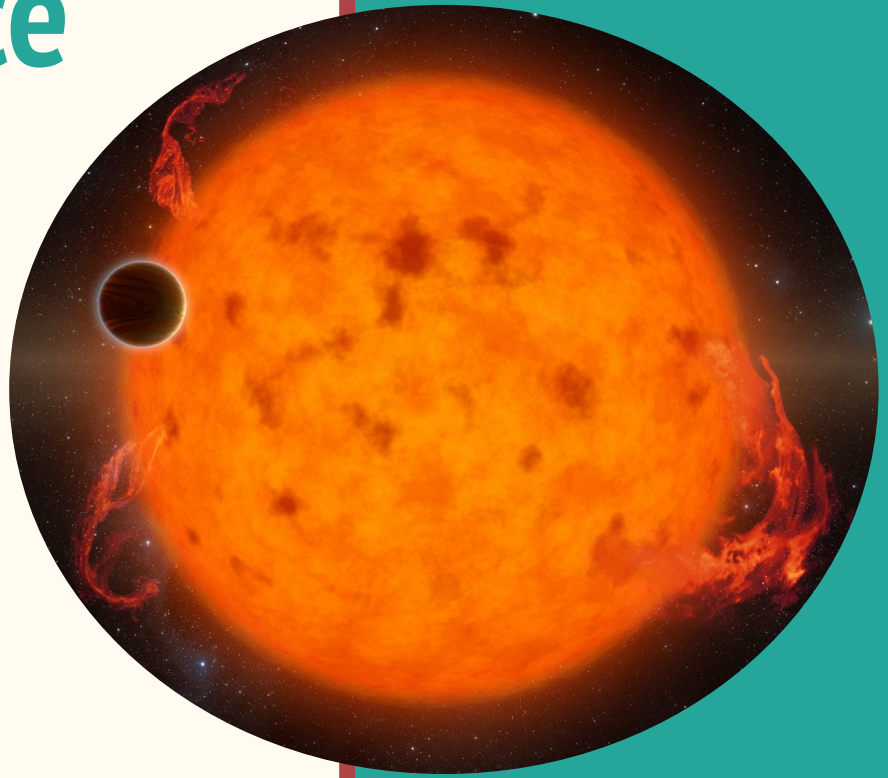
Hazy with a Chance of Star Spots:

Constraining the Atmosphere of the Young Planet, K2-33b

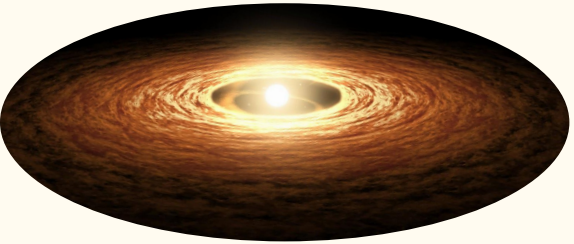


Pa Chia Thao | UNC Chapel Hill

ExoExplorers Talk
March 17th, 2023

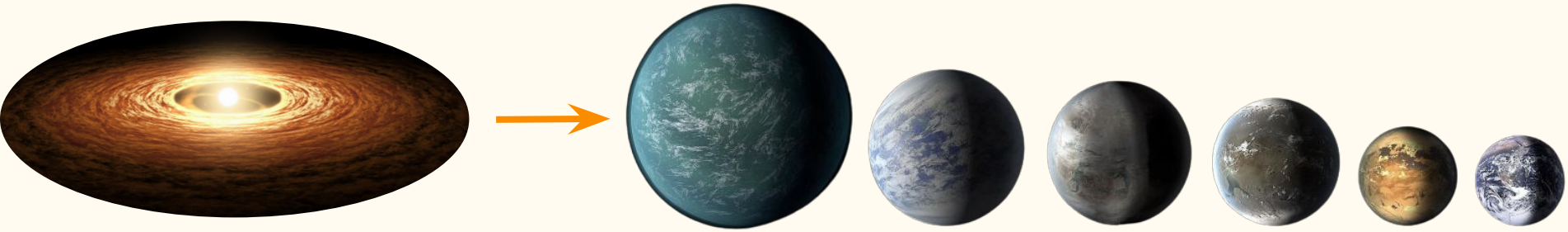
Image Credit: NASA/JPL-Caltech

How do planets evolve throughout their lifetime?



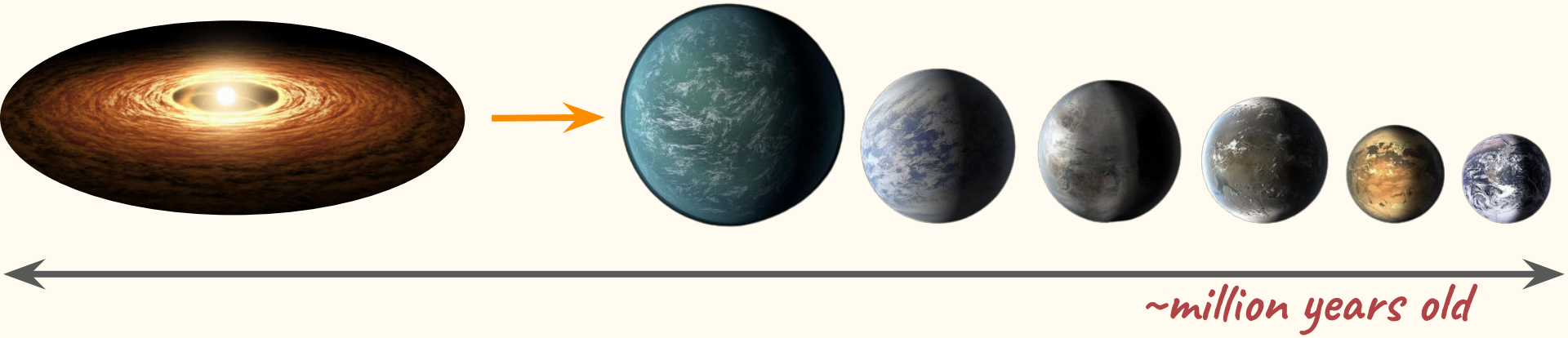
How do planets evolve throughout their lifetime?

Image Credit: NASA/JPL-Caltech



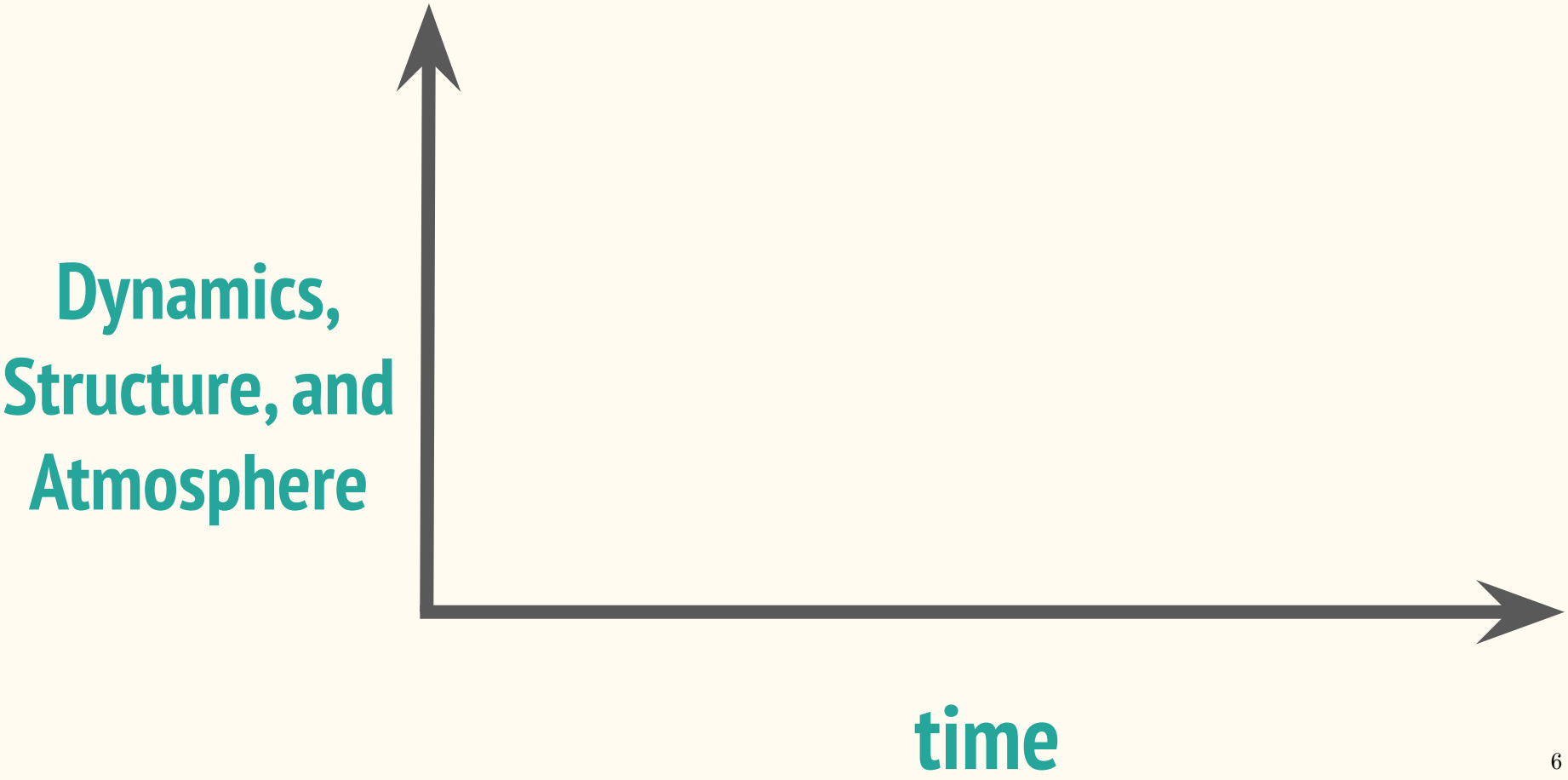
How do planets evolve throughout their lifetime?

Image Credit: NASA/JPL-Caltech

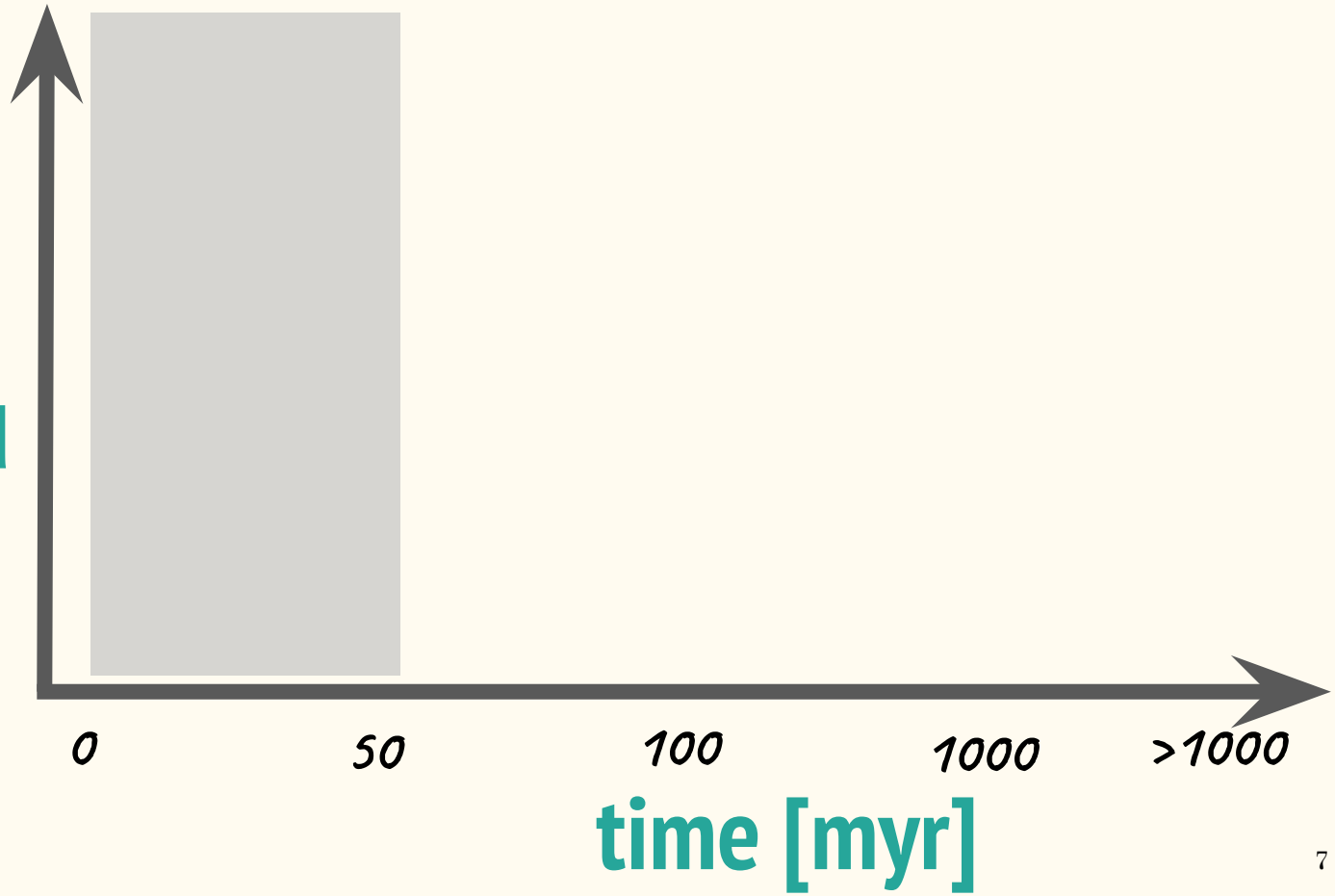


How do planets evolve throughout their lifetime?

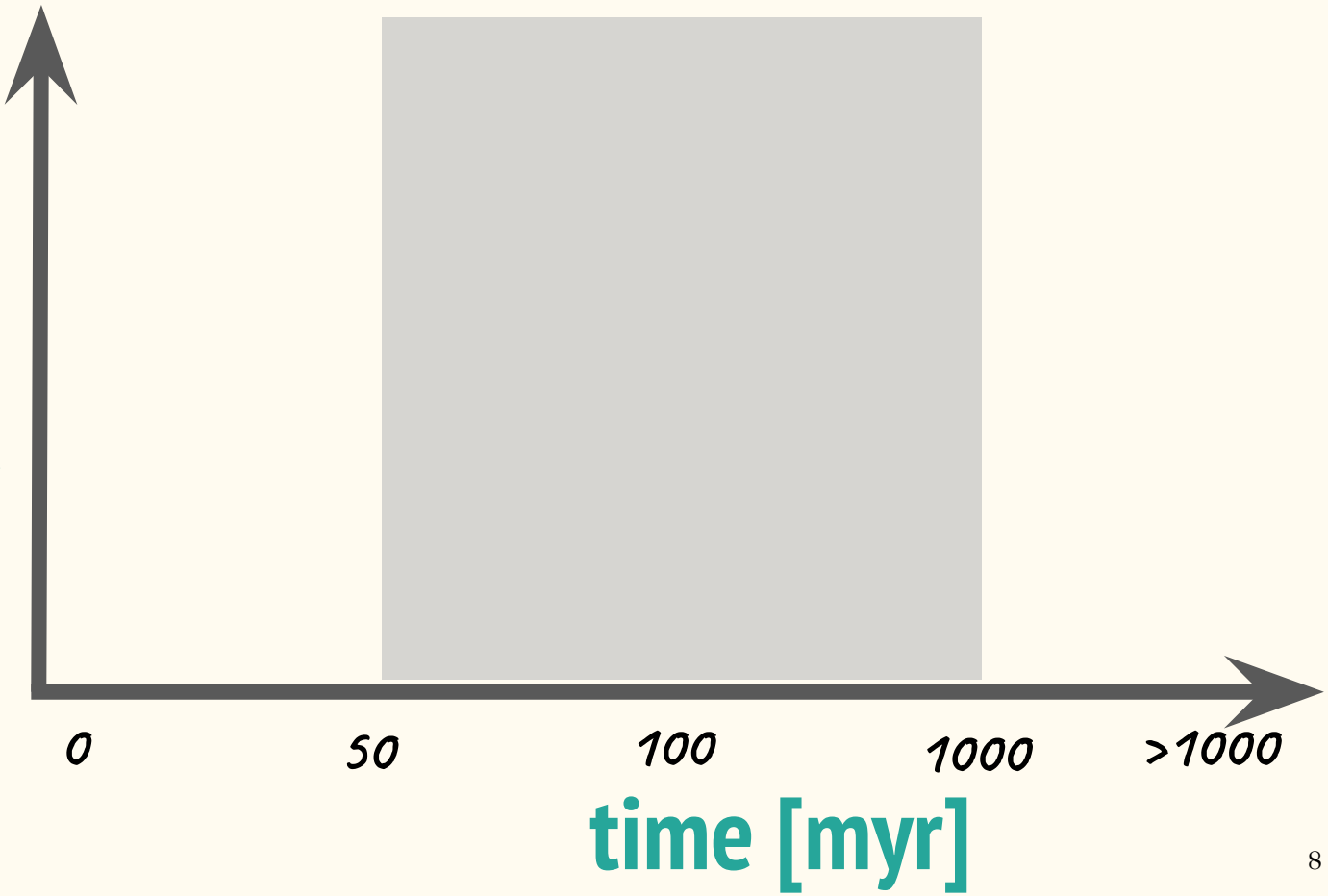
Image Credit: NASA/JPL-Caltech


Dynamics, Structure, and Atmosphere
time

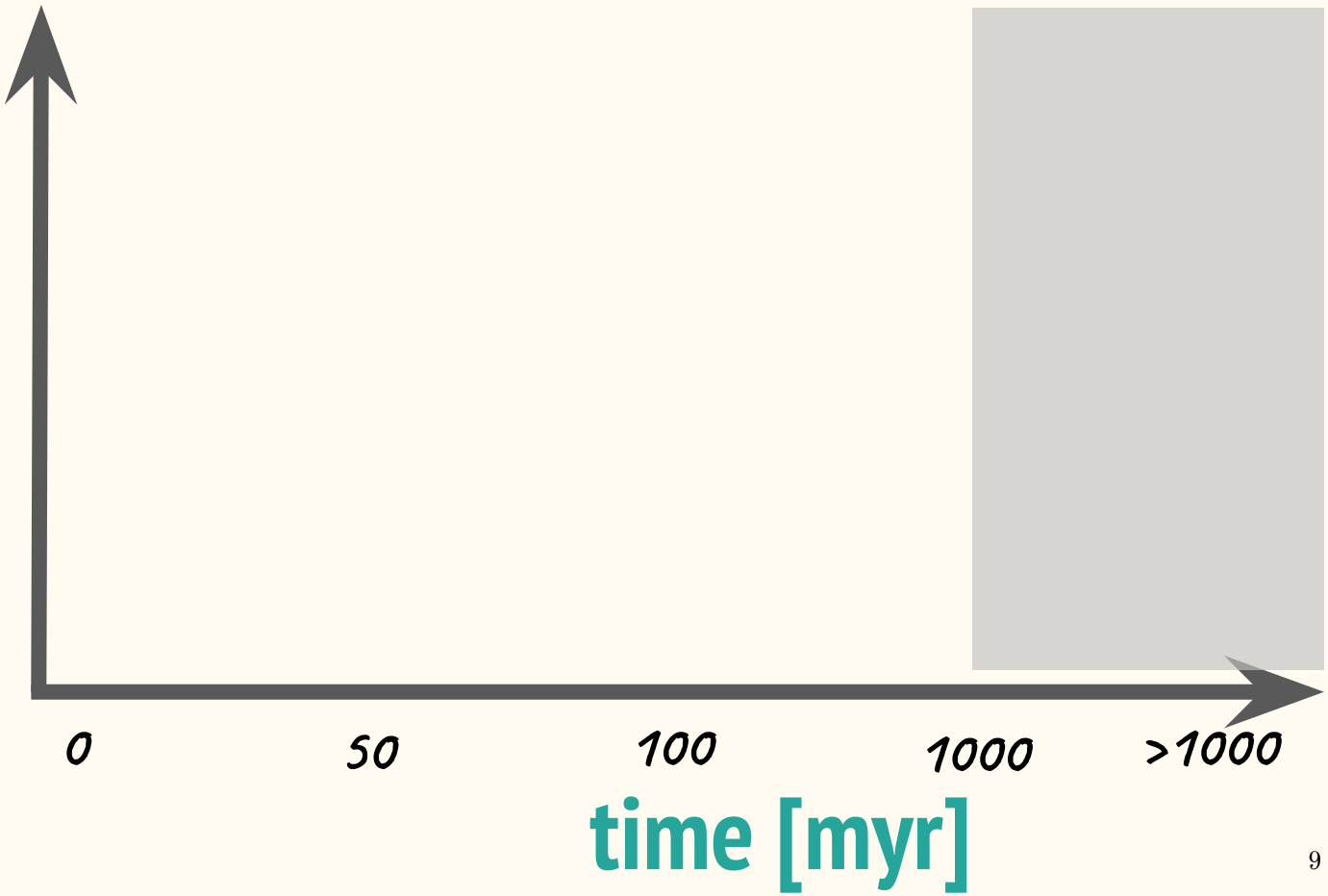
Dynamics, Structure, and Atmosphere

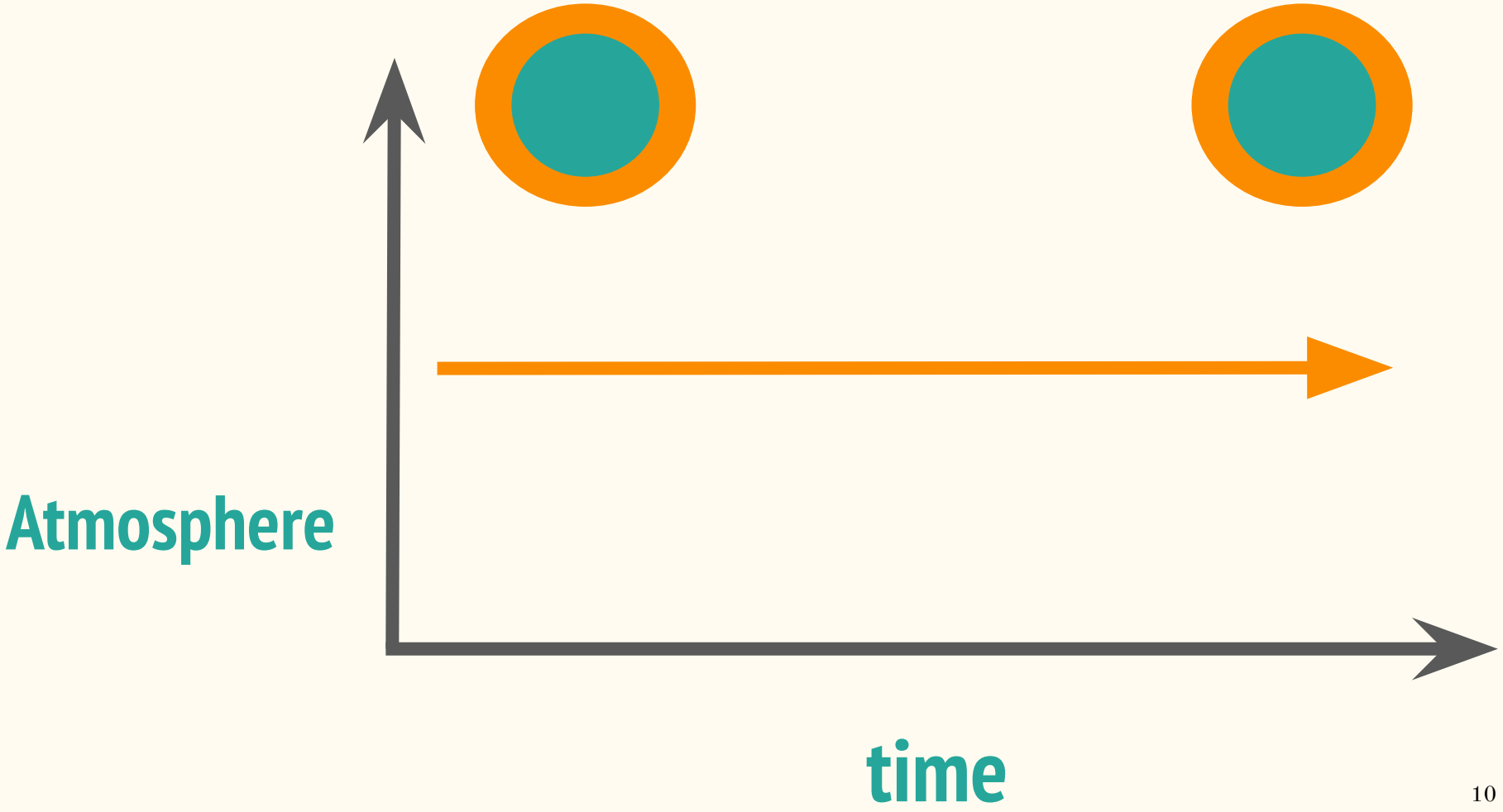


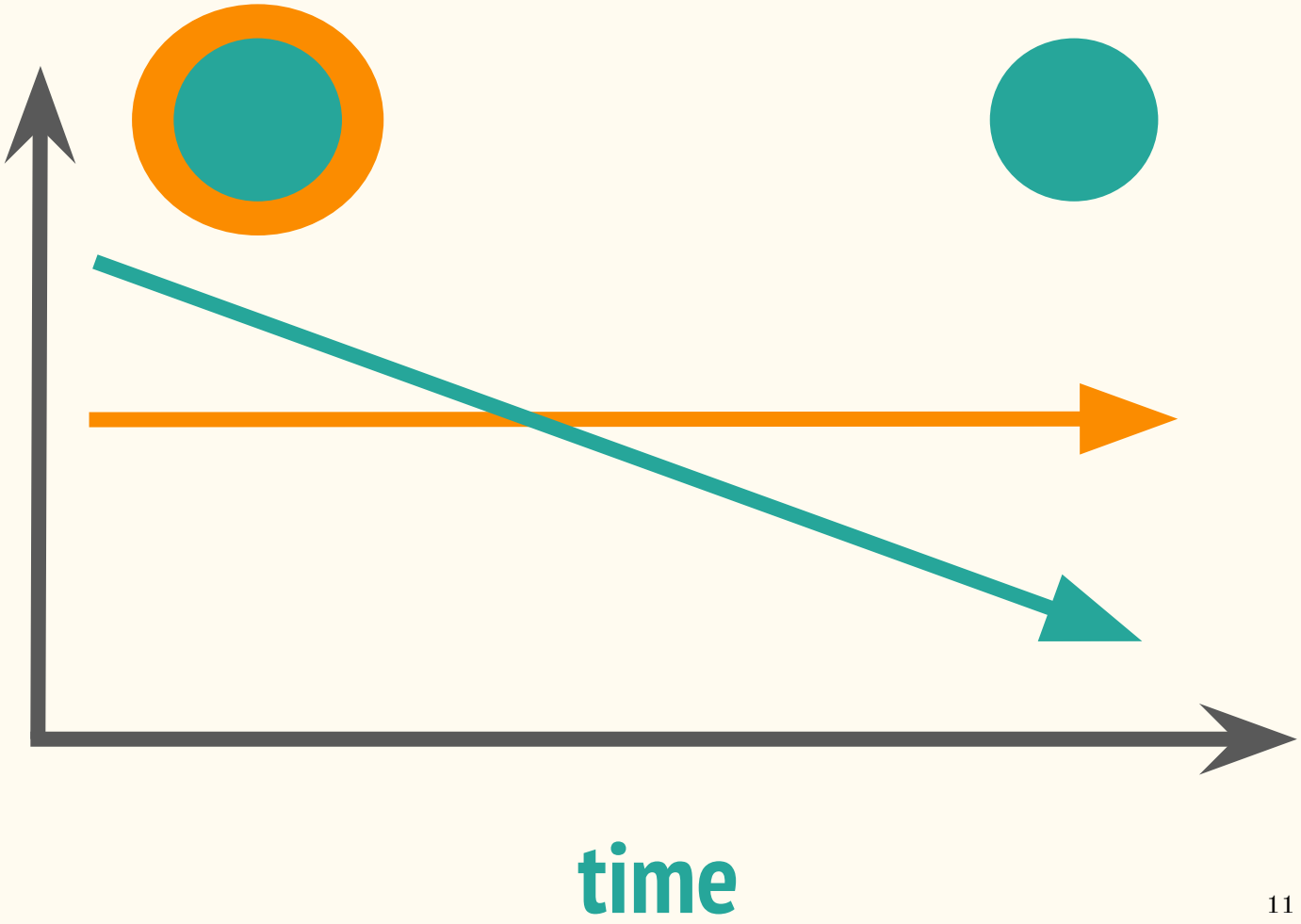
Dynamics, Structure, and Atmosphere

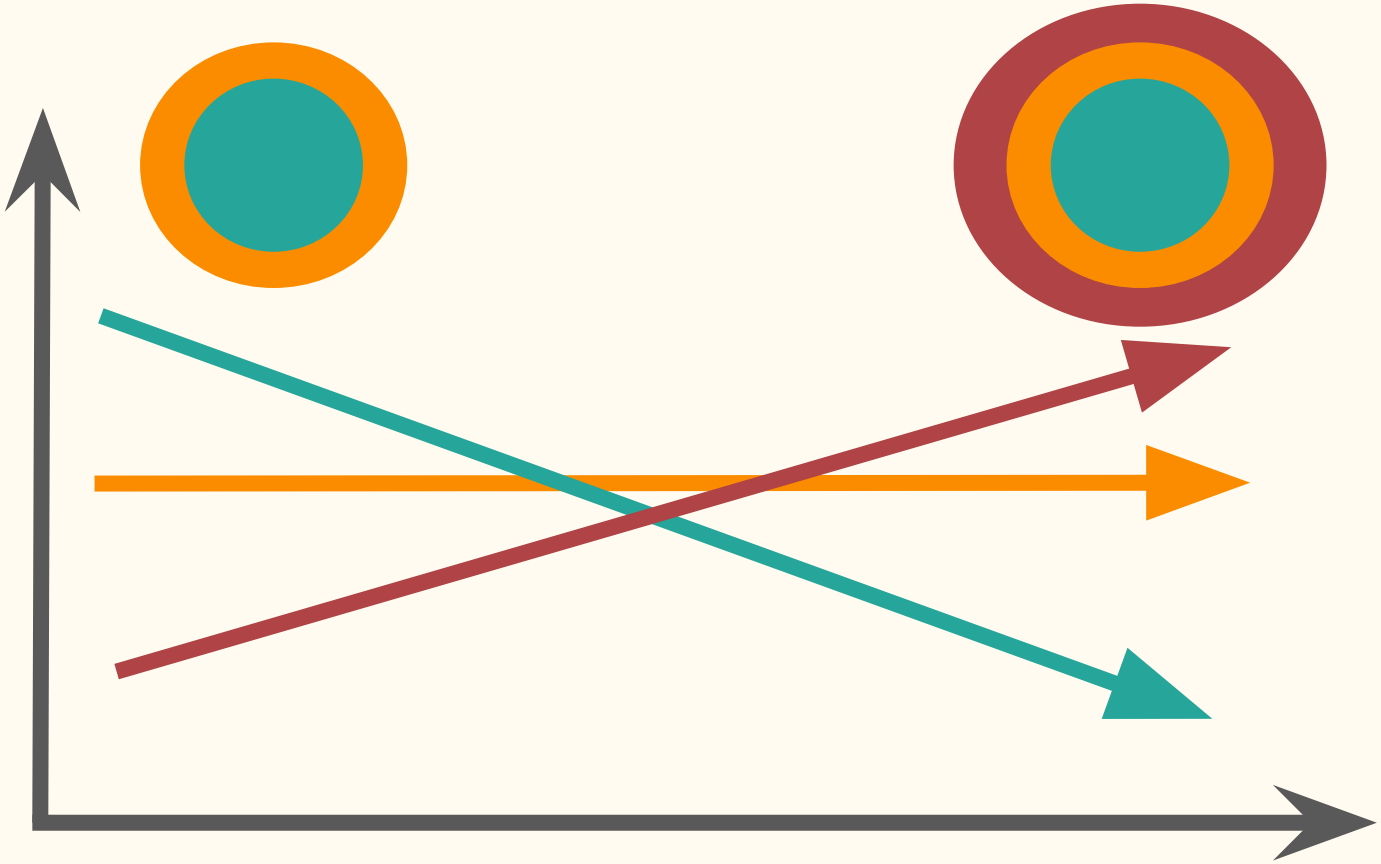


Dynamics, Structure, and Atmosphere

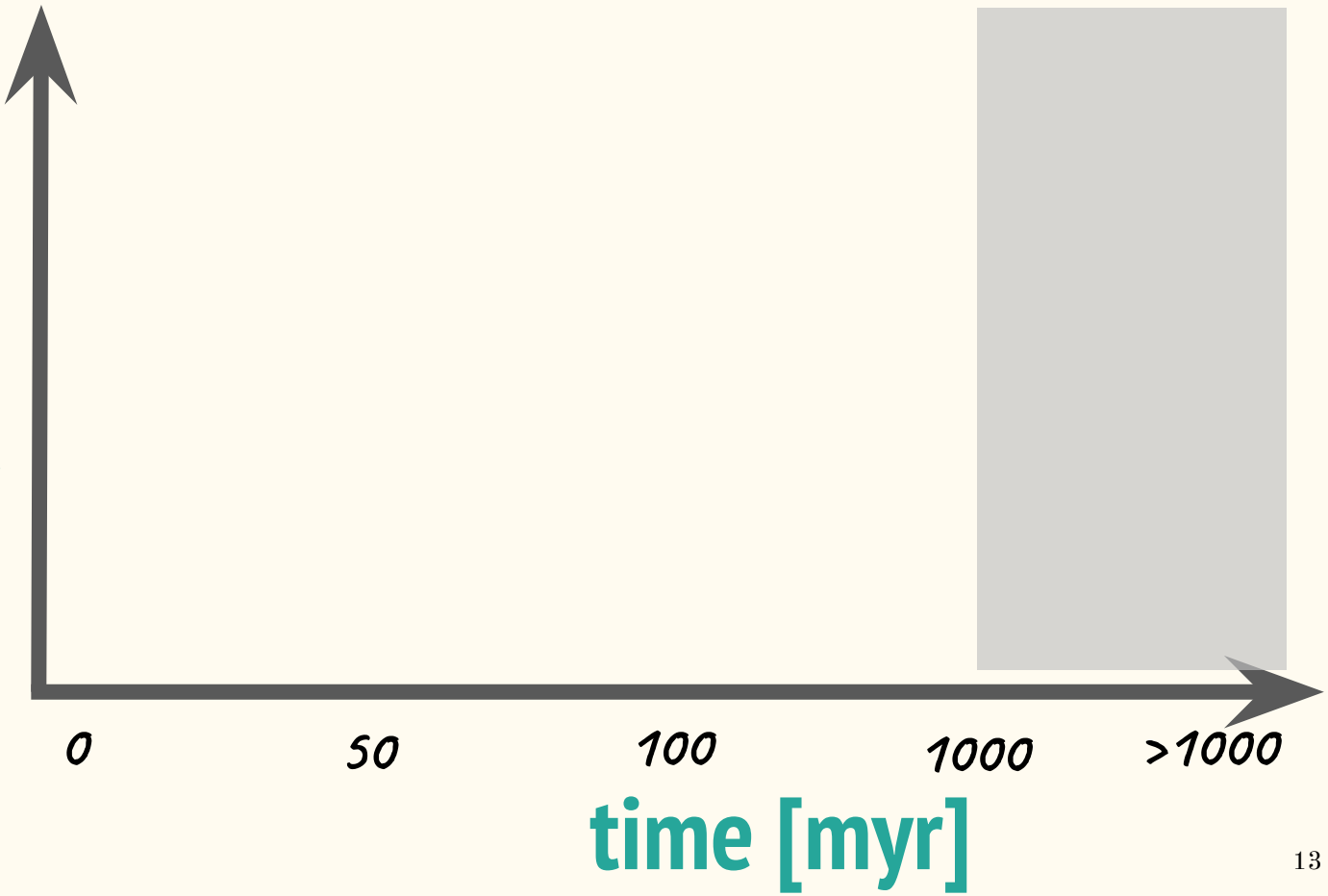



Atmosphere
time

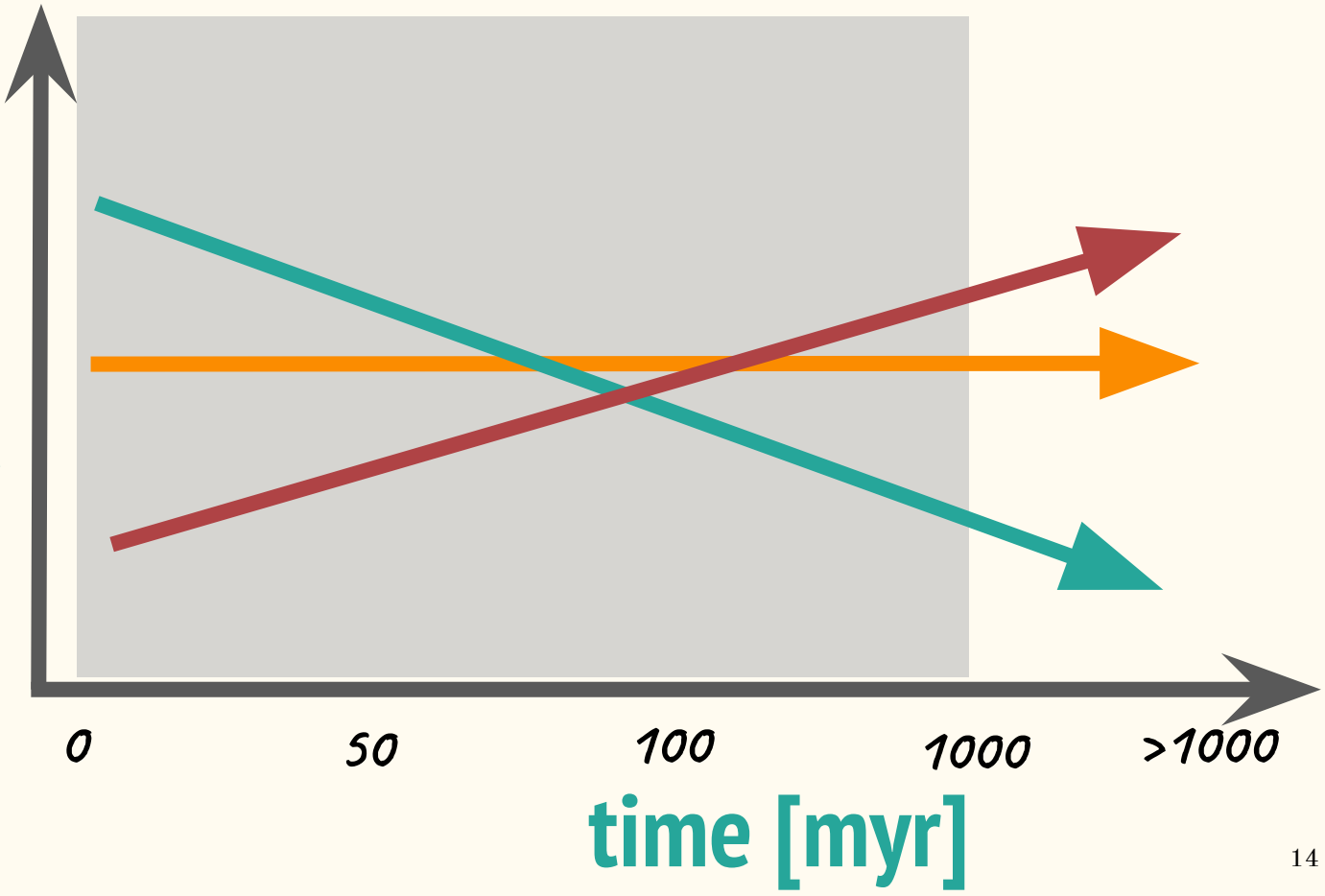

Atmosphere
time


Atmosphere
time

Dynamics, Structure, and Atmosphere



Dynamics, Structure, and Atmosphere



Dynamics, Structure, and Atmosphere

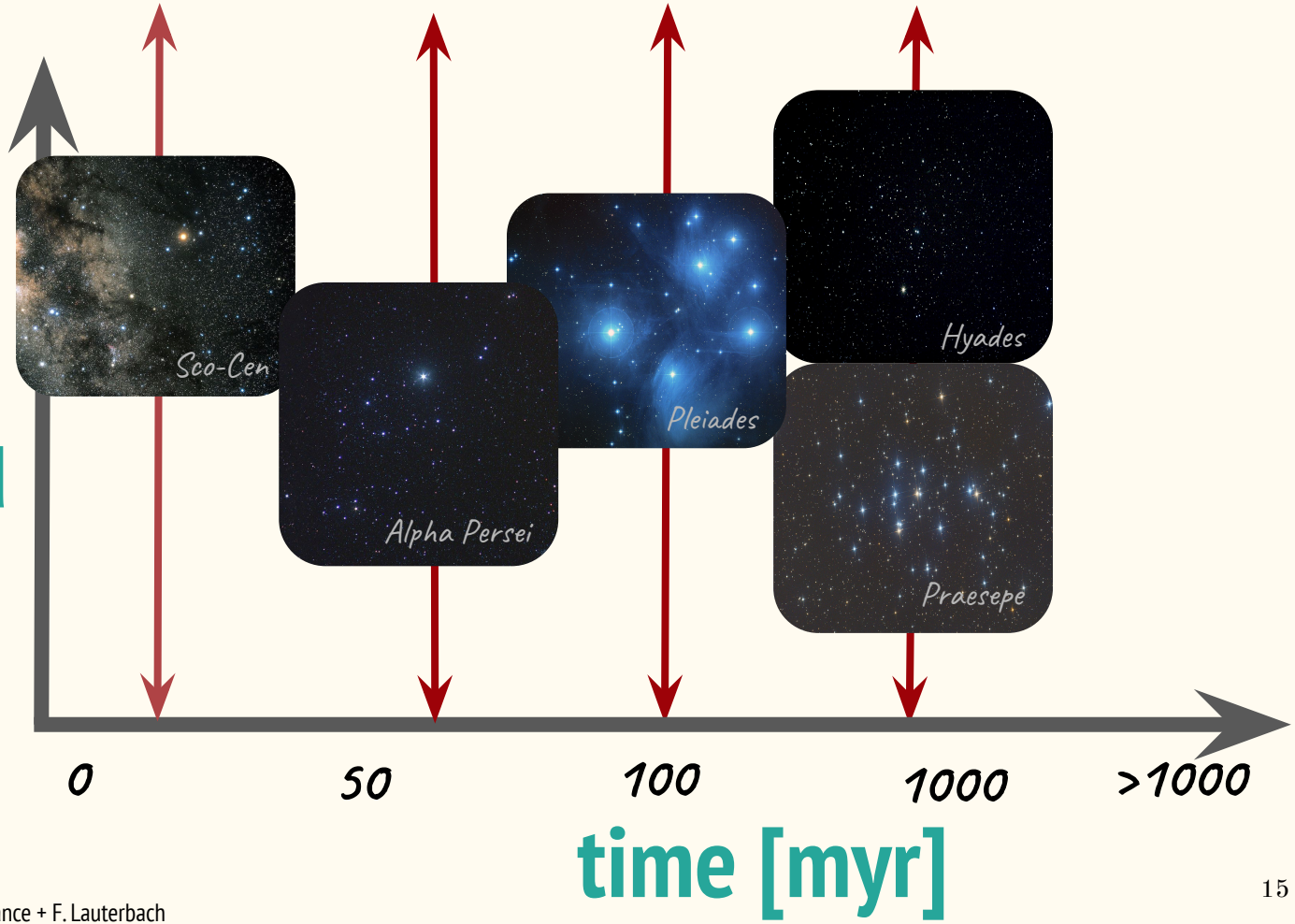
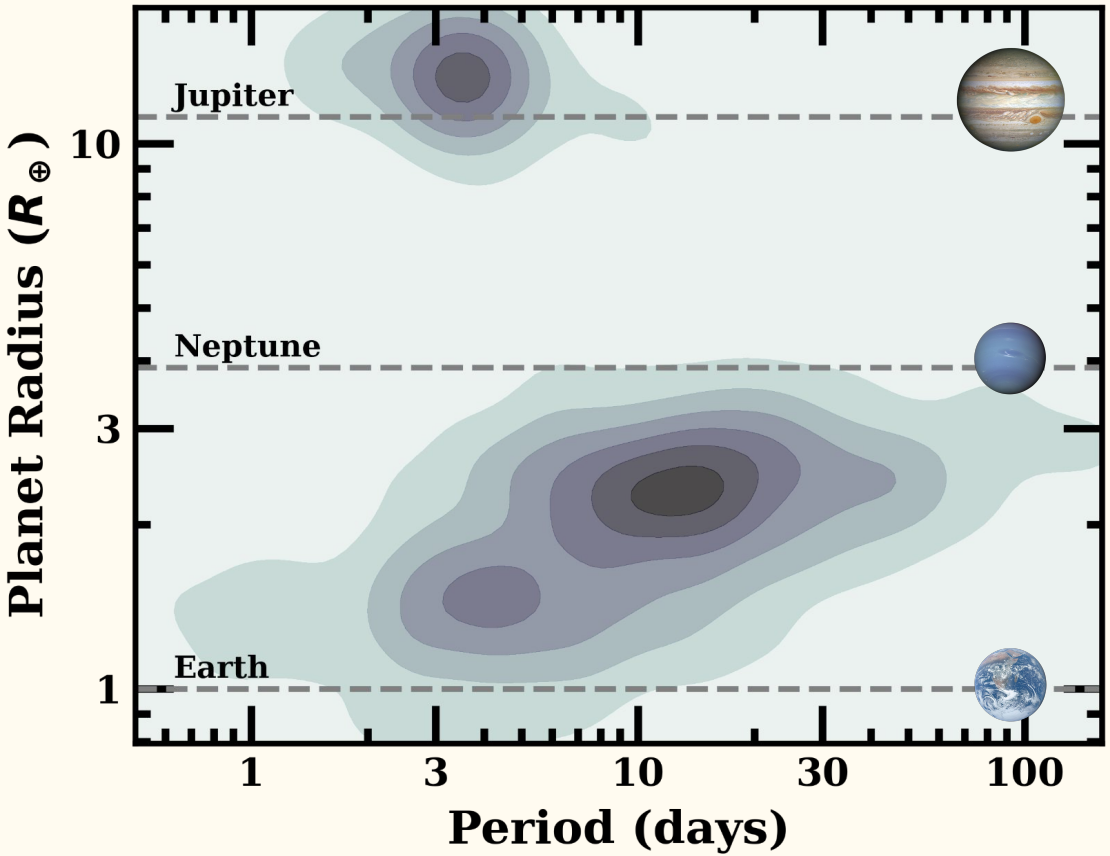


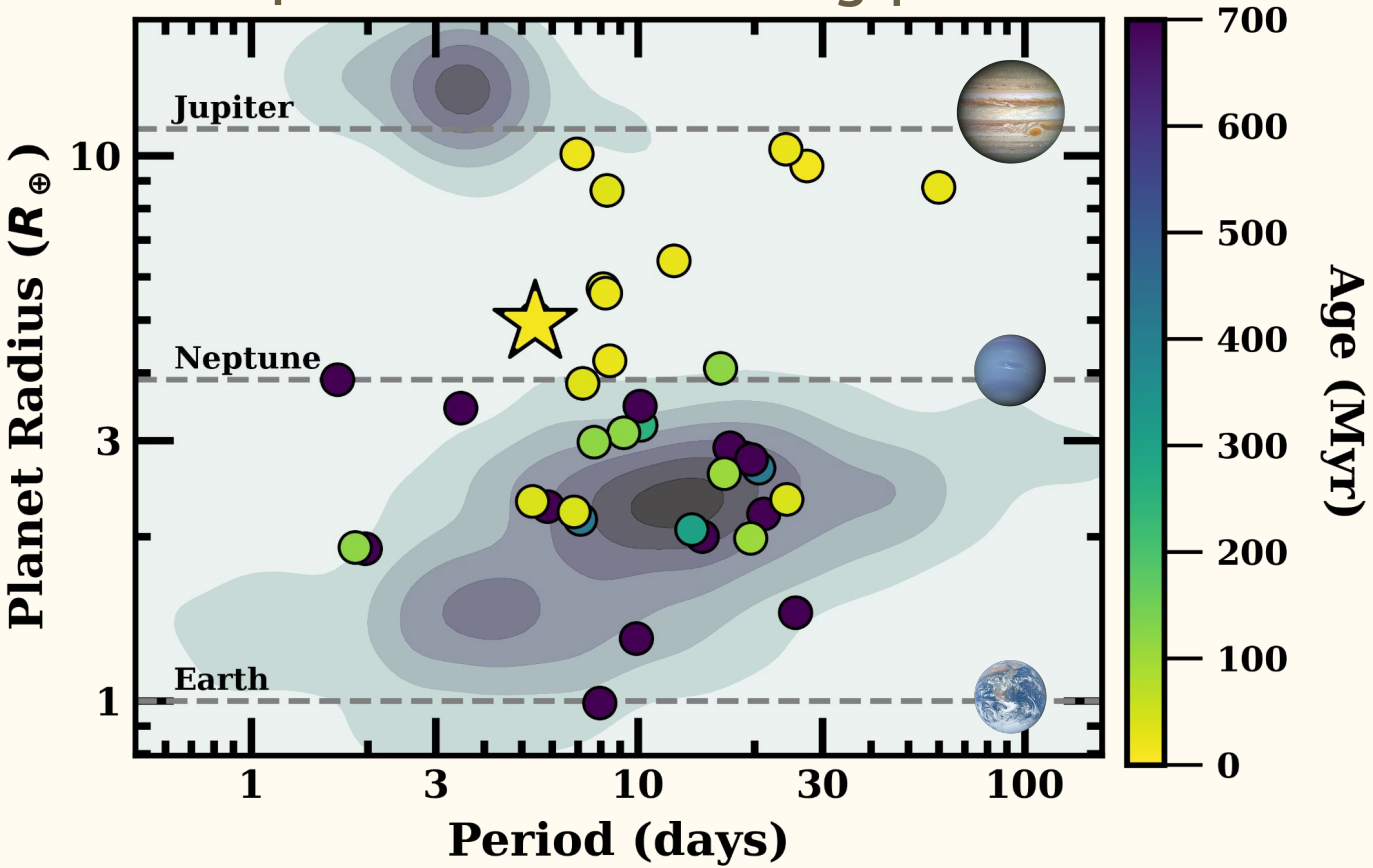
Image Credit: NASA + A. Fuji/ESA + M. Gembec + T. Vance + F. Lauterbach

Old planets



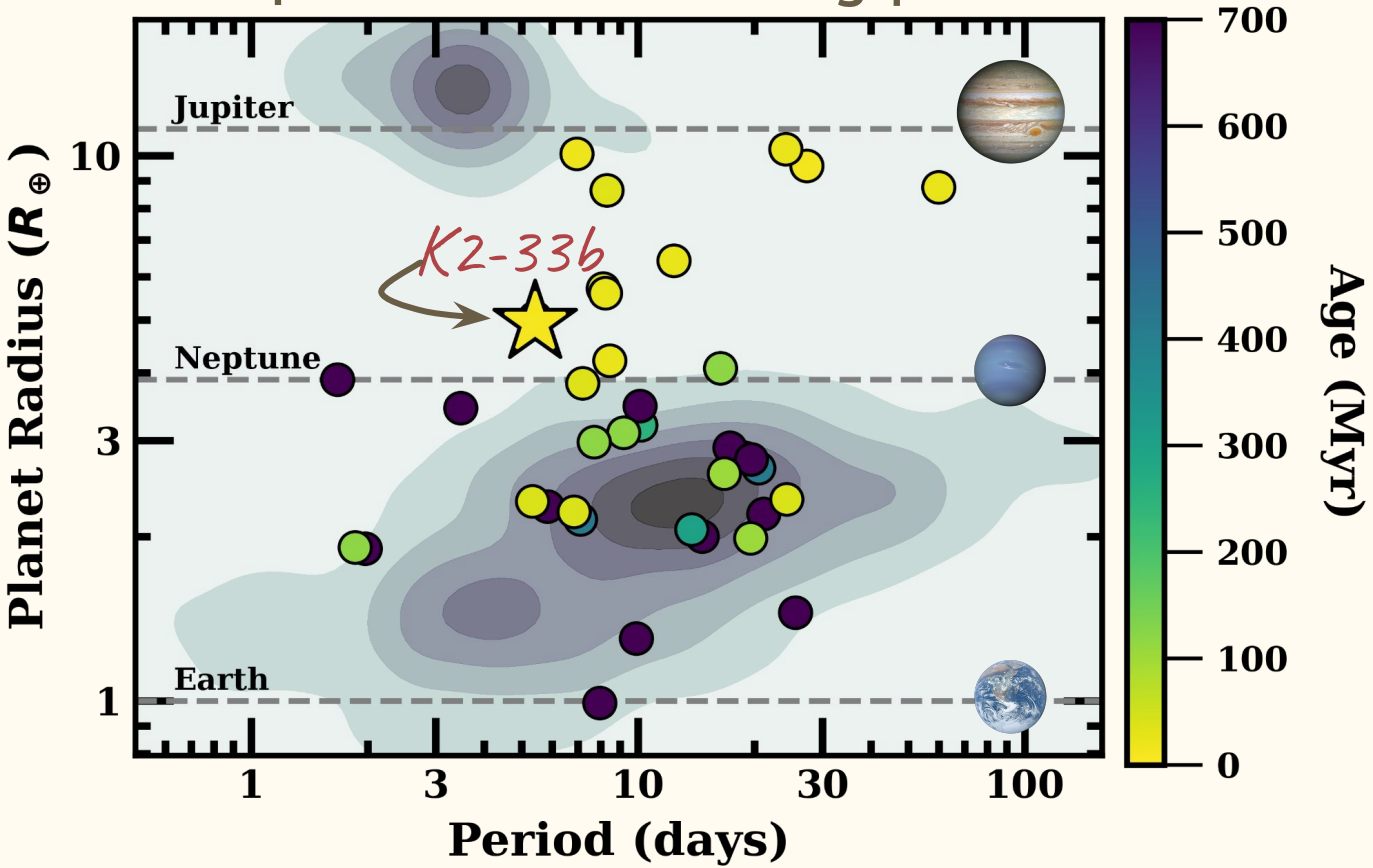
Credit: NASA Exoplanet Archive

Old planets *vs.* Young planets



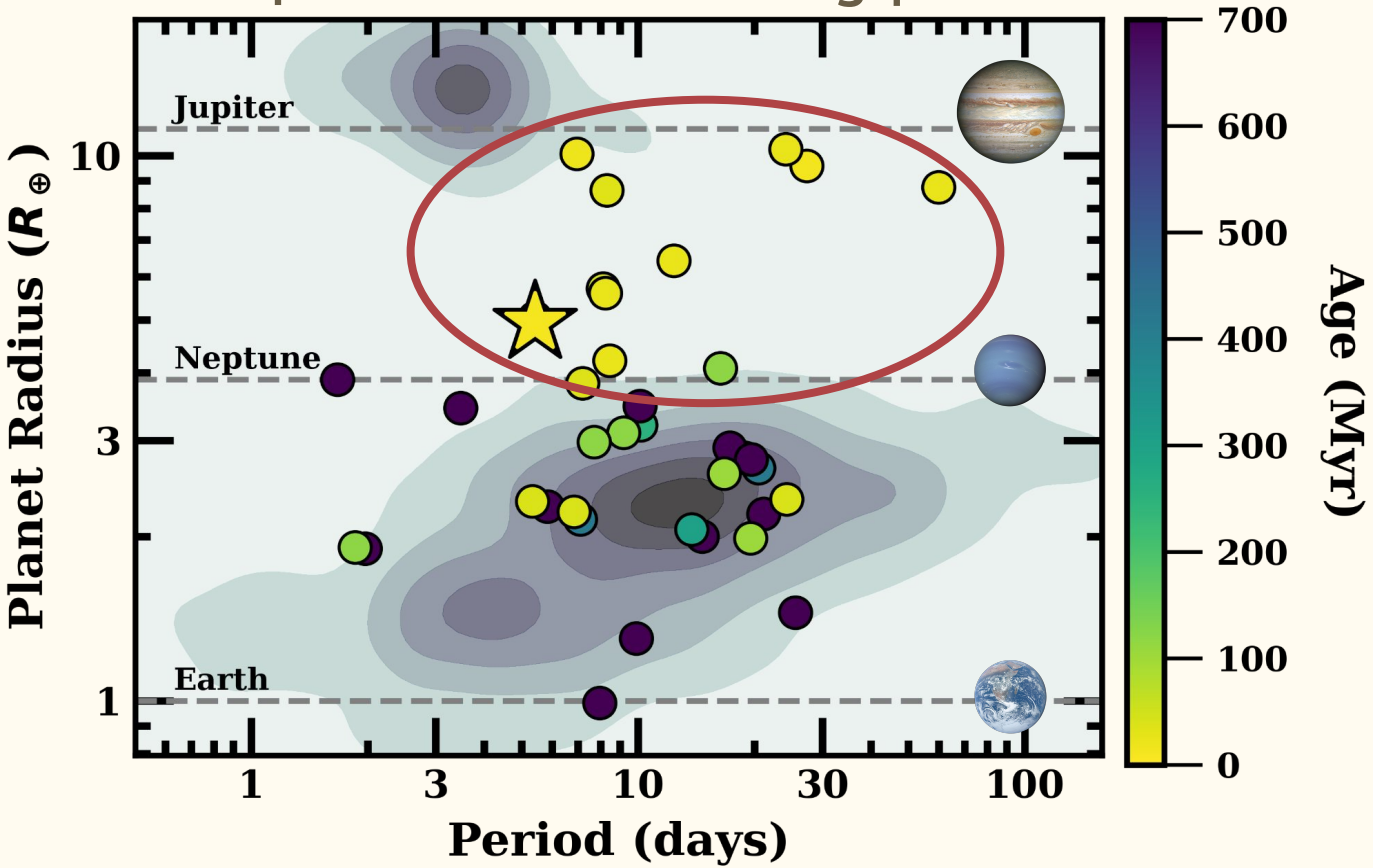
Credit: NASA Exoplanet Archive; Plavchan+2020, Gilbert+2022, Newton+2019, Mann+2017, Tofflemire+2021, Mann+2020, Rizzuto+2020, Barragán+2020, Mann+2017, Mann+2018, Stefansson+2020, Rizzuto+2018,Mann+2016, Obermeier+2016, Bouma+2020, Mann+2022, Newton+2021, David+2019, Newton+2022, Barber+2022, Zhou+2022

Old planets *vs.* Young planets



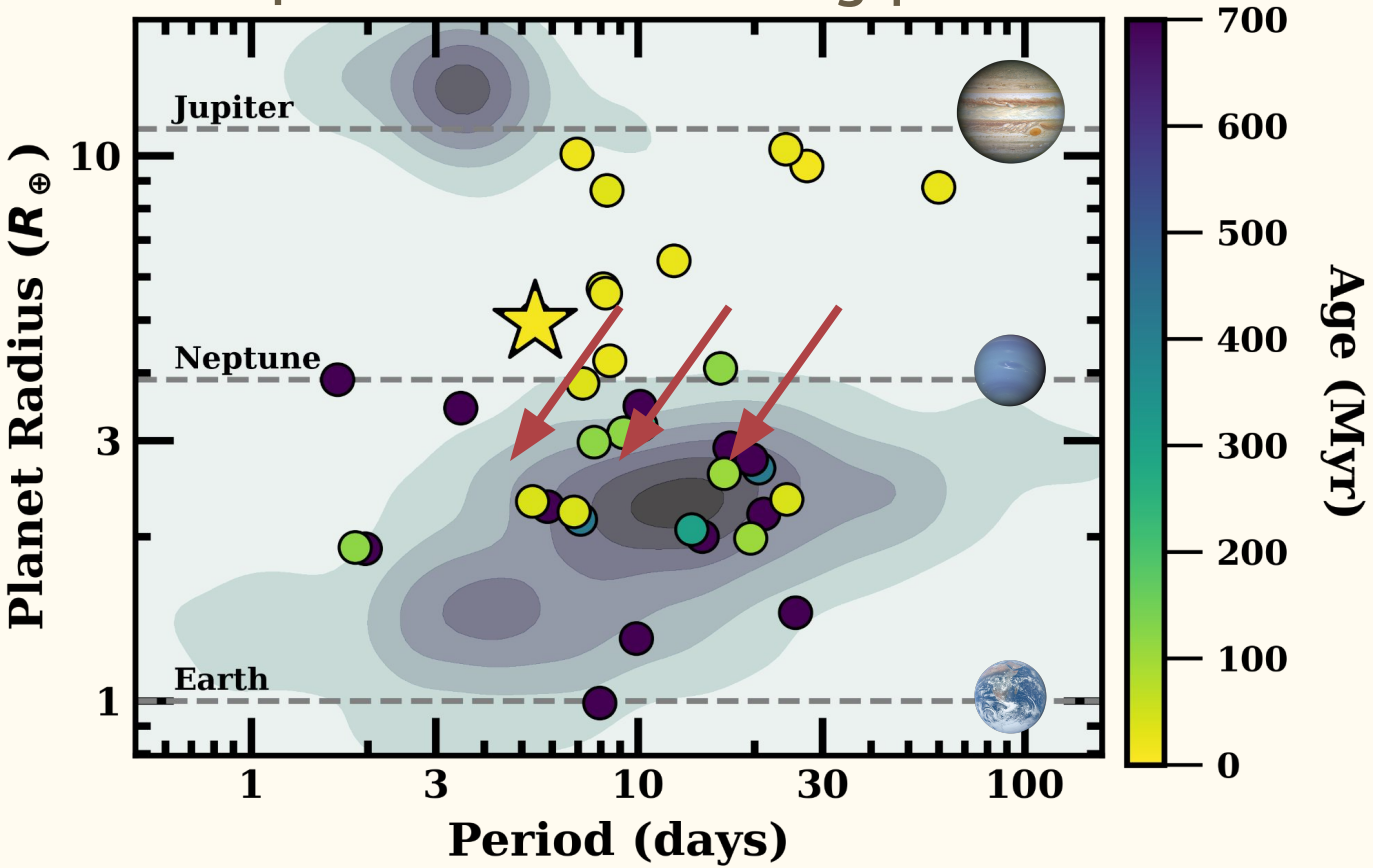
Credit: NASA Exoplanet Archive; Plavchan+2020, Gilbert+2022, Newton+2019, Mann+2017, Tofflemire+2021, Mann+2020, Rizzuto+2020, Barragán+2020, Mann+2017, Mann+2018, Stefansson+2020, Rizzuto+2018,Mann+2016, Obermeier+2016, Bouma+2020, Mann+2022, Newton+2021, David+2019, Newton+2022, Barber+2022, Zhou+2022

Old planets *vs.* Young planets



Credit: NASA Exoplanet Archive; Plavchan+2020, Gilbert+2022, Newton+2019, Mann+2017, Tofflemire+2021, Mann+2020, Rizzuto+2020, Barragán+2020, Mann+2017, Mann+2018, Stefansson+2020, Rizzuto+2018,Mann+2016, Obermeier+2016, Bouma+2020, Mann+2022, Newton+2021, David+2019, Newton+2022, Barber+2022, Zhou+2022

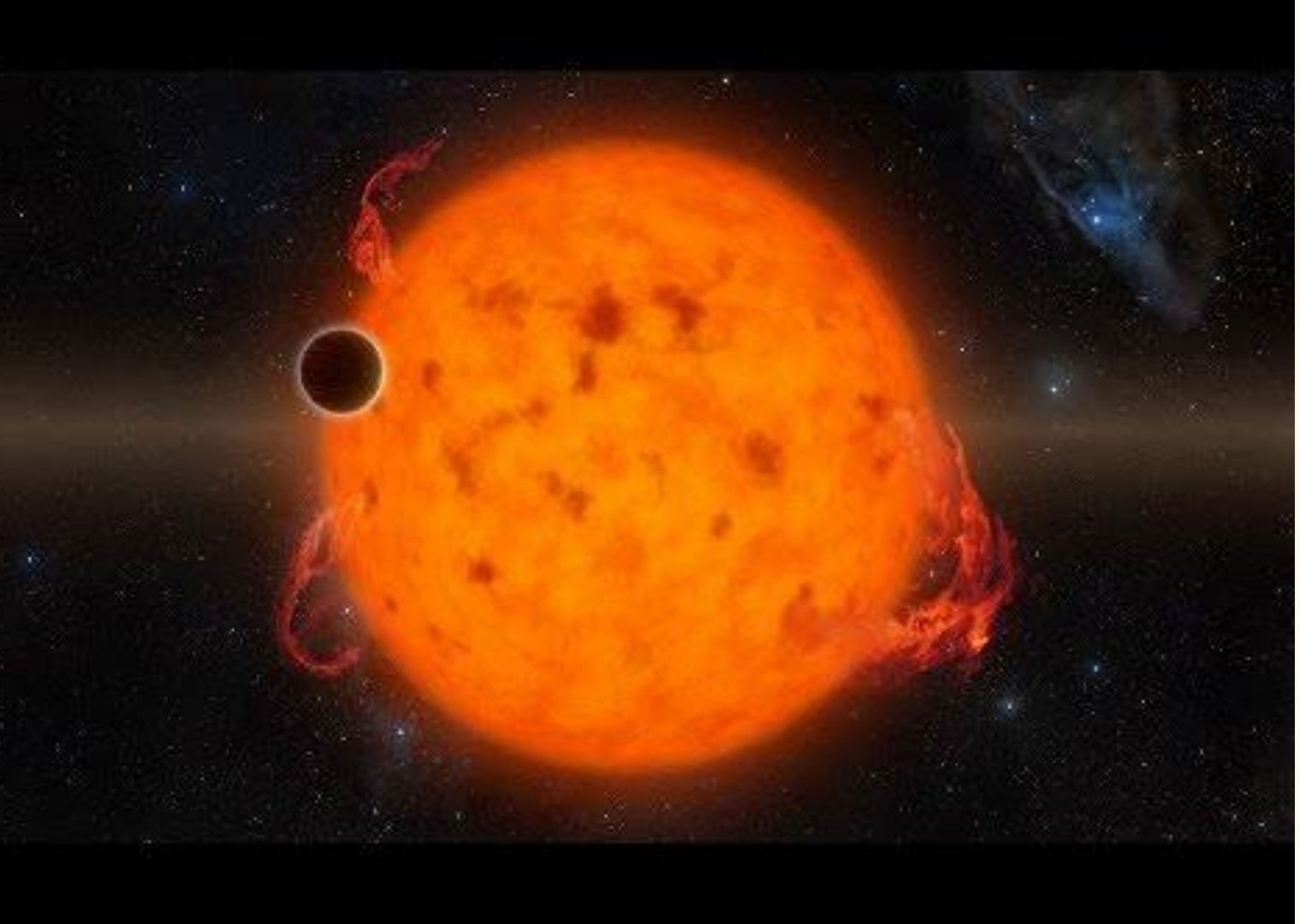
Old planets *vs.* Young planets



Credit: NASA Exoplanet Archive; Plavchan+2020, Gilbert+2022, Newton+2019, Mann+2017, Tofflemire+2021, Mann+2020, Rizzuto+2020, Barragán+2020, Mann+2017, Mann+2018, Stefansson+2020, Rizzuto+2018,Mann+2016, Obermeier+2016, Bouma+2020, Mann+2022, Newton+2021, David+2019, Newton+2022, Barber+2022, Zhou+2022

Goal:

to characterize the atmosphere of the young planet, **K2-33b**



K2-33b

Age ~ 10 Myr

P = 5.5 days

R_p = 5.0 $R_\oplus$

T_{eff} = 768 K

Video Credit: NASA/JPL-Caltech

33 transits
0.64 - 4.5μm

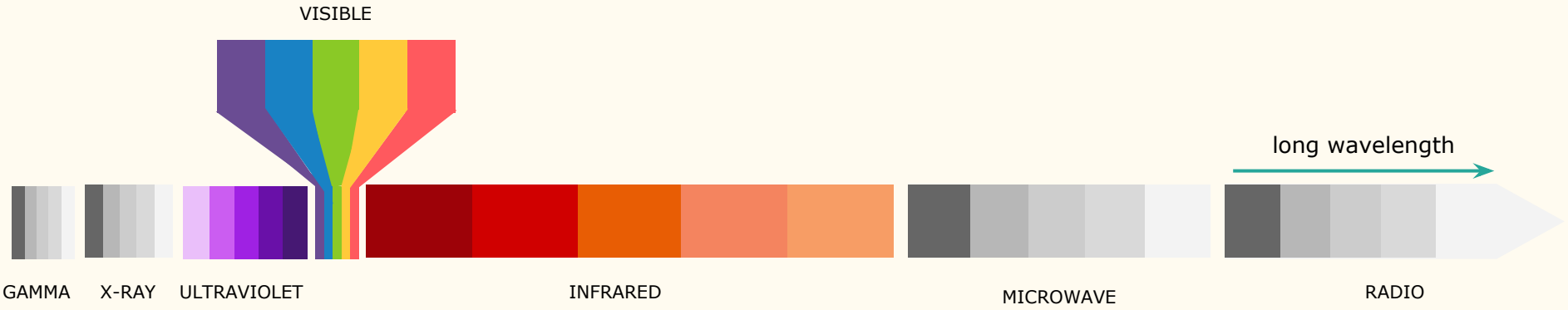
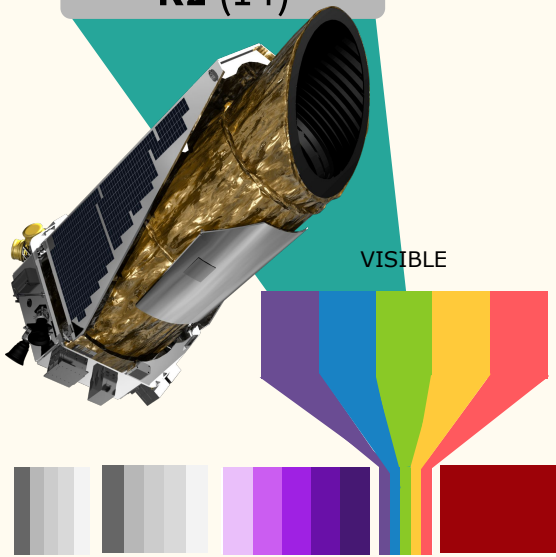


Image adapted from: NASA, J. Olmsted (STScI)

K2 (14)



33 transits
0.64 - 4.5μm

Image adapted from: NASA, J. Olmsted (STScI)

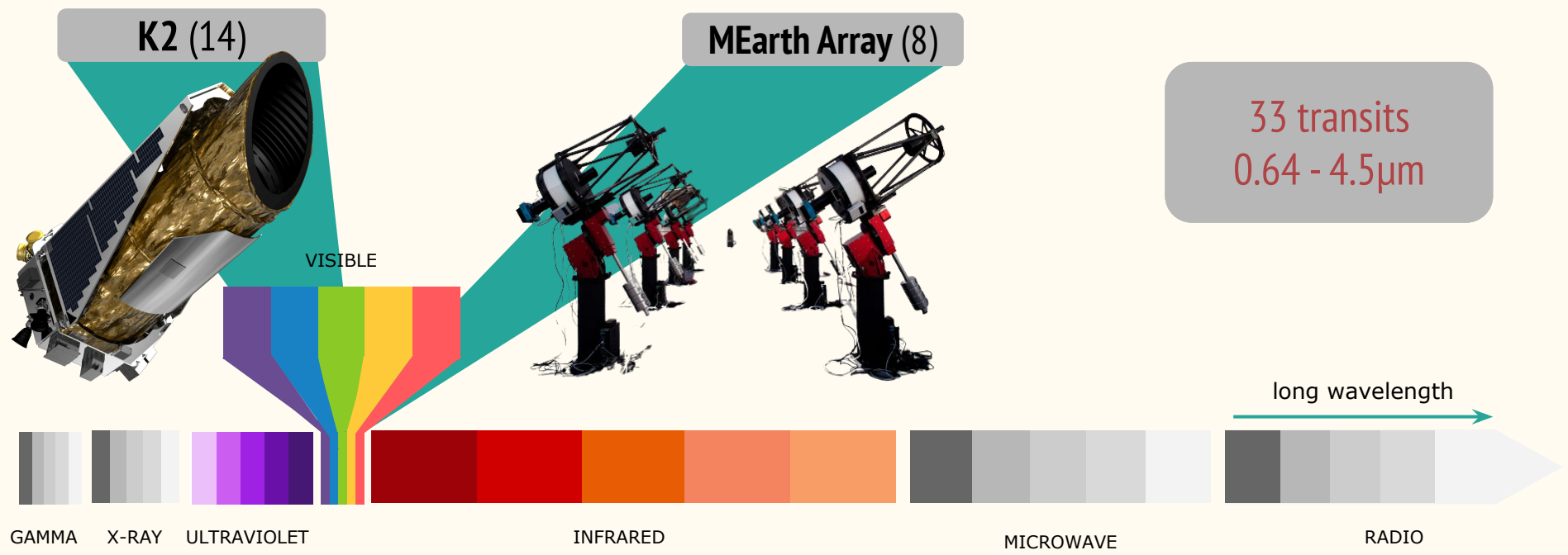


Image adapted from: NASA, J. Olmsted (STScI); MEarth Project

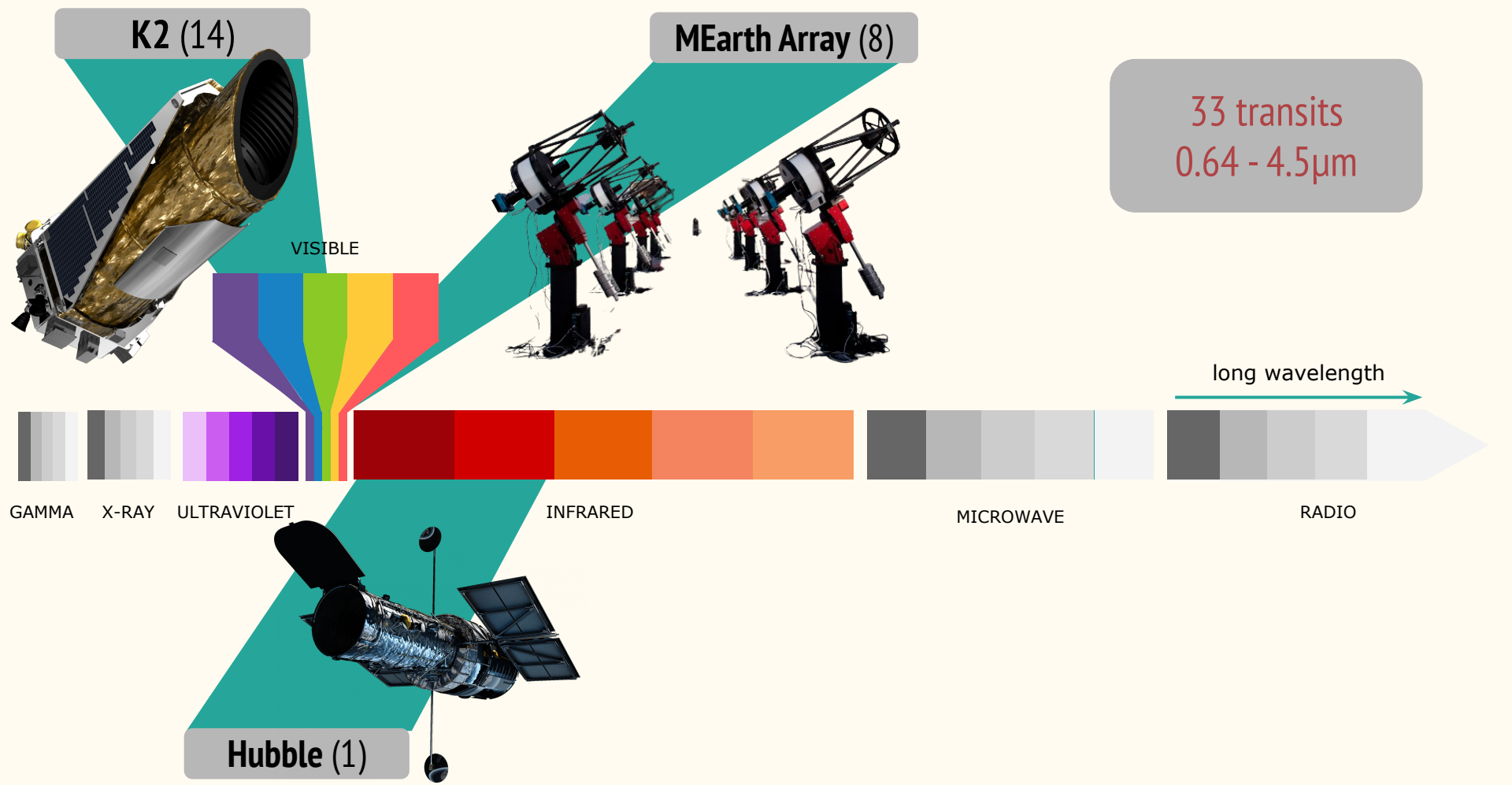
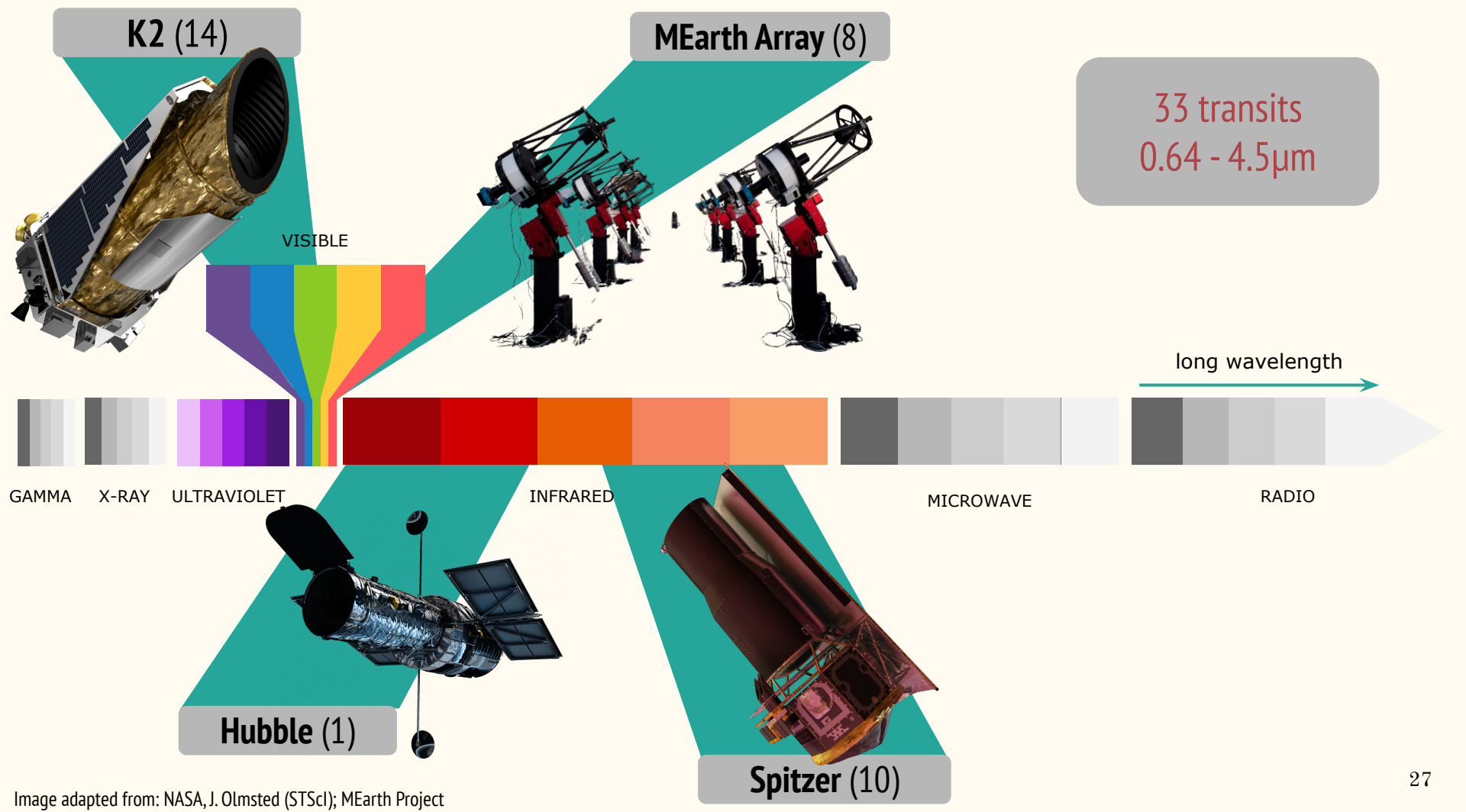


Image adapted from: NASA, J. Olmsted (STScI); MEarth Project



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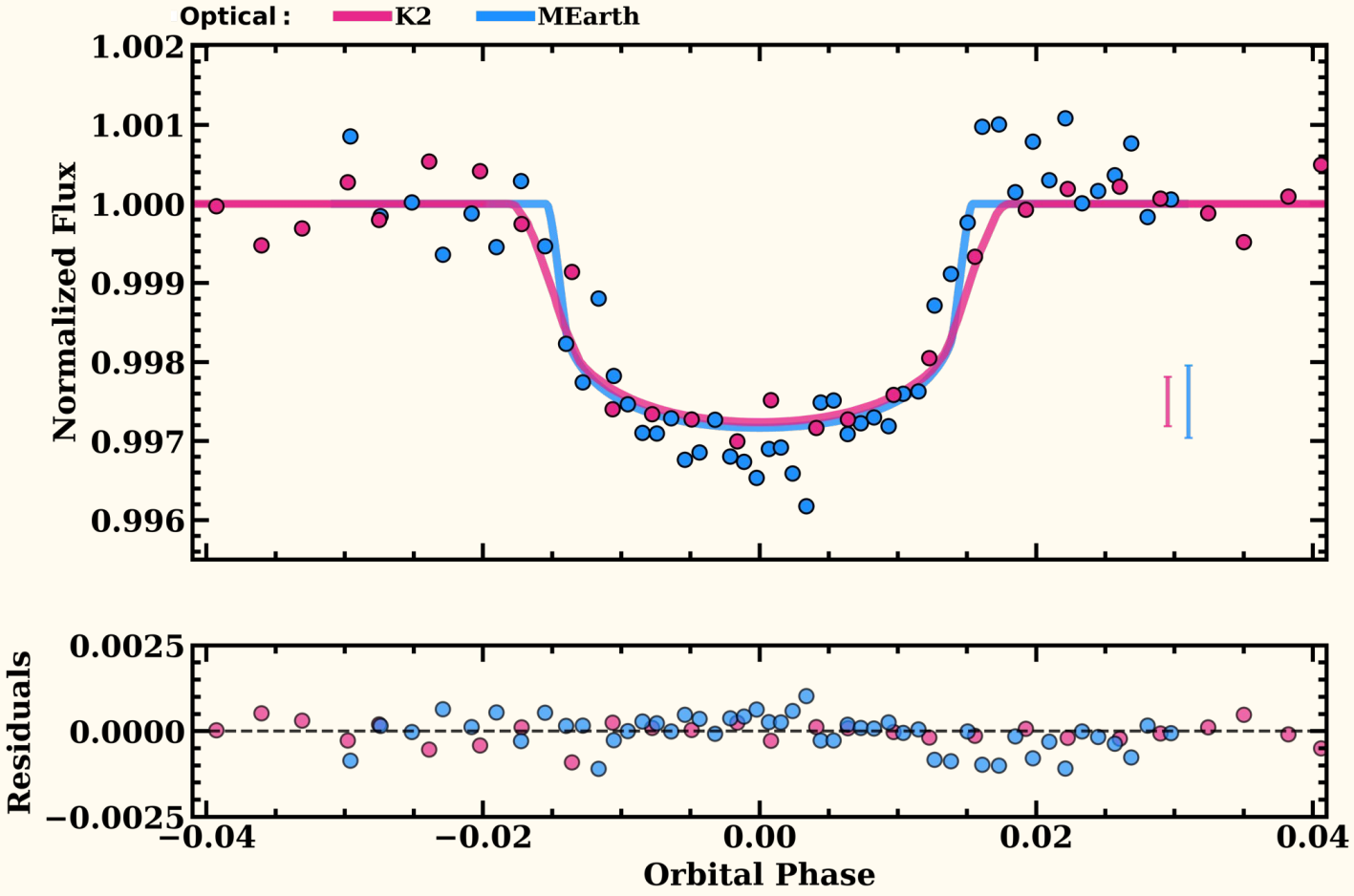
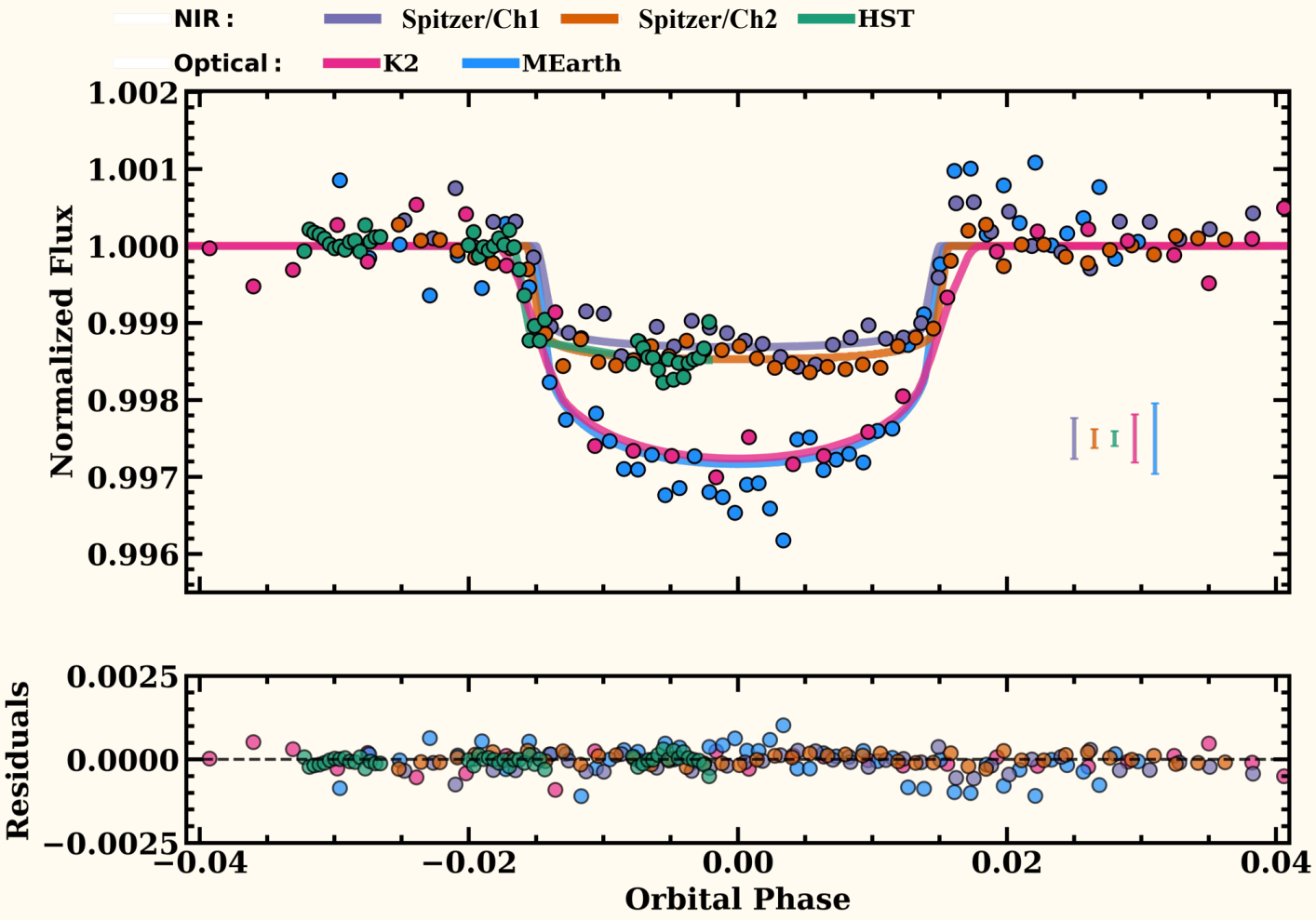
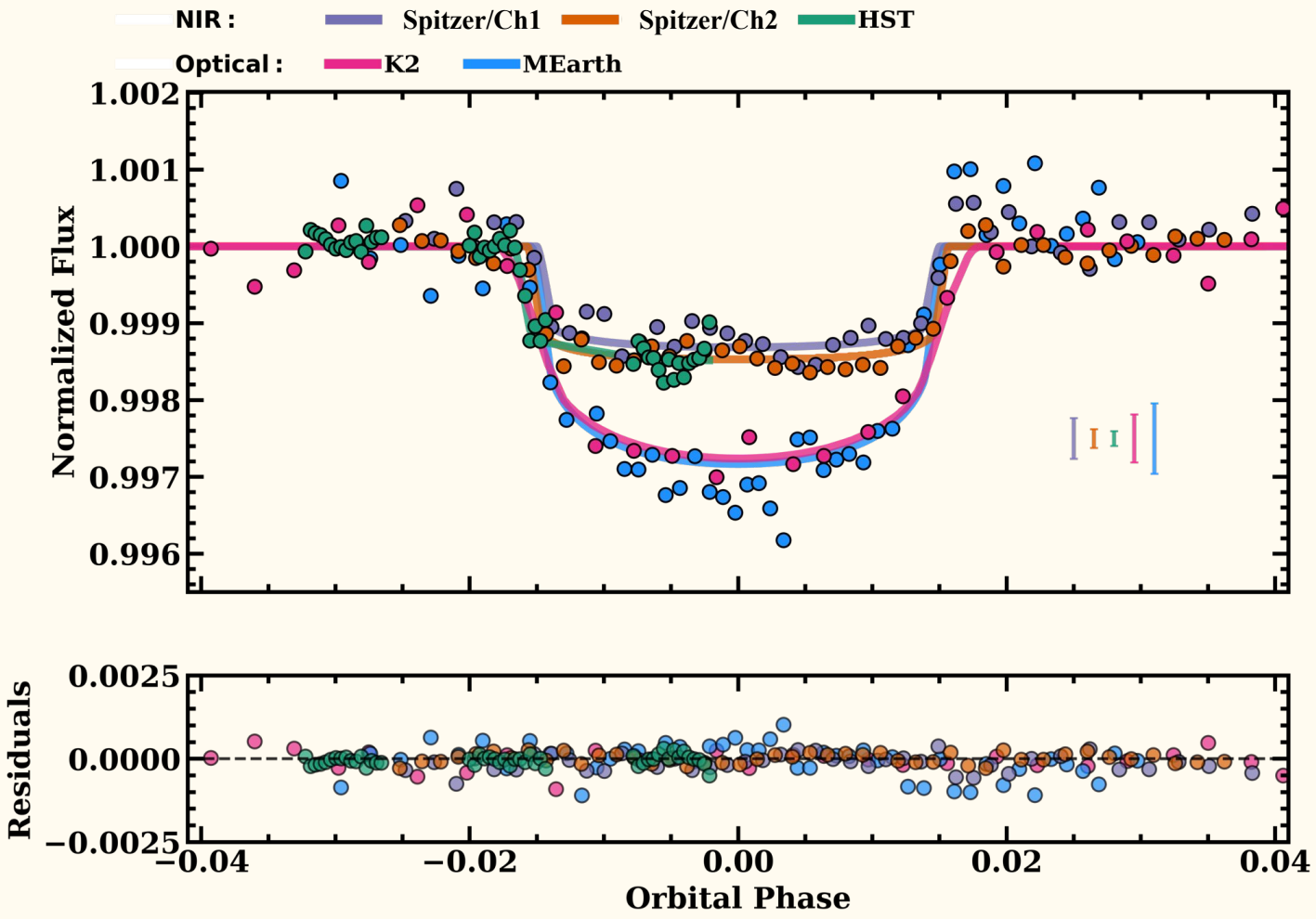
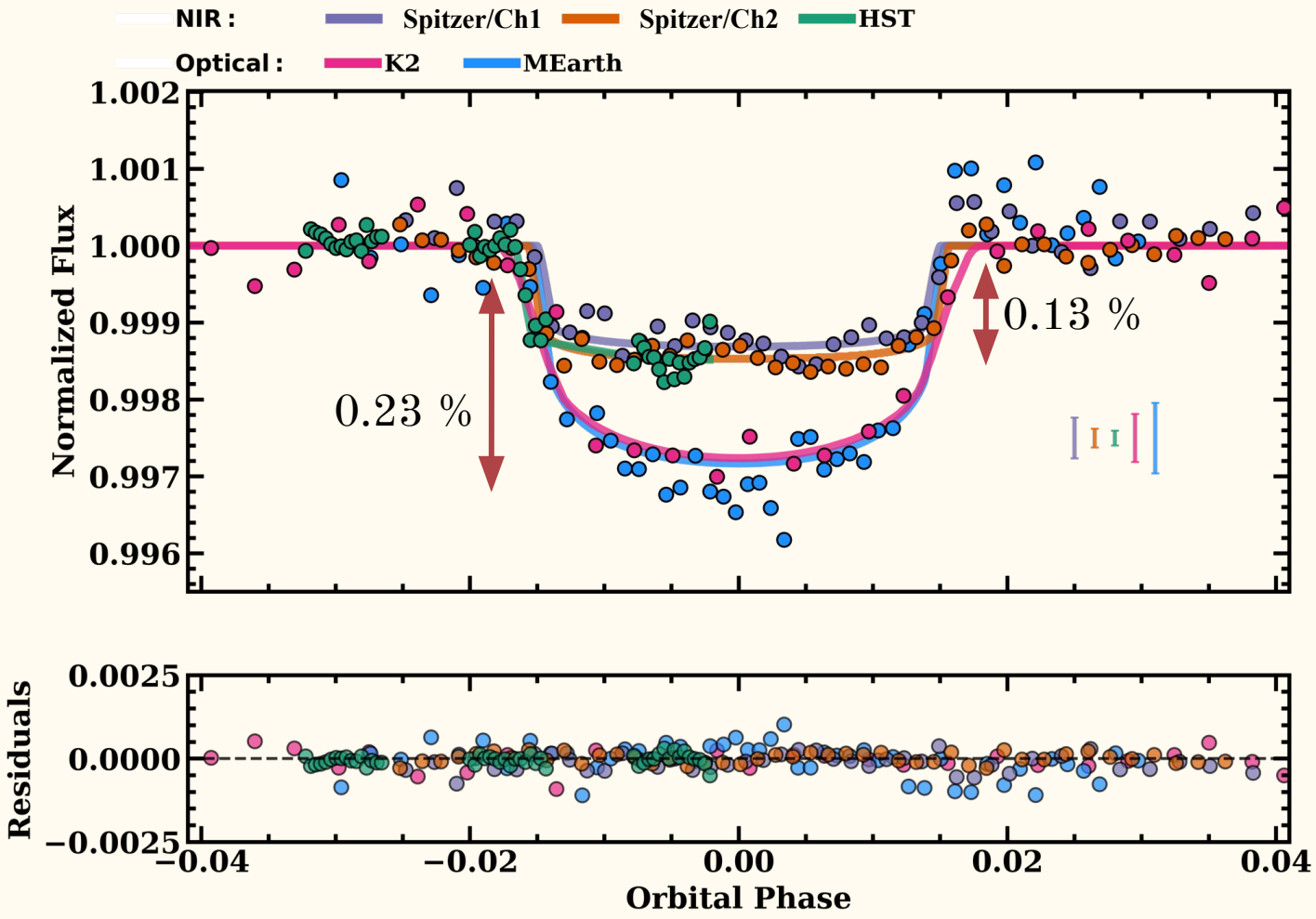
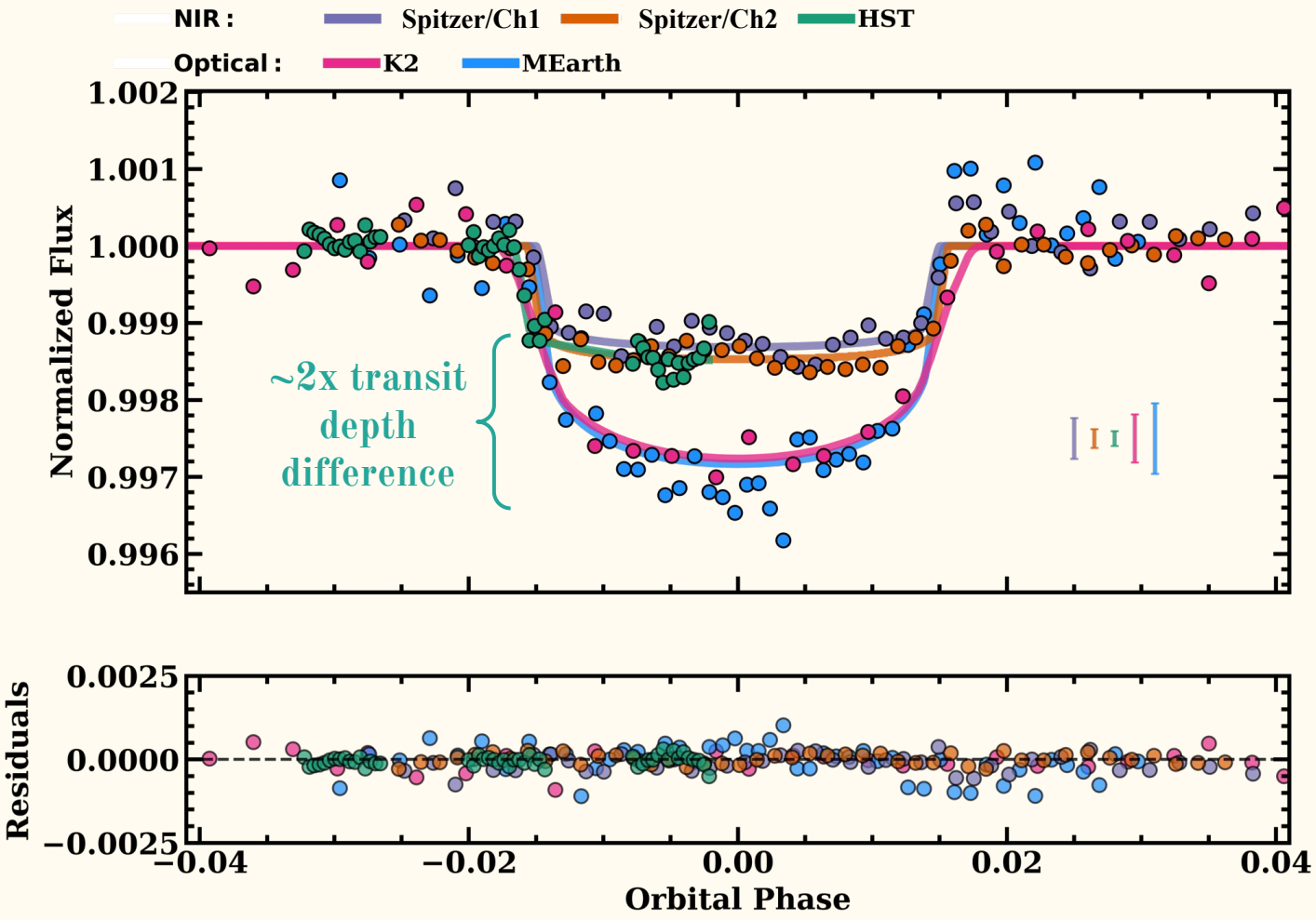

Optical :
K2
MEarth
Normalized Flux
1.002
1.001
1.000
0.999
0.998
0.997
0.996
Residuals
0.0025
0.0000
−0.0025
−0.04
−0.02
0.00
0.02
0.04
Orbital Phase


NIR :
Spitzer/Ch1
Spitzer/Ch2
HST
Optical :
K2
MEarth
Normalized Flux
1.002
1.001
1.000
0.999
0.998
0.997
0.996
Residuals
0.0025
0.0000
−0.0025
−0.04
−0.02
0.00
0.02
0.04
Orbital Phase


NIR :
Spitzer/Ch1
Spitzer/Ch2
HST
Optical :
K2
MEarth
Normalized Flux
1.002
1.001
1.000
0.999
0.998
0.997
0.996
Residuals
0.0025
0.0000
−0.0025
−0.04
−0.02
0.00
0.02
0.04
Orbital Phase


NIR :
Spitzer/Ch1
Spitzer/Ch2
HST
Optical :
K2
MEarth
Normalized Flux
1.002
1.001
1.000
0.999
0.998
0.997
0.996
0.23 %
0.13 %
Residuals
0.0025
0.0000
−0.0025
−0.04
−0.02
0.00
0.02
0.04
Orbital Phase


NIR :
Spitzer/Ch1
Spitzer/Ch2
HST
Optical :
K2
MEarth
Normalized Flux
1.002
1.001
1.000
0.999
0.998
0.997
0.996
~2x transit depth difference
Residuals
0.0025
0.0000
−0.0025
−0.04
−0.02
0.00
0.02
0.04
Orbital Phase

~2x transit depth difference

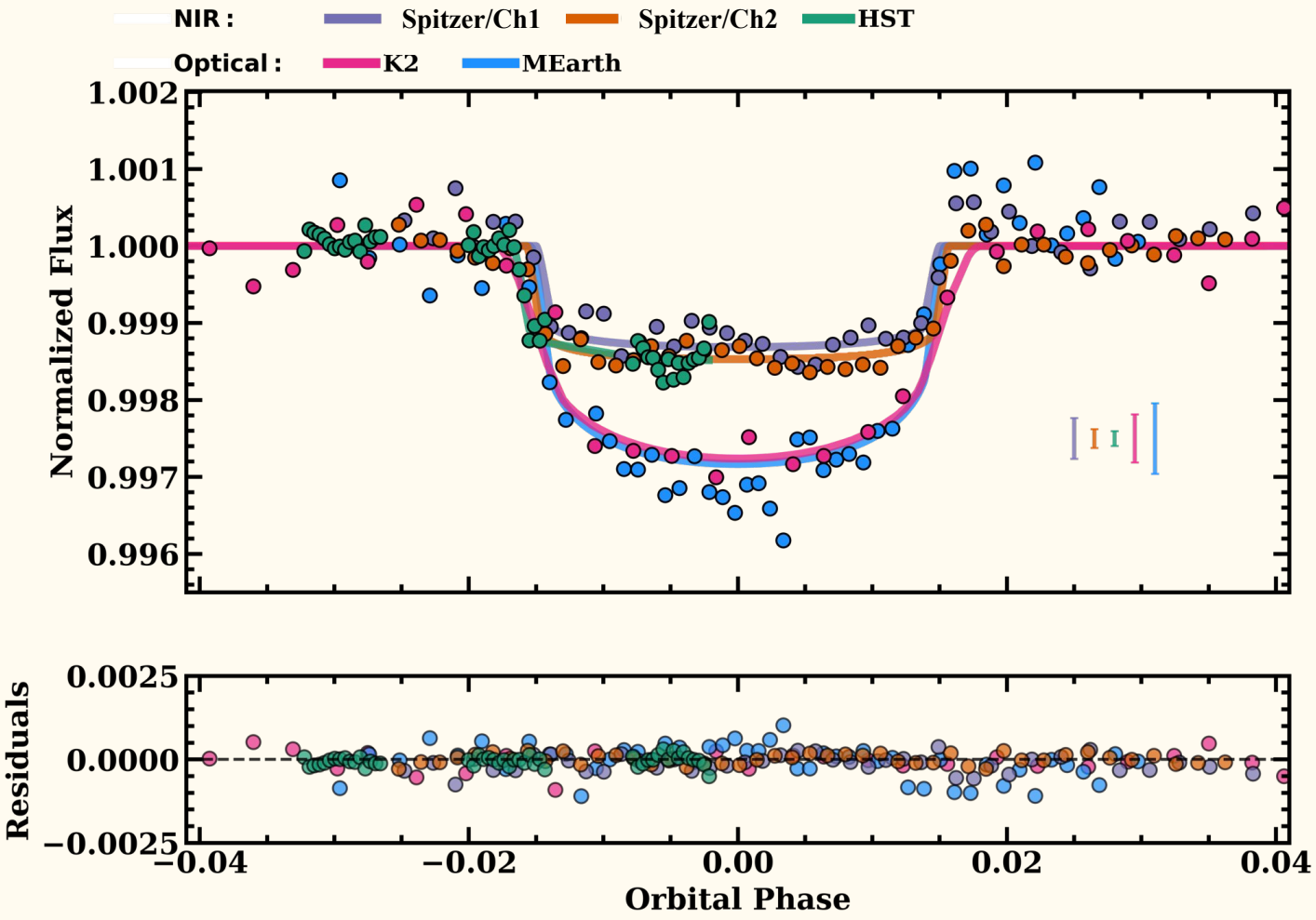
~2x transit depth difference

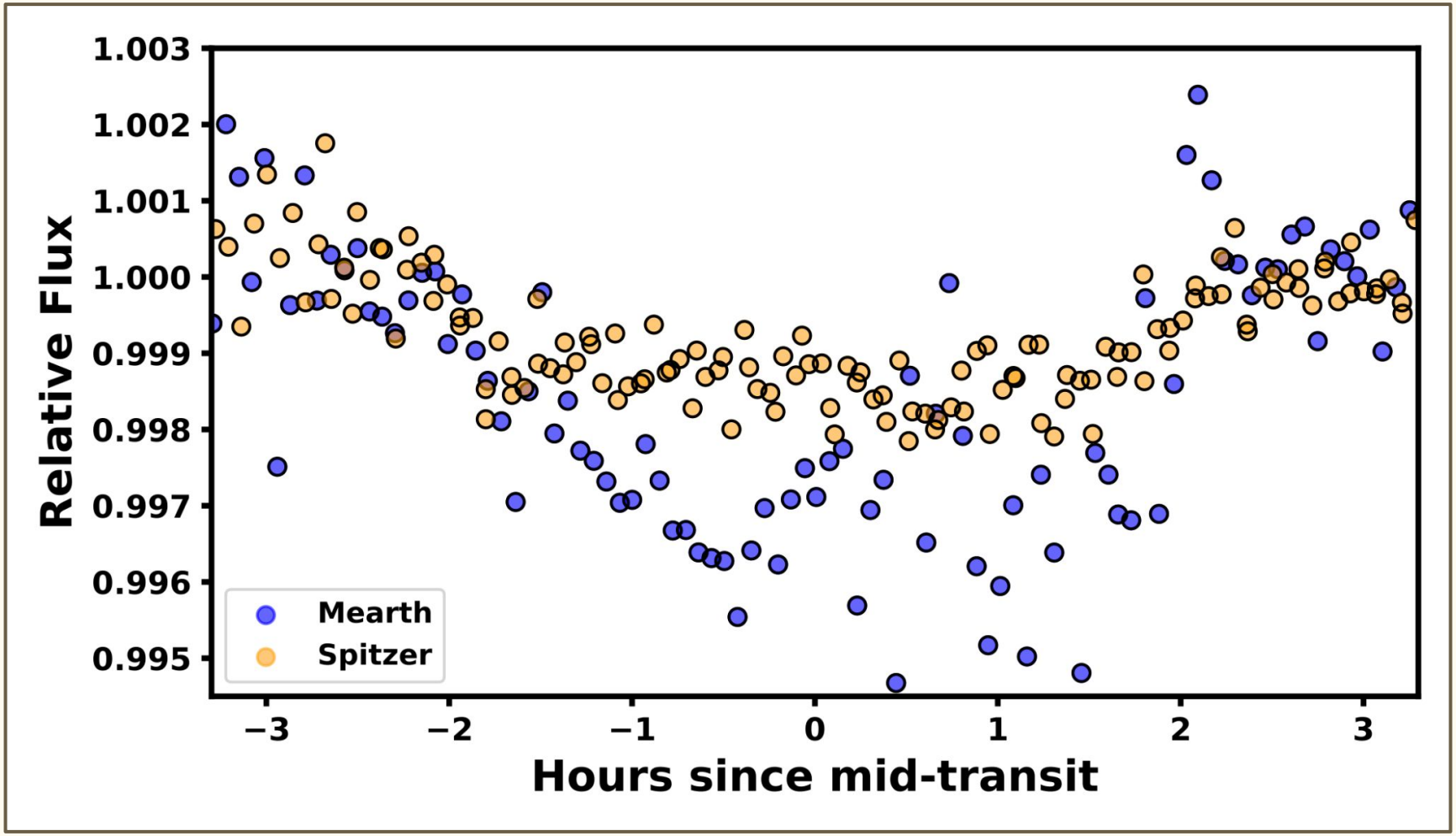
Unconstrained Systematics

~2x transit depth difference

Unconstrained Systematics

Astrophysical


NIR :
Spitzer/Ch1
Spitzer/Ch2
HST
Optical :
K2
MEarth
Normalized Flux
1.002
1.001
1.000
0.999
0.998
0.997
0.996
Residuals
0.0025
0.0000
−0.0025
−0.04
−0.02
0.00
0.02
0.04
Orbital Phase


1.003
1.002
1.001
1.000
0.999
0.998
0.997
0.996
0.995
Relative Flux
Mearth
Spitzer
−3
−2
−1
0
1
2
3
Hours since mid-transit

~2x transit depth difference

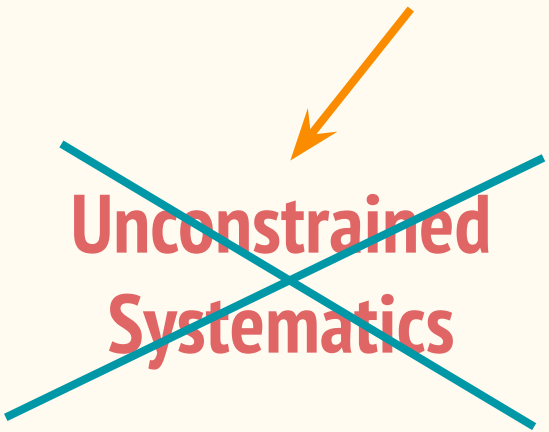
Unconstrained Systematics

Astrophysical

Difference hold across datasets

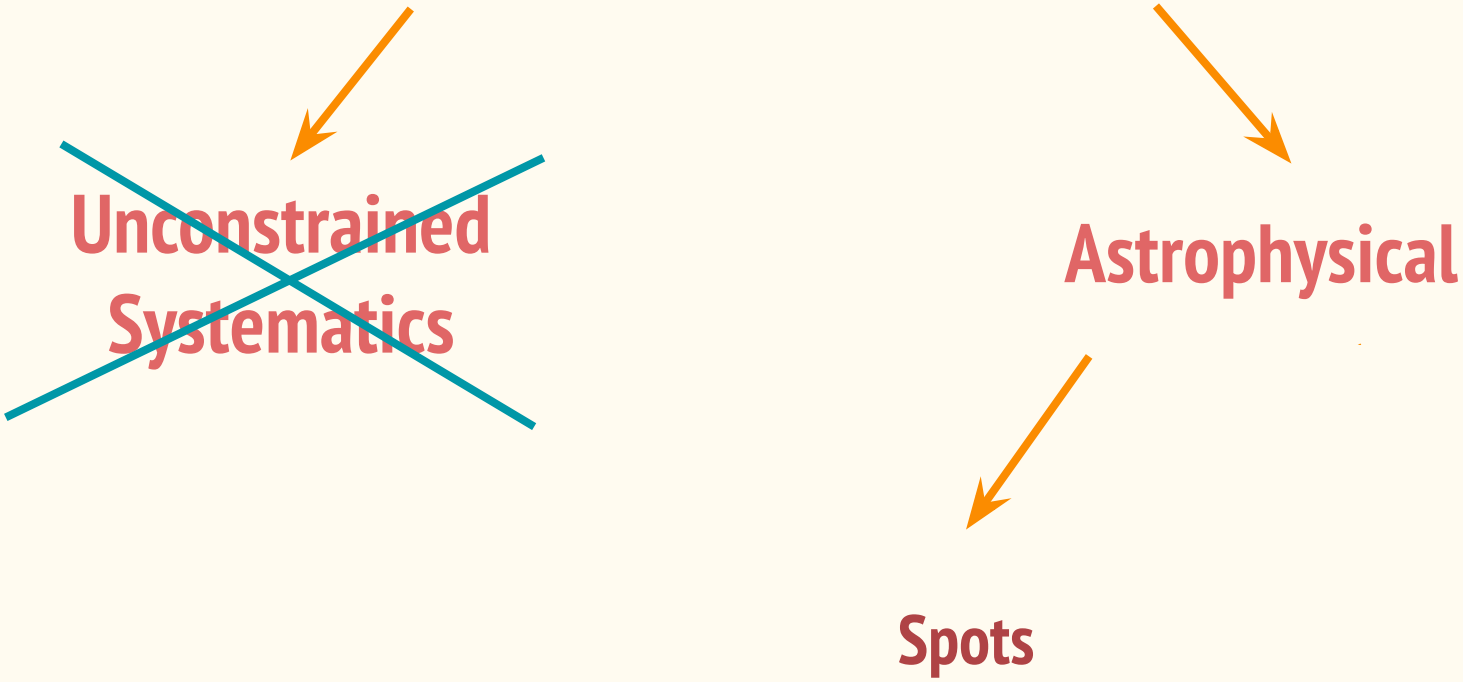
Overlapping Datasets

~2x transit depth difference

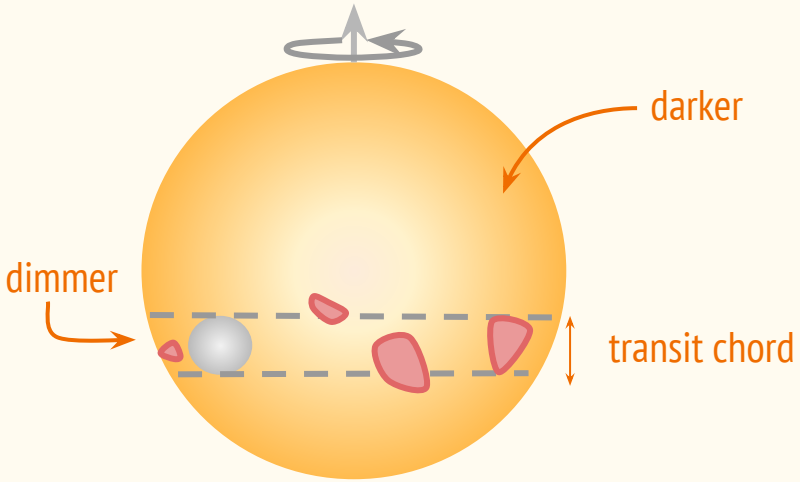


Astrophysical

~2x transit depth difference



Occulted Spots



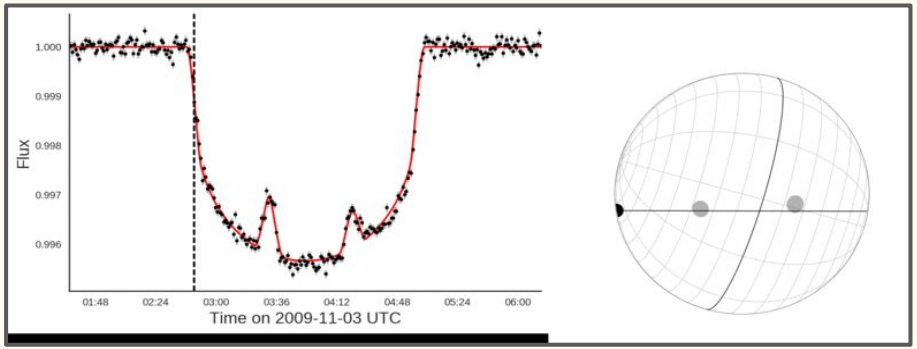
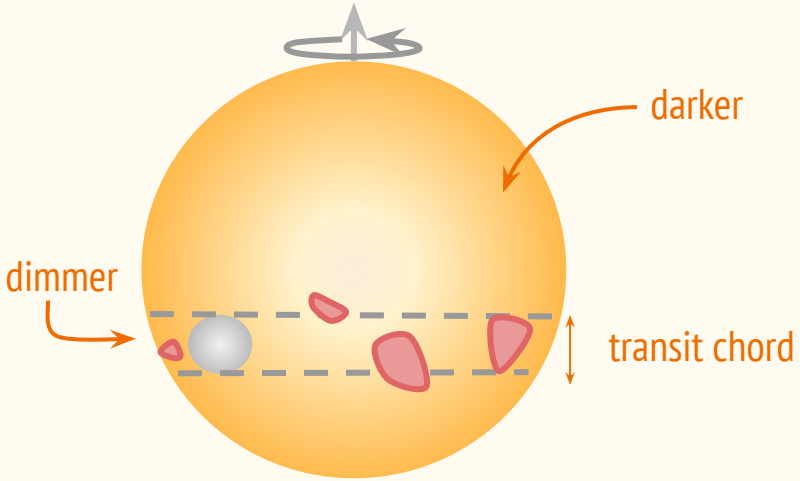
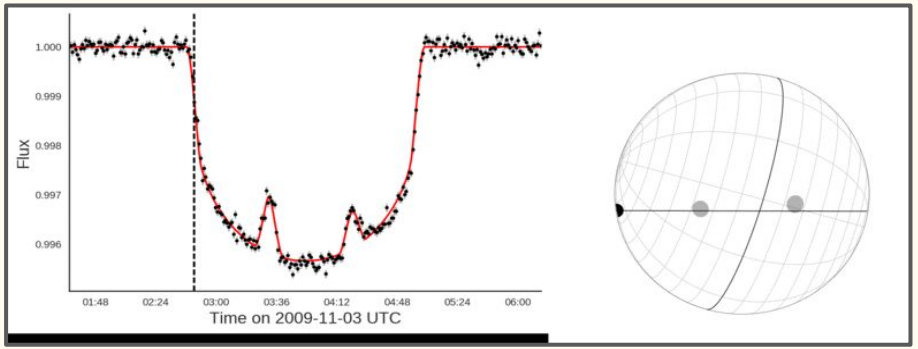


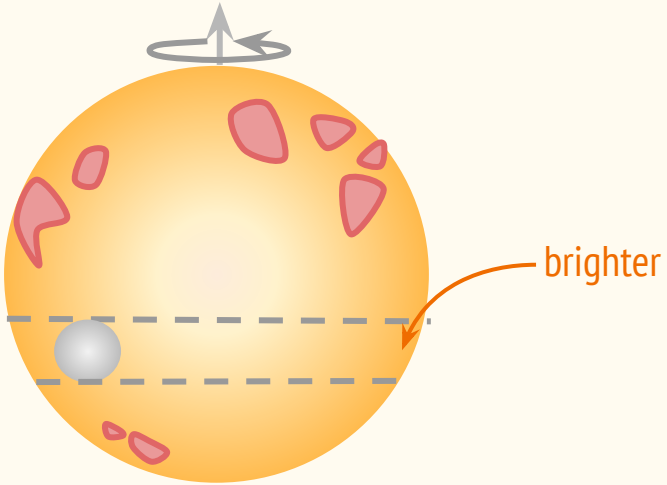
Figure credit: B. Morris (HAT-P-11b)

Occulted Spots





Unocculted Spots



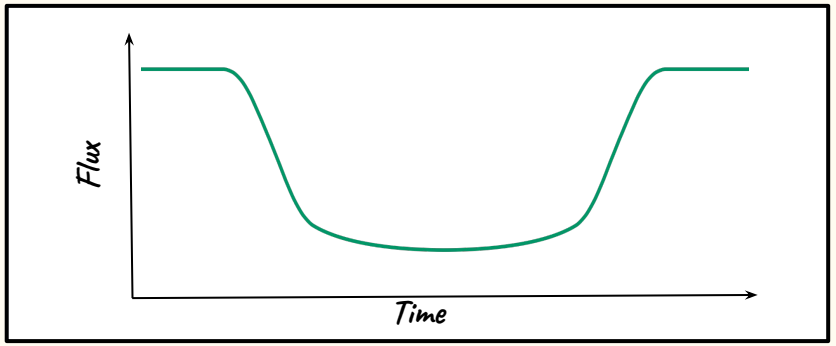
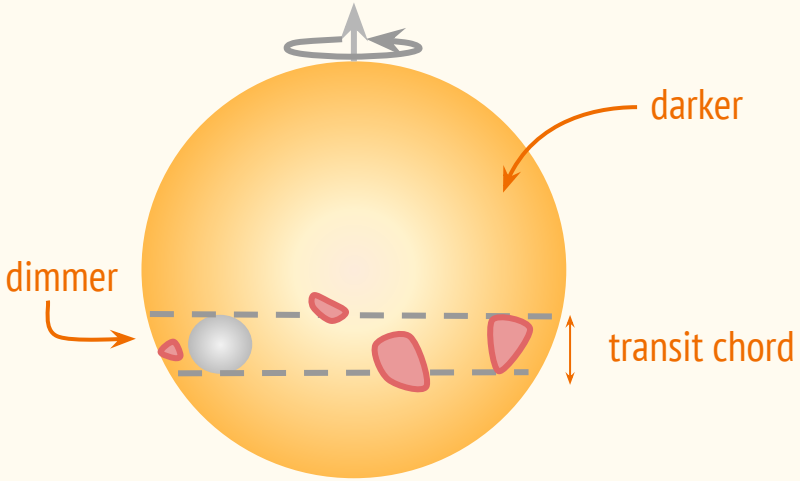
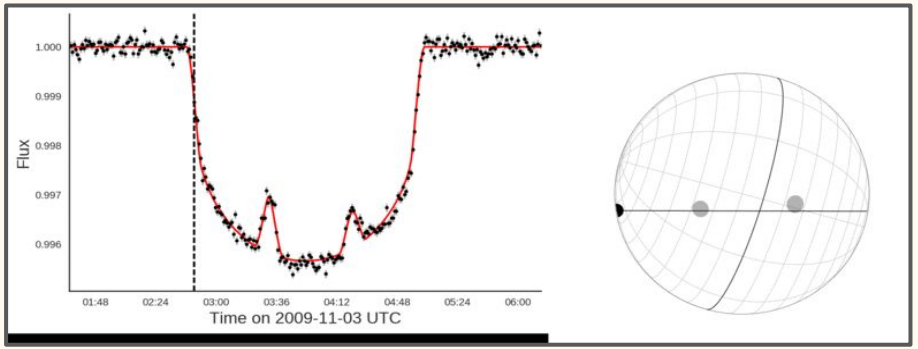


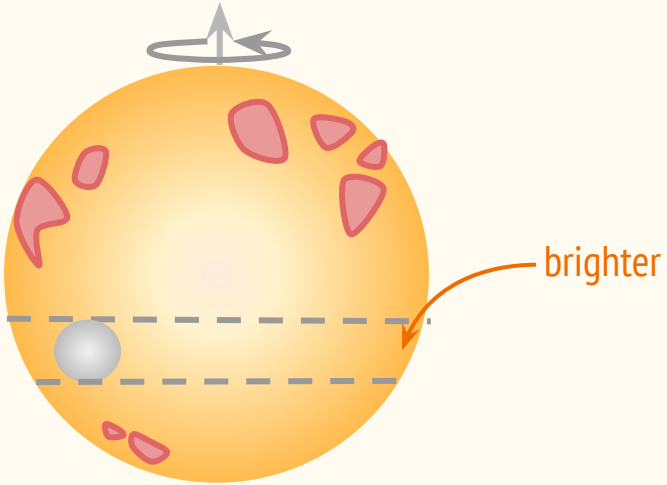
Figure credit: B. Morris (HAT-P-11b)

Occulted Spots





Unocculted Spots



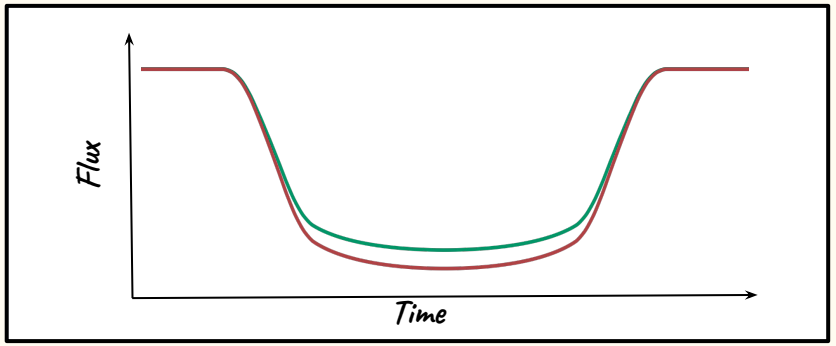
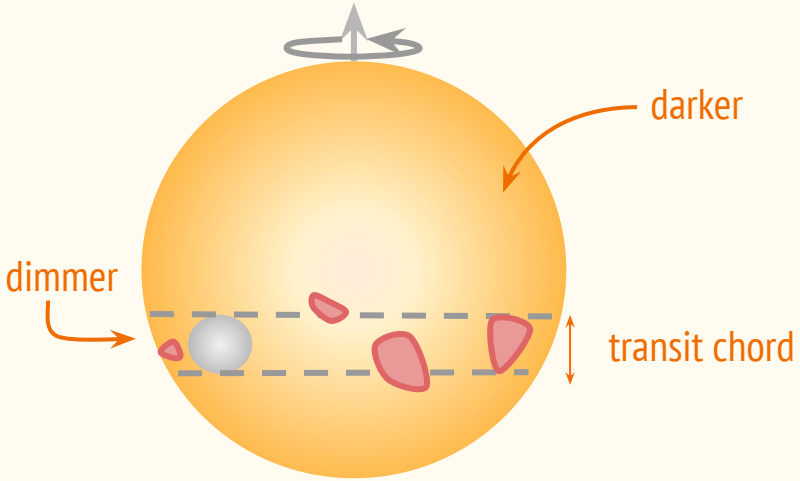
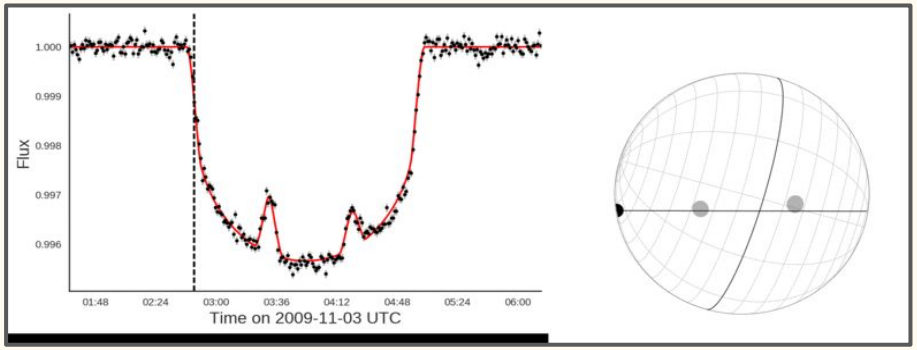


Figure credit: B. Morris (HAT-P-11b)

Occulted Spots





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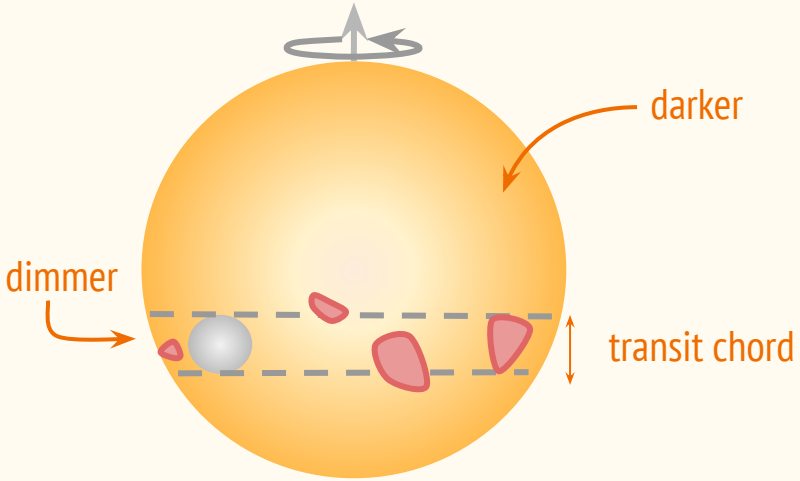
Occulted Spots



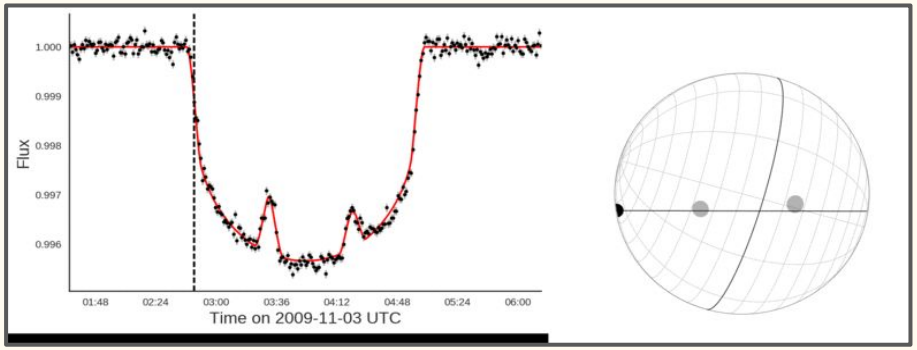
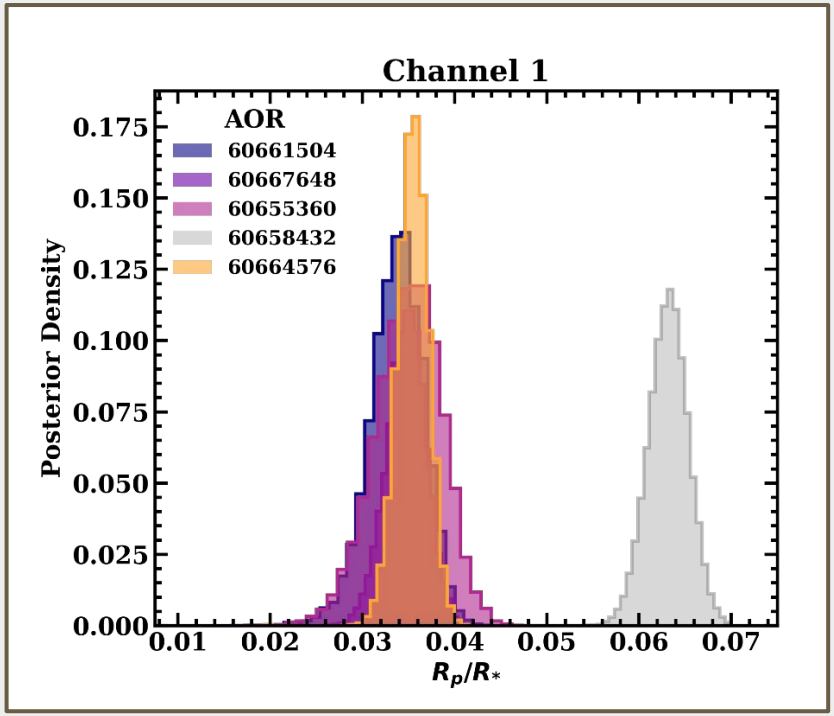
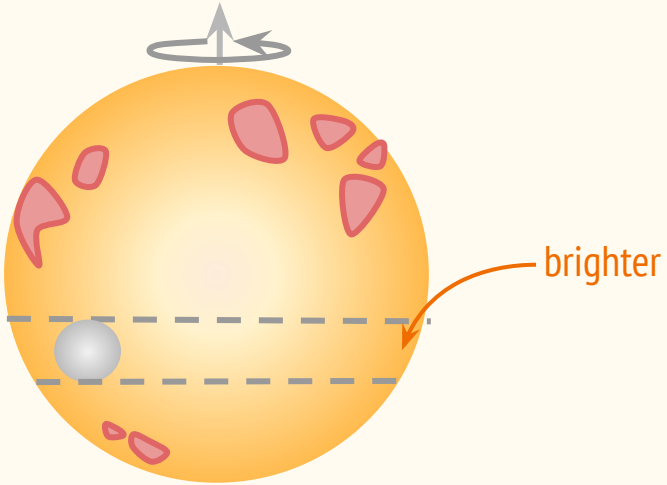


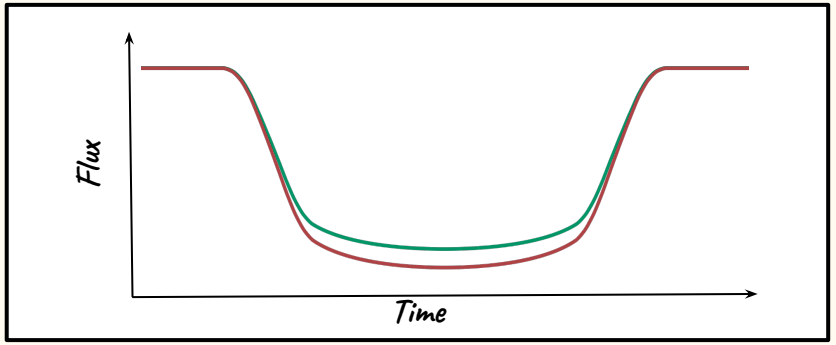
Figure credit: B. Morris (HAT-P-11b)

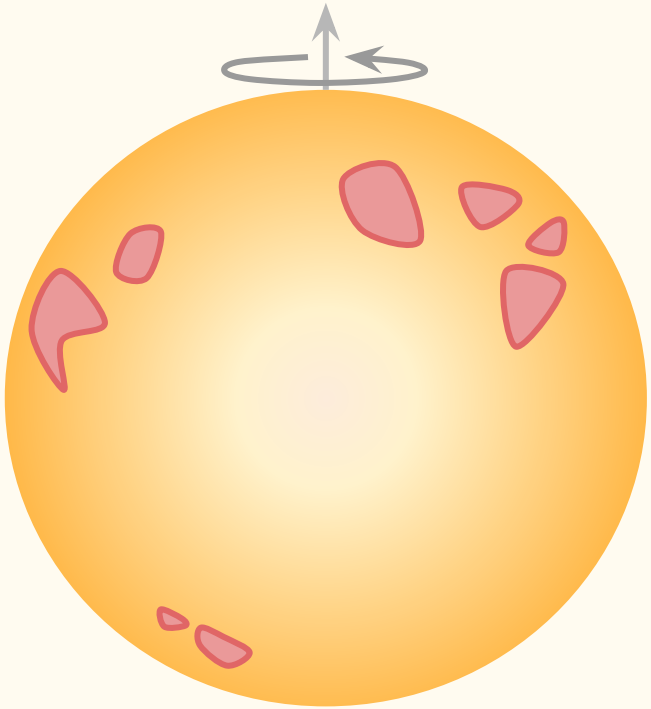


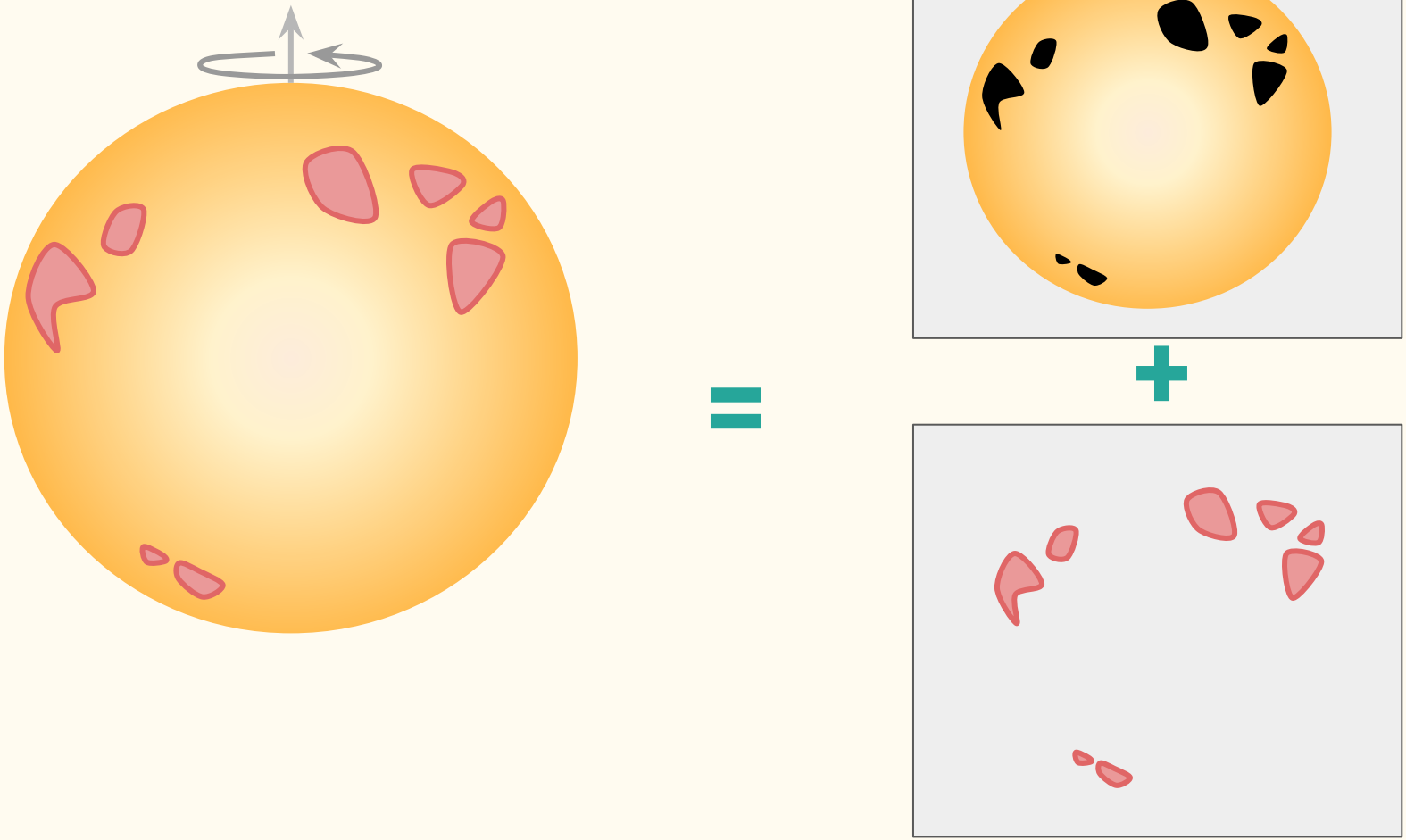
Q: What is the spot coverage fraction required to produce the observe transit depths?

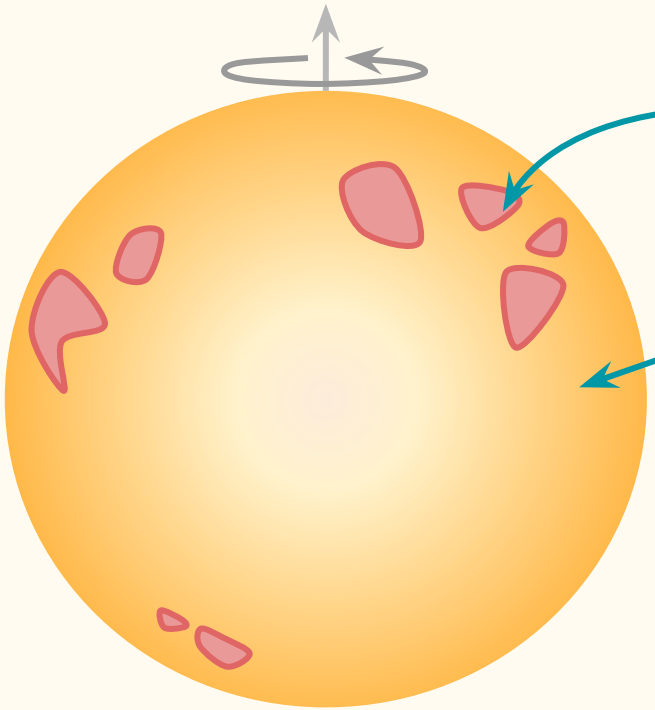
Unocculted Spots







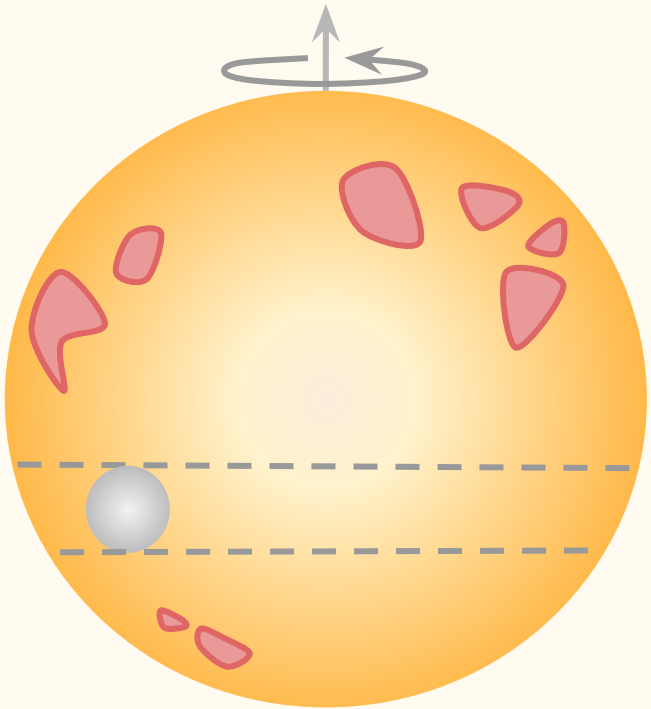




T_{spot} = spot temperature

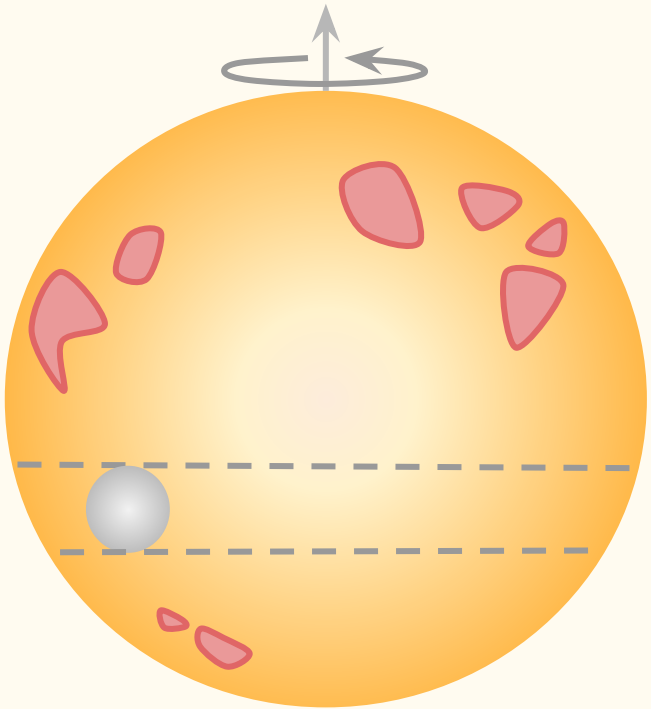
T_{star} = star temperature

f_{spot} = fraction of star with spots



$$\delta_{\lambda,obs} = \frac{\delta_{\lambda,true}}{1 - f_{spot}(1 - \frac{F_{\lambda,spot}}{F_{\lambda,star}})}$$

McCullough+2014; Rackham+2018

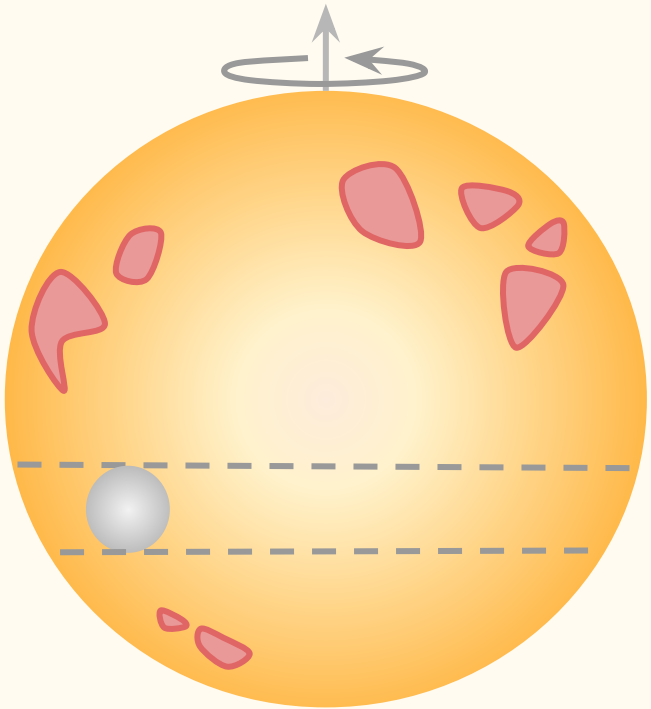


$$\delta_{\lambda,obs} = \frac{\delta_{\lambda,true}}{1 - f_{spot}(1 - \frac{F_{\lambda,spot}}{F_{\lambda,star}})}$$

star area coverage

spot contrast

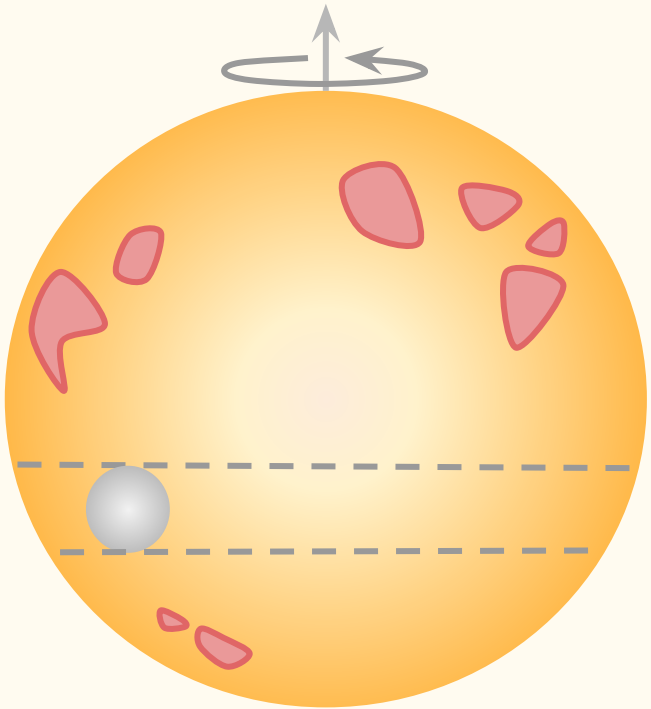
McCullough+2014; Rackham+2018



$$\delta_{\lambda,obs} = \frac{\delta_{\lambda,true}}{1 - f_{spot}(1 - \frac{F_{\lambda,spot}}{F_{\lambda,star}})}$$

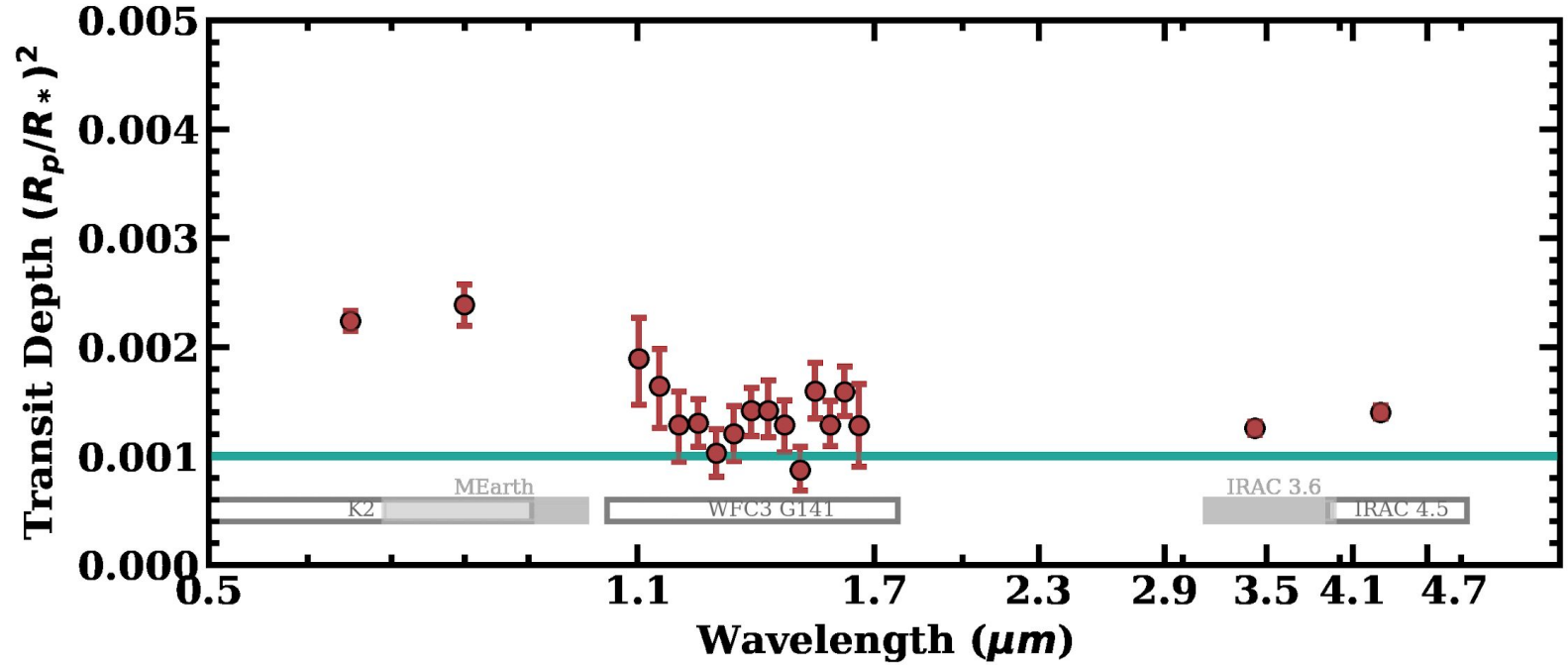
3540 K

McCullough+2014; Rackham+2018

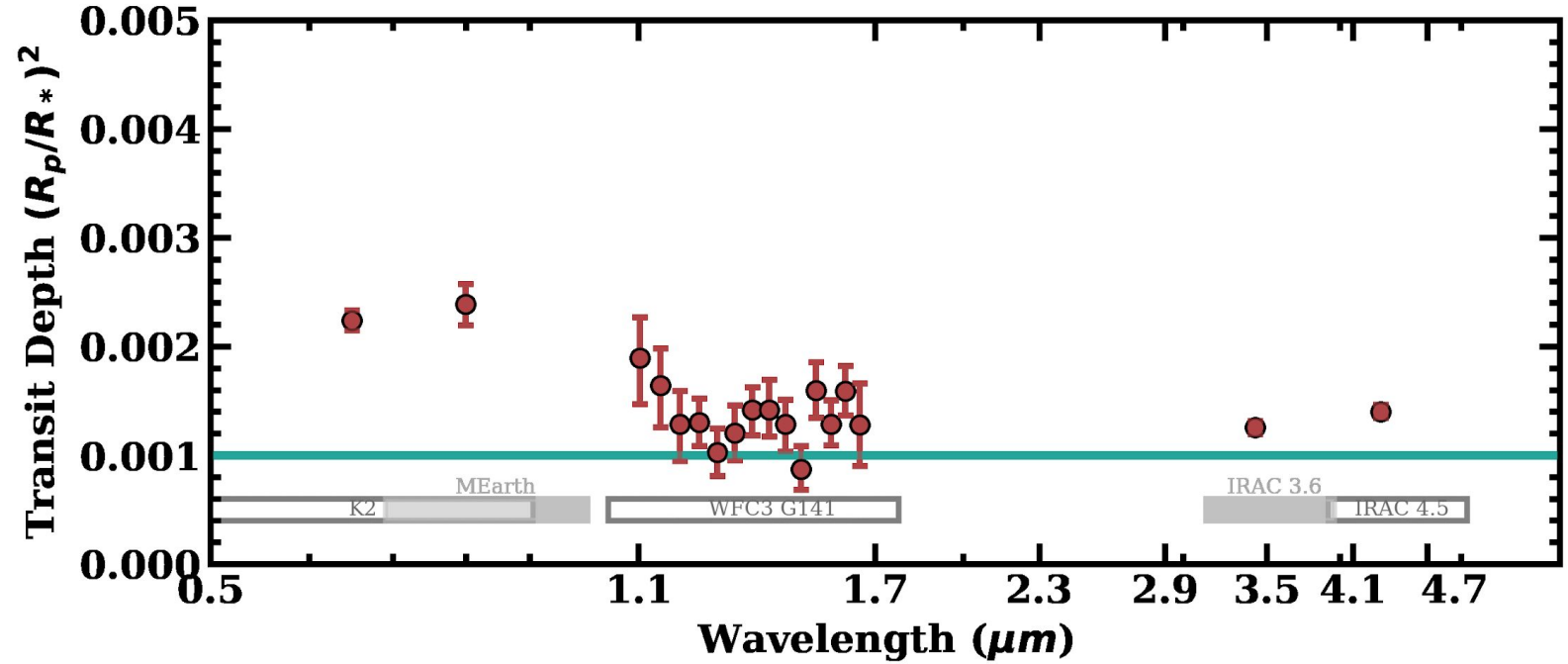


$$\delta_{\lambda,obs} = \frac{\delta_{\lambda,true}}{1 - f_{spot}\left(1 - \frac{F_{\lambda,spot}}{F_{\lambda,star}}\right)}$$

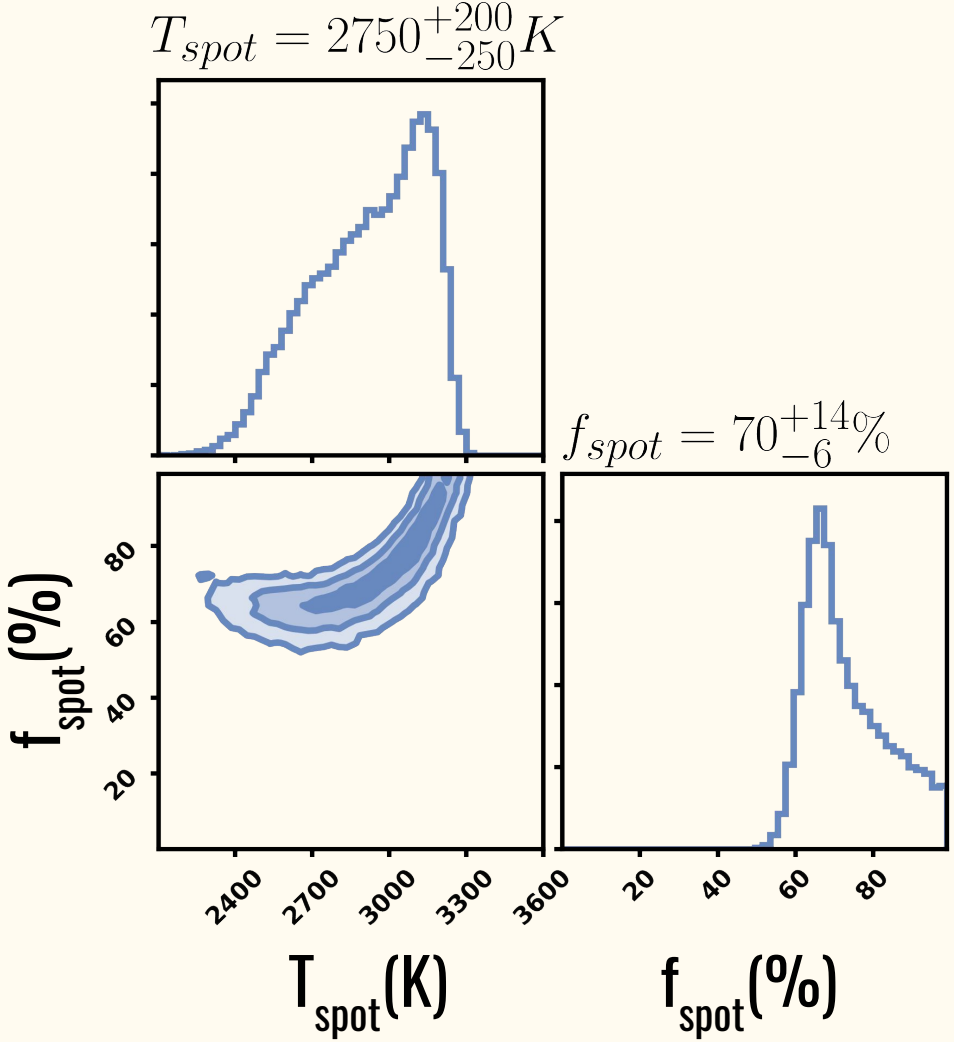
McCullough+2014; Rackham+2018

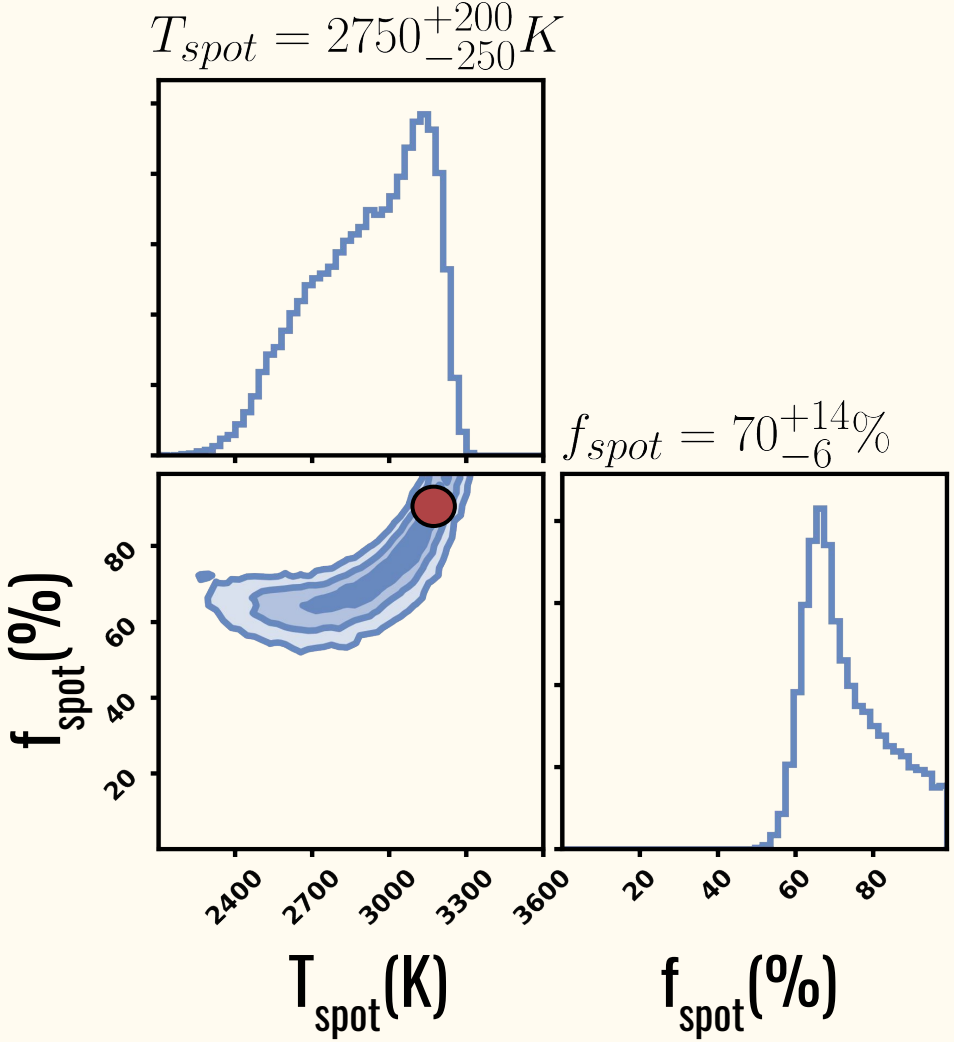

0.005
0.004
0.003
0.002
0.001
0.000
Transit Depth (R_p/R_*)^2
0.5
1.1
1.7
2.3
2.9
3.5
4.1
4.7
Wavelength (μm)
MEarth
K2
WFC3 G141
IRAC 3.6
IRAC 4.5

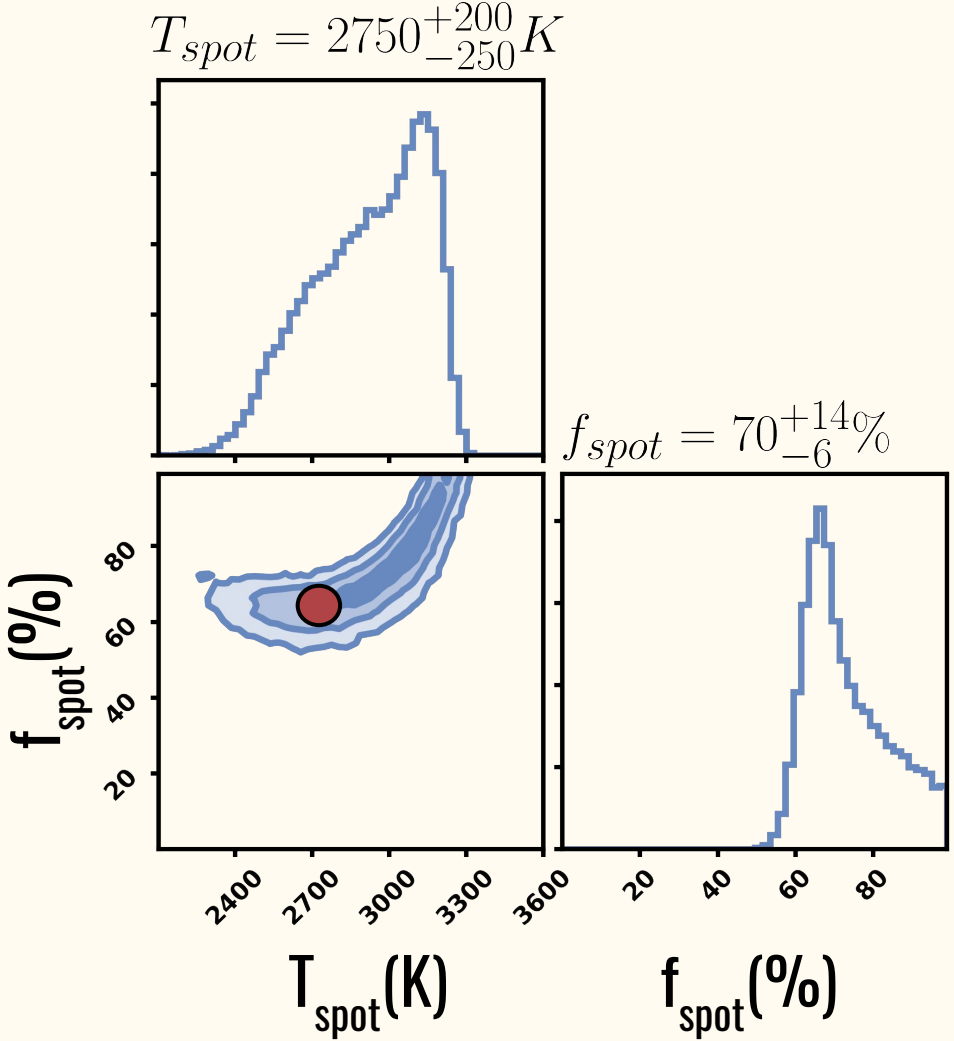

T_{star} (K)
T_{spot} (K)
f_S
3540
3045
0.00


0.005
0.004
0.003
0.002
0.001
0.000
Transit Depth (R_p/R_*)^2
0.5
1.1
1.7
2.3
2.9
3.5
4.1
4.7
Wavelength (μm)
MEarth
K2
WFC3 G141
IRAC 3.6
IRAC 4.5

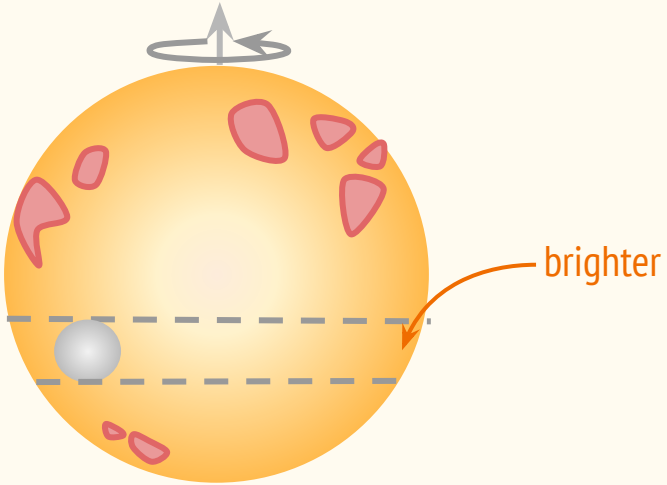

T_{star} (K)
T_{spot} (K)
f_S
3540
3540
0.60


$T_{spot} = 2750^{+200}_{-250} K$
$f_{spot} = 70^{+14}_{-6}\%$
f_{spot}(%)
20
40
60
80
2400
2700
3000
3300
3600
20
40
60
80
T_{spot}(K)
f_{spot}(%)


$T_{spot} = 2750^{+200}_{-250} K$
$f_{spot} = 70^{+14}_{-6}\%$
f_{spot}(%)
80
60
40
20
2400
2700
3000
3300
3600
20
40
60
80
T_{spot}(K)
f_{spot}(%)

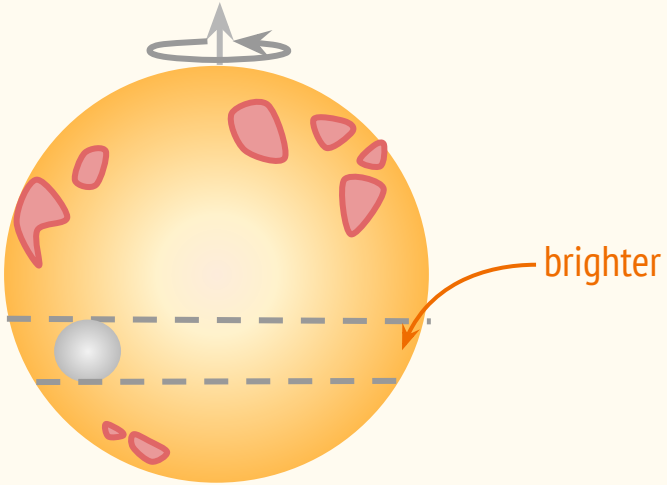

$T_{spot} = 2750^{+200}_{-250} K$
$f_{spot} = 70^{+14}_{-6}\%$
f_{spot}(%)
80
60
40
20
2400
2700
3000
3300
3600
20
40
60
80
T_{spot}(K)
f_{spot}(%)

Unocculted Spots



Q: What is the spot coverage fraction required to produce the observe transit depths?

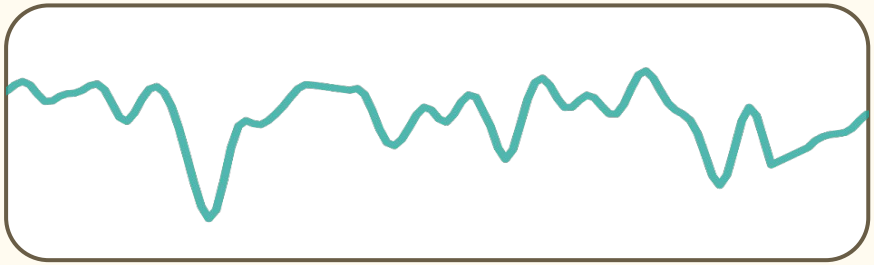
Unocculted Spots



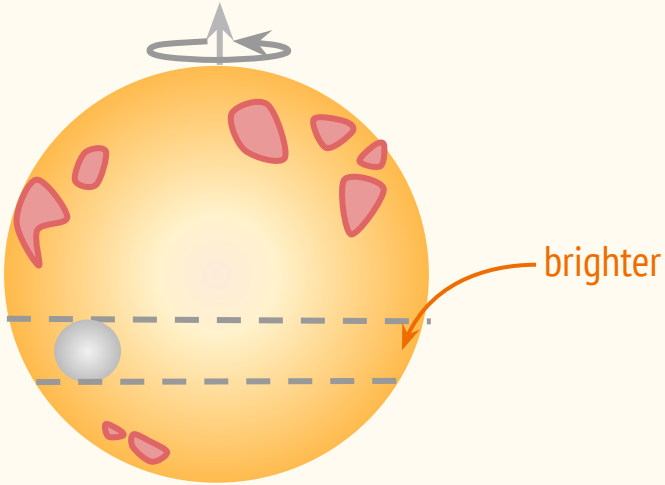
Q: What is the spot coverage fraction required to produce the observe transit depths?

A: $f_{spot} > 60\%$

Stellar Spectra



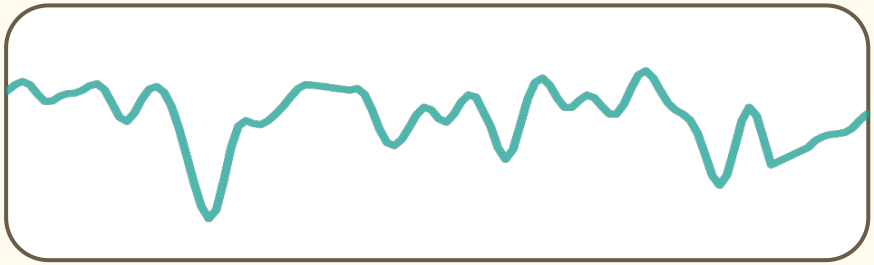
Unocculted Spots



Q: What is the spot coverage fraction required to produce the observe transit depths?

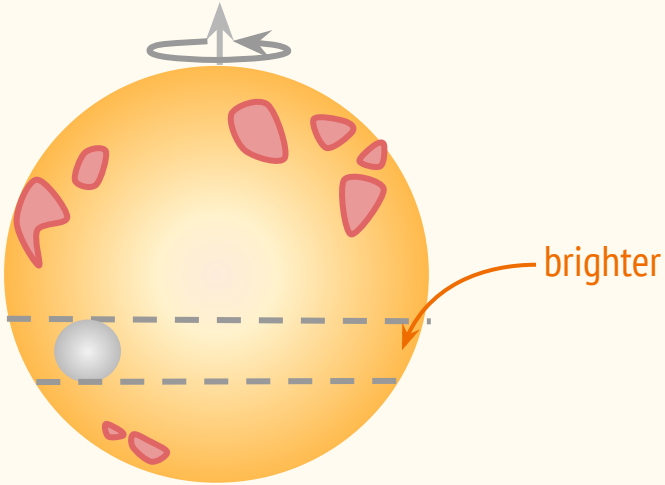
A: $f_{spot} > 60\%$

Stellar Spectra



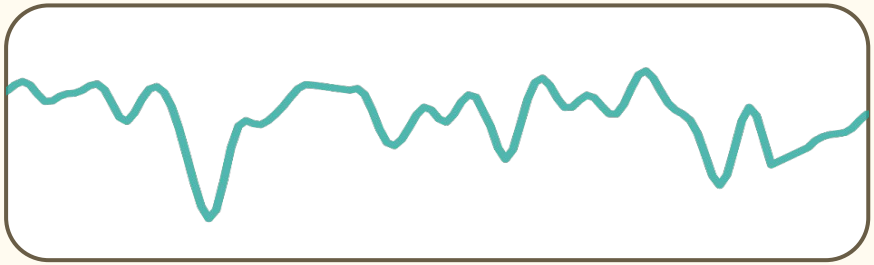
Q: What is the spot coverage fraction constrained from the stellar spectrum?

Unocculted Spots



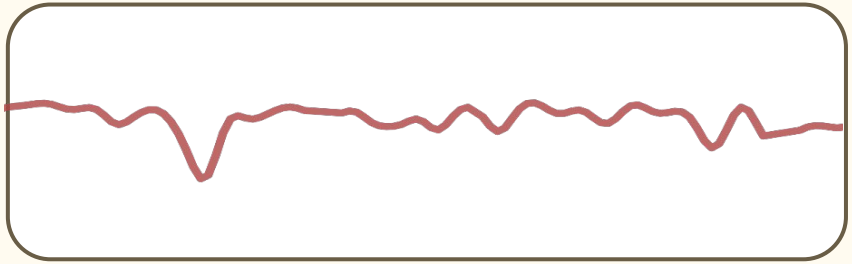
Q: What is the spot coverage fraction required to produce the observe transit depths?

A: $f_{spot} > 60\%$



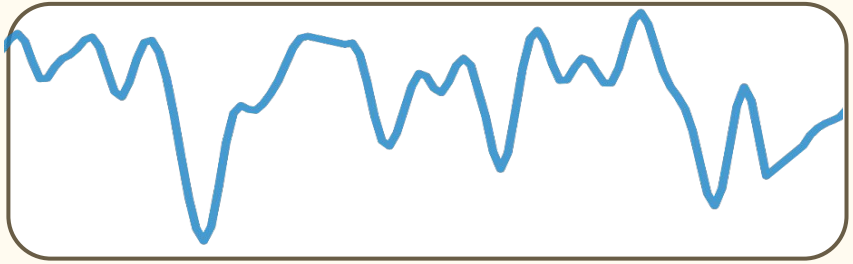
observed spectrum

=

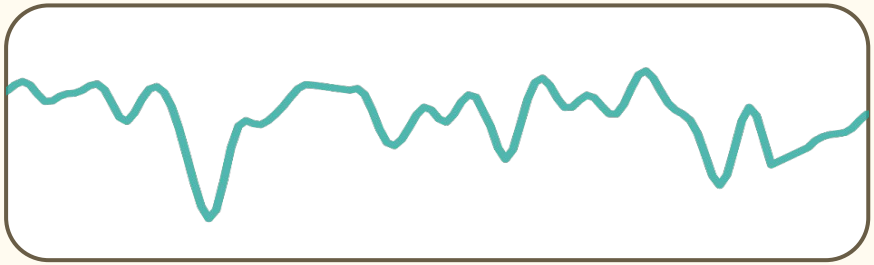


photosphere

+

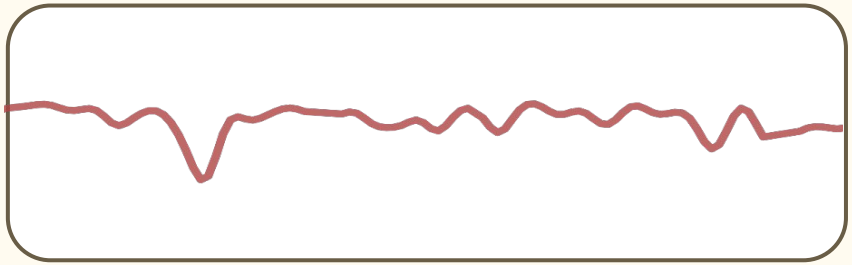


spot



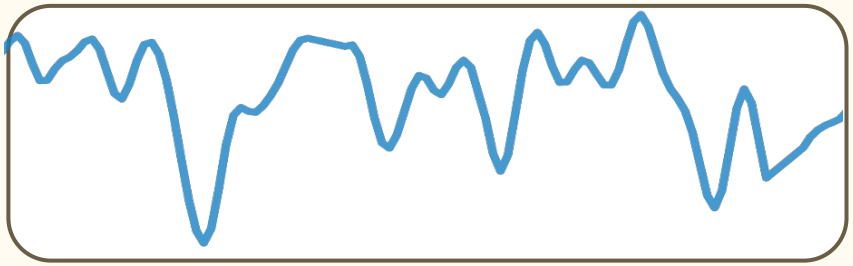
observed spectrum

=



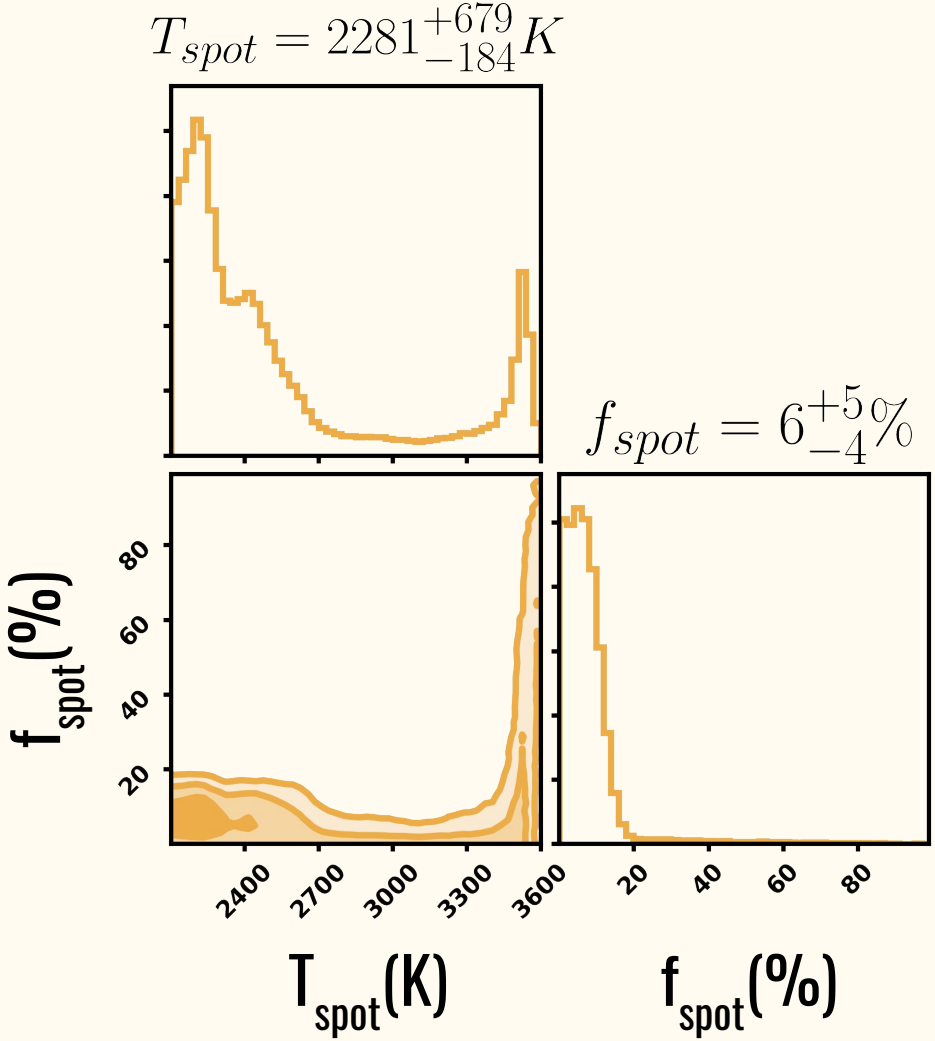
photosphere

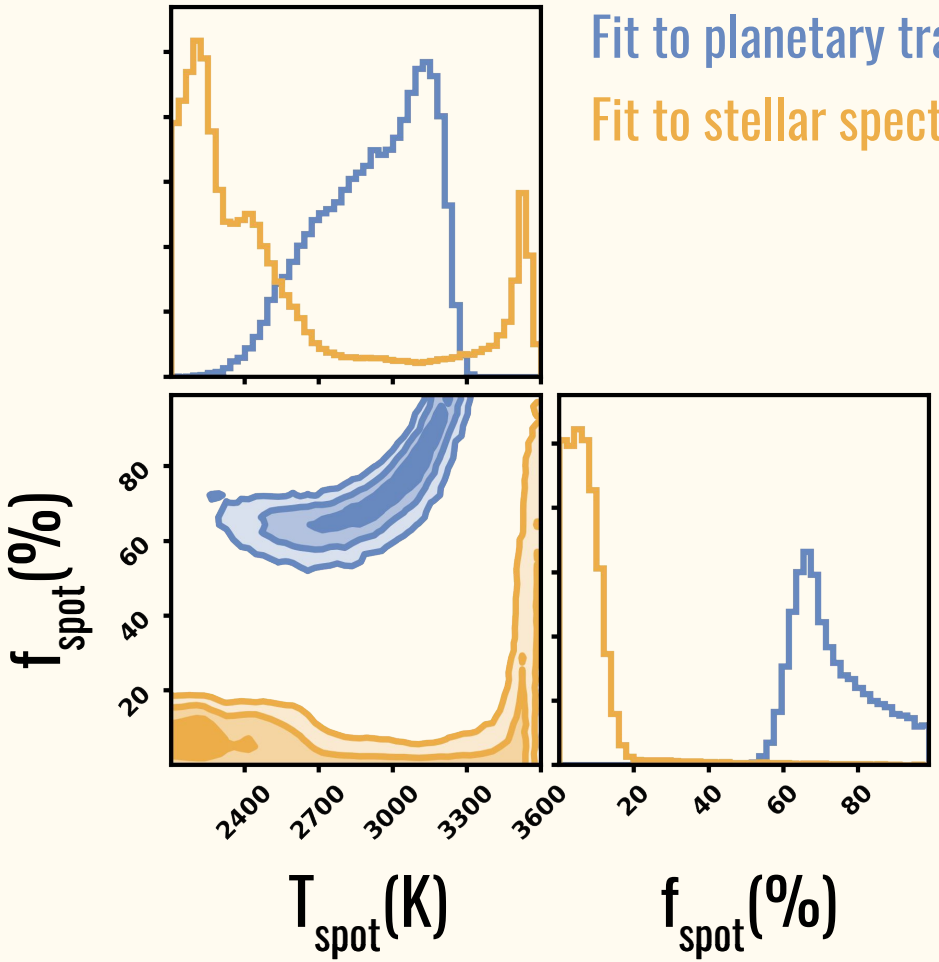
+



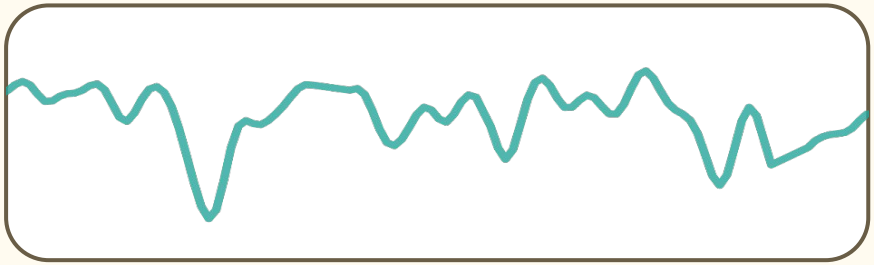
spot

+ *fraction of spots (f_{spot}), calibration terms, extinction (A_V), underestimated errors (σ)*


$T_{spot} = 2281^{+679}_{-184} K$
$f_{spot} = 6^{+5}_{-4}\%$
f_spot(%)
20
40
60
80
2400
2700
3000
3300
3600
20
40
60
80
T_spot(K)
f_spot(%)


Fit to planetary transmission spectrum
Fit to stellar spectrum
f_{spot}(%)
20
40
60
80
2400
2700
3000
3300
3600
T_{spot}(K)
20
40
60
80
f_{spot}(%)

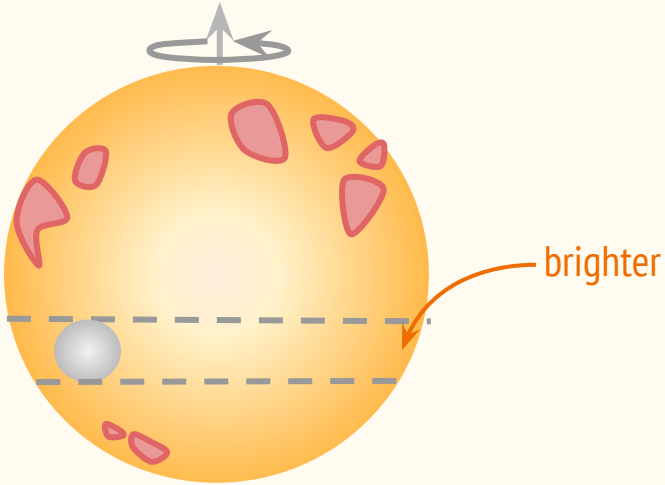
Stellar Spectra



Q: What is the spot coverage fraction constrained from the stellar spectrum?

A: $f_{spot} < 20\%$

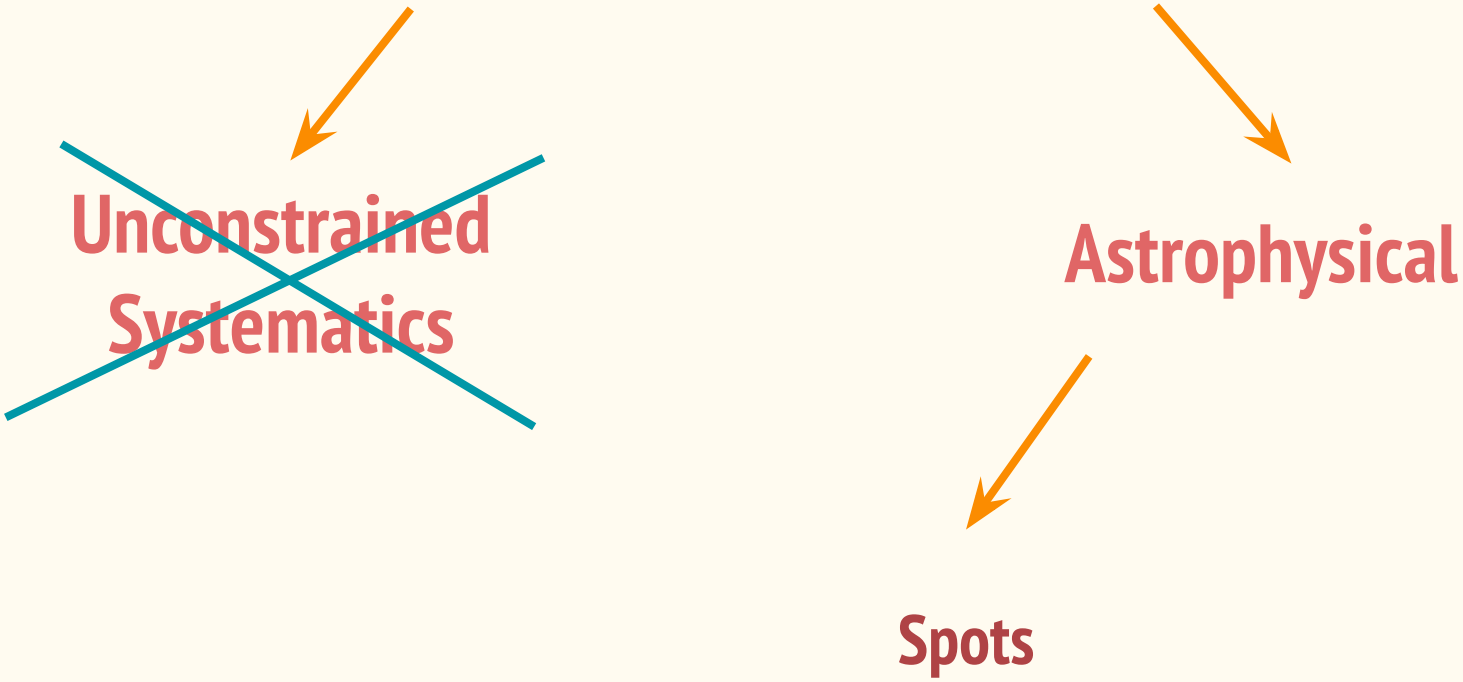
Unocculted Spots



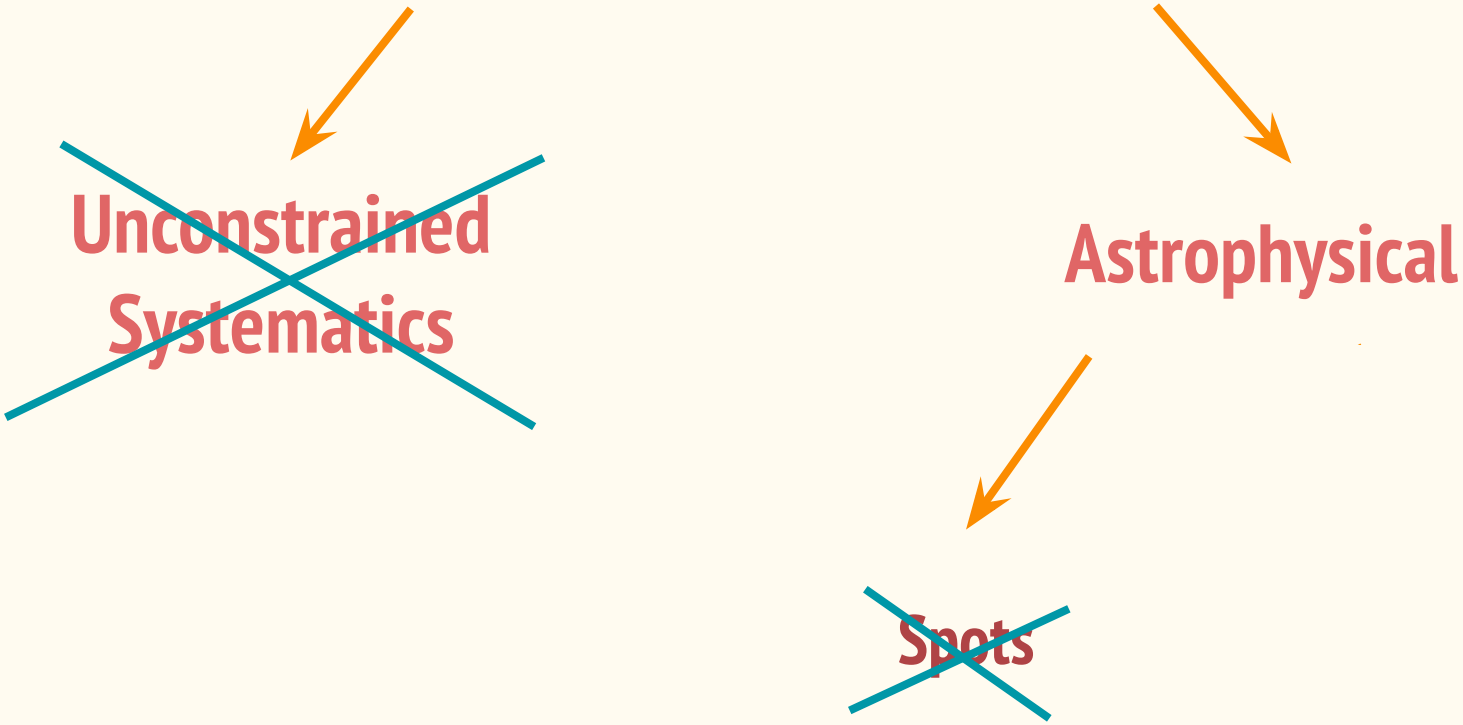
Q: What is the spot coverage fraction required to produce the observe transit depths?

A: $f_{spot} > 60\%$

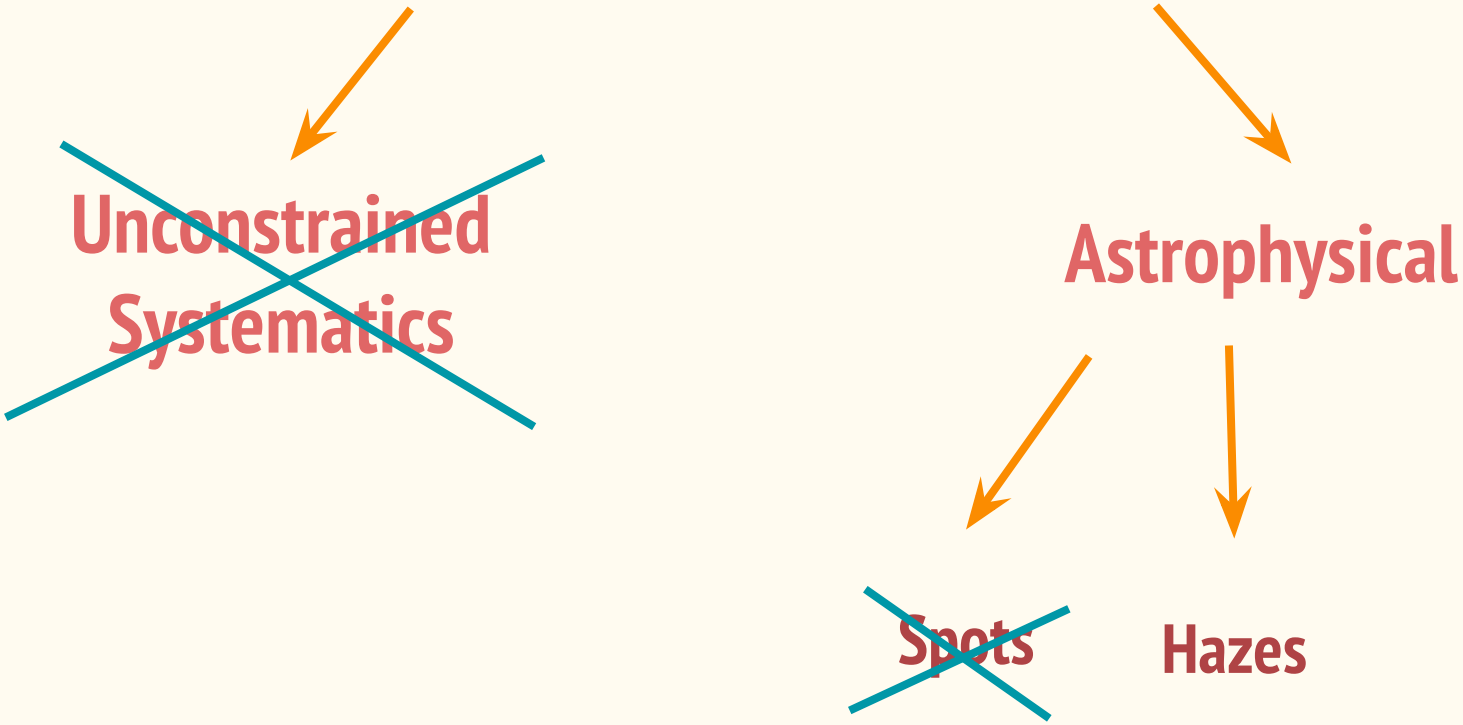
~2x transit depth difference



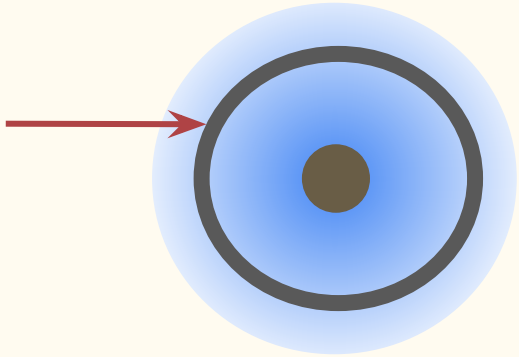
~2x transit depth difference



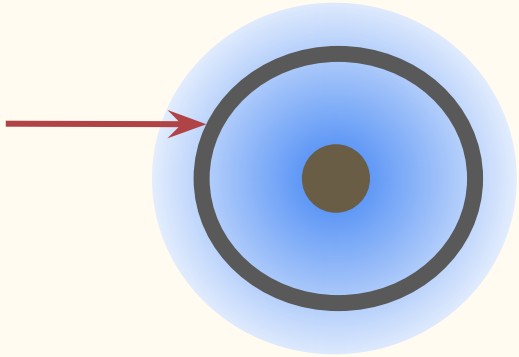
~2x transit depth difference

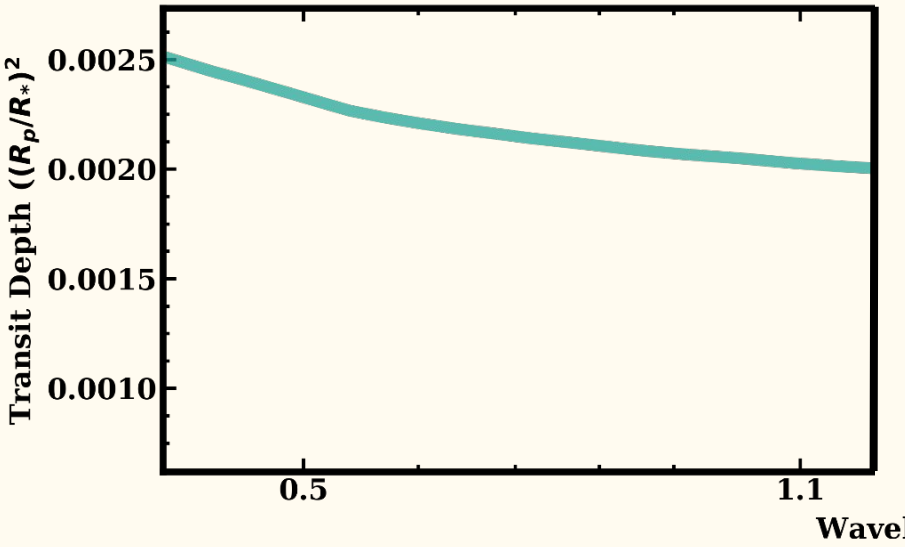


Size ~ Optical λ

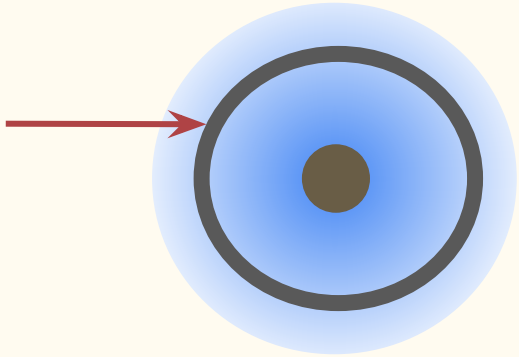


Size ~ Optical λ

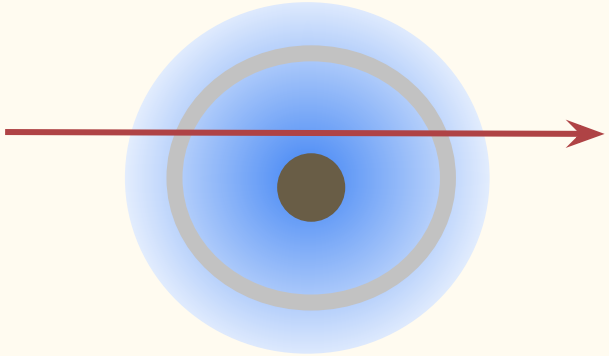


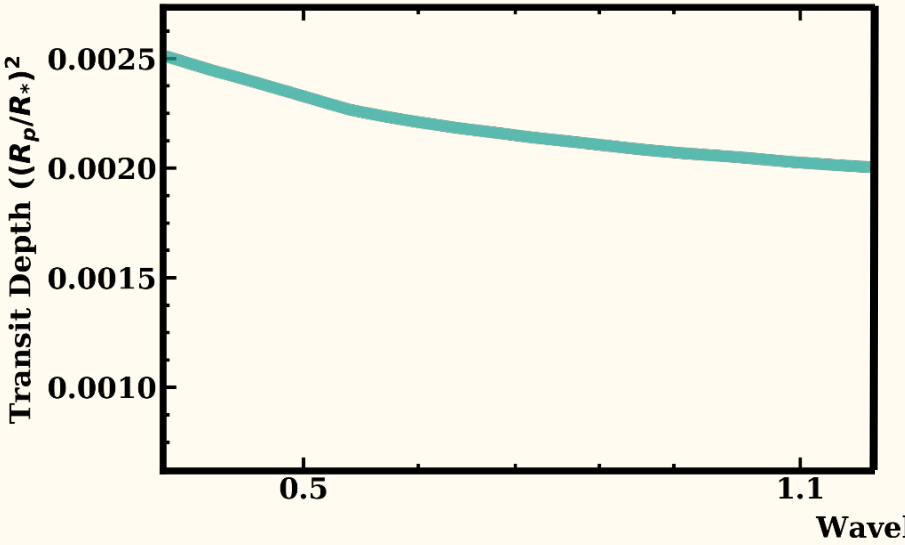


Size ~ Optical λ



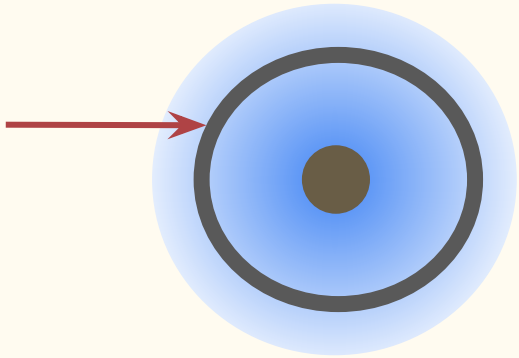
Size > NIR λ

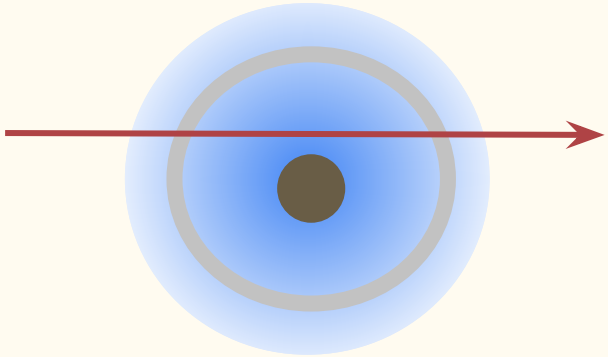


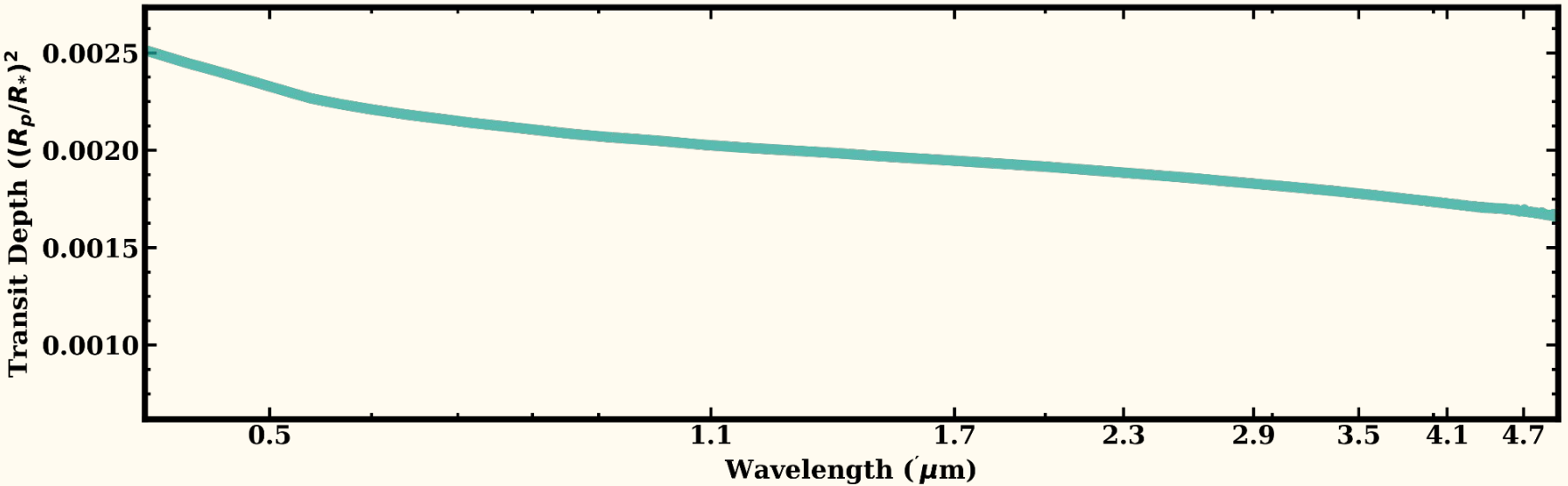


Size ~ Optical λ

Size > NIR λ

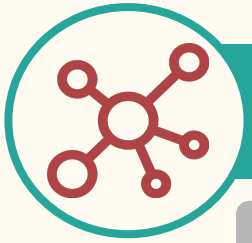






Haze parameters

Haze parameters



Composition

Tholin

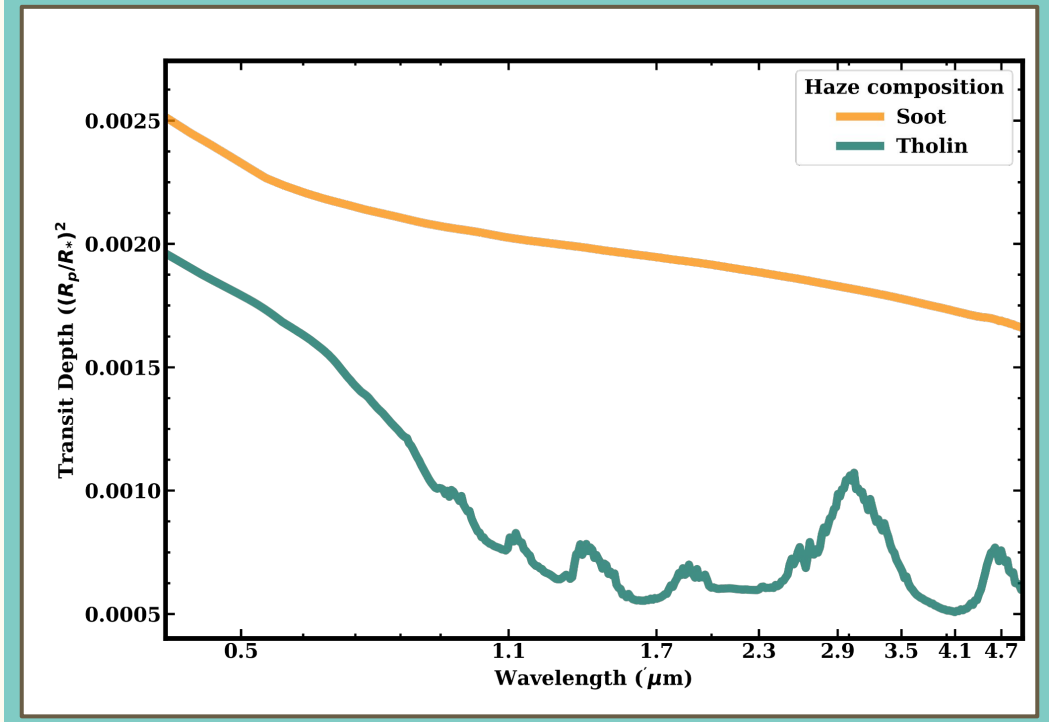
Soot

Haze parameters

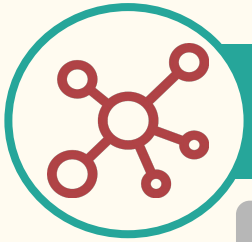
Composition

Tholin

Soot



Haze parameters



Composition

- Tholin
- Soot

Carbon

- Methane (CH_4)
- Carbon monoxide (CO)

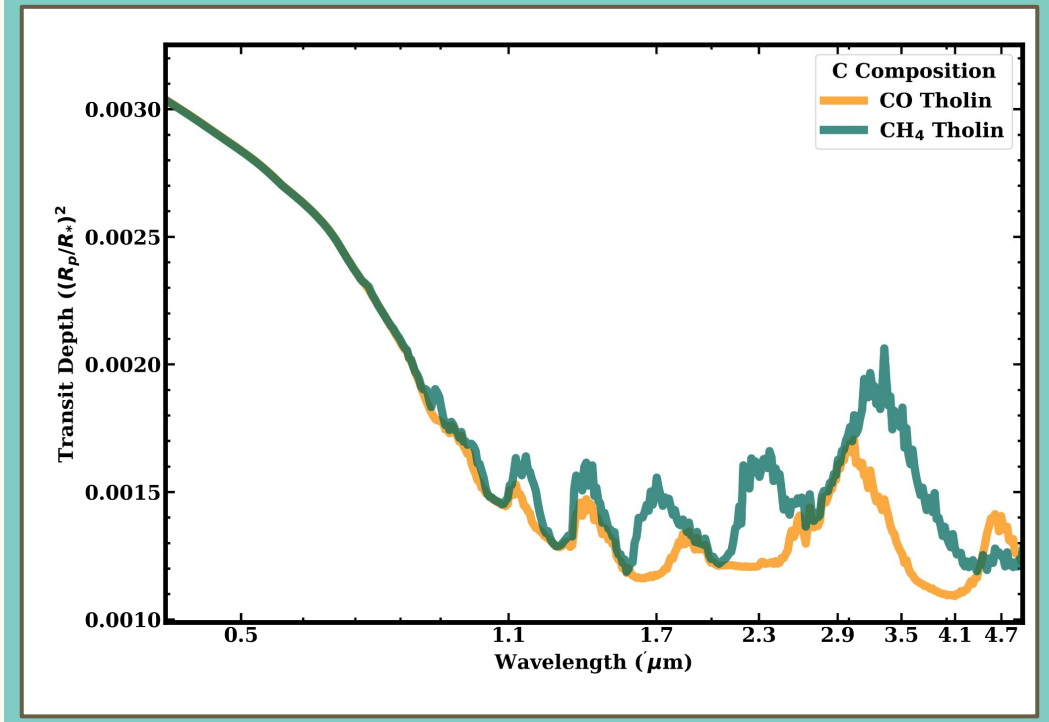
Haze parameters

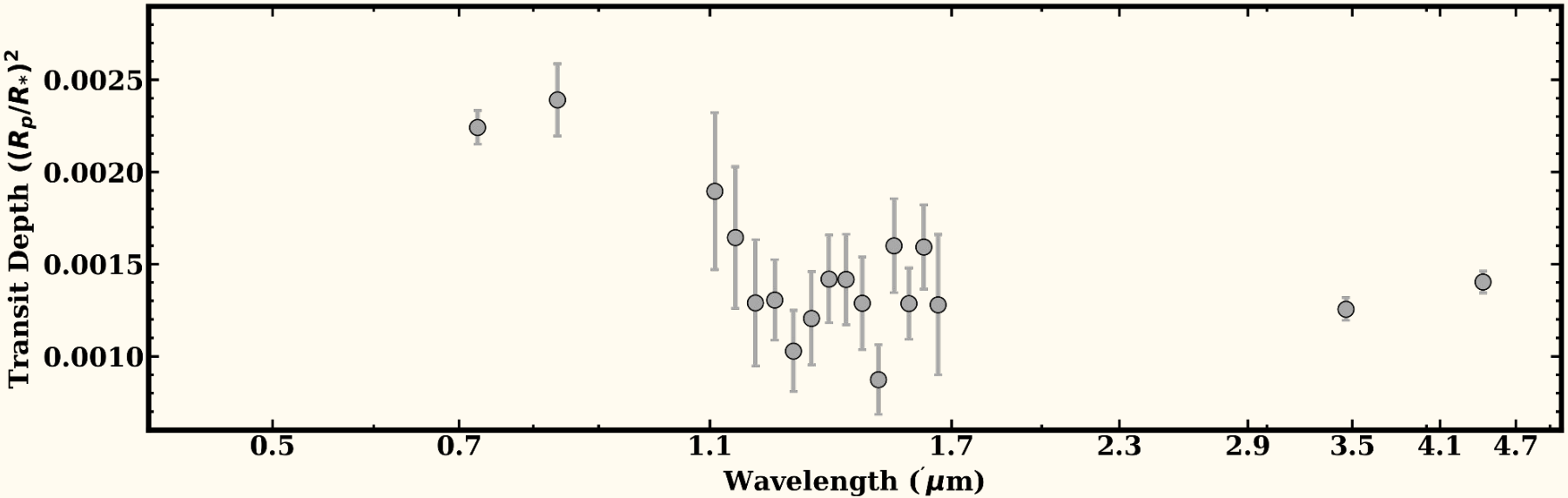
Composition

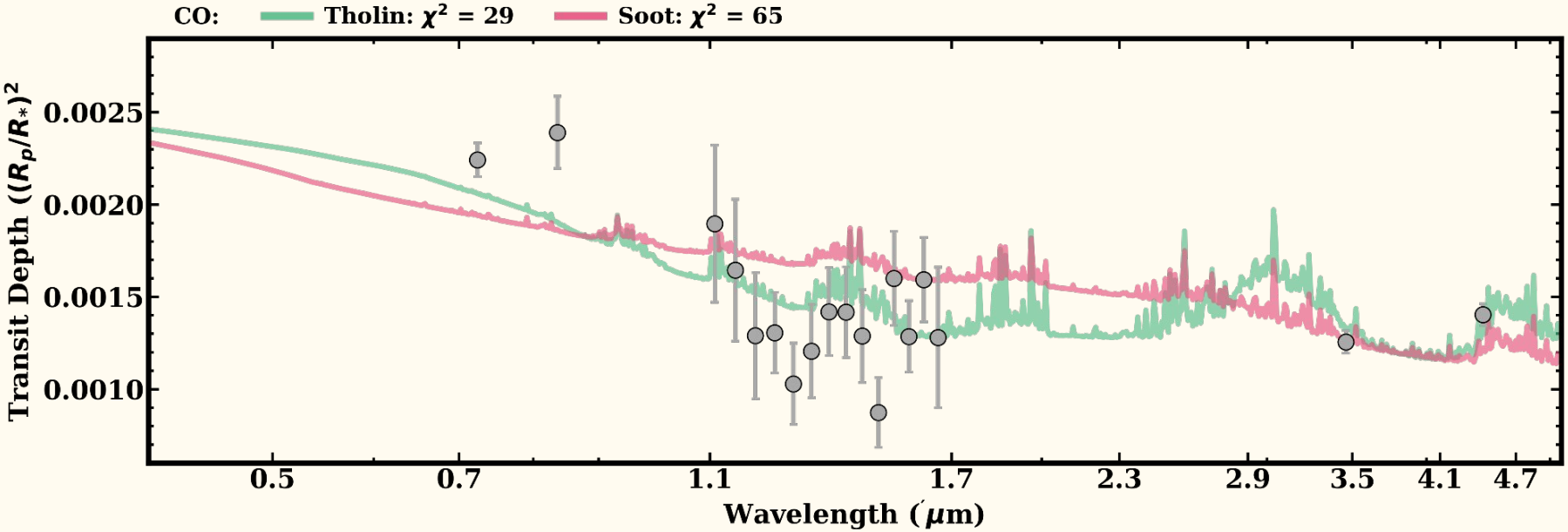
- Tholin
- Soot

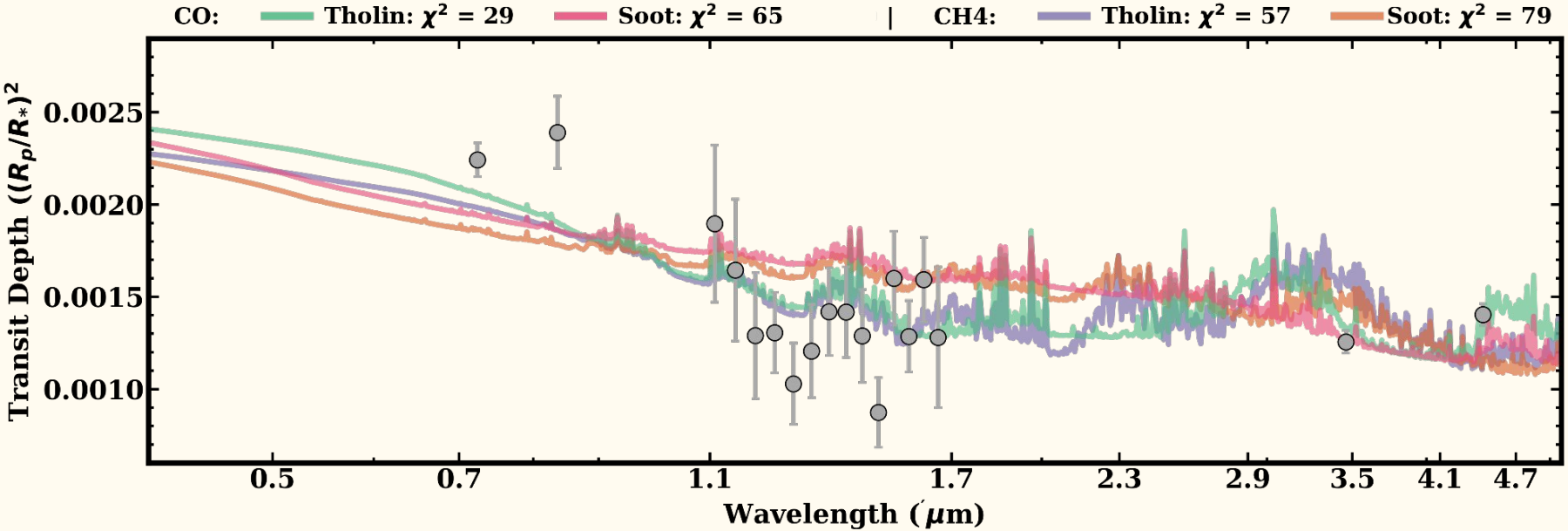
Carbon

- Methane (CH_4)
- Carbon monoxide (CO)

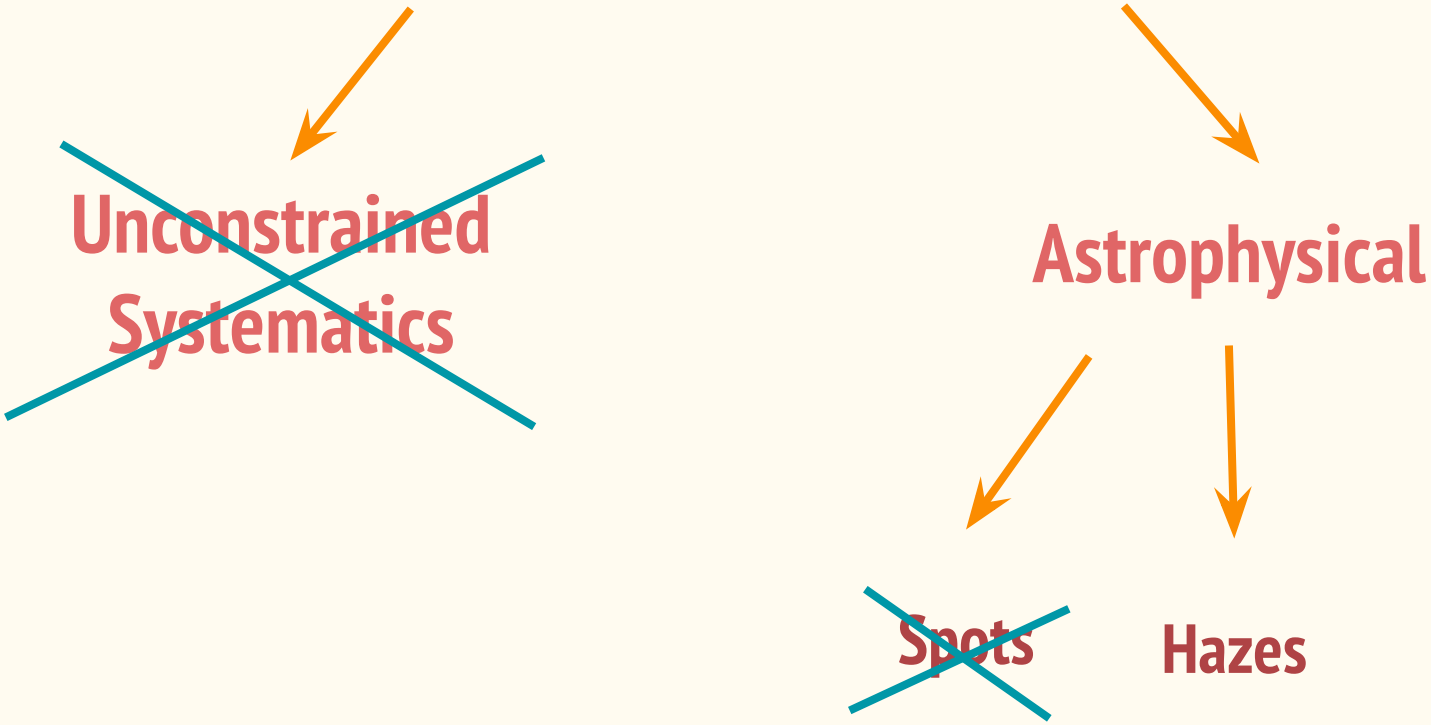



Transit Depth ($(R_p/R_*)^2$)
0.0025
0.0020
0.0015
0.0010
0.5
0.7
1.1
1.7
2.3
2.9
3.5
4.1
4.7
Wavelength (μm)

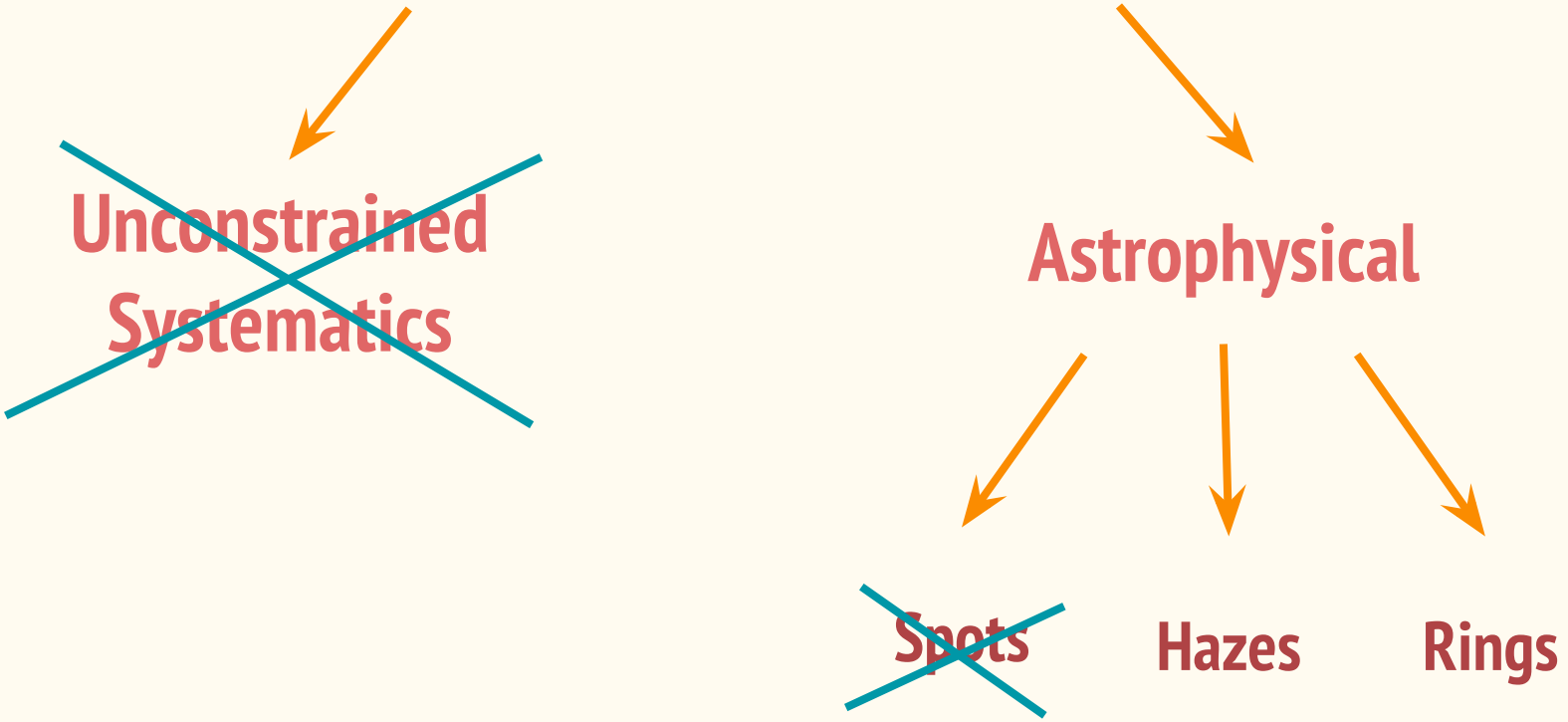

CO:
Tholin: χ^2 = 29
Soot: χ^2 = 65
Transit Depth ($(R_p/R_*)^2$
0.0025
0.0020
0.0015
0.0010
0.5
0.7
1.1
1.7
2.3
2.9
3.5
4.1
4.7
Wavelength (μm)


CO:
Tholin: χ^2 = 29
Soot: χ^2 = 65
|
CH4:
Tholin: χ^2 = 57
Soot: χ^2 = 79
Transit Depth ($(R_p/R_*)^2$)
0.0025
0.0020
0.0015
0.0010
0.5
0.7
1.1
1.7
2.3
2.9
3.5
4.1
4.7
Wavelength (μm)

~2x transit depth difference



~2x transit depth difference



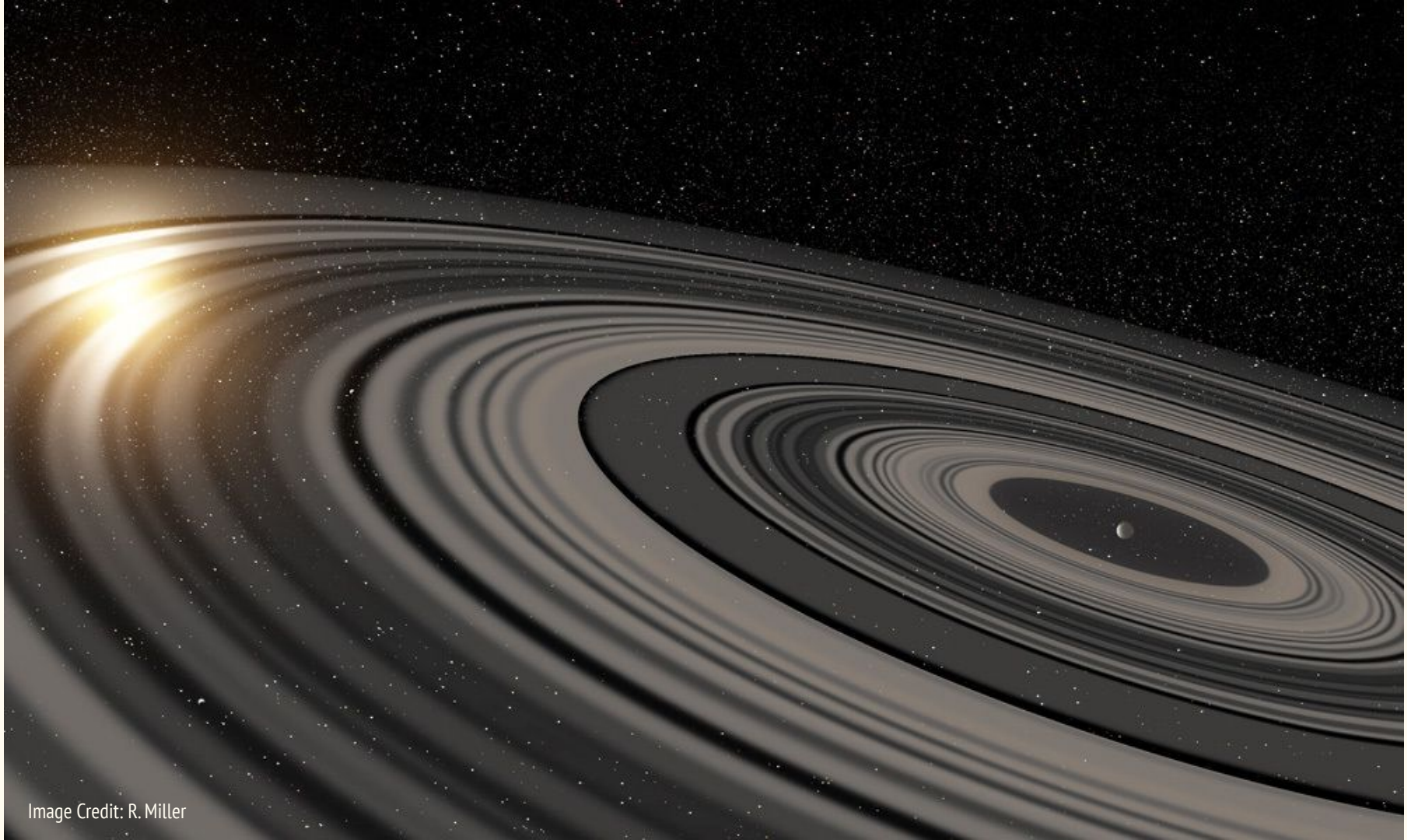
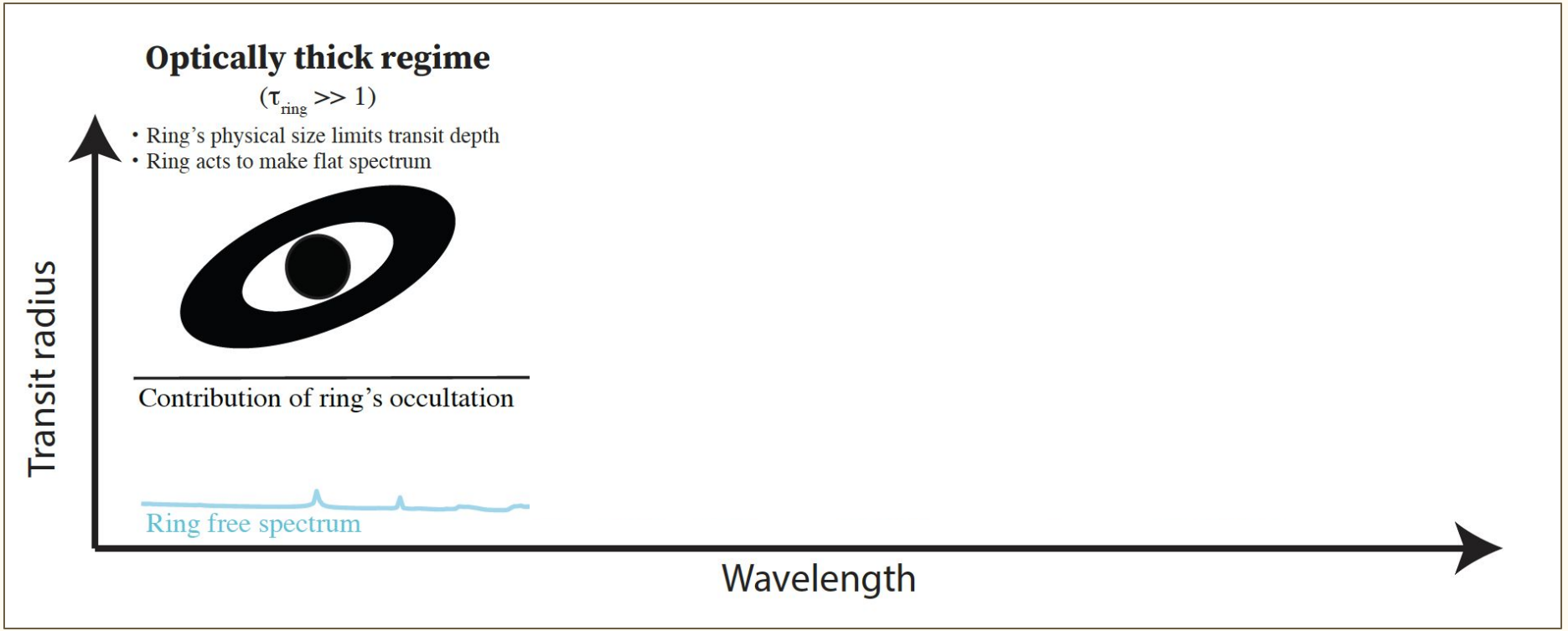
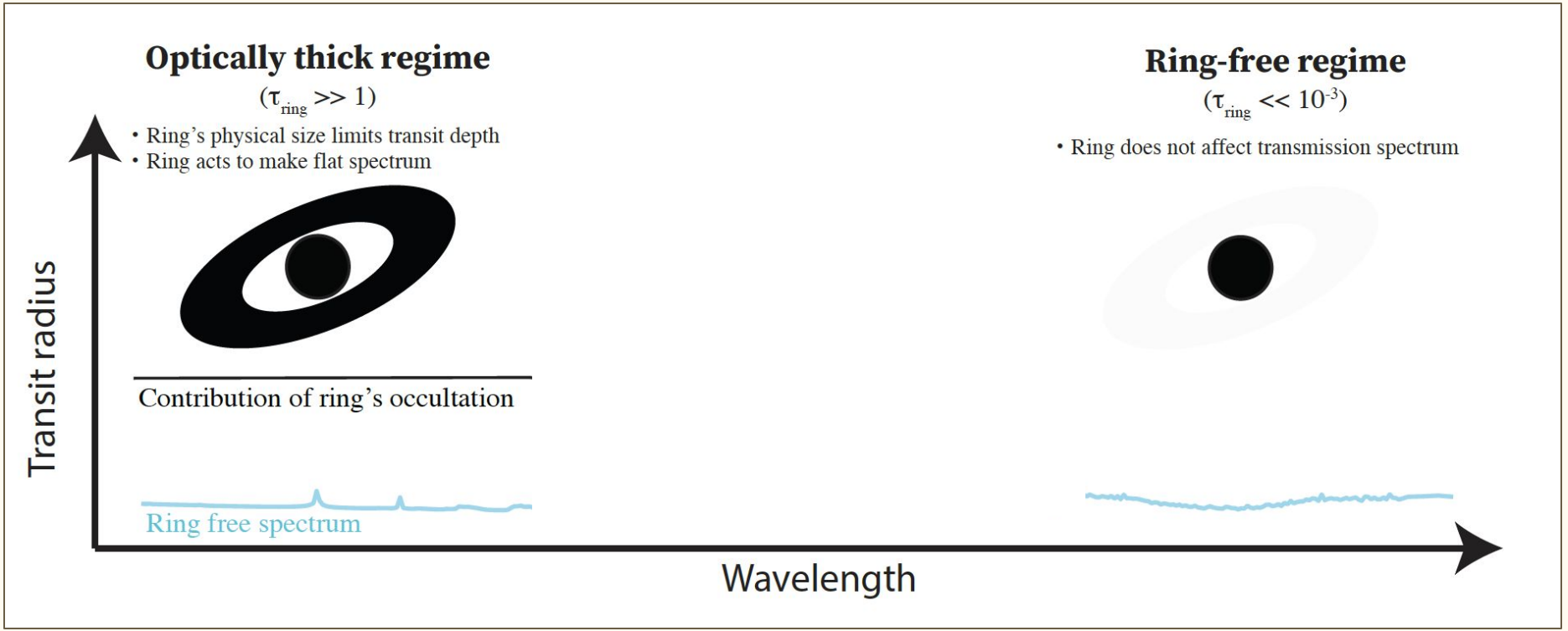


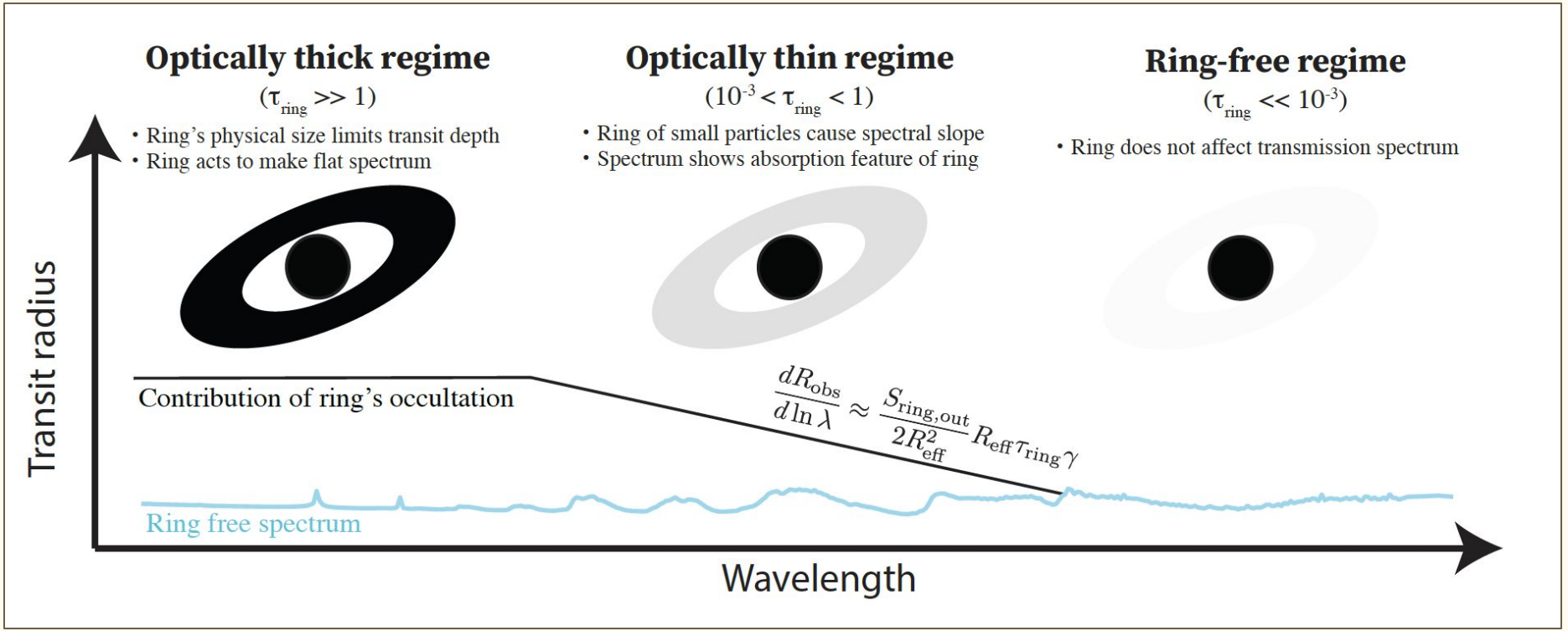
Image Credit: R. Miller


Optically thick regime
(τ_{ring} >> 1)
• Ring's physical size limits transit depth
• Ring acts to make flat spectrum
Contribution of ring's occultation
Ring free spectrum
Transit radius
Wavelength

Ohno+2023


Optically thick regime
($\tau_{ring} >> 1$)
• Ring's physical size limits transit depth
• Ring acts to make flat spectrum
Contribution of ring's occultation
Ring free spectrum
Ring-free regime
($\tau_{ring} << 10^{-3}$)
• Ring does not affect transmission spectrum
Transit radius
Wavelength

Ohno+2023


Optically thick regime
($\tau_{ring} >> 1$)
• Ring's physical size limits transit depth
• Ring acts to make flat spectrum
Optically thin regime
($10^{-3} < \tau_{ring} < 1$)
• Ring of small particles cause spectral slope
• Spectrum shows absorption feature of ring
Ring-free regime
($\tau_{ring} << 10^{-3}$)
• Ring does not affect transmission spectrum
Transit radius
Contribution of ring's occultation
$\frac{dR_{obs}}{d\ln\lambda} \approx \frac{S_{ring,out}}{2R_{eff}^2} R_{eff}\tau_{ring}\gamma$
Ring free spectrum
Wavelength

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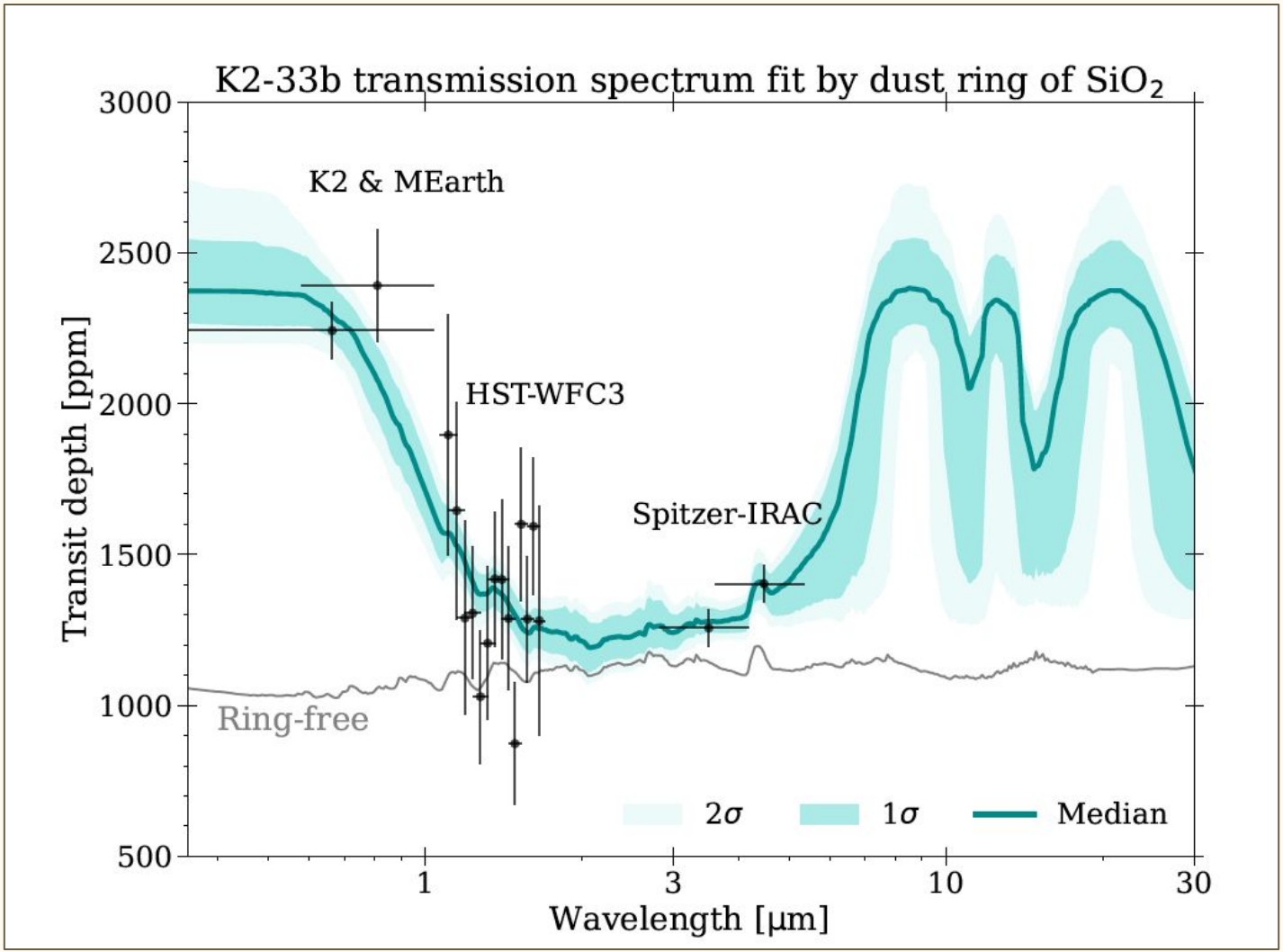
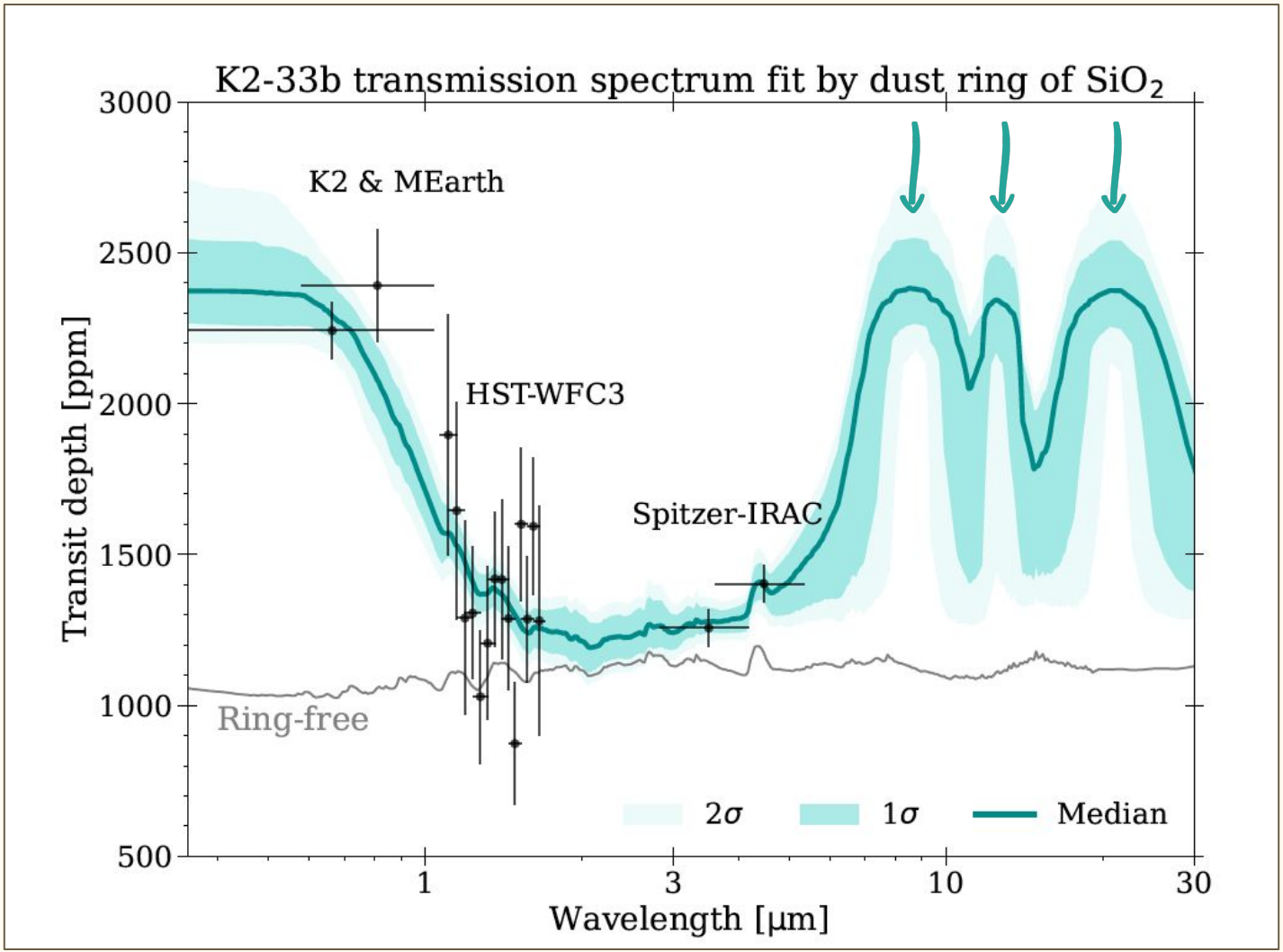

K2-33b transmission spectrum fit by dust ring of SiO_2
K2 & MEarth
HST-WFC3
Spitzer-IRAC
Ring-free
2σ
1σ
Median
Transit depth [ppm]
Wavelength [μm]
3000
2500
2000
1500
1000
500
1
3
10
30

Ohno+2023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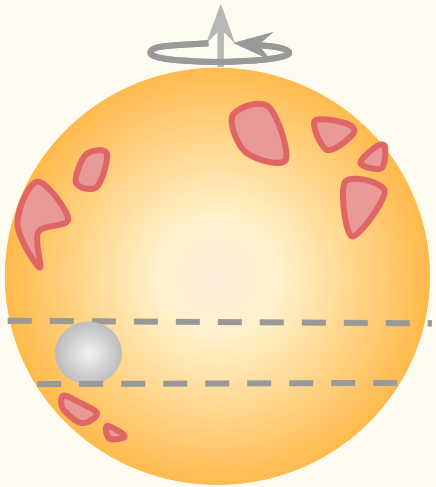
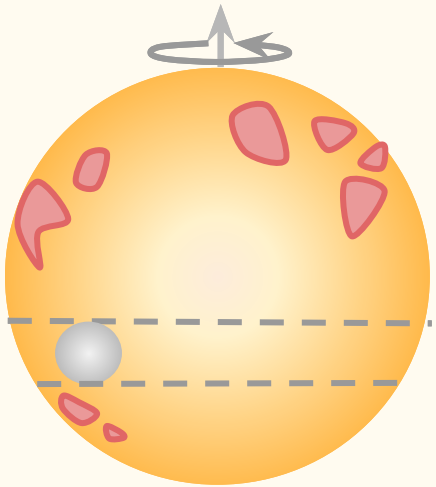
2σ
1σ
Median
Transit depth [ppm]
Wavelength [μm]
3000
2500
2000
1500
1000
500
1
3
10
30

Ohno+2023

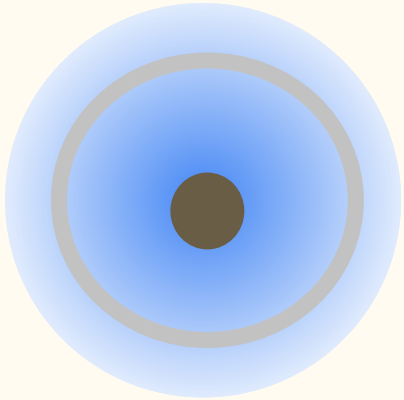
Spots



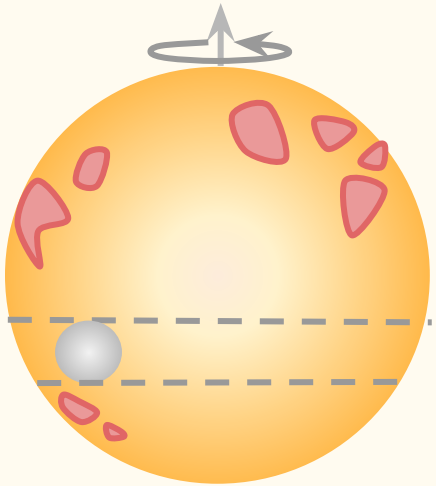
Spots



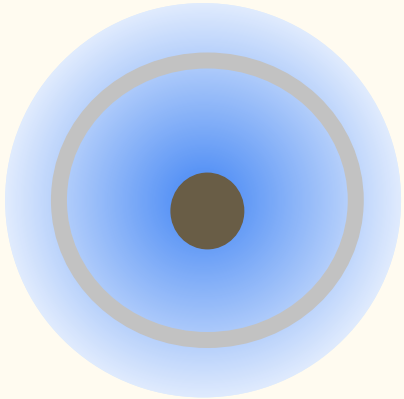
Hazes



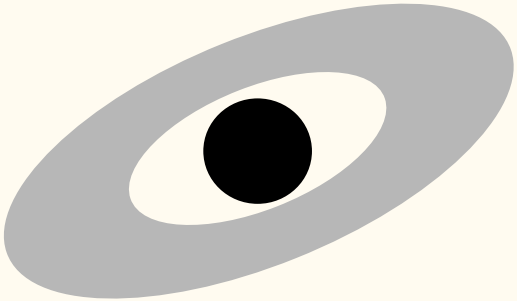
Spots



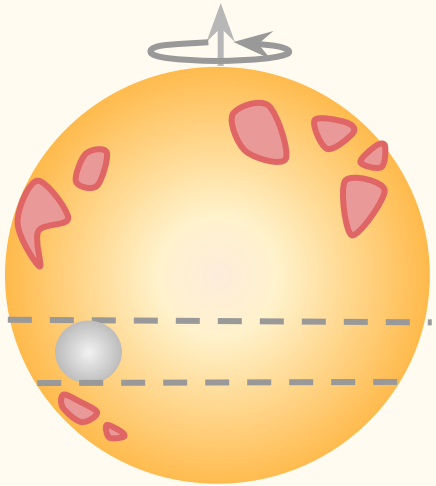
Hazes



Rings

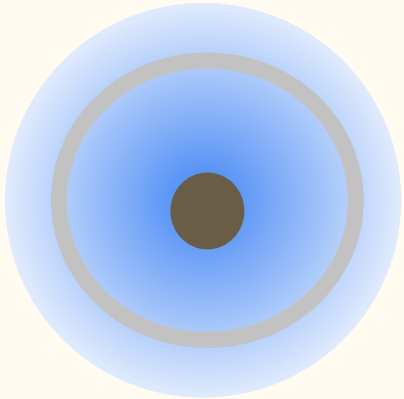


Spots

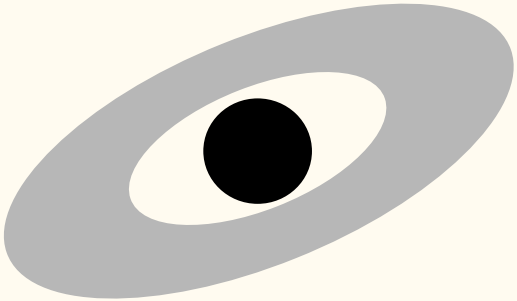


Always present

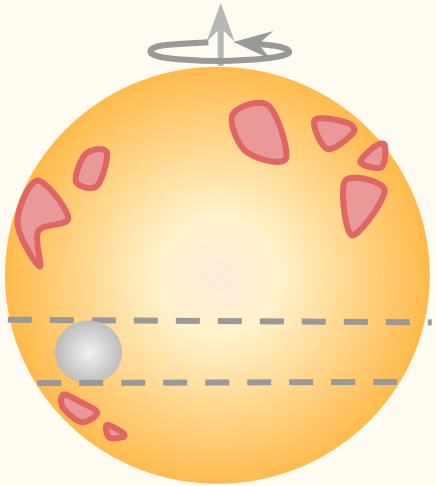
Hazes



Rings

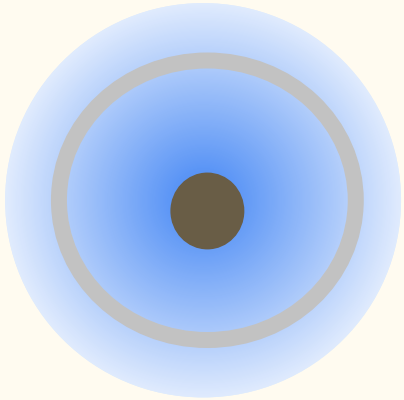


Spots

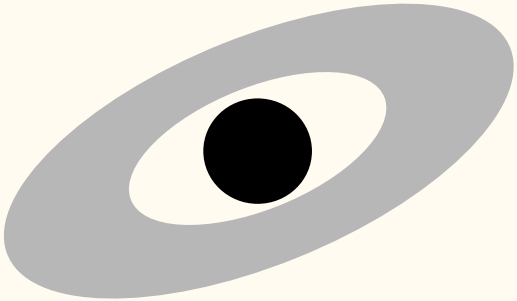


Always present

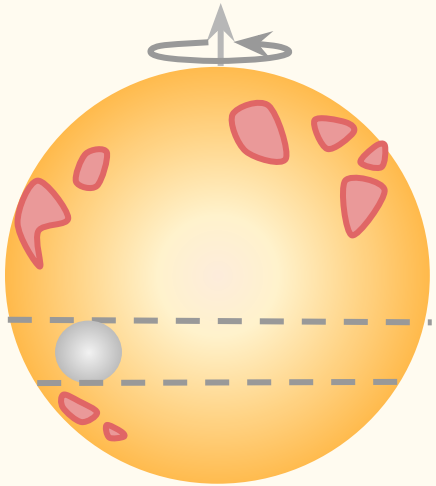
Hazes



Rings

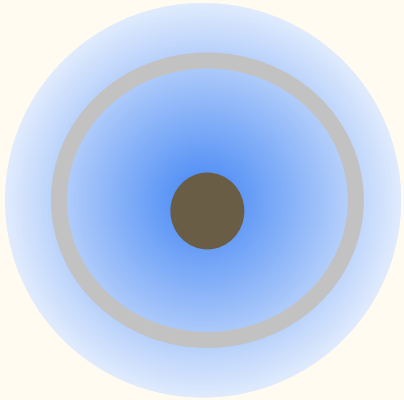


Spots



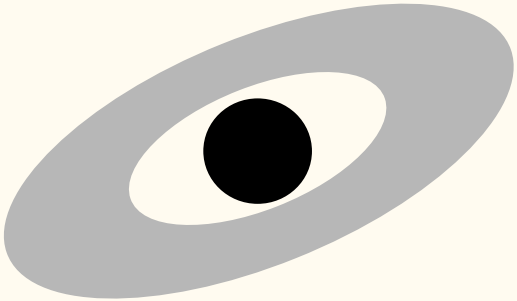
Always present

Hazes

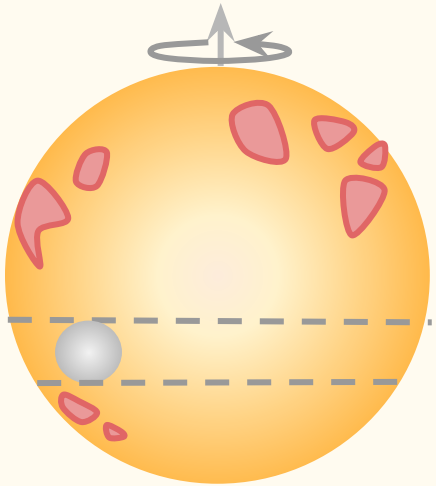


$M_p < 5M_\oplus$

Rings

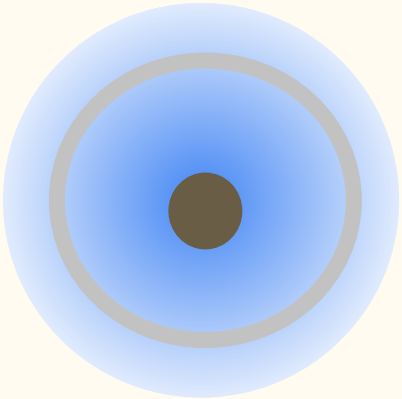


Spots



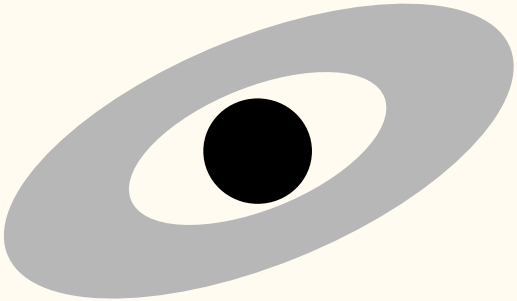
Always present

Hazes

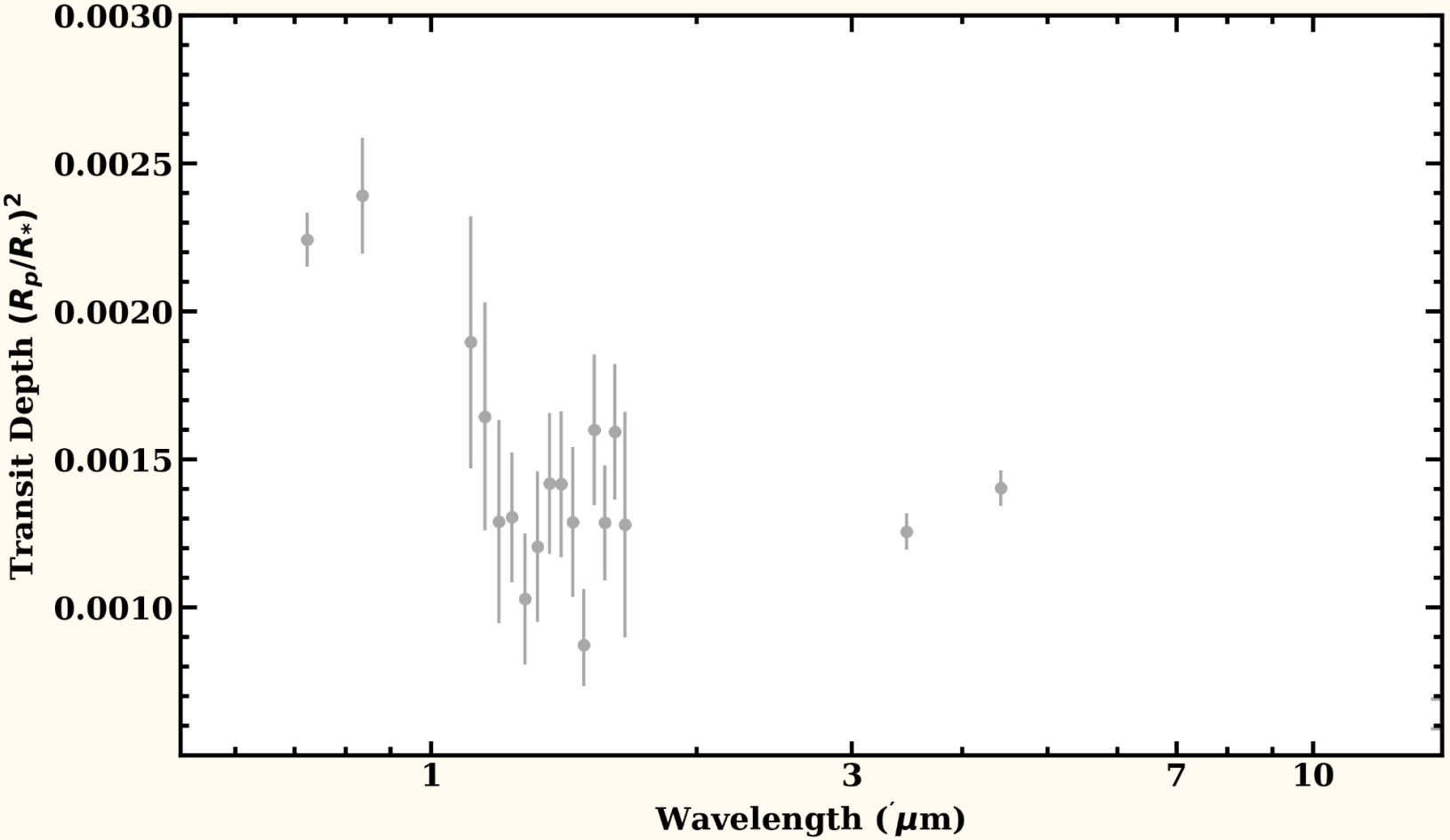


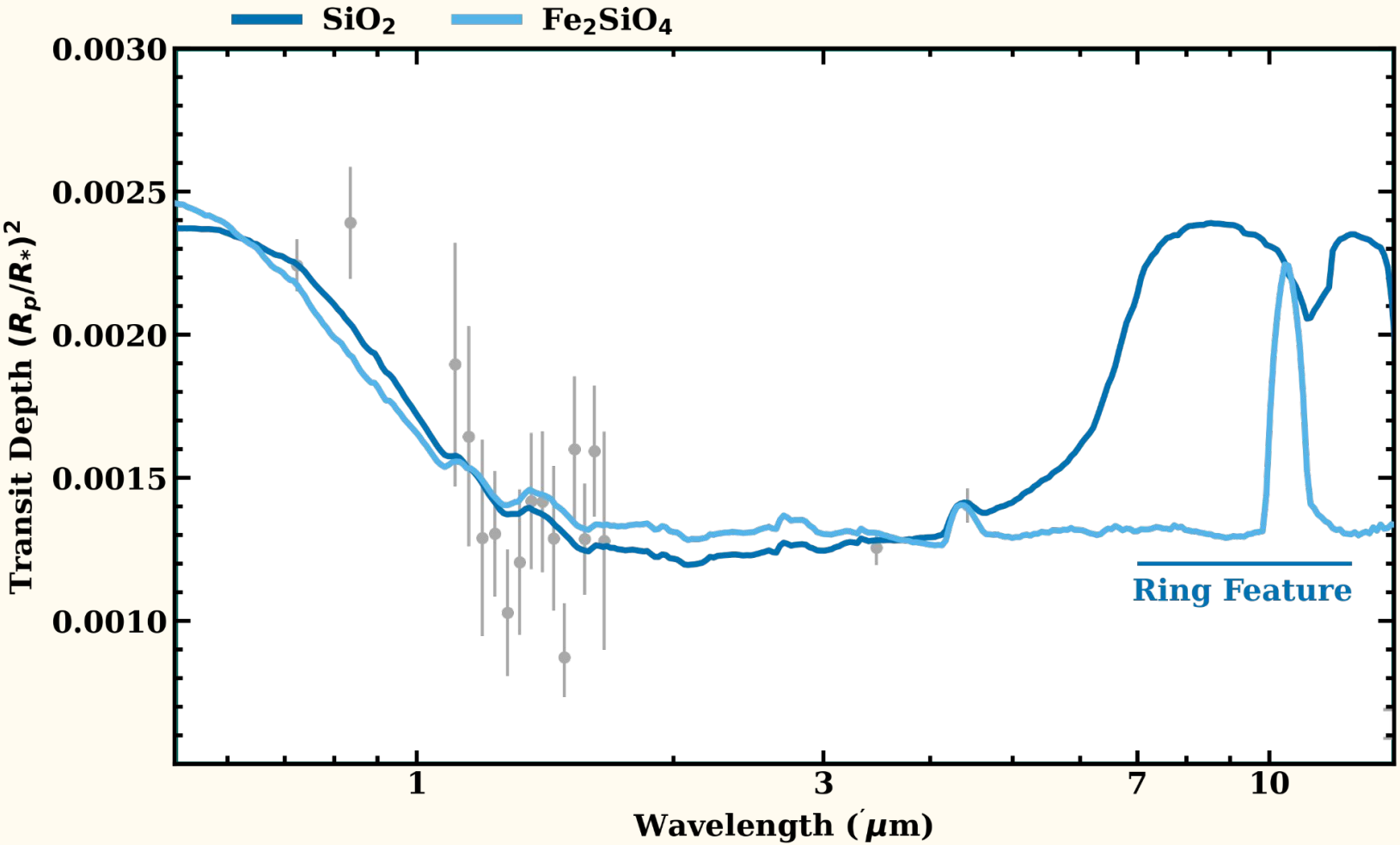
$M_p < 5M_\oplus$

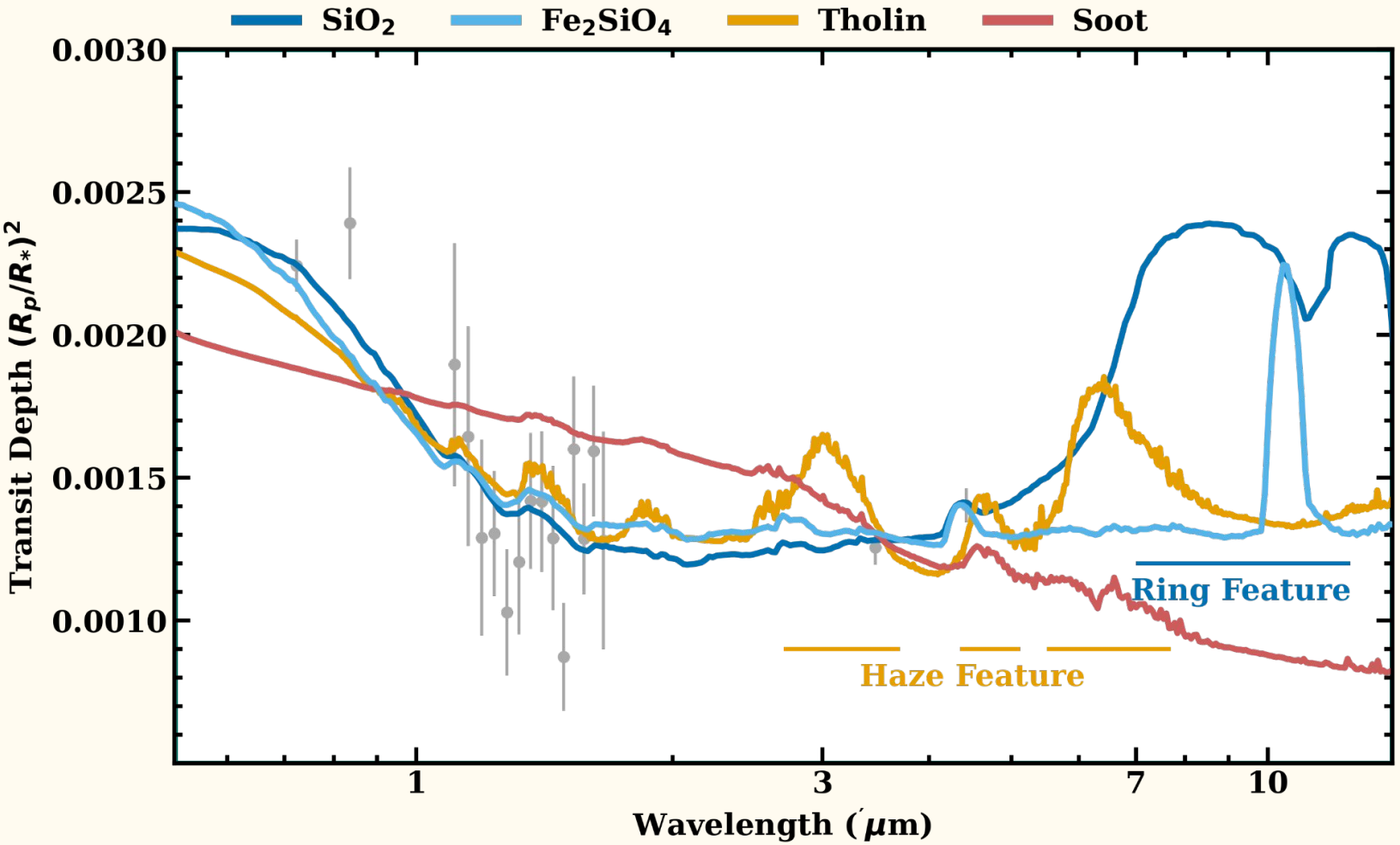
Rings

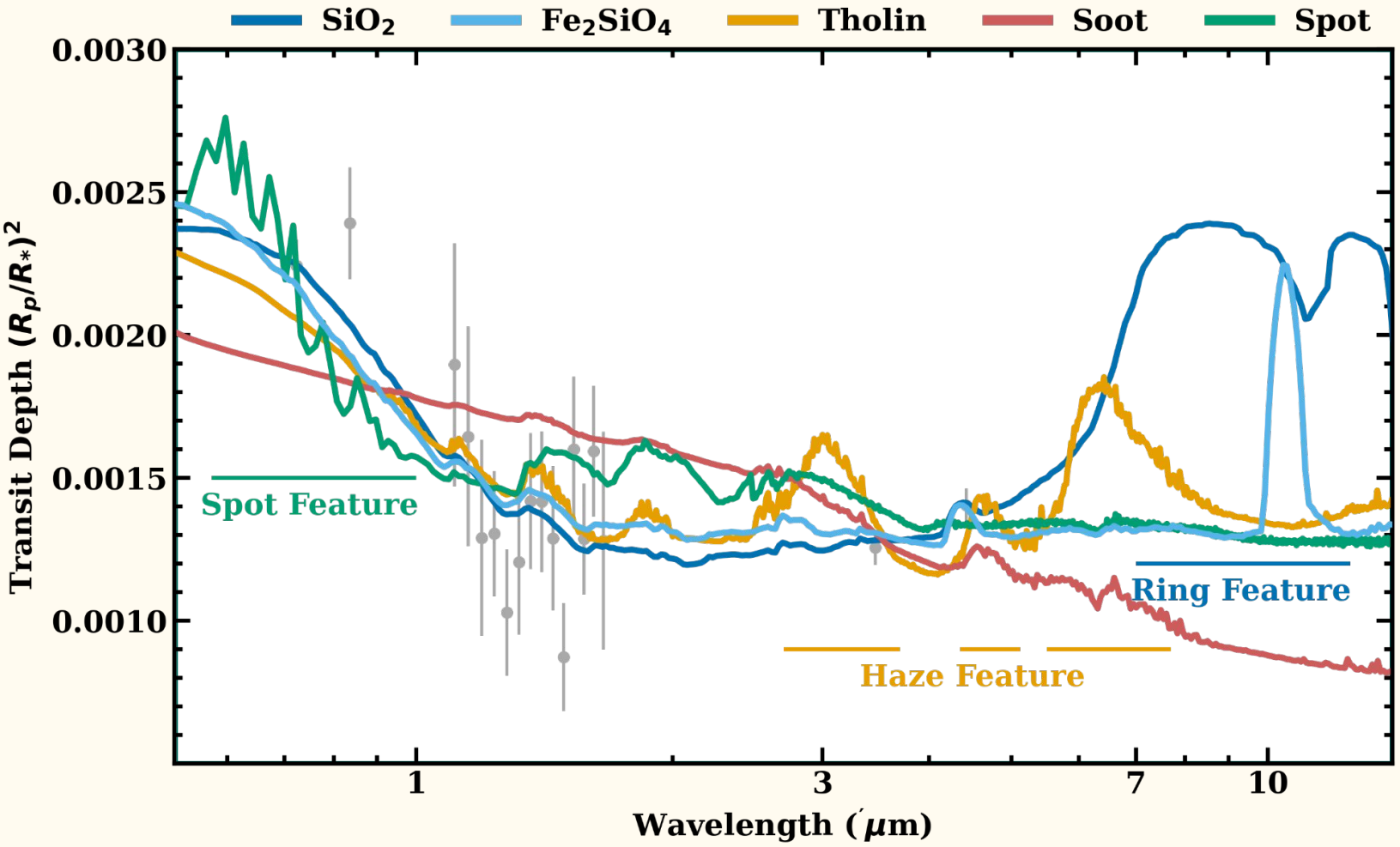


$M_p > 7M_\oplus$


0.0030
0.0025
0.0020
0.0015
0.0010
Transit Depth $(R_p/R_*)^2$
1
3
7
10
Wavelength (μm)


SiO2
Fe2SiO4
0.0030
0.0025
0.0020
0.0015
0.0010
Transit Depth (Rp/R*)2
1
3
7
10
Wavelength (μm)
Ring Feature


SiO2
Fe2SiO4
Tholin
Soot
0.0030
0.0025
0.0020
0.0015
0.0010
Transit Depth (Rp/R*)2
Ring Feature
Haze Feature
1
3
7
10
Wavelength (μm)


SiO_2
Fe_2SiO_4
Tholin
Soot
Spot
0.0030
0.0025
0.0020
0.0015
0.0010
Transit Depth $(R_p/R_*)^2$
Spot Feature
Ring Feature
Haze Feature
1
3
7
10
Wavelength (μm)

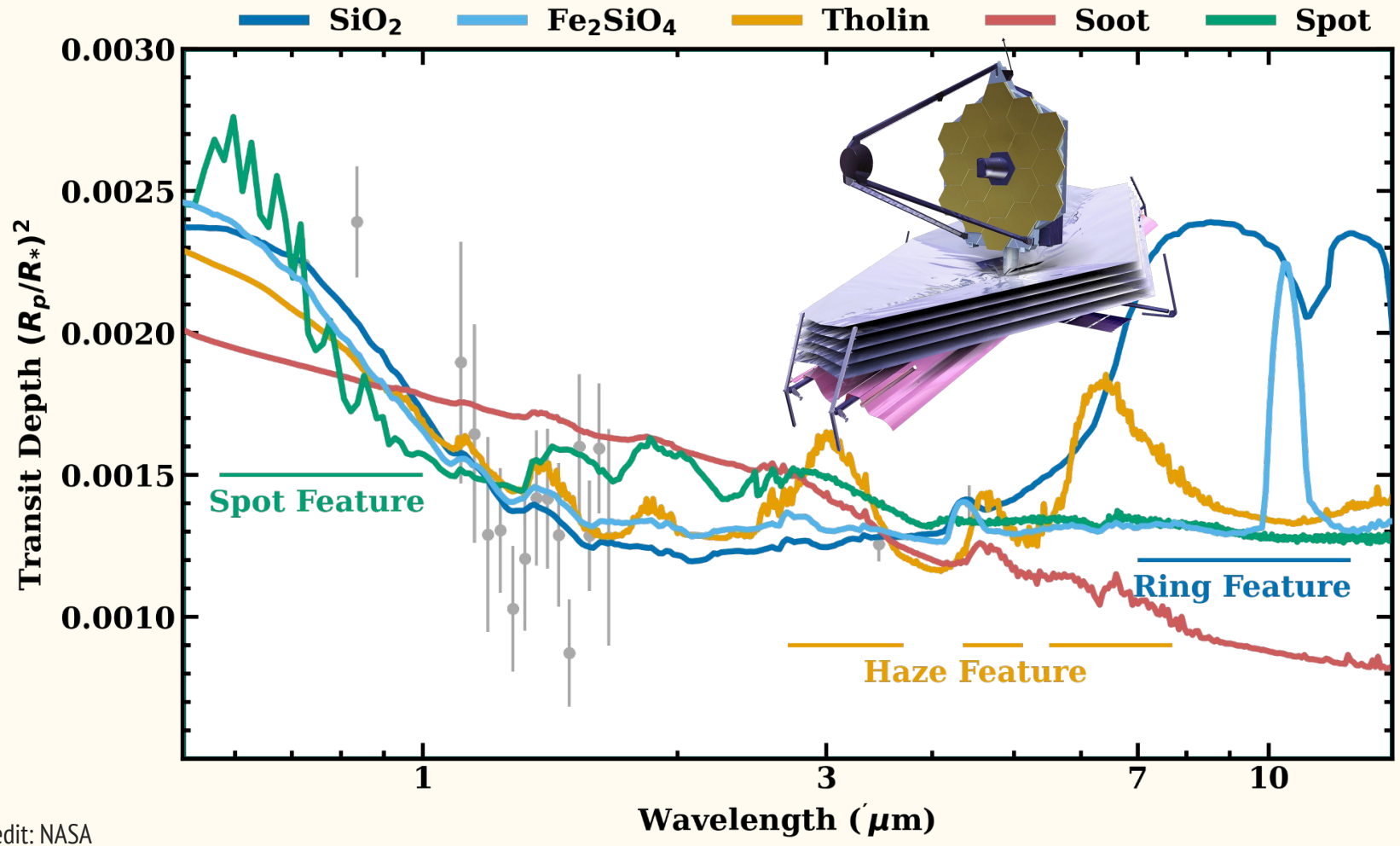


Image credit: NASA

Summary

- Young planets are pivotal to the picture of planetary evolution

Pa Chia Thao | pachia@live.unc.edu

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Young Worlds Lab

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NASA

JACK KENT COOKE FOUNDATION

ZONTA INTERNATIONAL

NSF

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

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