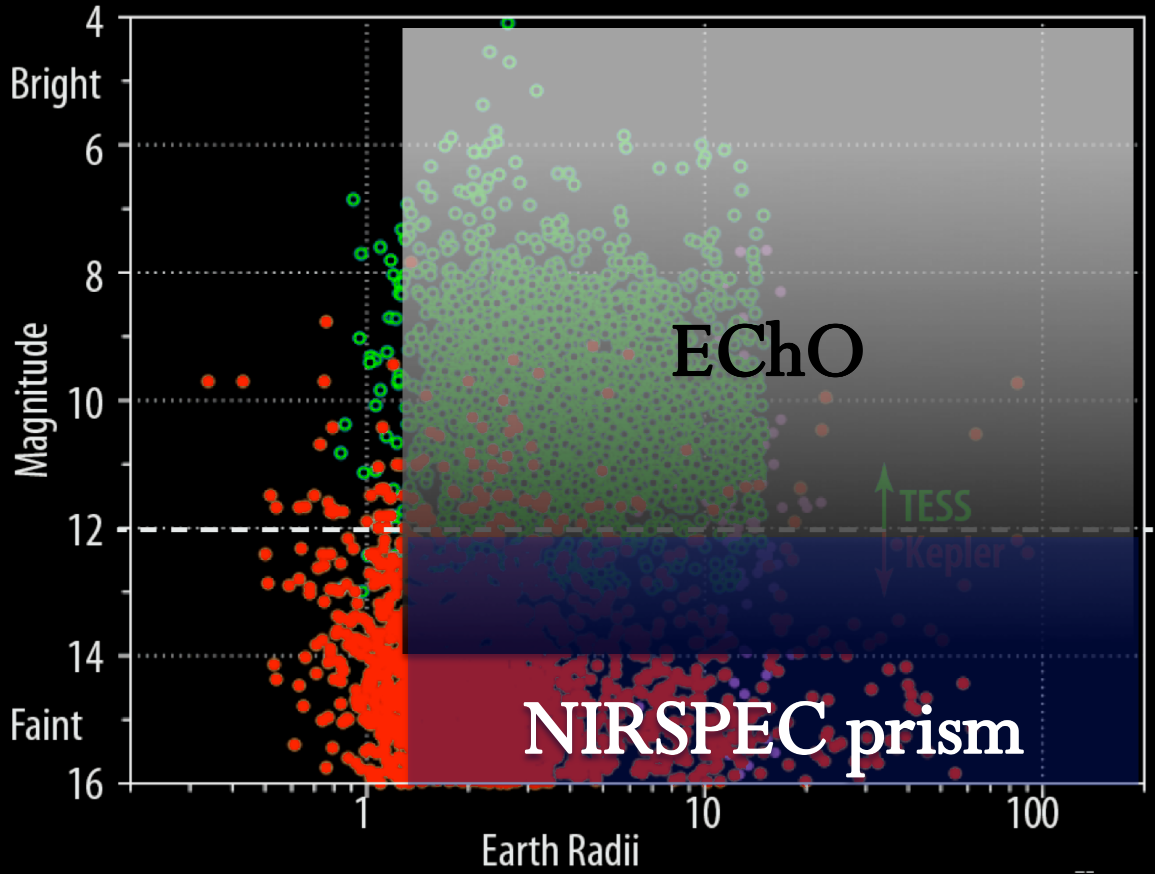

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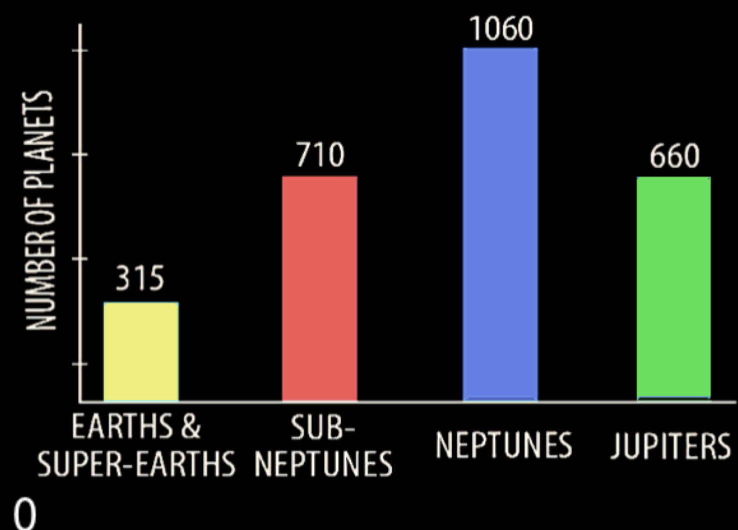
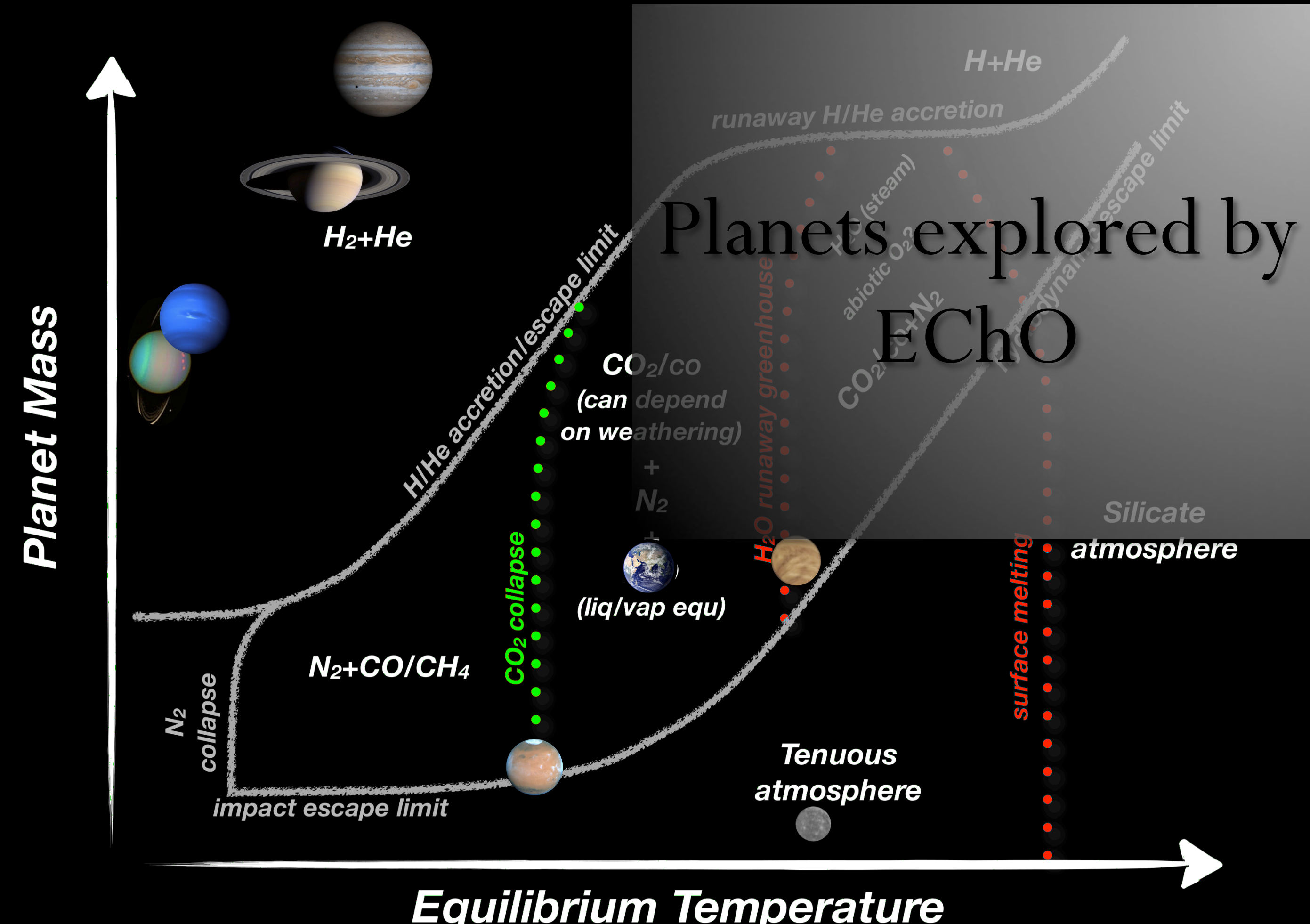


Courtesy of the TESS team

EChO *Chemical Census & Origin*

Exploring the chemical diversity & understanding the physical processes

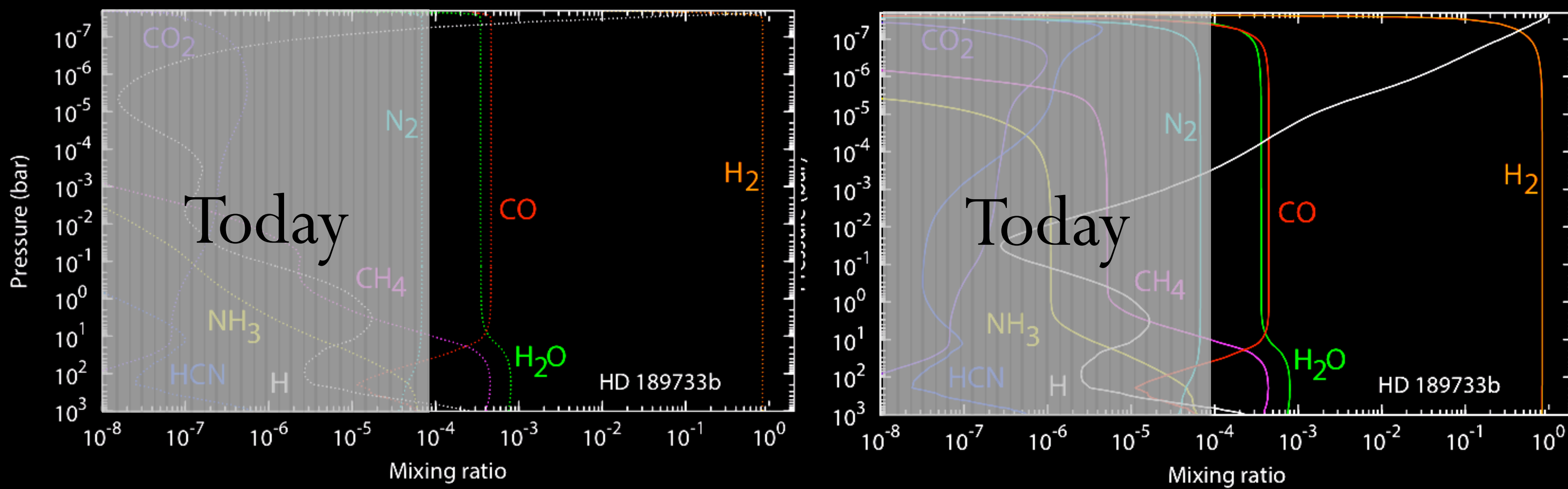


Forget & Leconte, 2013

Current observations

Detecting only the most abundant molecules

Equilibrium chemistry | Non-equilibrium chemistry



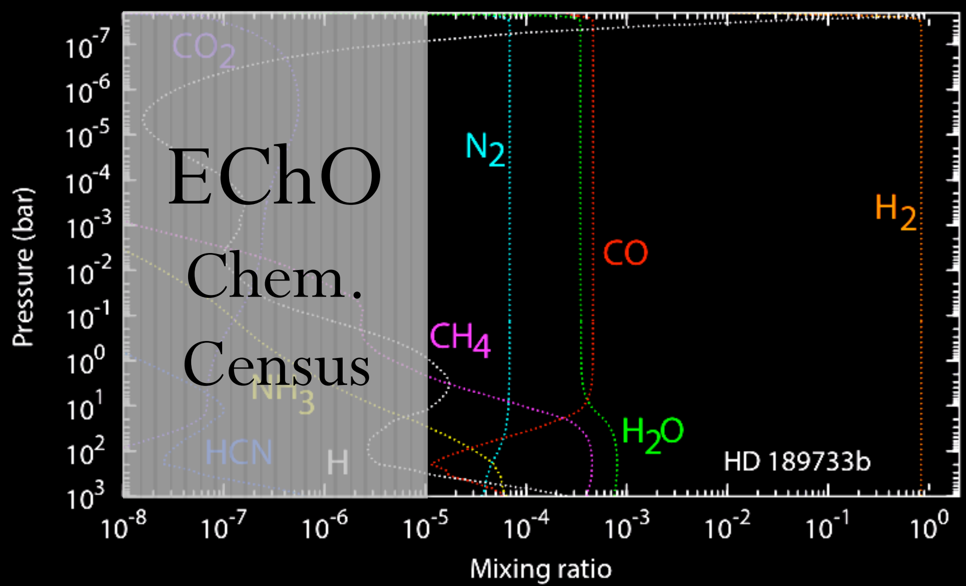
~ 10 planets

Venot et al., 2012

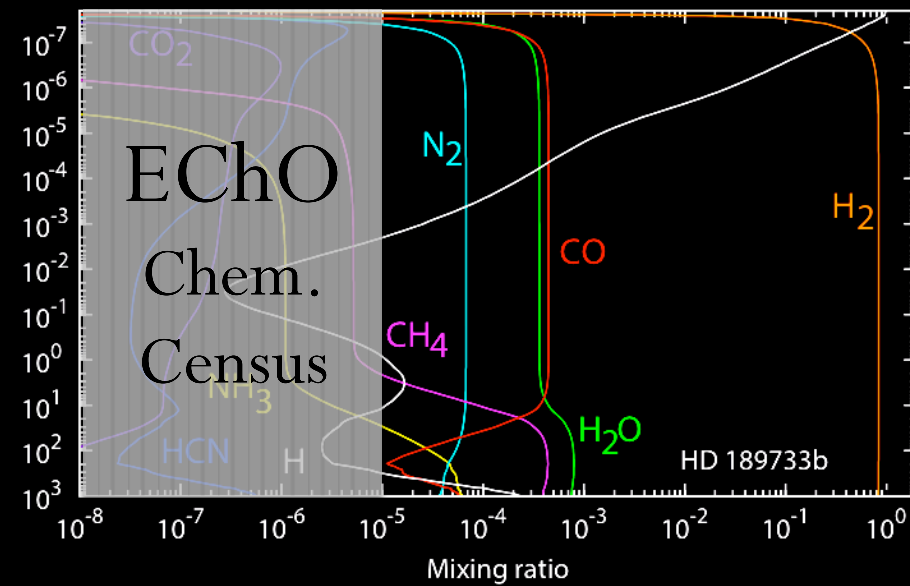
EChO *Chemical Census* survey

Detecting key molecules, mapping the chemical diversity

Equilibrium chemistry



Non-equilibrium chemistry

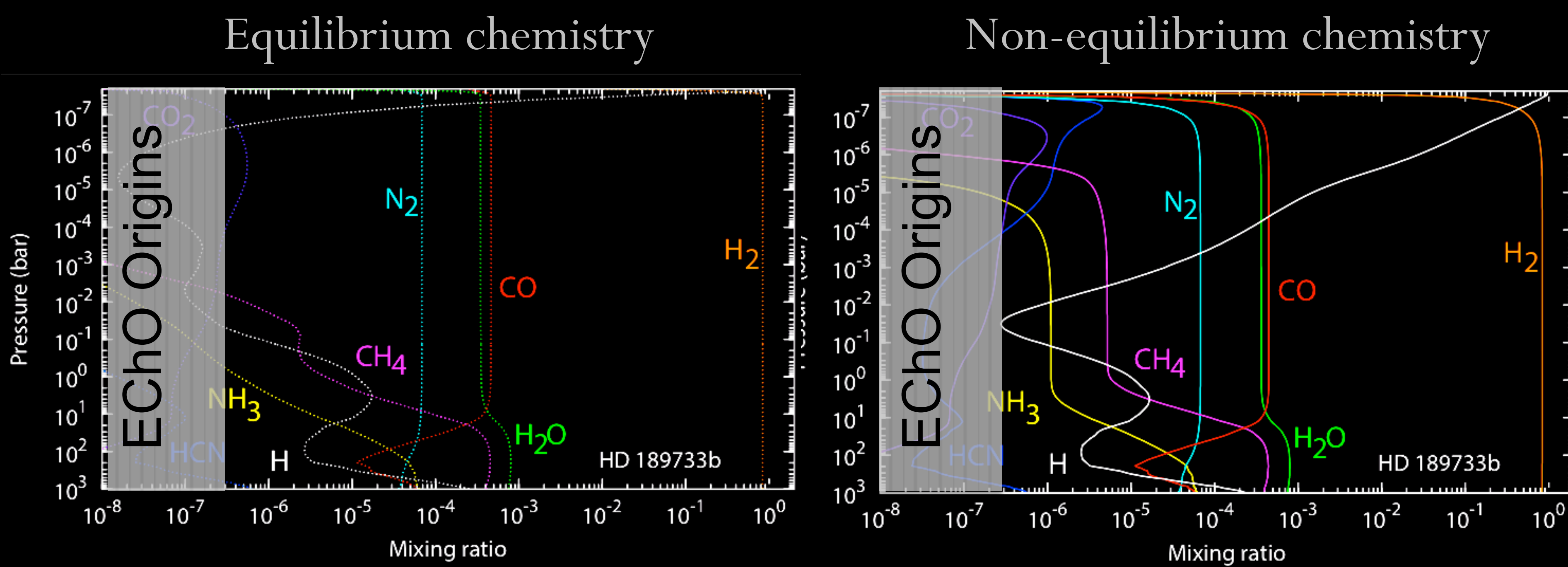


~ 150-300 planets

Venot et al., 2012

EChO *Origin* survey

Understanding the role of non-equilibrium chemistry

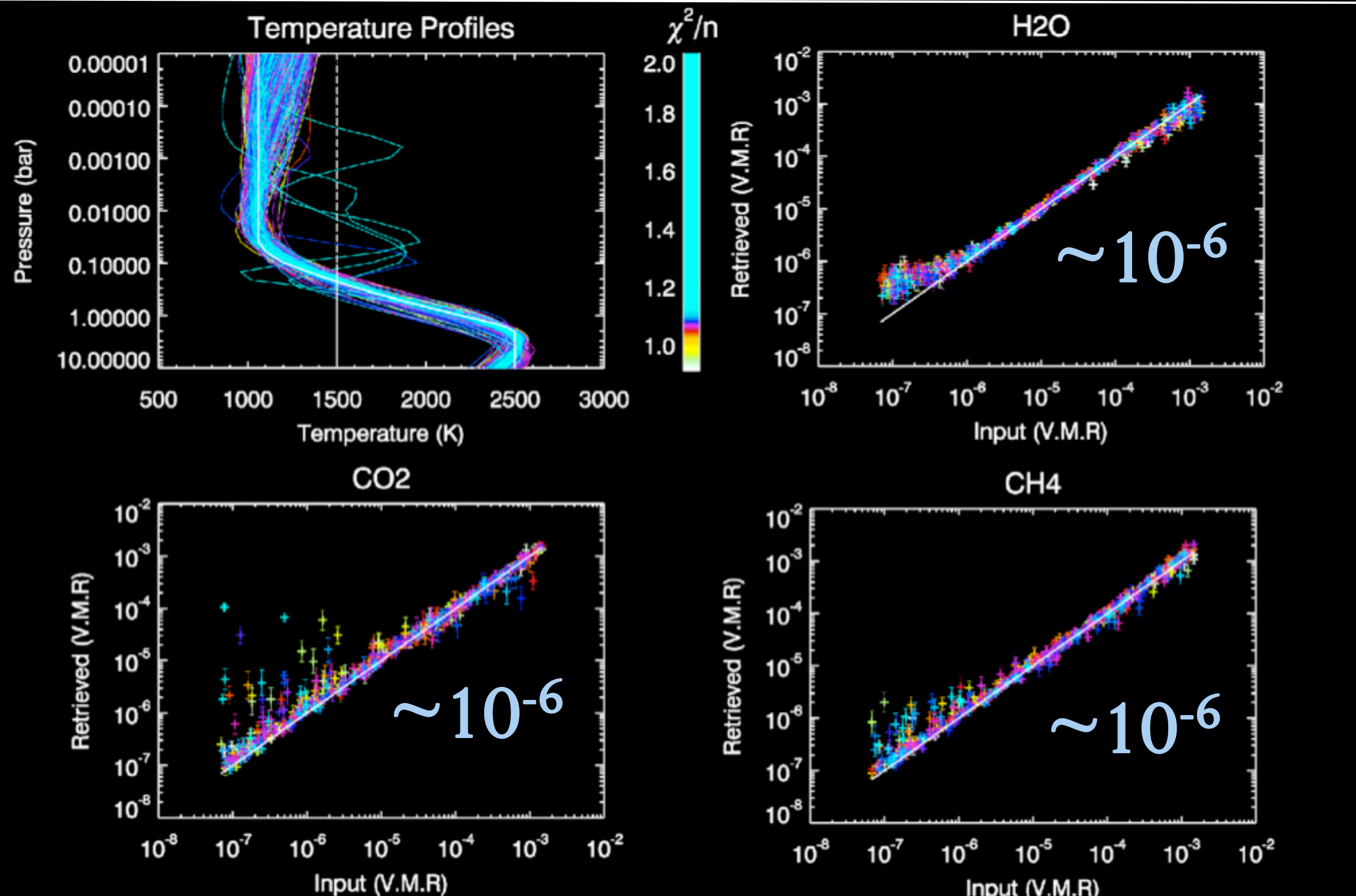


~ 50-100 planets

Venot et al., 2012

EChO *Origin* survey

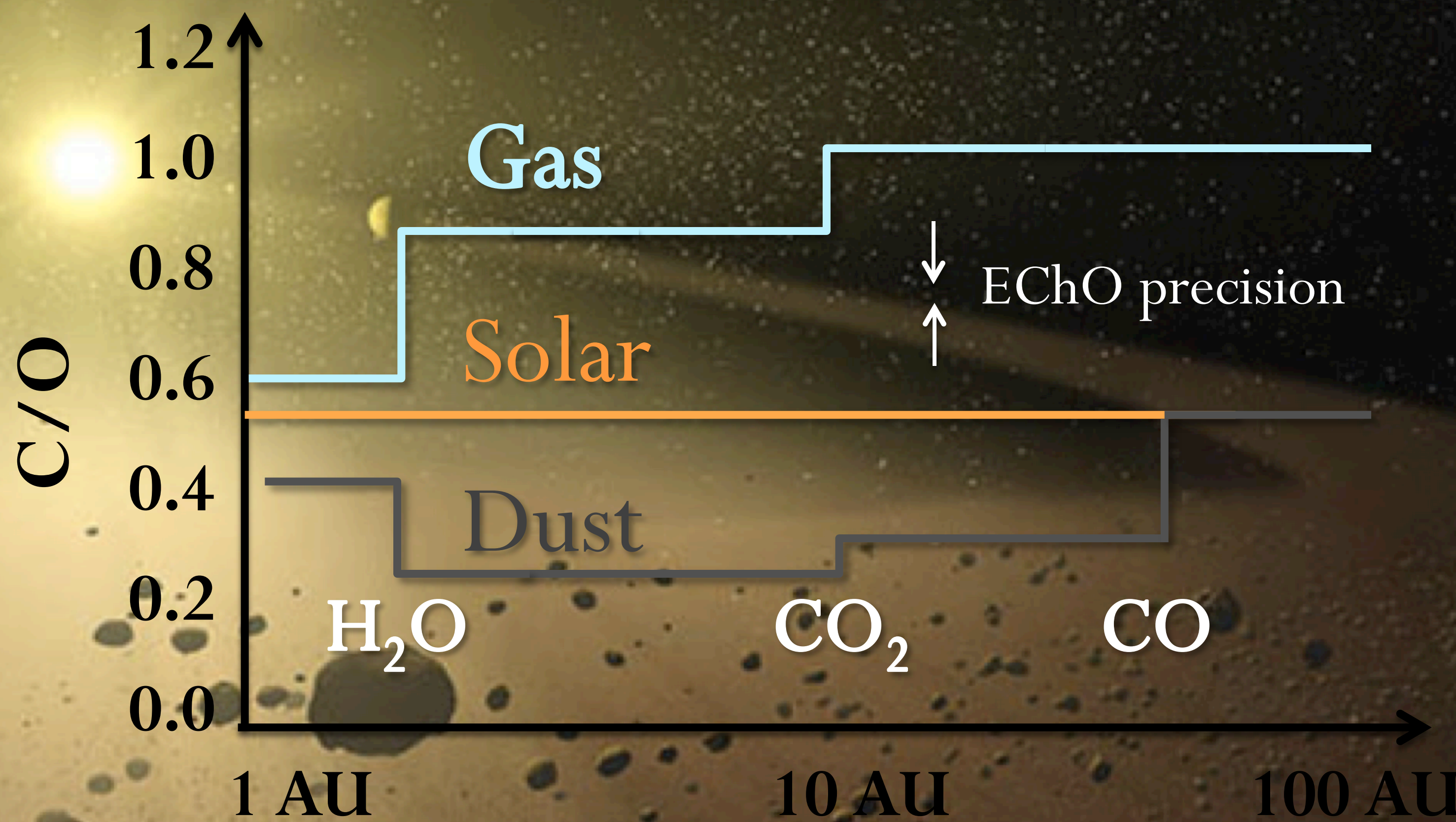
Spectral retrieval thermal structure & molecular abundances



Barstow et al., 2012

EChO *Origin* survey

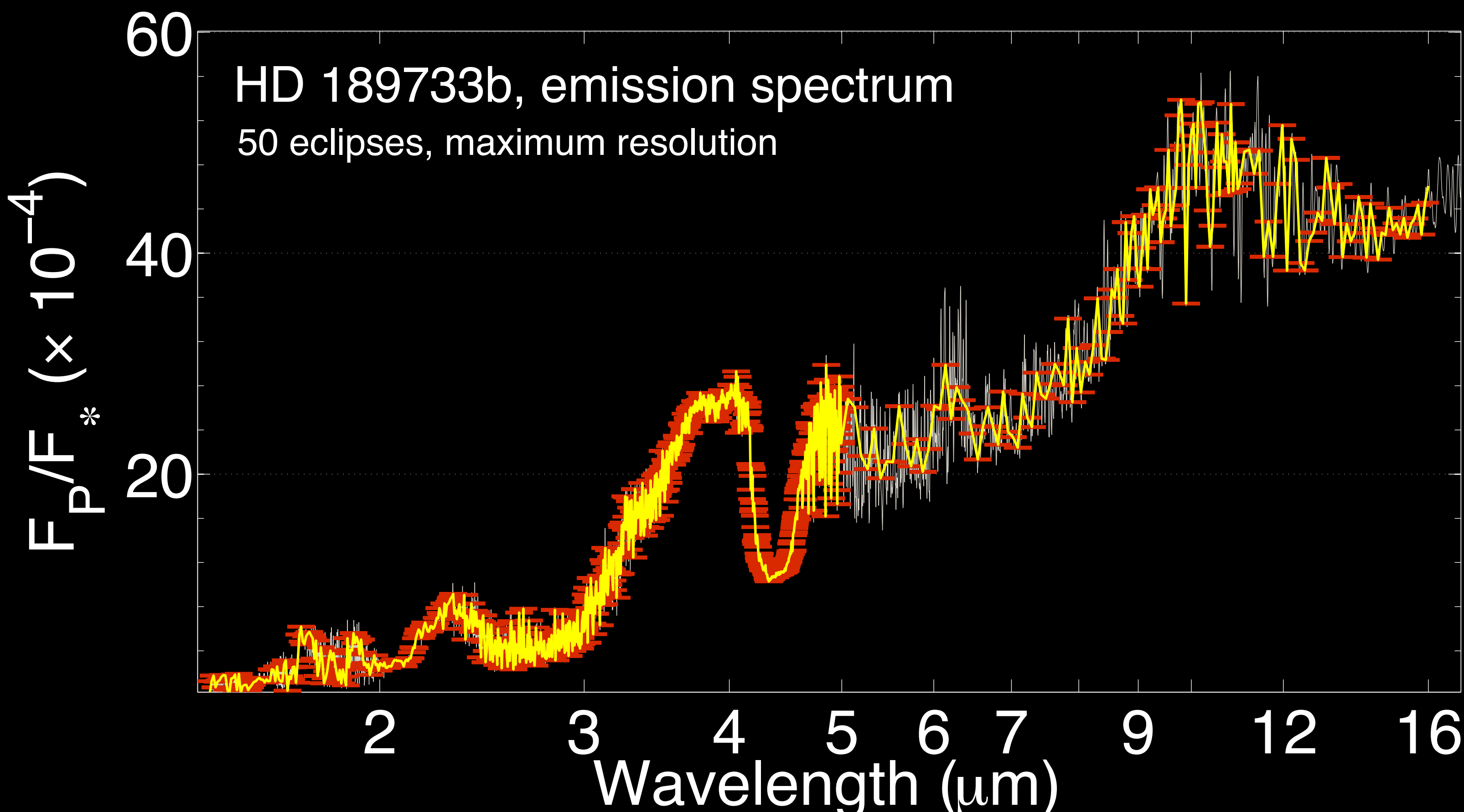
Understanding planet formation/migration processes



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

EChO *Rosetta Stones* survey

Benchmark cases to understand classes of planets



Varley et al, 2014

EChO *Rosetta Stones* survey

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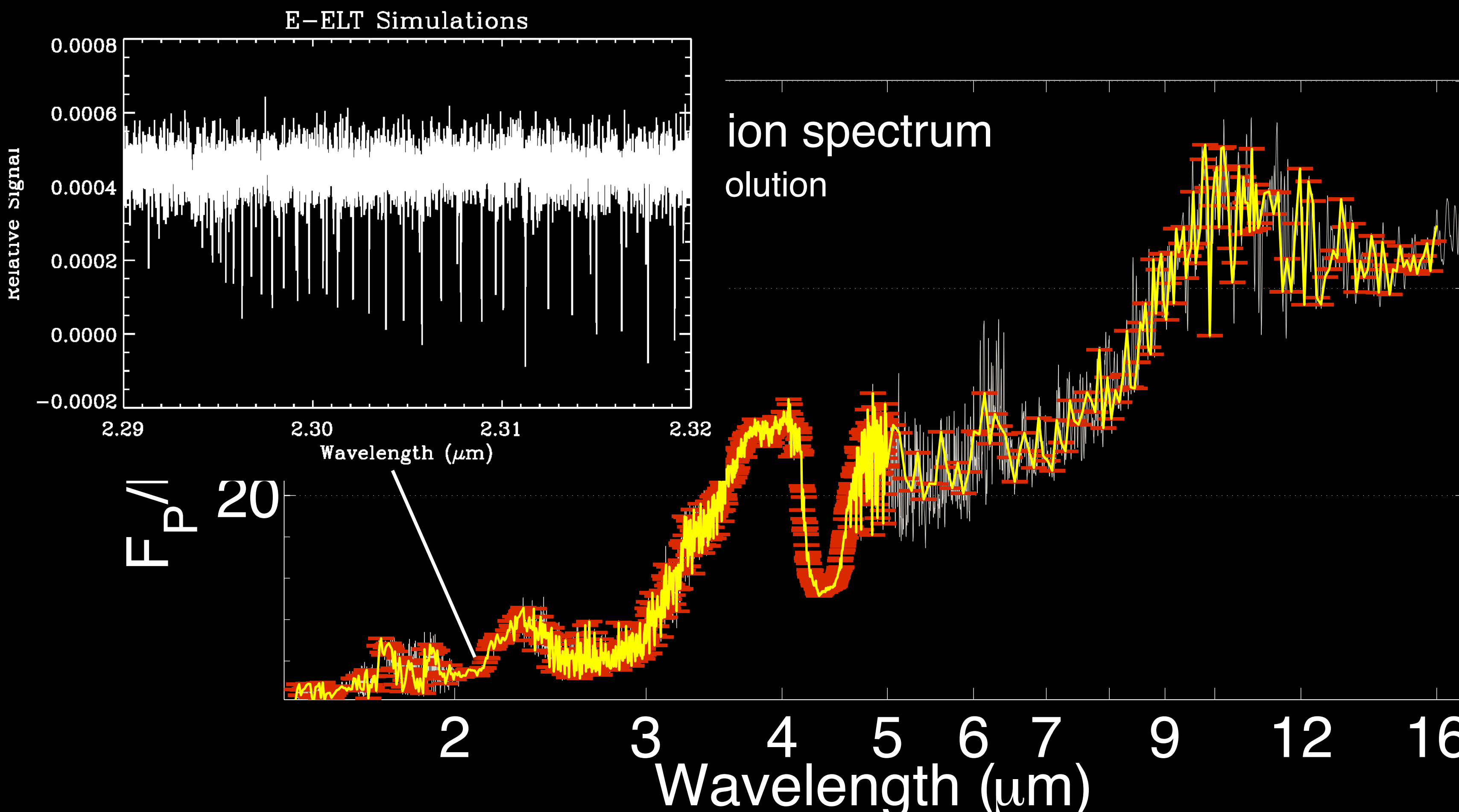
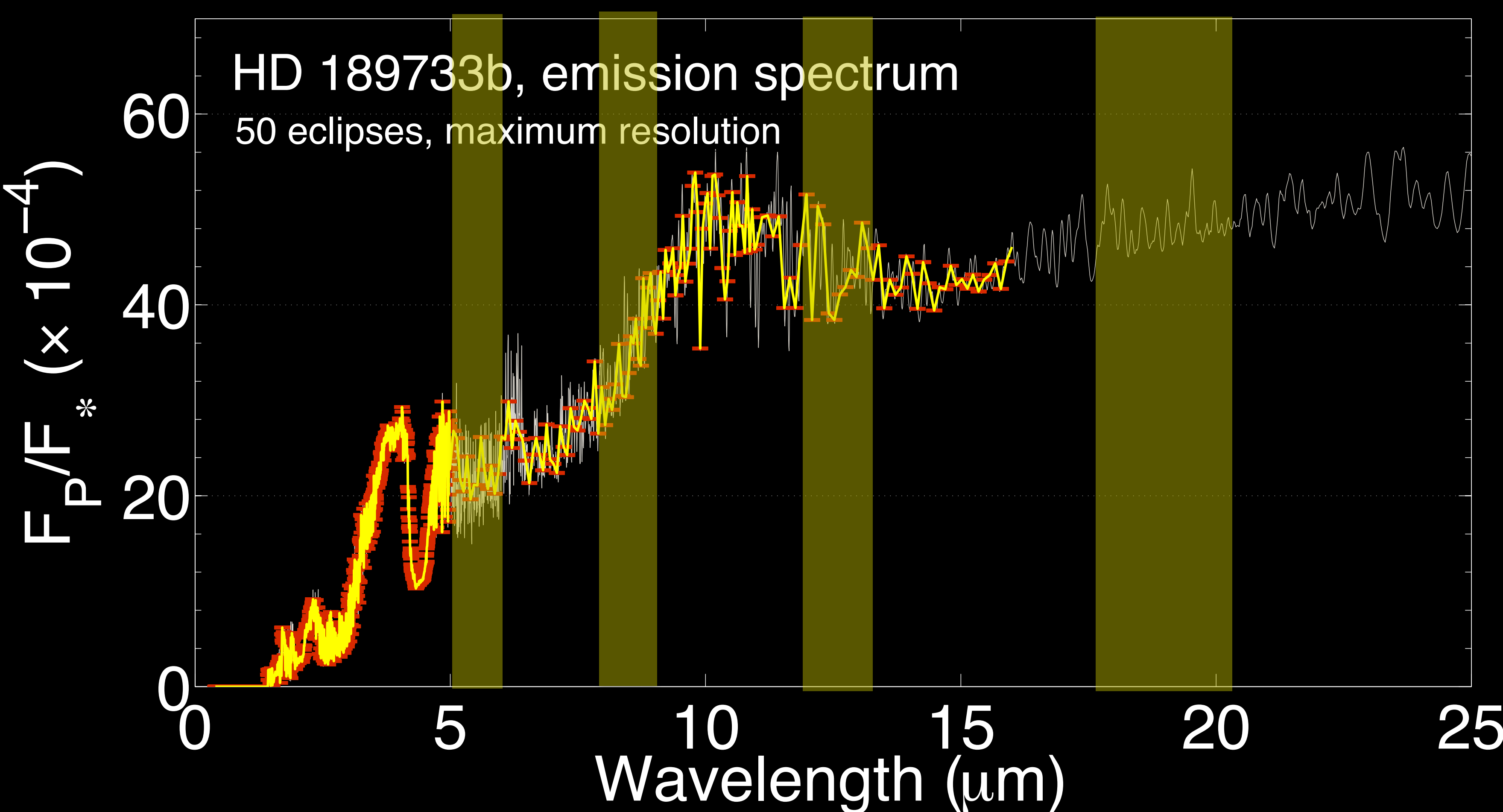


Varley et al, 2014

EChO *Rosetta Stones* survey

Synergy with MIRI Filters



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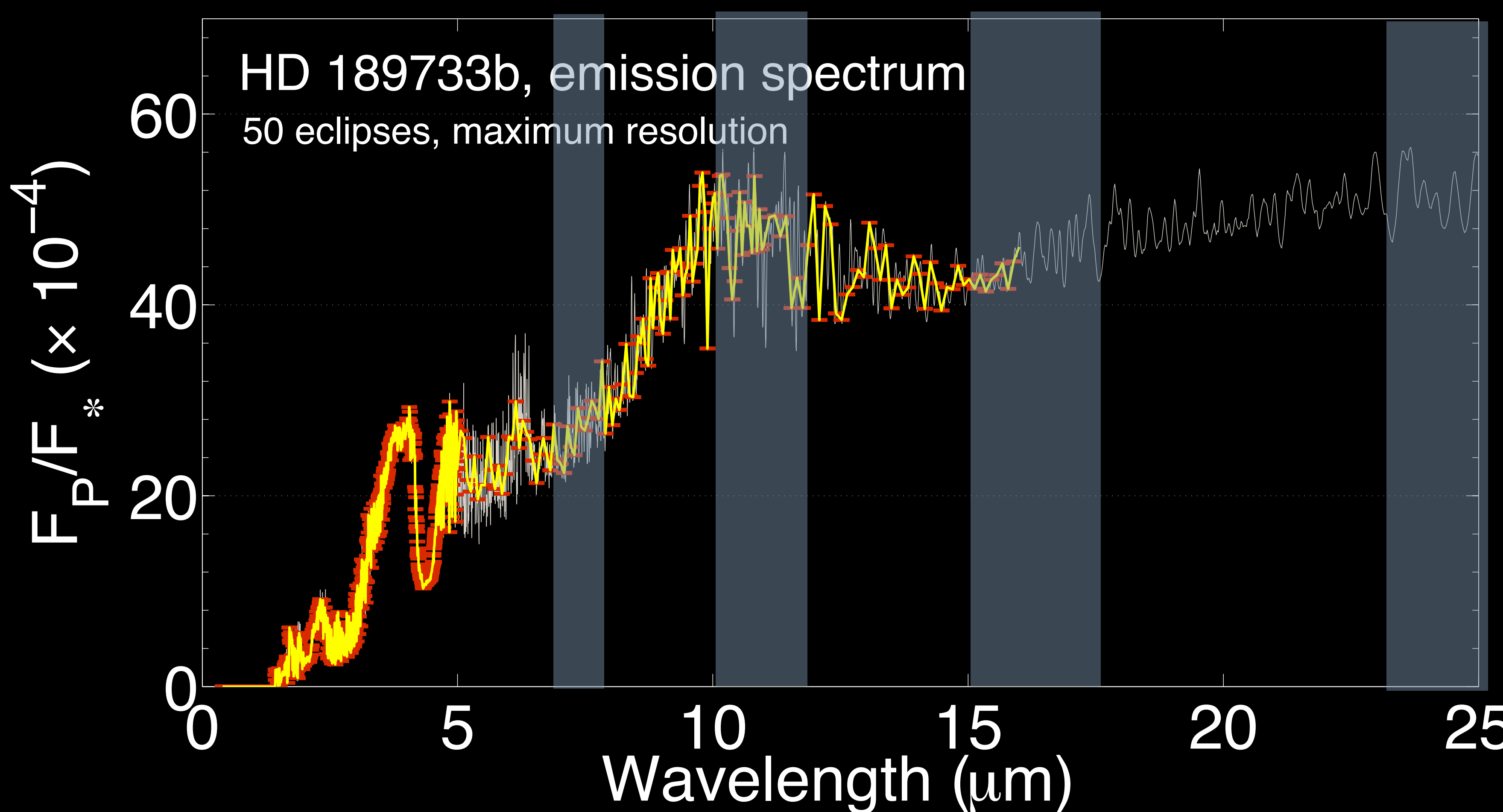

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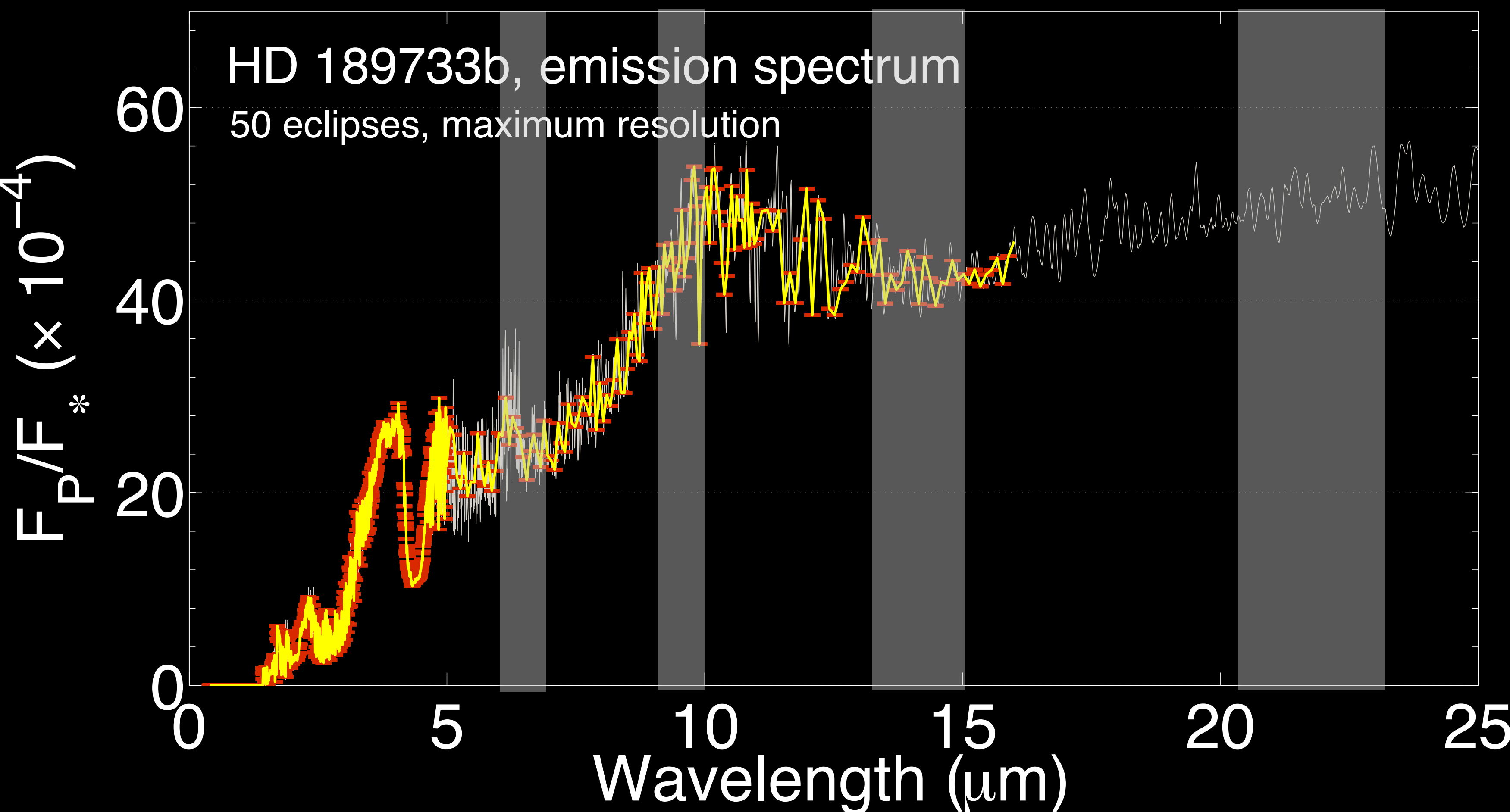
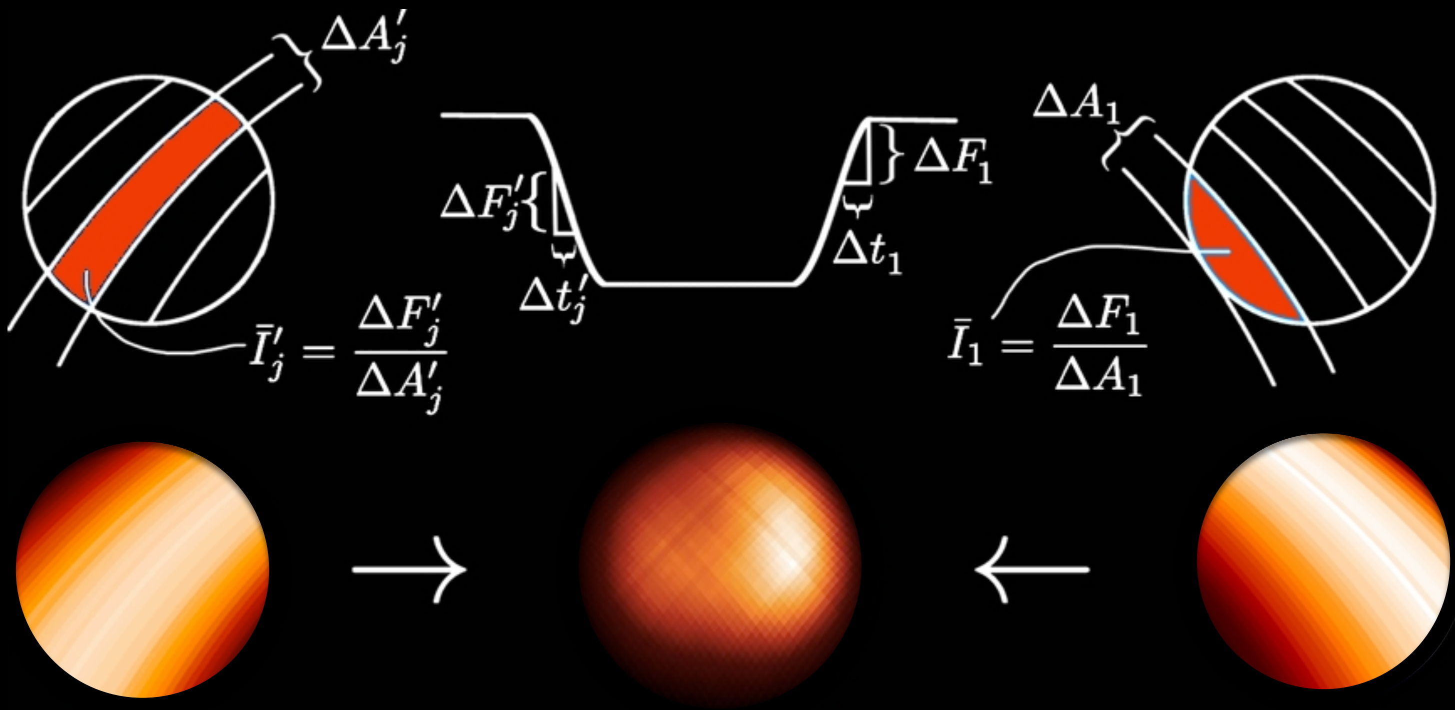


Varley et al, 2014

ECHO *Rosetta Stones* survey

2D images of the planet

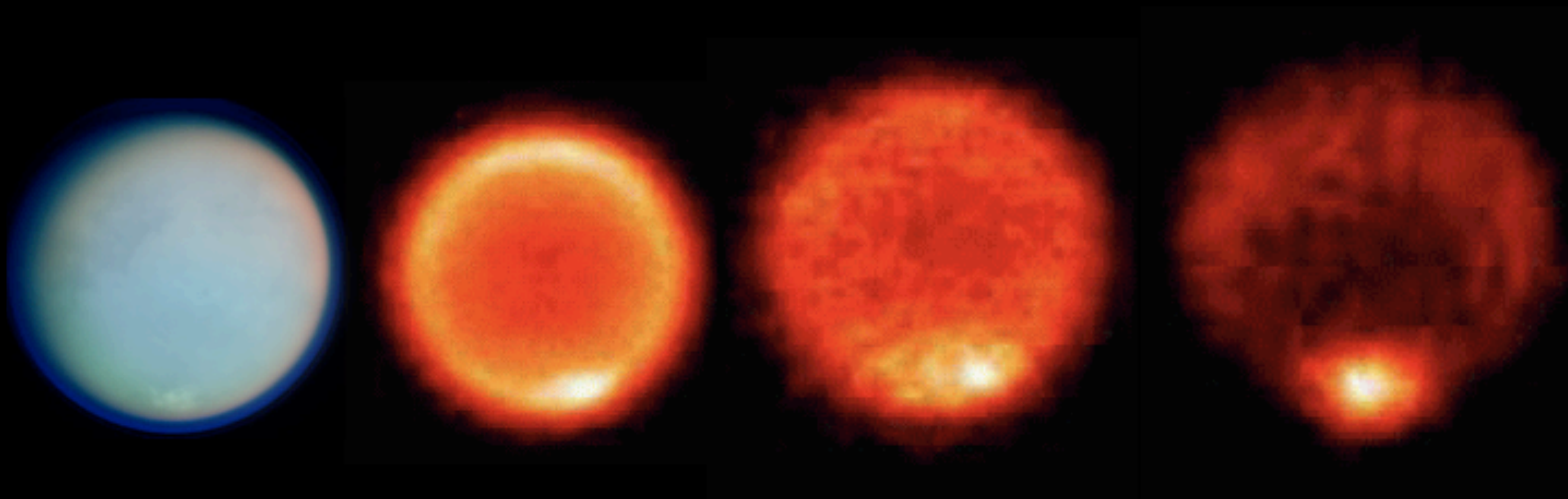


Majeau et al., 2014

EChO *Rosetta Stones* survey

2D images of the planet

Exploring spatial variability @ multiple λ

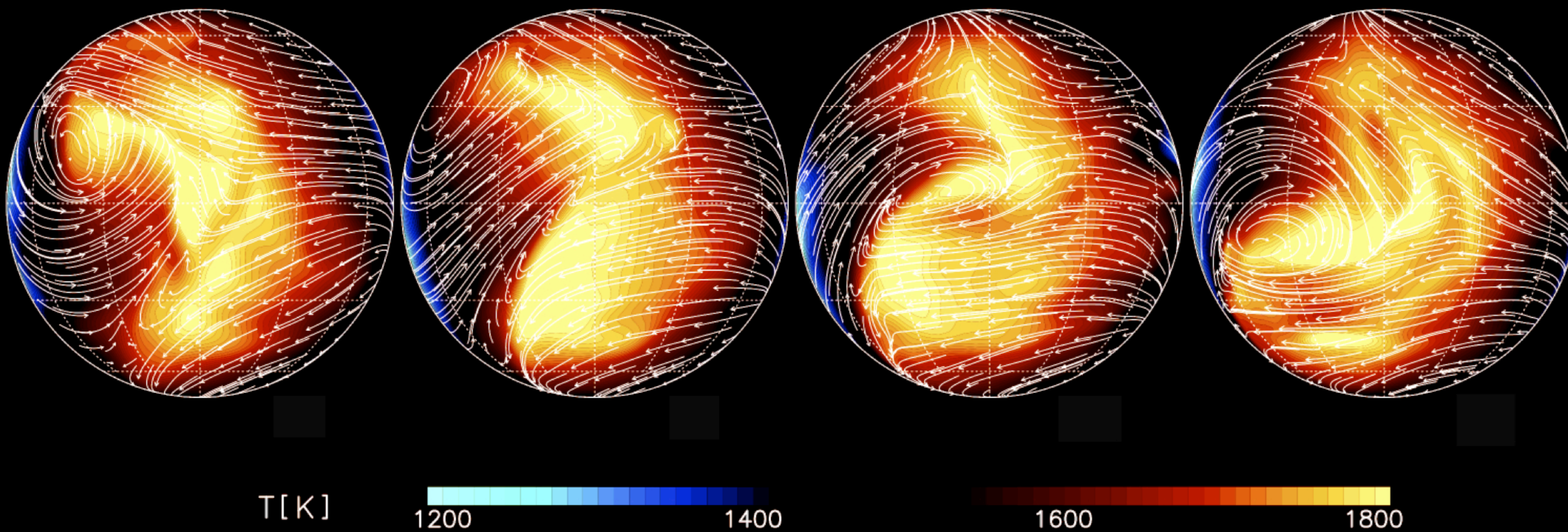


0.4-1 μm 2-4 μm 7-11 μm 11-16 μm

EChO *Rosetta Stones* survey

Weather & temporal variability

Understanding the role of dynamics (repeating > 20 times)

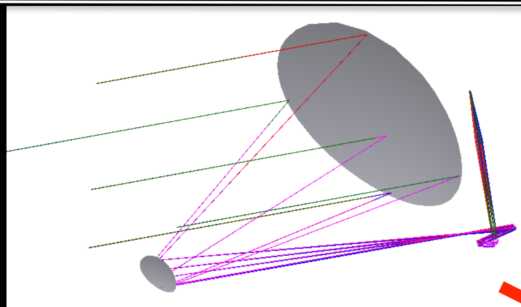


Thrastarson & Cho, 2012

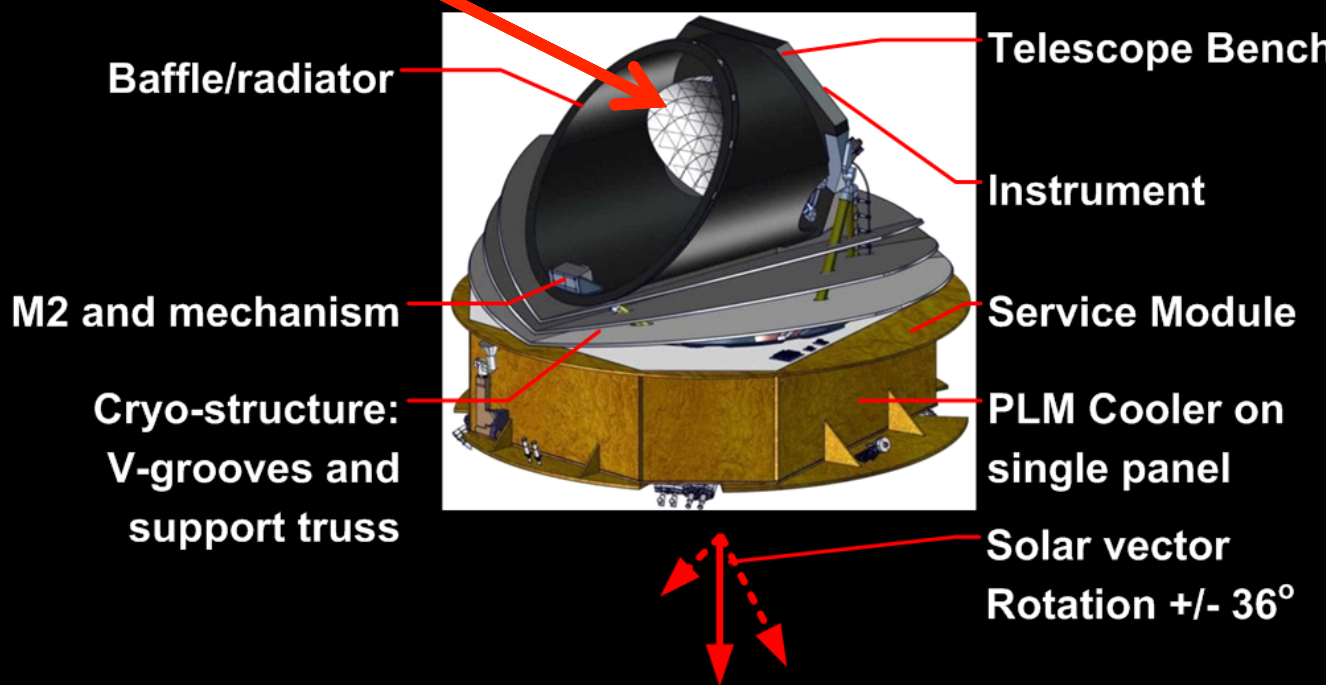
Mission Requirements

- Observe transmission and emission spectra
- Observe a wide variety of systems
  - ✓ Vis to Thermal IR
  - ✓ Contiguous spectra
  - ✓ High photometric stability ~ 10^{-4}
  - ✓ Large sky coverage
  - ✓ Agile spacecraft
  - ✓ Optimised calibration scheme
- Stay within the M-class envelope – Soyuz….

Major Systems Components

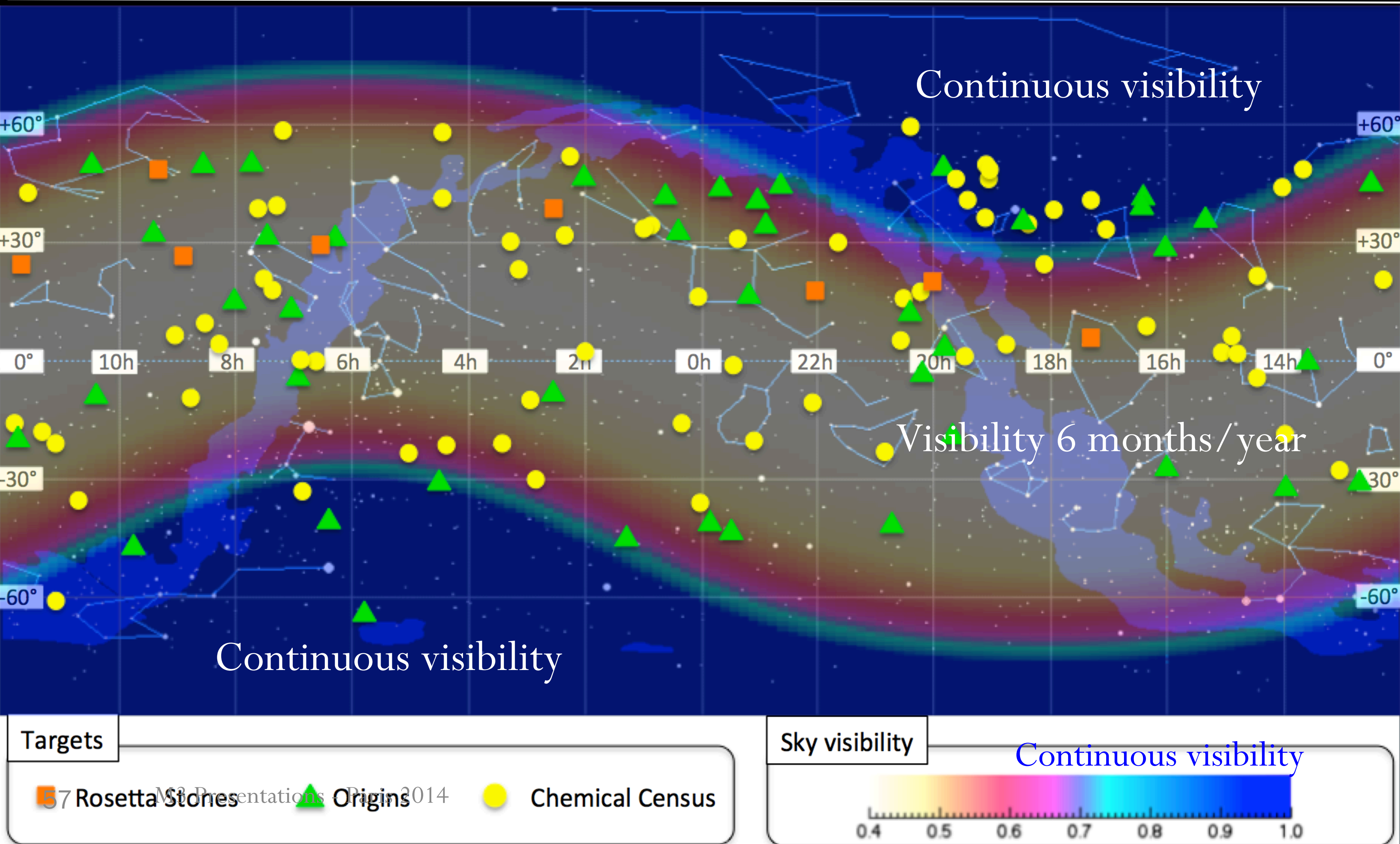


Off-axis three mirror telescope using silicon carbide

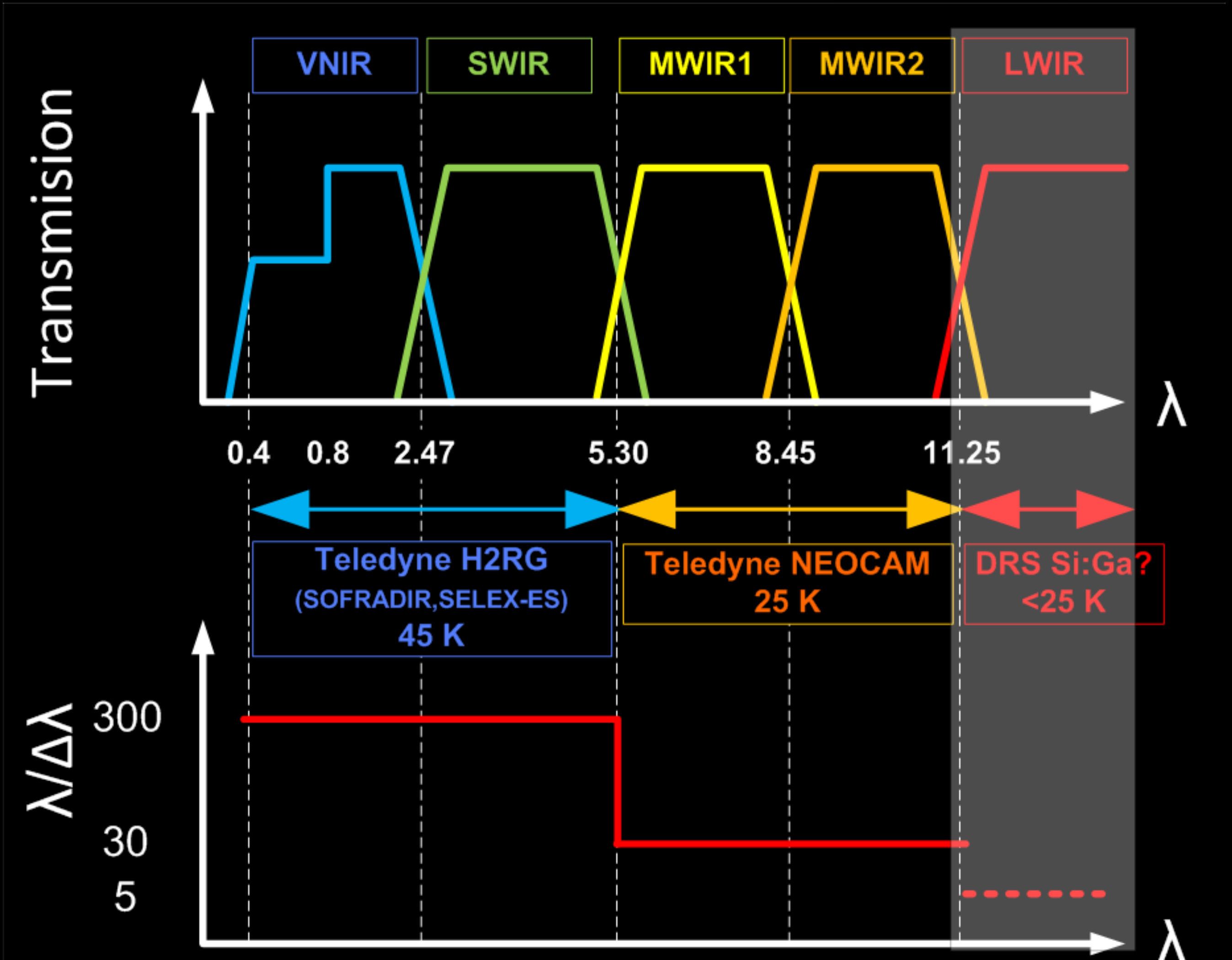


Visibility of Targets

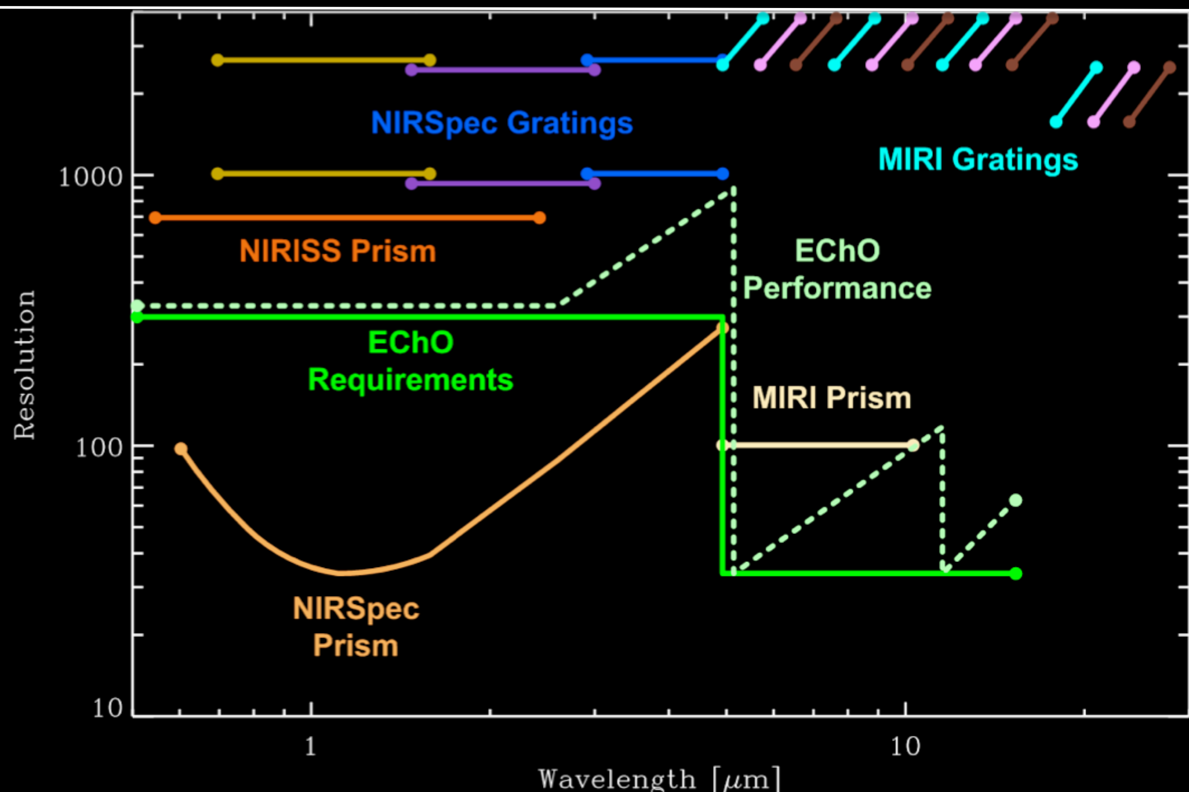
All targets observable within in 4 yr mission

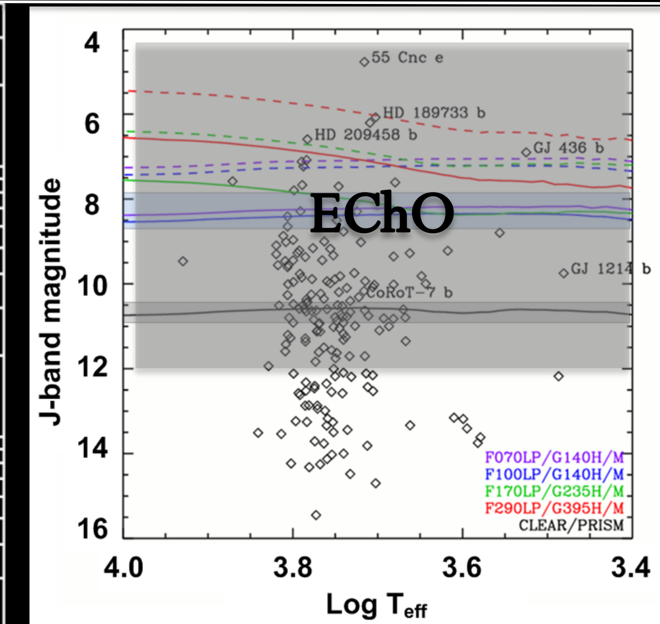


Instrument Concept



JWST and EChO Spectrometer Coverage



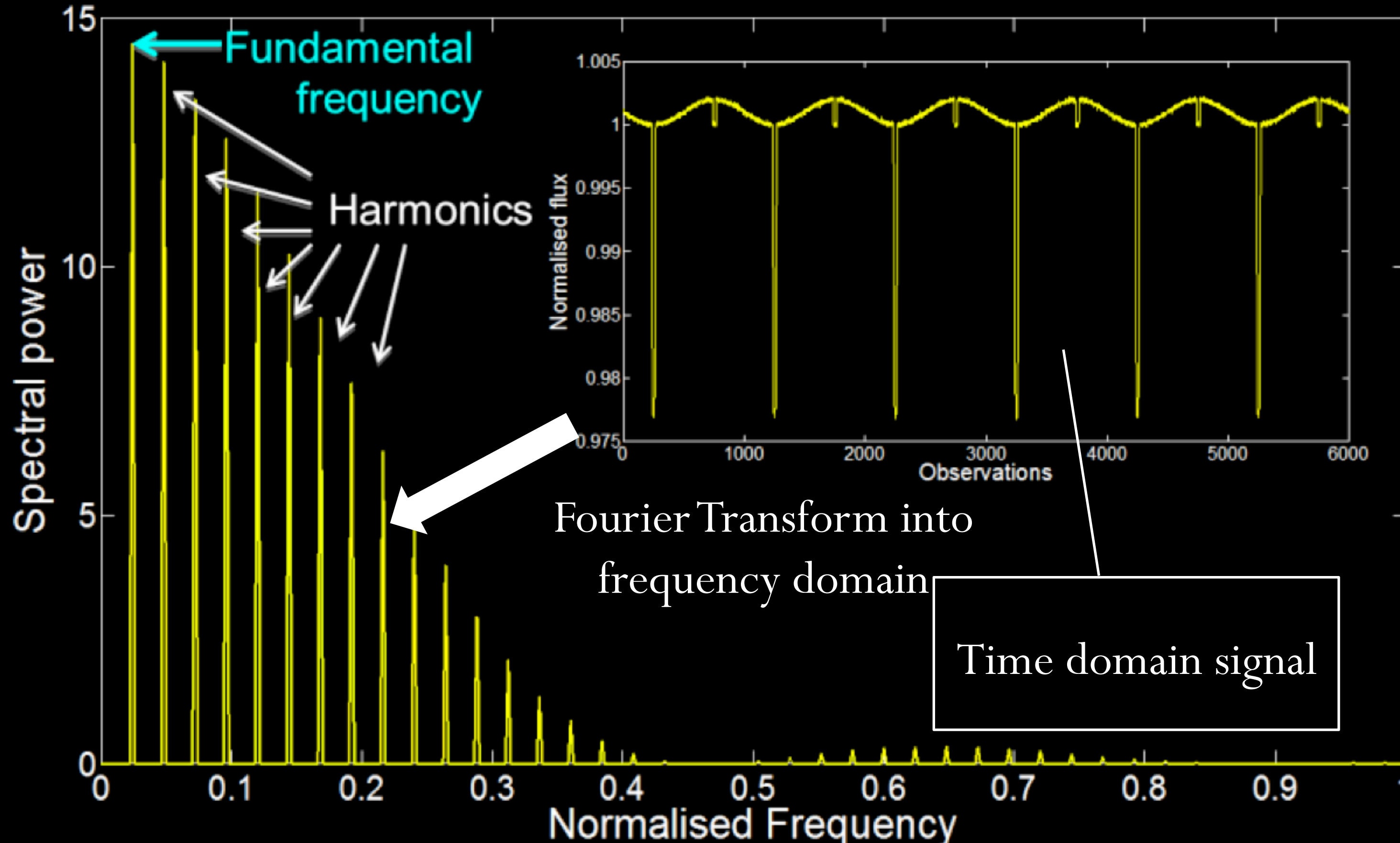


NIRSpec
Saturation limits

- Same colour on the diagram indicates instantaneous coverage
- NIRISS, NIRSpec and MIRI cannot be used simultaneously
- NIRSpec prism saturates somewhere in the band on targets brighter than J~11
- MIRI prism saturates at about K=6 (although not completely clear where limit is)

EChO Yellow Book

Photometric Stability

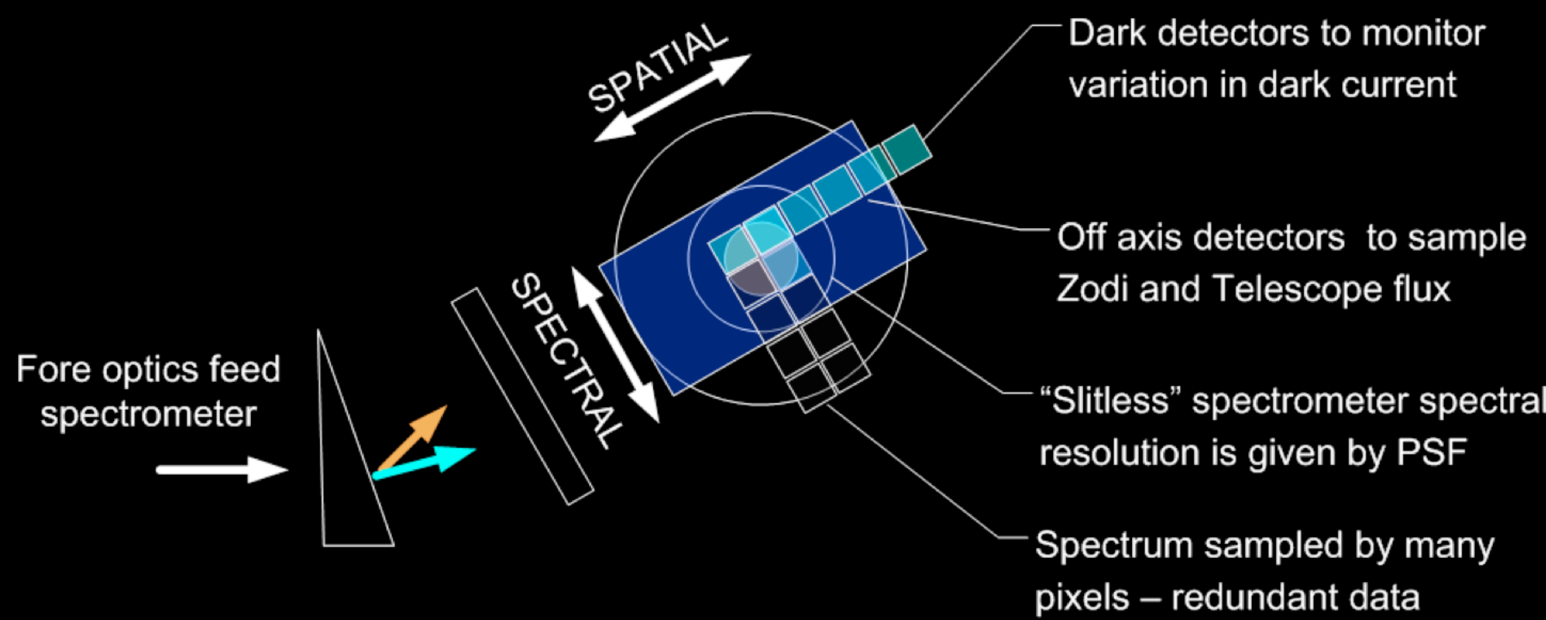


Frequency band of interest: 2.8×10^{-5} Hz (~10 hrs) to ~4 mHz (~5 minutes)

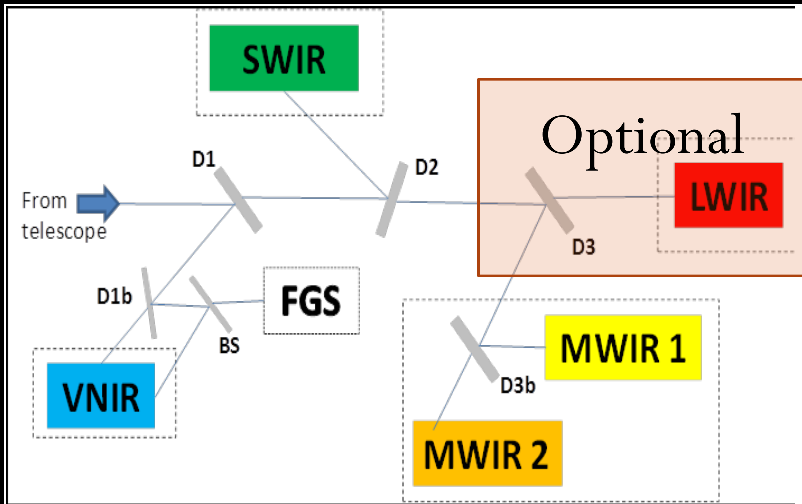
Noise or photometric variations at higher or lower frequencies do not affect the measurement

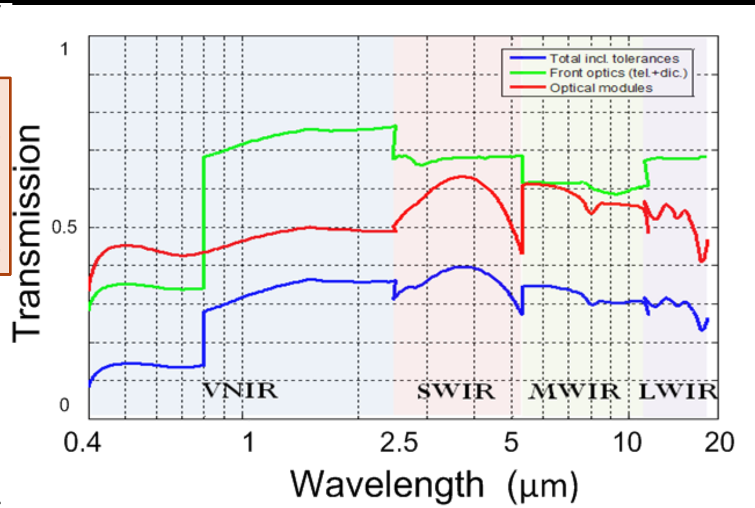
Generic Design for Photometric Stability

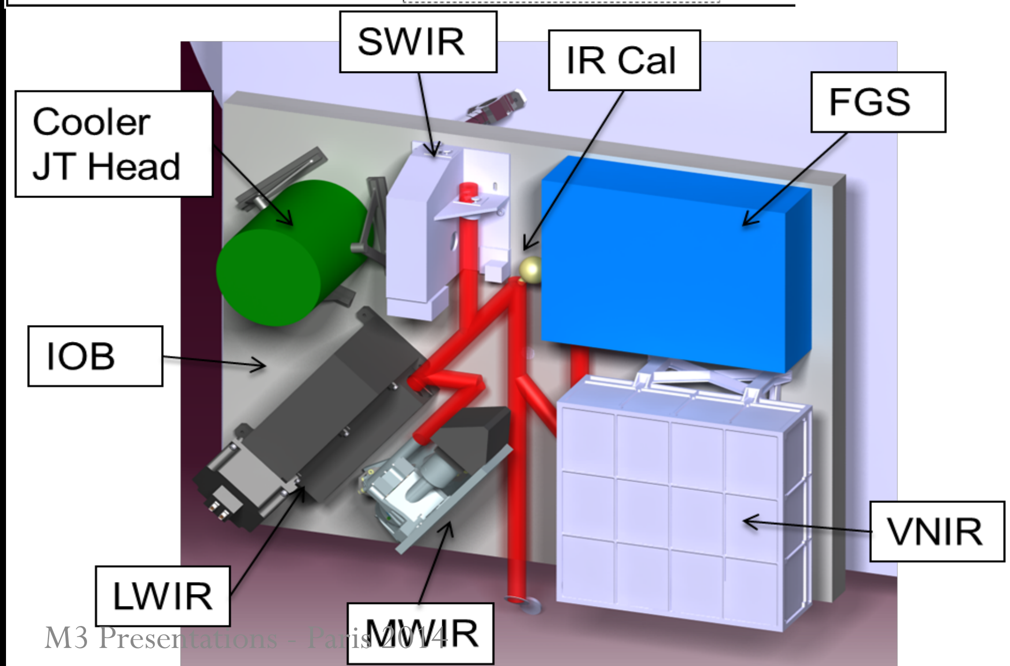
- Spectometers are essentially “slitless”
- Larger entrance field aperture in SWIR, MWIR and LWIR allows off axis light to be monitored
- At least 2 pixels per spatial and spectral element
- Redundant data allow de-correlation of pointing jitter

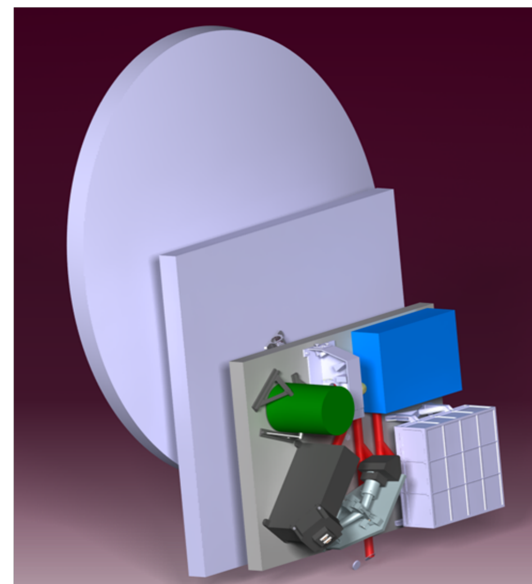


Instrument Design Implementation





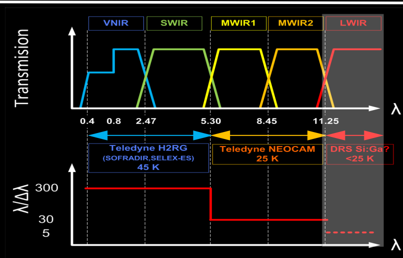




EChO Yellow Book

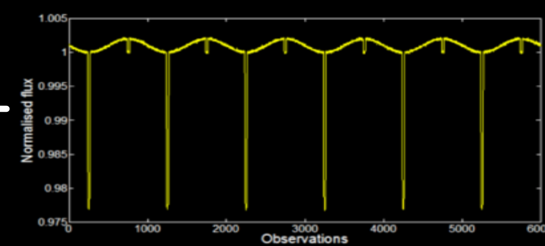
Simulating EChO Performance

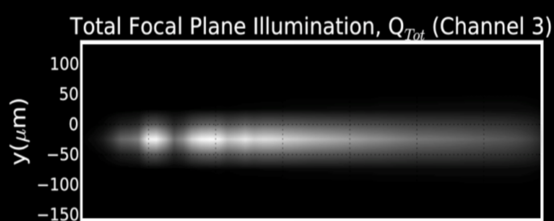
EChOSim



Input
Astrophysical + Instrumental

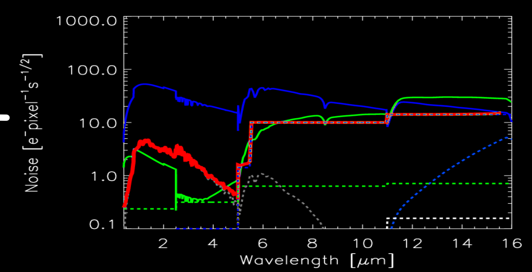
Astroscene
+
Foregrounds



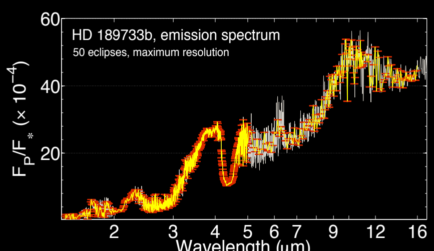


Telescope
+
Instruments

Noise Sources

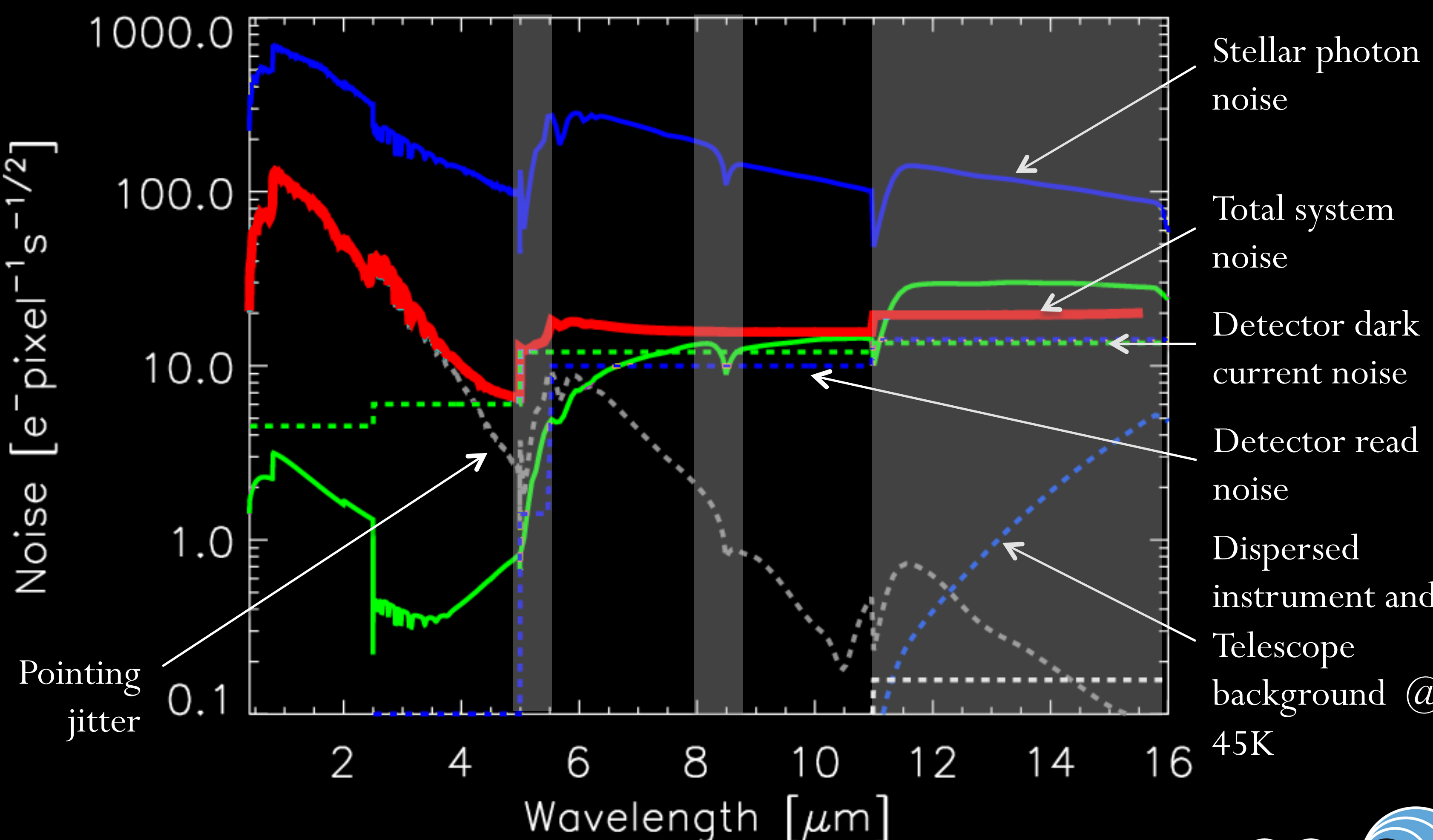


Output
Spectra + SNR



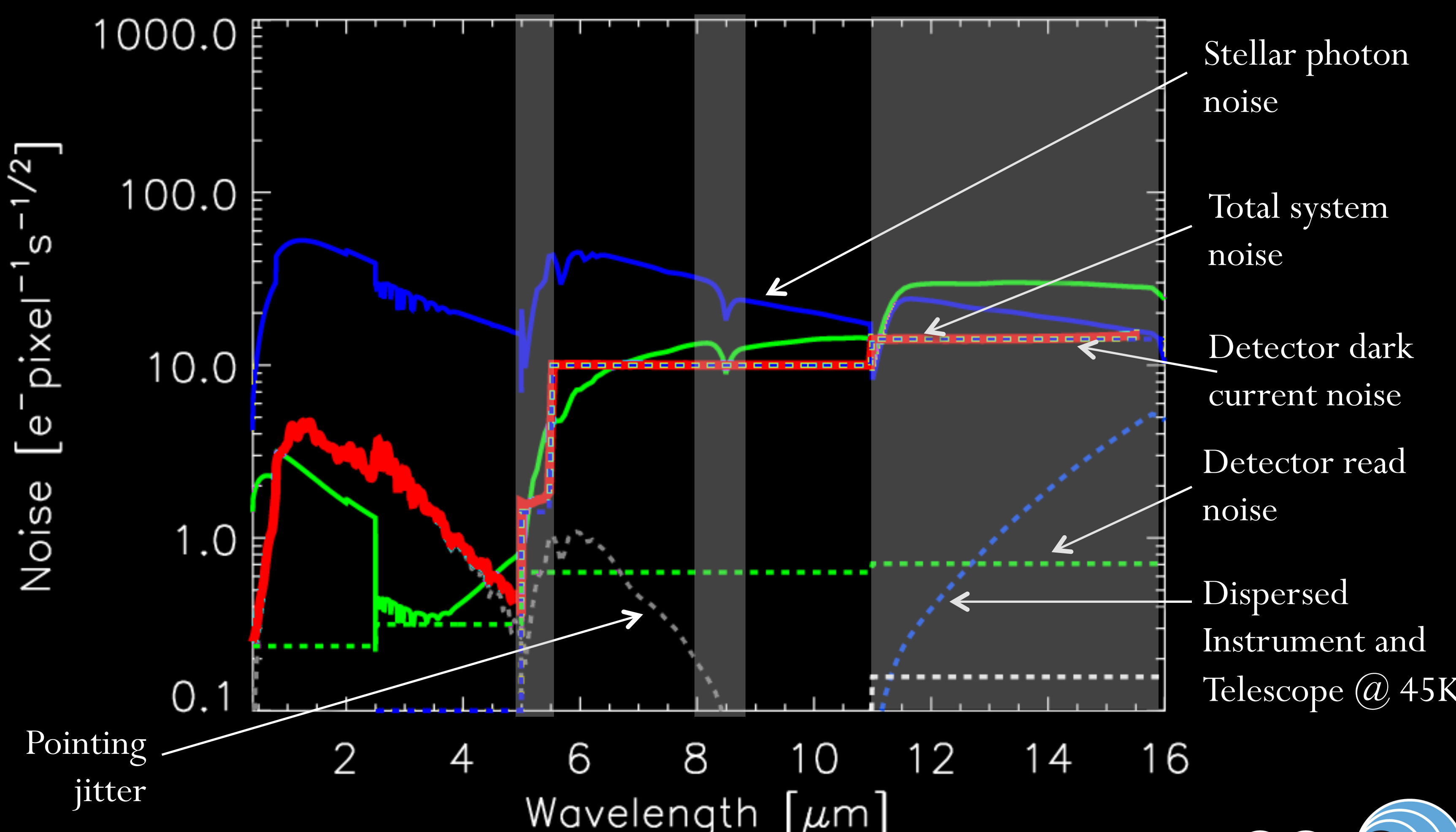
Performance vs Requirement

Bright Source – dominated by stellar photon noise



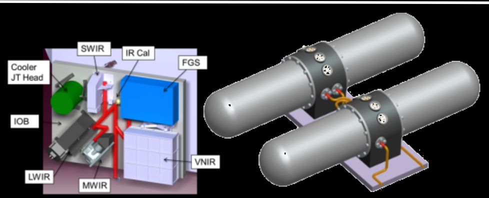
Performance vs Requirement

Faint Source – detector dark current noise important

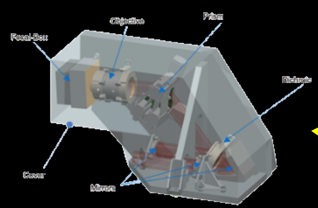


Instrument Consortium

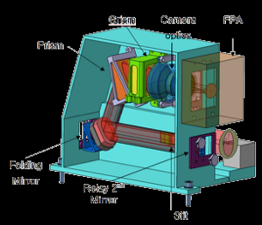
EChO is a 100% open mission



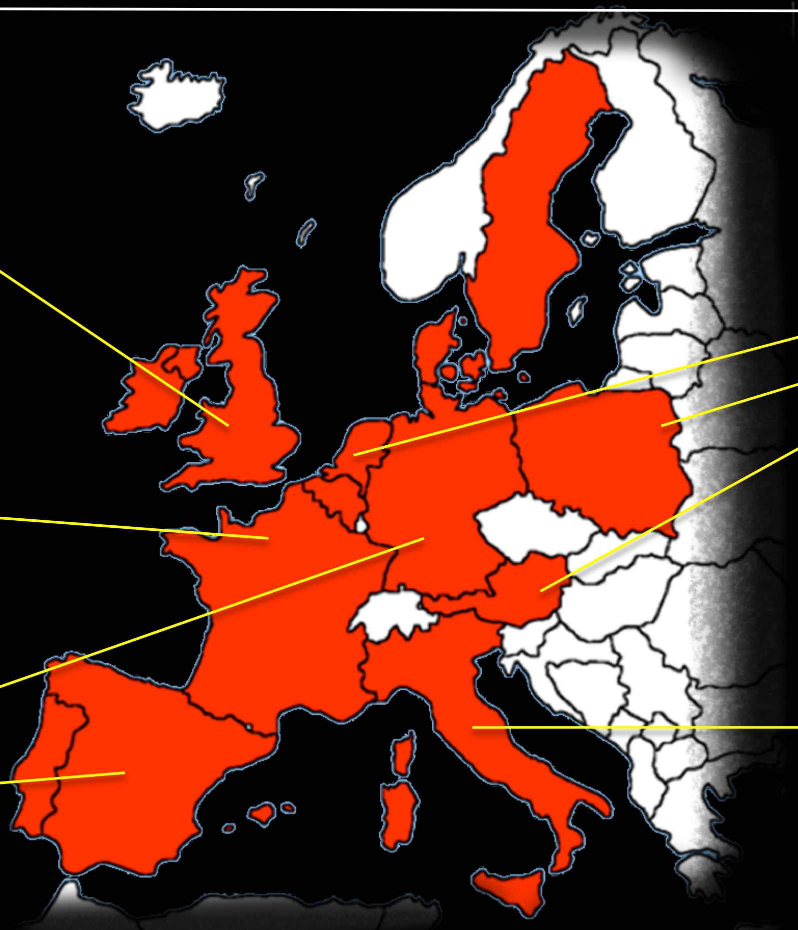
AIV, Coolers, Management, Detectors

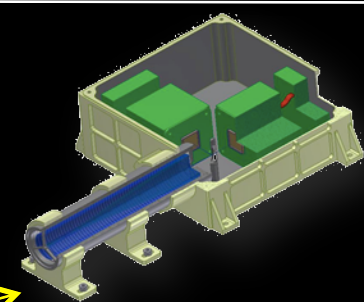


MWIR Channel

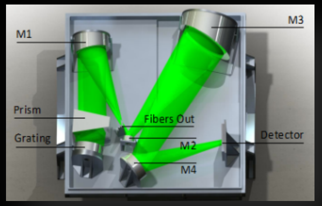


SWIR Channel





FGS Channel



VNIR Channel
Electronics

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

Instrument data centre contributions from all partners

Open data policy

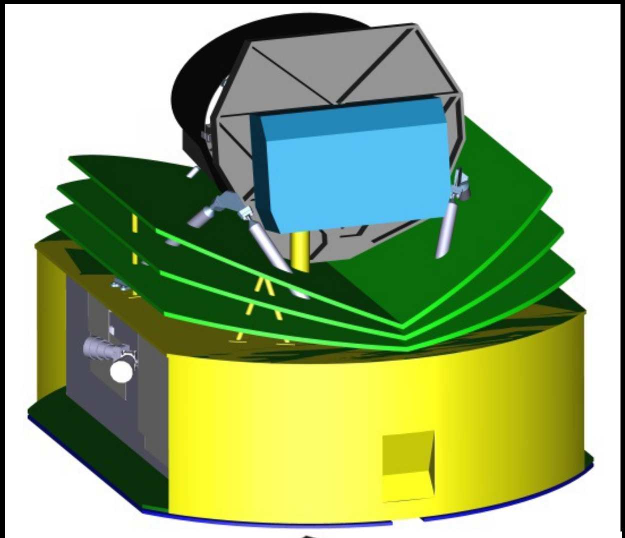
Conclusions

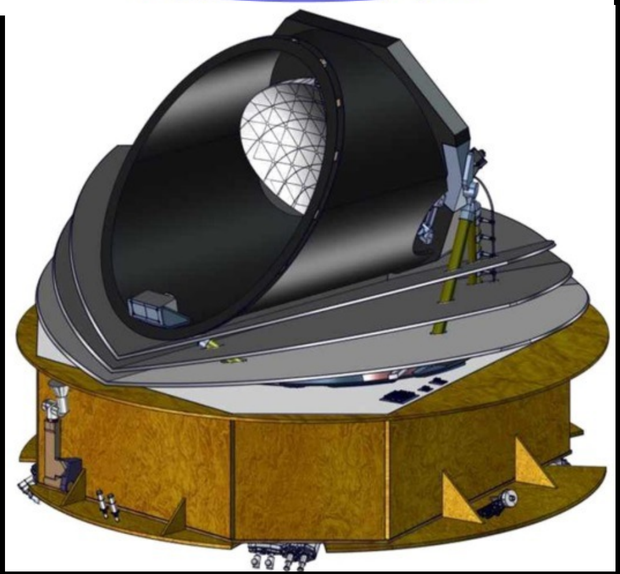
- Solar System is no longer the paradigm!
- We now need to understand how planets form & evolve
- The way forward is to study the *atmospheric chemistry of exoplanets*
- EChO will deliver *transformational science:*
  - First broad survey of planetary atmospheres
  - > 200 planets spectroscopically observed
  - Molecular abundances 3 orders of magnitude lower than currently possible
  - Fourfold increase in the number of detected molecules
- 100% open data policy & survey definition
- No showstoppers, ready to go!

Backup slides

Spacecraft Design

- Two industrial studies undertaken (Astrium and Thales); solutions to spacecraft design very similar
- Off-axis three mirror telescope built from silcon/carbon ceramic type material
- Instrument and telescope mounted from common structure
- Passive cooling provided by nested v-groove shields
- Cooling for some detectors provided by active cooler
- Attitude and orbital control by combination of cold-gas +reaction wheels or fine gyros+reaction wheels
- Closed loop through fine guidance sensor in focal plane





EChO Performance

Minimum abundances retrievable for hot/warm gaseous planets

Warm Neptune around K star (eclipse)

	CH_4		CO		CO_2			NH_3			H_2O		
Obs. Mode	$3.3\mu m$	$8\mu m$	$2.3\mu m$	$4.6\mu m$	$2.8\mu m$	$4.3\mu m$	$15\mu m$	$3\mu m$	$6.1\mu m$	$10.5\mu m$	$2.8\mu m$	$5\text{-}8\mu m$	$11\text{-}16\mu m$
Rosetta St.	10^{-7}	10^{-6}	10^{-4}	10^{-6}	10^{-7}	10^{-7}	10^{-7}	10^{-7}	10^{-6}	10^{-7}	10^{-6}	10^{-6}	10^{-5}
Origins	10^{-7}	10^{-6}	10^{-3}	10^{-5}	10^{-6}	10^{-7}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-5}	10^{-4}
Ch. Census	10^{-7}	10^{-5}	10^{-3}	10^{-4}	10^{-6}	10^{-7}	10^{-5}	10^{-5}	10^{-5}	10^{-5}	10^{-5}	10^{-5}	10^{-4}

	HCN			PH_3		C_2H_6		H_2S			C_2H_2		
Obs. Mode	$3\mu m$	$7\mu m$	$14\mu m$	$4.3\mu m$	$10\mu m$	$3.3\mu m$	$12.2\mu m$	$2.6\mu m$	$4.25\mu m$	$8\mu m$	$3\mu m$	$7.5\mu m$	$13.7\mu m$
Rosetta St.	10^{-7}	10^{-5}	10^{-7}	10^{-7}	10^{-6}	10^{-6}	10^{-6}	10^{-5}	10^{-4}	10^{-4}	10^{-7}	10^{-5}	10^{-7}
Origins	10^{-6}	10^{-5}	10^{-6}	10^{-7}	10^{-6}	10^{-5}	10^{-5}	10^{-5}	10^{-4}	10^{-3}	10^{-7}	10^{-4}	10^{-6}
Ch. Census	10^{-6}	10^{-4}	10^{-5}	10^{-7}	10^{-5}	10^{-5}	10^{-5}	10^{-4}	10^{-3}	-	10^{-7}	10^{-3}	10^{-5}

Tessenyi et al, 2013, 2014

EChO Performance

Minimum abundances retrievable for hot/warm gaseous planets

Hot super-Earth around G-star (eclipse)

	H_2O			CO_2		
Obs. Mode	$2.8\mu m$	5 - $8\mu m$	11 - $16\mu m$	$2.8\mu m$	$4.3\mu m$	$15\mu m$
Rosetta St.	10^{-4}	10^{-4}	10^{-4}	10^{-5}	10^{-7}	10^{-5}
Origins	10^{-4}	10^{-3}	10^{-3}	10^{-5}	10^{-6}	10^{-4}
Ch. Census	10^{-3}	-	-	10^{-4}	10^{-5}	-

Temperate super-Earth around late M-dwarf (eclipse, R=20)

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

Tessenyi et al, 2013, 2014