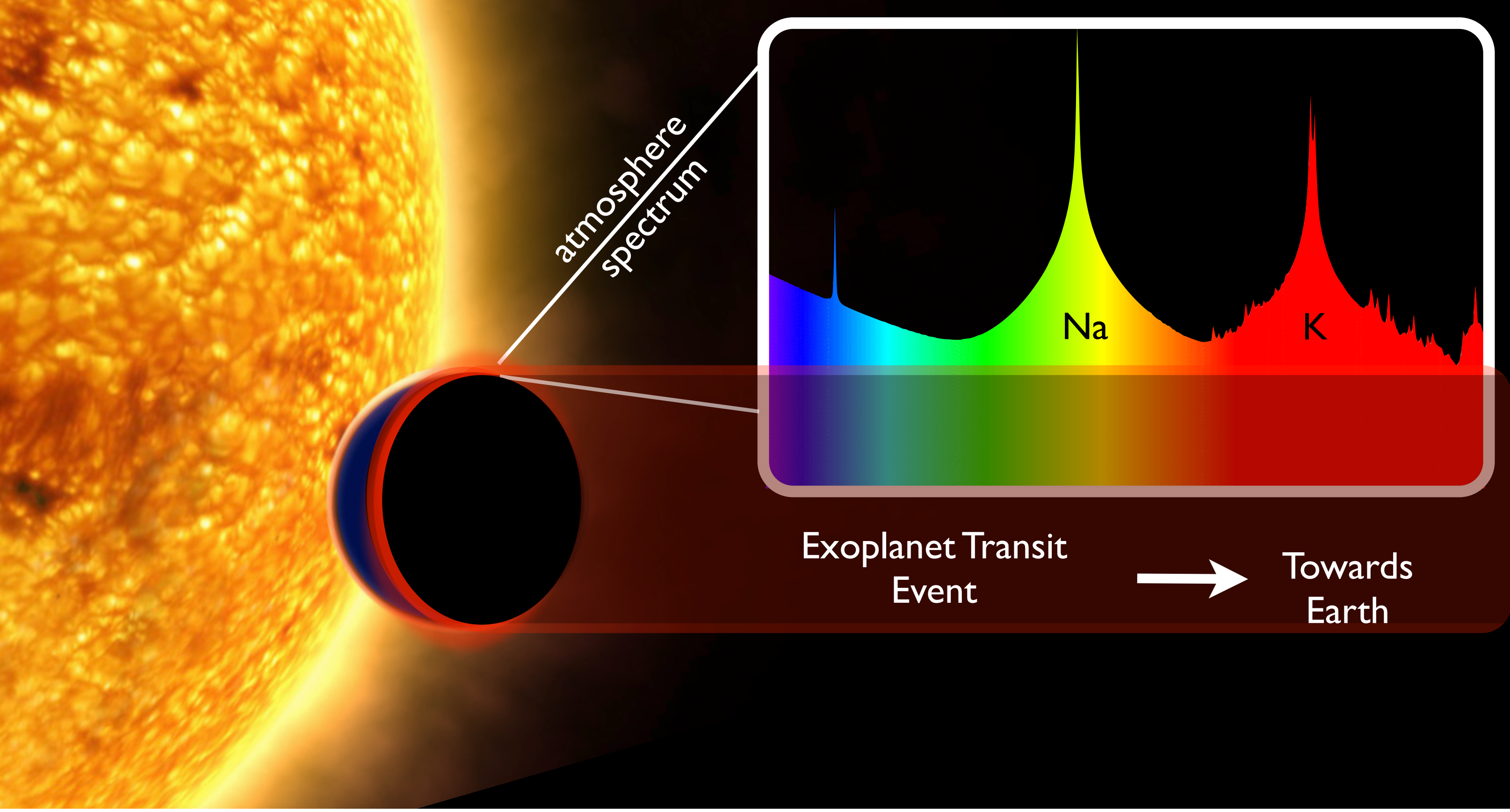
How do we study the atmospheres of transiting exoplanets?

Prof. David Sing

Johns Hopkins University



How do we study the atmospheres of transiting exoplanets?

Outline

- What are the basic signals we can observe (transit, eclipse, phase curve)?
- What can we learn from them? How do they work?
- Planning Transit Observations. How does photon noise affect observations of transiting planets?
- What are other instrumental or astrophysical sources of noise to be aware of?

Reviews

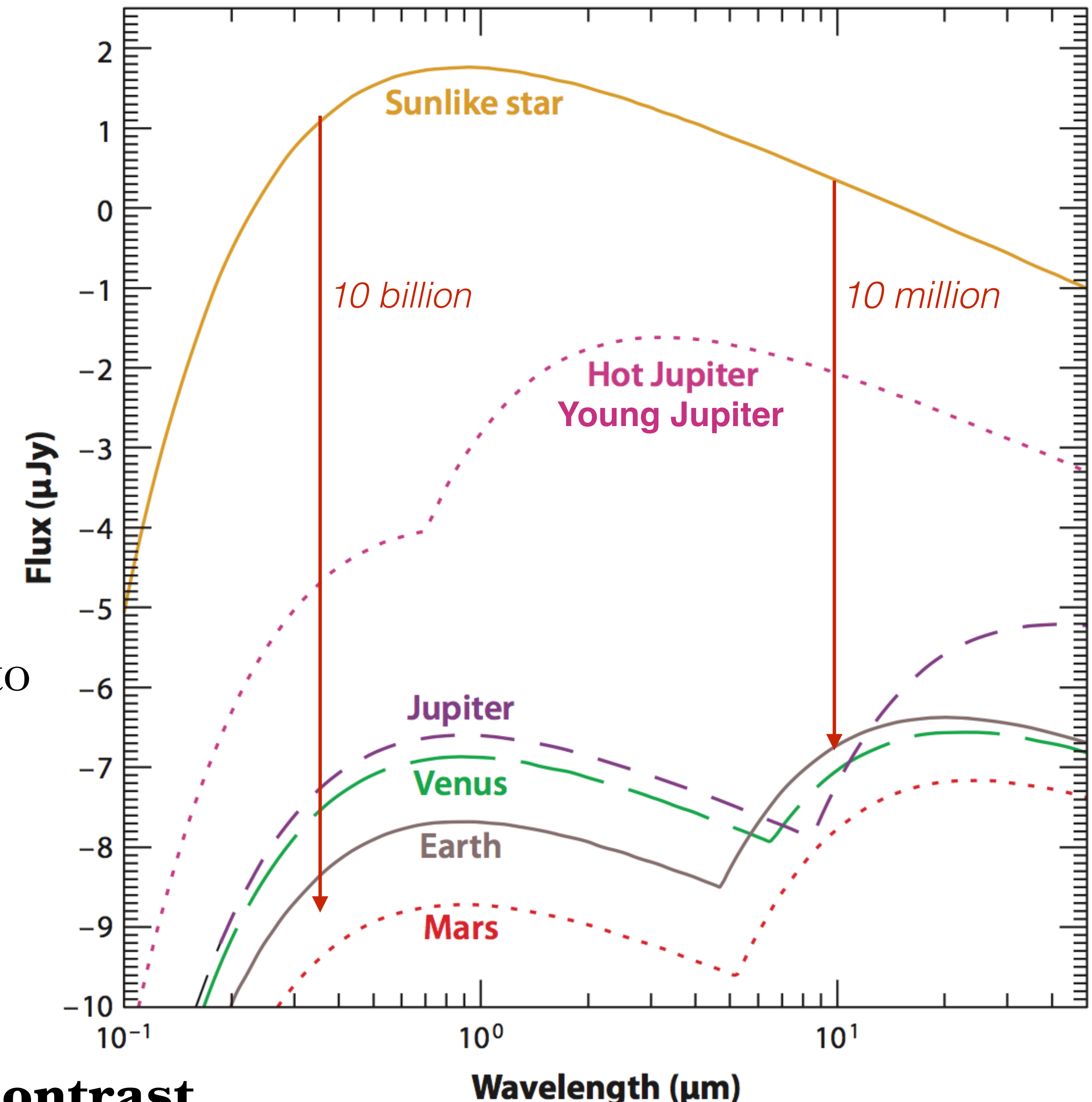
Observational Techniques With Transiting Exoplanetary Atmospheres	Sing (2018)	https://arxiv.org/pdf/1804.07357.pdf
How to Characterize the Atmosphere of a Transiting Exoplanet	Deming et al. (2019)	https://arxiv.org/pdf/1810.04175.pdf
Exoplanet Atmosphere Measurements from Transmission Spectroscopy and Other Planet Star Combined Light Observations	Kreidberg (2018)	https://arxiv.org/pdf/1709.05941.pdf
Observations of Exoplanet Atmospheres	Crossfield (2015)	https://arxiv.org/pdf/1507.03966.pdf
Transits and Occultations	Winn (2010)	https://arxiv.org/pdf/1001.2010.pdf

- Ask Questions in the chat
- Questions/discussion after in breakout rooms

Basic Challenge:
1) Star Outshines a Nearby Planet by Many Orders of Magnitude. Need Planet/Star *Flux Contrast*

AND

2) is located very Close to the host star. Need Planet/Star *Separation Contrast*



Difficult Problem of Contrast, Separating Star and Planet Signal

Seager - *Exoplanet Atmospheres*

<u>Basic Challenge</u>:

1) is located very <u>Close</u> to the host star.

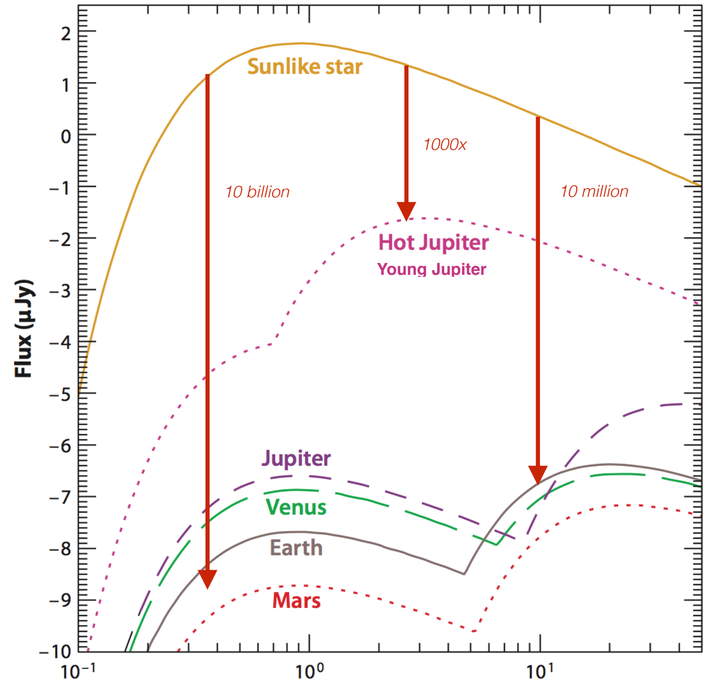
Need Planet/Star

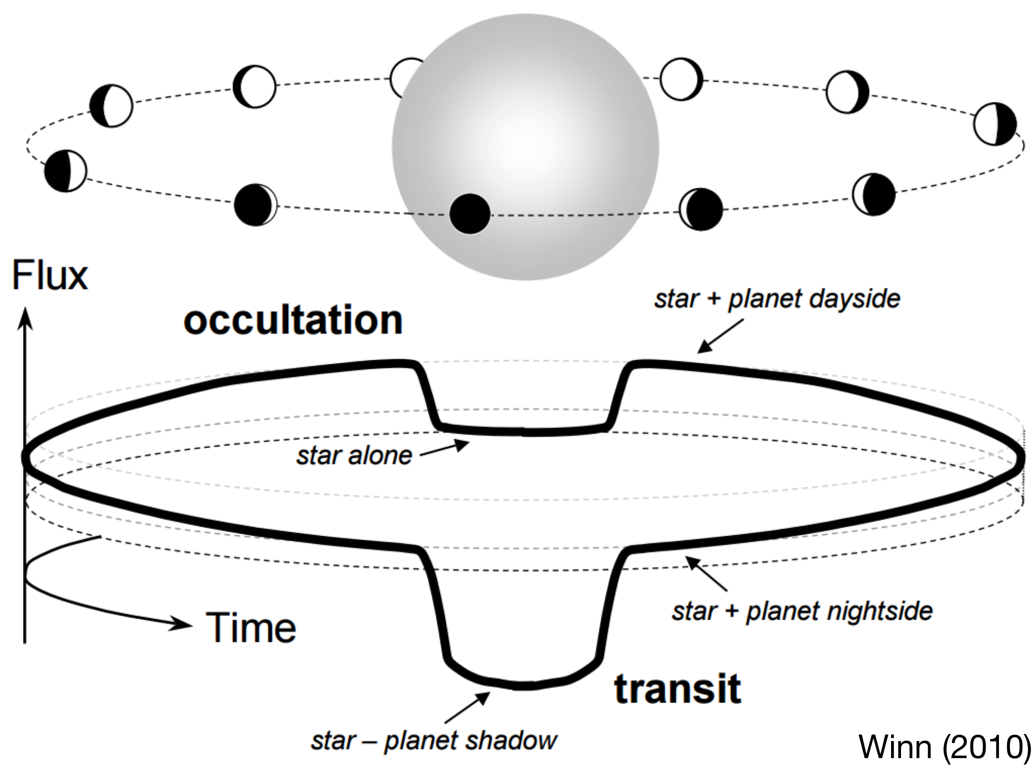
Separation Contrast

<u>Solutions:</u>

1) Direct Imaging; Look for the widest-separation hottest nearest planets

2) Separate the Star/Planet light not spatially but in Time





Can Separate Atmosphere in 3 Dimensions $\hat{t}$ $\hat{x}, \hat{y}$ $\hat{\lambda}$

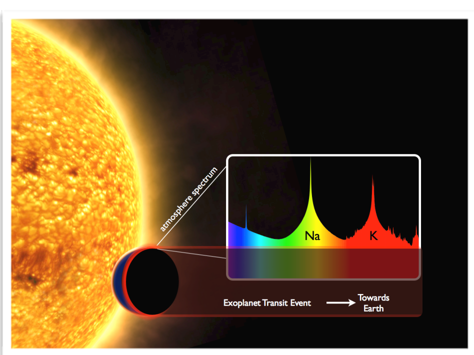
Exoplanet Atmosphere Spectra

$\hat{t}$ Transits

Close-In Planets

Atmo. Composition
Clouds/Hazes
Thermal profile
- Stratospheres
- Thermospheres
- Exospheres

Escape
Dynamics, Winds
Chemistry

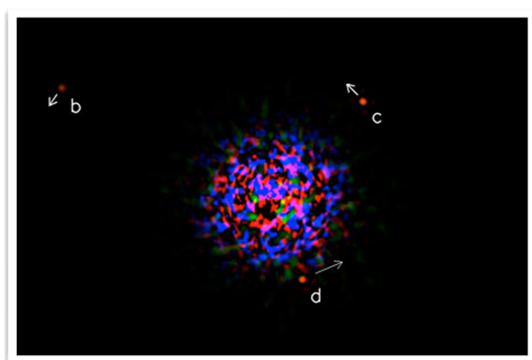


$\hat{x}, \hat{y}$ Direct Imaging

Wide-Separations

Atmo. Composition
Clouds/Hazes
Thermal profile

Dynamics
Chemistry

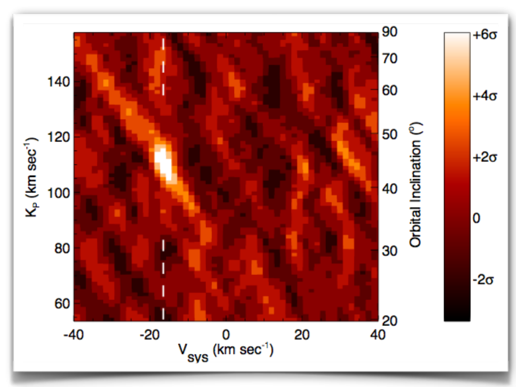


$\hat{\lambda}$ Radial Velocity

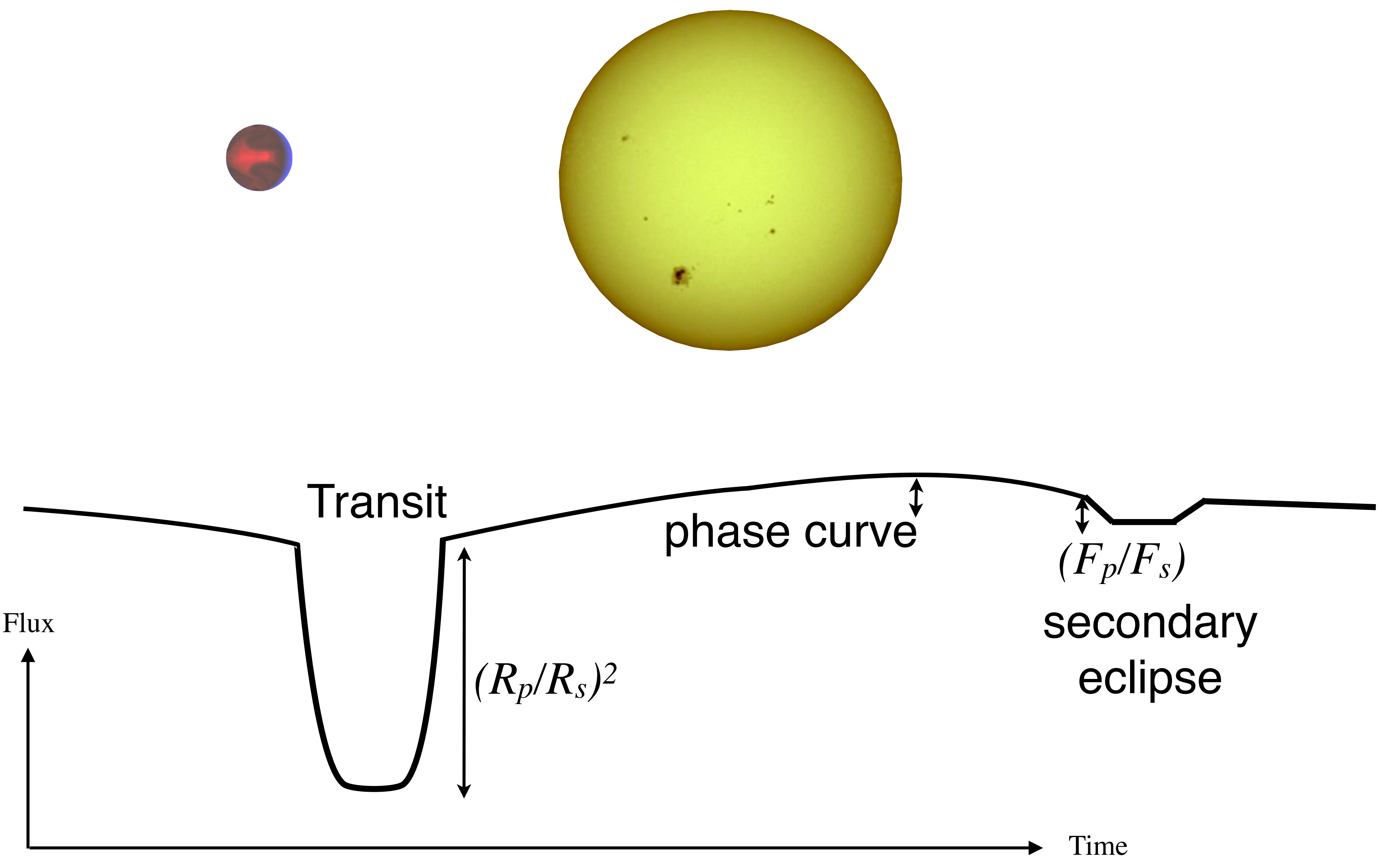
Bright Targets

Atmo. Composition
Clouds/Hazes
Thermal profile
- Stratospheres
- Thermospheres

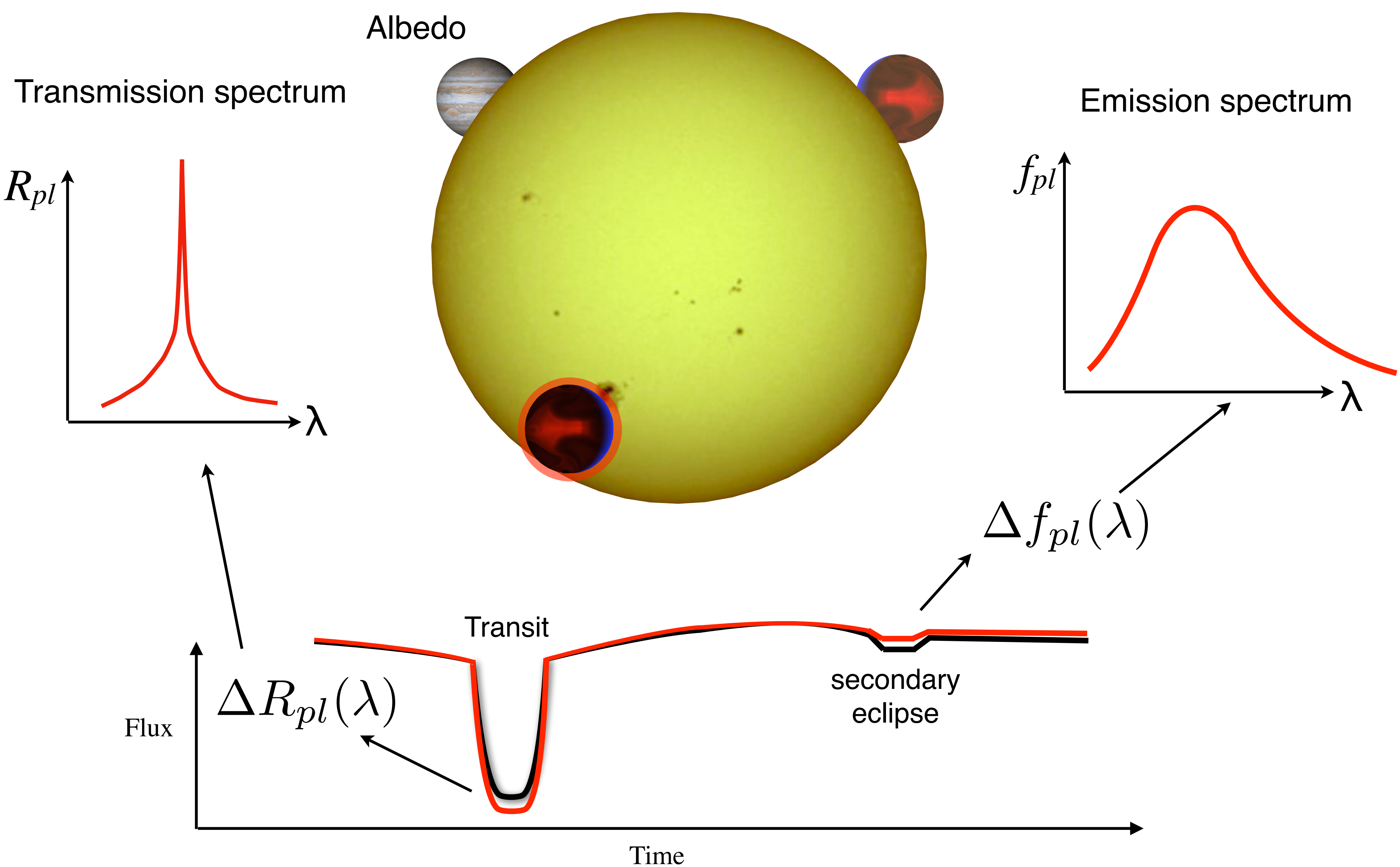
Escape
Dynamics, Winds
Chemistry



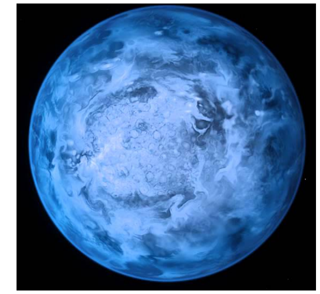
Exoplanet Light Curve
Transit, Eclipse, Phase Curve



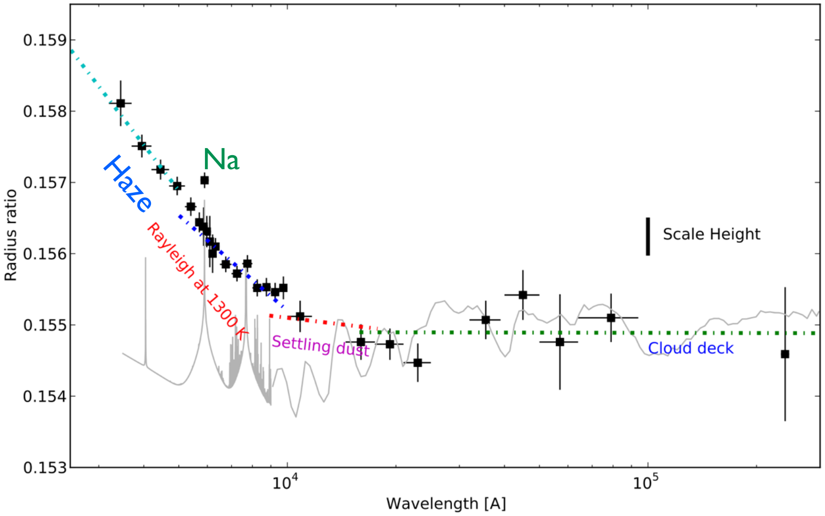
Exoplanet Spectra



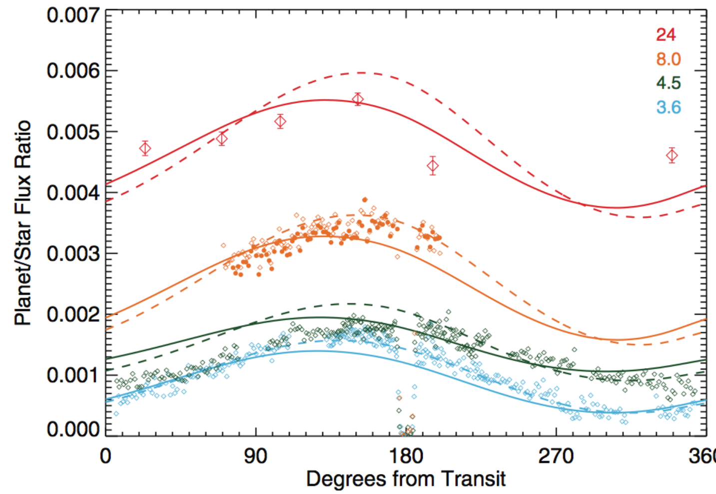
3 Techniques in Action: Benchmark HD 189733b



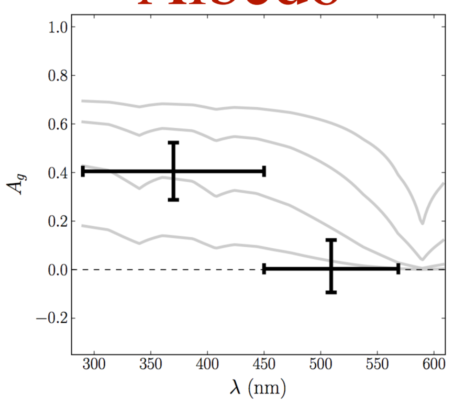
Transmission



Phase Curve



Albedo



Composition: Na, H_α, H_2O and CO

Aerosol Haze

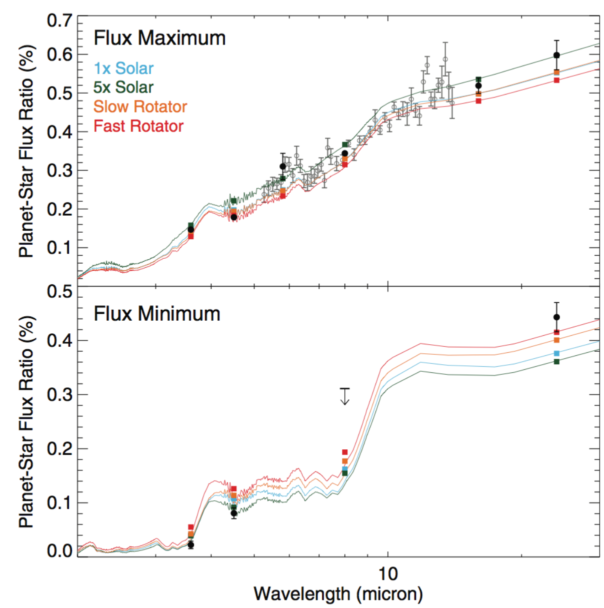
'blue planet'

Offset Hot Spot - 'Jets'

Efficient heat re-distribution

Much more…

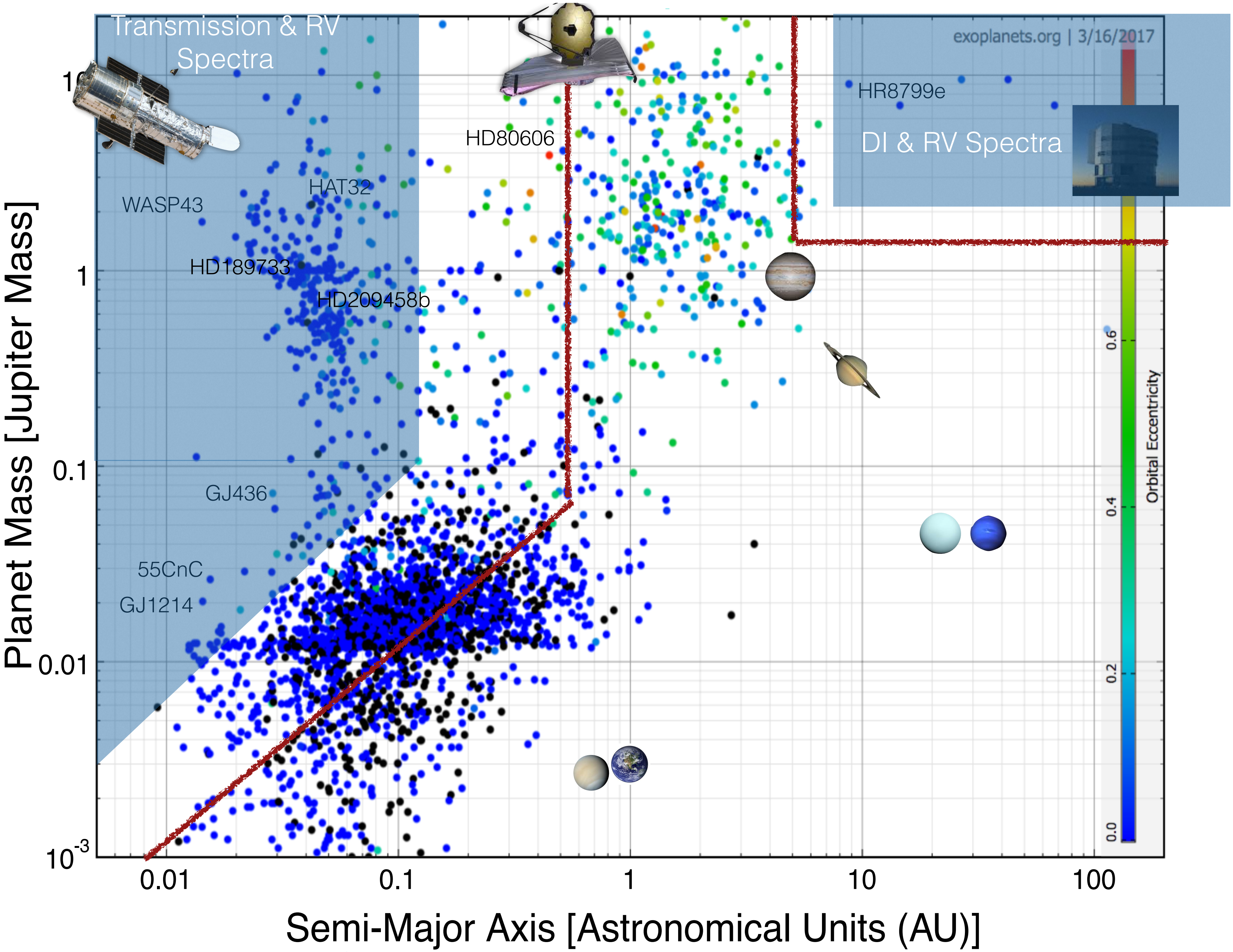
Emission



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)

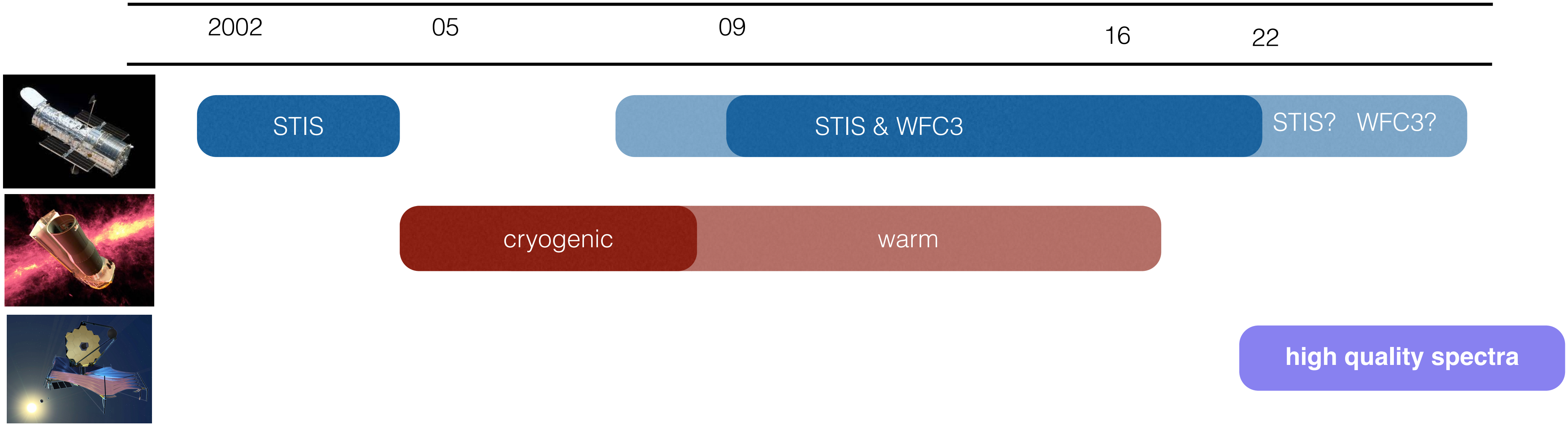
Birkby et al. (2013)
Desert et al. ('09,'11)
Agol et al. (2010)
Gibson et al. ('11,'12)
Huitson et al. (2012)
Evans et al. (2013)

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



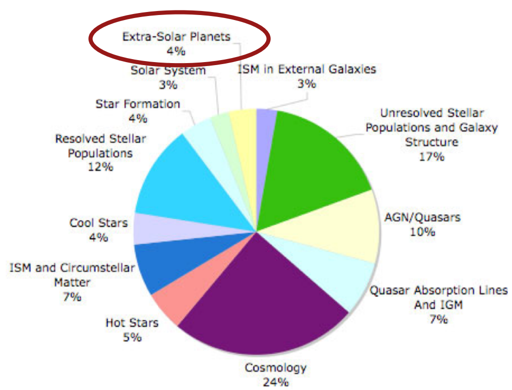
Transmission & RV Spectra
exoplanets.org | 3/16/2017
HR8799e
DI & RV Spectra
HD80606
HAT32
WASP43
HD189733
HD209458b
GJ436
55CnC
GJ1214
Planet Mass [Jupiter Mass]
Semi-Major Axis [Astronomical Units (AU)]
Orbital Eccentricity
0.0
0.2
0.4
0.6
10
1
0.1
0.01
10^-3
0.01
0.1
1
10
100

Transiting Exoplanet Atmospheres in Space



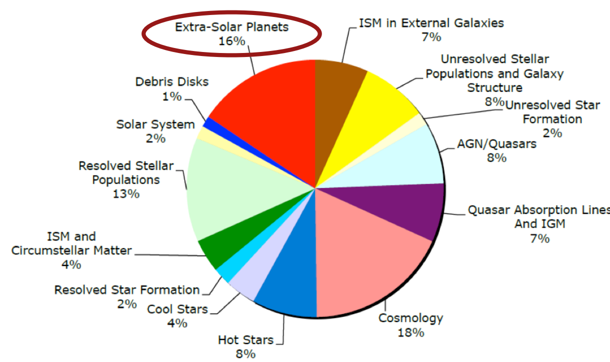
4%

2008 HST Science Category by Orbits



16%

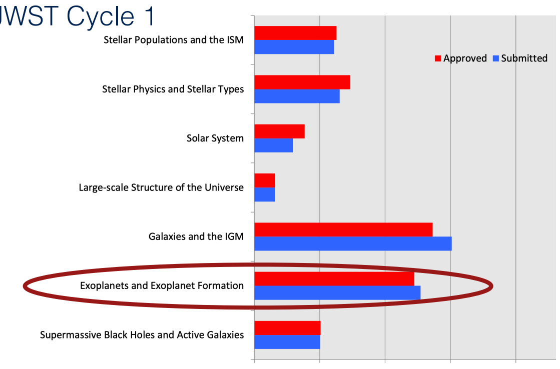
2015 HST Science Category by Orbits



25%

Science Category Distribution for Proposals

JWST Cycle 1

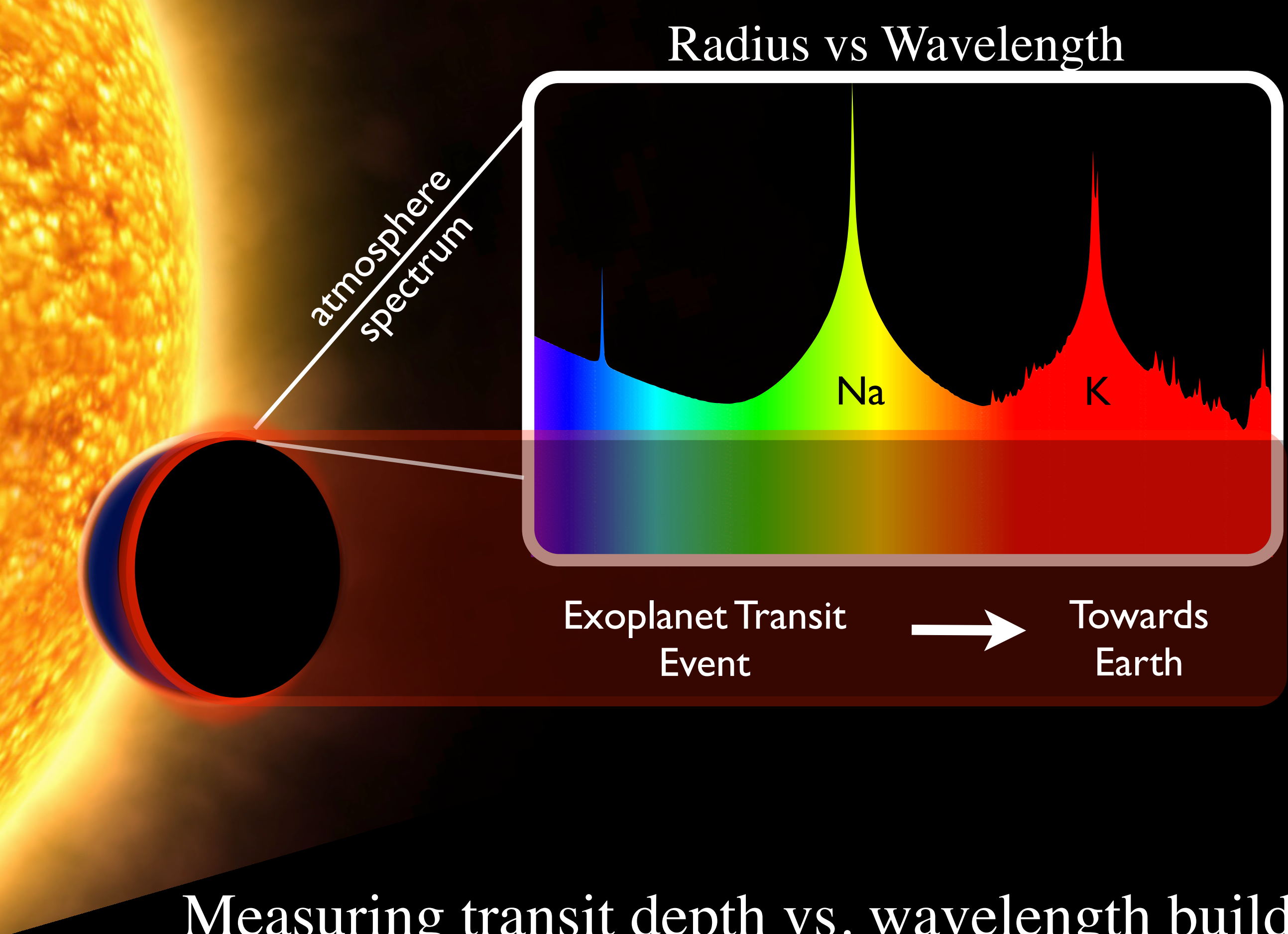


http://www.stsci.edu/institute/stuc/

Exoplanets now one of the biggest Astro Fields, multiple multi-Million (billion?) dollar space missions

Transmission Spectra Basics

How? Species in the atmosphere absorb/scatter leading to larger radius at characteristic wavelengths. Planet radius is wavelength dependent. Absorption Spectra



slant transit geometry

Measuring transit depth vs. wavelength builds up **transmission spectrum**.

Observable Transiting Exoplanets - Transmission Spectra

Several Hundred Transiting Exoplanets. Some good for spectroscopy, others more difficult.

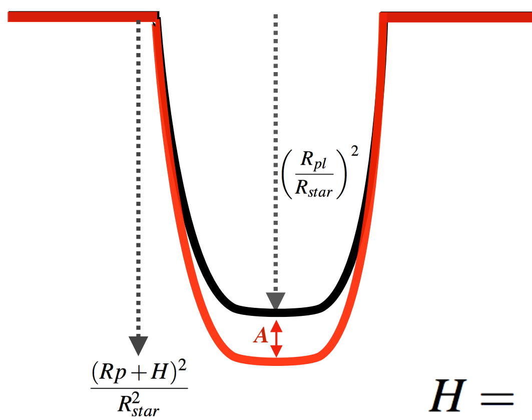
Estimate Transmission Spectra Signal. Contrast in area ***A*** between the annular region of the atmosphere and Star

$$A = \frac{(Rp+H)^2}{R_{star}^2} - \left(\frac{R_{pl}}{R_{star}}\right)^2$$

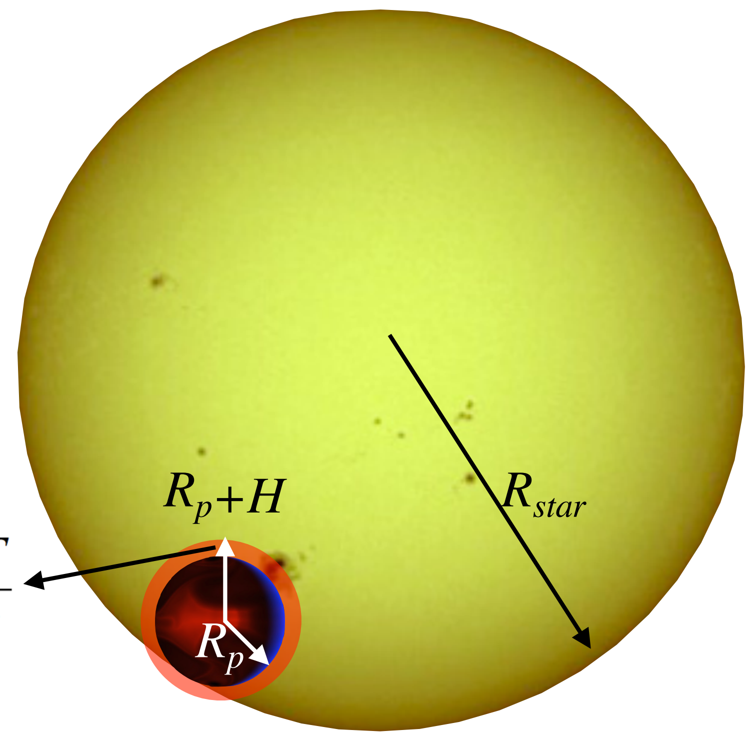
assuming $H << R_{pl}$

$$\boxed{A = \frac{2R_{pl}H}{R_{star}^2}}$$

Transit Light Curve



$$H = \frac{k_B T}{\mu g}$$



Assume: Signal is about 1 Pressure Scale Height

Planet is equilibrium temperature $T_{eq} = (1/4)^{1/4} T_{eff} \sqrt{\frac{R_{star}}{a}}$

For Giant Planets, atmosphere dominated by a H/He mixture of near-solar composition, which gives mean mass $\mu = 2.3 \times u$

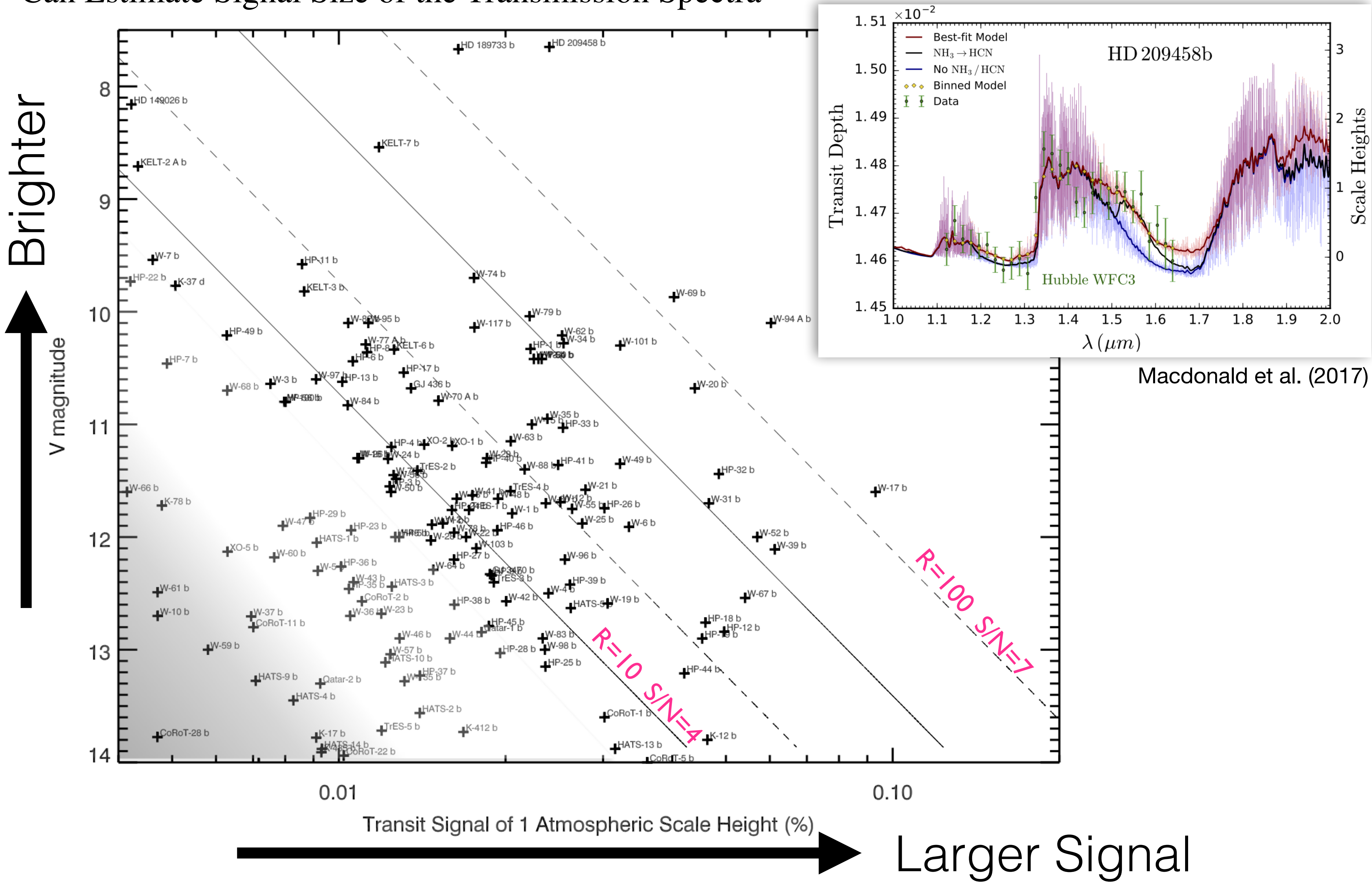
u is the unified atomic mass unit

Planet	A (ppm)
HD189733b	150 H_2
HD209458b	200 H_2
HAT-P-26b	230 H_2
Trappist-1b	18 CO_2

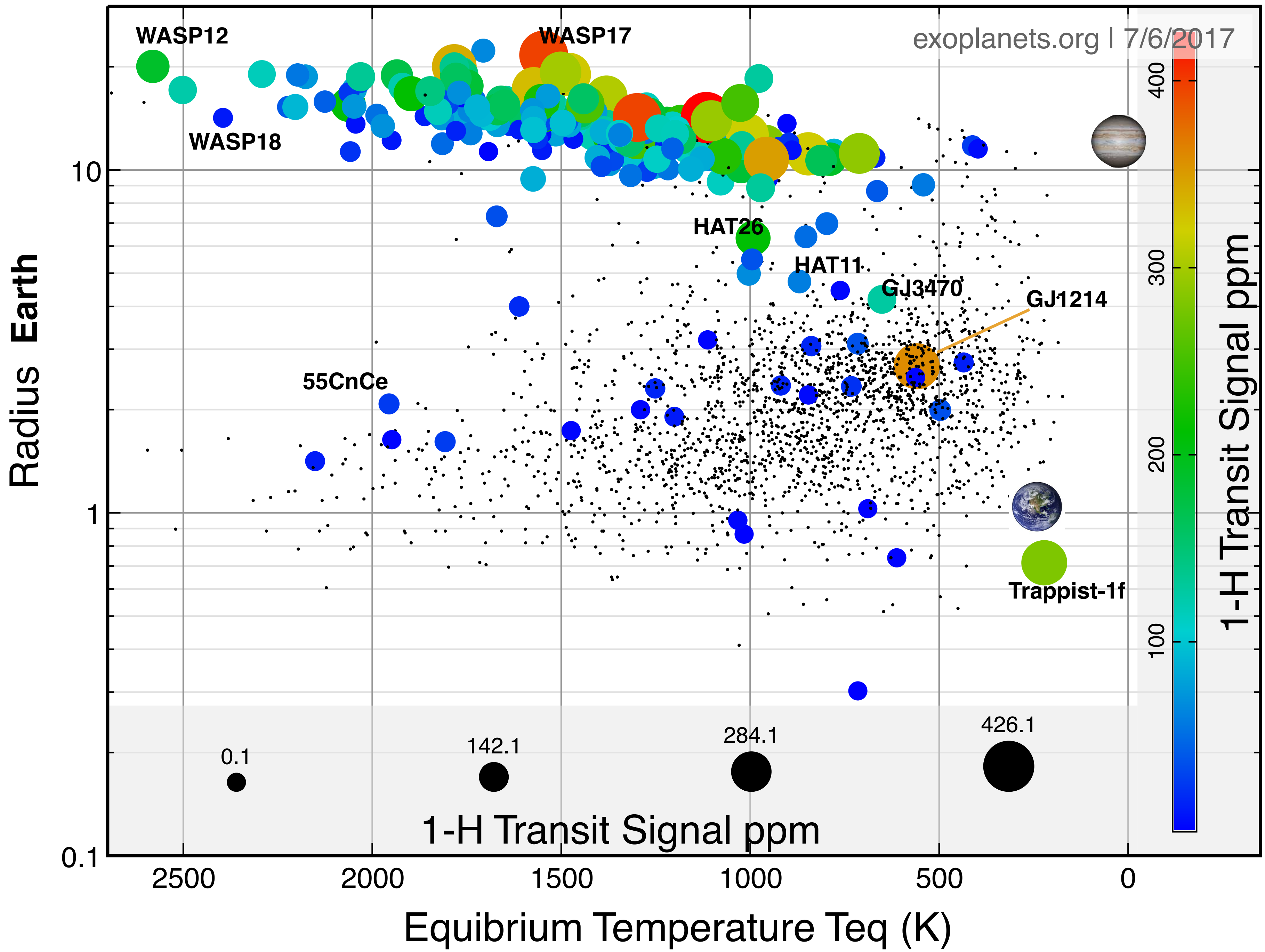
Observable Transiting Exoplanets - Transmission Spectra

Several Hundred Transiting Exoplanets. Some good for spectroscopy, others more difficult.

Can Estimate Signal Size of the Transmission Spectra



Macdonald et al. (2017)



Small/Cold Planets Can Be Characterised NOW* With Transmission Spectra

***Assumes Hydrogen Dominated Atmosphere**

M-dwarf opportunity

Large Signal Boost for Smaller Stars. Rocky planets possible to study.

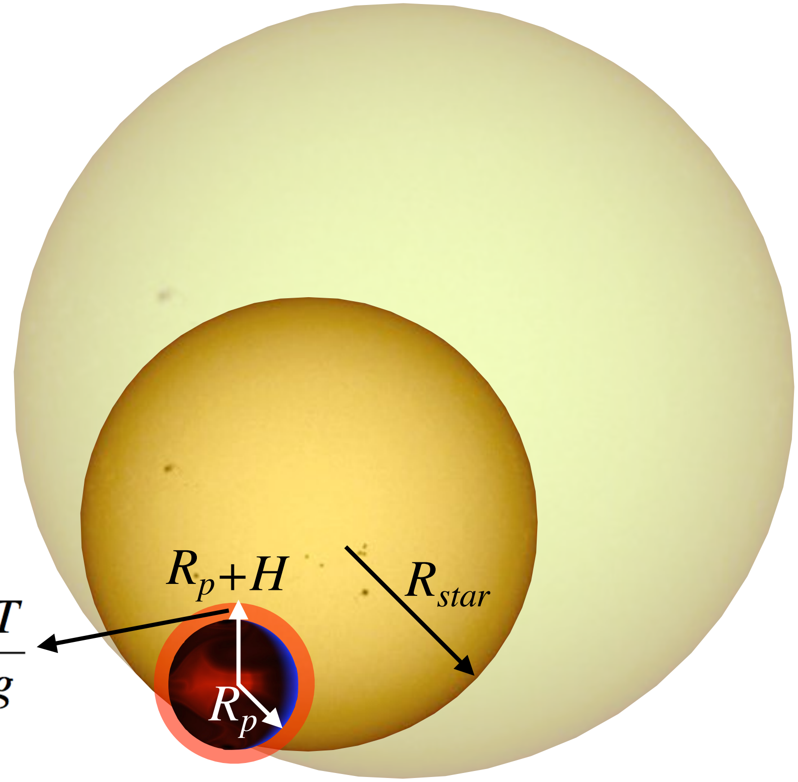
For the Best Stellar Parameters:

http://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt

				Earth H=10 km		Hot Jupiter H=500 km	
#SpT	Teff	Msun	R_Rsun	(Re/Rs)^2	A	(RJup/Rs)^2	A
	K			%	ppm	%	ppm
A0V	9700	2.3	2.09	0.002	0.1	0.2	35
A5V	8080	1.85	1.94	0.002	0.1	0.3	41
A9V	7440	1.67	1.84	0.003	0.1	0.3	45
F0V	7220	1.59	1.79	0.003	0.1	0.3	48
F5V	6510	1.33	1.46	0.004	0.1	0.5	72
F9V	6040	1.14	1.23	0.006	0.2	0.7	101
G0V	5920	1.08	1.12	0.007	0.2	0.8	122
G5V	5660	0.98	0.982	0.009	0.3	1.0	159
G6V	5590	0.97	0.939	0.010	0.3	1.1	174
G7V	5530	0.96	0.949	0.009	0.3	1.1	170
G8V	5490	0.94	0.909	0.010	0.3	1.2	185
G9V	5340	0.9	0.876	0.011	0.3	1.3	200
K1V	5170	0.85	0.814	0.013	0.4	1.5	231
K9V	3940	0.61	0.552	0.028	0.9	3.3	503
M0V	3870	0.6	**0.559**	**0.027**	0.8	3.2	490
M1V	3700	0.53	**0.496**	**0.034**	1.1	4.1	623
M4.5V	3100	0.18	**0.243**	**0.170**	4.5	16.9	2594
M5V	3030	0.15	**0.199**	**0.214**	6.7	-	-
M9V	2400	0.065	**0.095**	**0.938**	**29.3**	-	-

$$A = \frac{2R_{pl}H}{R_{star}^2}$$

$$H = \frac{k_B T}{\mu g}$$



<u>Astronomy Telescope Photometric Precision Context</u>

- Human eye ~10%
- Photographic Plates ~ 2%
- CCD+Backyard Telescope 0.1% 1000 ppm
- Ground-Based 8 meter. 0.01% 100 ppm
- Hubble Telescope 0.002% 20 ppm
- Kepler Telescope 0.0001% 1 ppm

- *JWST??* *1-20 ppm??*

Bright-Star opportunity

Photometric Signal Boost for Bright Stars.
Have limited transit time to gather light (~1hr)
Each magnitude lower is 2.5× brighter

				Earth H=10 km		Hot Jupiter H=500 km	
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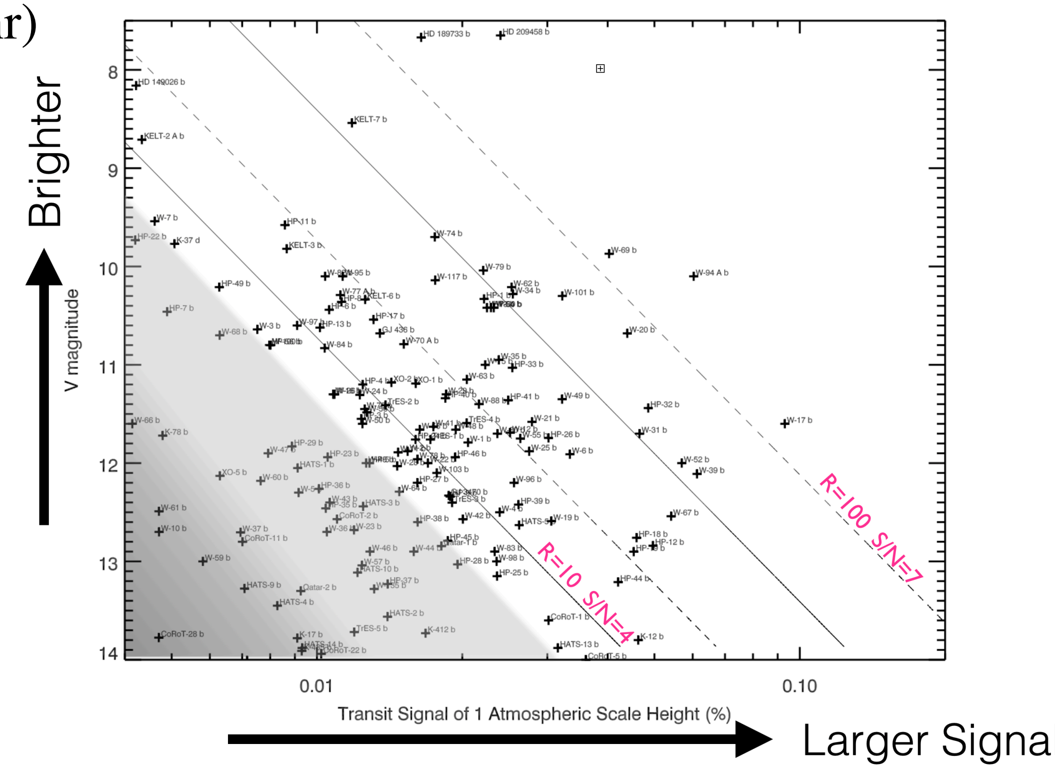

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- Kepler Telescope 0.0001% 1 ppm

- *JWST?? 1-20 ppm??*

Observable Transiting Exoplanets - Secondary Eclipse

Several Hundred Transiting Exoplanets. Some good for spectroscopy, others more difficult. Can Estimate Signal Size of the secondary eclipse depth $\frac{\Delta f_{day}}{f}$

$$\frac{\Delta f_{day}}{f} = p_\lambda \left(\frac{R_{pl}}{a}\right)^2 + \frac{B_\lambda(T_{day})}{B_\lambda(T_{eff})} \times \left(\frac{R_{pl}}{R_{star}}\right)^2$$

Reflected Component *Thermal Emission Component*

<u>Takes into account:</u>

a reflection component with the wavelength dependant albedo $p\lambda$,
a thermal component $B\lambda$ which is approximated here assuming the planet radiates as black body with temperature T_{day}, and the star also radiates as a black body with temperature T_{eff}

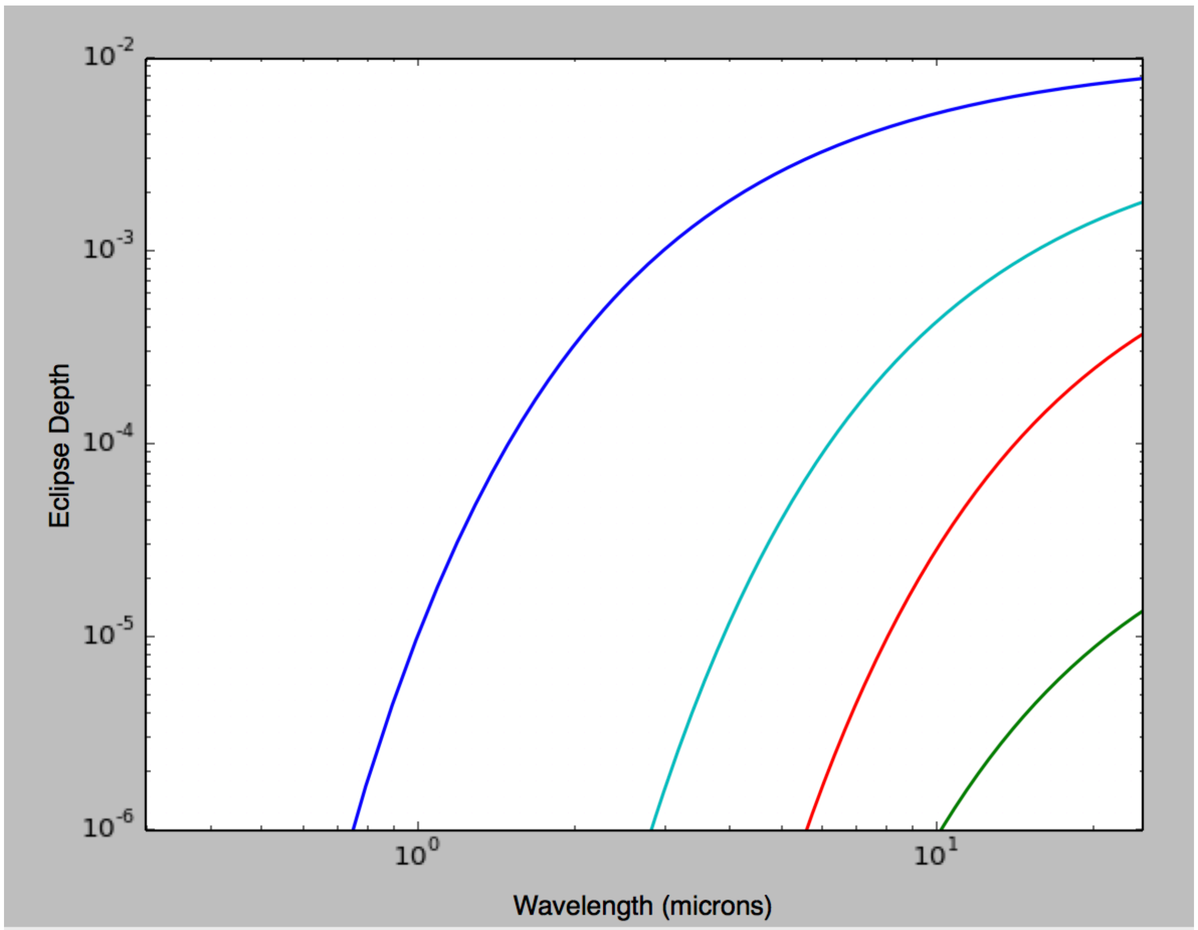
<u>Larger signals</u>: Hotter Planet, More reflective Planet, Cooler Star

Larger Planet, Smaller Star

Observable Transiting Exoplanets - Secondary Eclipse

Very Wavelength Dependent. Some good for spectroscopy, others more difficult. Can Estimate Signal Size of the secondary eclipse depth

$$\frac{\Delta f_{day}}{f} = p_\lambda \left(\frac{R_{pl}}{a}\right)^2 + \frac{B_\lambda(T_{day})}{B_\lambda(T_{eff})} \times \left(\frac{R_{pl}}{R_{star}}\right)^2$$

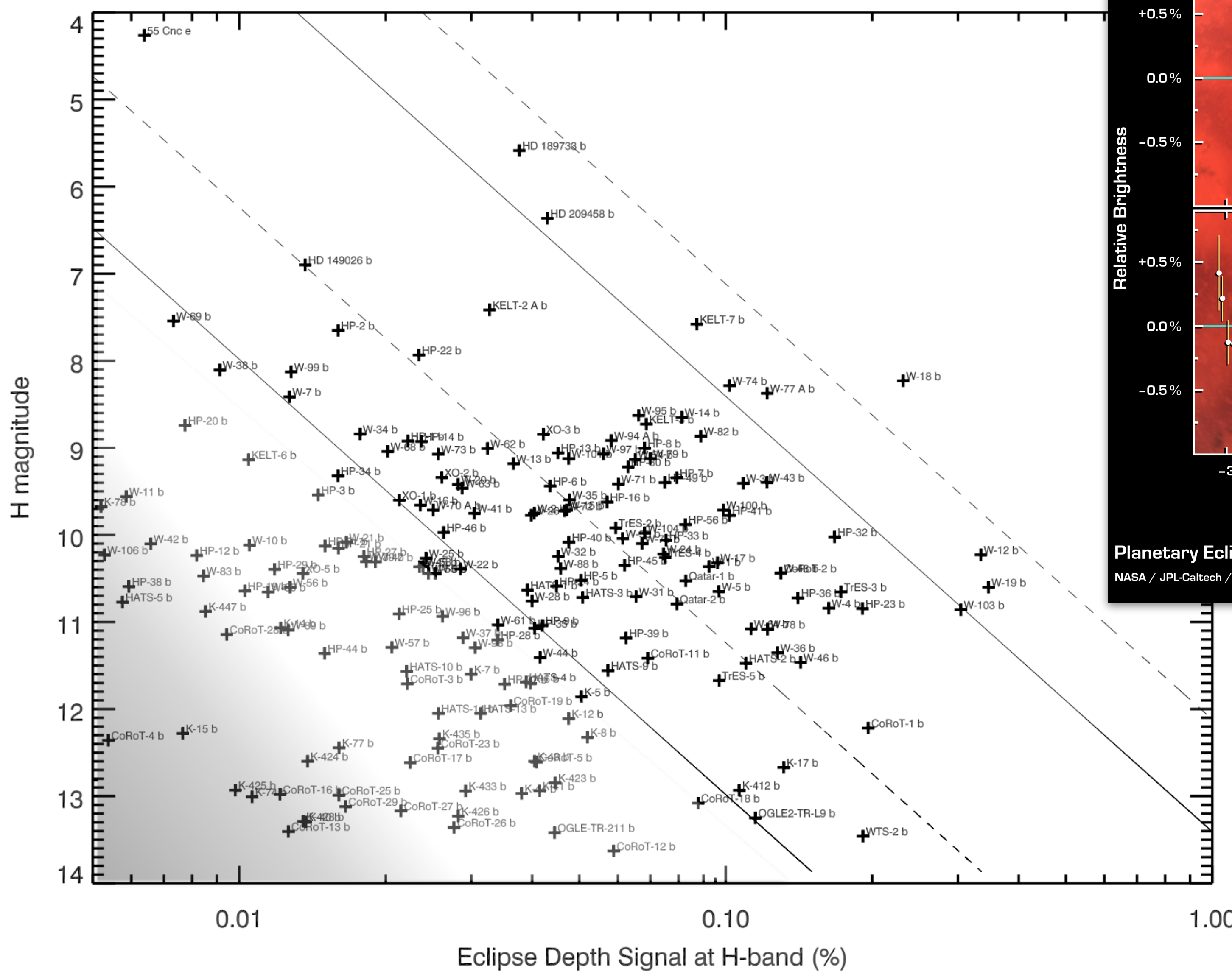


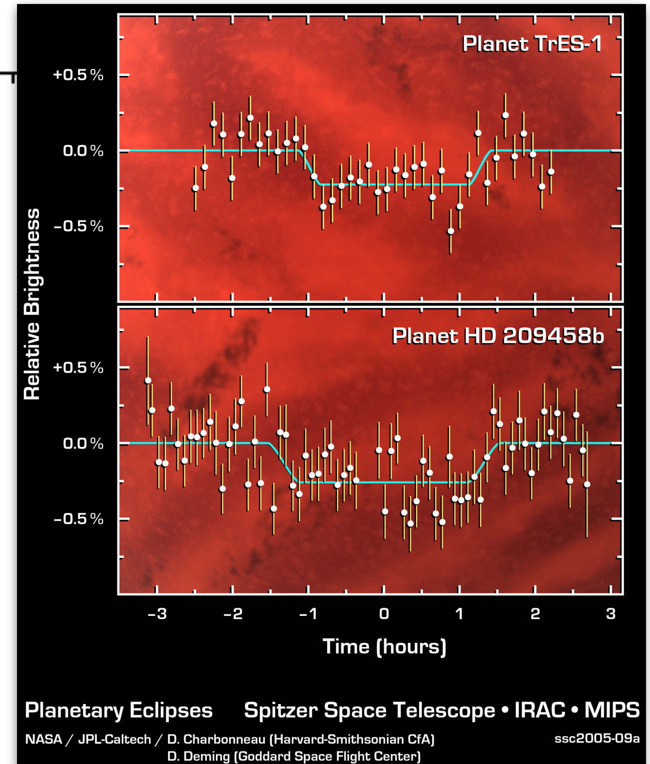
albedo=0
Hot Jupiter
Mearth
Warm Super Earth
Earth

Observable Transiting Exoplanets - Secondary Eclipse

Several Hundred Transiting Exoplanets. Some good for spectroscopy, others more difficult. Can Estimate Signal Size of the secondary eclipse depth

Brighter

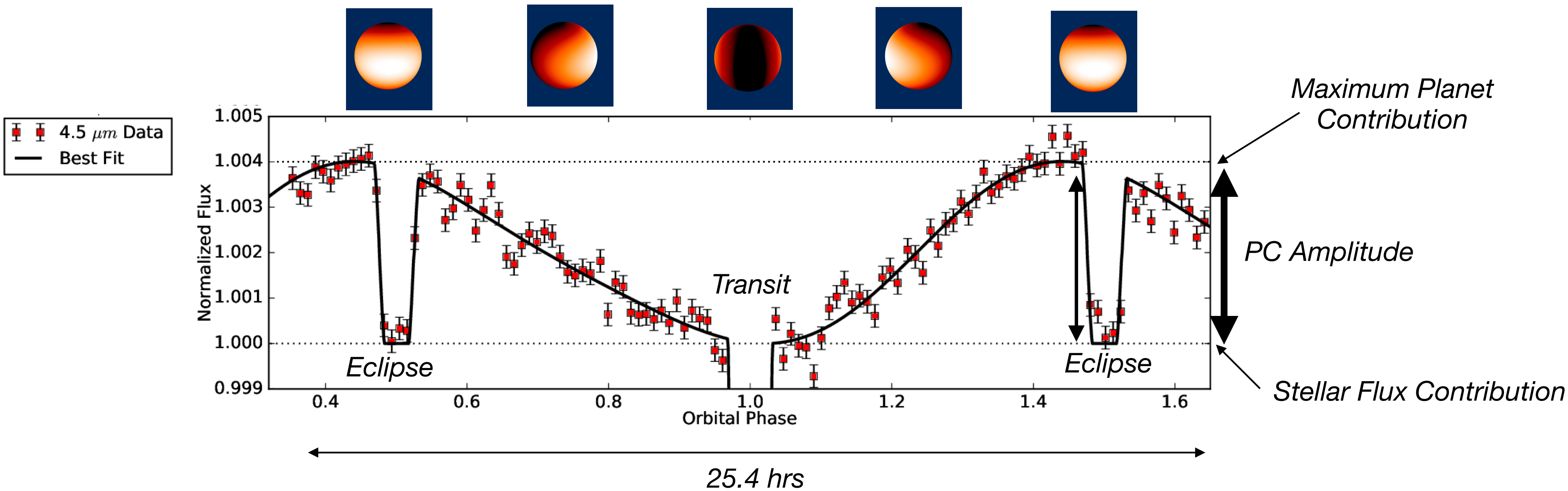




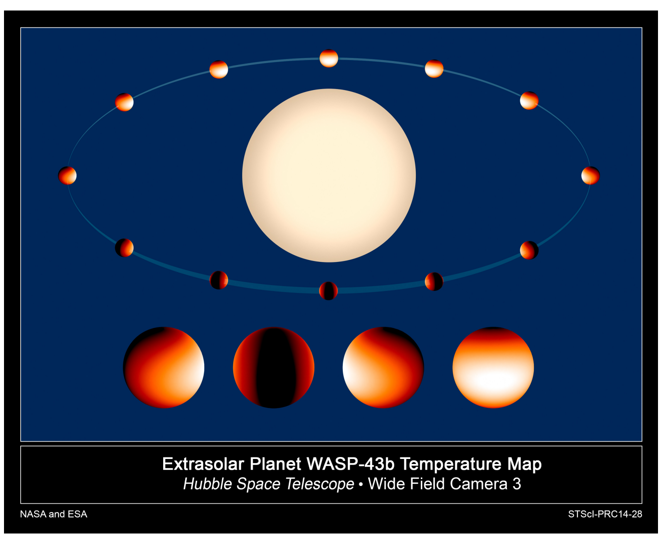
Larger Signal

Observable Transiting Exoplanets - Phase Curve

Phase curve amplitude well estimated from Eclipse Depth: $\frac{\Delta f_{day}}{f} = p_\lambda \left(\frac{R_{pl}}{a}\right)^2 + \frac{B_\lambda(T_{day})}{B_\lambda(T_{eff})} \times \left(\frac{R_{pl}}{R_{star}}\right)^2$



Typically Observe eclipse-to-eclipse to measure baseline Stellar Flux Contribution



Stevenson et al. (2016)

Observations take a whole planetary orbit

Favors short period planets (P~1 day typically)

Planning Transit Observations

S/N estimates
ETC calculators
HST JWST

Planning Transit Observations

Let's Setup An Observation

- S/N estimates
  - What exposure times should I use?
  - How precise is my time-series observation going to be (ppm on transit depth or eclipse depth)

Needed for proposal stage

Planning Transit Observations

Why Simulate Transit Observations?

- Transit S/N calculations different from Classical ETC *(need to include Time series)*
- Can check if spectral feature is observable, detectable, and at what significance level
- Can check sensitivity to different models (hypothesis testing)
- Demonstrate Visually Observations to Skeptical Panel Reviewer

Planning Transit Observations

Advice for Planing Proposals & Simulating Spectra

- Need To Give Plausible Range for Signal
- Don't Rely only on Optimistic Predictions.
  Don't oversell the observations. Will not end up with detections or any results
- Photon noise is always optimistic
- True signals usually smaller than predicted
- Can degrade by ~sqrt(2) in most cases

Very rewarding to see idea shepherded through to detection

Planning Transit Observations

So How Do We Prepare???

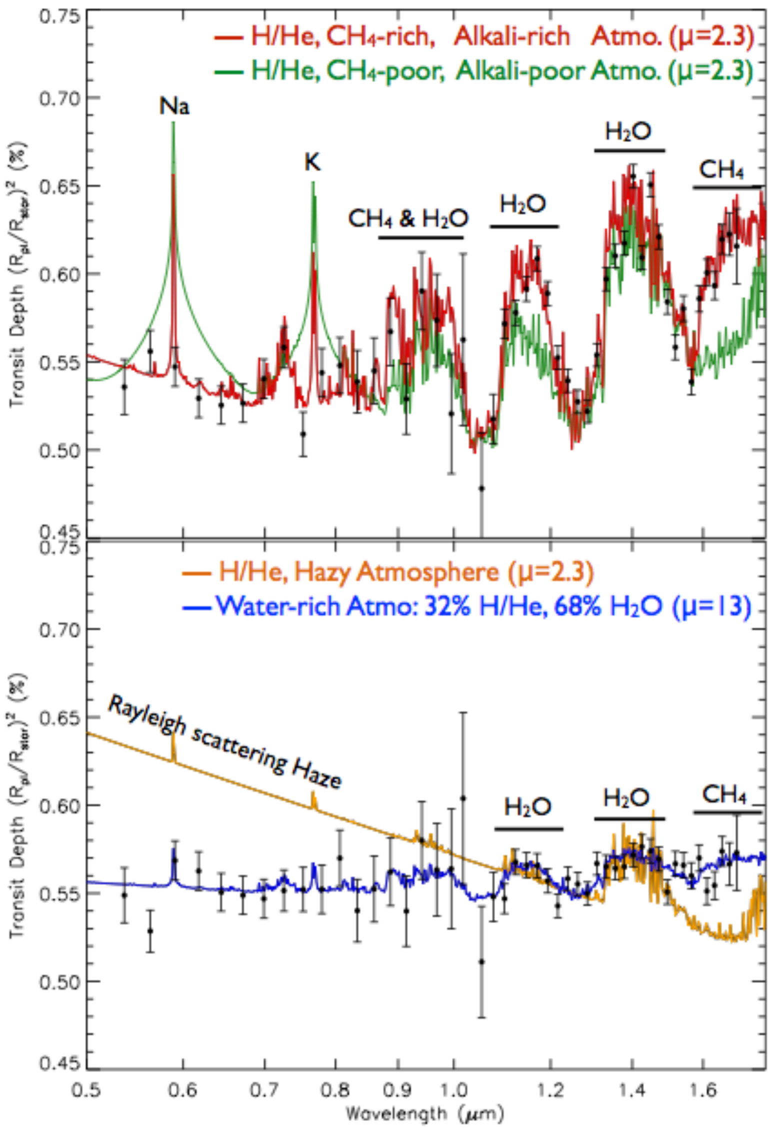
Brilliant Idea

- Need to Familiarize Instruments
  Which modes for transits
- ETCs, PandExo - SNR, simulate observations, compare to models
- APT - setup observations & submit proposal
- APT - submit proposal

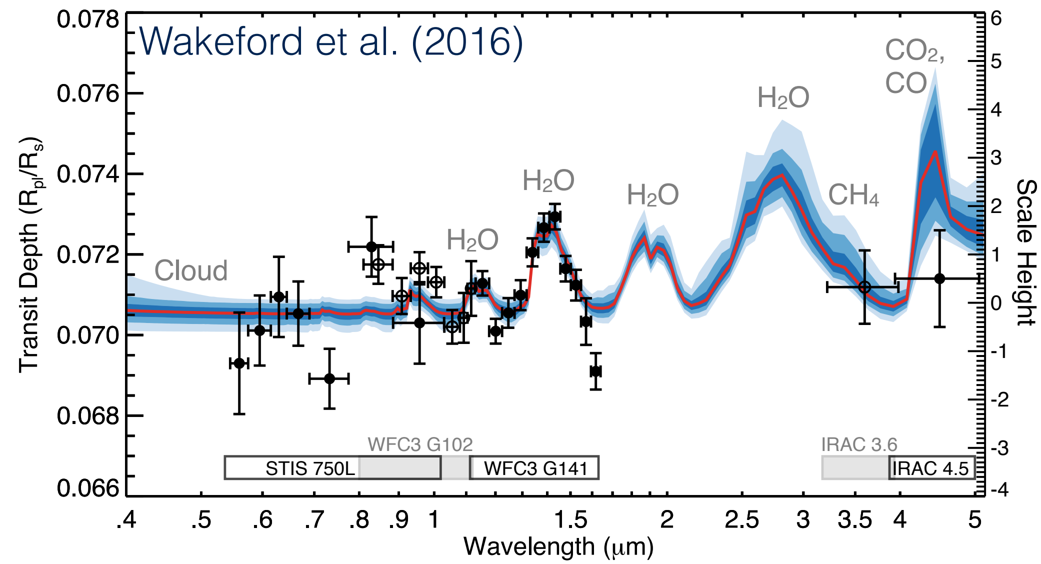
Chance for Brilliant Data & Paper

Planning Transit Observations

Simulated Spectra from Actual Proposal



Reality



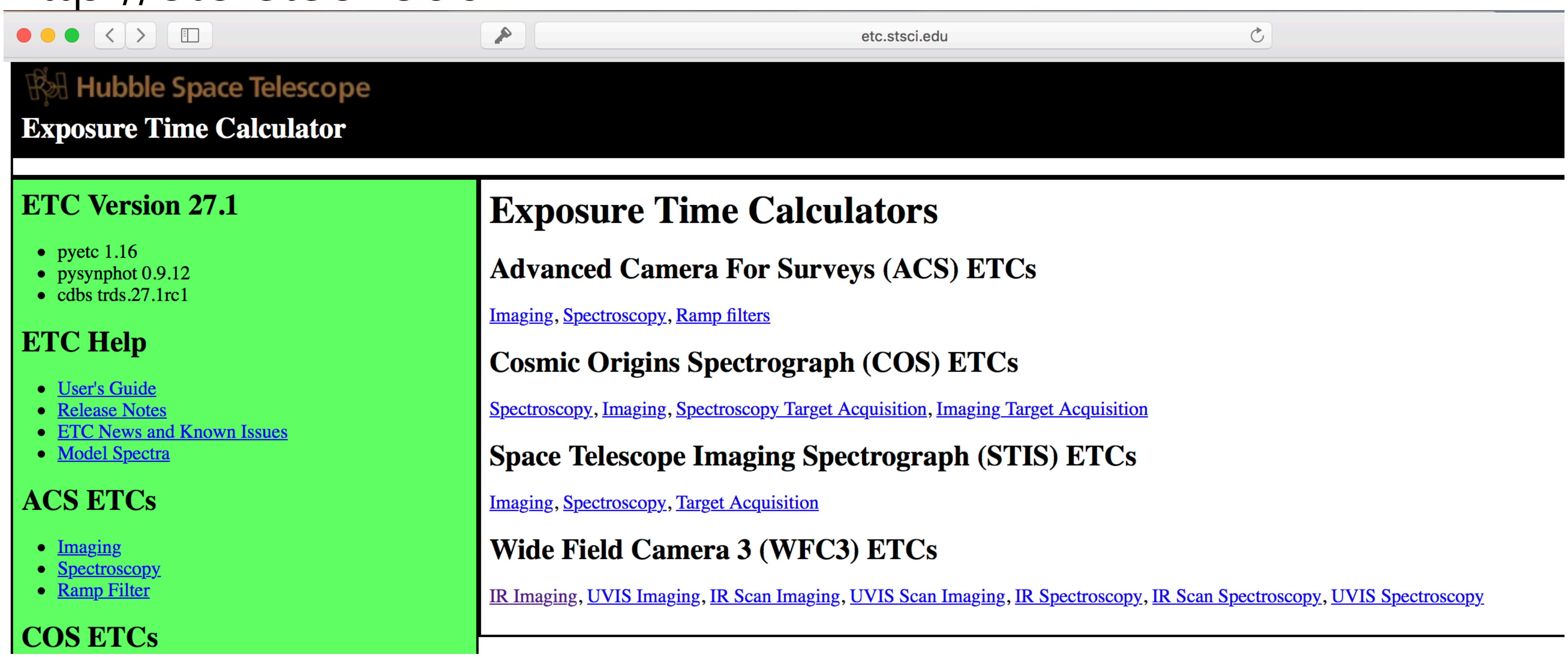
H_2O size ~half way between proposal estimates (solid detection made)

Give Realistic Range in S/N
Don't rely only Optimistic Signals

Signal-to-Noise Calculations: Can we detect atmospheric features?

- Example: Hubble
  - Use Exposure time calculators for single image
  - Need to know saturation, how many photons/image will be acquired

http://etc.stsci.edu



Signal-to-Noise Calculations: Can we detect atmospheric features?

- Example: Hubble HD209458b G750L (R=500)
- Choose Instrument setup based on science case
  - Want to collect as many photons as possible without saturating. Aim, high photometric S/N
- Look up target magnitude
- Can guess/check to find saturation time
- Aim for ~2/3 to 3/4 well depth

http://simbad.u-strasbg.fr/simbad/

V* V376 Peg -- Star showing eclipses by its planet

Other object types:	* (Ref,AG,...), EP* (Ref), V* (V*), IR (2MASS
ICRS coord. *(ep=J2000) :*	22 03 10.7729598762 +18 53 03.548248479 (Op
FK4 coord. *(ep=B1950 eq=1950) :*	22 00 48.0708187341 +18 38 32.195344556 [4
Gal coord. *(ep=J2000) :*	076.7533207456460 -28.5269067211539 [0.048
Proper motions *mas/yr* :	29.579 -17.890 [0.083 0.075 90] A 2018yCat.
Radial velocity / Redshift / cz :	V(km/s) -15.01 [0.29] / z(spectroscopic) -((Opt) A 2018yCat.1345....0G
Parallaxes *(mas)*:	20.6745 [0.0526] A 2018yCat.1345....0G
Spectral type:	F9V C 2001AJ....121.2148G
Fluxes (6) :	B 8.21 [0.02] D 2000A&A...355L..27H
	V 7.63 [0.01] D 2000A&A...355L..27H
	G 7.5087 [0.0004] C 2018yCat.1345....0G
	J 6.591 [0.020] C 2003yCat.2246....0C
	H 6.37 [0.04] C 2003yCat.2246....0C
	K 6.308 [0.026] C 2003yCat.2246....0C

How accurate is Magnitude, Stellar Type, ect?

Don't want to saturate

http://etc.stsci.edu/etc/results/STIS.sp.1315134/

ETC Request ID: STIS.sp.1315134

Exposure time (seconds) = 60.0000 at wavelength 6000.00 Å
gives: SNR = 1,152.4449 (per resolution element)
gives: Time to Saturation (for a single exposure) = 21.07 seconds
Exposure time calculation HAD WARNINGS.
WARNING MESSAGE: CCD Full Well limits: total counts per native pixel 341668 exceeds bright limit 12
WARNING MESSAGE: "Electrons per pixel due to background (1.6) is less than the recommended thresho
charge transfer efficiency (CTE). We suggest you consider CTE mitigation strategies described in the STIS

Table of Source and Noise Counts per Pixel

Plots

Total Counts | Signal-to-noise | Input Target Spectrum | Throughput | Observed Target Spectrum

Detailed Information	**Count rate** (e-/s)	**Total counts** (e-)
Counts (box 7 pixels high)	(1 pix x 7 pix)	(2 pix resel x 7 pix)
Source	11,076.153	1,329,138.31
Background	0.183	22.01
Sky	0.001	0.17
Dark Current	0.182	21.84
Read Out		
Total in selected region	11,076.336	1,329,160.32
Brightest Pixel (single exposure) (at 5833.80 Å)	5,694.467	341,667.99

Shows Saturation in 21 seconds

So use 3/4*21 = **16 sec integration**

Signal-to-Noise Calculations: Can we detect atmospheric features?

Example HD209458b. 16 second integration

http://etc.stsci.edu/etc/results/STIS.sp.1315136/

ETC Request ID: STIS.sp.1315136

Exposure time (seconds) = 16.0000 at wavelength 6000.00 Å
gives: SNR = 594.5132 (per resolution element)
gives: Time to Saturation (for a single exposure) = 21.07 seconds
Exposure time calculation HAD WARNINGS.
WARNING MESSAGE: Total counts per binned pixel 91111.5 is within 70 percent of the CCD fullwell limit 120000
WARNING MESSAGE: "Electrons per pixel due to background (0.42) is less than the recommended threshold of 20 electrons to avoid poor charge transfer efficiency (CTE). We suggest you consider CTE mitigation strategies described in the STIS Instrument Handbook."

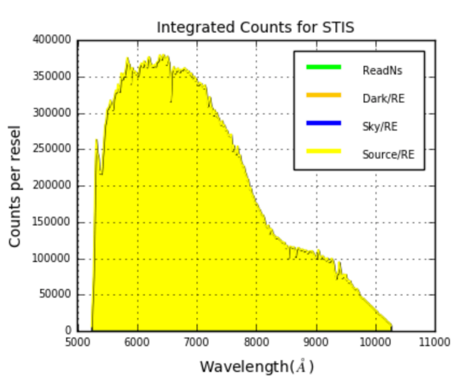
Table of Source and Noise Counts per Pixel

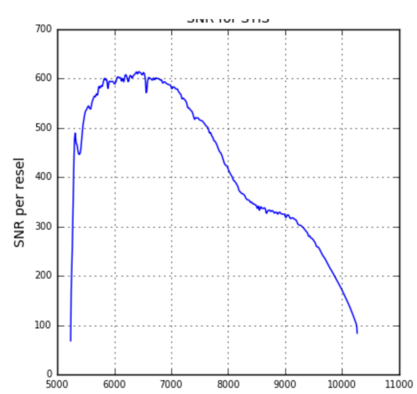
Plots

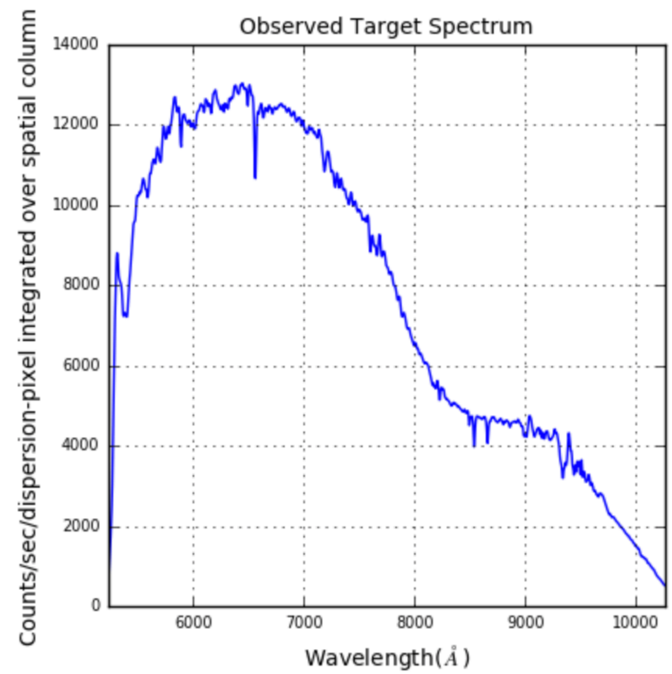
Total Counts | Signal-to-noise | Input Target Spectrum | Throughput | Observed Target Spectrum

Detailed Information	Count rate (e-/s)	Total counts (e-)	Associated noise (e-)
Counts (box 7 pixels high)	(1 pix x 7 pix)	(2 pix resel x 7 pix)	
Source	11,076.153	354,436.88	595.35
Background	0.183	5.87	2.42
Sky	0.001	0.04	0.21
Dark Current	0.182	5.82	2.41
Read Out			31.43
Total in selected region	11,076.336	354,442.75	596.18
Brightest Pixel (single exposure) (at 5833.80 Å)	5,694.467	91,111.46	
Global Count Rates			
Source only	7,812,268.054	124,996,288.870	
Background (sky+dark)	27,405.295	438,484.71	

Encircled energy fraction 0.92







So how does this translate to planet spectra?

Signal-to-Noise Calculations: Can we detect atmospheric features?

From STScI HST Exposure Time Calculator

Detailed Information	Count rate (e-/s)	Total counts (e-)	Associated noise (e-)
Counts (box 7 pixels high)	(1 pix x 7 pix)	(2 pix resel x 7 pix)	
Source	11,076.153	354,436.88	595.35
Background	0.183	5.87	2.42
Sky	0.001	0.04	0.21
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Read Out			31.43
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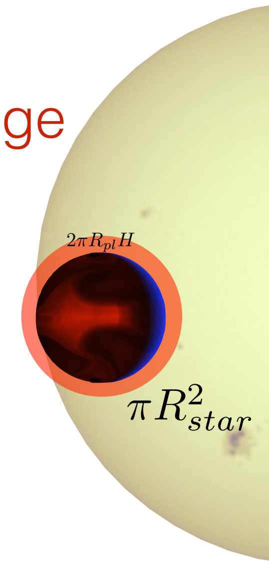
Global Count Rates			
Source only	7,812,268.054	124,996,288.870	
Background (sky+dark)	27,405.295	438,484.71	

Encircled energy fraction 0.92

S: Spectra counts per image per spectral resolution element

White light curve counts per image



Signal (e-) *Photon Noise* *Photometric Precision of time series observation*

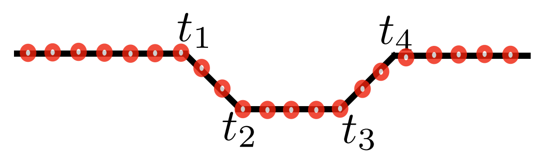
$$S \longrightarrow N = \sqrt{S} \longrightarrow PP = \frac{1}{N}$$

Transmission Signal of planet 1H

$$A = \frac{2\pi R_{pl} H}{\pi R^2_{star}}$$

How many exposures in-transit ($t_2 \rightarrow t_3$)? N_{tr}

- calculate duty cycle, exposure time + readout time



Calculate photometry precision per Transit/eclipse event

- Divide $\boldsymbol{PP}$ by $\sqrt{N_{tr}}$ to boost SNR by number of exposures
- Degrade by $\sqrt{2}$ to account for baseline flux uncertainty

$$PP_{tr} = \sqrt{2}\frac{PP}{\sqrt{N_{tr}}}$$

Final uncertainty per transit (ppm)

N_{tr} = 64
PP_{tr}=296 ppm

$$PP_{tr} < A$$

296 < 200

*YES - **Atmosphere is likely Detectable***

NO - **Bin in Wavelength and/or add transits to Increase Precision**

(Note reduced resolution with wave bin) PP_{tr}=209 ppm at R=250

Signal-to-Noise Calculations: Can we detect atmospheric features?

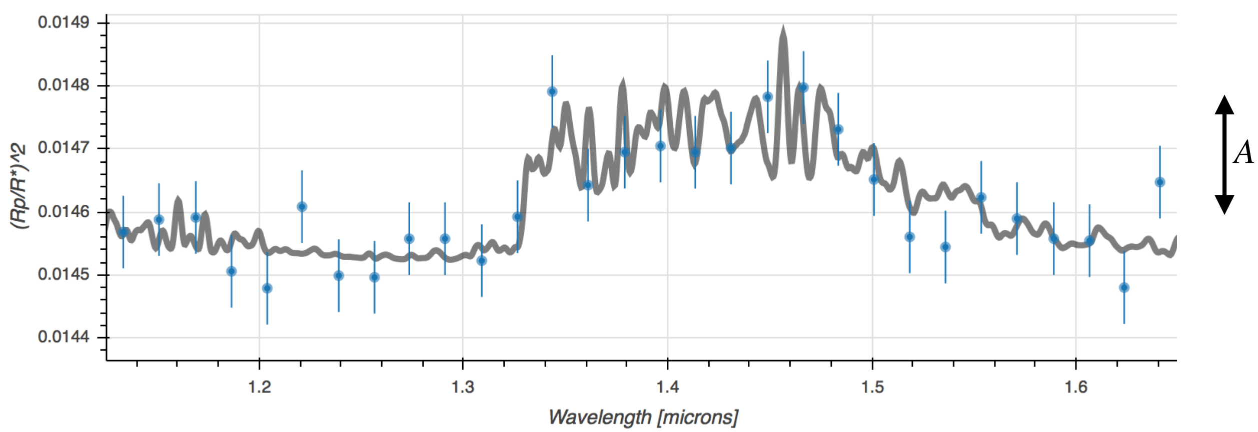
$$\boxed{PP_{tr} < A}$$

YES - Atmosphere is likely Detectable

NO - **Bin in Wavelength and/or add transits to Increase Precision**

Compare to Atmosphere Model

Error Bars = PP_{tr}

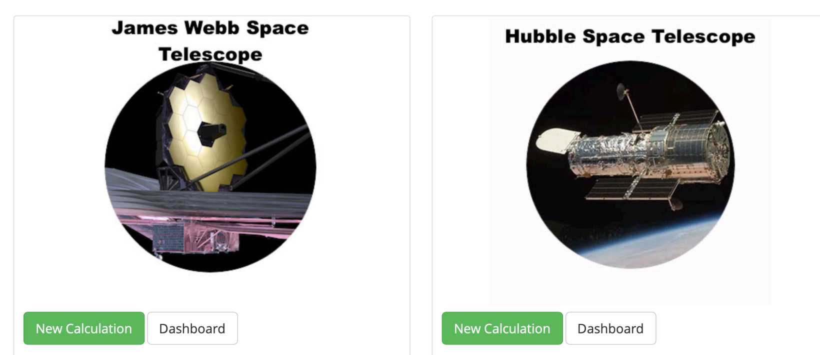


Tools: TSO calculator for HST & JWST

Simulates Transmission, Emission, Phase Curve observations

(Batalha et al. 2017)

Exoplanet Characterization Toolkit ExoCTK https://exoctk.stsci.edu/

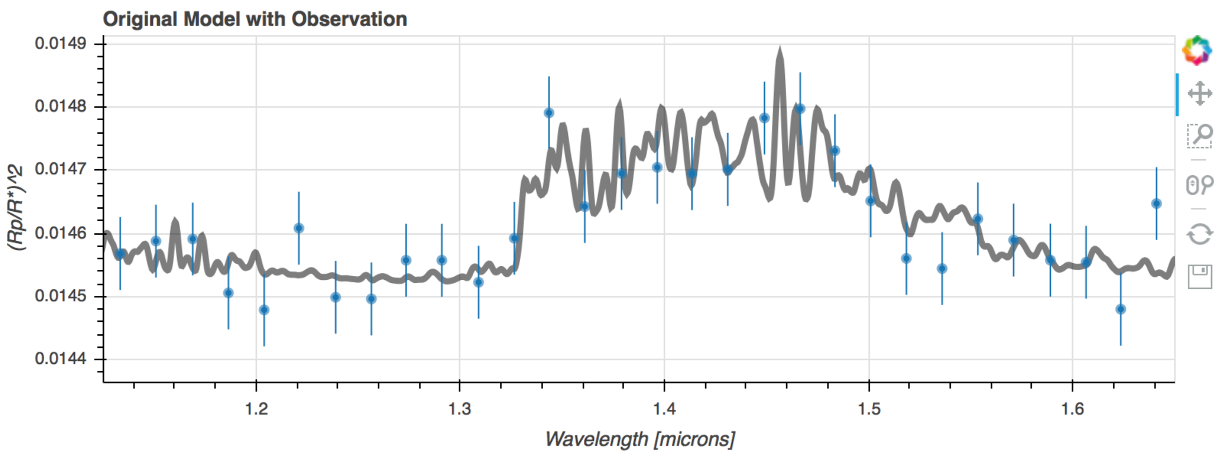


Can we detect atmospheric features?

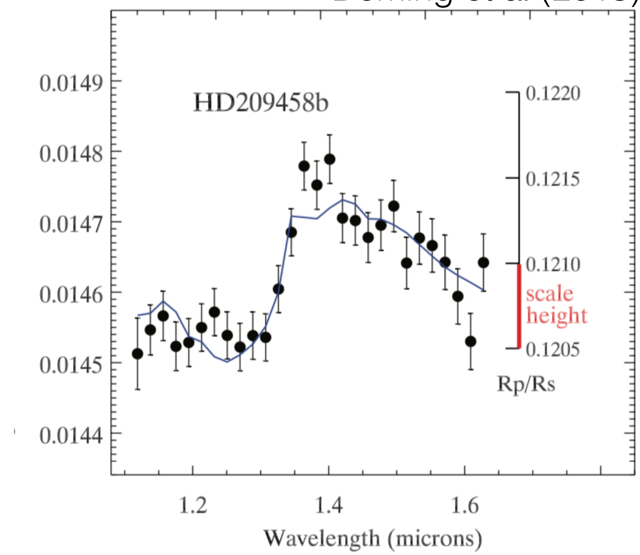
Exoplanet Characterization Toolkit
ExoCTK

https://exoctk.stsci.edu/

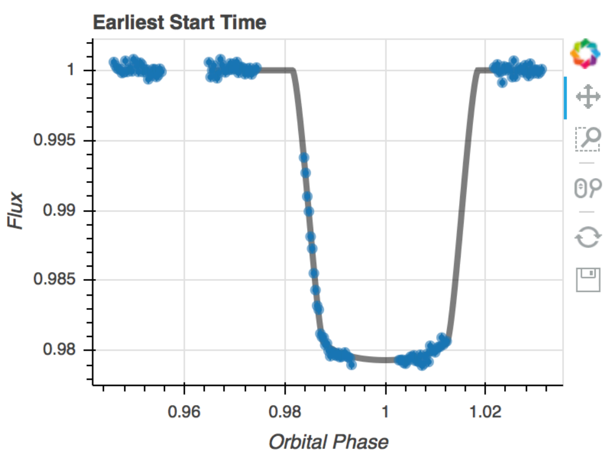
Spectrum

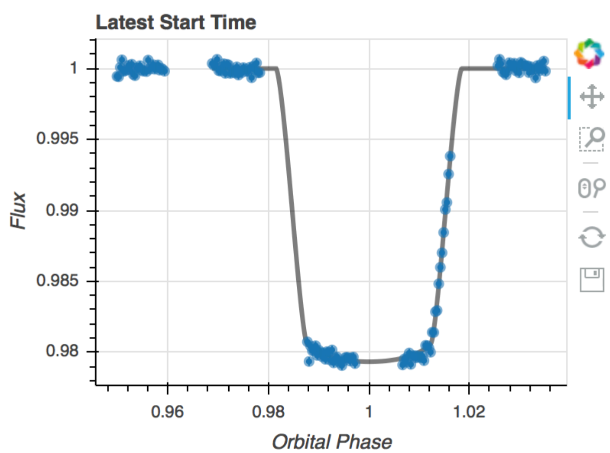


Deming et al (2013)



Timing

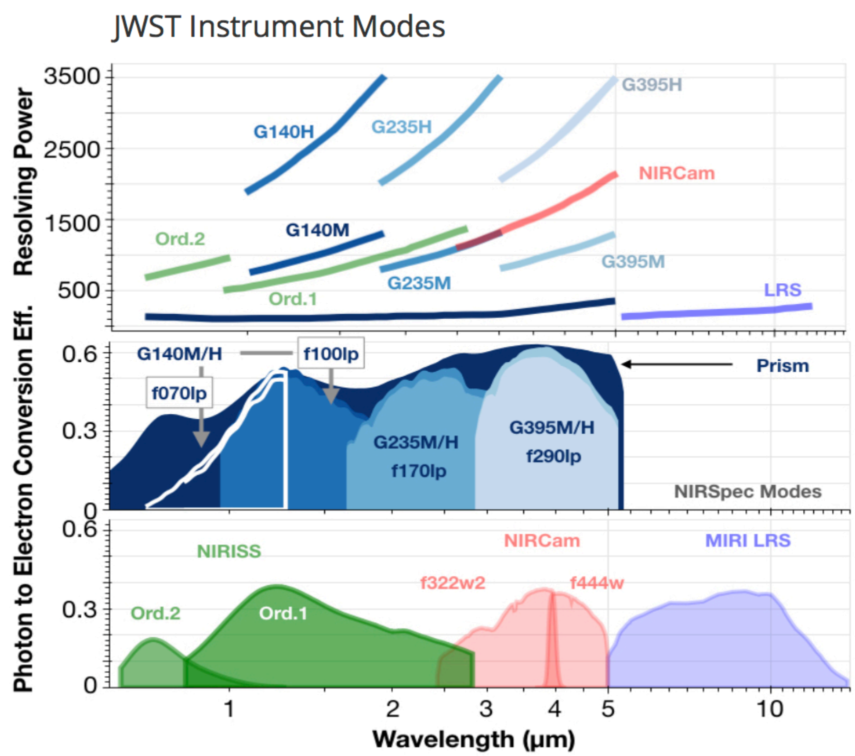




Used Cloudy model
Good Agreement!

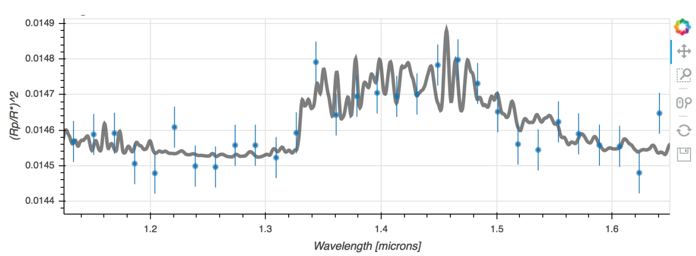
Can we detect atmospheric features? How about JWST?

Exoplanet Characterization Toolkit
ExoCTK

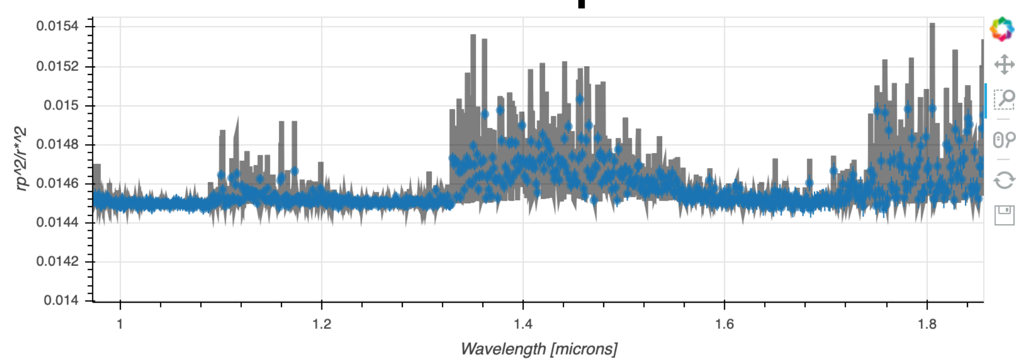


	Mode	Approx. 2 group saturation
NIRSpec	Prism	J>10.5
	Grisms	J>6
NIRISS	Substrip 256	J>8
	Substrip 96	J>7
NIRCam	Grisms	L>3.7
MIRI	LRS	K>4

HST WFC3

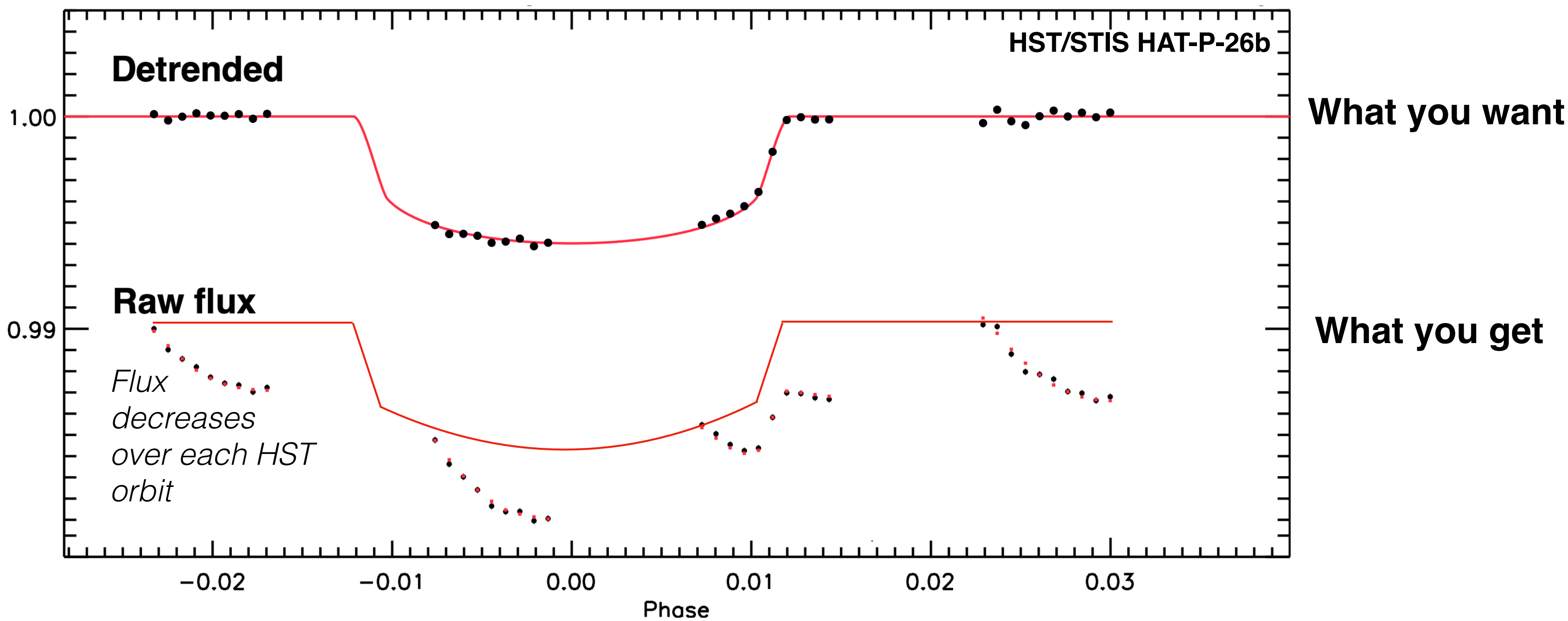


JWST NIRSpec



Correcting For Systematic Errors in the Time Series

- All instruments introduce systematic effects/trends in to the light curve
- Need a Full model with transit and systematics taken into account *(need to know/find what is affecting our data)*



- Correct using Detrending Vectors *S(**x**)* which correlate with the photometry (e.g. detector position)

$$f(t) = \underbrace{T(t,\theta)}_{\text{Transit Model}} \times \underbrace{F_0}_{\text{Stellar Flux}} \times \underbrace{S(\mathbf{x})}_{\text{Systematic error model}}$$

- For HST STIS, major effects are Thermal Breathing (Brown 2001) & detector position (Sing 2011)

$$f(t) = T(t,\theta) \times F_0 \times (p_1\phi_{HST} + p_2\phi^2_{HST} + p_3\phi^3_{HST} + p_4\phi^4_{HST} + 1) \times (p_5 S_\lambda + 1) \times (p_6 X_{psf} + 1) \times (p_7 Y_{psf} + 1)$$

- JWST will have systematics with observatory pointing/jitter
- A main Job for JWST Observers will be to explore methods to model $S(\mathbf{x})$

Have Overview of Time-series Observations

Differential Photometric Measurement: Don't care about absolute flux, just *relative* change in dimming during transit. Many systematics are removed in differential measurement.

A Few Ground/Space Transit Tips - Designed to help differential phot. Measurement

1. Observe whole time series on the Same Pixel, sub-pixel as possible
2. Choose setting (e.g. gain) to get as many counts as reasonably possible per image
3. Choose detector setting (subarray, readouts) to get as many images per transit as possible
4. Readnoise is almost never important
5. Detector electronics can introduce noise (1/f noise for JWST)
6. Wide slits/apertures are needed to avoid light losses
7. Have a uniform detector
8. Get long enough baseline to measure full eclipse/transit depth
9. Have systematic(s) value(s) in baseline cover same systematic values in transit
10. Ingress/egress not very useful to measure depth, needed to measure a/Rstar, inclination
11. Avoid non-linearities in detector if possible
12. Reference stars need to be very similar to target in type & magnitude (within 1 mag, and sub-type)
13. Near-IR is hard from the ground… but not impossible
14. Philosophy differs in flat fielding (I suggest gathering 100's, test to see if the improve things or not)
15. Cosmic Rays are important
16. Look at all the ways your spectra/photometry changes in time
17. Stellar Variability can affect Transit Depths, weaker in IR
18. Be Wary of Hidden companions
19. Be Wary of Unphysical results (result of systematics?)