Observations of exoplanet atmospheres

from super-Earths to hot Jupiters

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IAP Paris
2015 July 3

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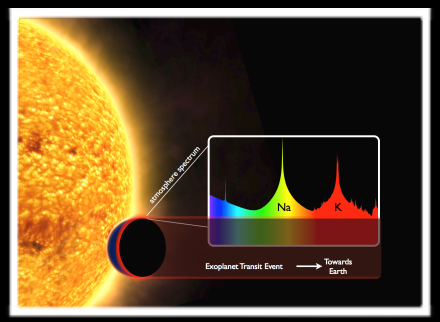
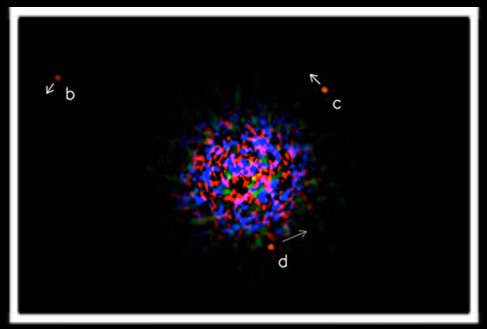
Outline

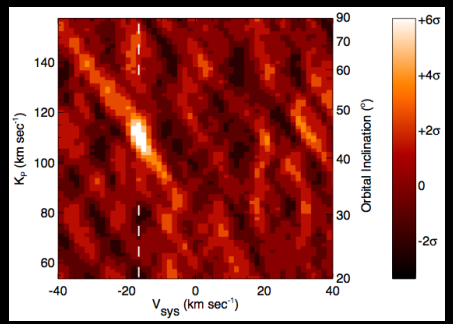
- Review different Techniques
- Highlight a few current Science Questions
- State of the field
- Look forward

Exoplanet Atmosphere Characterization by Spectra

Transits	Direct Imaging	Radial Velocity
Close-In Planets	Wide Orbit Planets	Bright Targets
S-Earths/Nept/HotJup	Young Jupiters	Young/Old close/far Jup
Atmo. Composition	Atmo. Composition	Atmo. Composition
Clouds/Hazes	Clouds/Hazes	
C/O	C/O	C/O
Thermal profile	Temperatures	Stratospheres
Strat.-Thermosph.		
Exospheres		
Escape		
Dynamics, Winds	Dynamics	Dynamics, Winds
Photochemistry	Chemistry	







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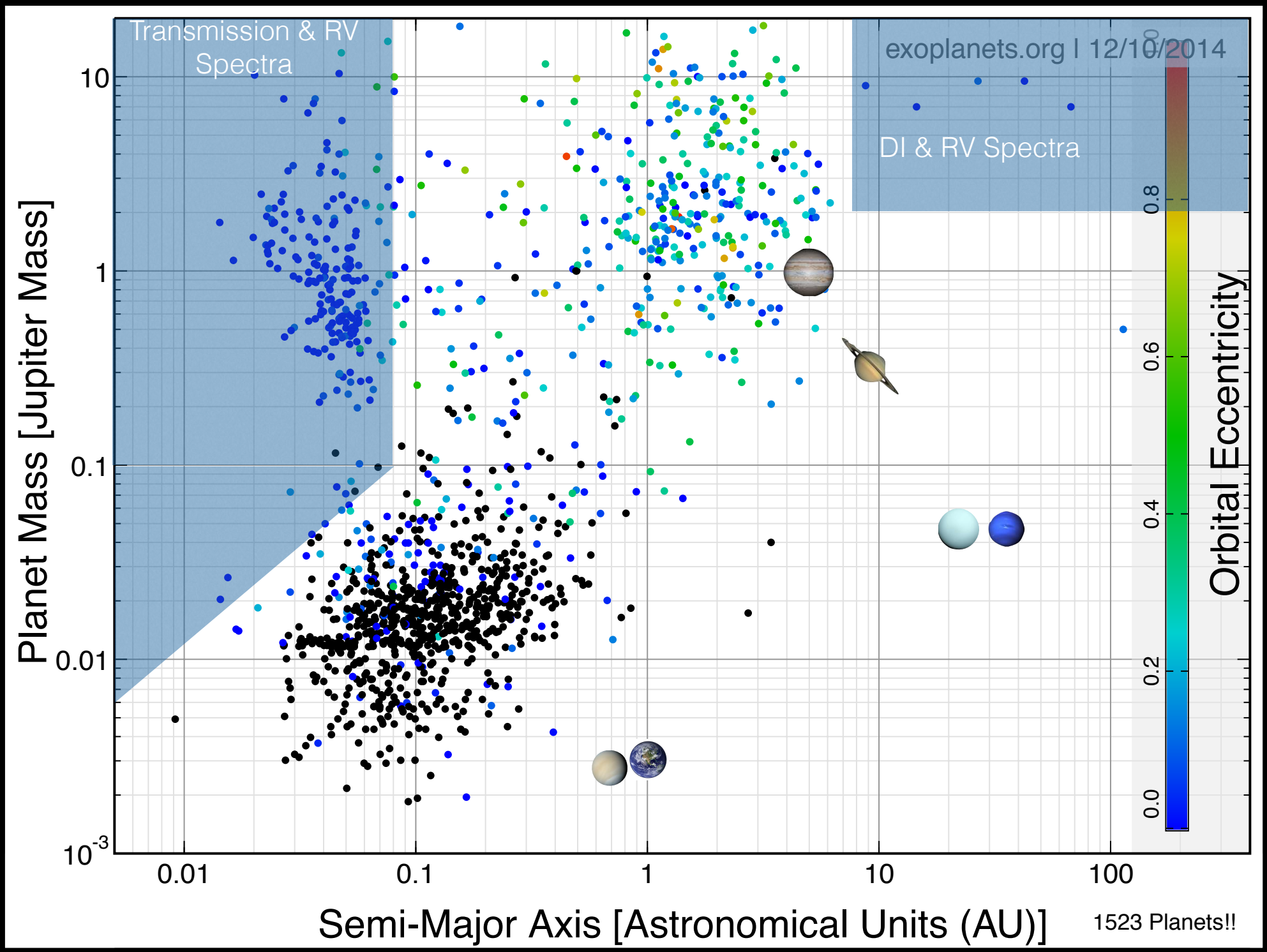
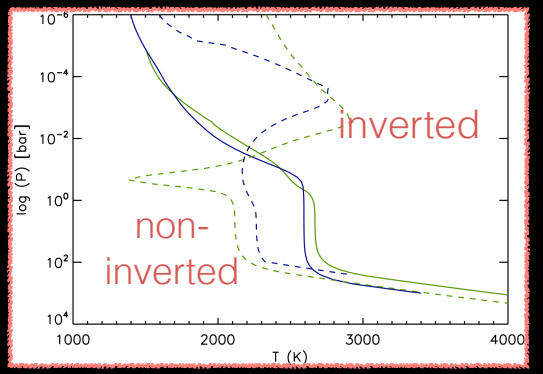

Transmission & RV Spectra
exoplanets.org | 12/10/2014
DI & RV Spectra
Planet Mass [Jupiter Mass]
Orbital Eccentricity
Semi-Major Axis [Astronomical Units (AU)]
1523 Planets!!
10
1
0.1
0.01
10^{-3}
0.01
0.1
1
10
100
0.0
0.2
0.4
0.6
0.8

Major Science Q's

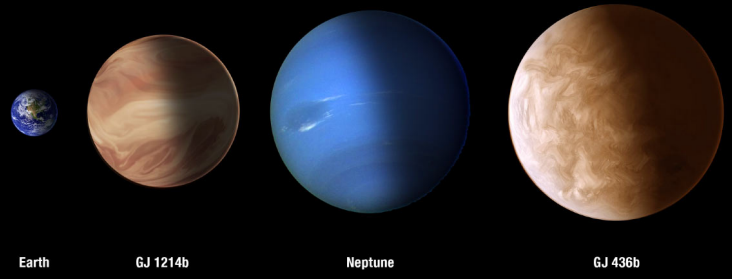
- Composition & Formation
  C/O? H_2O? Chem? Abundances?



- Atmospheric Sciences
  Temp. profile? Wind profiles?
  Night contrasts? Advection?

- Clouds & Hazes?

- Who's who: what are small planets made of?



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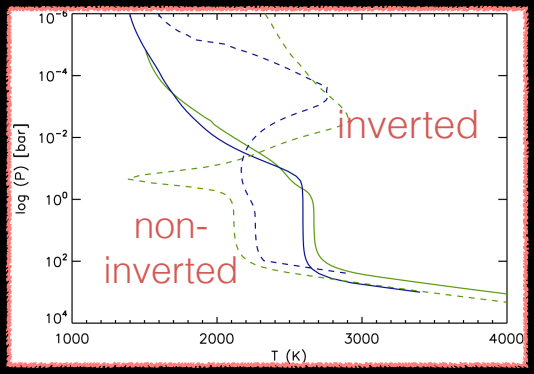
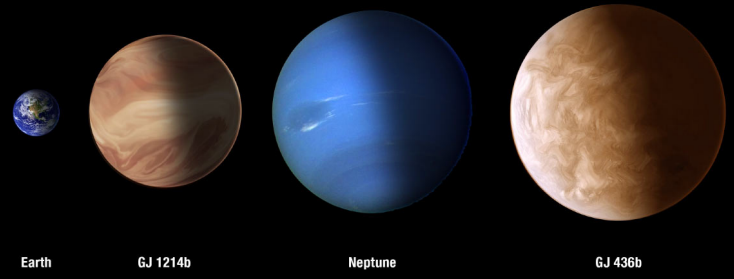


Atmospheric Data for Exoplanets is so sparse, we will need all information from all techniques to solve major Science Q's

Different exoplanet communities need to work together



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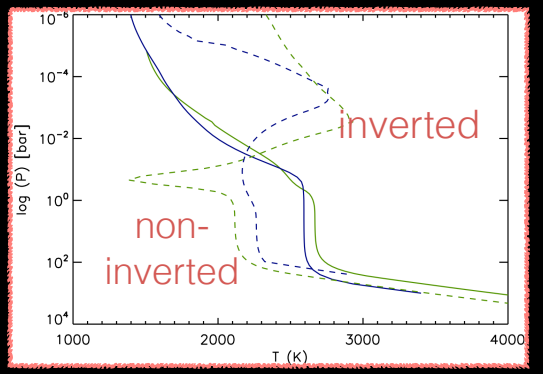

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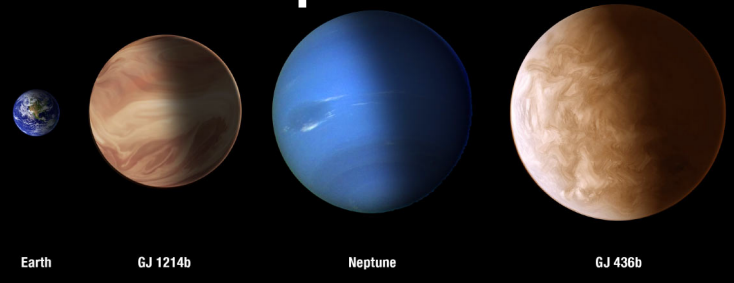
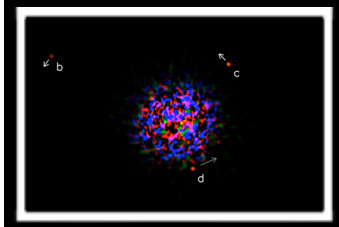


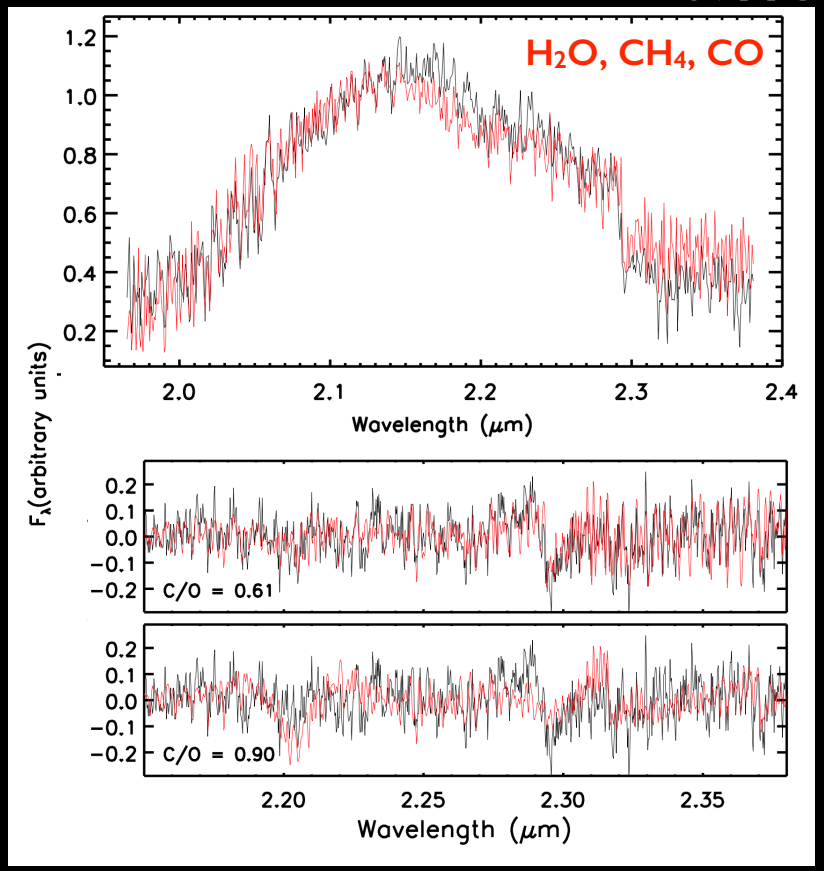


Direct Imaging Spectra

- Young Hot Massive
  Wide orbit
  Exoplanets

- High S/N (R~4000)
  Near-IR emission
  spectra

HR8799b



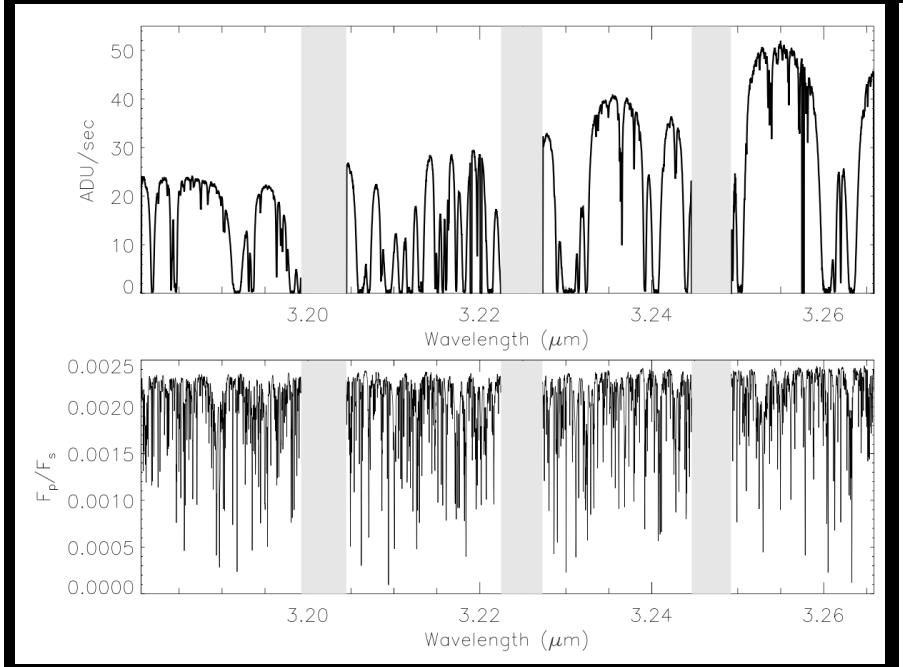
Barman et al. (2015)

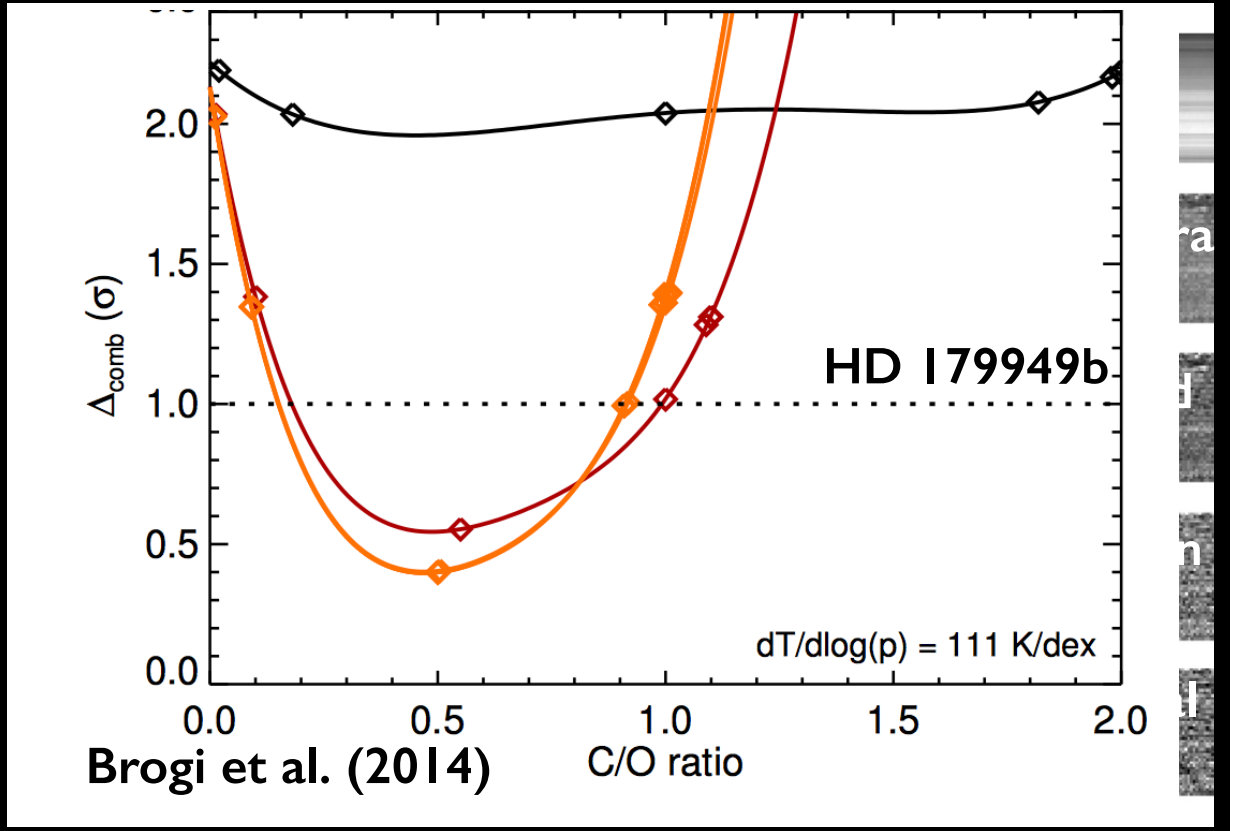
- Super-stellar C/O could indicate planet formation by core-accretion, Uncertainty large

- More precise values of the bulk properties (e.g., Teff, surface gravity) are needed for improved abundance estimates.

- Compare Transit to Direct Imaging Spectra

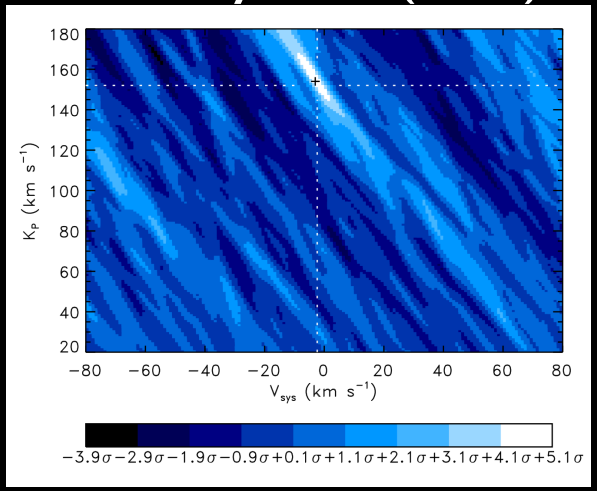
Radial Velocity Atmospheric Spectra



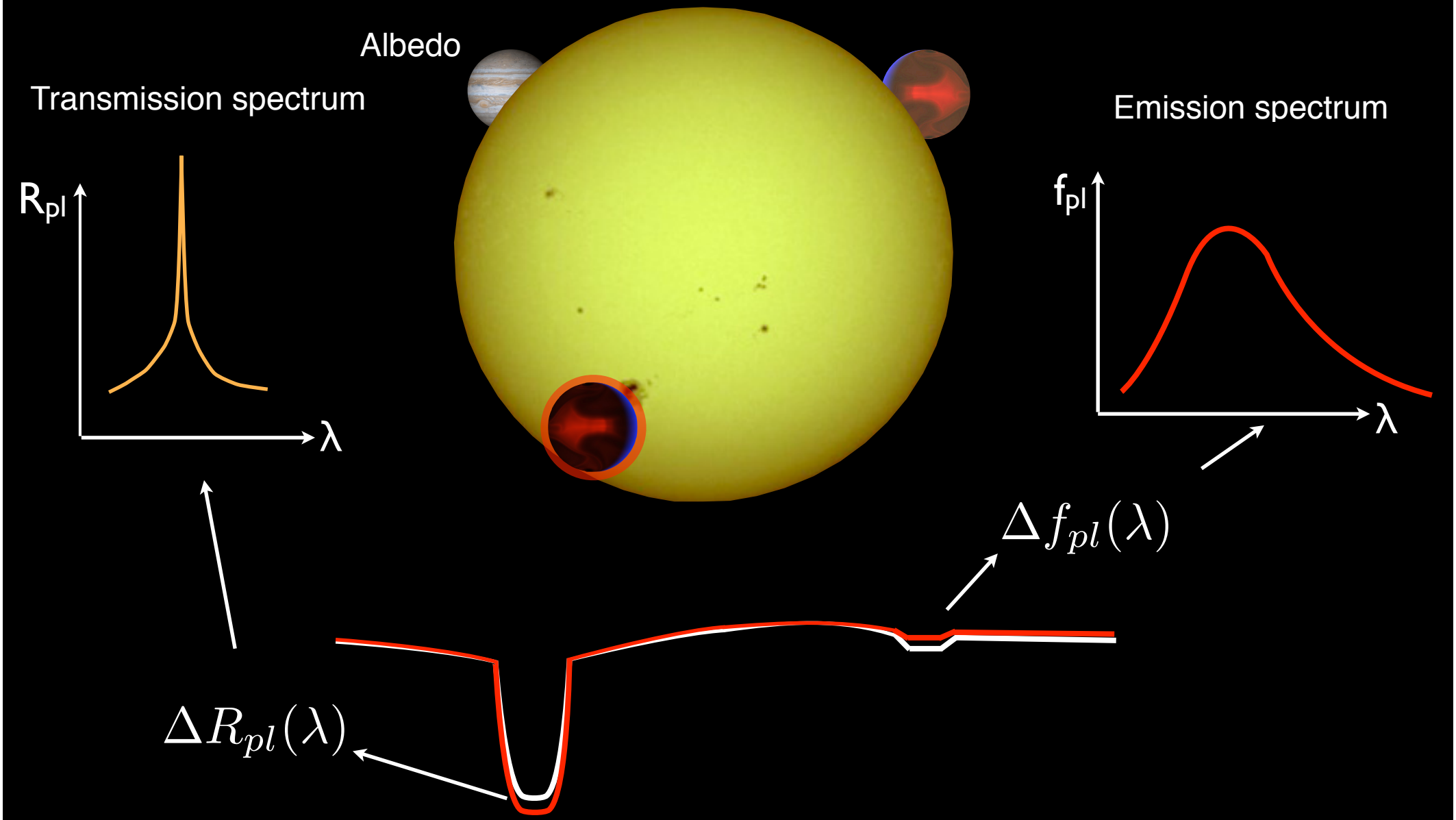


- Needs Bright Planets
  Infrared, non-transiting too
- Rely on Planet moving in λ space during night
- Cross-Correlate Model Planet Spectra Template
- Sensitive to molecular detections: CO, H_2O, CH_4
- Can measure C/O ratios, current constraints loose

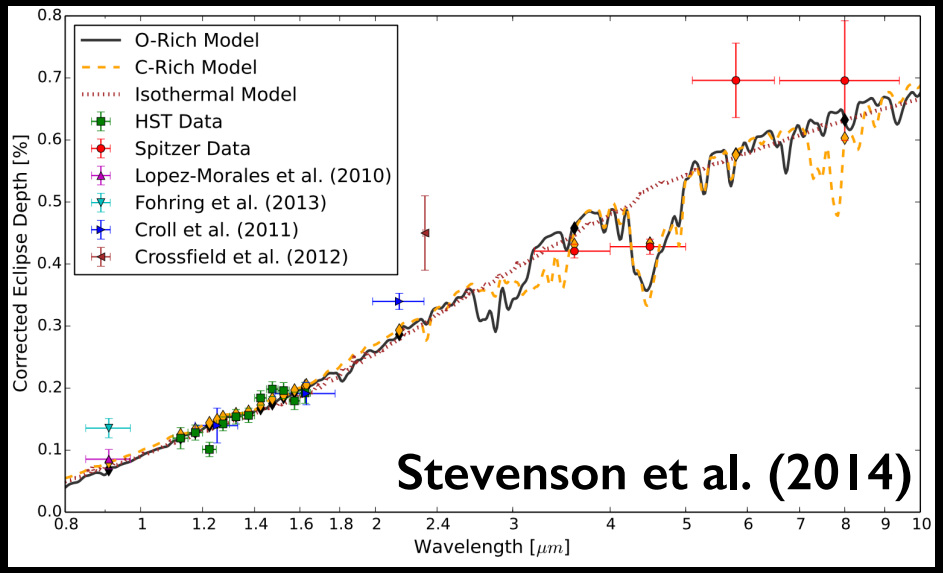
Birkby et al. (2013)

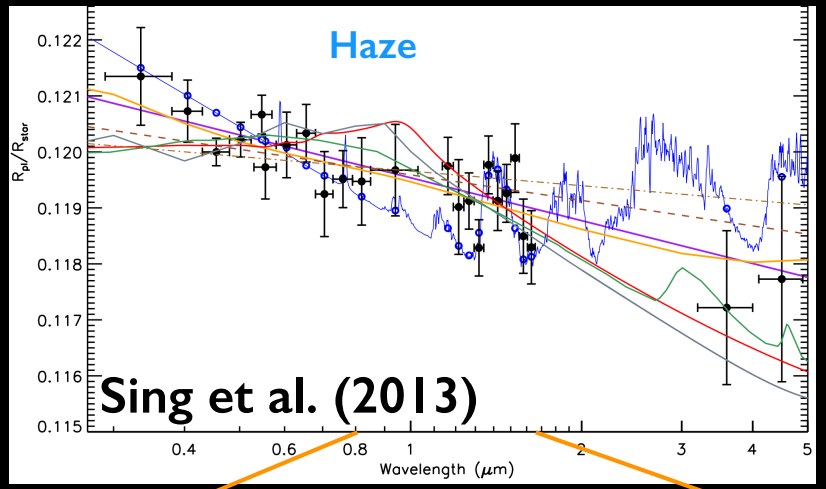


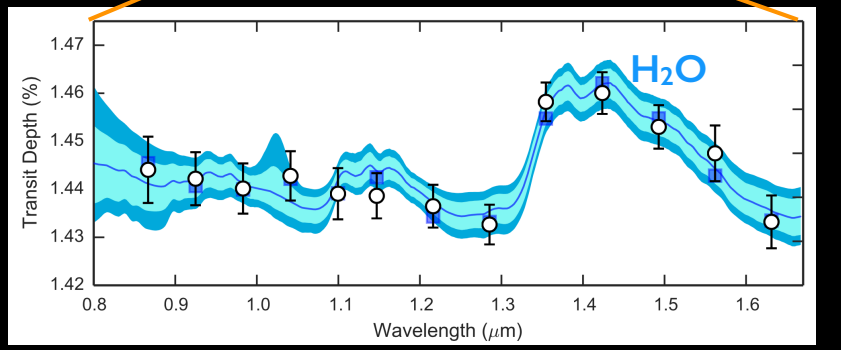
Transiting Exoplanet Spectra



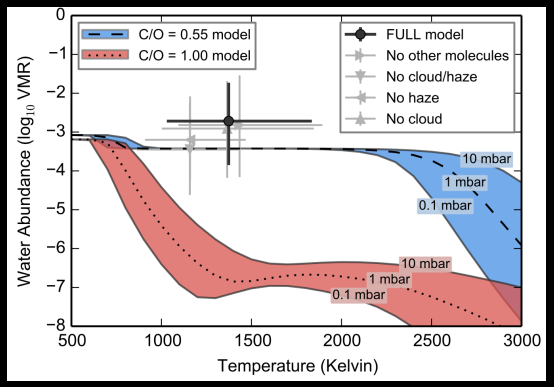
WASP-12b: is it Carbon or Oxygen rich?







Kreidberg et al. (2015)



- High C/O from Eclipse photometry
  Mahusudhan et al. (2011)
- Early data affected by unseen M-dwarfs
- Dayside still favours C-rich
- Terminator has haze & is O-rich
- Will need Eclipse Spectroscopy in IR (JWST)

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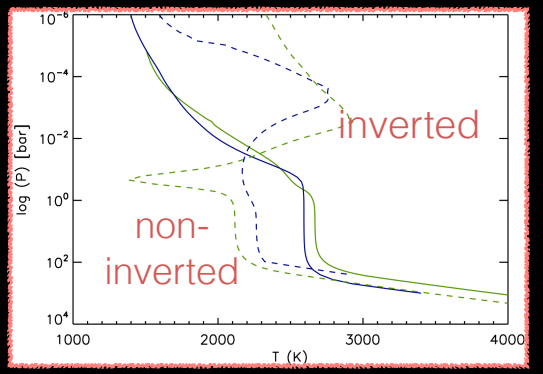

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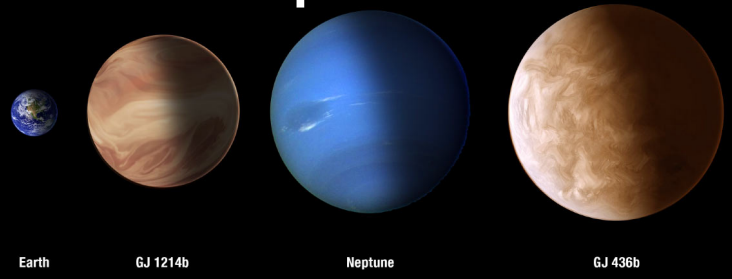
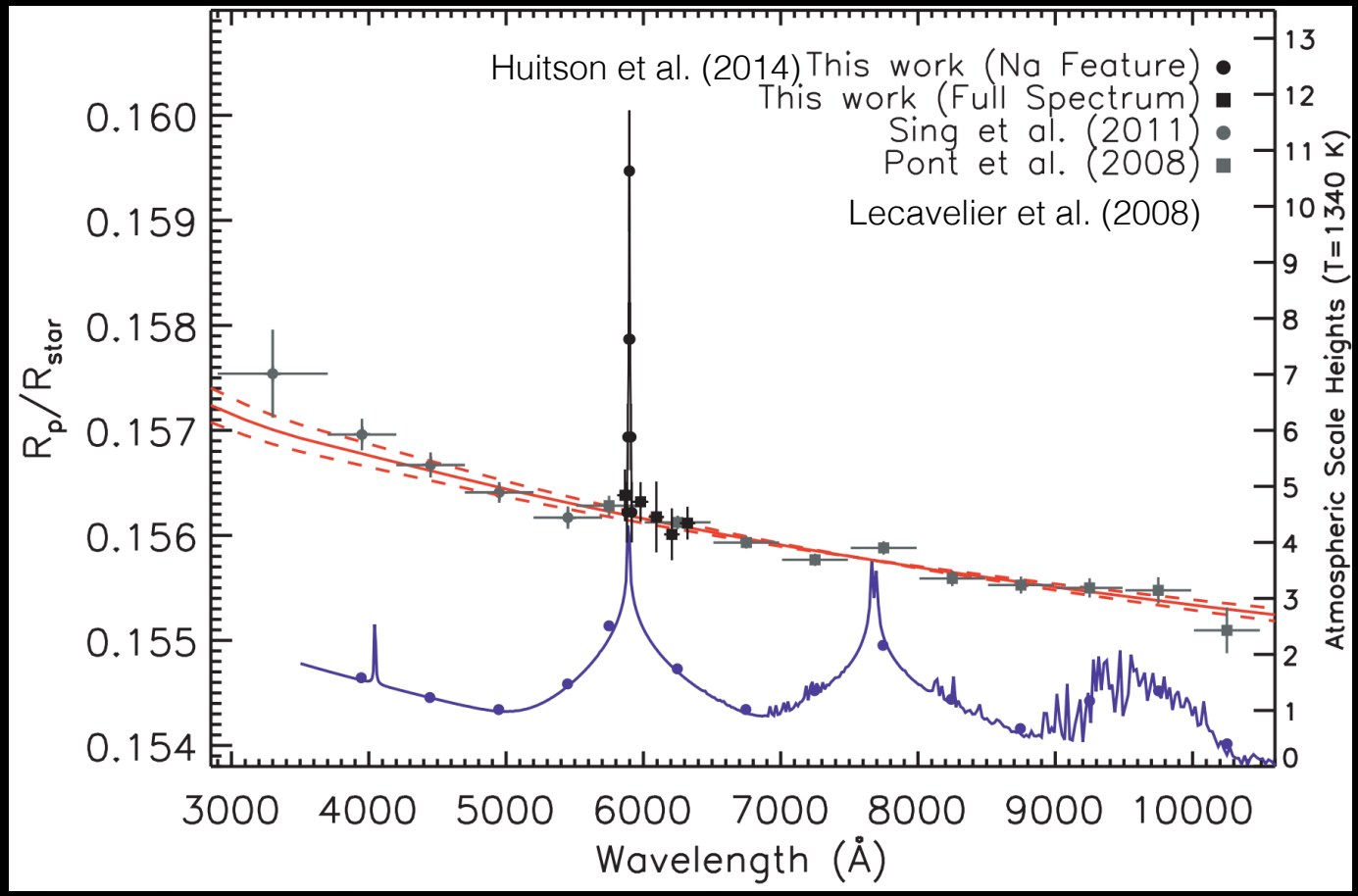


Ground and Space Transmission Spectroscopy

working together



- High Res. Ground (Redfield et al. 2008)
- Low and Medium Res. Space HST
- Na and Haze detected
- Measure Atmospheric Temperatures (1340K Rayleigh Slope)
  3000K Thermosphere (Na)

Ground and Space Transmission Spectroscopy

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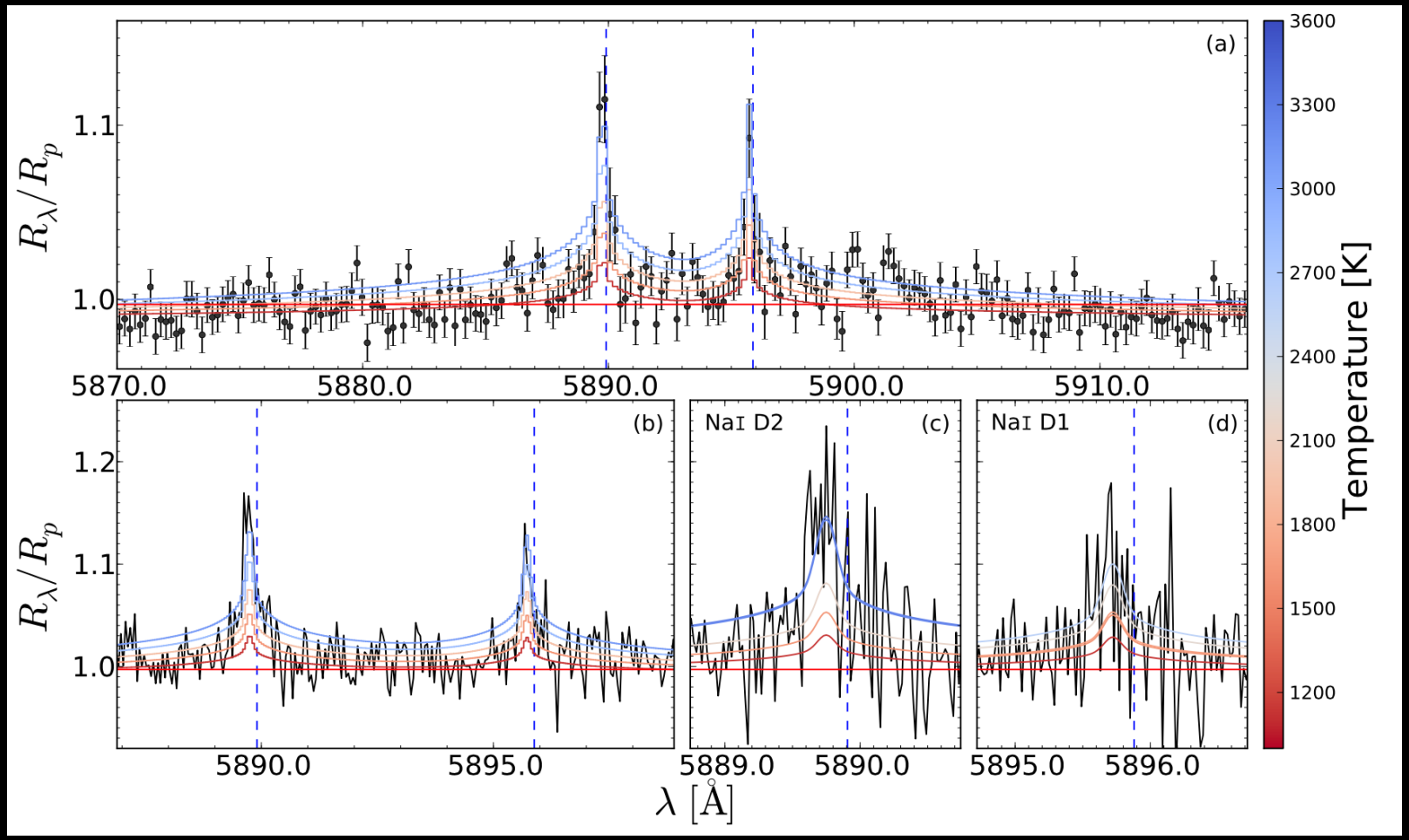

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- Low and Medium Res. Space HST
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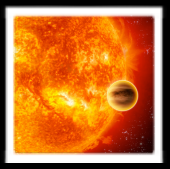
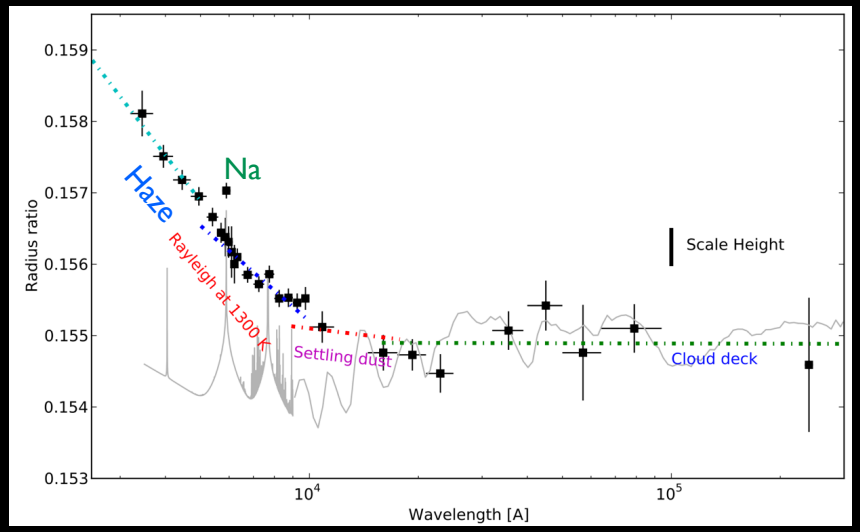
- Measure Atmospheric Temperatures (1340K Rayleigh Slope)
  3000K Thermosphere (Na)
- HARPS (Wyttenbach et al. 2015)

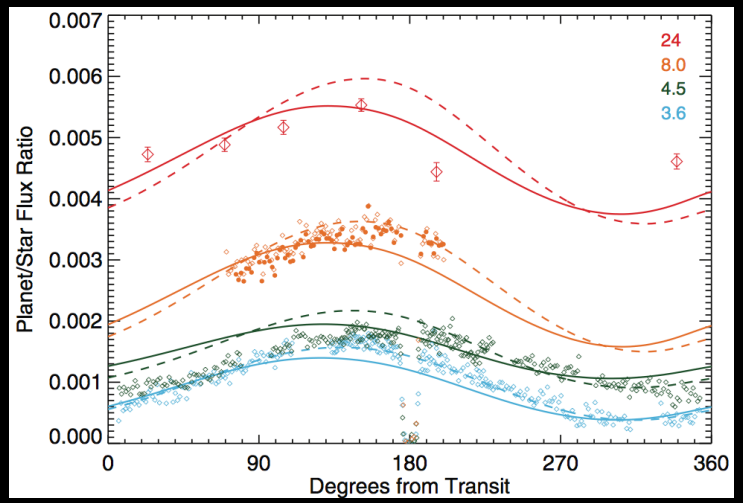
HD 189733b: Atmospheric Measurements from many directions



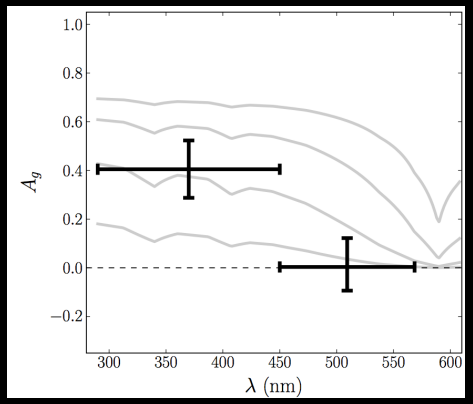
Transmission



Phase Curve



Albedo



Optical Haze

'blue planet'

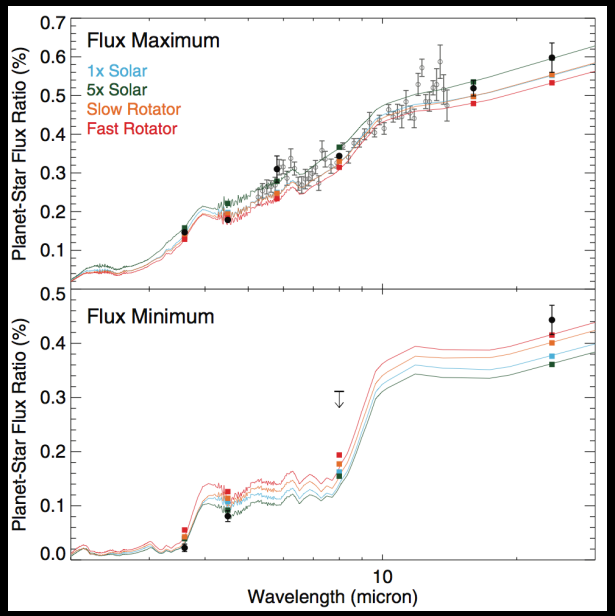
offset Hot Spot - 'Jets'

Na, H, H_2O and CO present

Efficient heat re-distribution

evaporating

Emission



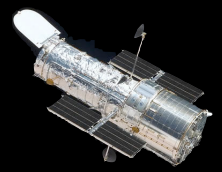
Charbonneau et al. (2008)
Grillmair et al. (2007)
Knutson et al. ('07,'09,'12)
Pont et al. ('07, '13)
Sing et al. ('09, '12)
de Kok et al. (2013)

Birkby et al. (2013)
Desert et al. ('09,'11)
Agol et al. (2010)
Gibson et al. ('11,'12)
Huitson et al. (2012)
Evans et al. (2013)

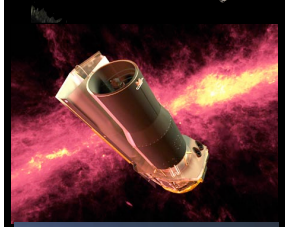
Jensen et al. (2012)
Redfield et al. (2008)
McCullough (2014)
Lecavelier et al. (2010)

Transiting Exoplanet Atmospheres Timeline

2002 04 05 08 09 11 14 16 18 20

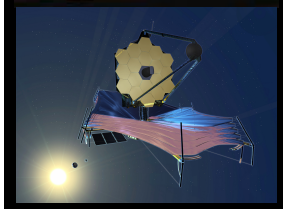


STIS | STIS & WFC3 | STIS?? WFC3?



cryogenic | warm

HR Phot MOS CRIRES dedicated atmo instrumentation?



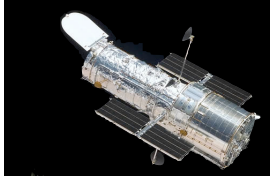
"*real*" high quality spectra

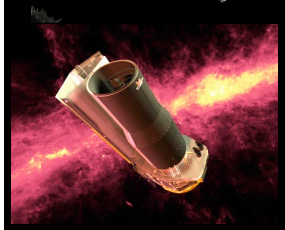
Transiting Planets: 1 | 10 | 100 | 1000

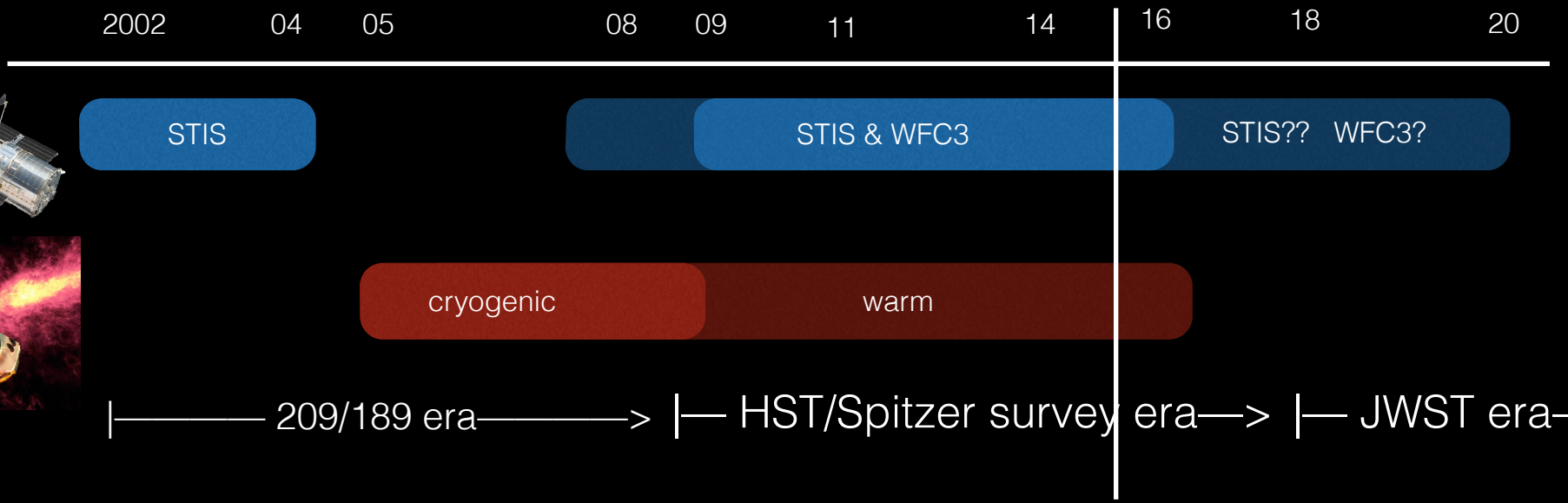
Spectra for... |——— 209/189 era———> |— HST/Spitzer survey era—> |— JWST era—>

lower atmos. spec.detected: Na | haze | H_2O | CO | K

Transiting Exoplanet Atmospheres Timeline







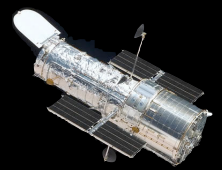
Current Capability?

STIS & WFC3 spectroscopy
Spitzer IRAC photometry

UV
Optical, near-IR
0.3 -1.7 um + 3-5 um
20 ppm
R ~ 50

Transiting Exoplanet Atmospheres Timeline

2002 04 05 08 09 11 14 16 18 20



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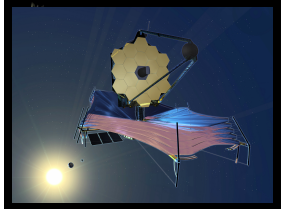
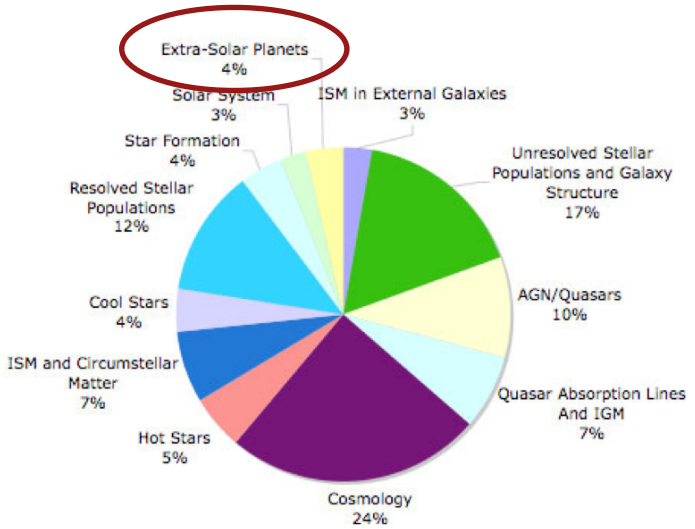


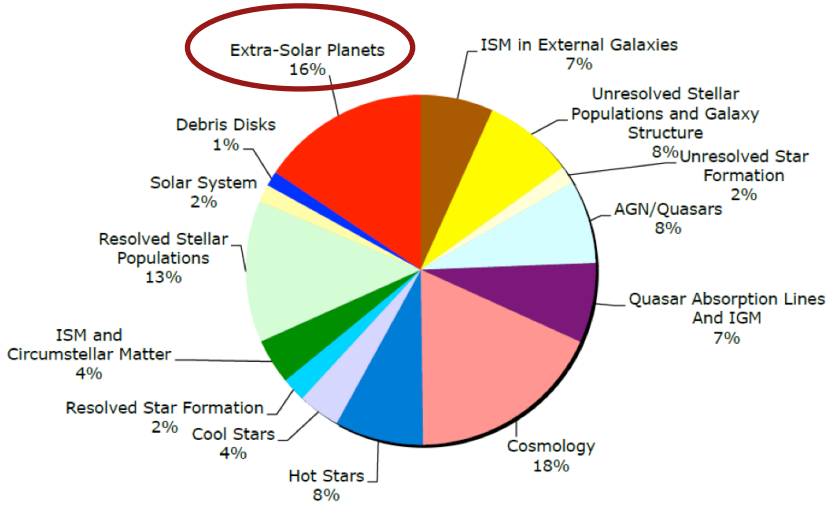
"*real*" high quality spectra

|——— 209/189 era———> |— HST/Spitzer survey era—> |— JWST era—>

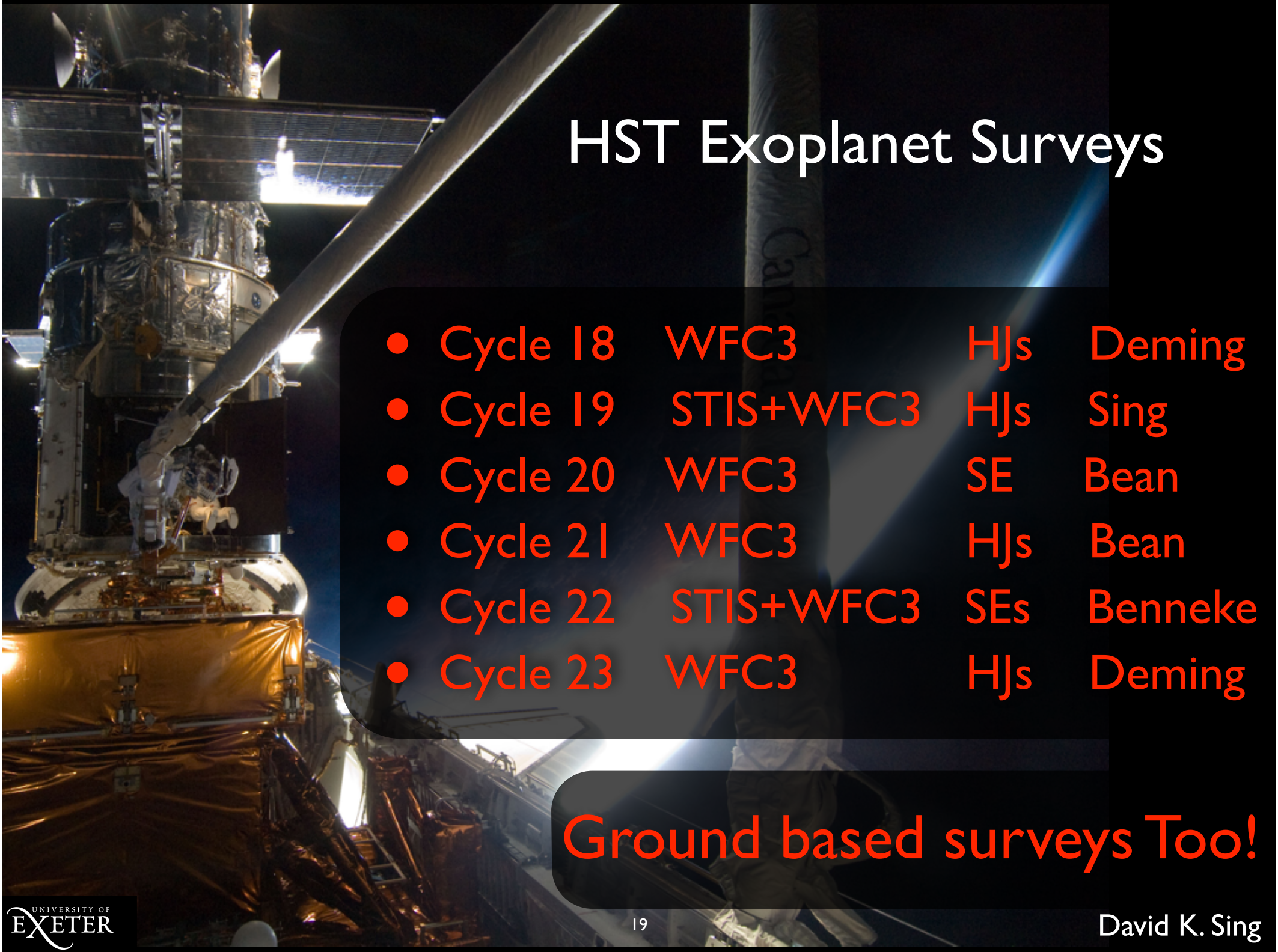
2008 HST Science Category by Orbits



2015 HST Science Category by Orbits



http://www.stsci.edu/institute/stuc/



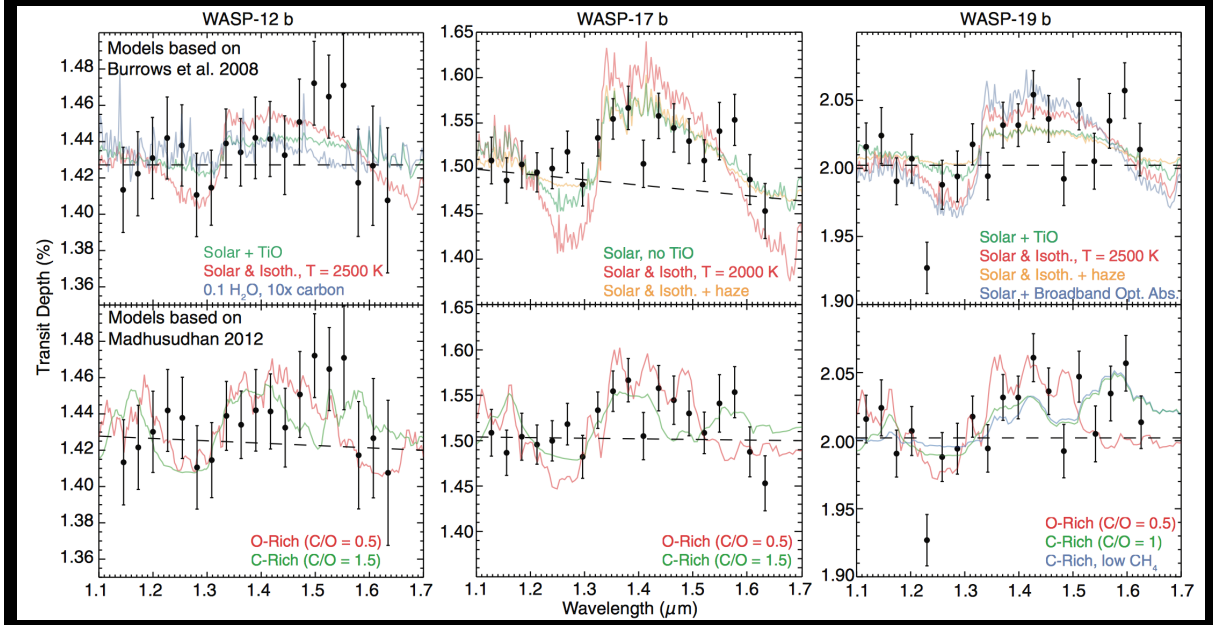
HST Exoplanet Surveys

• Cycle 18	WFC3	HJs	Deming
• Cycle 19	STIS+WFC3	HJs	Sing
• Cycle 20	WFC3	SE	Bean
• Cycle 21	WFC3	HJs	Bean
• Cycle 22	STIS+WFC3	SEs	Benneke
• Cycle 23	WFC3	HJs	Deming

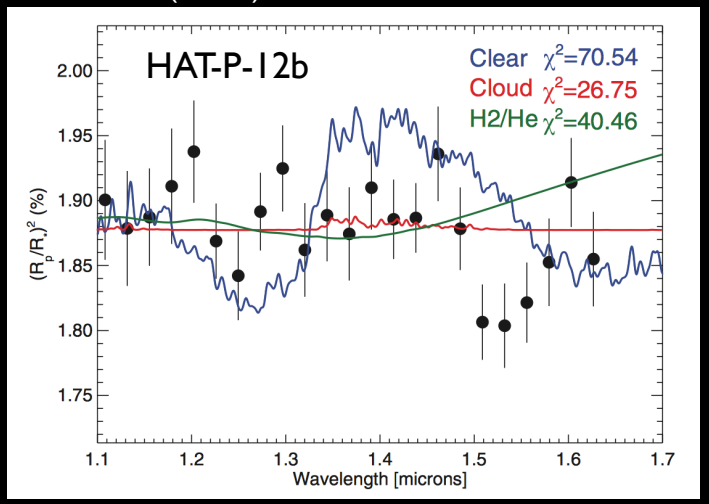
Ground based surveys Too!

HST WFC3 Hot Jupiter Survey P.I. Deming

Mandell et al. (2014)



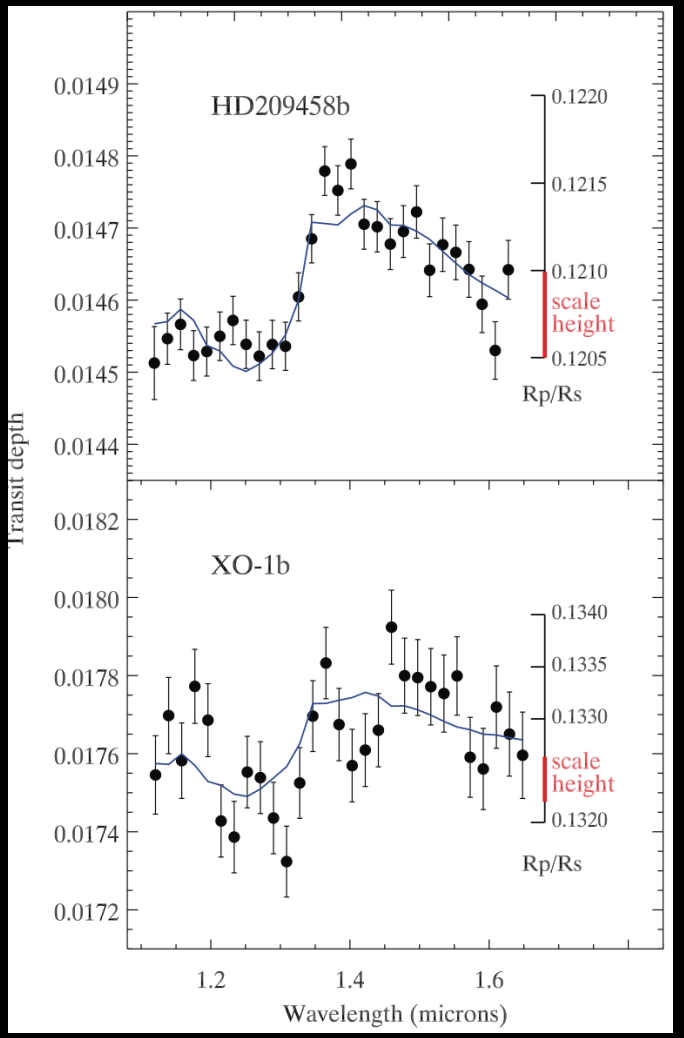
Line et al. (2013)



H_2O
Detected &
Spectral Resolved

Variety of Amplitudes
Clouds?
Hazes?
Low Abundances?

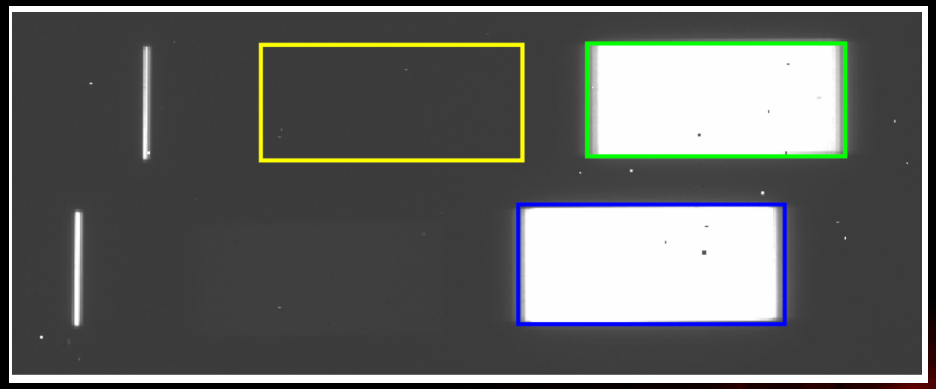
Deming et al. (2013)



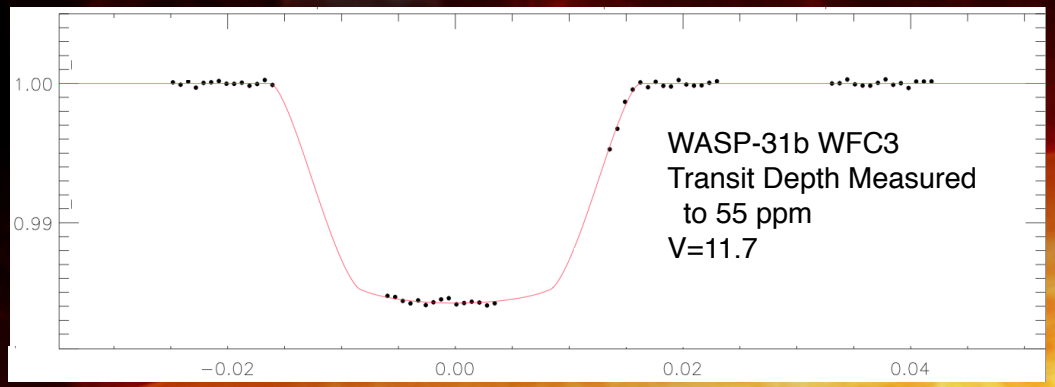
Spatial Scanning

HST WFC3 Scanning Mode: A little preview of JWST

- Spacial-scan drastically increases duty cycle
- Much higher S/N per image
- Systematics are common-mode, relative transit depths preserved (easy to reliably remove, no complex controversial de-trending required)

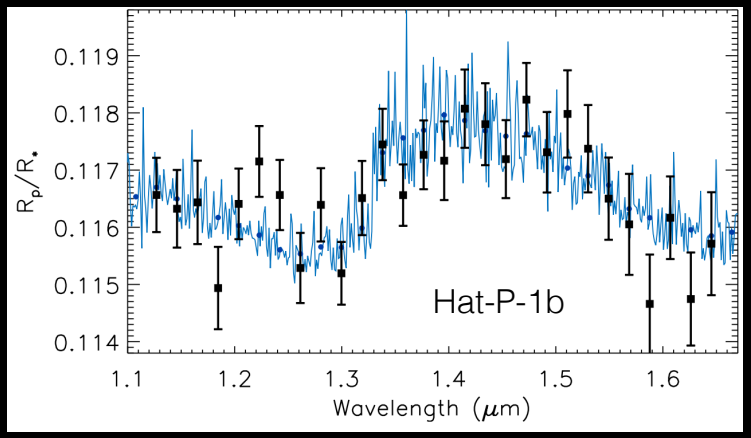


telescope slews in cross-dispersion direction during exposure



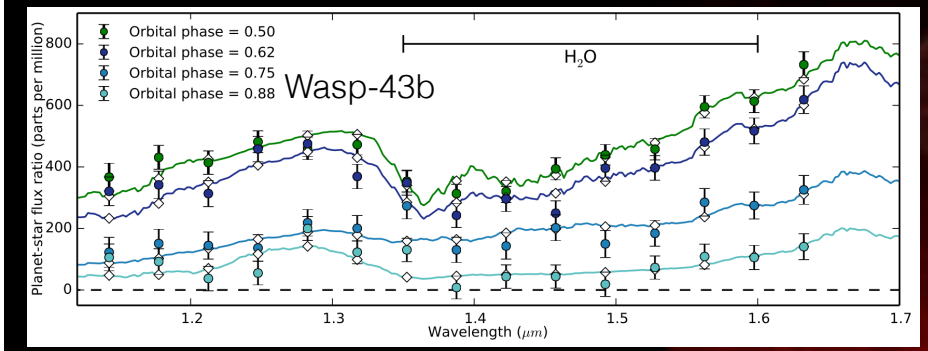
HST WFC3 Scanning Mode: A little preview of JWST

Wakeford et al. (2013)

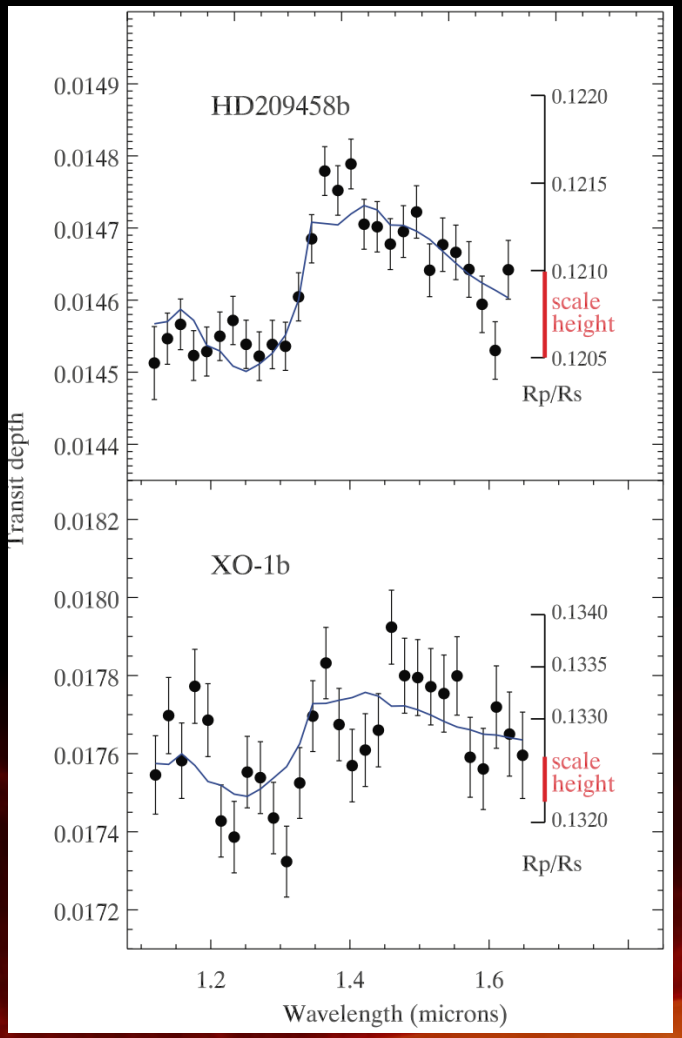


H_2O is Robustly Detected & Spectral Resolved
JWST will give access to Carbon Molecule Spectra

Stevenson et al. (2014)

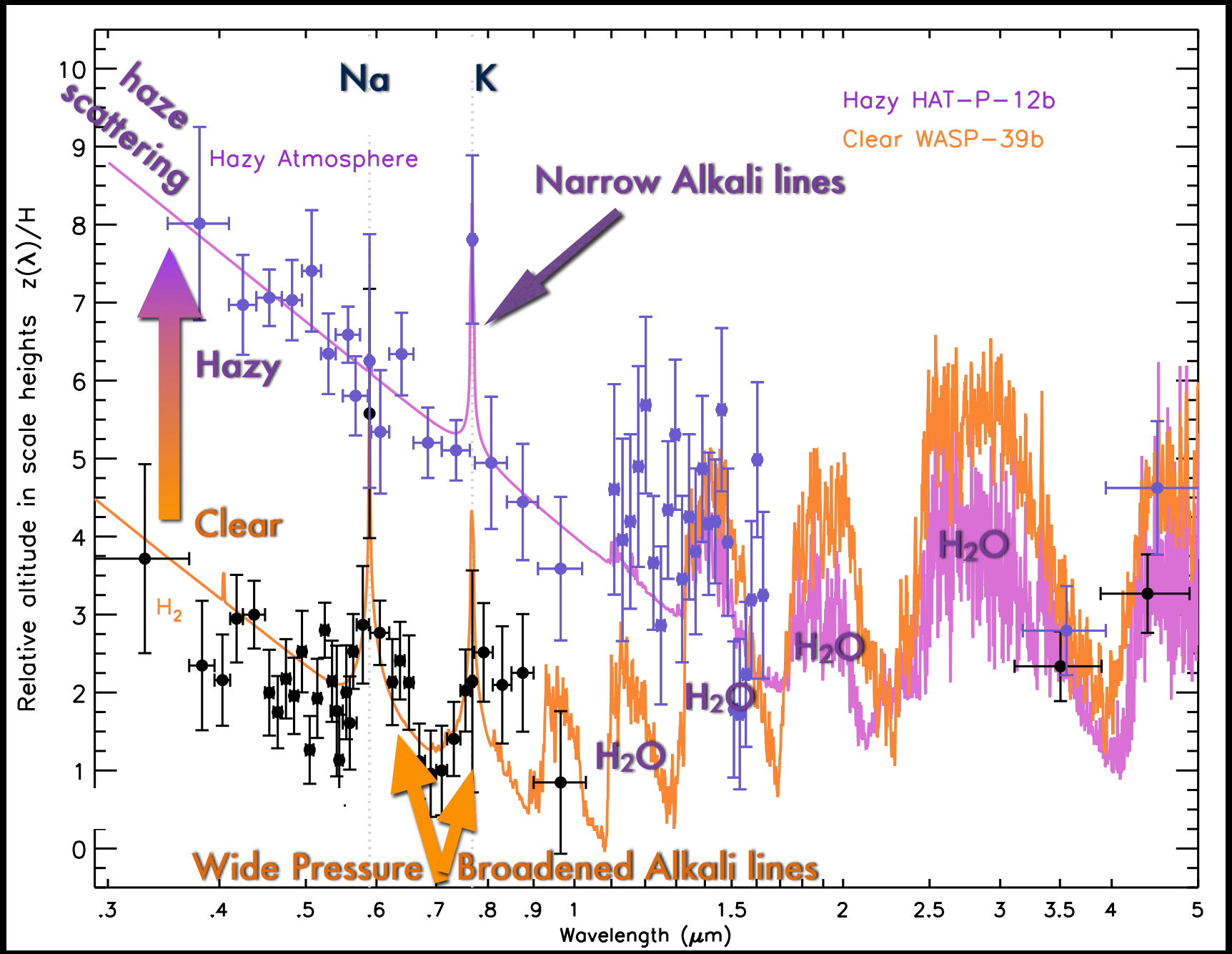


Deming et al. (2013)

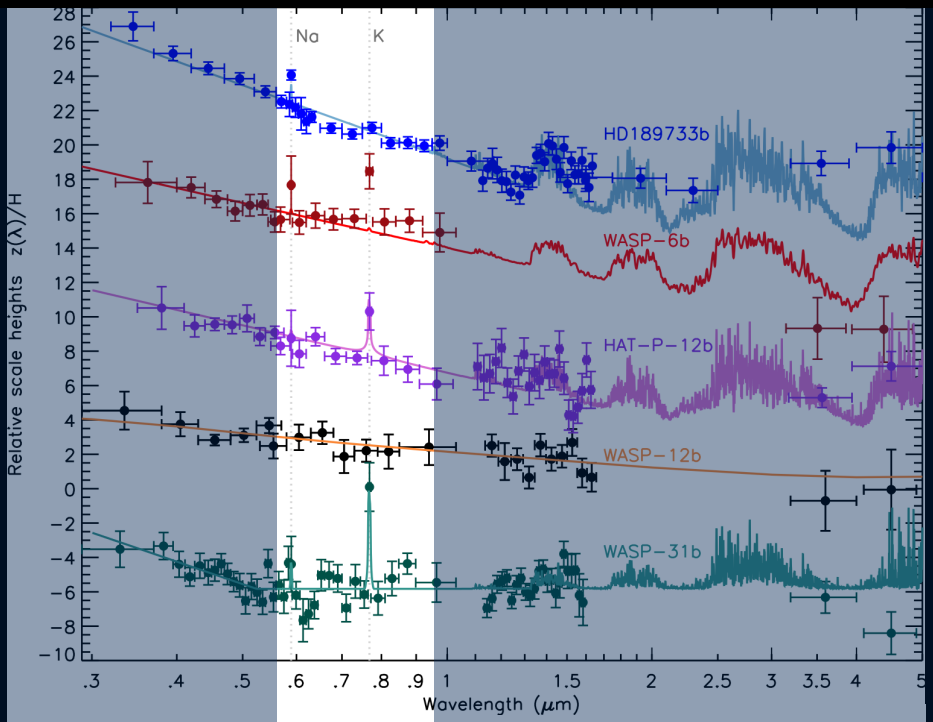


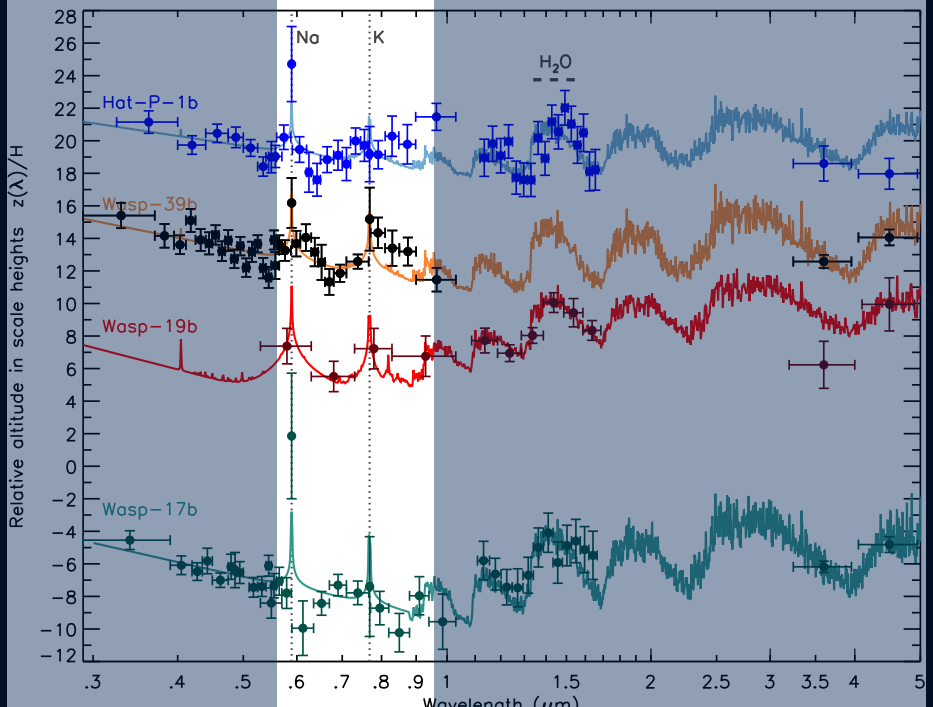
Spatial Scanning

Hazy vs Clear Hot Jupiter Atmospheres



Hot Jupiter Broadband Transmission Spectra





Clouds/Hazes a major distinguishing Characteristic for Hot Jupiters

Transmission Spectra ARE NOT FLAT!

HJ spectral challenge:

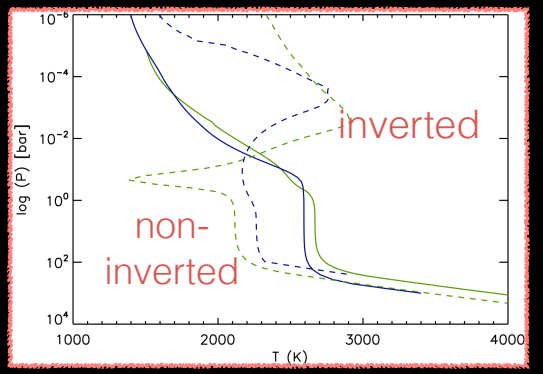
- narrow lines (need high res)
- muted features (need high S/N)
- many have scattering slopes (need broadband)

With multi-instrument data:

- need uniform analysis of system parameters, limb-darkening treatment
- otherwise significant shifts occur

Major Science Q's

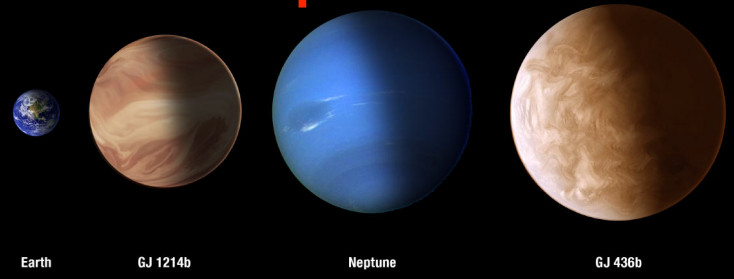
- Composition & Formation
  C/O? H_2O? Chem? Abundances?



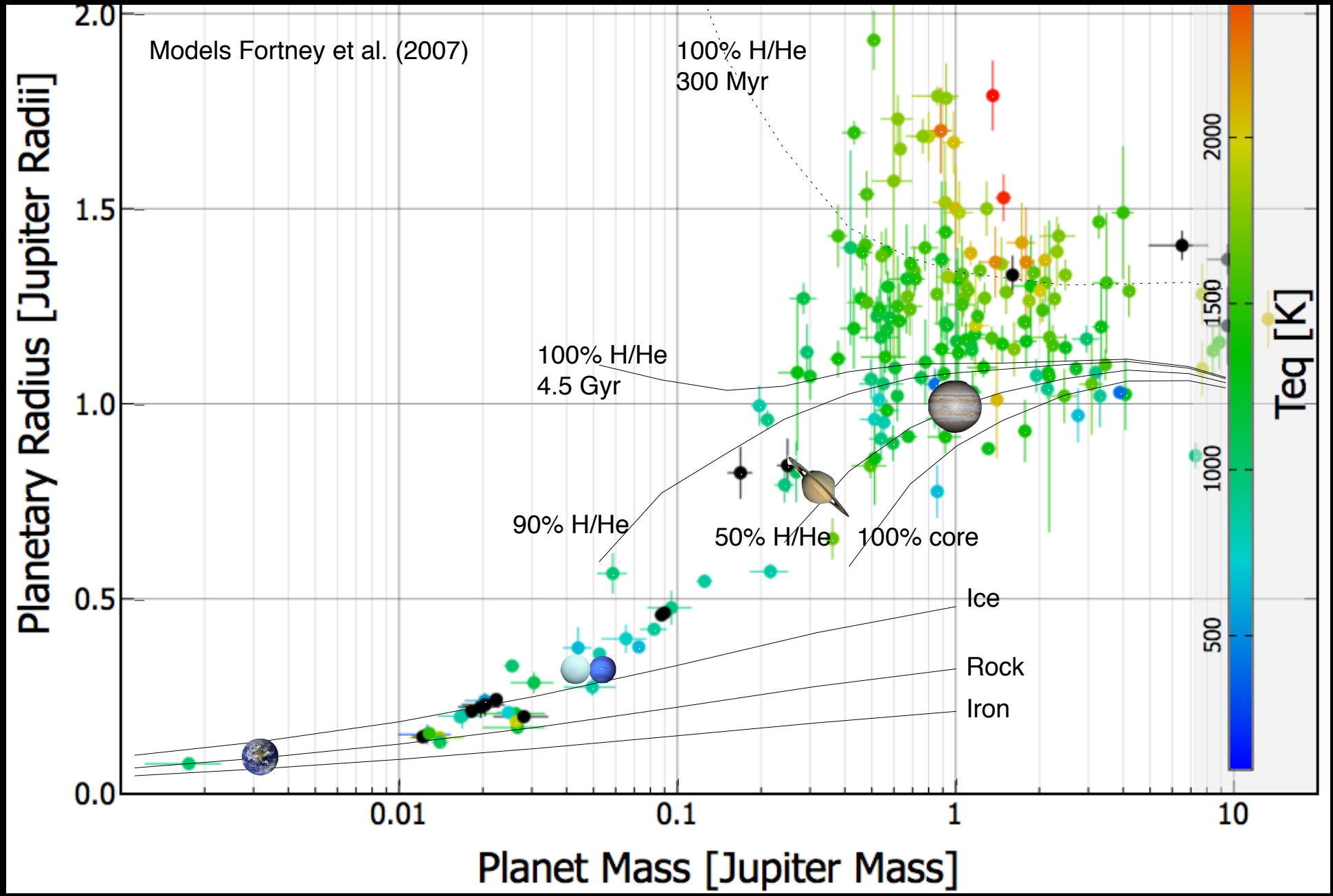
- Atmospheric Sciences
  Stratospheres? Wind profiles?
  Day/Night contrasts? Advection?

- Clouds & Hazes?

- Who's who: what are small planets made of?



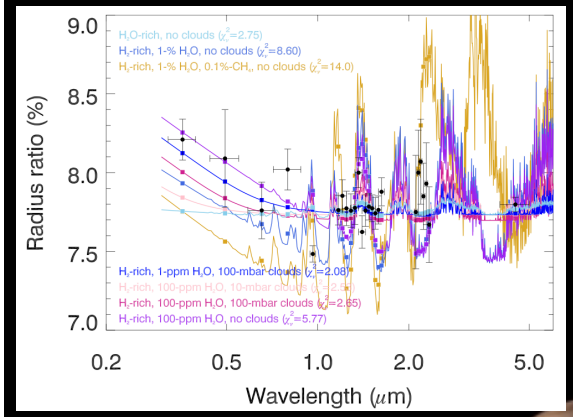
Small Exoplanets Who's Who?



Small Exoplanets

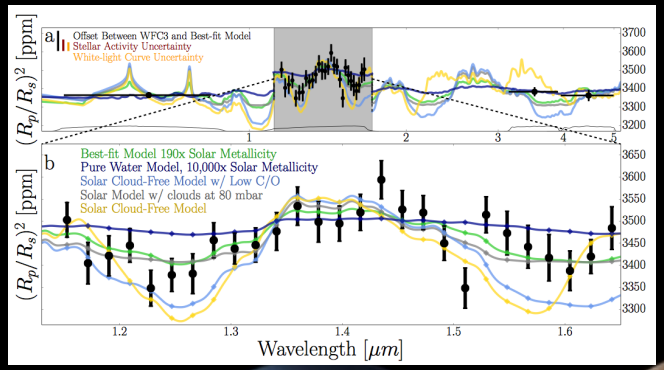
Who's Who? Flat spectra. High molecular weight or Clouds?

GJ3470b



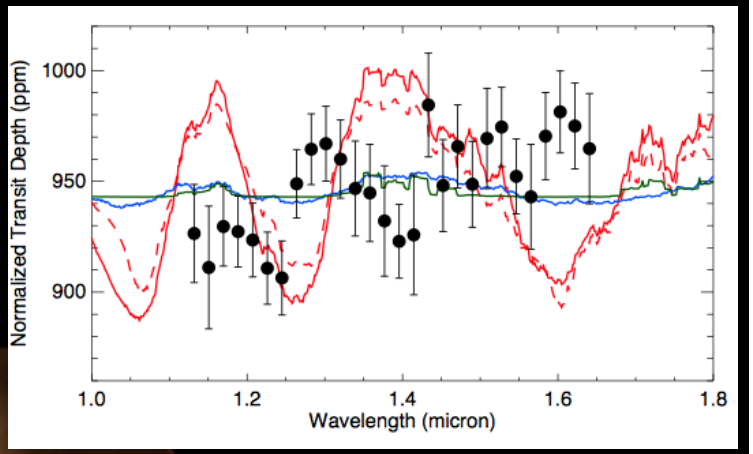
Ehrenreich et al. (2014)

Hat-P-11b

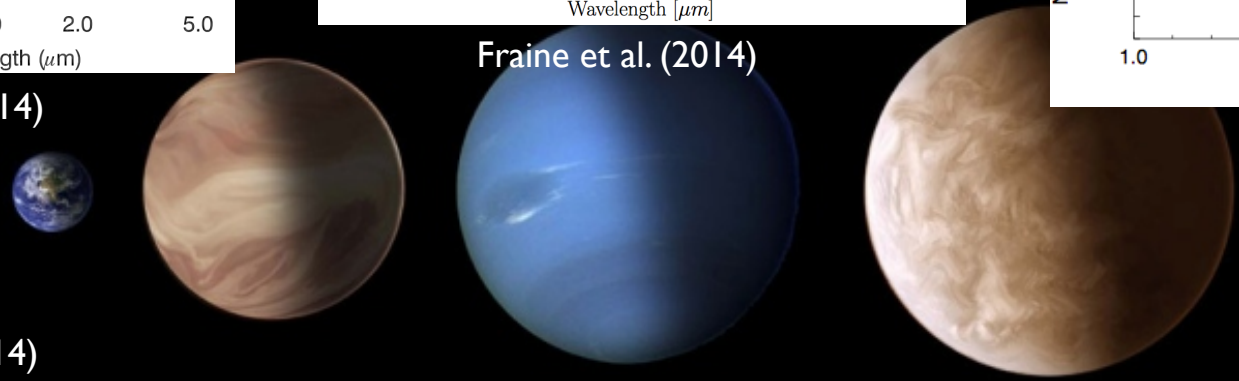


Fraine et al. (2014)

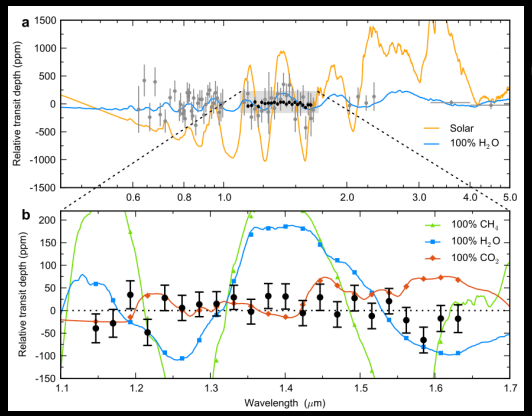
HD97658b



Knutson et al. (2014)



Kreidberg et al. (2014)



GJ 1214b

Neptune

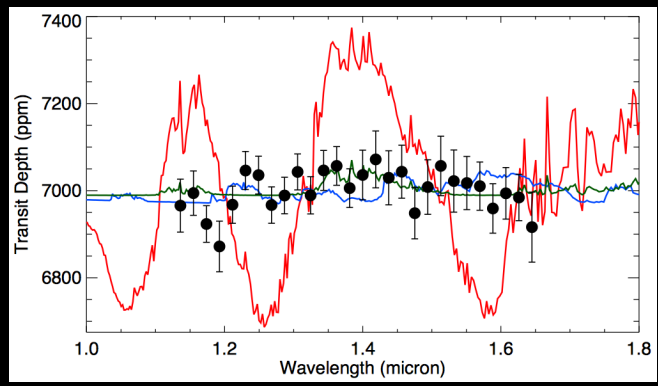
GJ 436b

Clouds covering features in many Super-Earths / hot Neptunes

or

H-poor

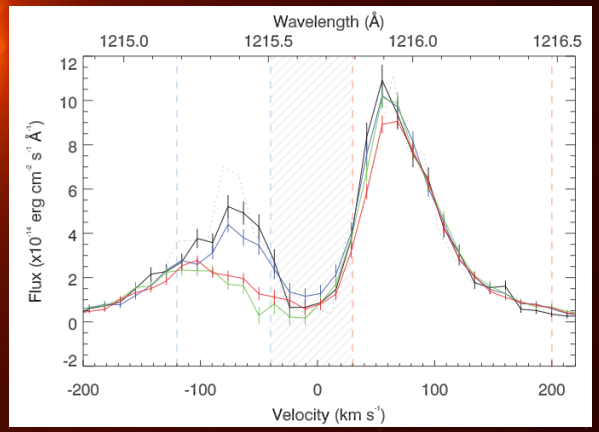
Knutson et al. (2014)

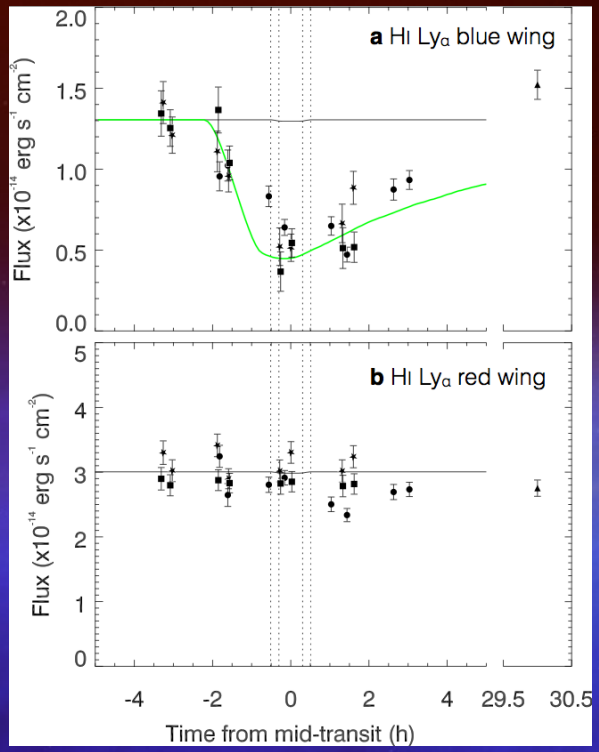


GJ436b

GJ1214b

A giant comet-like escape of GJ 436b





3 visits of HST STIS + Chandra
50% eclipse depth at Lyman alpha!
Extended tail observed

Could have lost ~10% of it's mass through escape

There is a substantial H atmosphere, but how much remains?

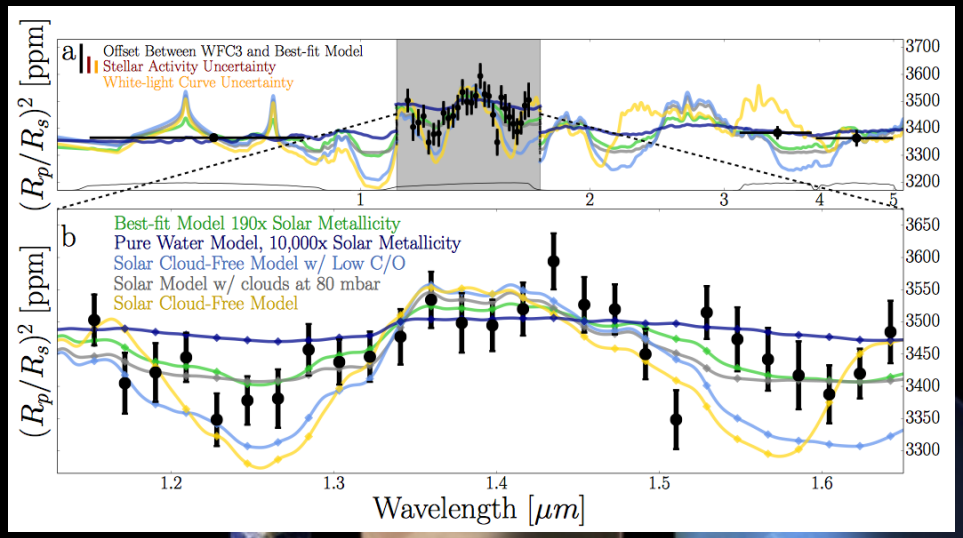
How much H is in the atmosphere of Nept/Super-E's.

Ehrenreich et al. (2015, Nature)

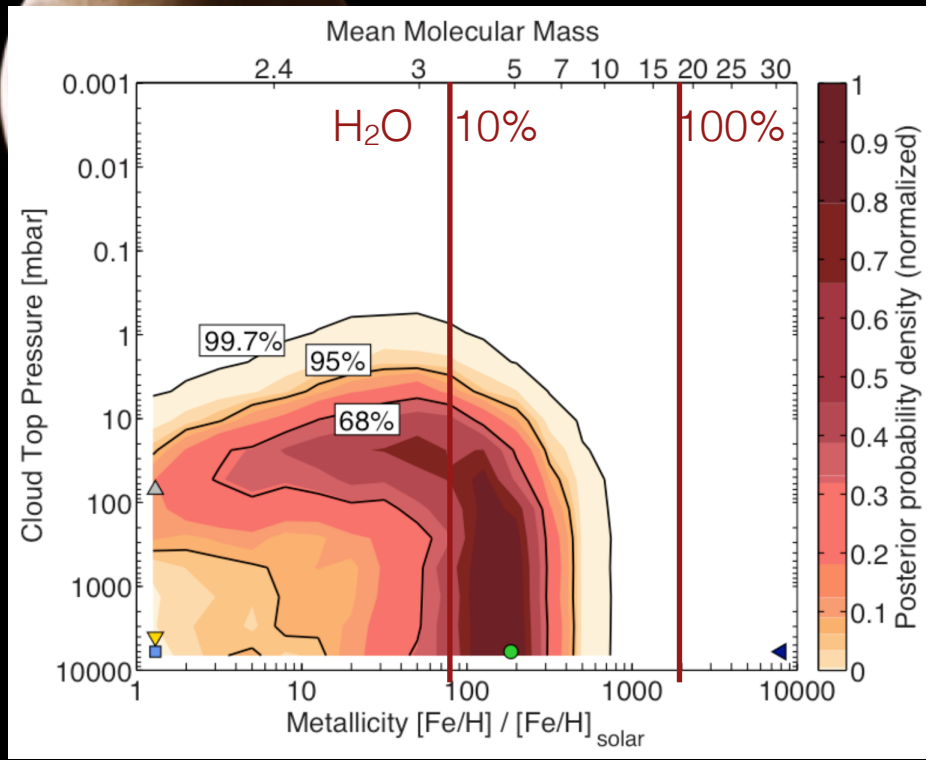
Small Exoplanets: Clouds & H_2O

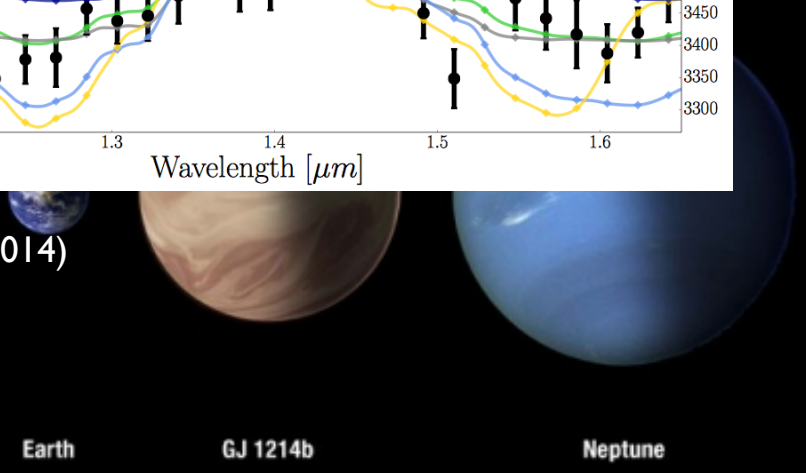
Who's Who? Flat spectra. High molecular weight or Clouds?

Hat-P-11b



Fraine et al. (2014)

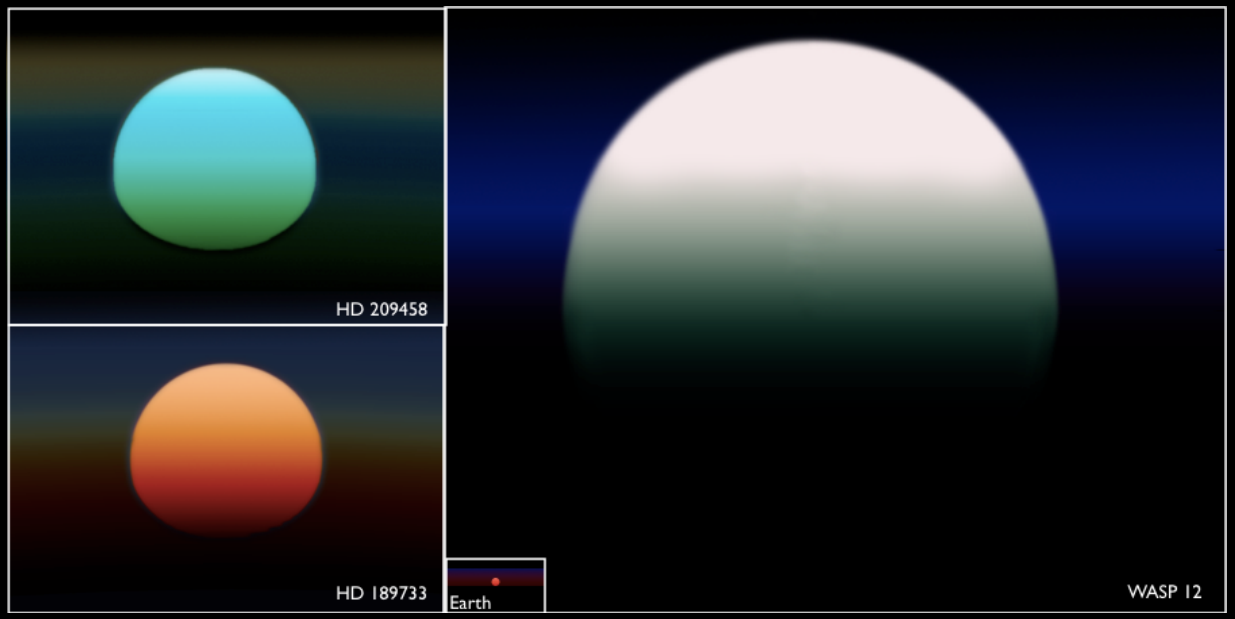


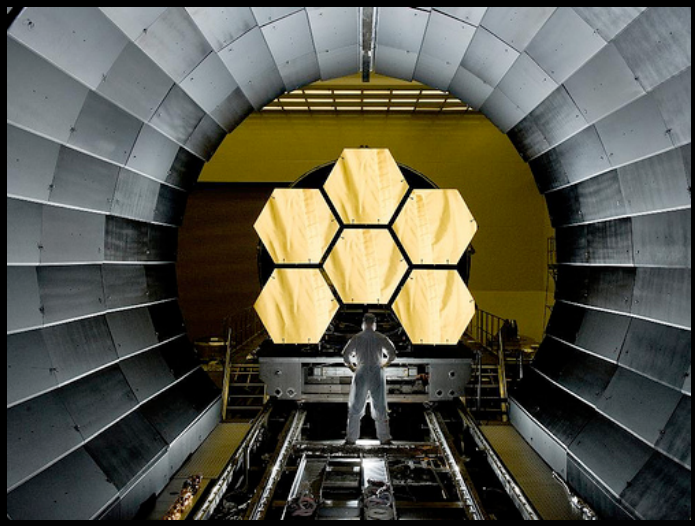


Features require significant H/He atmo.

1000's?! more of these with NGTS, TESS & PLATO

Looking forward





jwst.nasa.gov

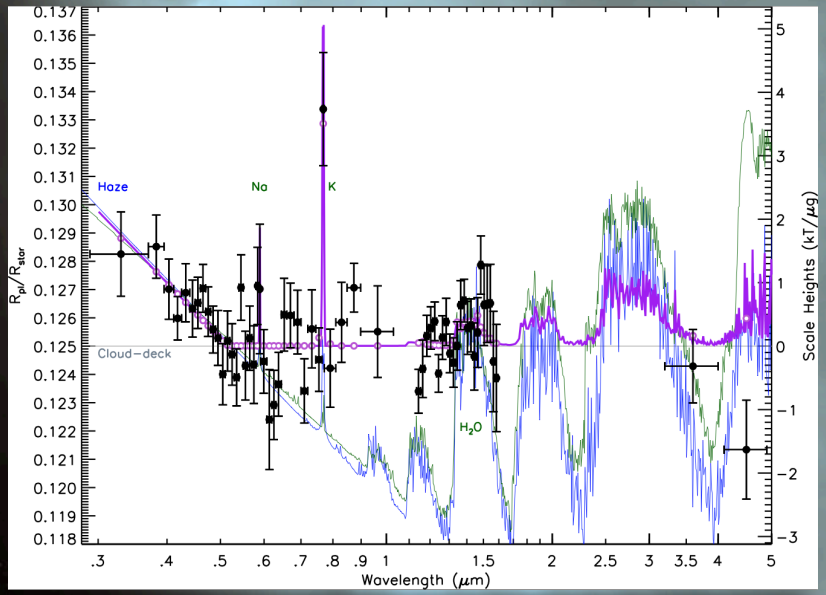
JWST

4 orders of magnitude improvement for atmospheric transit work

precision: 15x HST

resolution, wave coverage, new planets

What do we do with cloudy planets??
WASP-31b: Clouds Haze & K



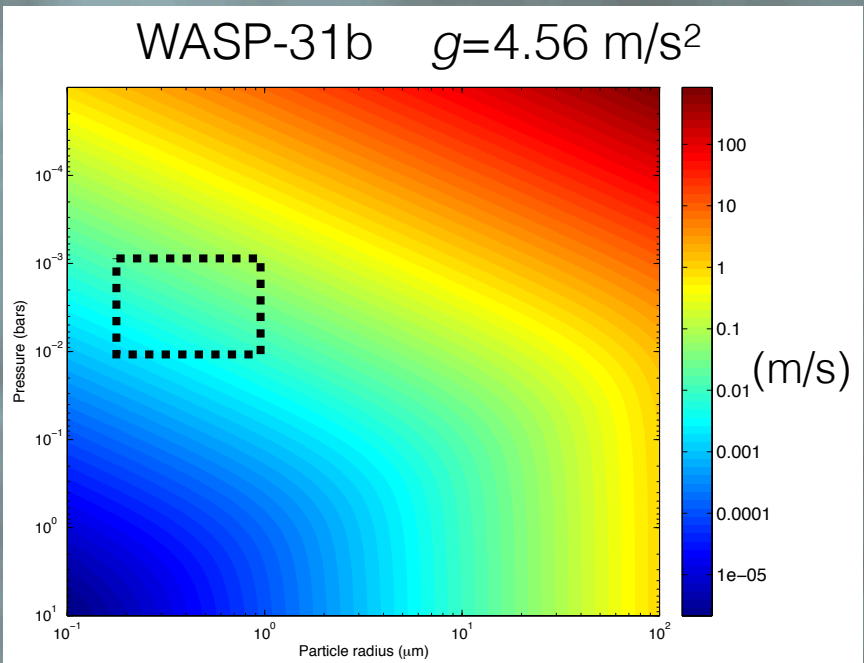
Mie Scattering Fit

Particle size ~0.5 um

K profile Fit (broadening)

Pressure ~ 1 to 10 mbar

Sing et al. (2015)



Spectral Constraints

K_{zz}~10^{-4} m^2 s^{-1} at 10 mbar

K_{zz}~10^{-5} m^2 s^{-1} at 1 mbar

Atmo. Circulation can mix particles upward to 1–10 mbar. Need 3D Global Circulation Models

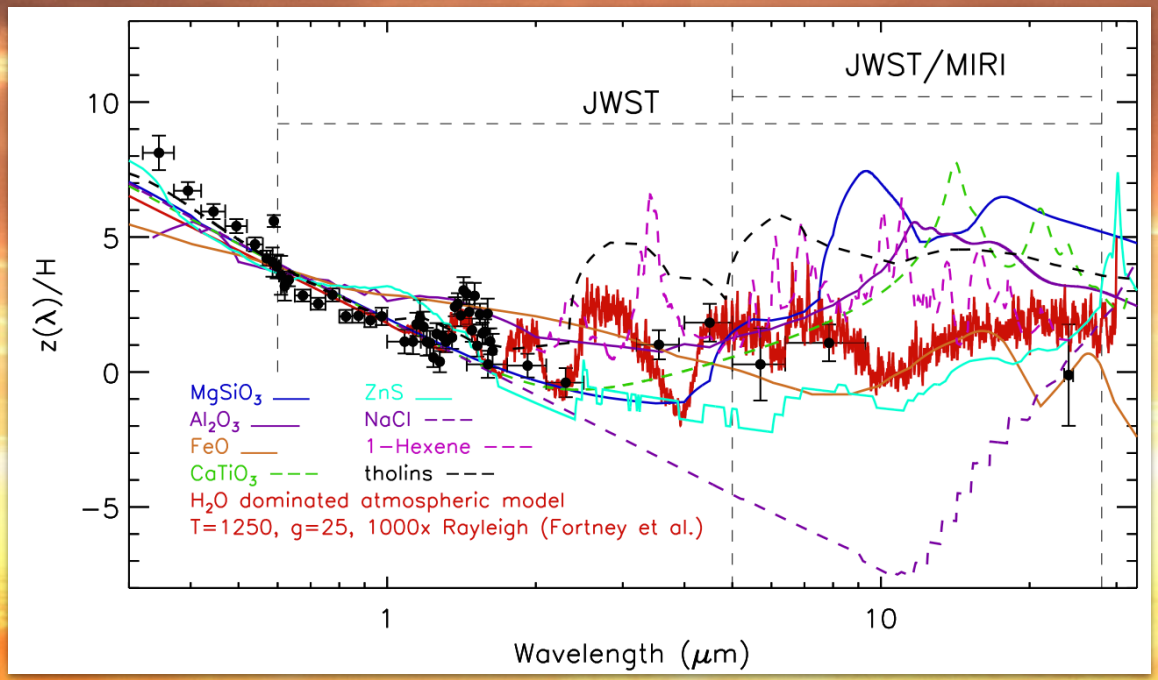
Theoretical Expectation

Parmentier et al. (2013)

K_{zz}~10^{-5} m^2 s^{-1} at 10 mbar

K_{zz}~10^{-6} m^2 s^{-1} at 1 mbar

Transmission Spectra Properties of clouds & hazes



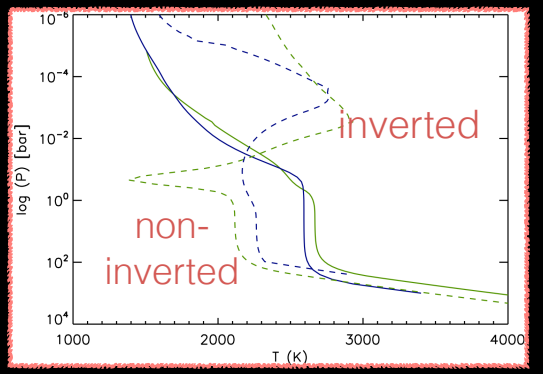
Wakeford & Sing (2015)

- JWST Can constrain basic cloud composition with MIRI
- Condensation vs. Photo-Chemistry

  Si-O C-H

Conclusions

- **Composition & Formation**
  Loose constraints now but, all techniques are getting there.



- **Atmospheric Sciences**
  Strong leverage on entire profile and winds

- **Clouds & Hazes?**
  JWST can detect cloud species. Transit spectra can constrain relevant parameters

- **Who's who: what are small planets made of?** I don't know.
  but with TESS/NGTS/JWST it will be fun finding out.

New Post in Exeter

Lecturer in Astrophysics (tenure track)

Open to all areas of exoplanets

https://jobregister.aas.org/job_view?JobID=51185

Applications due 31 July

EXOCLIMES 2016
1-4 Aug
Squamish Canada