T^3 w/JWST

(Cowan, Greene, et al. 2015, PASP)

Nick Cowan

(Physics + EPS, McGill University)

Institut Spatial de McGill

INSTITUT DE RECHERCHE SUR LES EXOPLANÈTES

INSTITUTE FOR RESEARCH ON EXOPLANETS

iREx

McGill Space Institute

Transiting Temperate Terrestrials w/James Webb Space Telescope

(Cowan, Greene, et al. 2015, PASP)

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Transiting Temperate Terrestrials

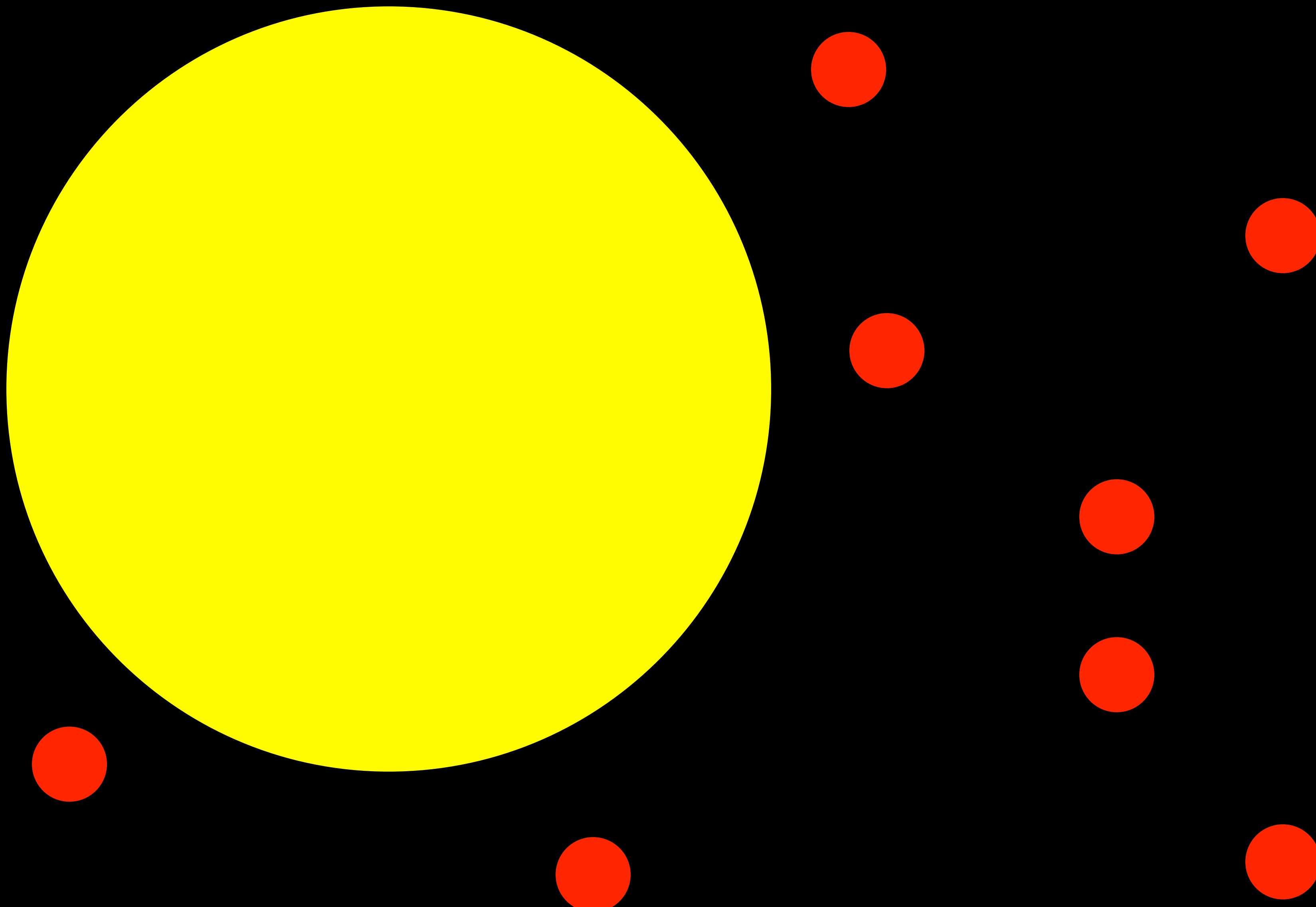
Probability = 0.5%
Period = 1 year
Depth = 10^{-4}

Probability = 0.5%
Period = 1 day
Depth = 10^{0}

Probability = 10%
Period = 1 day
Depth = 10^{-2}

Probability = 1%
Period = 1 month
Depth = 10^{-2}

The Faint Majority



90-99% of Temperate Terrestrials Orbit an M-Dwarf

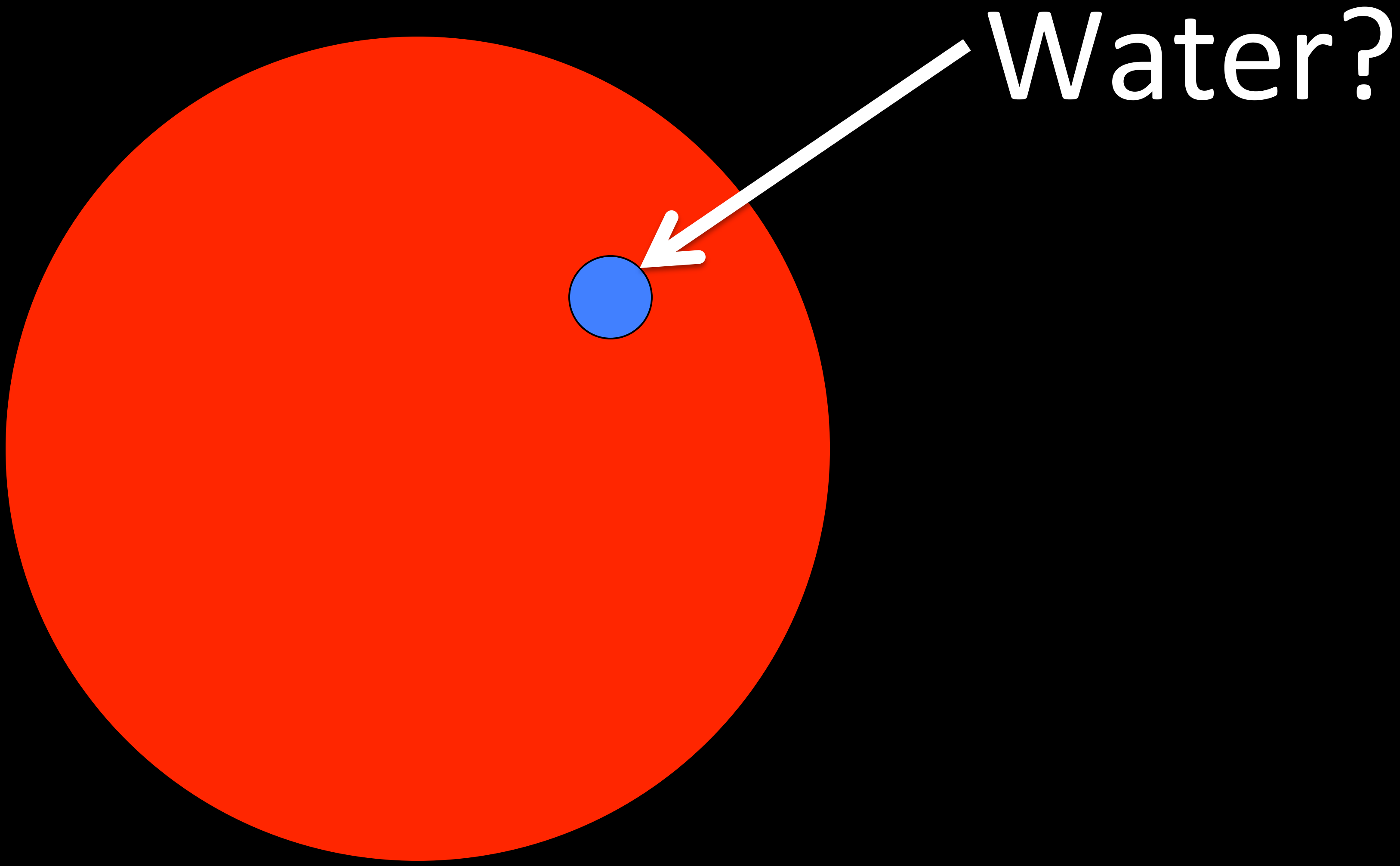
(Dressing & Charbonneau 2013, 2015; Foreman-Mackey+2014, Farr+2015)

M-Dwarf Objections

- Tidal Locking
  - (Dole 1964)
- Stellar Activity
  - (Lammer+2007)
- Pre-MS Luminosity
  - (Luger & Barnes 2015)

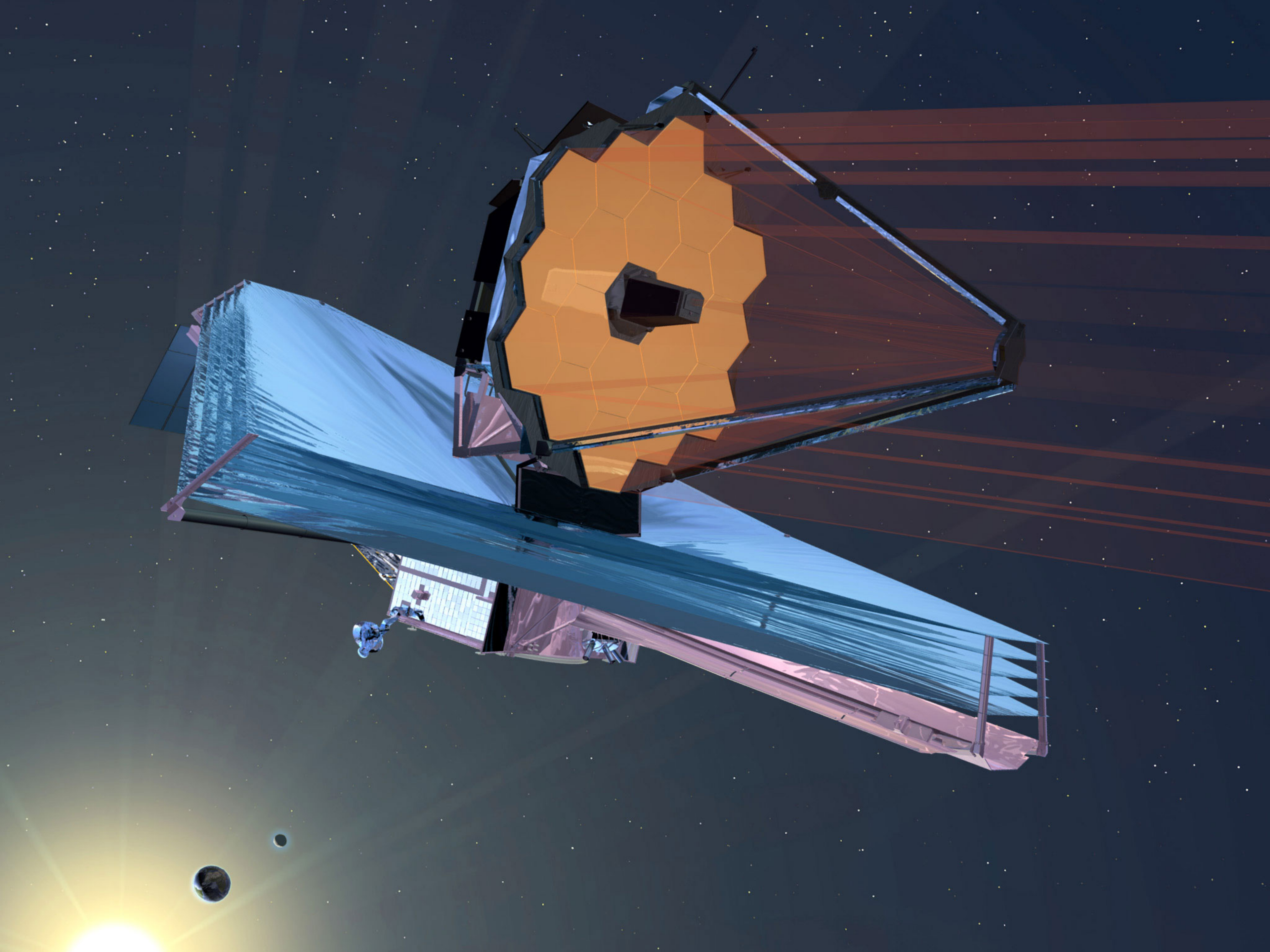
M-Dwarf Objections

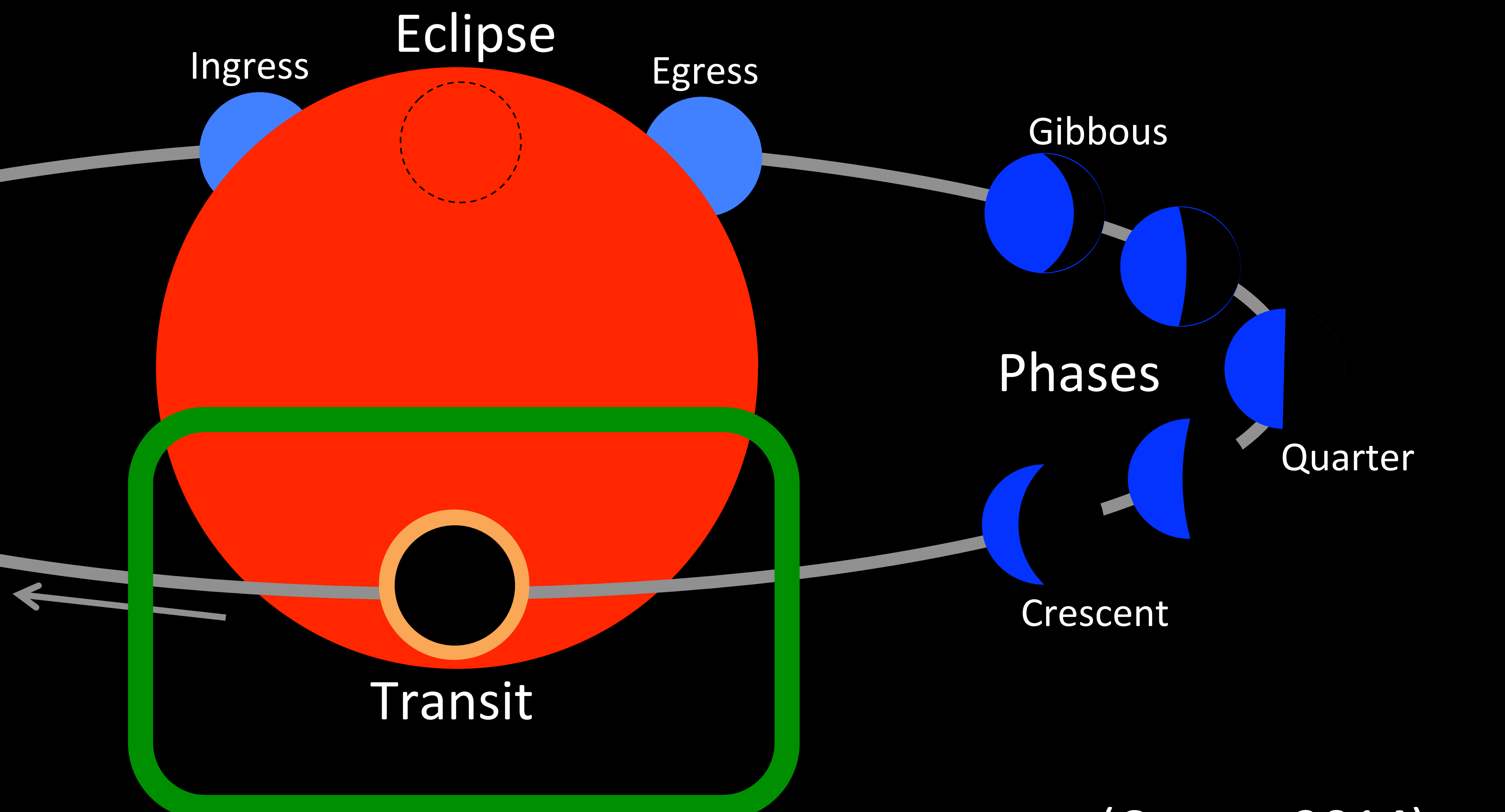
- ~~Tidal Locking~~
  - (Haberle+1996; Joshi+1997; Leconte 2014)
- ~~Stellar Activity~~
  - (Segura+2010)
- Pre-MS Luminosity?
  - (Luger & Barnes 2015)


Water?

Do M-Dwarf T^3 Have H_2O?

- Yes
  - Focus on M-Dwarf Planets
- No
  - Focus on G-Dwarf Planets

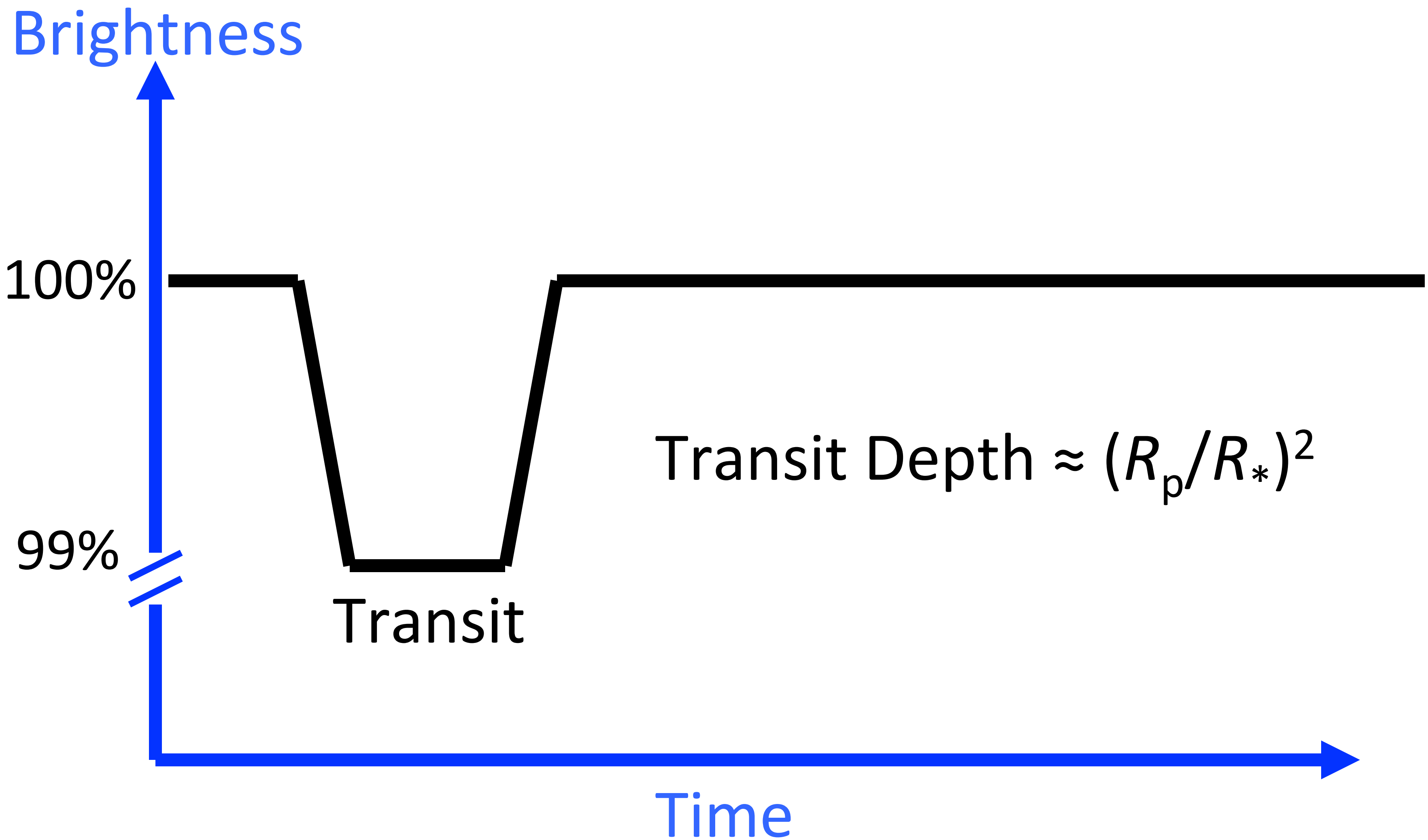


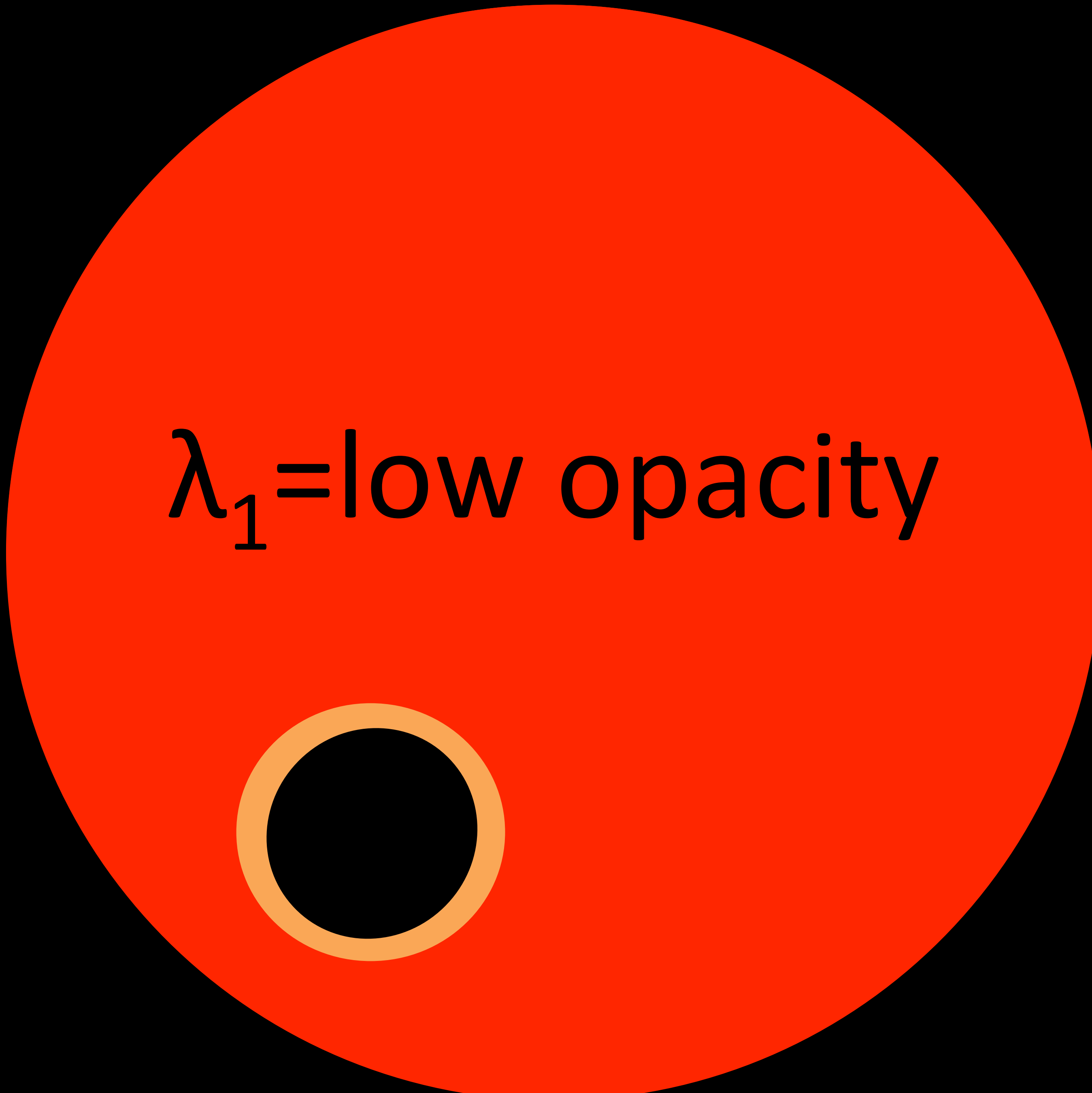

Eclipse
Ingress
Egress
Gibbous
Phases
Quarter
Crescent
Transit

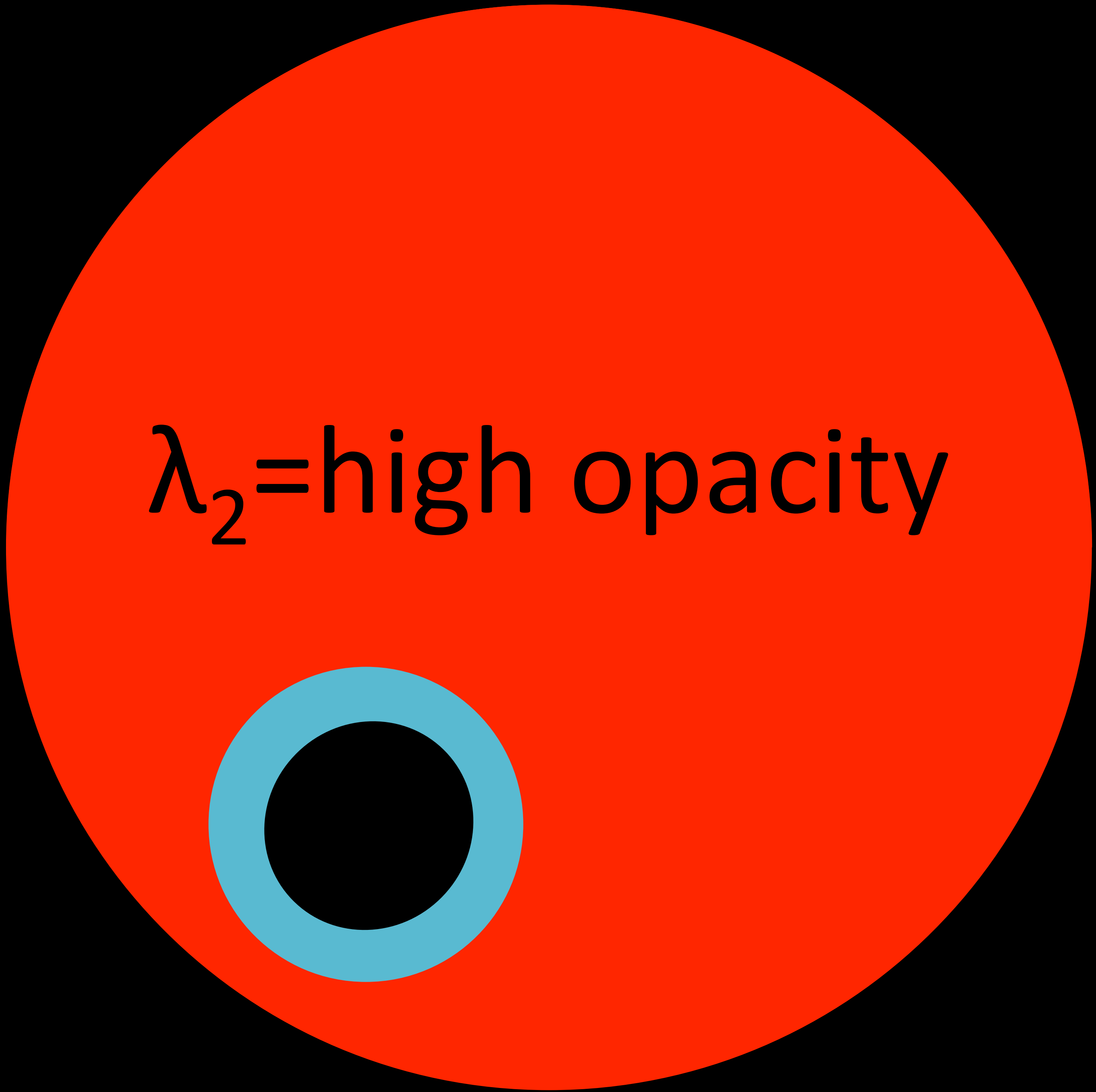
(Cowan 2014)

Transit

(Charbonneau+2000; Henry+2000)



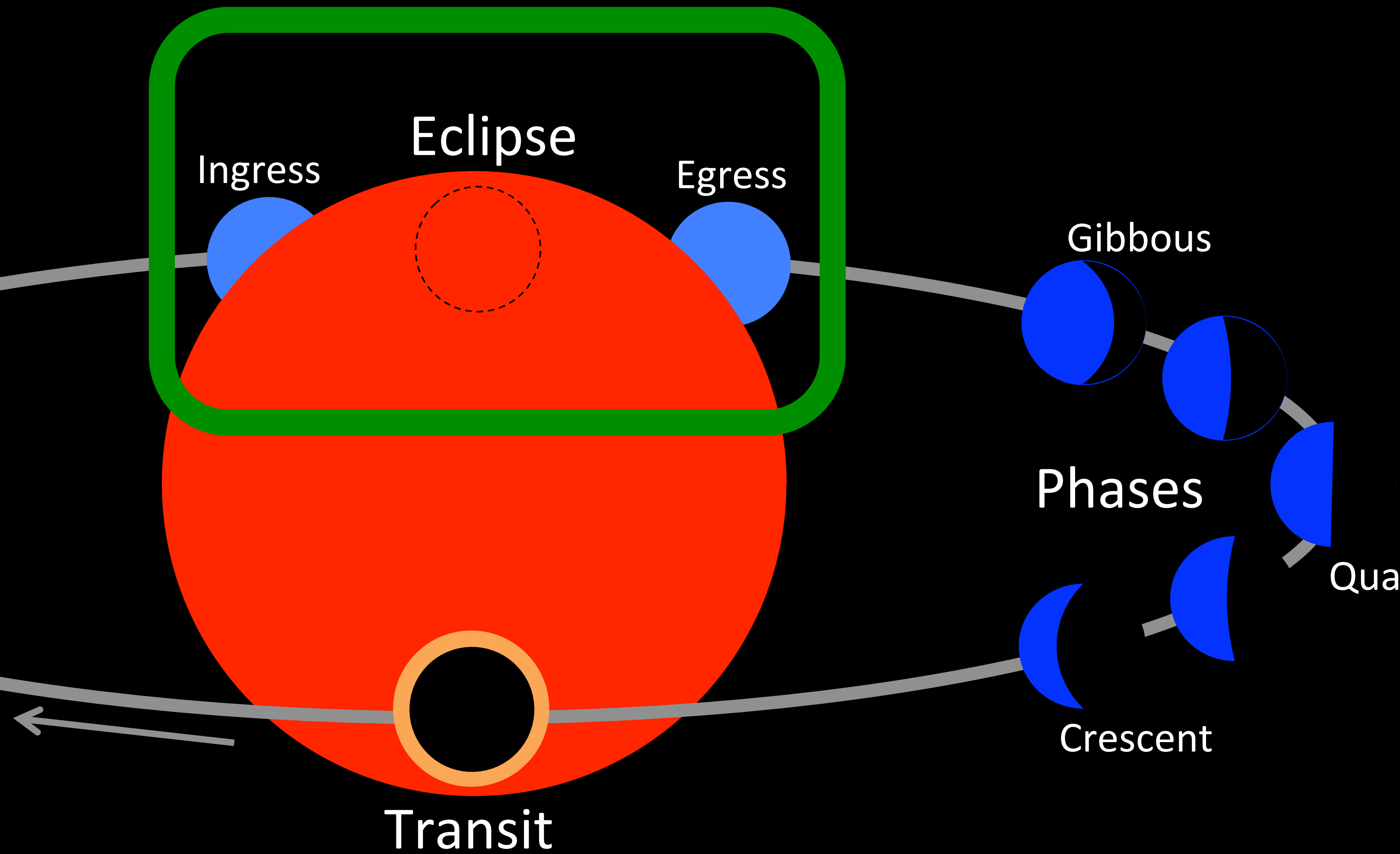

λ_1=low opacity


λ2=high opacity

Why Transit Spectroscopy?

(Burrows 2014)

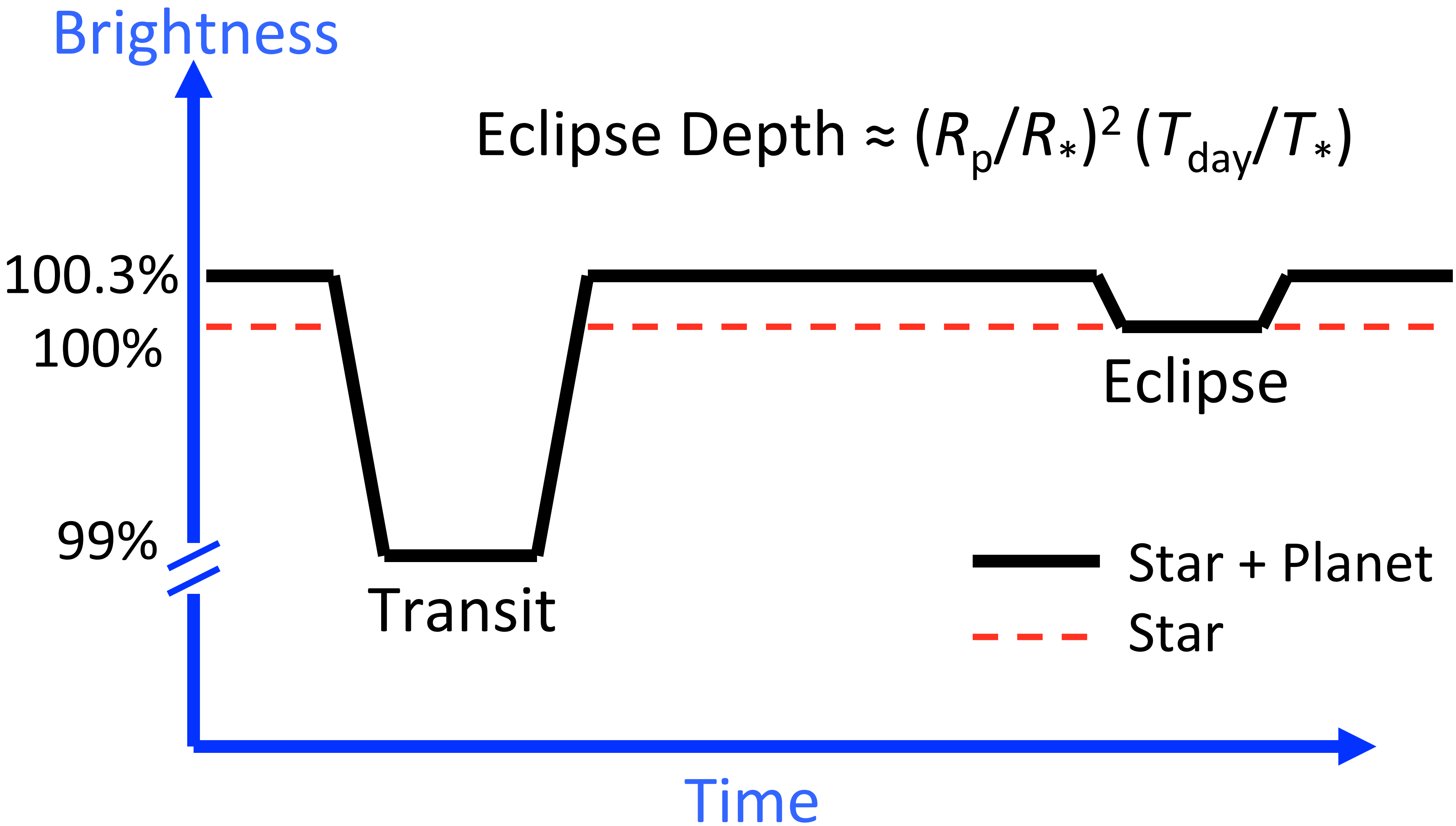
- Molecules *or Clouds*
- *If* Molecules:
  - Mean Molecular Mass
  - Abundances
  - Temperature


Eclipse
Ingress
Egress
Gibbous
Phases
Quarter
Crescent
Transit

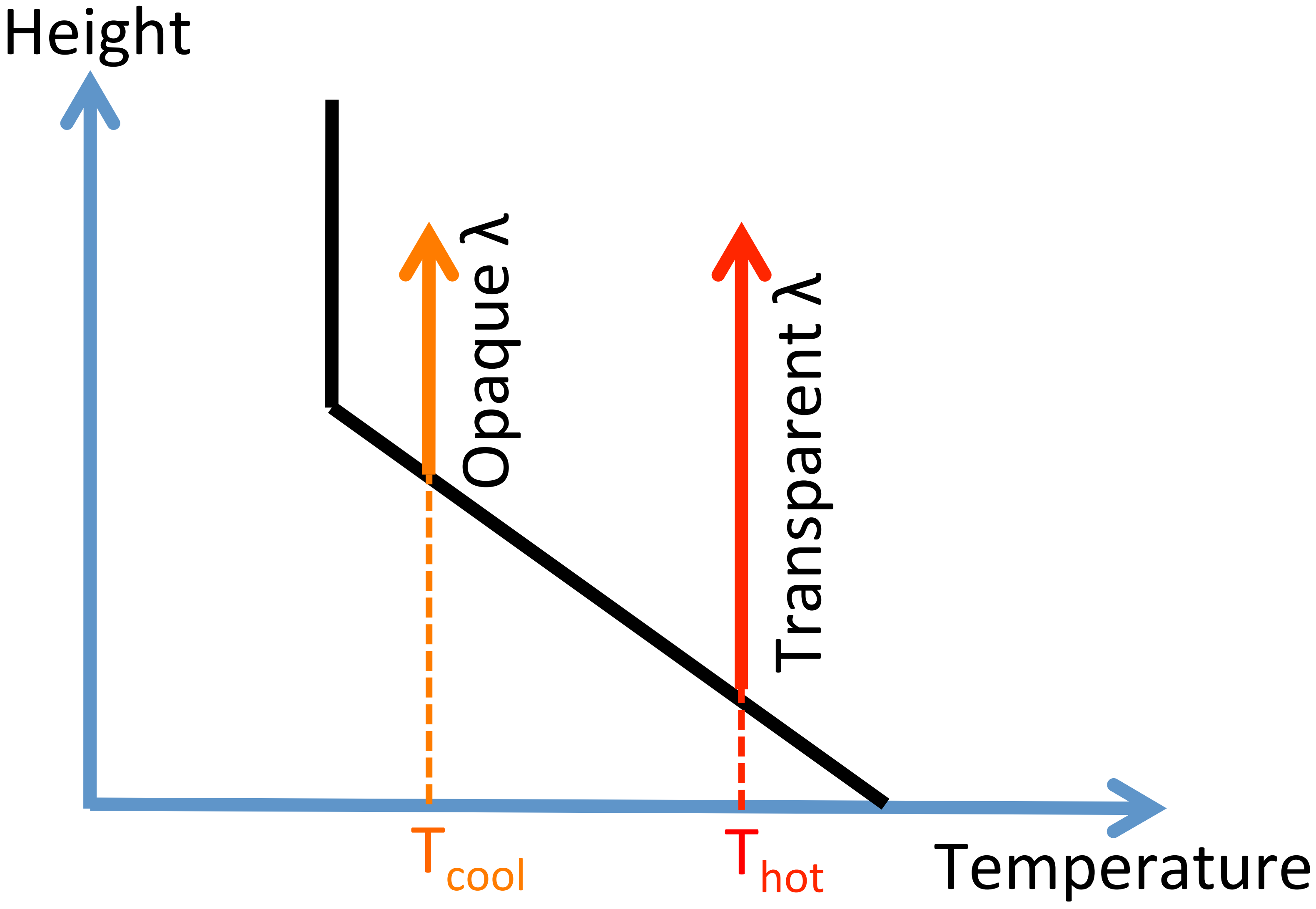
(Cowan 2014)

Eclipse

(Charbonneau+2005; Deming+2005)



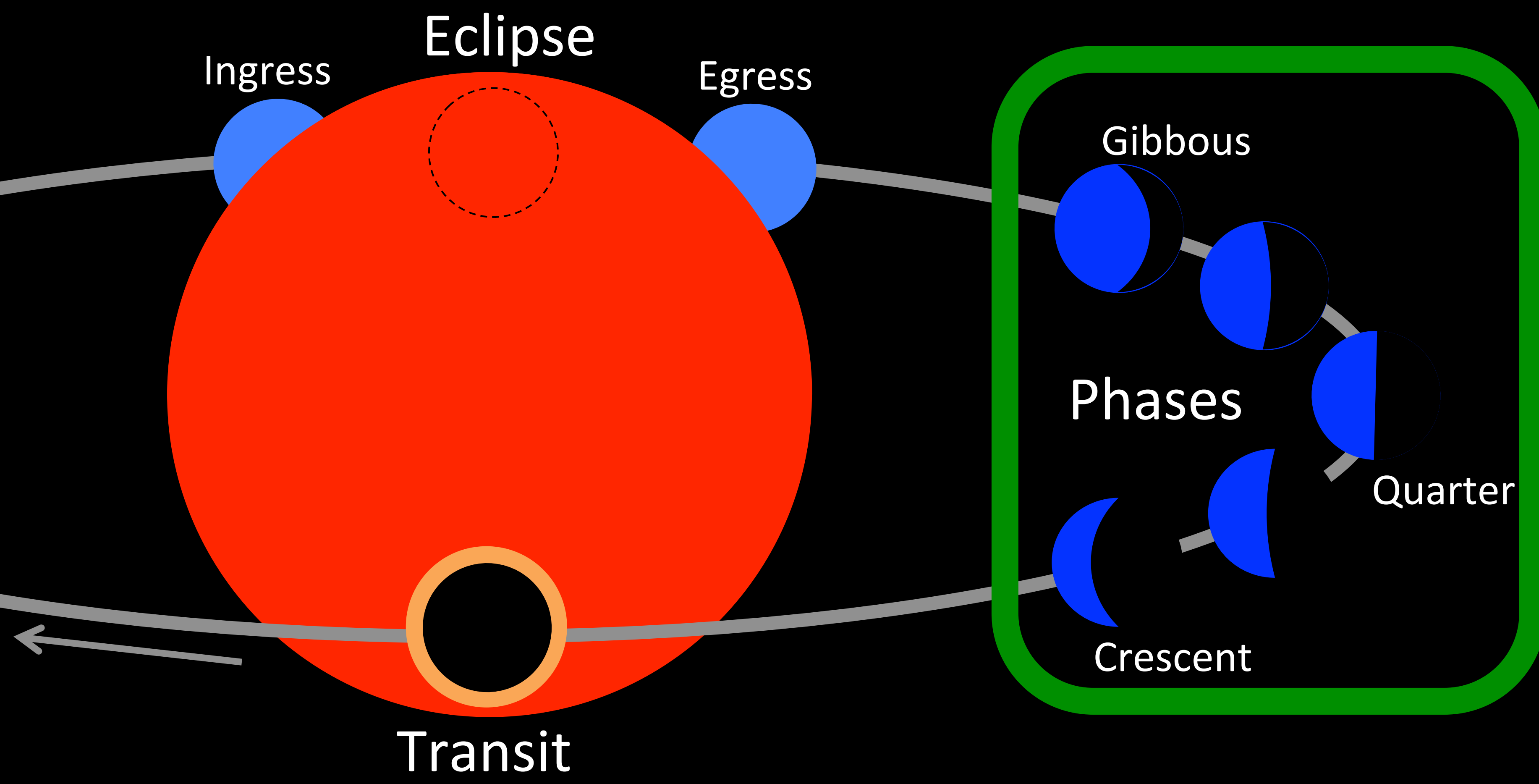
Emission Spectroscopy



Why Eclipse Spectroscopy?

(Burrows 2014)

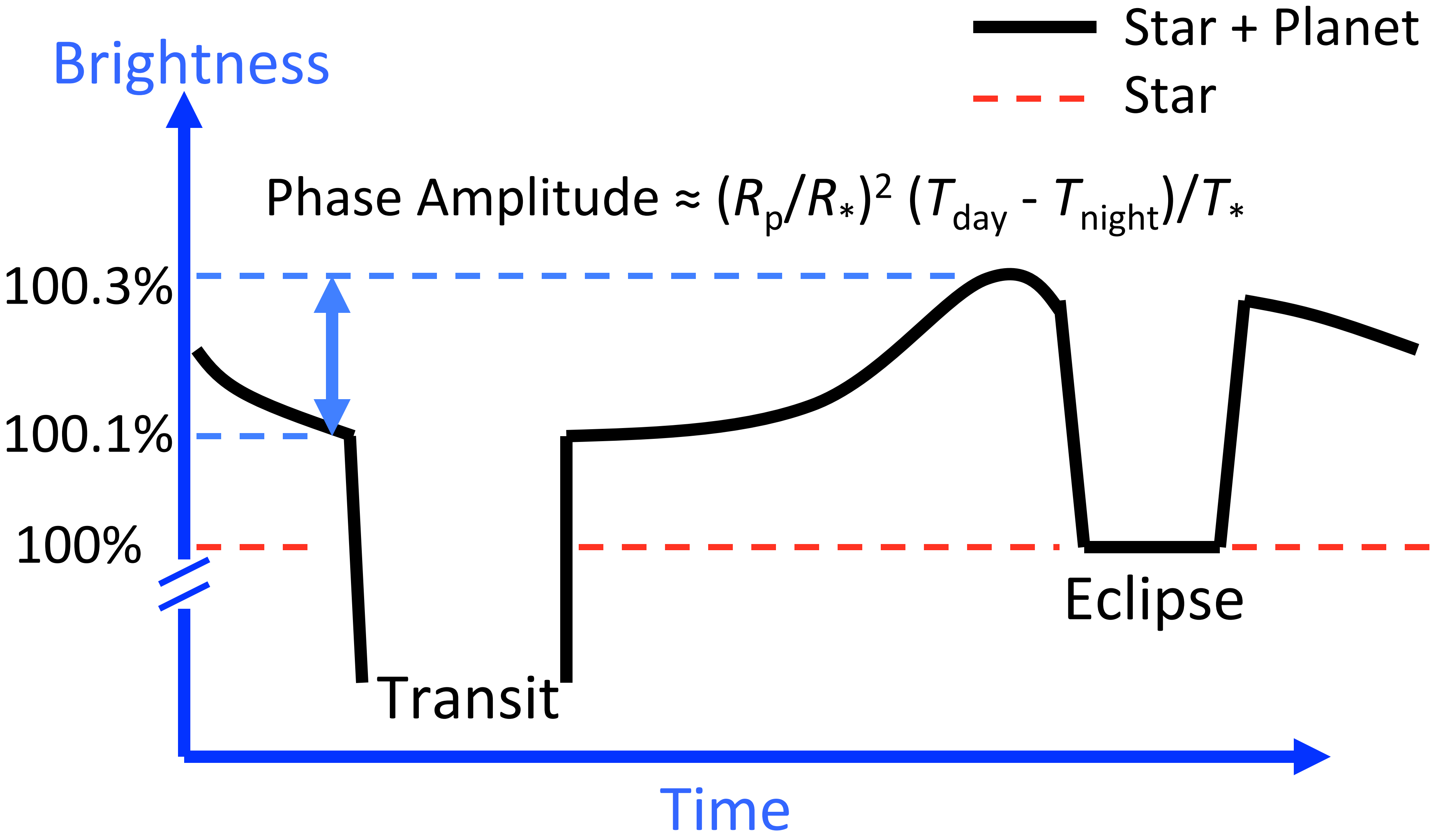
- Dayside Temperature
  - Bond Albedo
- Molecules
  - Abundances
  - Vertical Temperature Profile


Eclipse
Ingress
Egress
Transit
Gibbous
Phases
Quarter
Crescent

(Cowan 2014)

Phases

(Knutson+2007; Cowan+2007)

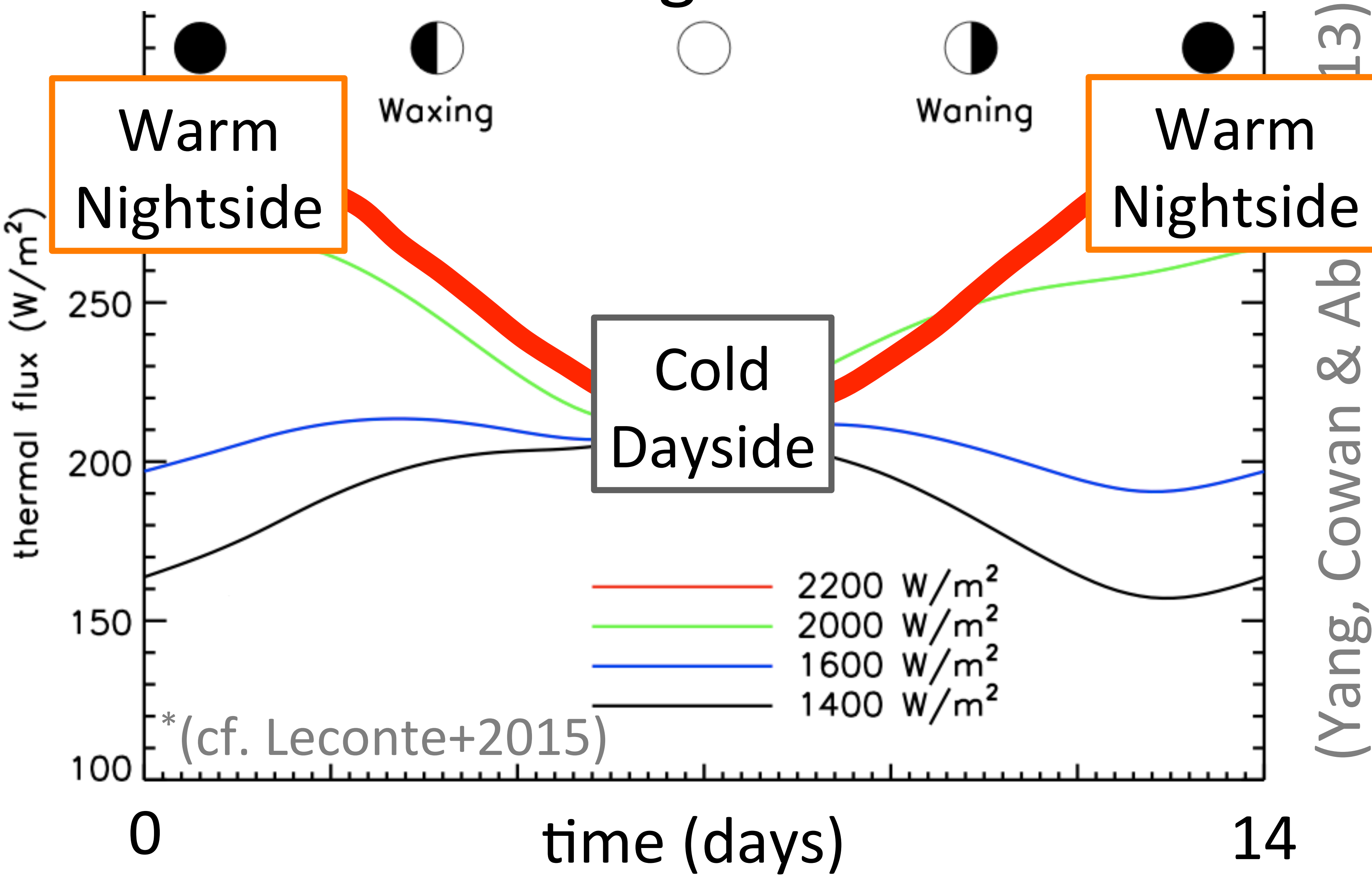


Why Phase Observations?

(Crossfield 2015)

- Nightside Temperature
  - Bond Albedo
  - Heat Transport
- *If* Phase Offset Detected:
  - Rotation and Winds
  - Clouds

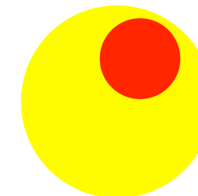
Simulated Phase Variations of T^3 Orbiting M5 Dwarf



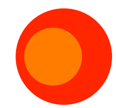

Cloud Shield

Archetypal Short-Period Planets

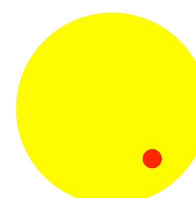
Hot Jupiter (HD 209458b, WASP-12b)



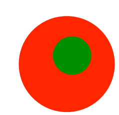
Warm Neptune (GJ 1214b)



Hot Earth (CoRoT-7b, Kepler 10b)

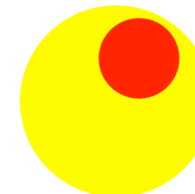


Temperate Earth (GJ XXXb)

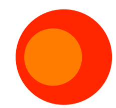


Single-Occultation JWST Performance

Reflected, Transit,
Peak Thermal, R-J Thermal



Reflected, Transit,
Peak Thermal, R-J Thermal

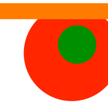


Reflected, Transit,
Peak Thermal, R-J Thermal

If Not Hazy/Cloudy

If MIRI → Poisson

Reflected, Transit,
Peak Thermal, R-J Thermal



JWST Observing Portfolio

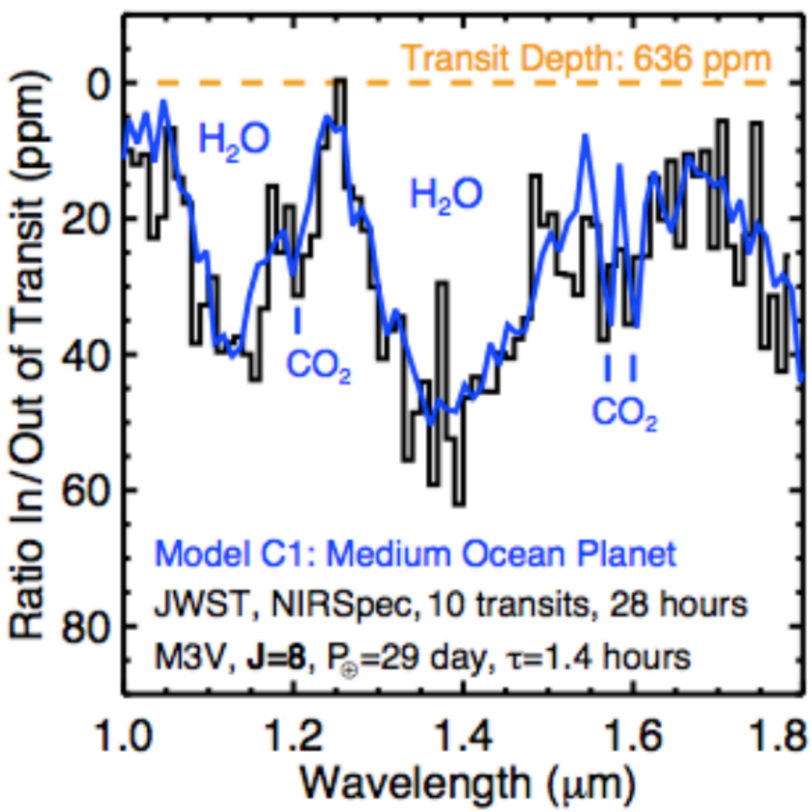
5 yrs
x 70% Duty Cycle
<u>x 25% for transits*</u> (Beichman)
= **300 days**

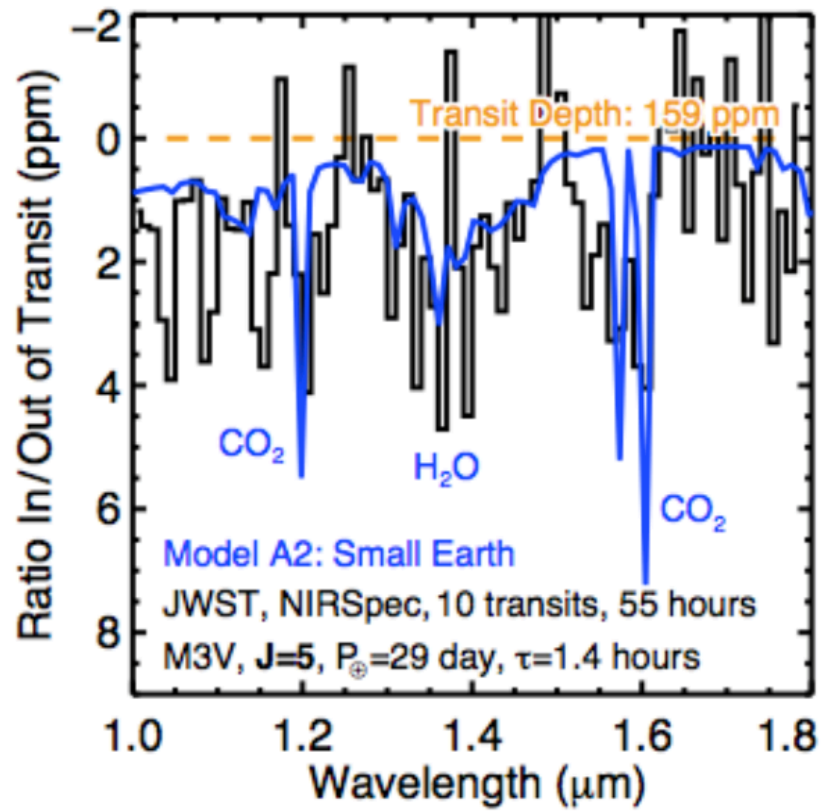
*If exoplaneteers write lots of proposals!

Temperate Terrestrials

Transit/Phase/Eclipse

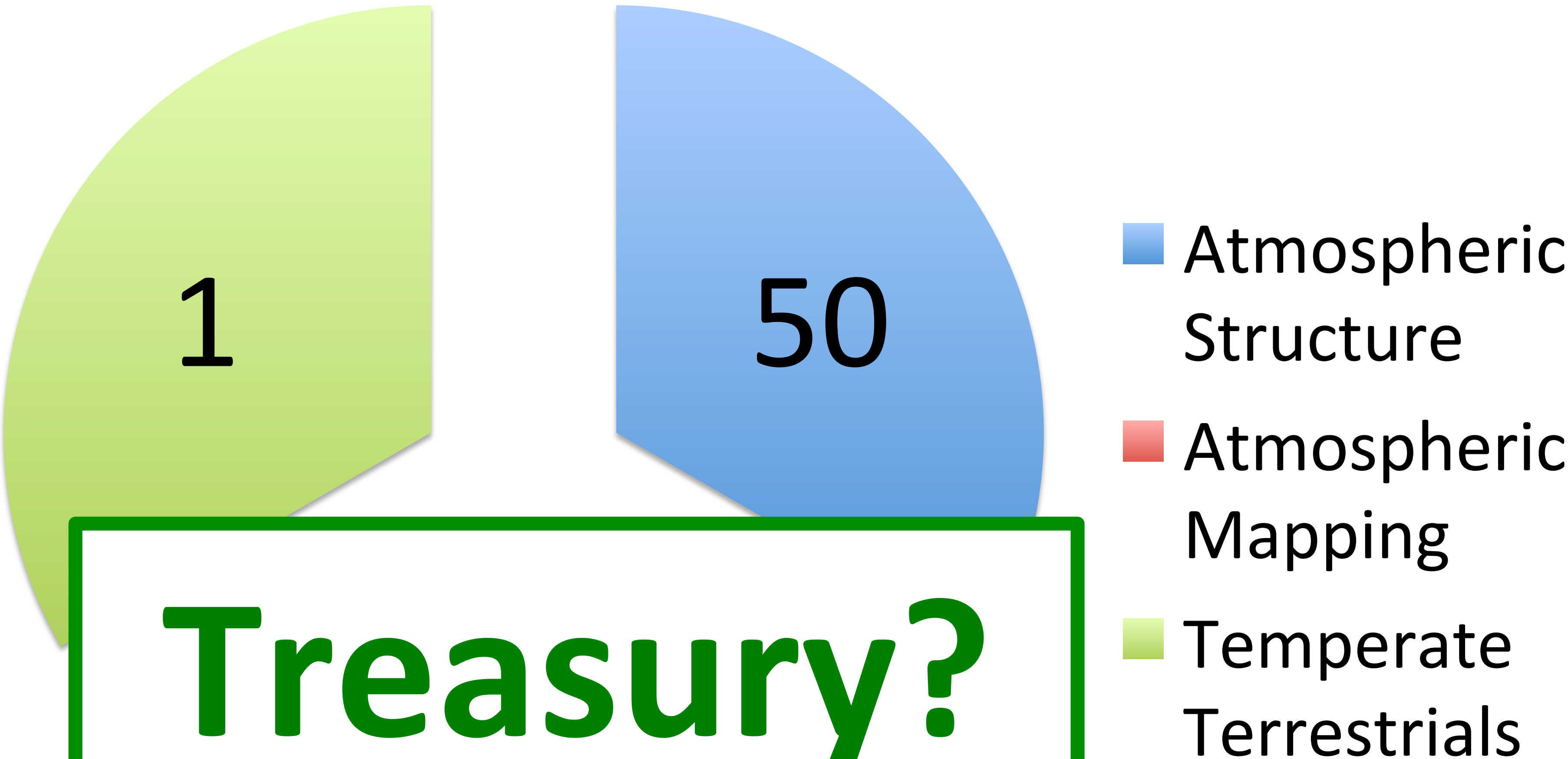
3 targets x 100 days/target = 300 days





(Seager, Deming & Valenti 2009)

JWST Observing Portfolio



Treasury?

DDT ?

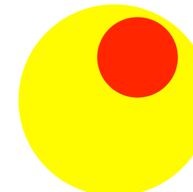
Take Home Points

- Most temperate terrestrials orbit M-Dwarfs
- JWST can observe Transits (NIR), Eclipses and Phases (MIR) of T^3
- Robustly detecting a T^3 atmosphere will take *100 days and some luck*

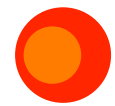
Extra Slides

Archetypal Short-Period Planets

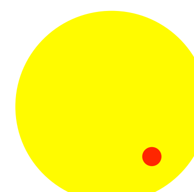
T_{eff}=5000 K, R_p=1.1R_J, a/R_*=5,
μ=2, g=20 m/s^2



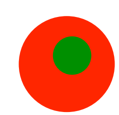
T_{eff}=3000 K, R_p=2.8$\mathrm{R_E}$, a/R_*=15,
μ=2, g=9 m/s^2



T_{eff}=5000 K, R_p=1.5R_E, a/R_*=3,
μ=140, g=12 m/s^2



T_{eff}=3000 K, R_p=1.5$\mathrm{R_E}$, a/R_*=90,
μ=28, g=12 m/s^2



Signal & Noise Assumptions

- Poisson Limit*
- Blackbody SEDs
- Transit Features: 4H
- Emission Features: $(1/2)^{1/4}$

*(feasible if we have A LOT of space-based data)

ATMOSPHERIC SIGNALS

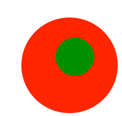
Planet type	Reflected contrast	Transit feature	Planet peak contrast	Rayleigh-Jeans contrast
Hot Jupiter	$\mathbf{2.6 \times 10^{-4}}$	$\mathbf{8.3 \times 10^{-4}}$	$\mathbf{7.4 \times 10^{-4}}$	$\mathbf{7.7 \times 10^{-3}}$
Hot Earth	$\mathbf{9.8 \times 10^{-6}}$	$\mathbf{3.0 \times 10^{-6}}$	$\mathbf{1.8 \times 10^{-5}}$	$\mathbf{1.4 \times 10^{-4}}$
Warm sub-Neptune	1.9×10^{-5}	$\mathbf{2.0 \times 10^{-3}}$	1.8×10^{-4}	$\mathbf{3.0 \times 10^{-3}}$
Temperate Earth	*1.5×10^{-7}*	2.3×10^{-5}	*1.5×10^{-5}*	3.5×10^{-4}

NOTE.—Fonts denote the difficulty of measuring these signals with *JWST* in the white-light photon-counting limit (cf. Table 3): bold indicates signal measured at $>10\sigma$ in a one hour integration, while italics denotes $<1\sigma$.

Single-Occultation JWST Performance

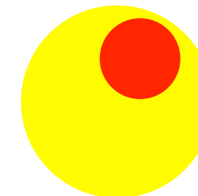
[1]Assuming No Hazes/Clouds
[2]Assuming MIRI Reaches Poisson Limit

Reflected, **Transit**[1],
Peak Thermal, **R-J Thermal**[2]



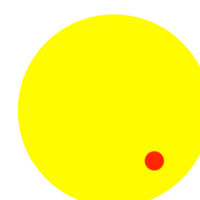
Single-Occultation JWST Performance

Reflected, Transit,
Peak Thermal, R-J Thermal

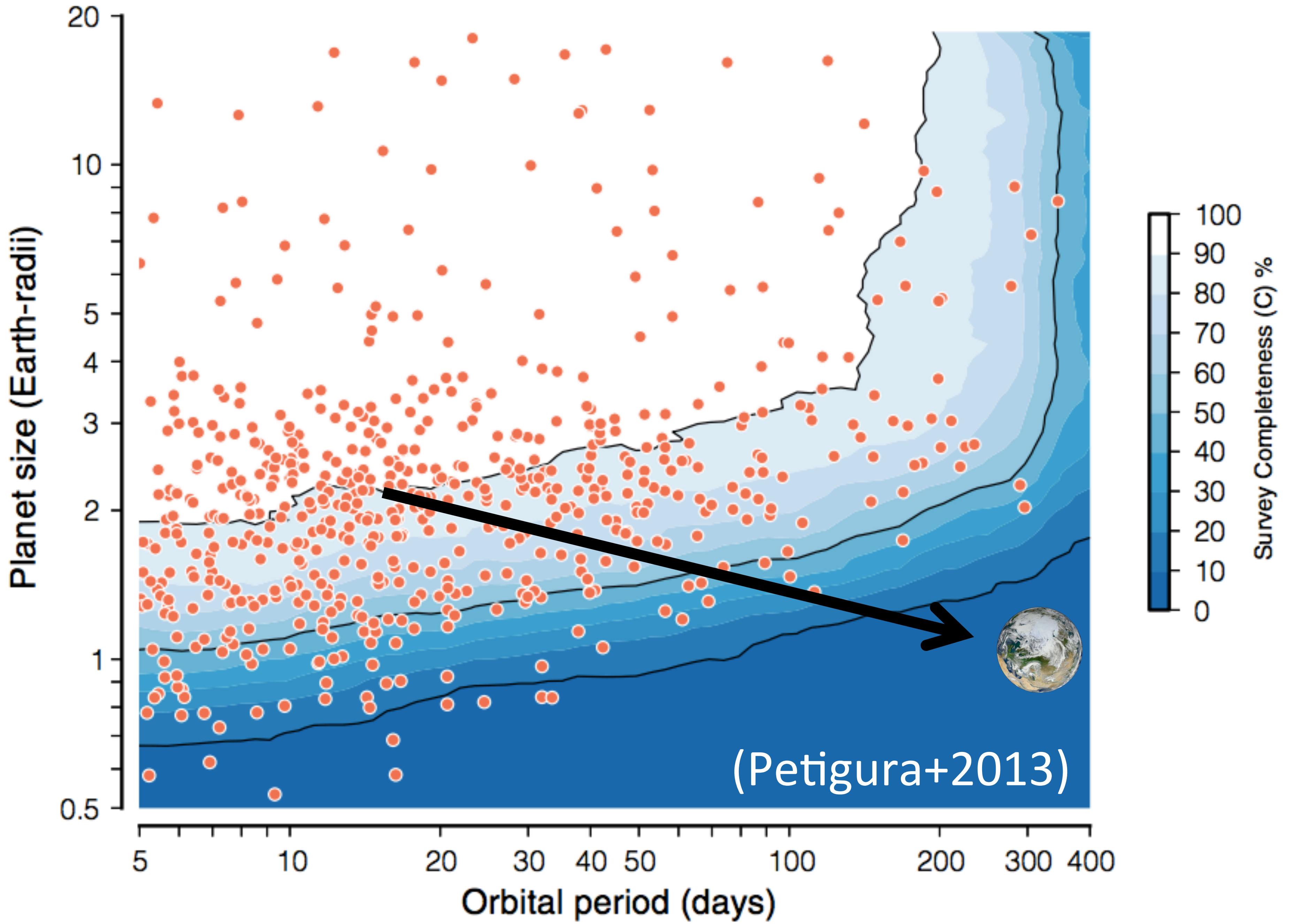


TESS Will Discover Hundreds of Bright Warm (Sub) Neptunes: Need Triage

Reflected, Transit,
Peak Thermal, R-J Thermal



[1]Assuming No Hazes/Clouds
[2]Assuming MIRI Reaches Poisson Limit



Planet size (Earth-radii)
20
10
5
4
3
2
1
0.5
5
10
20
30
40
50
100
200
300
400
Orbital period (days)
Survey Completeness (C) %
100
90
80
70
60
50
40
30
20
10
0
(Petigura+2013)

Drumroll, Please

22% of Sun-Like Stars have an Earth Analog

(Petigura+2013, Gaidos+2014)

…or more like 2%

(Foreman-Mackey+2014, Farr+2015)

The Faint Majority

15% of Red Dwarf Stars have an Earth Analog

(Dressing & Charbonneau 2013, 2015)

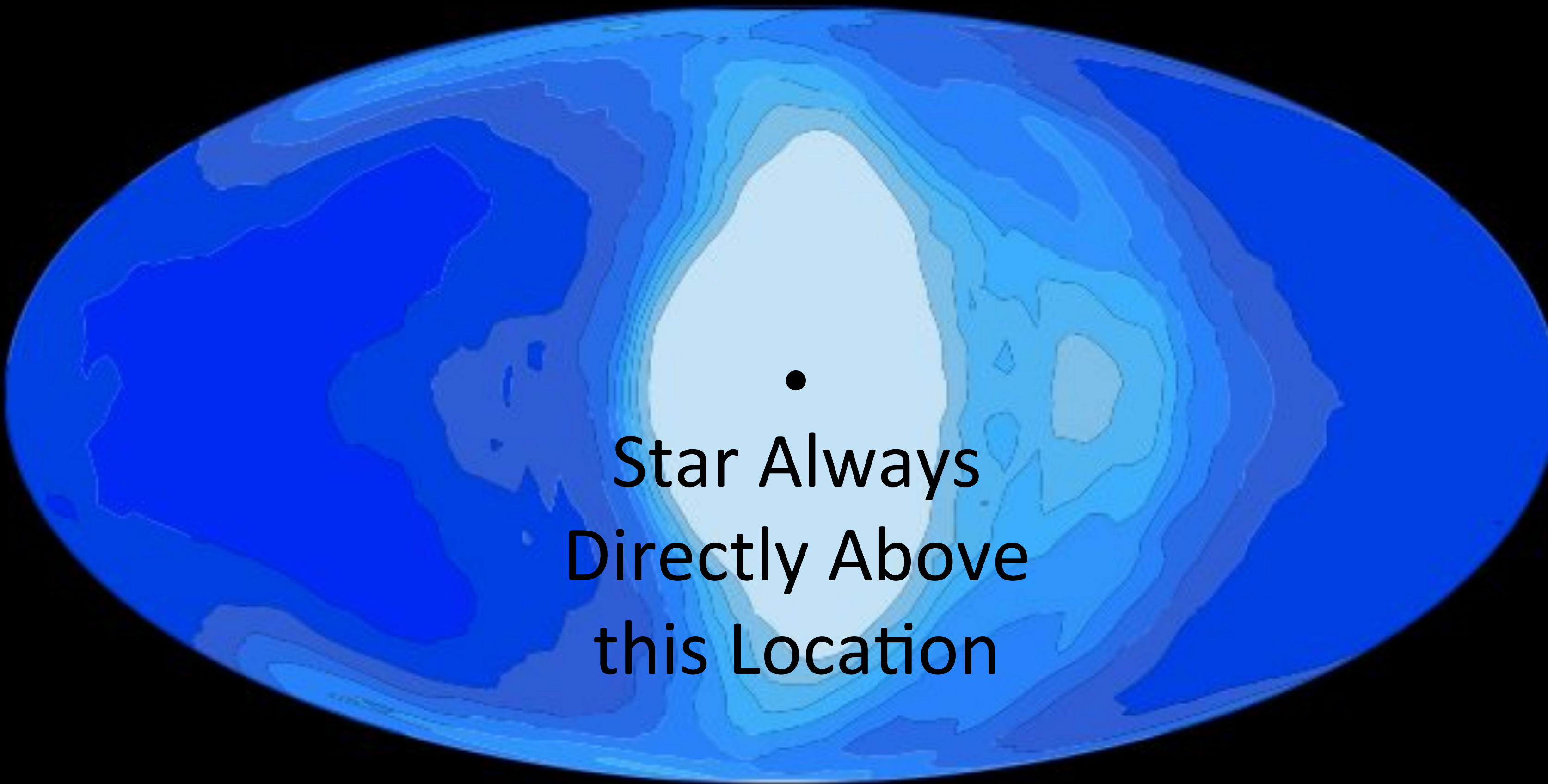
…or more like 50%

(Yang+2013)
(Kopparapu 2013)
(Morton+2014)

M-Dwarf Advantages

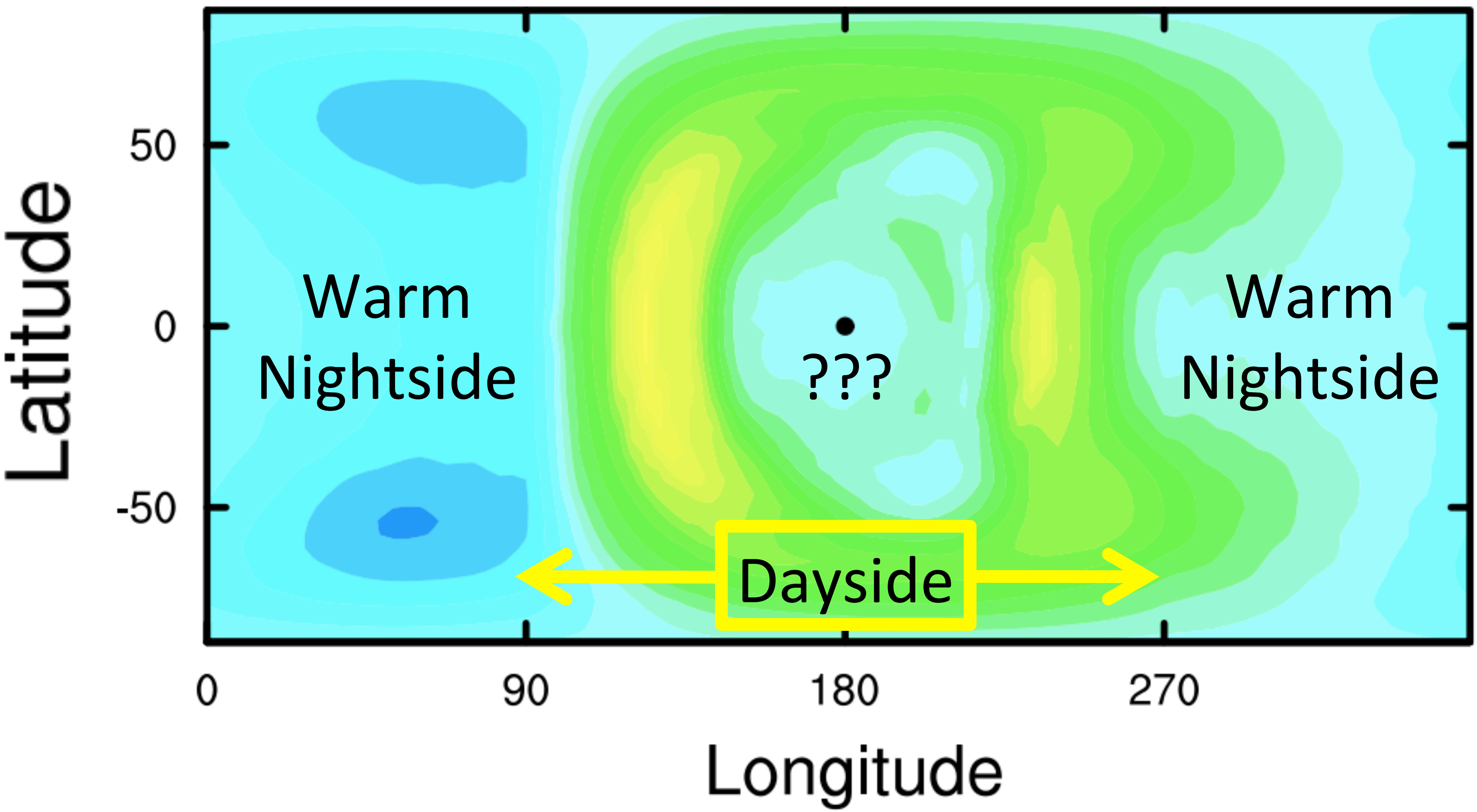
- Slow MS Evolution
  - (Kasting+1993)
- Stabler Climate
  - (Shields+2013, 2014)
- Cloud Shield
  - (Yang+2013, 2014)

Simulation of a Slowly-Rotating Earth



Yang, Cowan & Abbot (2013)

Simulated Thermal Map of Slowly-Rotating Earth



(Yang+2013, 2014)

Hubble eXtreme Deep Field
…for 1 planet !!

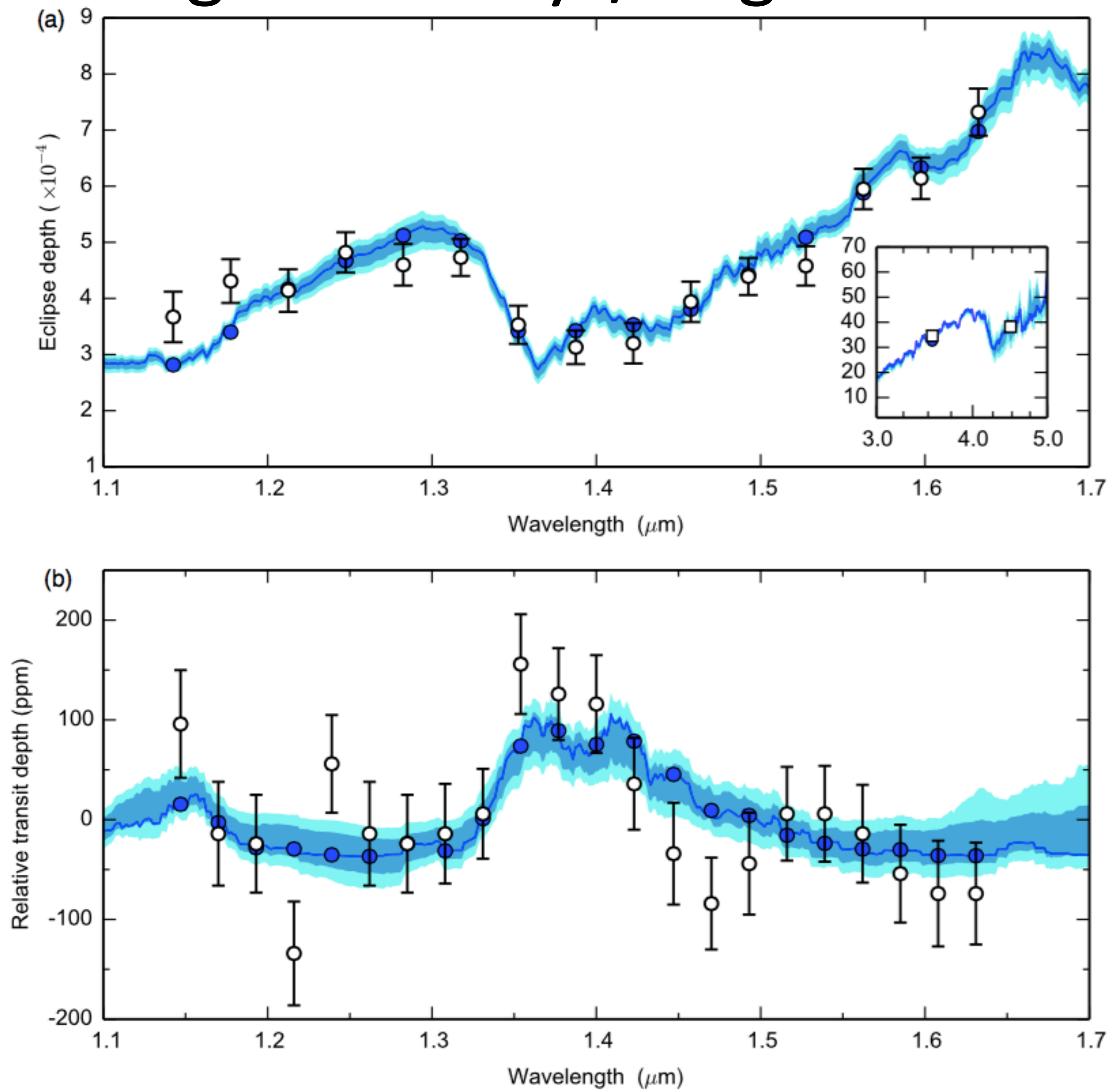
1. Nearly-Continuous Monitoring for Entire Planetary Orbit (1 month)
2. Every Transit of Planet Over Mission Lifetime (100 transits in 10 yrs = 1 month)

DDT !?

Atmospheric Structure

Transit + Eclipse Spectra

150 targets x 2 days/target = 300 days

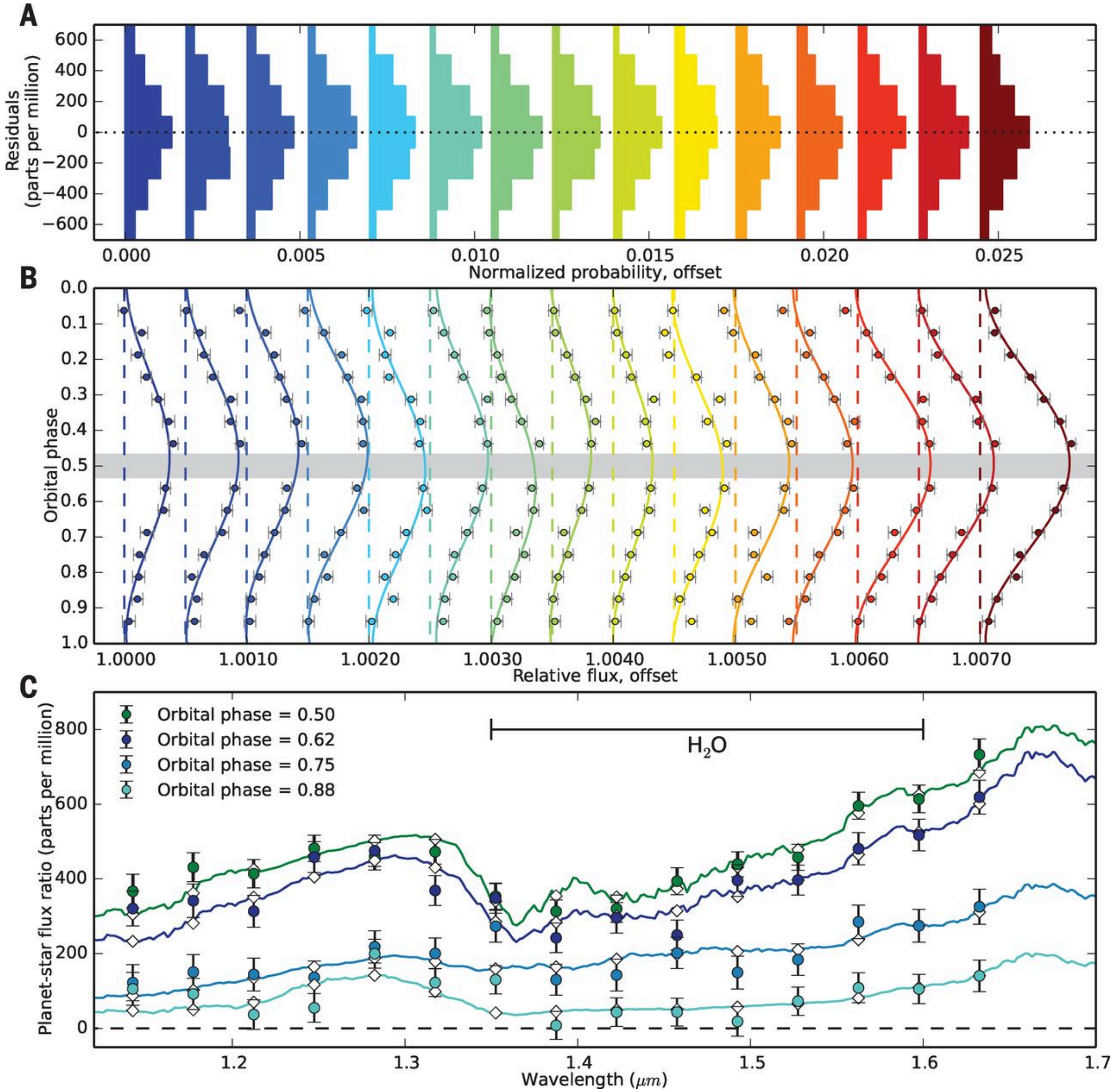


(Kreidberg et al. 2014)

Atmospheric Mapping

Phase Spectra

25 targets x 12 days/target = 300 days



(Stevenson et al. 2014)

and what should they know of England who only England know?

-Rudyard Kipling (1891)

and what should they know of Earth
who only Earth know?

-Nicolas Cowan (2015)