Transit Spectroscopy: Techniques and Results
(or, is there an atom or molecule in my data?)

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Sagan Exoplanet Summer Workshop
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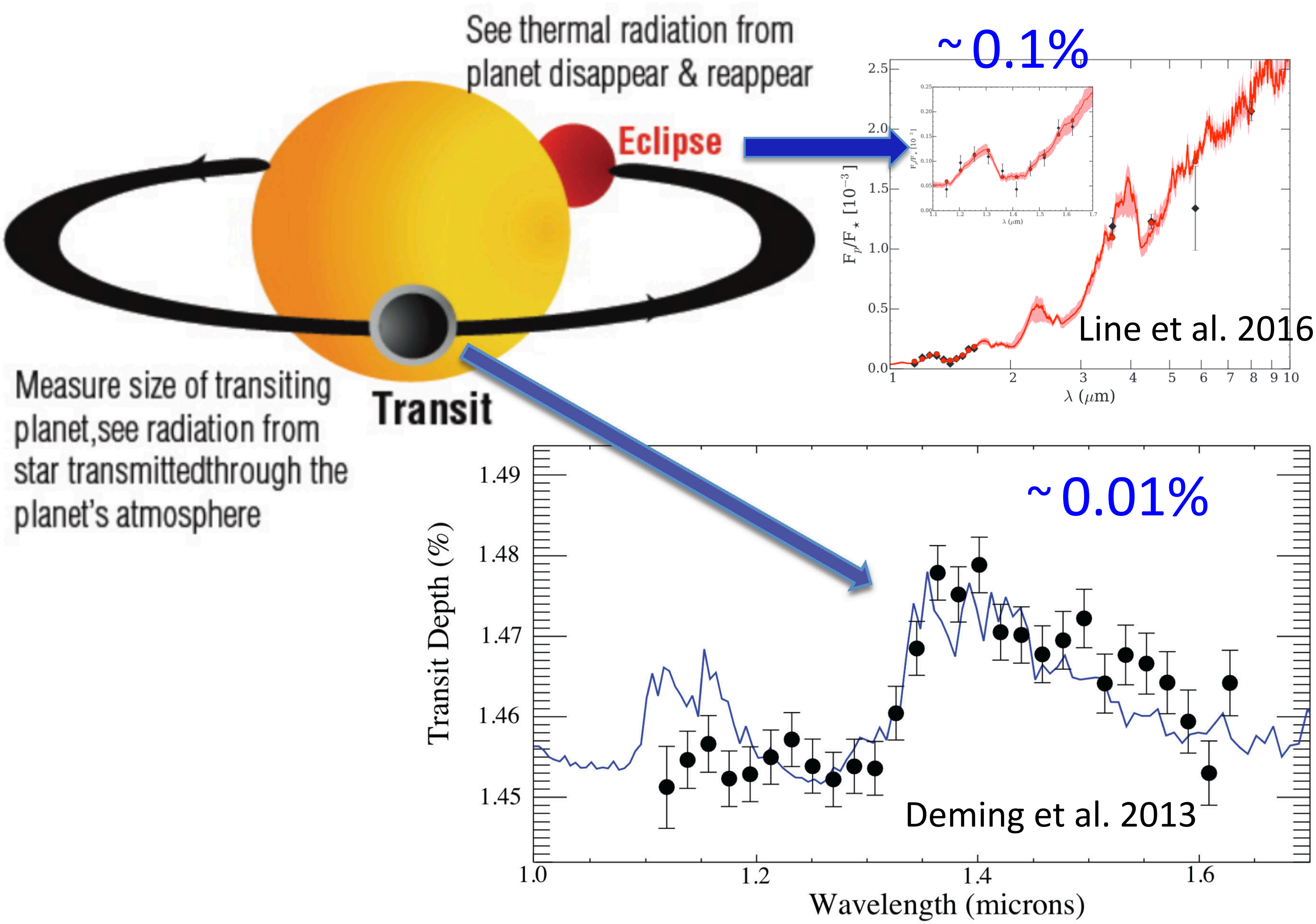
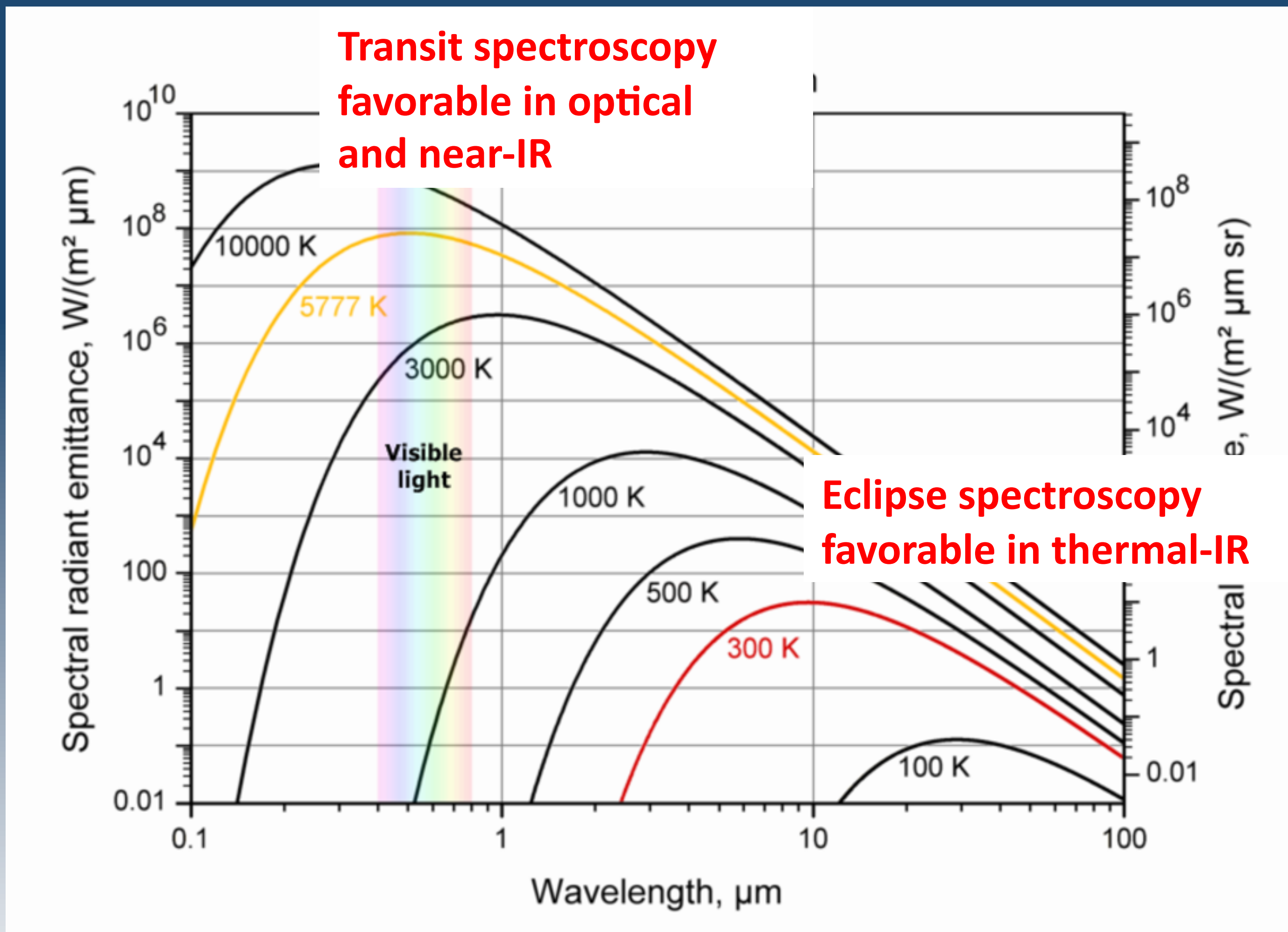
This talk:

Basics of transit (and eclipse) spectroscopy
Some past results
Current Hubble results – hot Jupiters
What to expect from JWST
(and the ELTs) – hot Jupiters to super-Earths



See thermal radiation from planet disappear & reappear
Eclipse
Transit
Measure size of transiting planet,see radiation from star transmittedthrough the planet's atmosphere
~0.1%
Line et al. 2016
λ (μm)
~0.01%
Deming et al. 2013
Transit Depth (%)
Wavelength (microns)

Signal-to-noise depends on the stellar brightness versus wavelength



Formal solution of the radiative transfer equation:

Emergent spectrum at eclipse

Transmission spectrum

$$I_\nu(\tau_\nu) = \int_0^{\tau_\nu} S_\nu(\tau_\nu) e^{(-(\tau_\nu - t_\nu))} dt_\nu + I_\nu(0) e^{(-\tau_\nu)}$$

S = planet atmospheric source function (Planck function)

I(0) = incident stellar intensity

τ = optical depth (contains molecular opacities)

(measured flux = integral of I over the planet's disk)

Transit and Eclipse Spectroscopy (Examples using HST)

Transit

long paths, sensitive to trace molecules (also to clouds & haze)

insensitive to dT/dτ

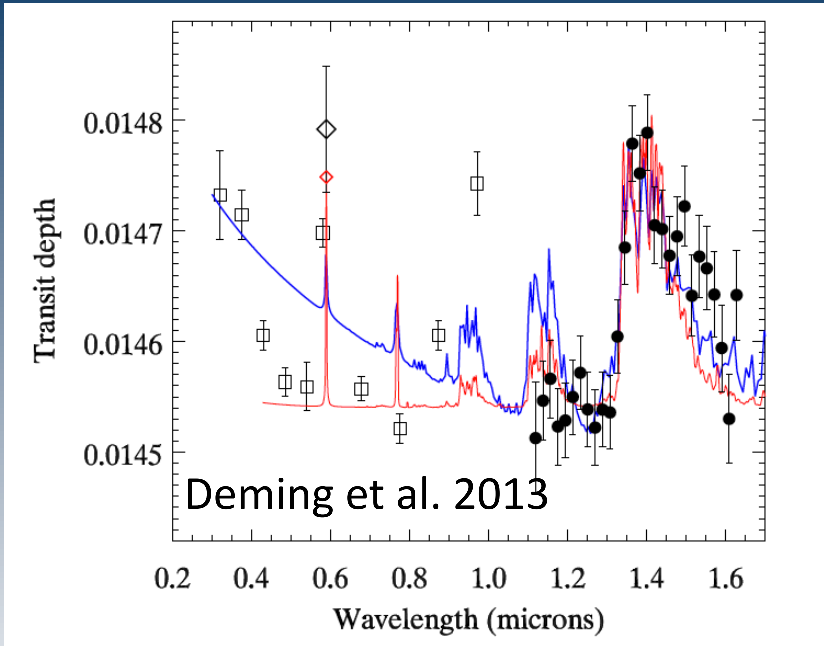
No emission features

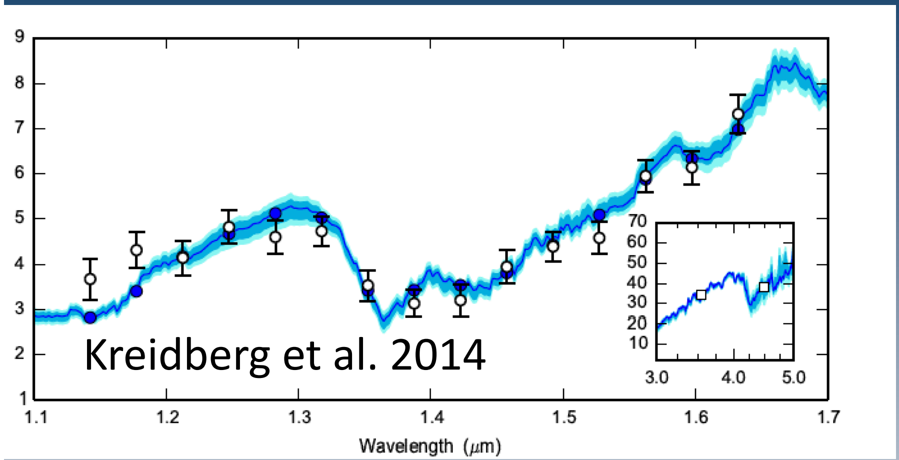
Eclipse

less sensitive to clouds (also to trace molecules)

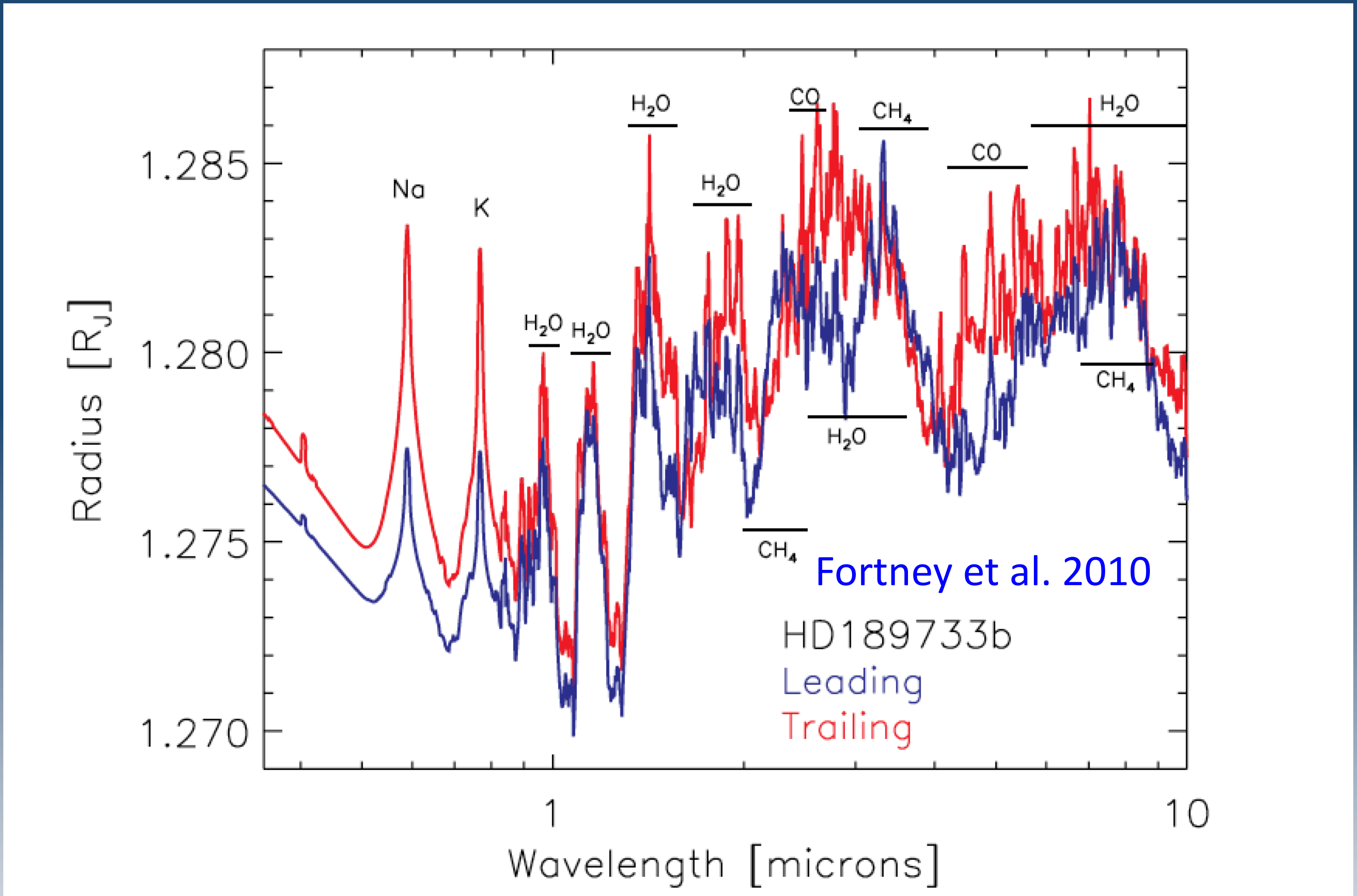
depends on dT/dτ

Emission & absorption

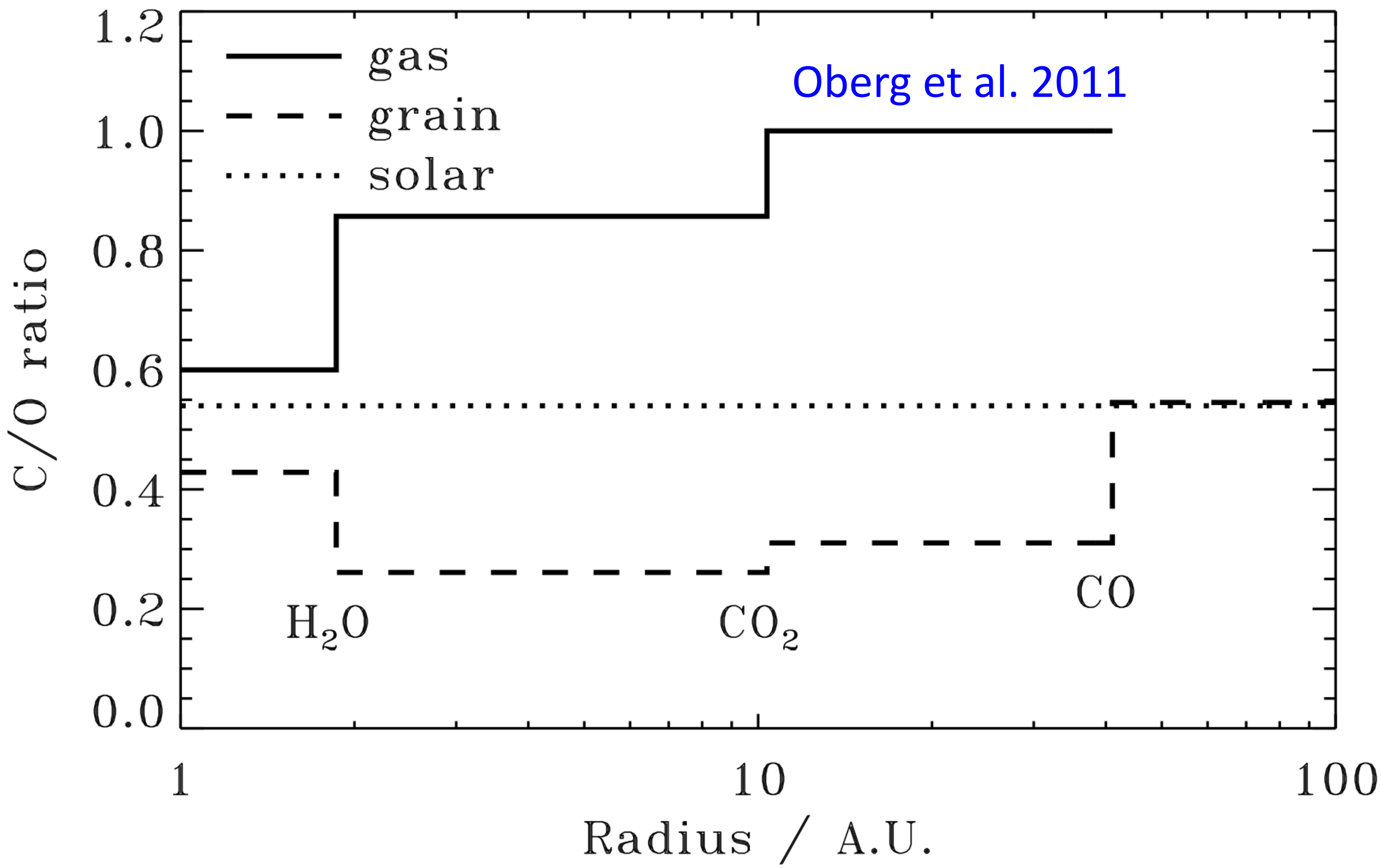




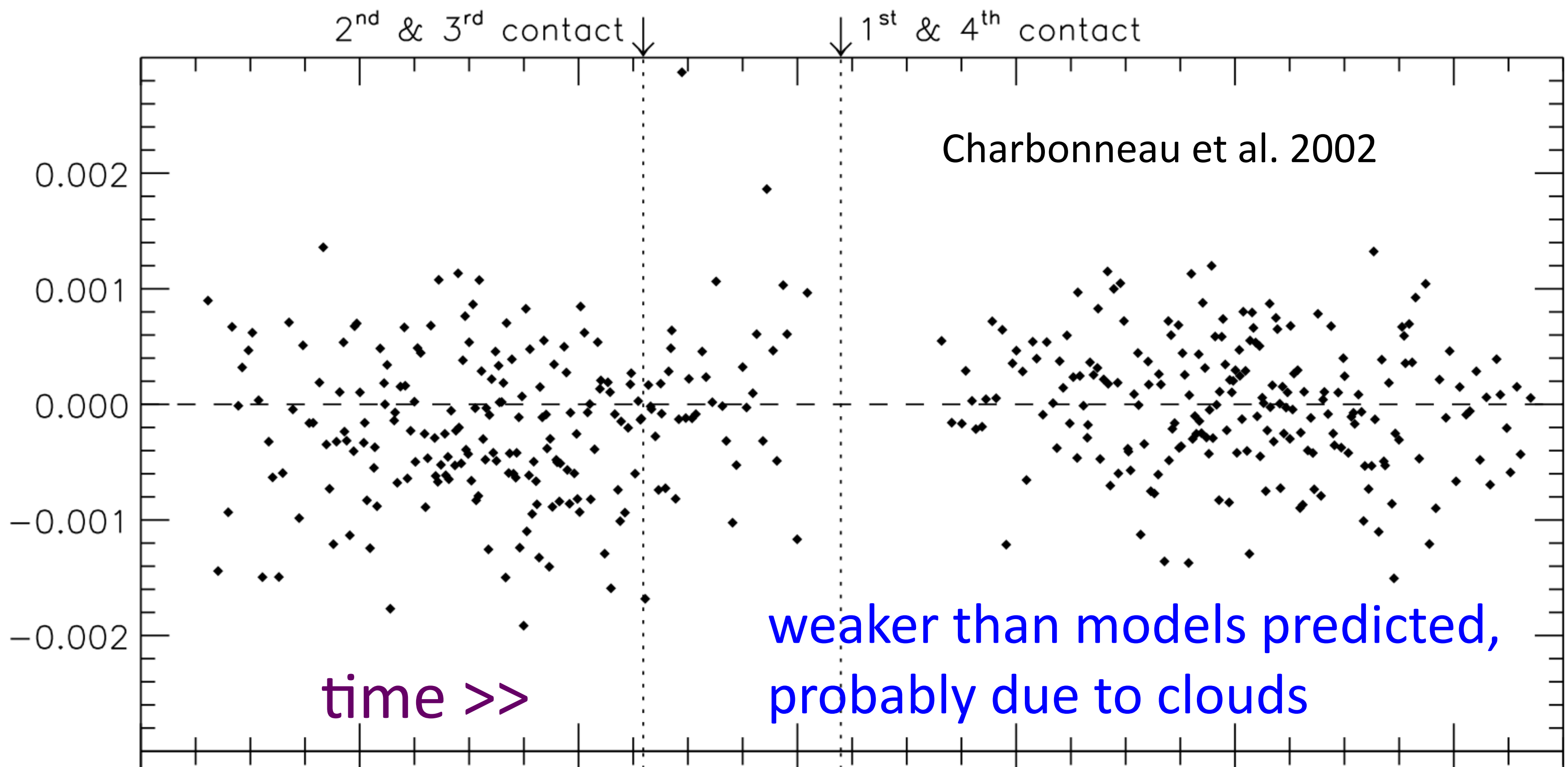
What we expect for a hot Jupiter from models



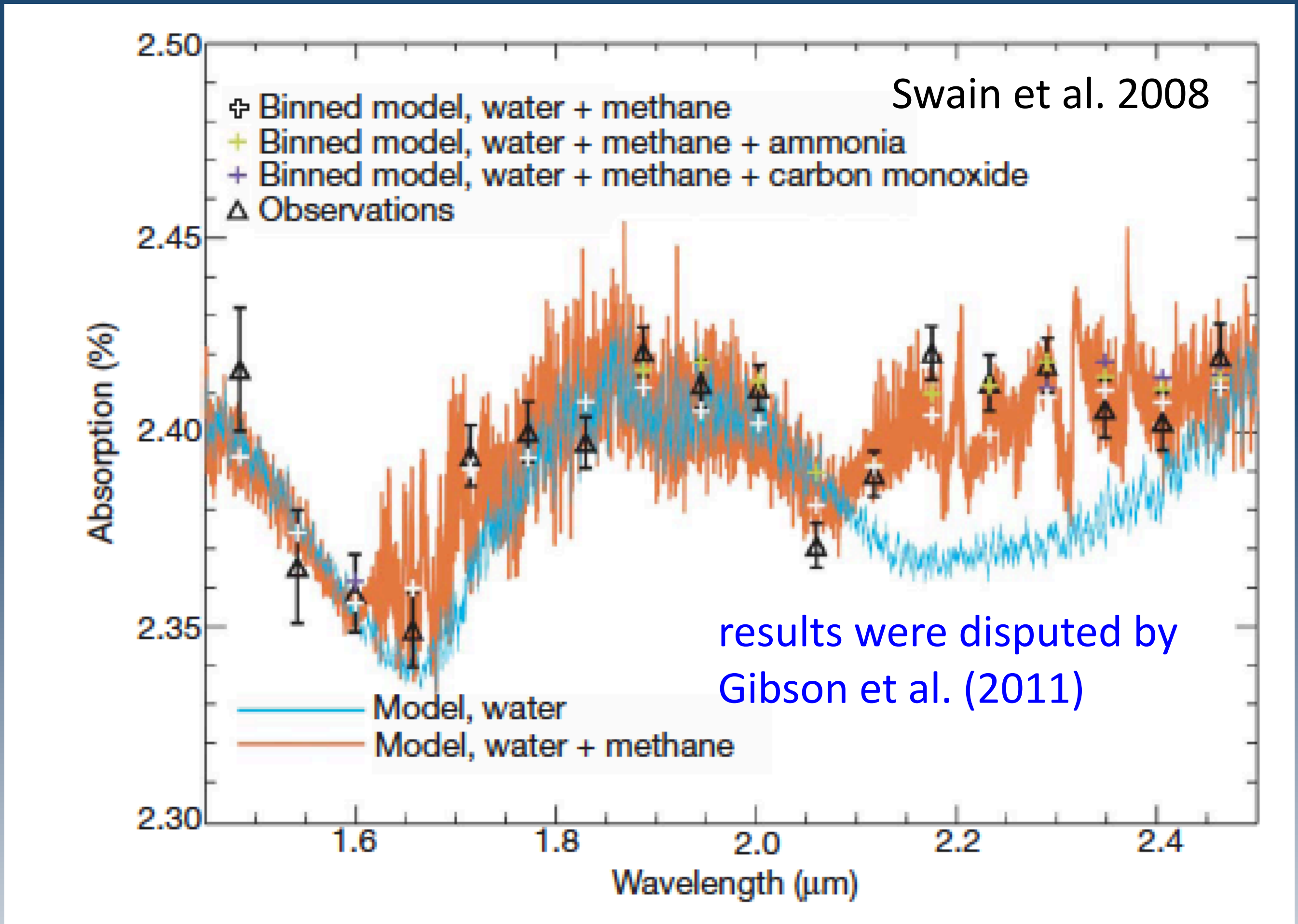
C/O in the atmosphere of an exoplanet can tell us about planet formation



The first transit spectroscopy used Hubble STIS to detect atomic sodium absorption



The first molecular transit spectroscopy used NICMOS on HST – very strong instrument effects



(my personal) lessons from the NICMOS spectroscopy:

With three molecules, you can fit an elephant

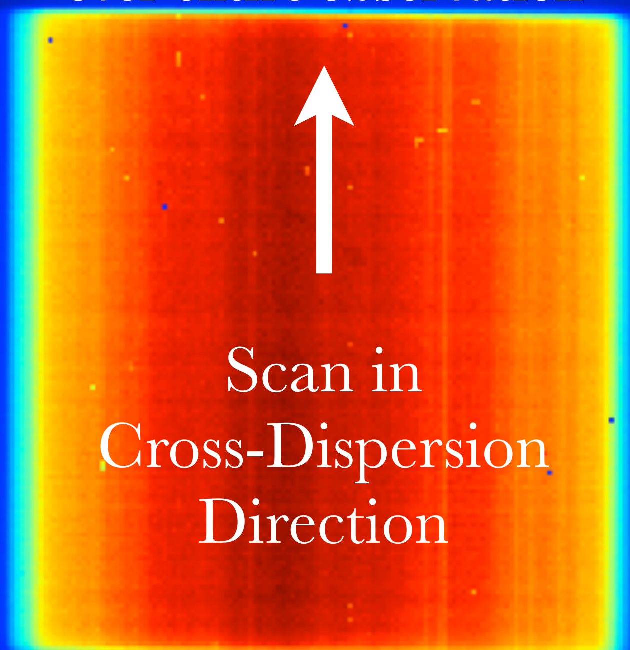
Be careful about parametric decorrelations of instrument errors
seek *physical* reasons (i.e., a physical model)

Be suspicious about unusual atmospheric requirements
e.g., clarity over 8 scale heights

Don't try to interpret every little wiggle in the spectrum

HST WFC3 G141: Spatial Scanning Mode

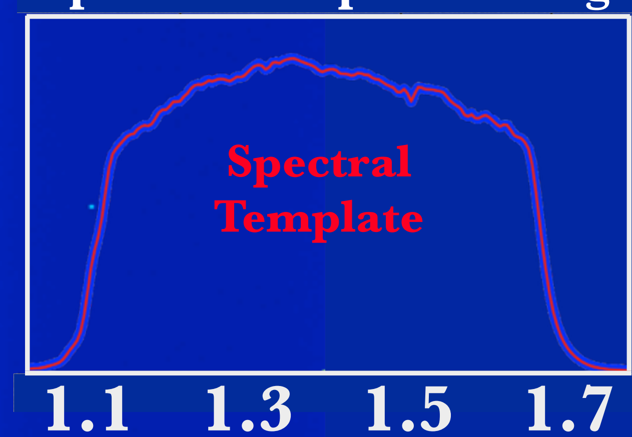
~10x Improvement in Efficiency over entire observation



Wavelength →

Errors down to tens of ppm

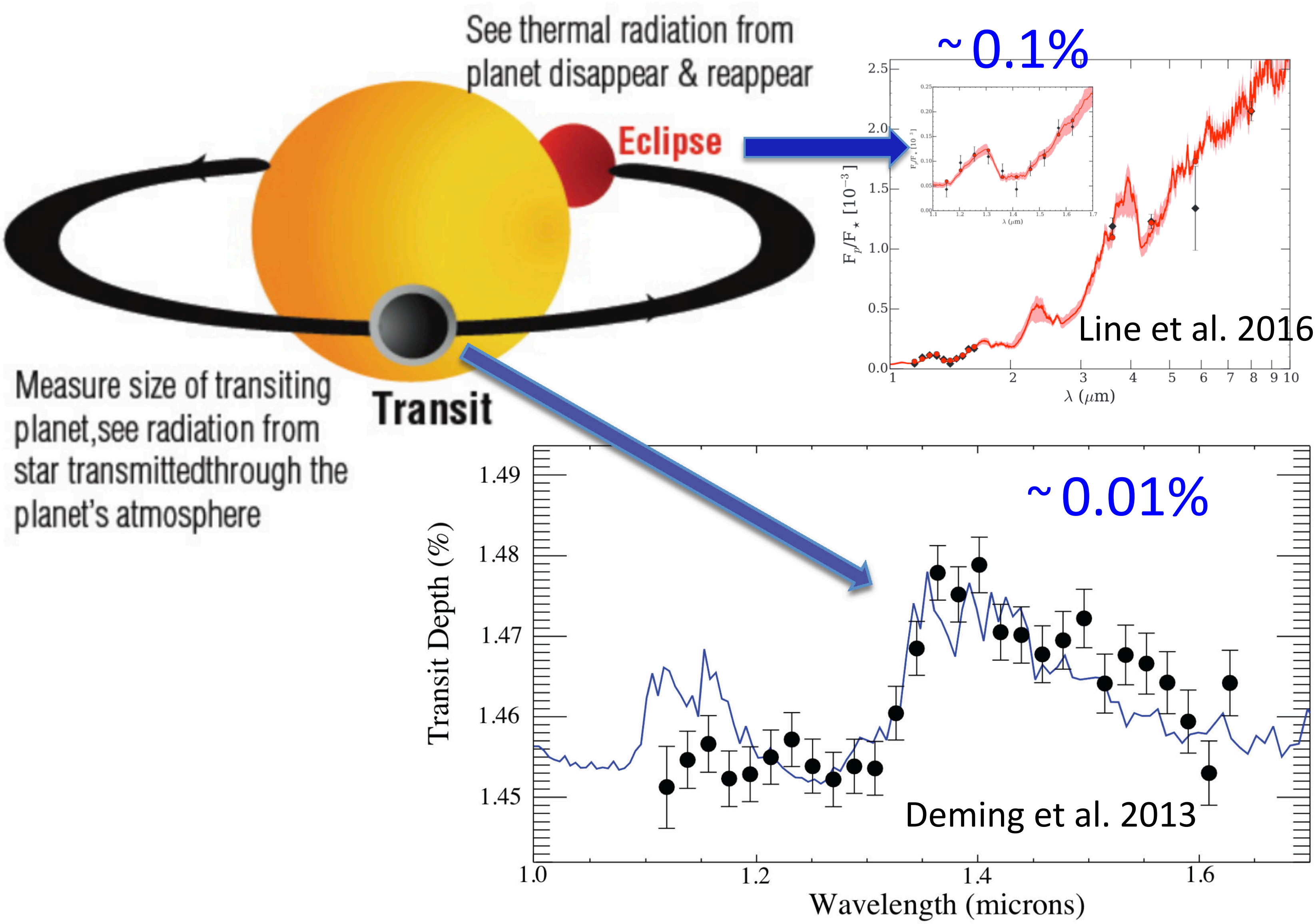
Spectral Template Fitting

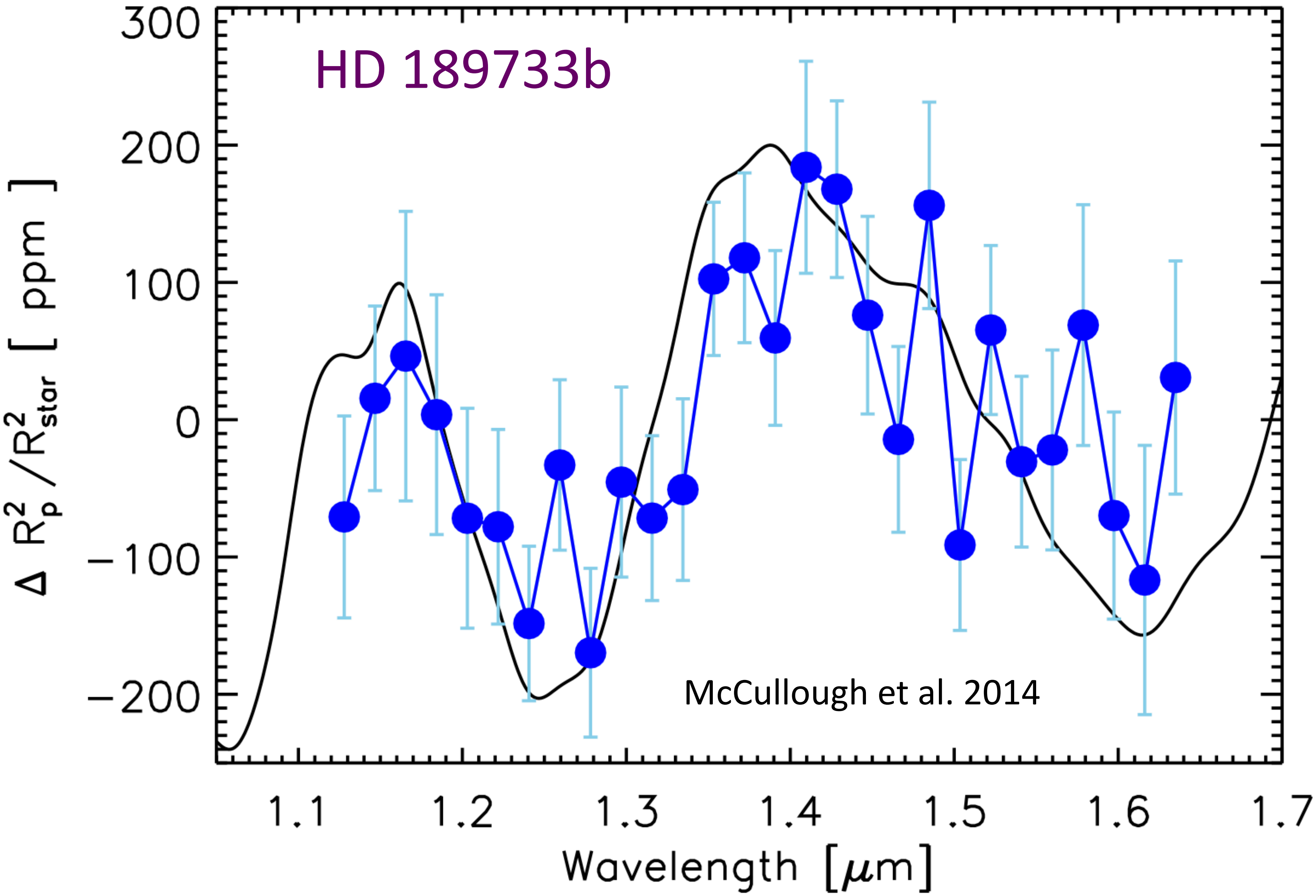


thanks to John MacKenty & Peter McCullough & many others

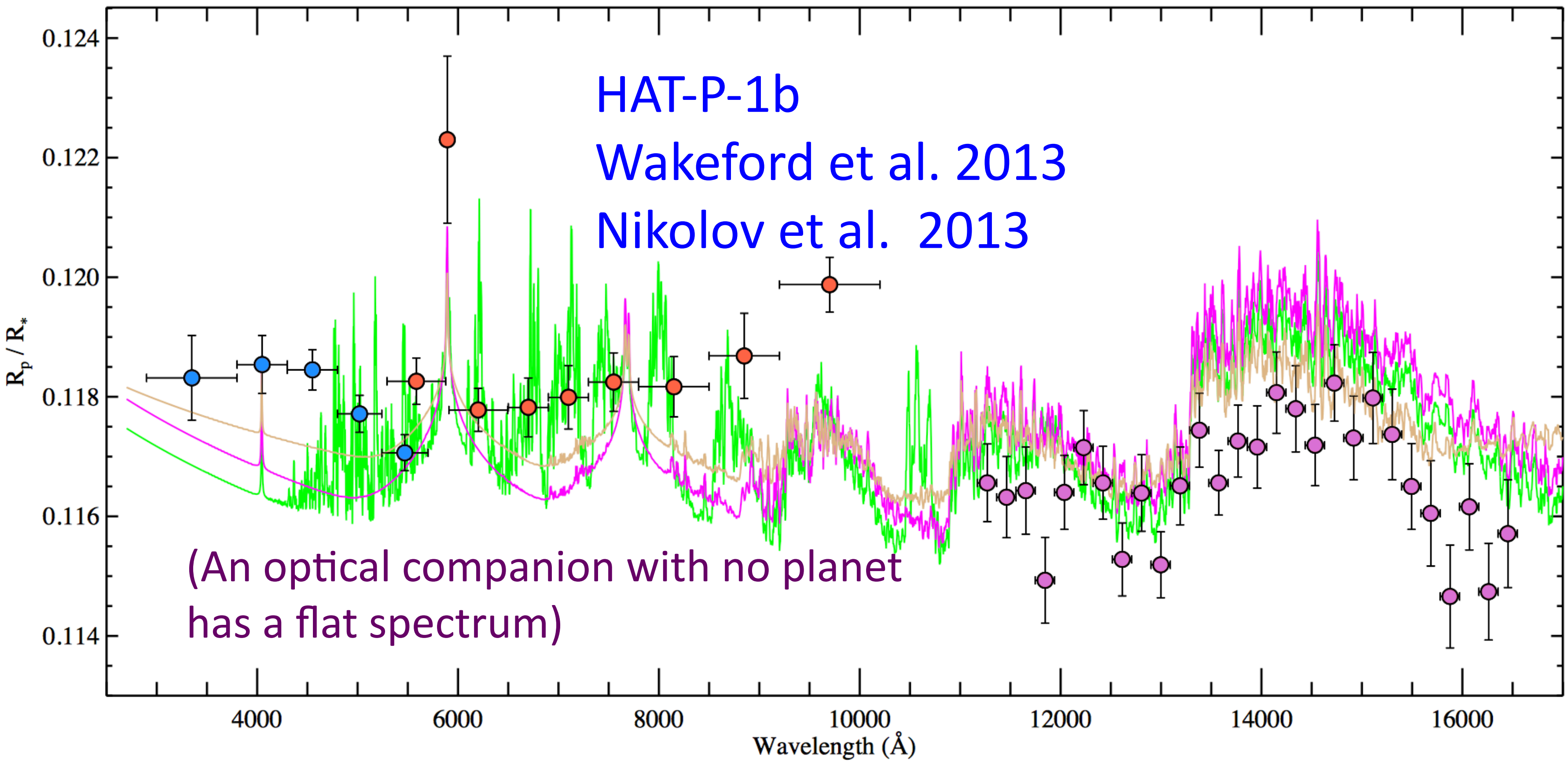
Why the WFC3 water detections are robust:

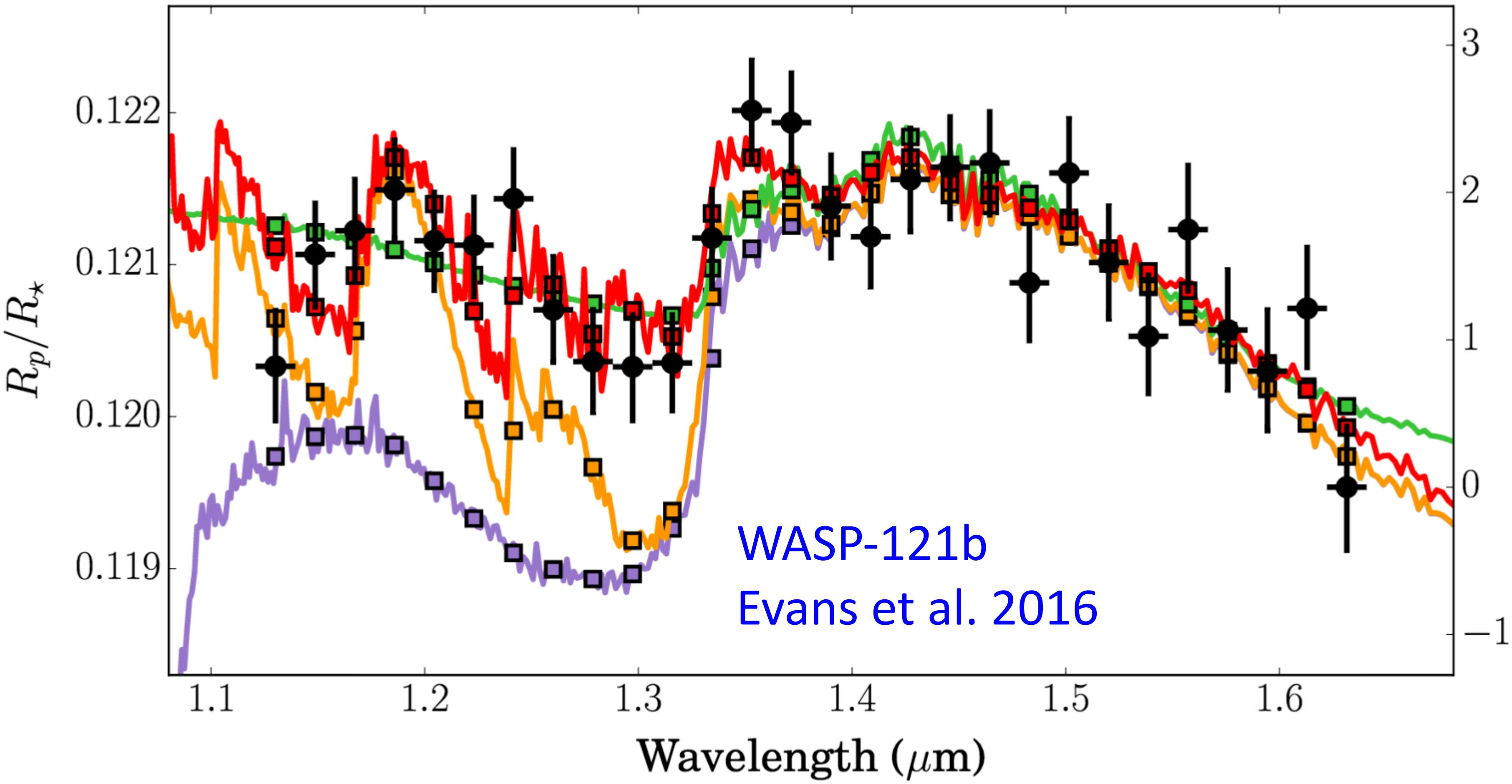
1. WFC3 instrument is clearly better than NICMOS
   - very simple analyses, no complex decorrelations
2. Band shape and strength are as expected
3. Multiple groups get consistent results
4. A "control" star without a planet shows no absorption


See thermal radiation from
planet disappear & reappear
Eclipse
Transit
Measure size of transiting
planet,see radiation from
star transmittedthrough the
planet's atmosphere
~0.1%
$F_p/F_\star$ [10^{-3}]
λ (μm)
Line et al. 2016
~0.01%
Transit Depth (%)
Wavelength (microns)
Deming et al. 2013

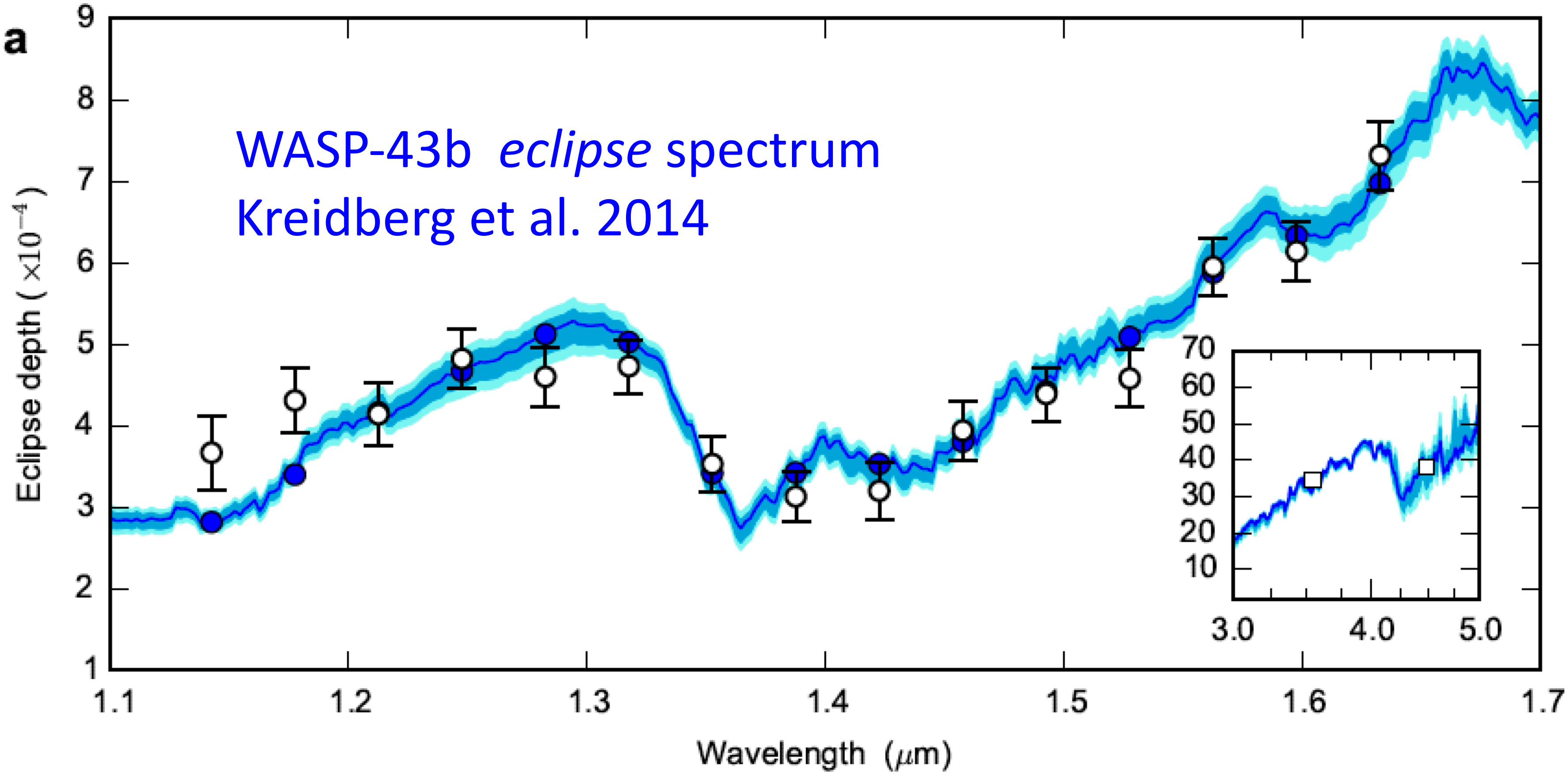


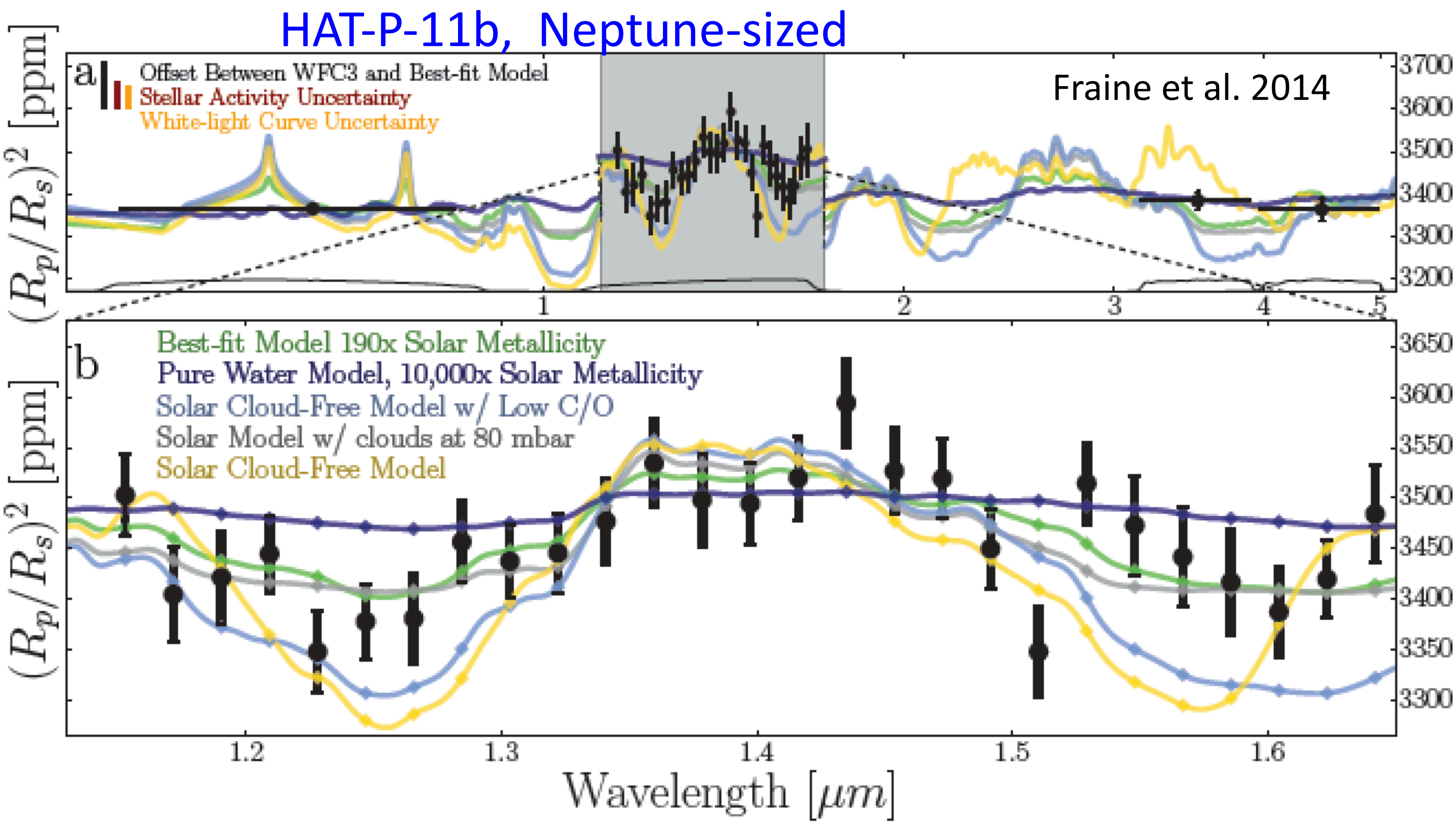
HD 189733b
McCullough et al. 2014
300
200
100
0
−100
−200
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Wavelength [μm]
Δ R^2_p /R$^2_{star}$ [ppm]

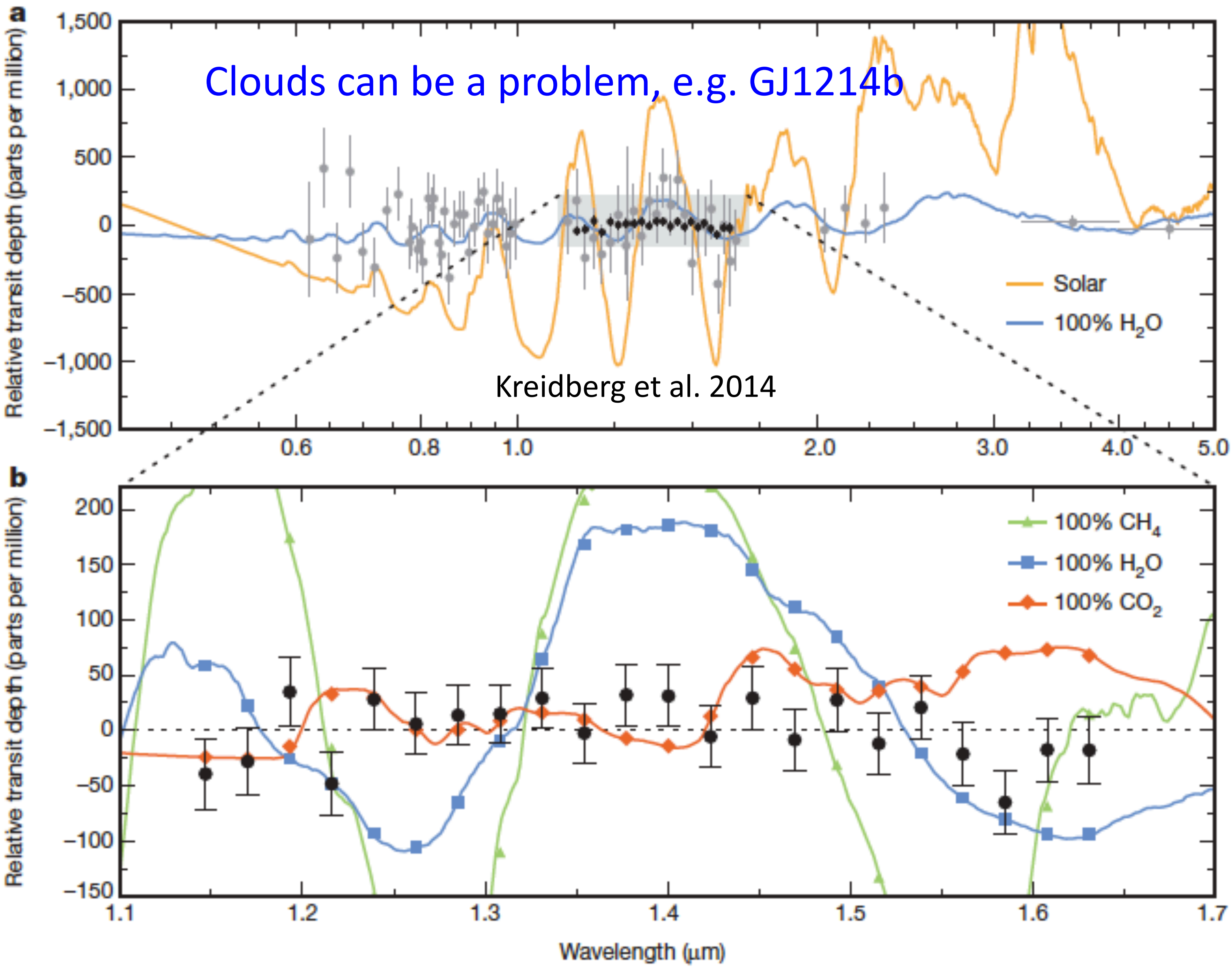

HAT-P-1b
Wakeford et al. 2013
Nikolov et al. 2013
(An optical companion with no planet
has a flat spectrum)
0.124
0.122
0.120
0.118
0.116
0.114
R_p / R_*
4000
6000
8000
10000
12000
14000
16000
Wavelength (Å)

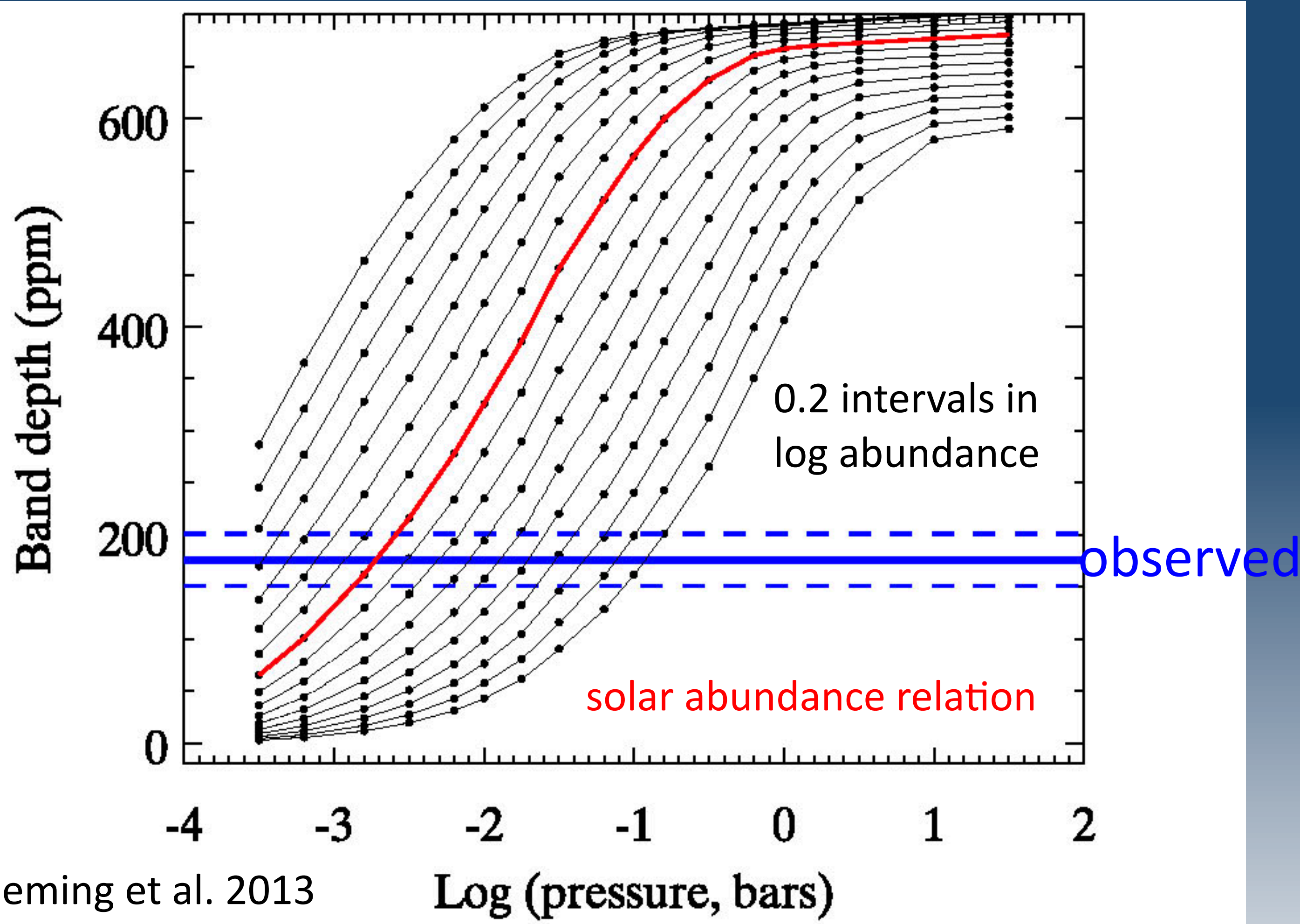


0.122
0.121
0.120
0.119
$R_p/R_\star$
3
2
1
0
−1
1.1
1.2
1.3
1.4
1.5
1.6
Wavelength (μm)
WASP-121b
Evans et al. 2016

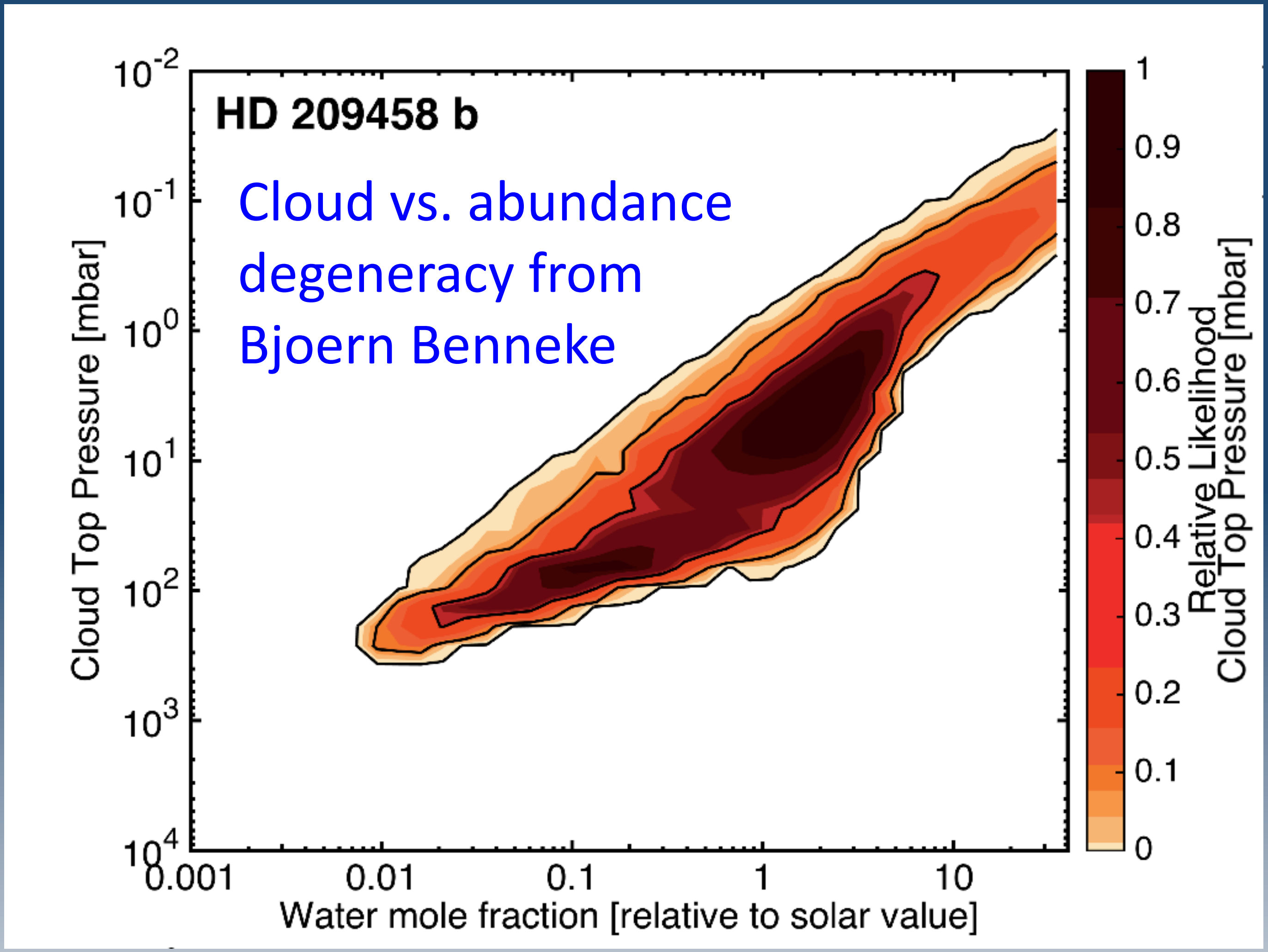

a
WASP-43b eclipse spectrum
Kreidberg et al. 2014
Eclipse depth (×10⁻⁴)
Wavelength (μm)
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1
2
3
4
5
6
7
8
9
70
60
50
40
30
20
10
3.0
4.0
5.0


HAT-P-11b, Neptune-sized
Fraine et al. 2014
a
Offset Between WFC3 and Best-fit Model
Stellar Activity Uncertainty
White-light Curve Uncertainty
b
Best-fit Model 190x Solar Metallicity
Pure Water Model, 10,000x Solar Metallicity
Solar Cloud-Free Model w/ Low C/O
Solar Model w/ clouds at 80 mbar
Solar Cloud-Free Model
$(R_p/R_s)^2$ [ppm]
Wavelength [μm]

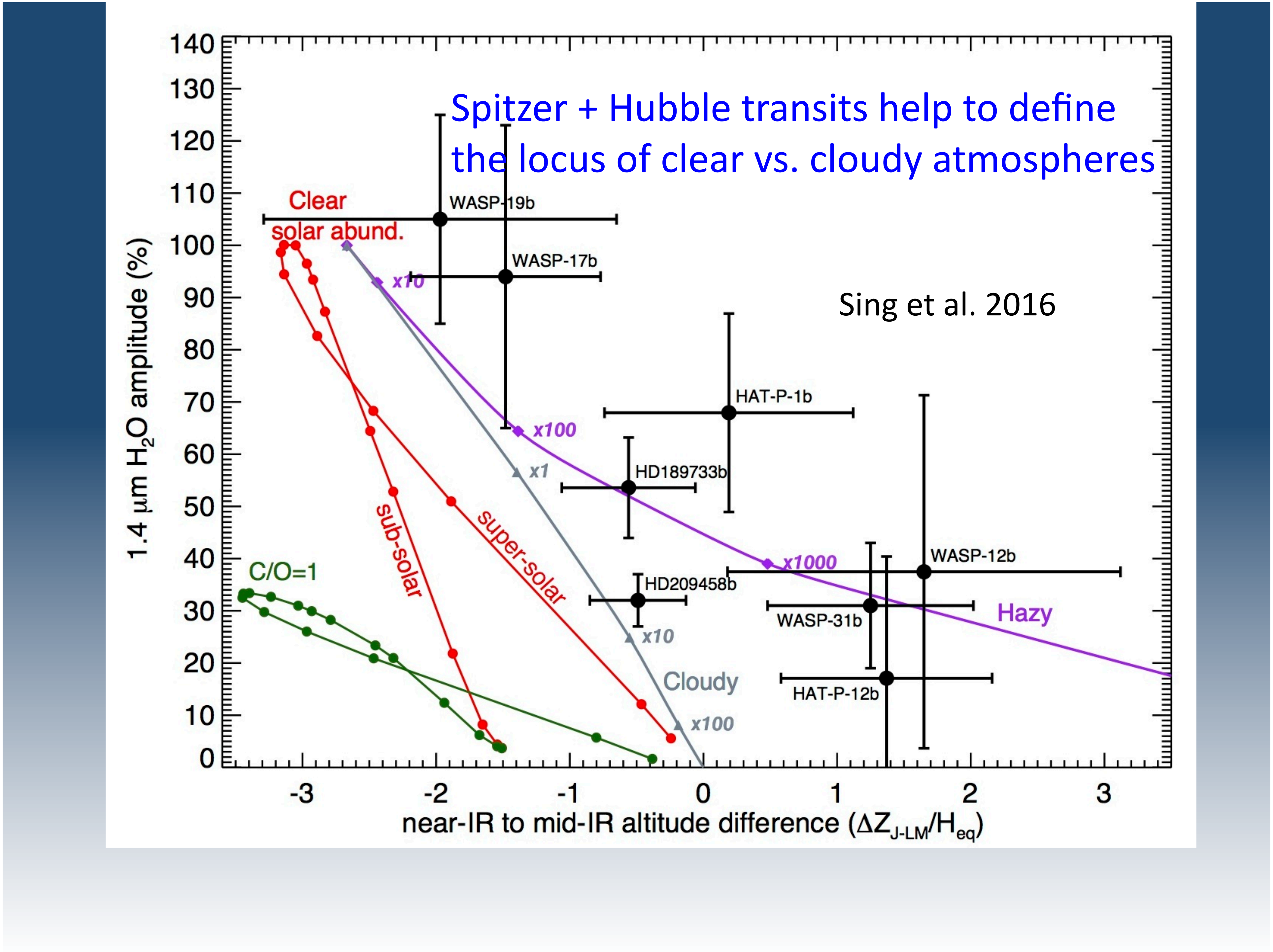

a
b
Clouds can be a problem, e.g. GJ1214b
Kreidberg et al. 2014
Relative transit depth (parts per million)
1,500
1,000
500
0
−500
−1,000
−1,500
0.6
0.8
1.0
2.0
3.0
4.0
5.0
Solar
100% H_2O
100% CH_4
100% H_2O
100% CO_2
200
150
100
50
0
-50
−100
−150
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Wavelength (μm)



Deming et al. 2013

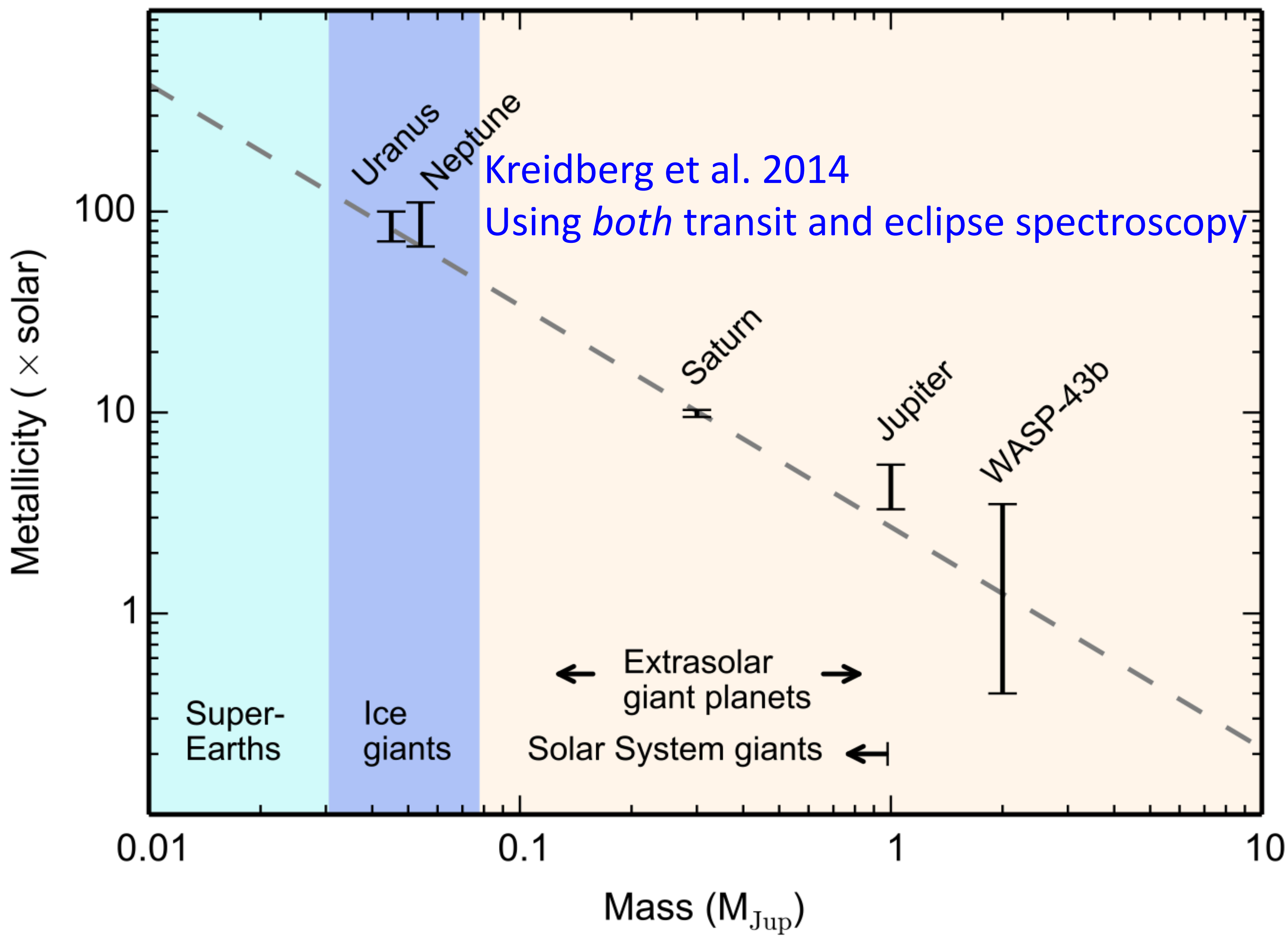


HD 209458 b
Cloud vs. abundance
degeneracy from
Bjoern Benneke
Cloud Top Pressure [mbar]
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
0.001
0.01
0.1
1
10
Water mole fraction [relative to solar value]
Relative Likelihood
Cloud Top Pressure [mbar]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0


Spitzer + Hubble transits help to define
the locus of clear vs. cloudy atmospheres
Sing et al. 2016
1.4 μm H2O amplitude (%)
near-IR to mid-IR altitude difference (ΔZJ-LM/Heq)
Clear
solar abund.
sub-solar
super-solar
C/O=1
Cloudy
Hazy
x1
x10
x100
x1000
WASP-19b
WASP-17b
HAT-P-1b
HD189733b
HD209458b
WASP-12b
WASP-31b
HAT-P-12b

Kreidberg et al. 2014

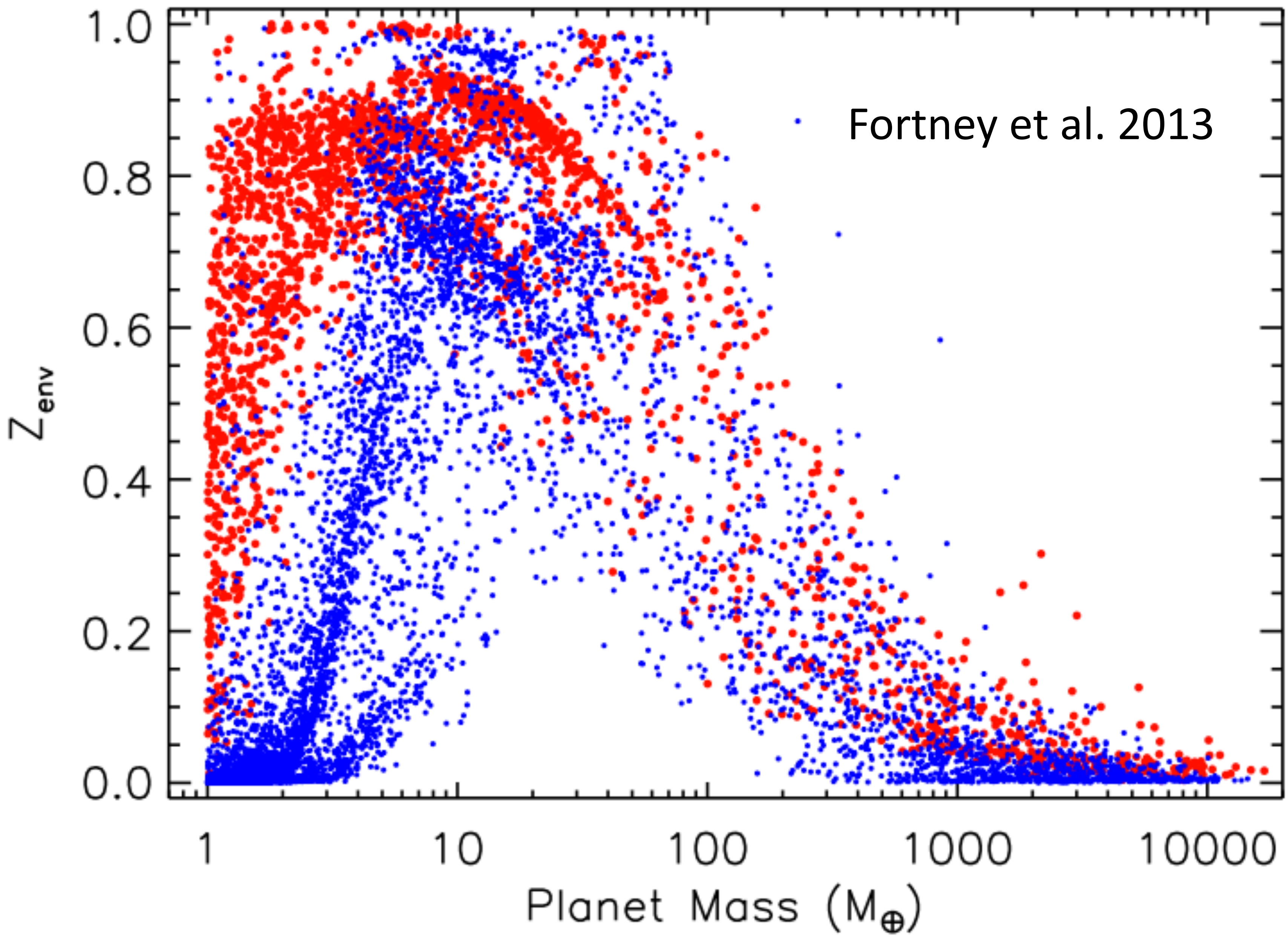
Using *both* transit and eclipse spectroscopy



It will be difficult to observe a mass-metallicity relation using transit (as opposed to eclipse) spectroscopy:

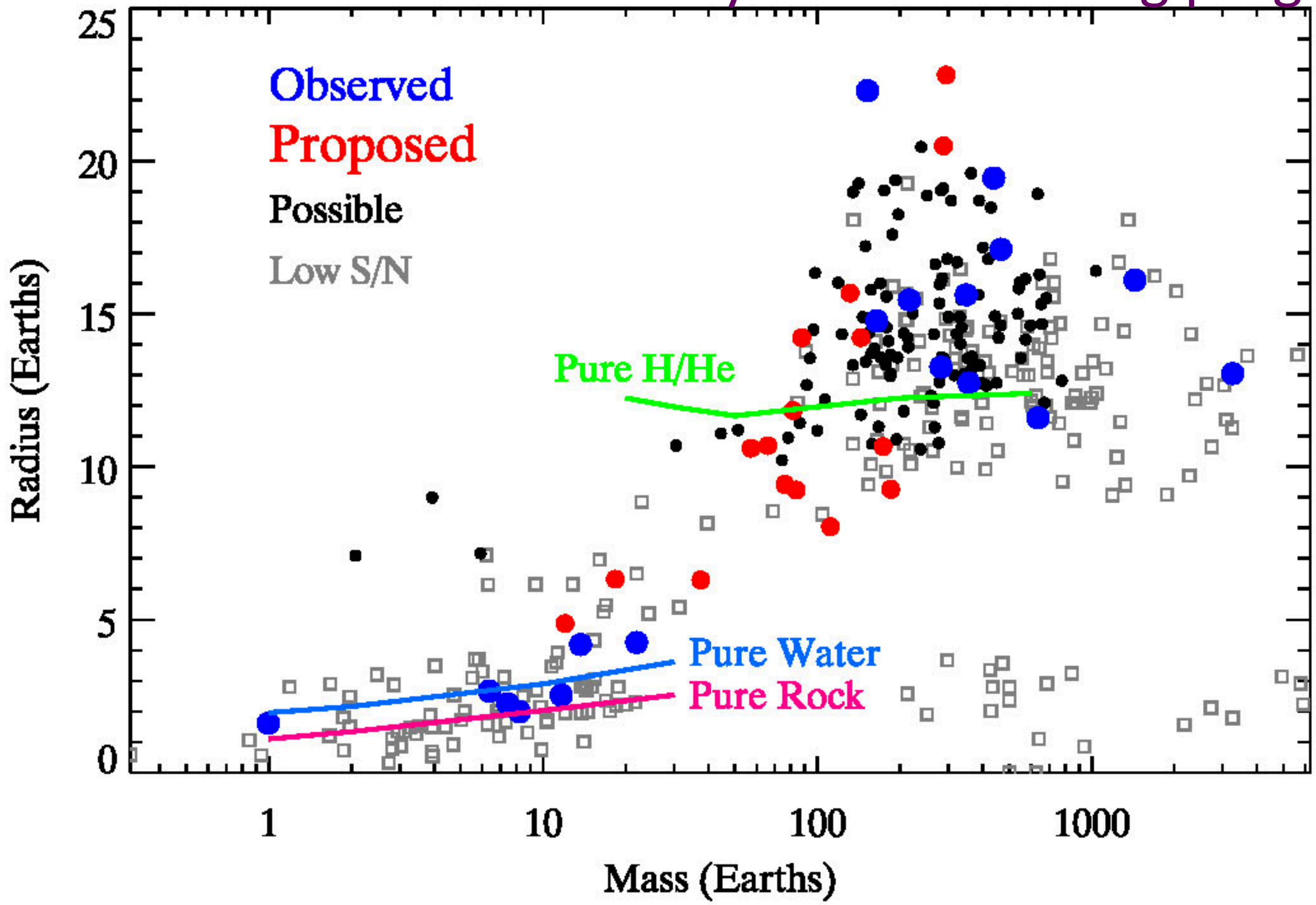
1. The lines are saturated in transit
2. Degeneracies with clouds
3. Uncertainty in the scale height (temperature)
4. Intrinsic scatter in the exoplanet population

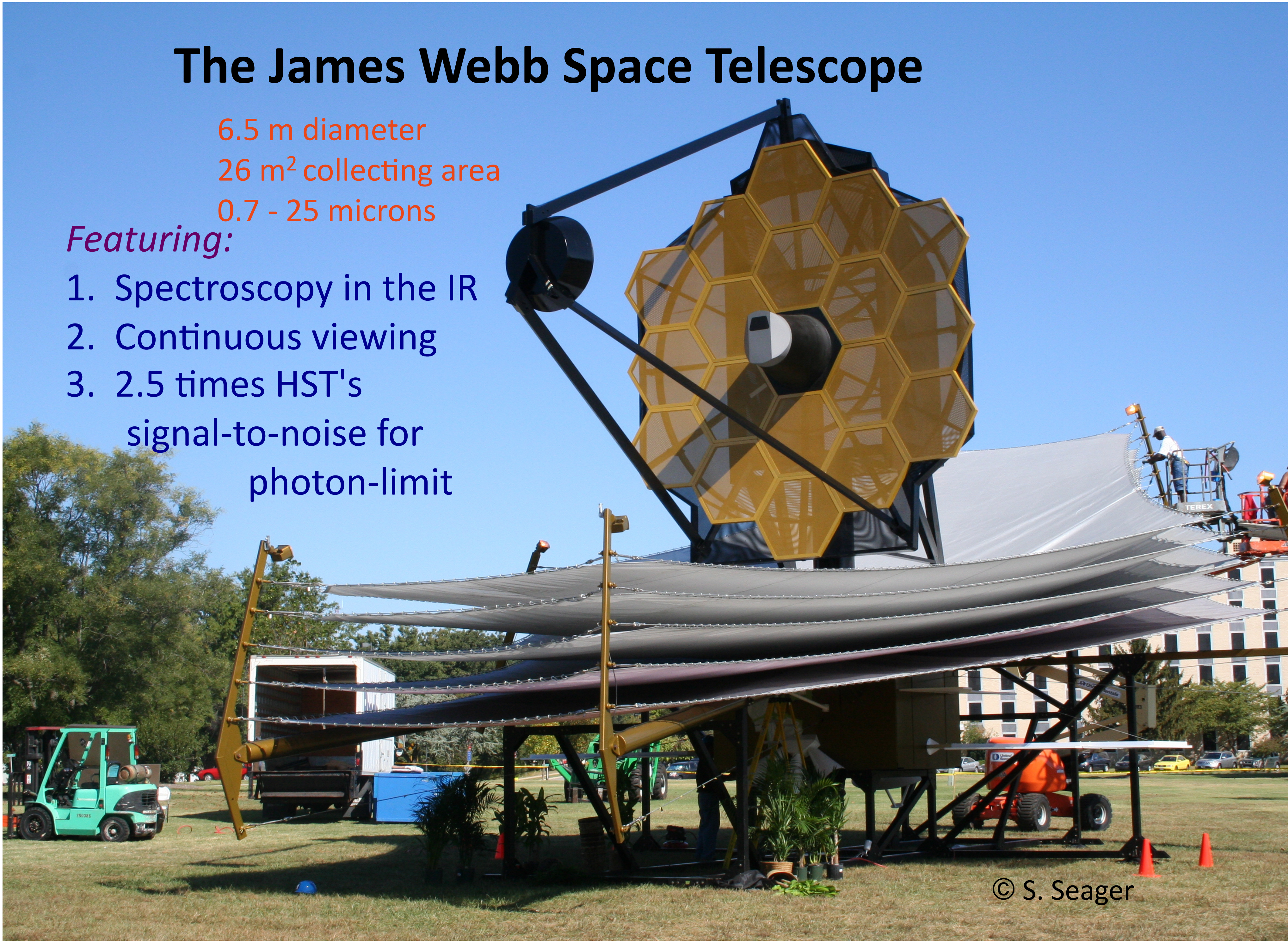
Adding eclipse spectroscopy (JWST) will be the best approach



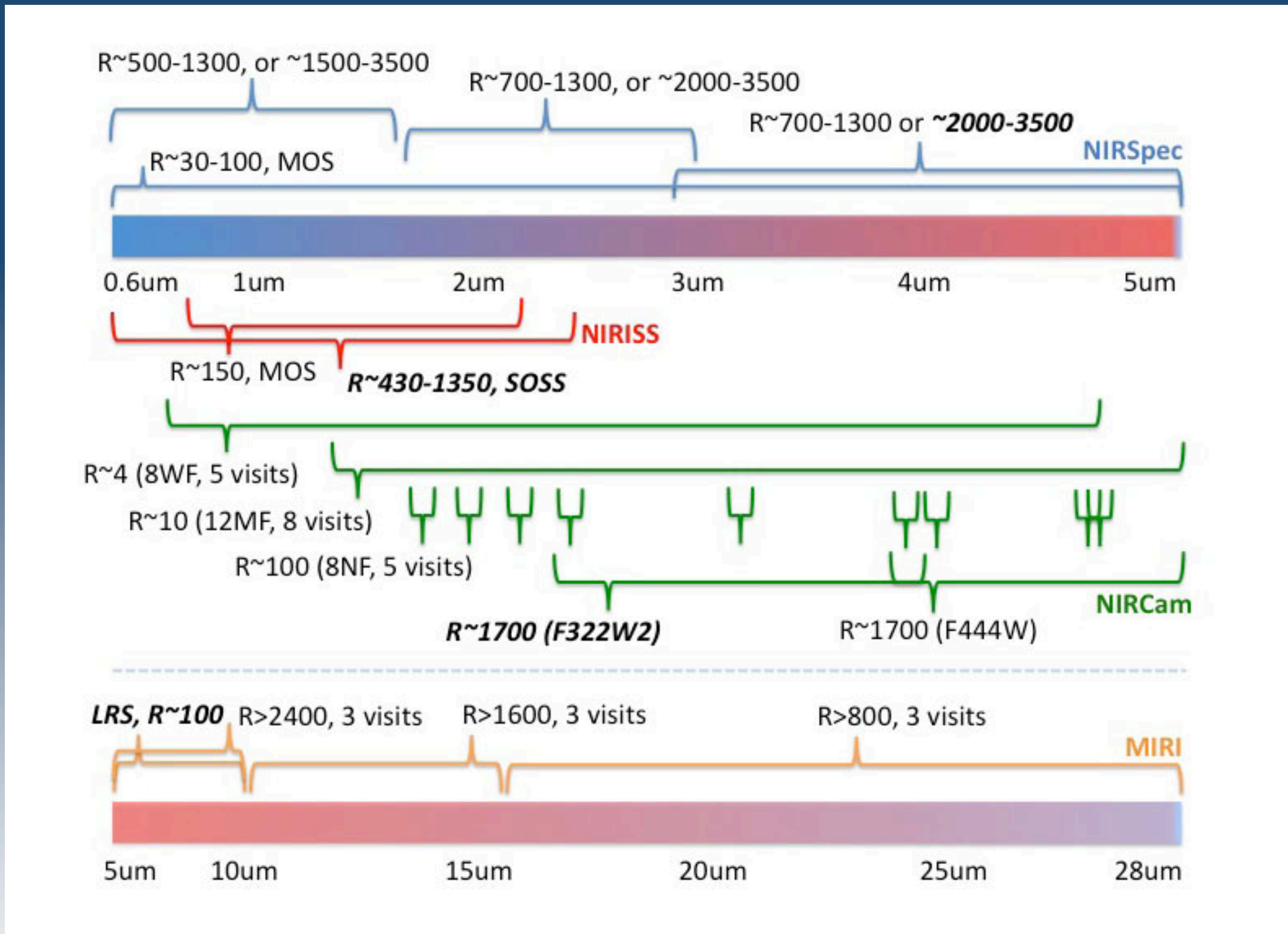
1.0
0.8
0.6
0.4
0.2
0.0
Z_env
1
10
100
1000
10000
Planet Mass (M⊕)
Fortney et al. 2013

Hubble Cycle 23 observing program



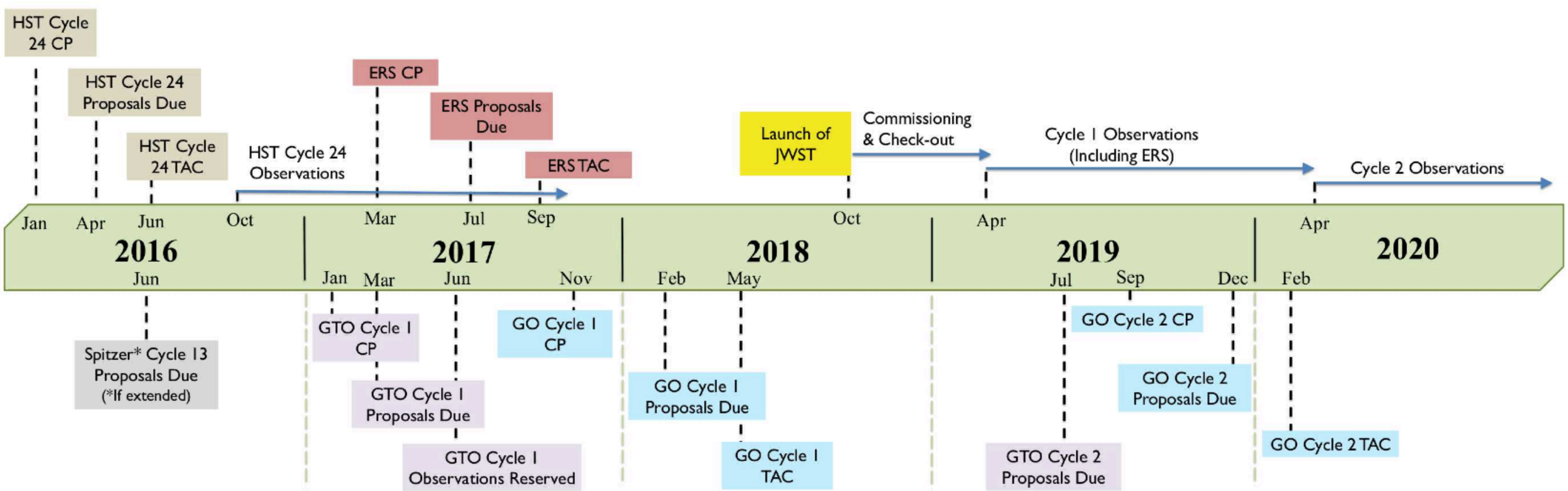

The James Webb Space Telescope
6.5 m diameter
26 m^2 collecting area
0.7 - 25 microns
Featuring:
1. Spectroscopy in the IR
2. Continuous viewing
3. 2.5 times HST's signal-to-noise for photon-limit
TEREX
© S. Seager

JWST covers the wavelength range where most molecules have strong vibration-rotation bands
And JWST has multiple spectroscopic modes



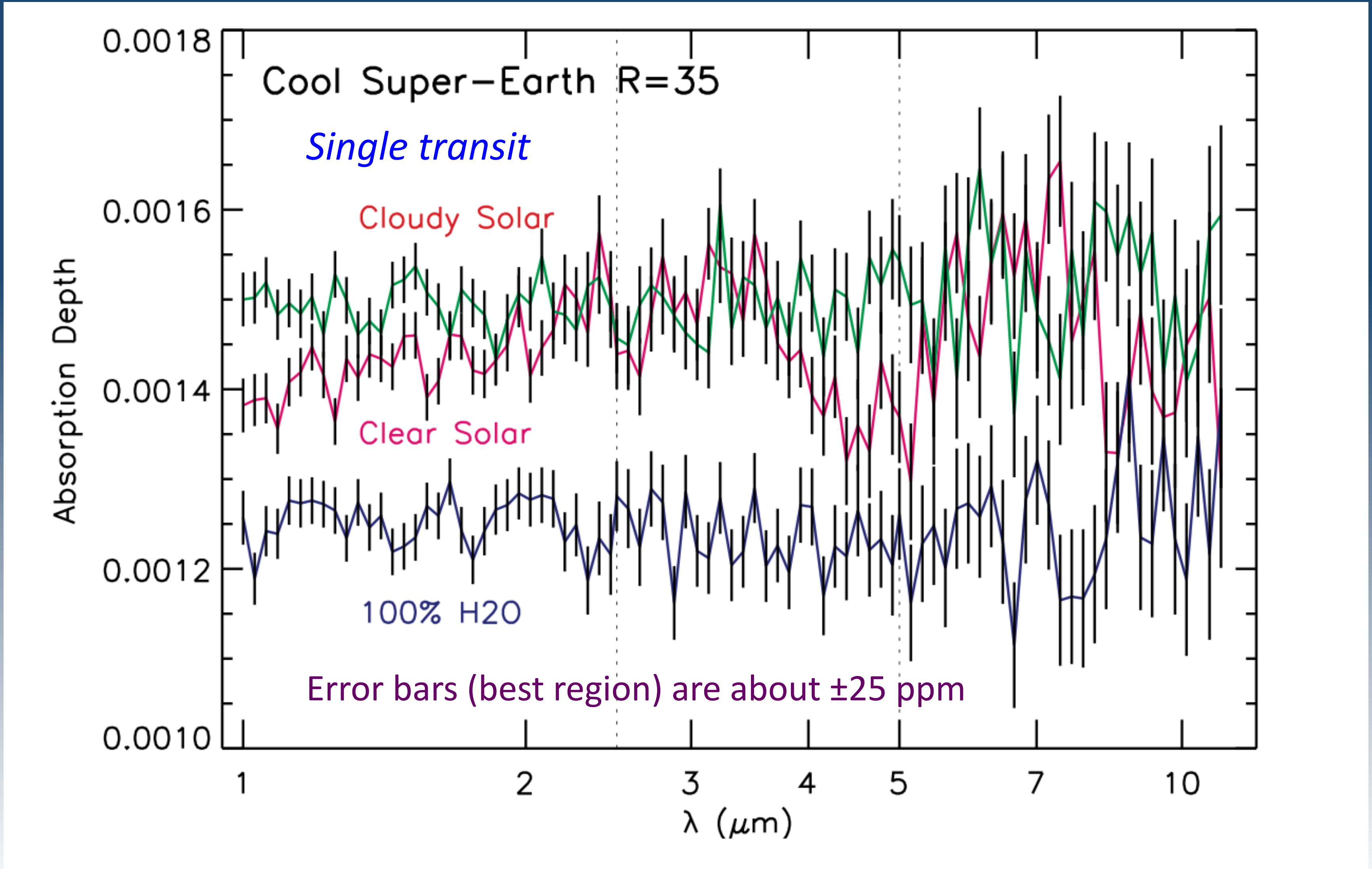
JWST timeline

Early release science will certainly include hot Jupiters, smaller planets are TBD



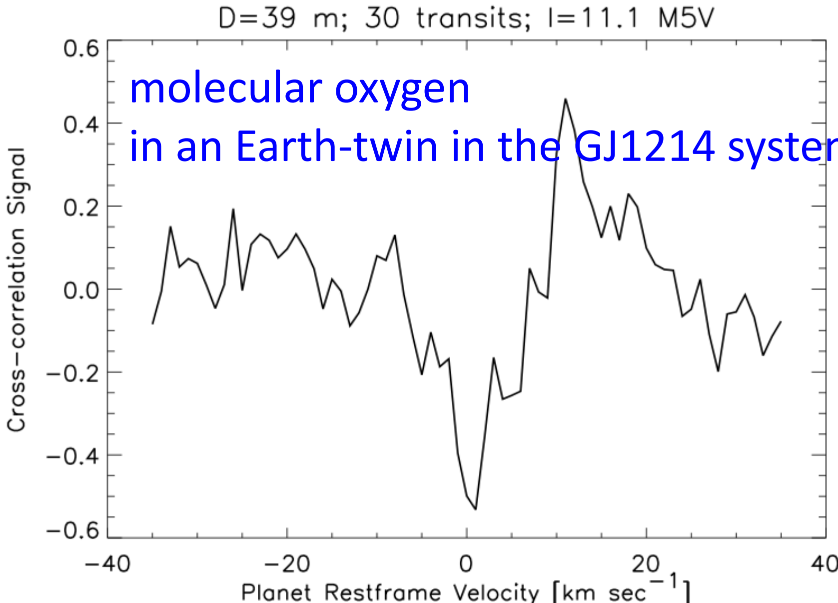
Synthetic transmission spectra for a single transit of a "cool" super-Earth (500K)

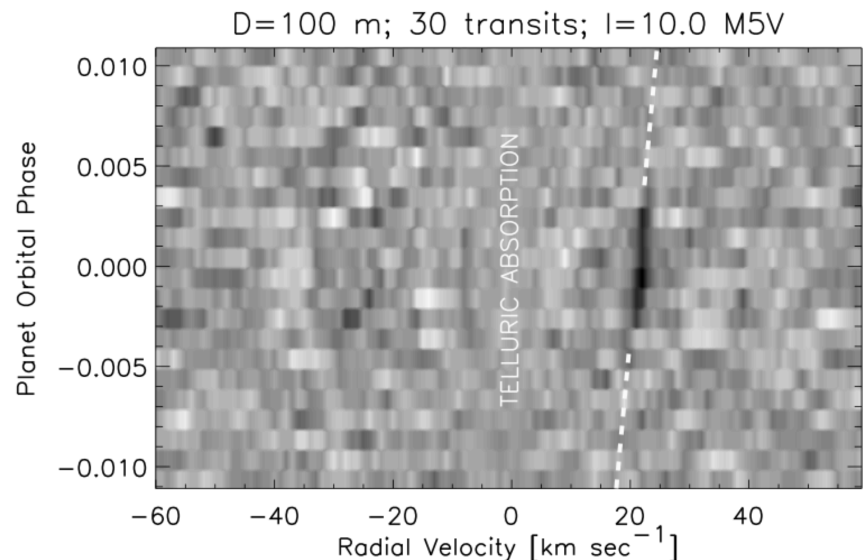
(Greene et al. 2016)



High spectral resolution using ground-based ELTs, can detect molecules by convolving with templates

molecular oxygen
in an Earth-twin in the GJ1214 system





You have to know – very precisely - what you're looking for, but the ELTs have huge light-gathering power, and you can average many transits

Summary:

Transit spectroscopy at short λ, eclipse spectroscopy at long λ

The combination of eclipse and transit spectroscopy is powerful

Water vapor spectroscopy in hot Jupiters to Neptunes is robust,
and we're trying to measure quantitative abundances
and map the occurrence of clouds

JWST will be great for eclipse spectroscopy, even super-Earths,
and C/O ratios

Ground-based ELTs should have great sensitivity using template
cross-correlations