Title: The Architecture of Exoplanetary Systems

Date: Oct 24, 2018 02:00 PM

URL: http://pirsa.org/18100002

Abstract: <p>The basic geometry of the Solar System - the shapes, spacings, and</p>

<p>orientations of the planetary orbits - has long been a subject of</p>

<p>fascination as well as inspiration for planet-formation theories. For</p>

<p>exoplanetary systems, those same properties have only recently come</p>

<p>into focus. I will review our current knowledge of the occurrence of</p>

<p>planets around other stars, their orbital distances and</p>

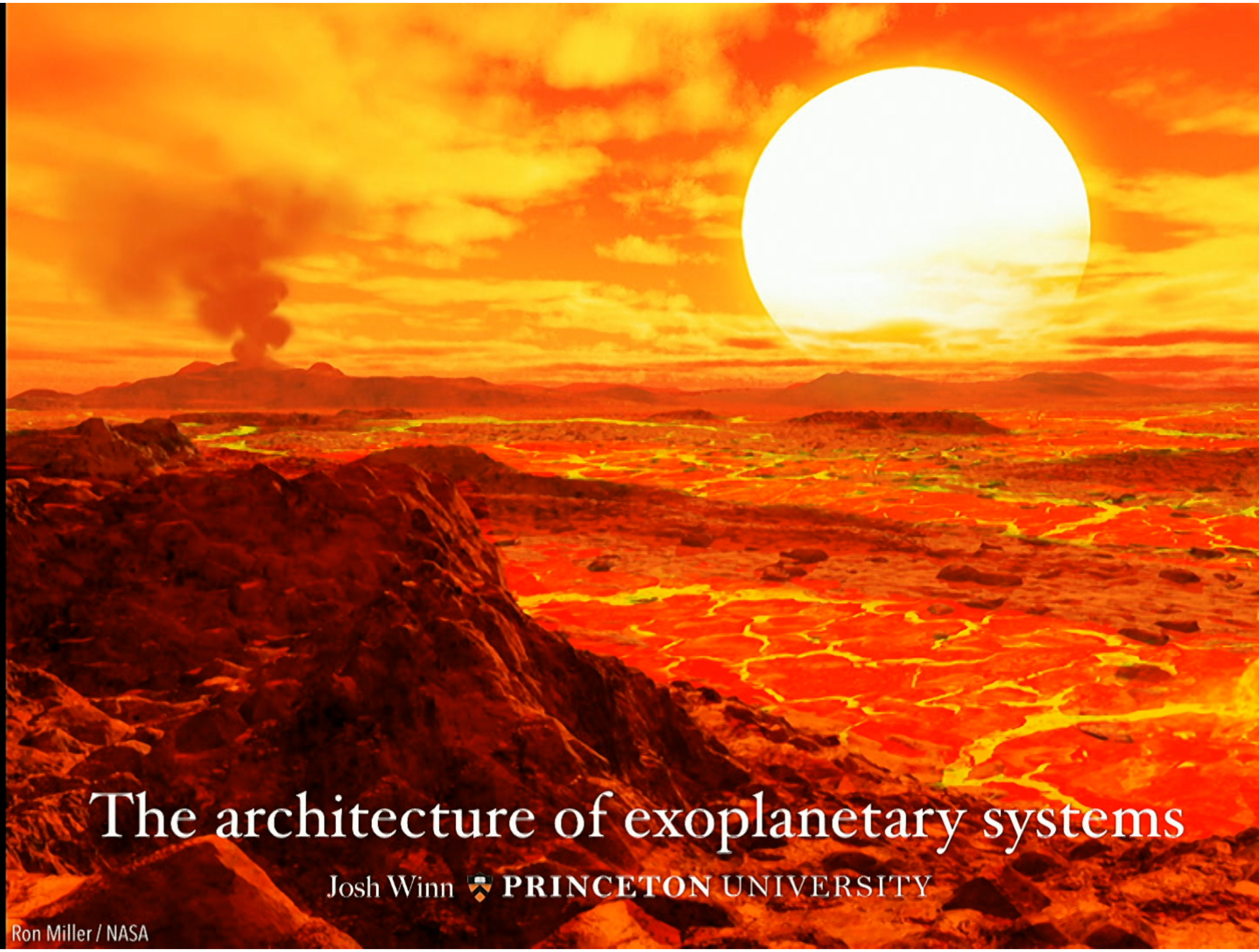
<p>eccentricities, the orbital spacings and mutual inclinations in</p>

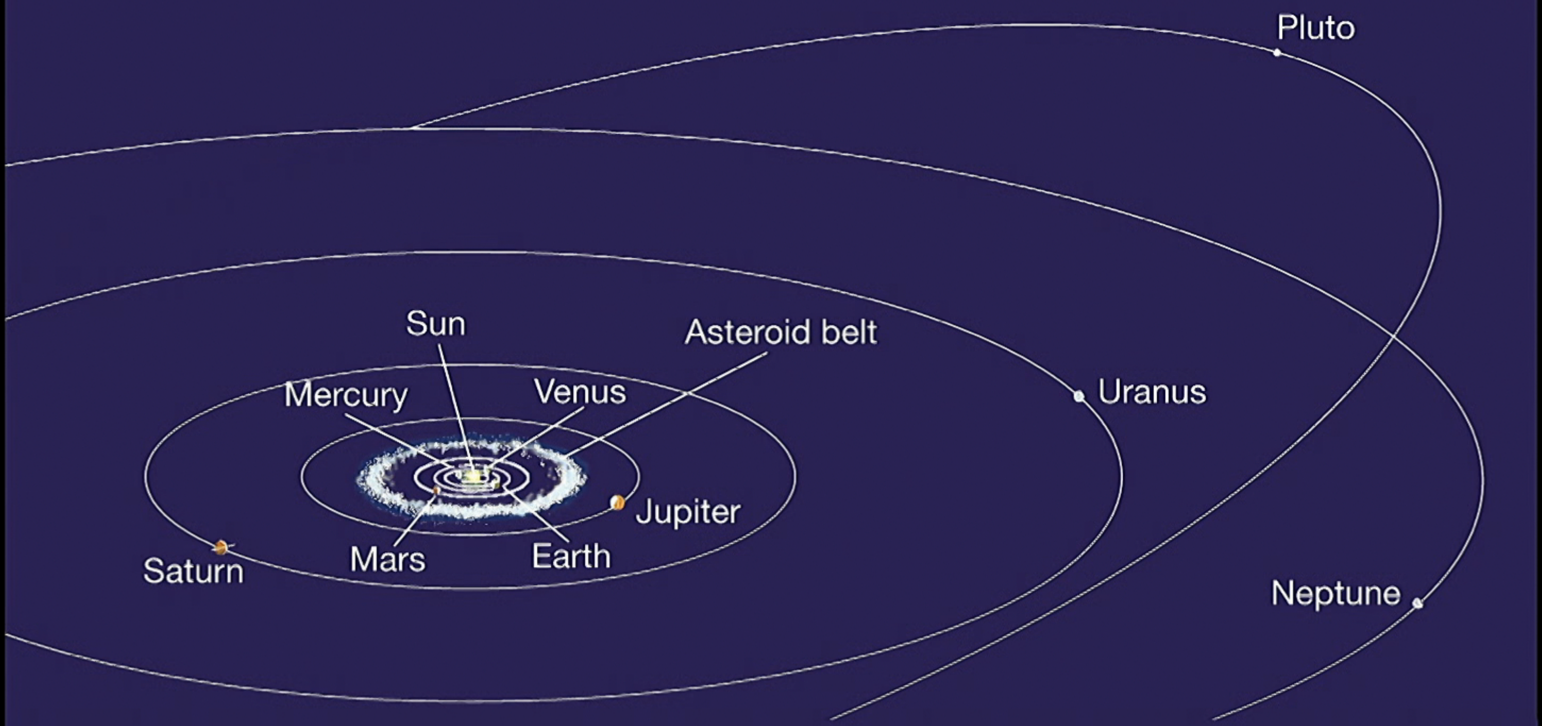
<p>multiplanet systems, the orientation of the host star's rotation axis,</p>

<p>and the properties of planets in binary-star systems. I will also</p>

<p>discuss opportunities to improve our understanding, with data from the</p>

<p>recently launched Transiting Exoplanet Survey Satellite.</p>

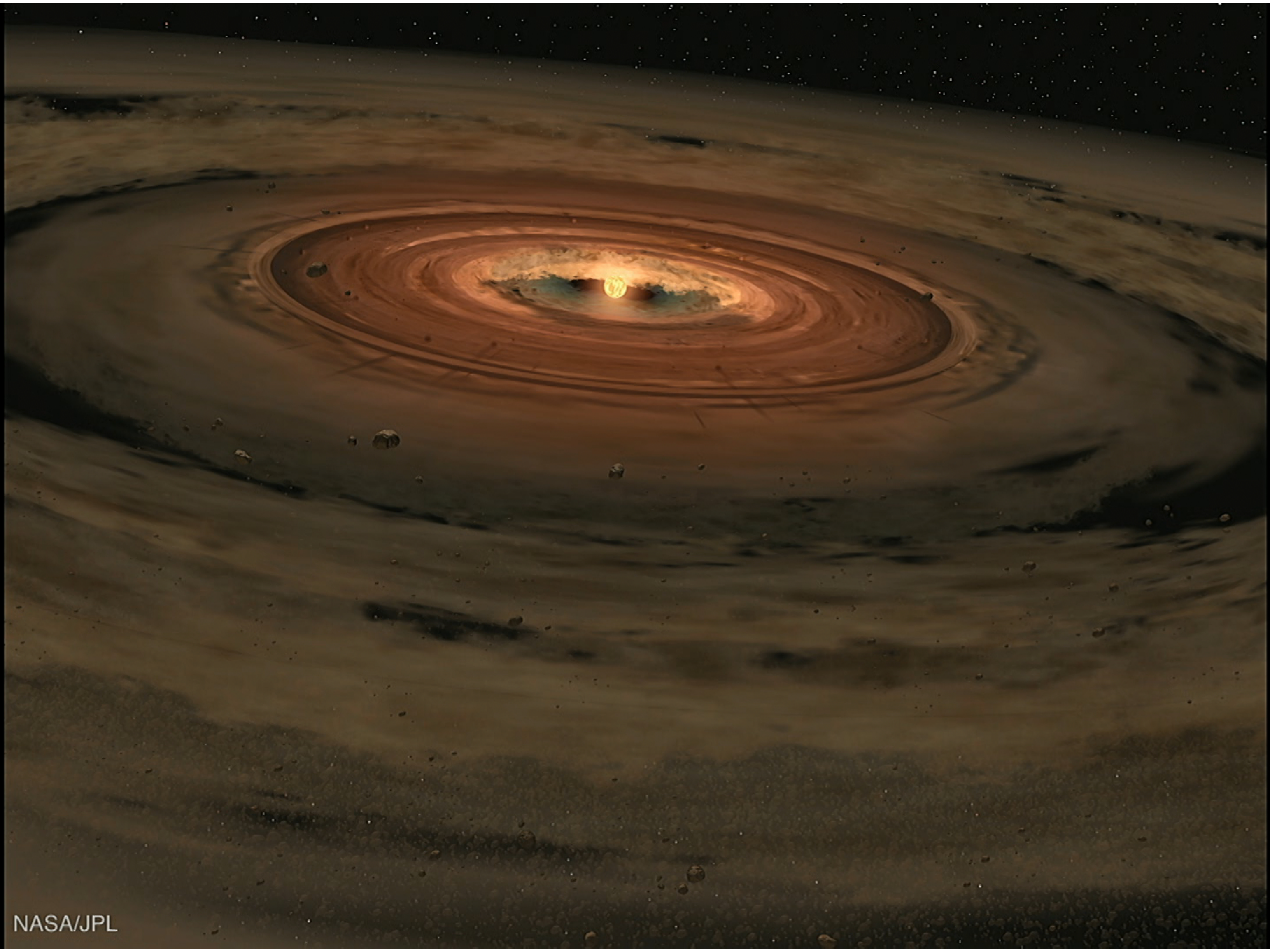

The architecture of exoplanetary systems
Josh Winn PRINCETON UNIVERSITY
Ron Miller / NASA

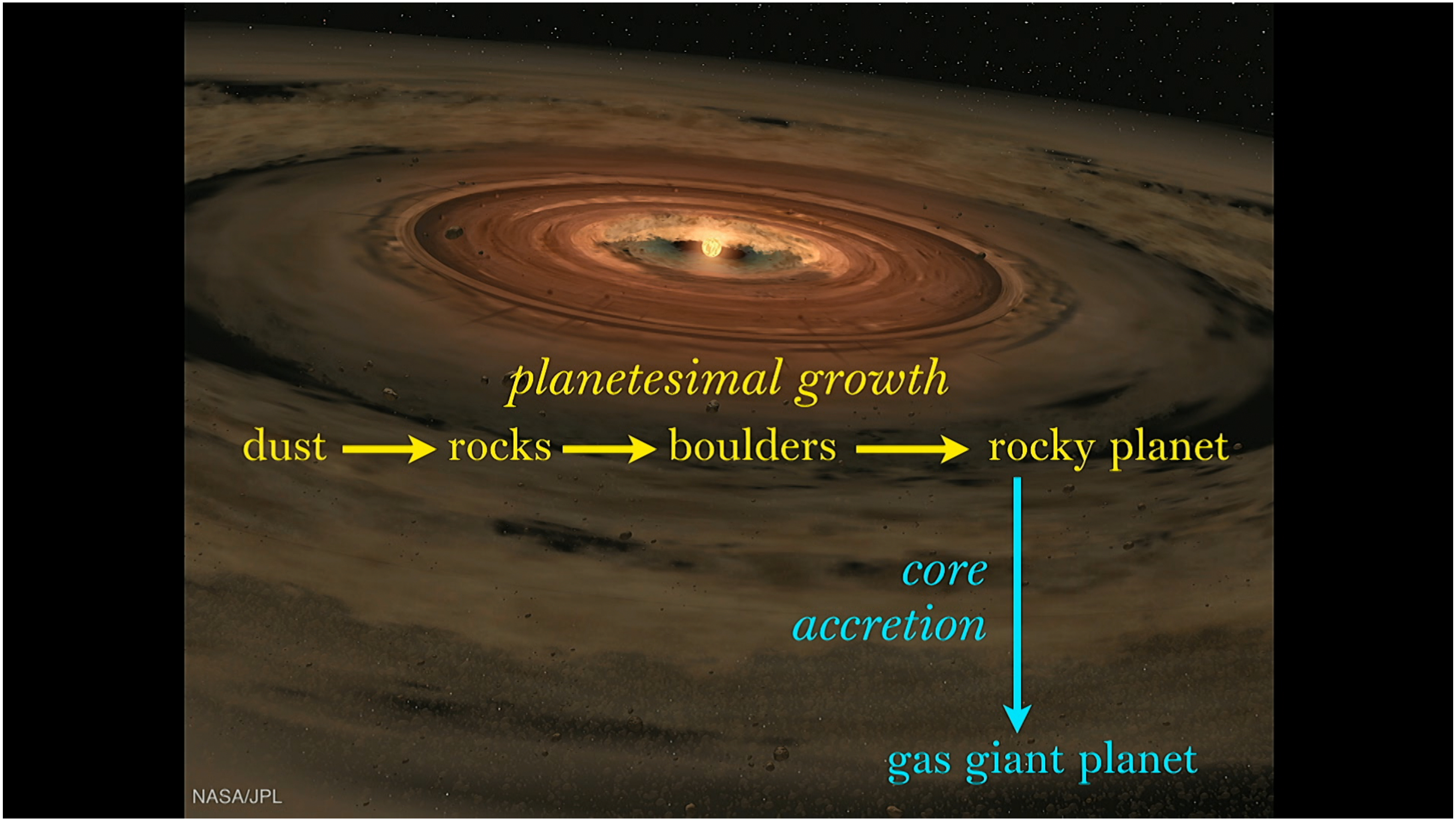


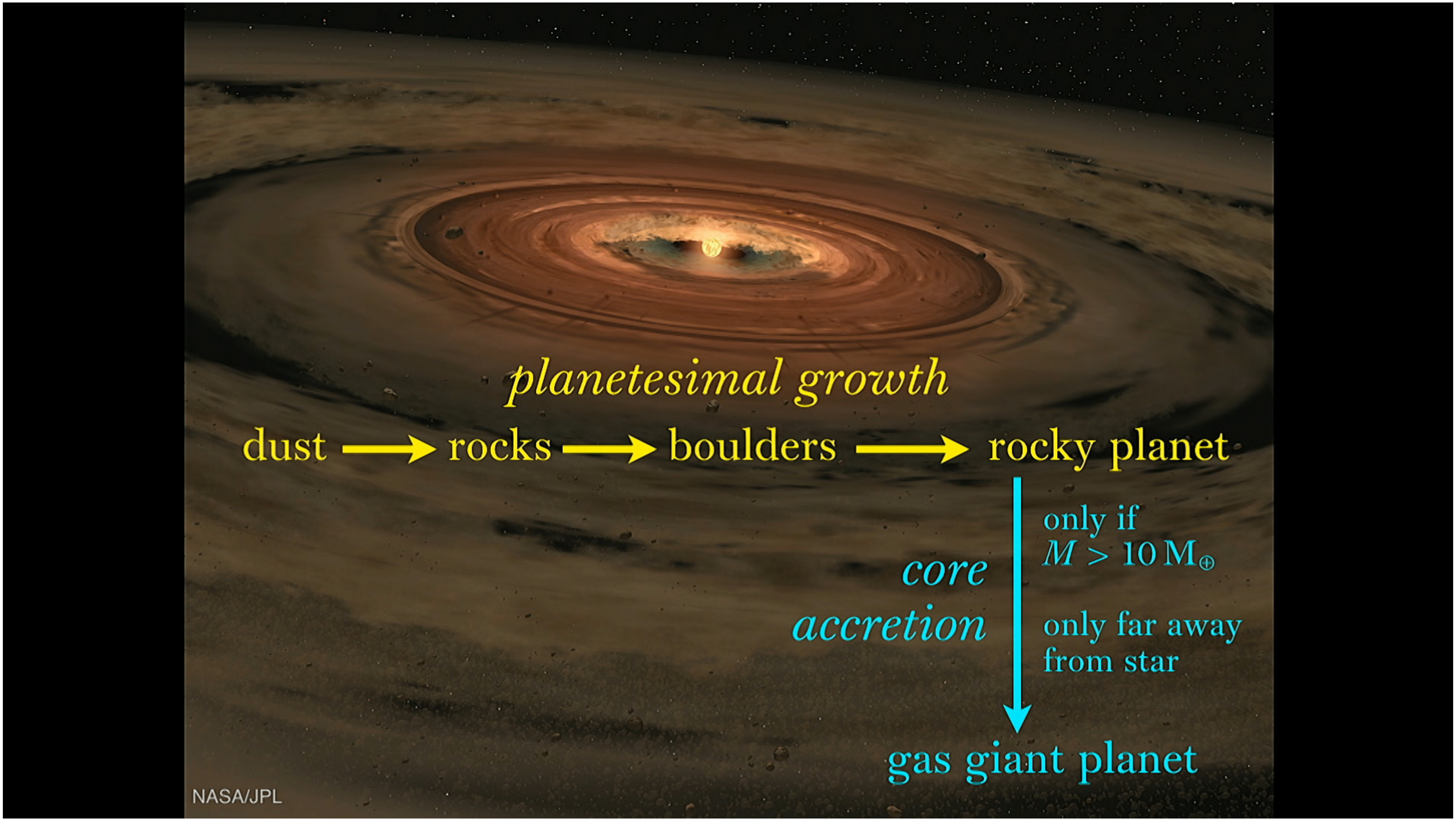
orbits are circular

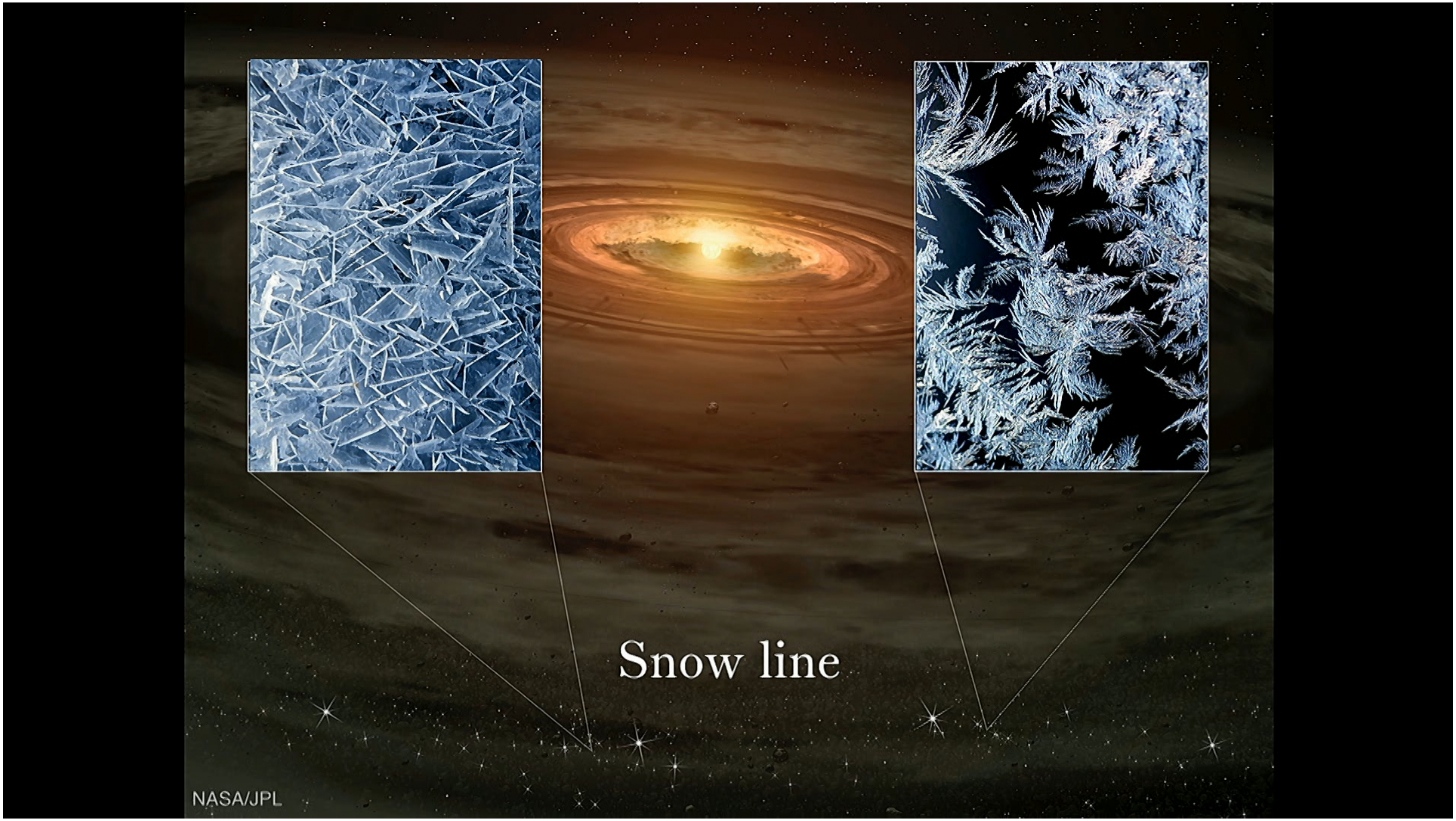
orbits are aligned with each other, and the Sun

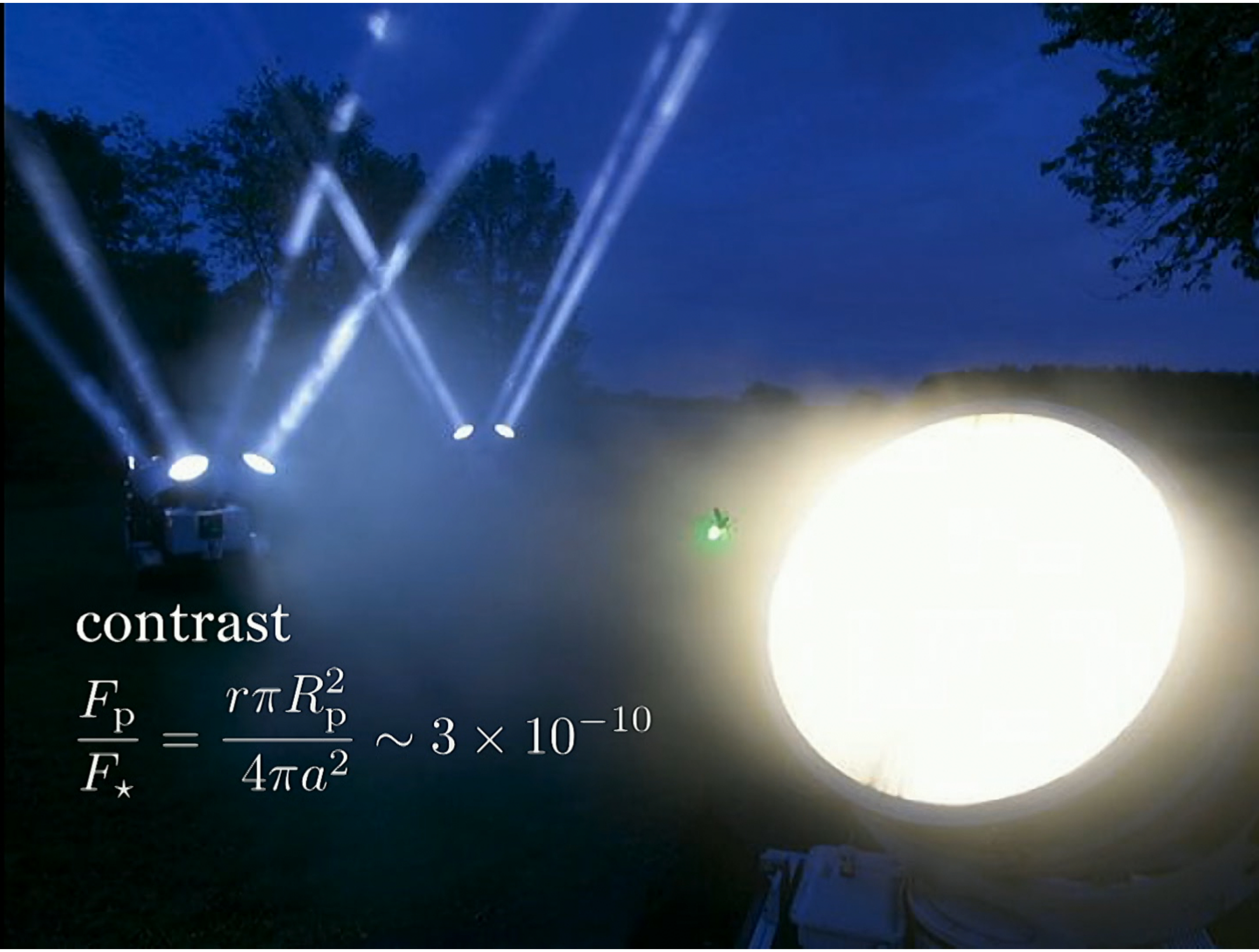
rocky planets 0.3 – 3 AU, giant planets 3 – 30 AU


NASA/JPL


planetesimal growth
dust → rocks → boulders → rocky planet
core
accretion
gas giant planet
NASA/JPL

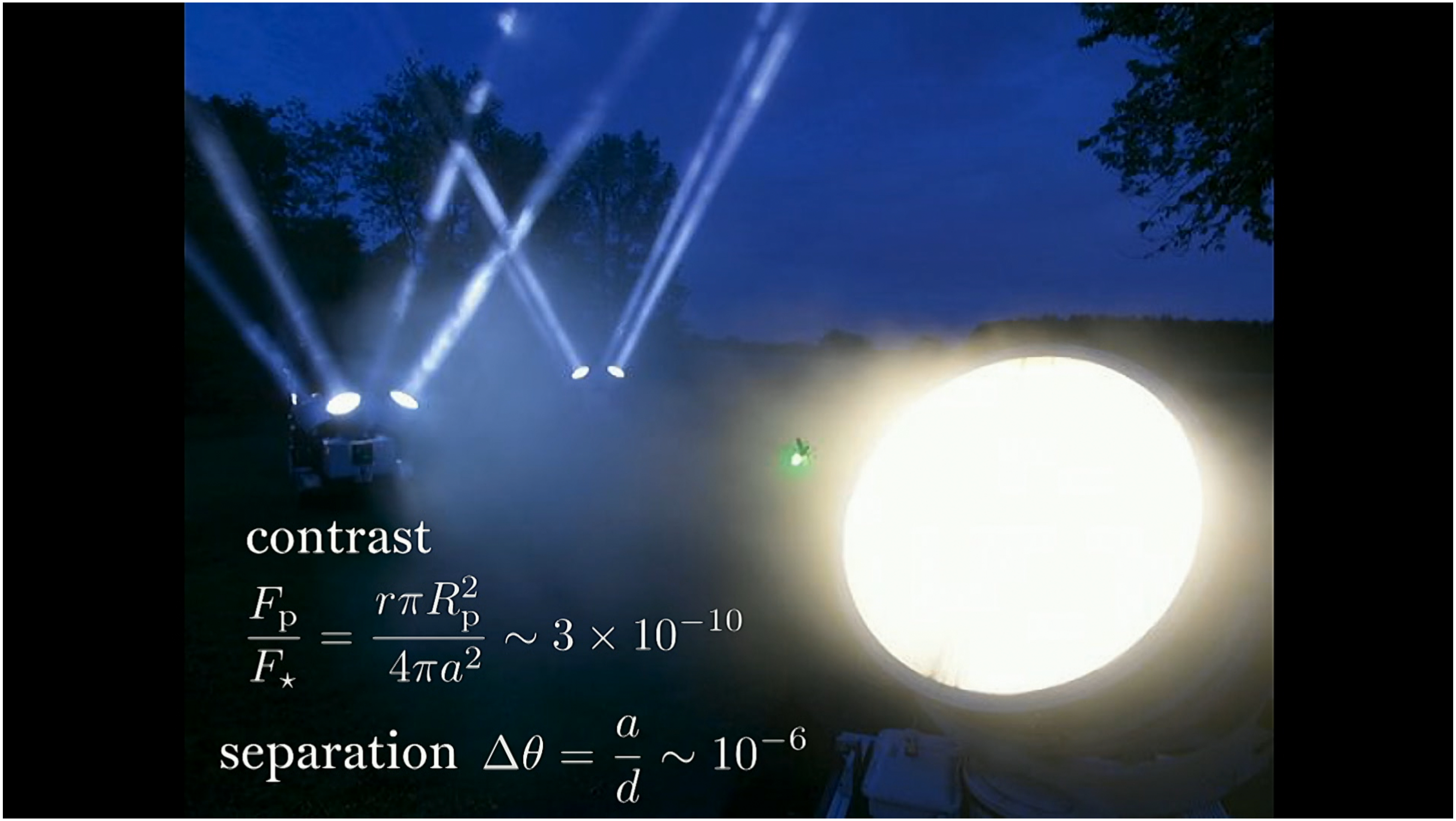

planetesimal growth
dust → rocks → boulders → rocky planet
core accretion
only if
$M > 10\,M_\oplus$
only far away from star
gas giant planet
NASA/JPL


Snow line
NASA/JPL



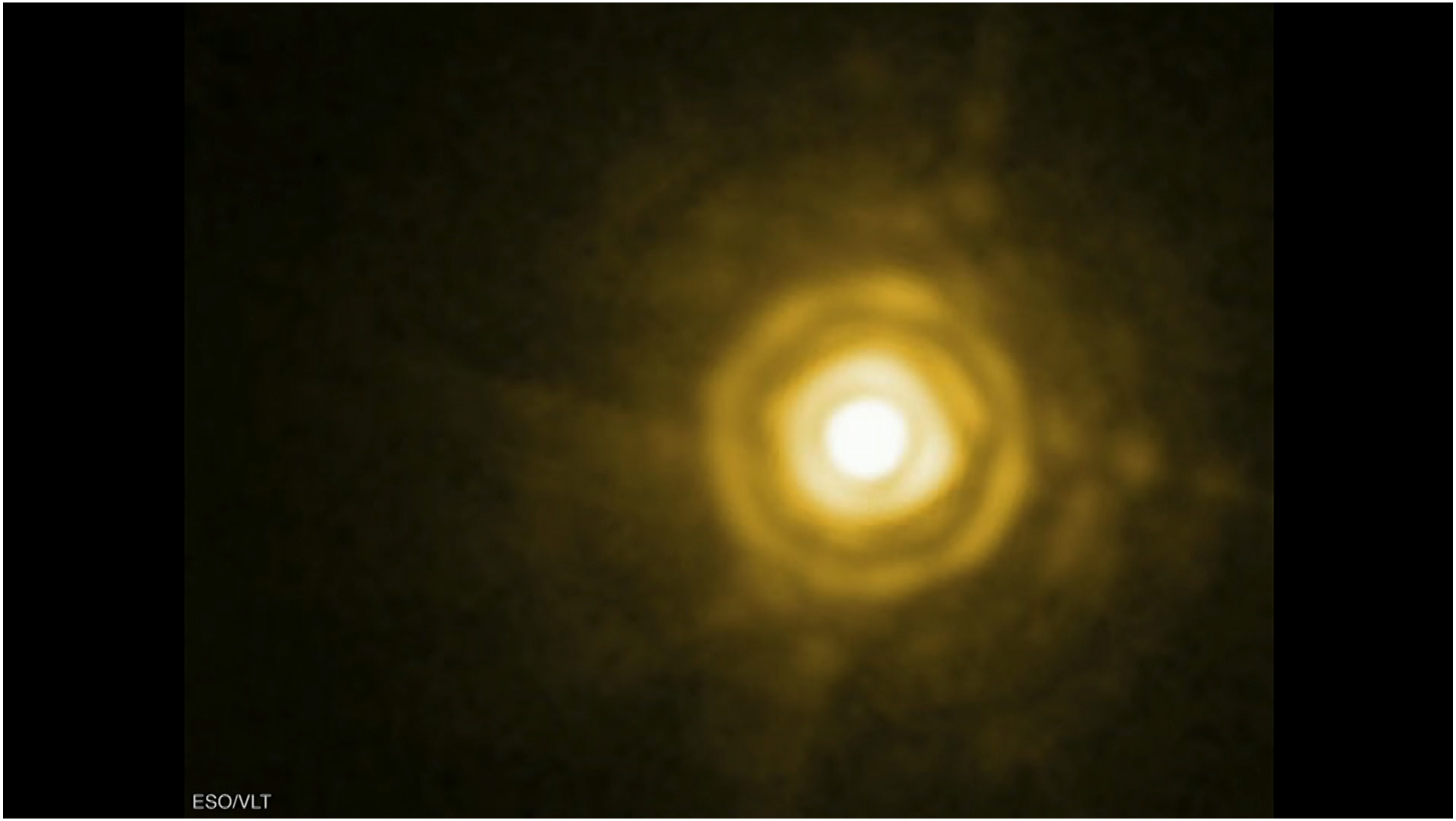
contrast

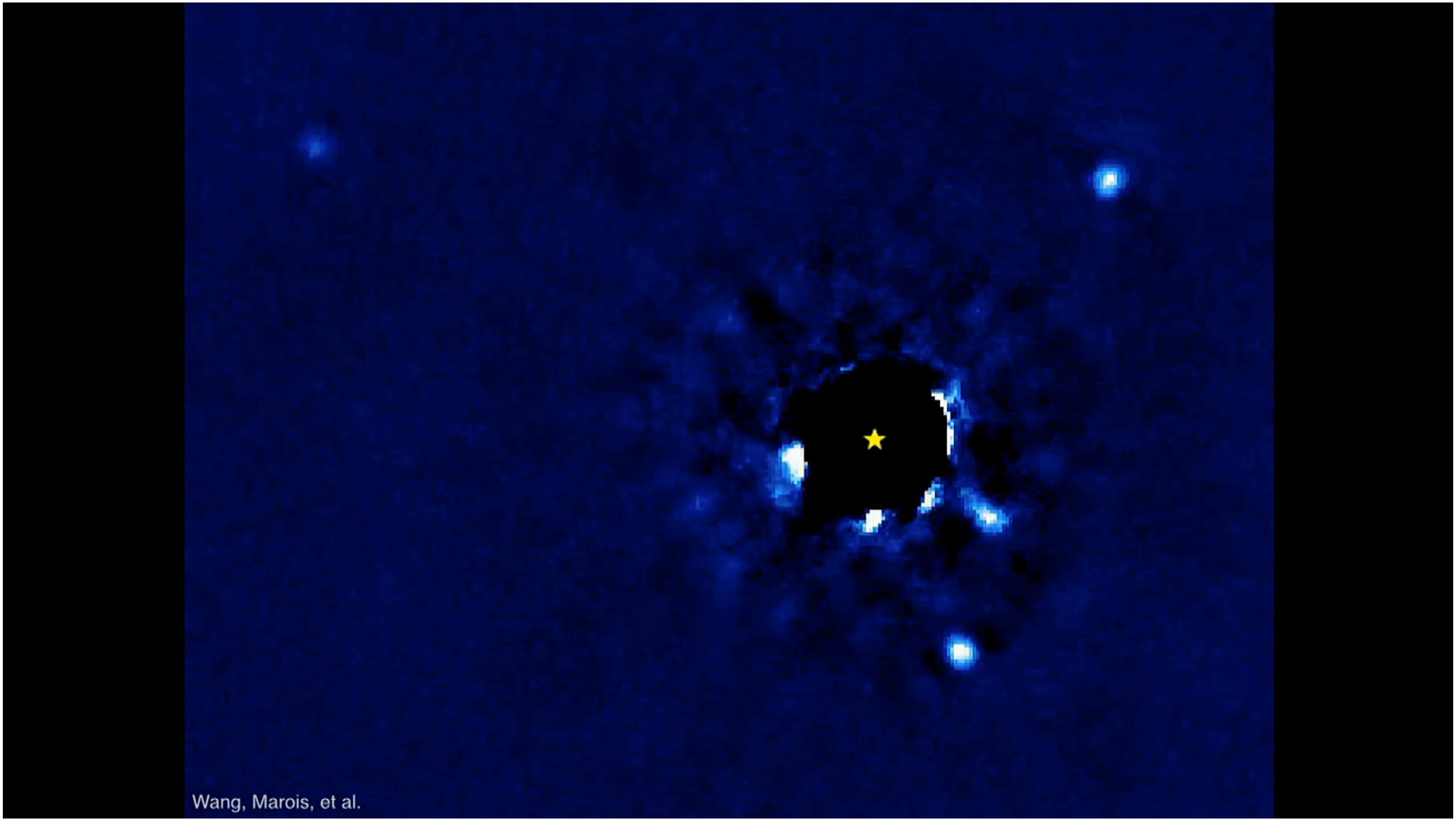
$$\frac{F_{\rm p}}{F_\star} = \frac{r\pi R_{\rm p}^2}{4\pi a^2} \sim 3 \times 10^{-10}$$



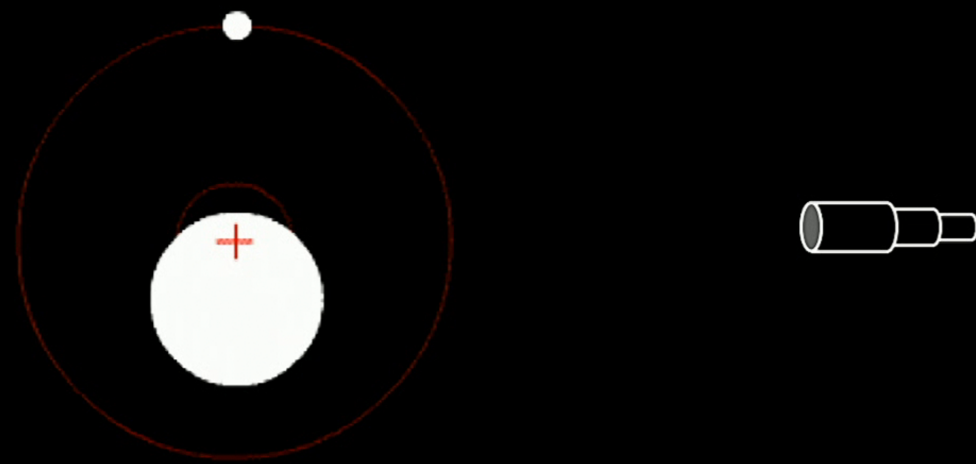
contrast
$\frac{F_{\rm p}}{F_\star} = \frac{r\pi R_{\rm p}^2}{4\pi a^2} \sim 3 \times 10^{-10}$
separation $\Delta\theta = \frac{a}{d} \sim 10^{-6}$


HR 8799

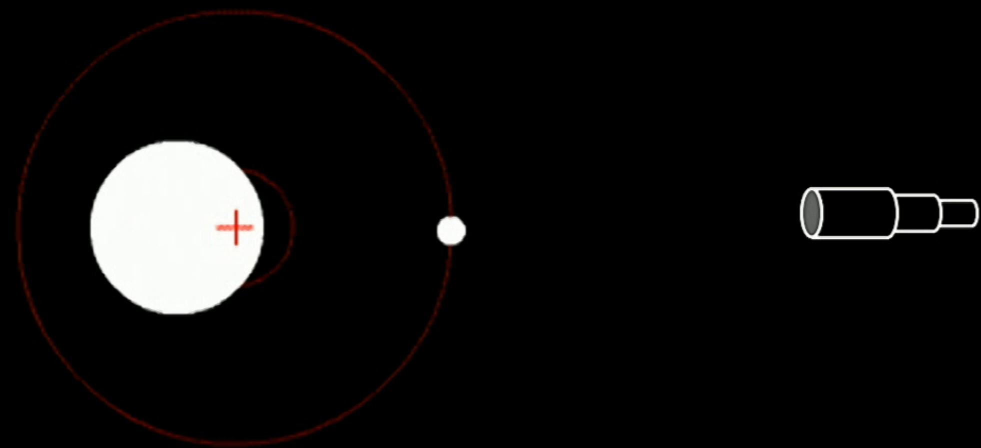

ESO/VLT


Wang, Marois, et al.

Doppler shift



Doppler shift



$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c} = \frac{1}{c}\left(\frac{2\pi a}{P}\frac{M_{\mathrm{p}}}{M_\star}\right)\sin I$$

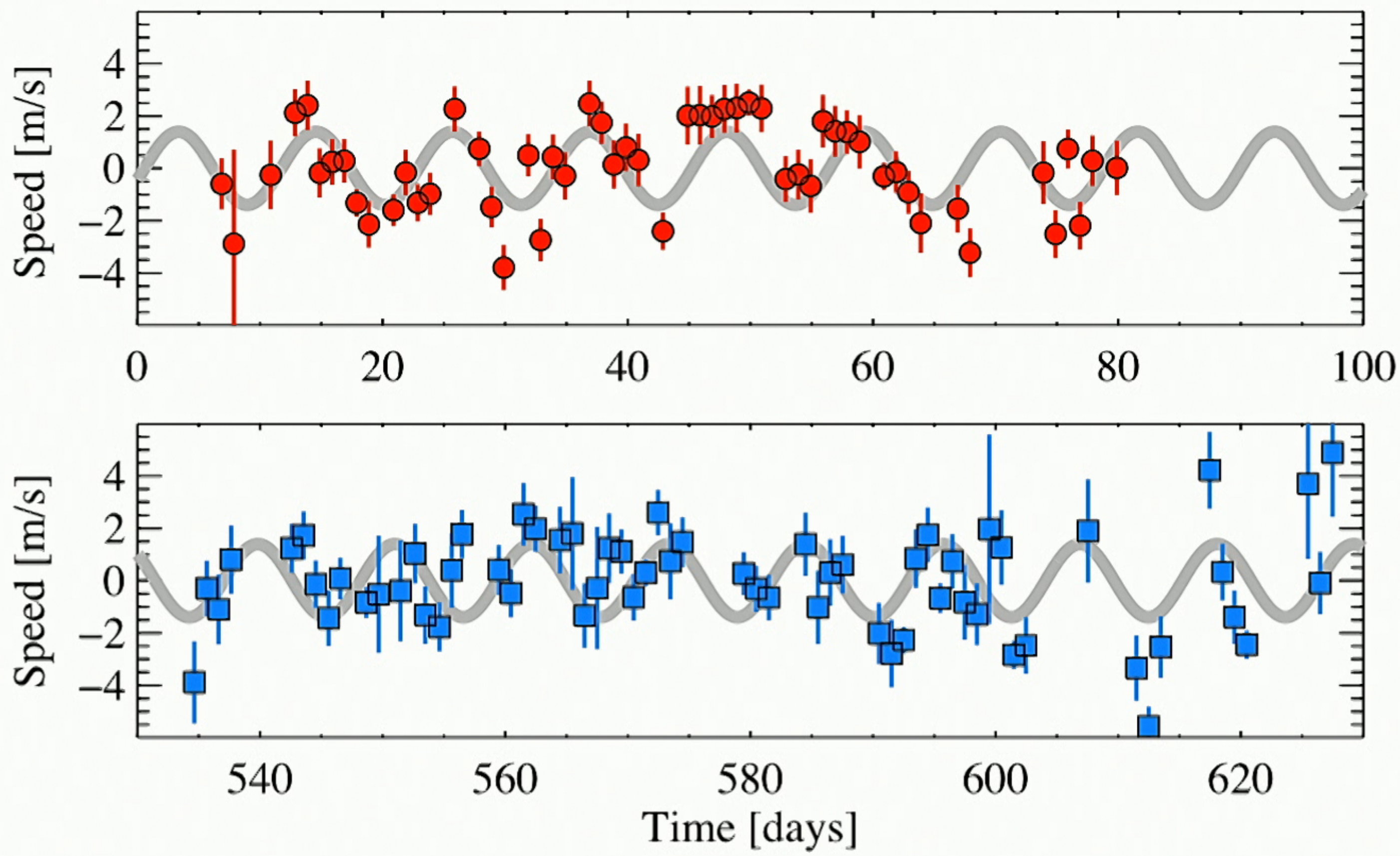
$$\approx 3 \times 10^{-10}$$


P.K. Chen

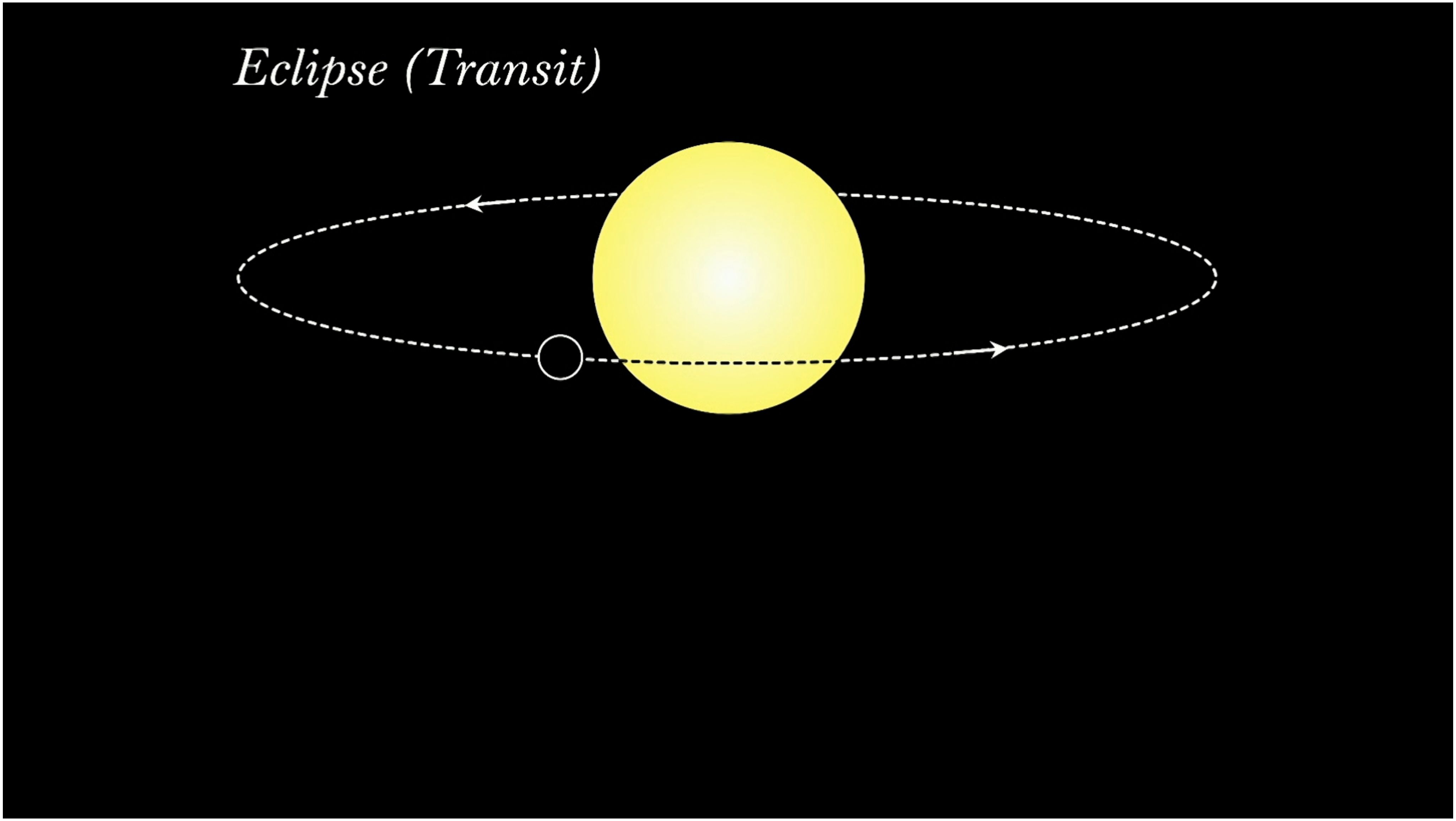

Proxima
Centauri
P.K. Chen

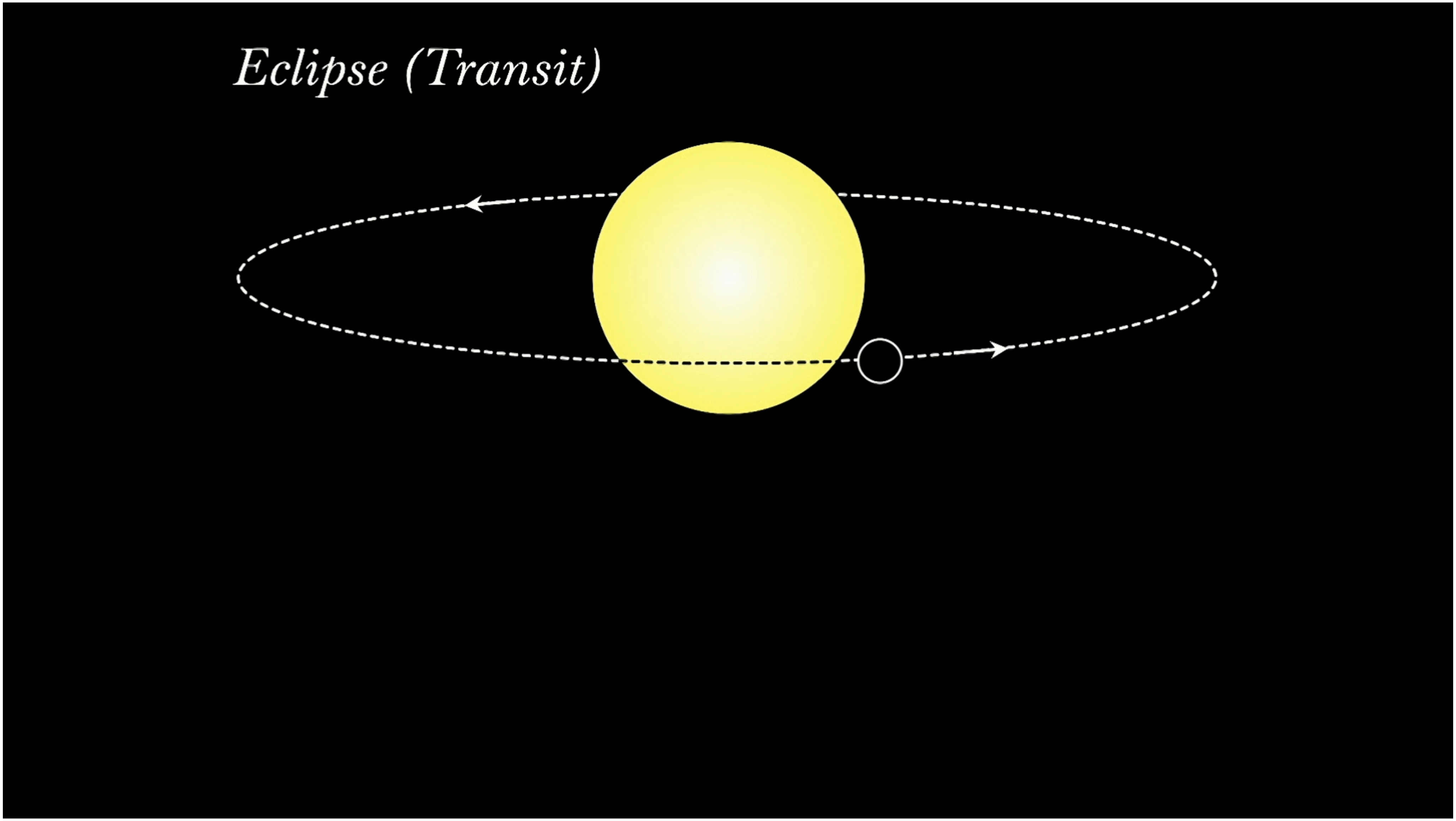

M. Kornmesser / ESO

Proxima Centauri

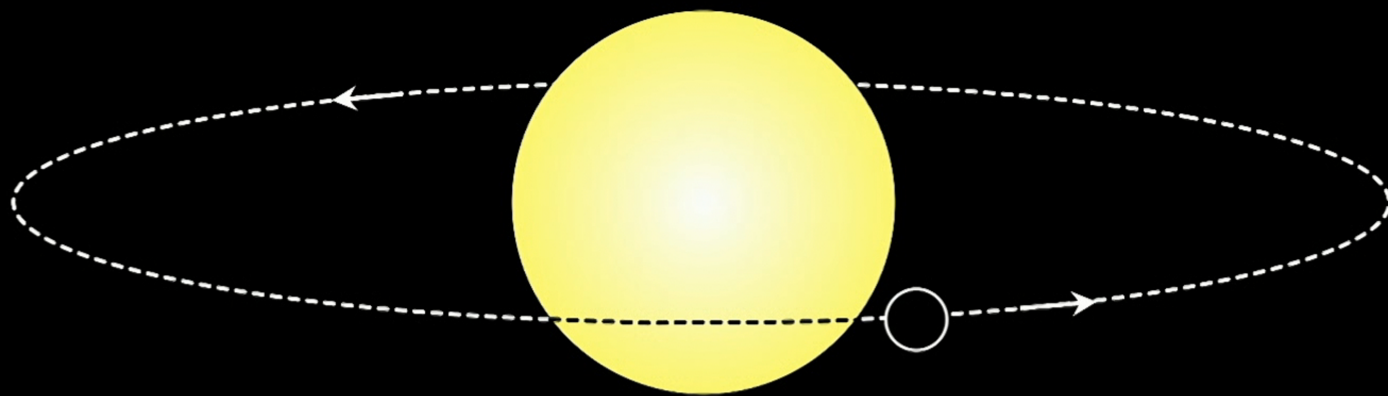


Anglada-Escude et al. (2016) and http://reddots.space


Eclipse (Transit)

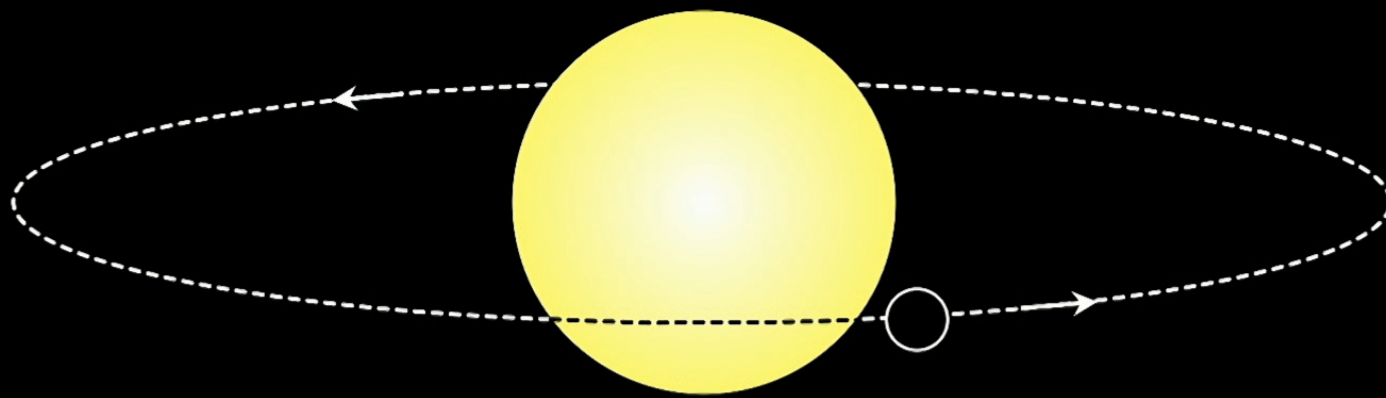

Eclipse (Transit)

Eclipse (Transit)



$$\frac{\Delta F}{F} = \frac{\pi R_{\mathrm{p}}^2}{\pi R_\star^2} \approx 8 \times 10^{-5}$$

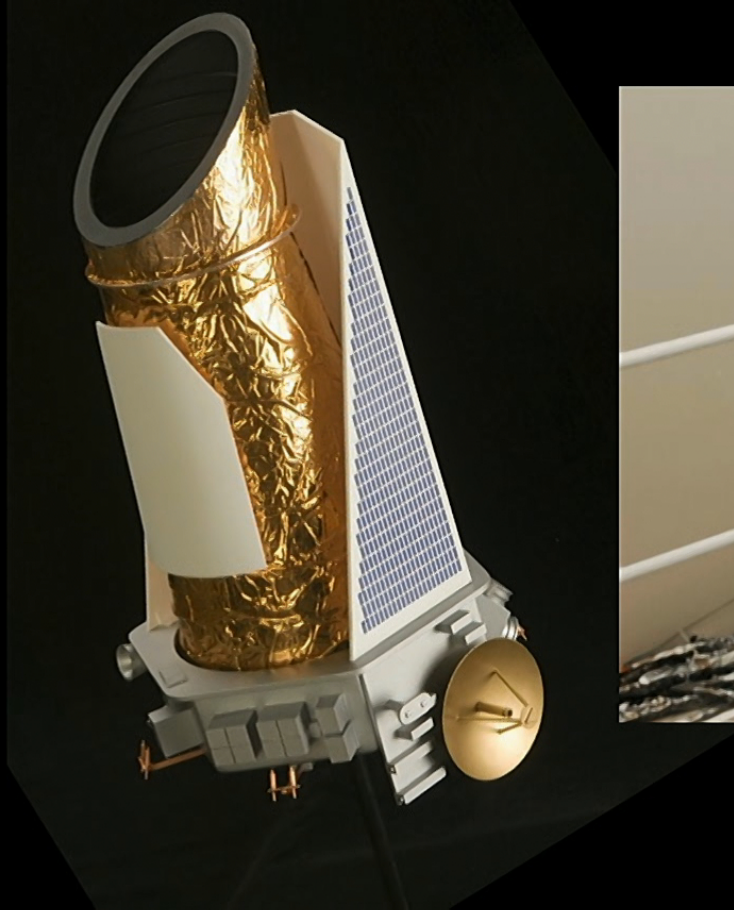
Eclipse (Transit)

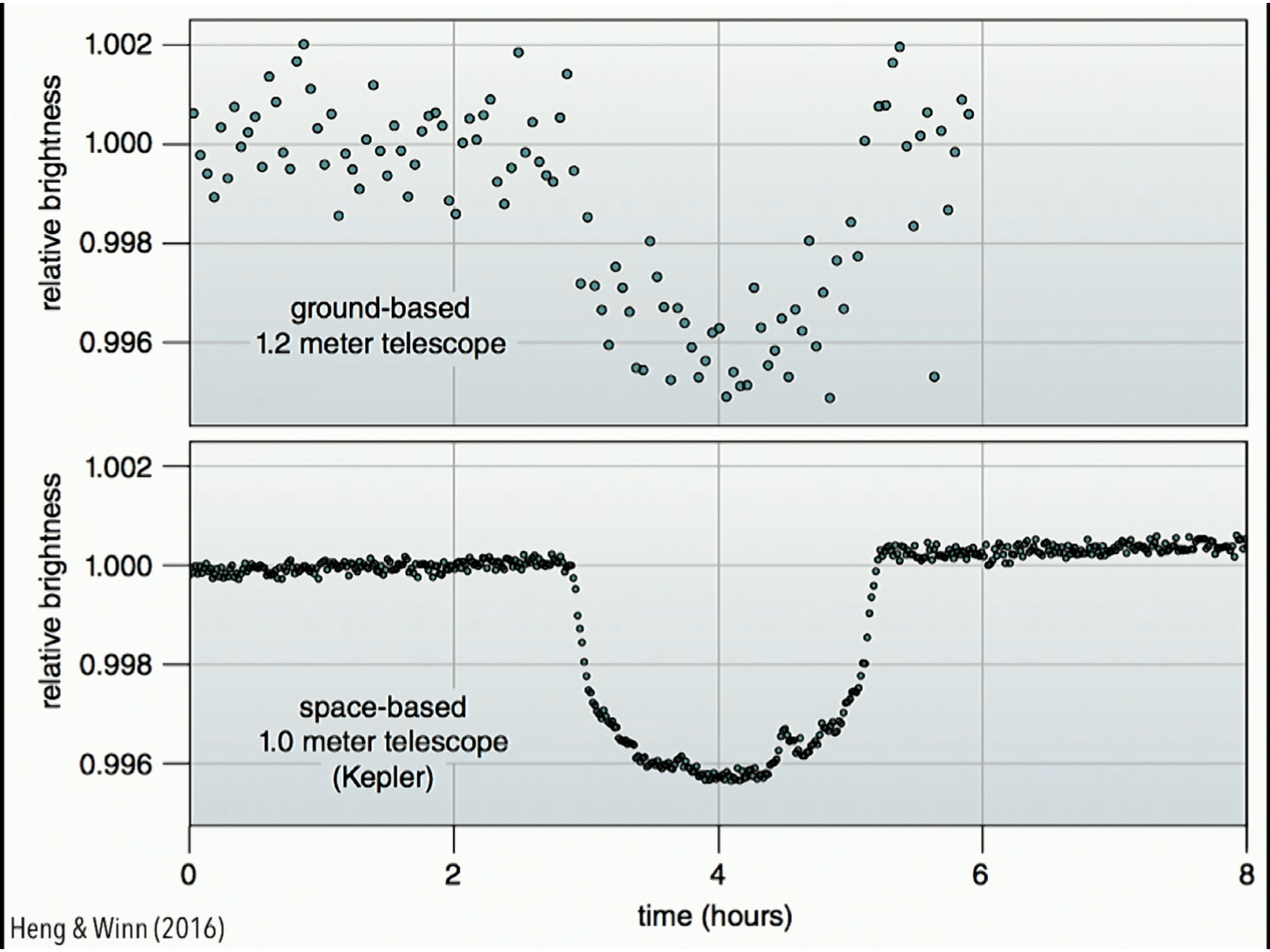


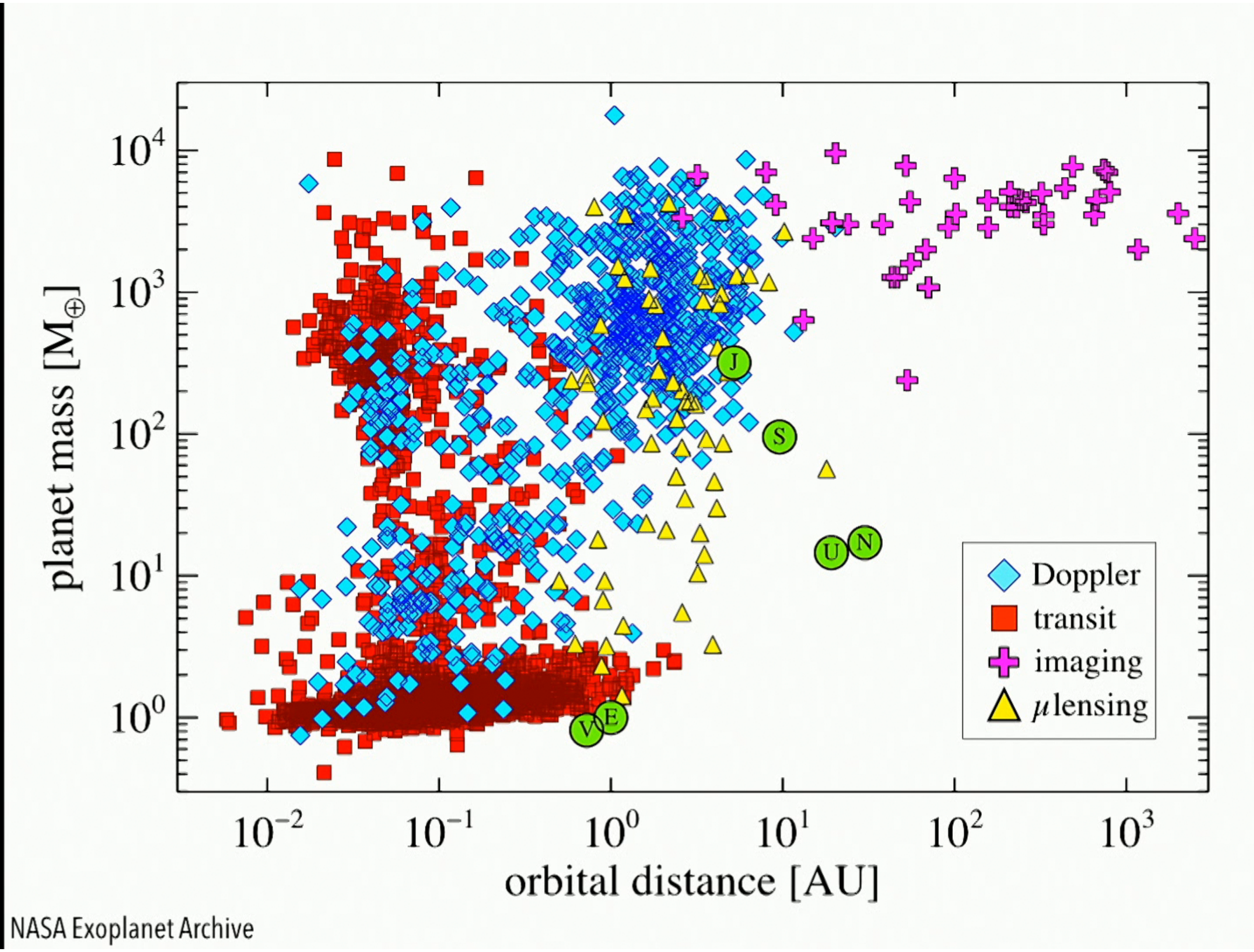
$$\frac{\Delta F}{F} = \frac{\pi R_{\rm p}^2}{\pi R_\star^2} \approx 8 \times 10^{-5}$$

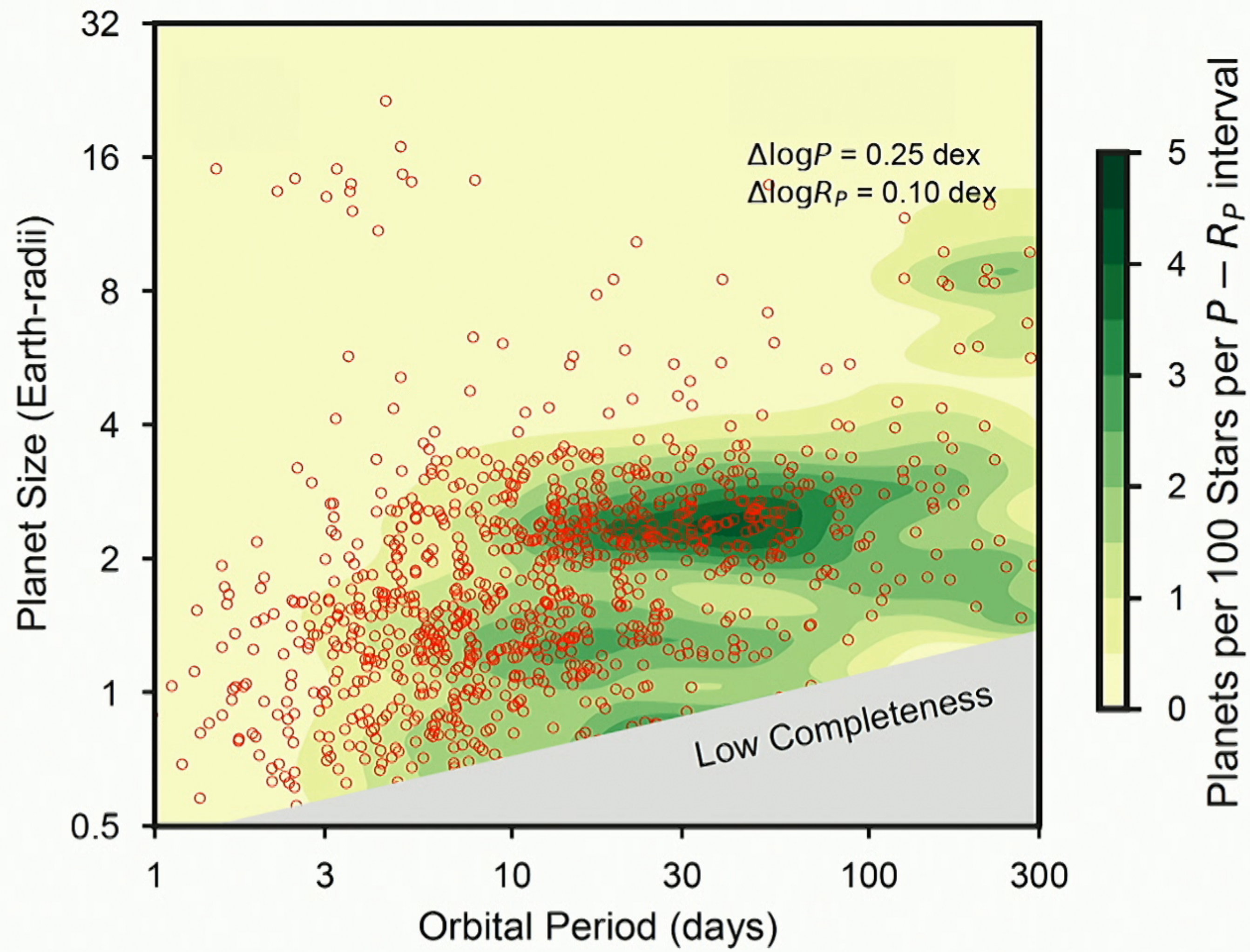
$$\text{prob.} = \frac{R_\star}{a} \approx 0.5\%$$

The Kepler space telescope

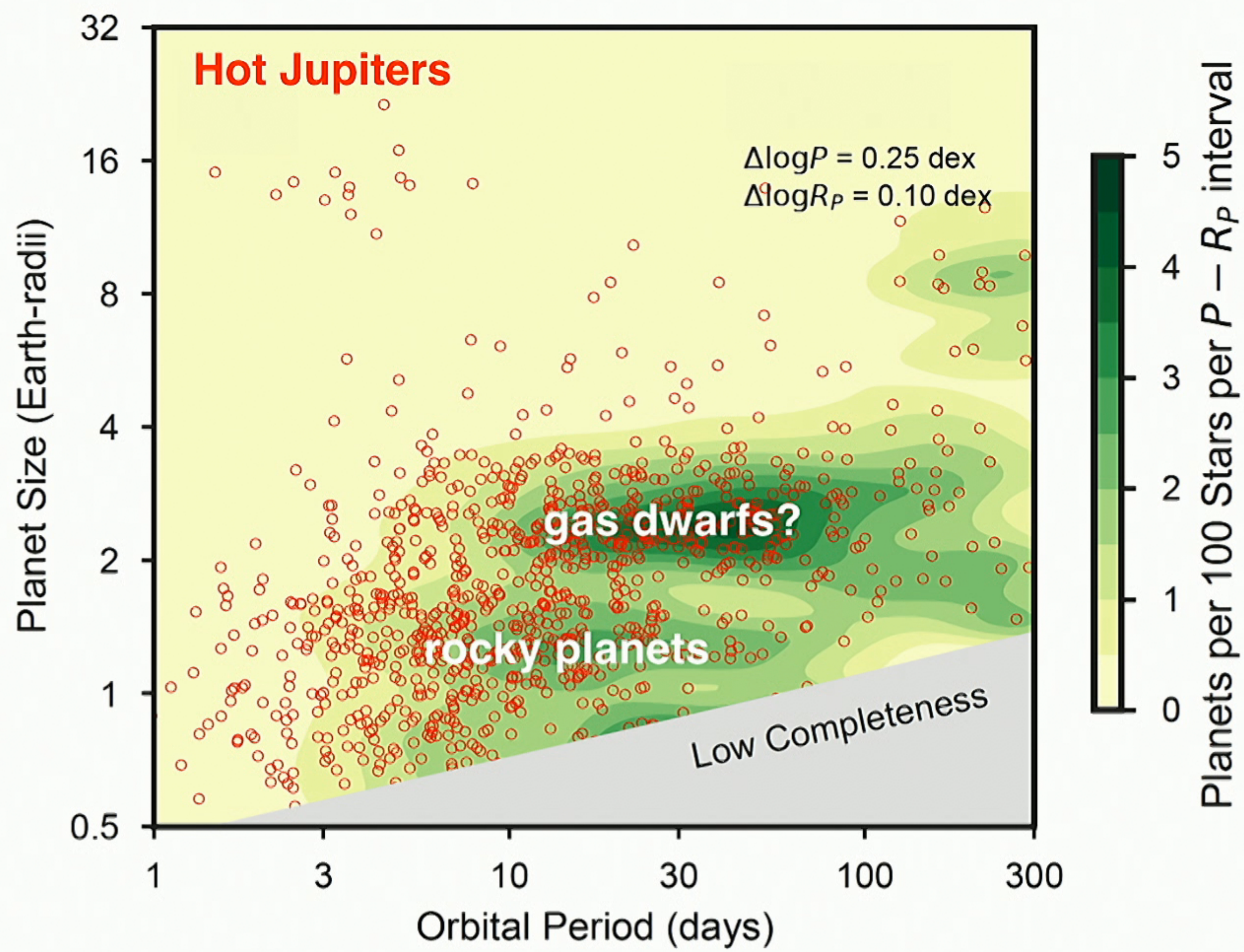



1.002
1.000
0.998
0.996
relative brightness
ground-based
1.2 meter telescope
1.002
1.000
0.998
0.996
relative brightness
space-based
1.0 meter telescope
(Kepler)
0
2
4
6
8
time (hours)
Heng & Winn (2016)

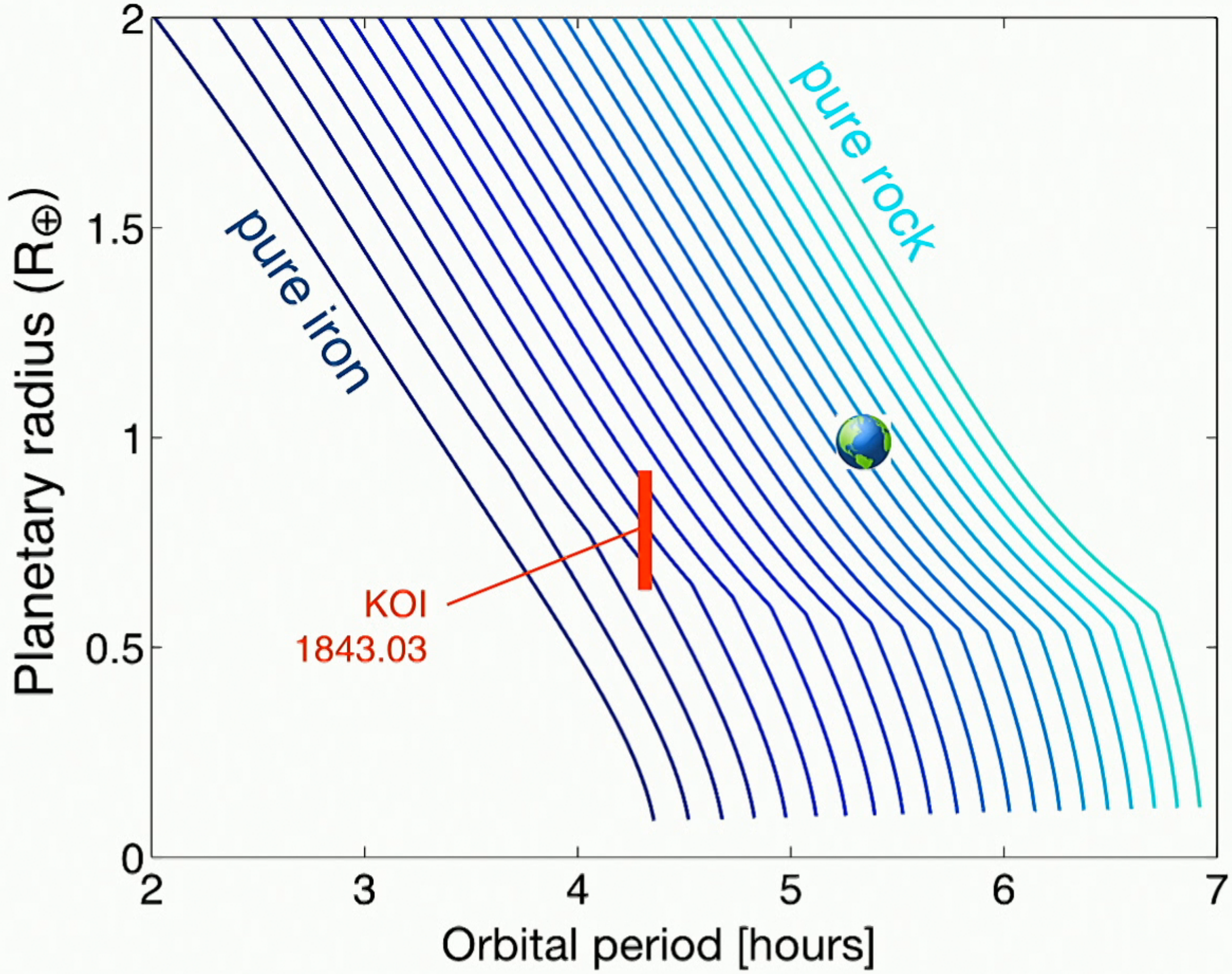

planet mass [M$_\oplus$]
orbital distance [AU]
10^0
10^1
10^2
10^3
10^4
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
J
S
U
N
V
E
Doppler
transit
imaging
μlensing
NASA Exoplanet Archive



Petigura, Marcy, Winn, et al. (2018)

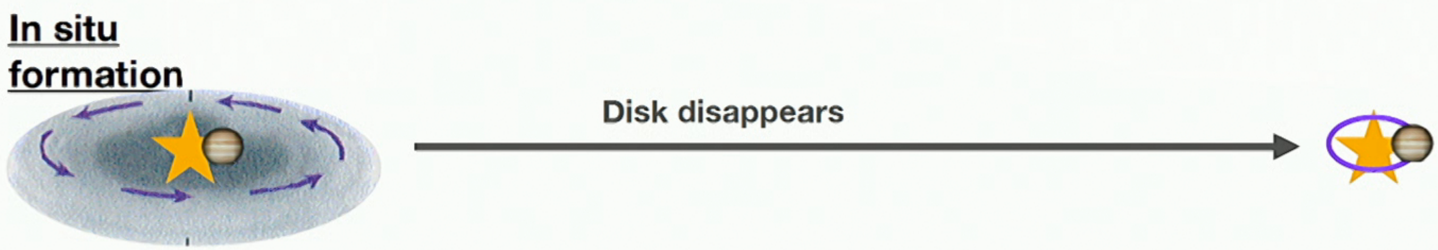


Petigura, Marcy, Winn, et al. (2018)

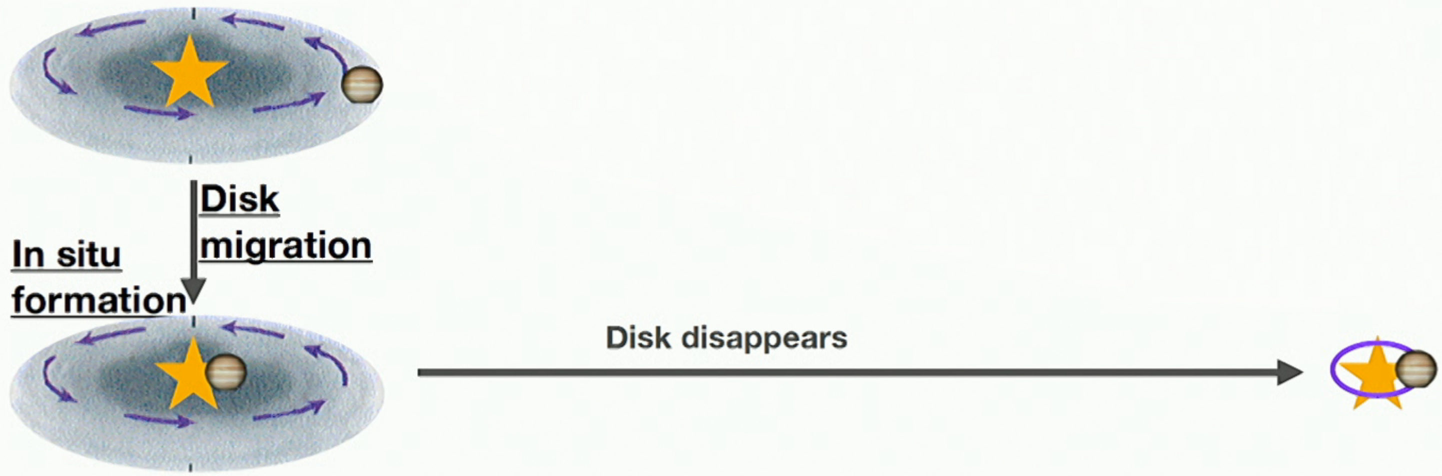


Rappaport, Sanchis-Ojeda, Rogers, et al. (2013)

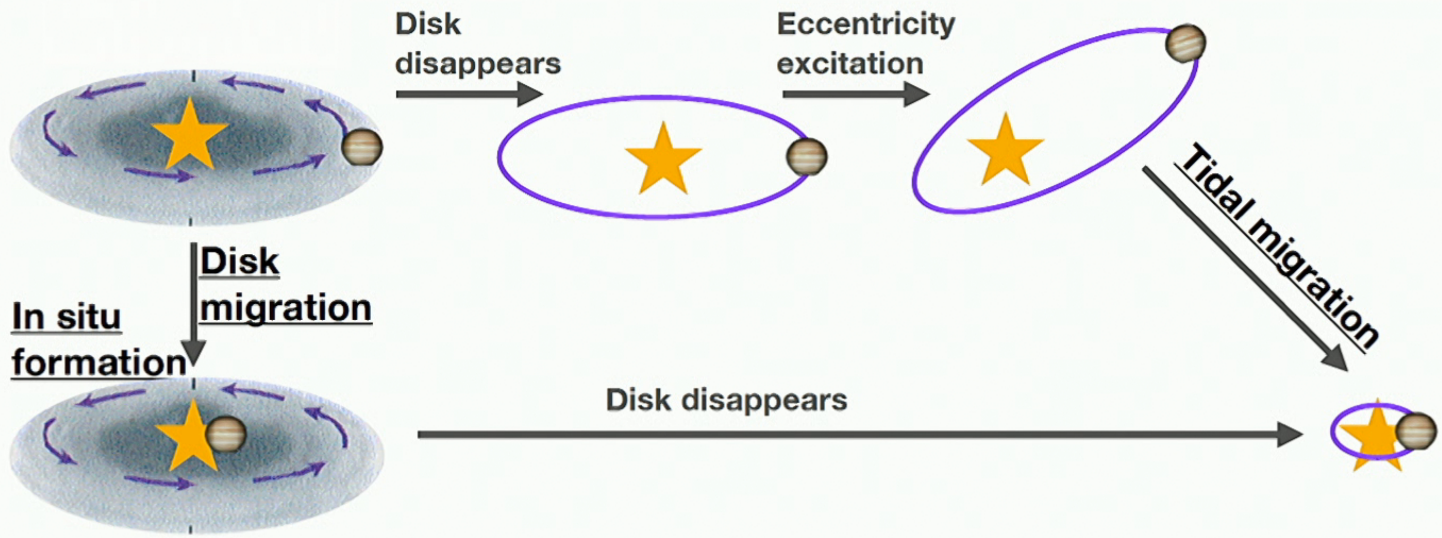
Dawson & Johnson (2018)



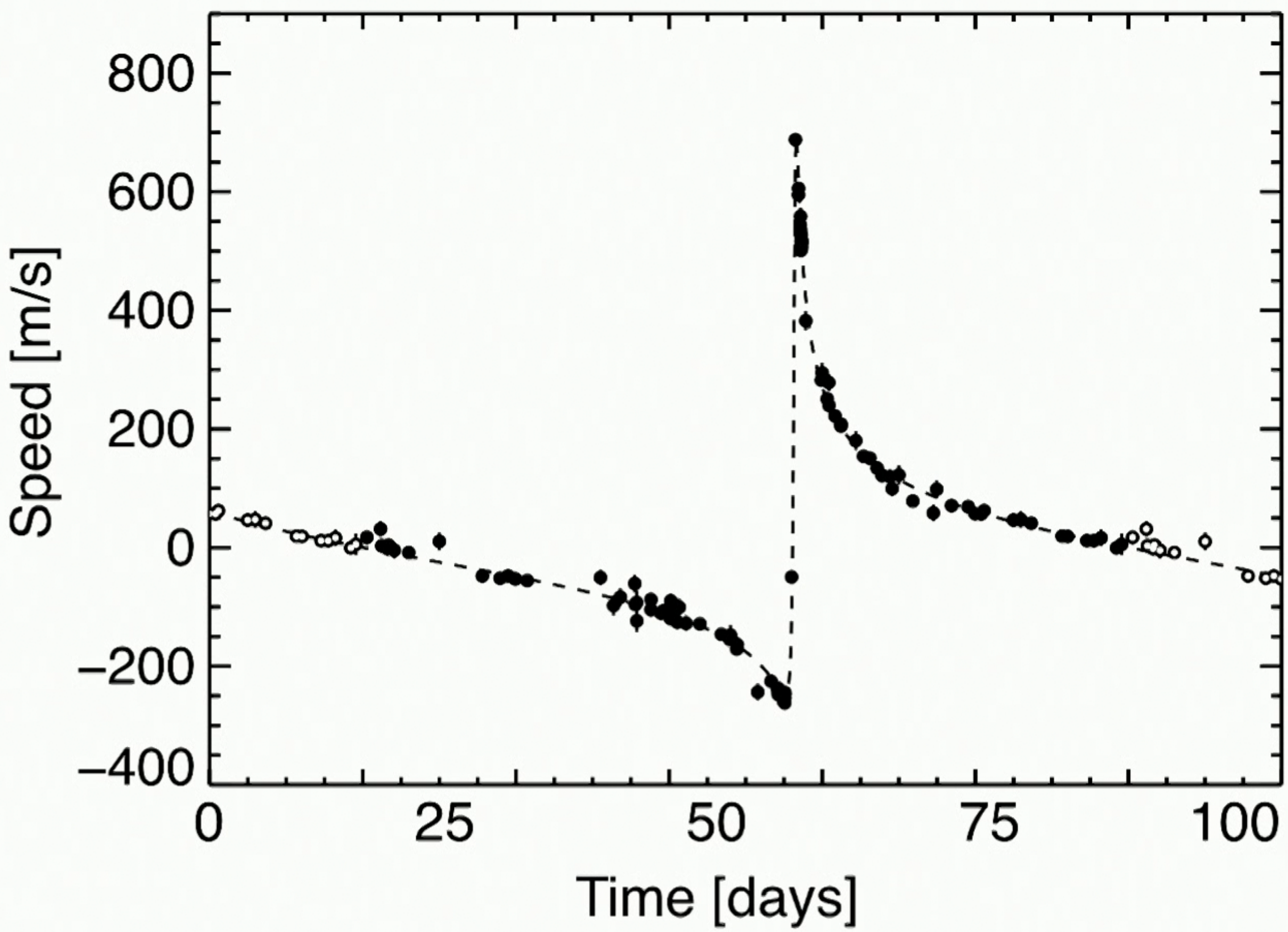
Dawson & Johnson (2018)

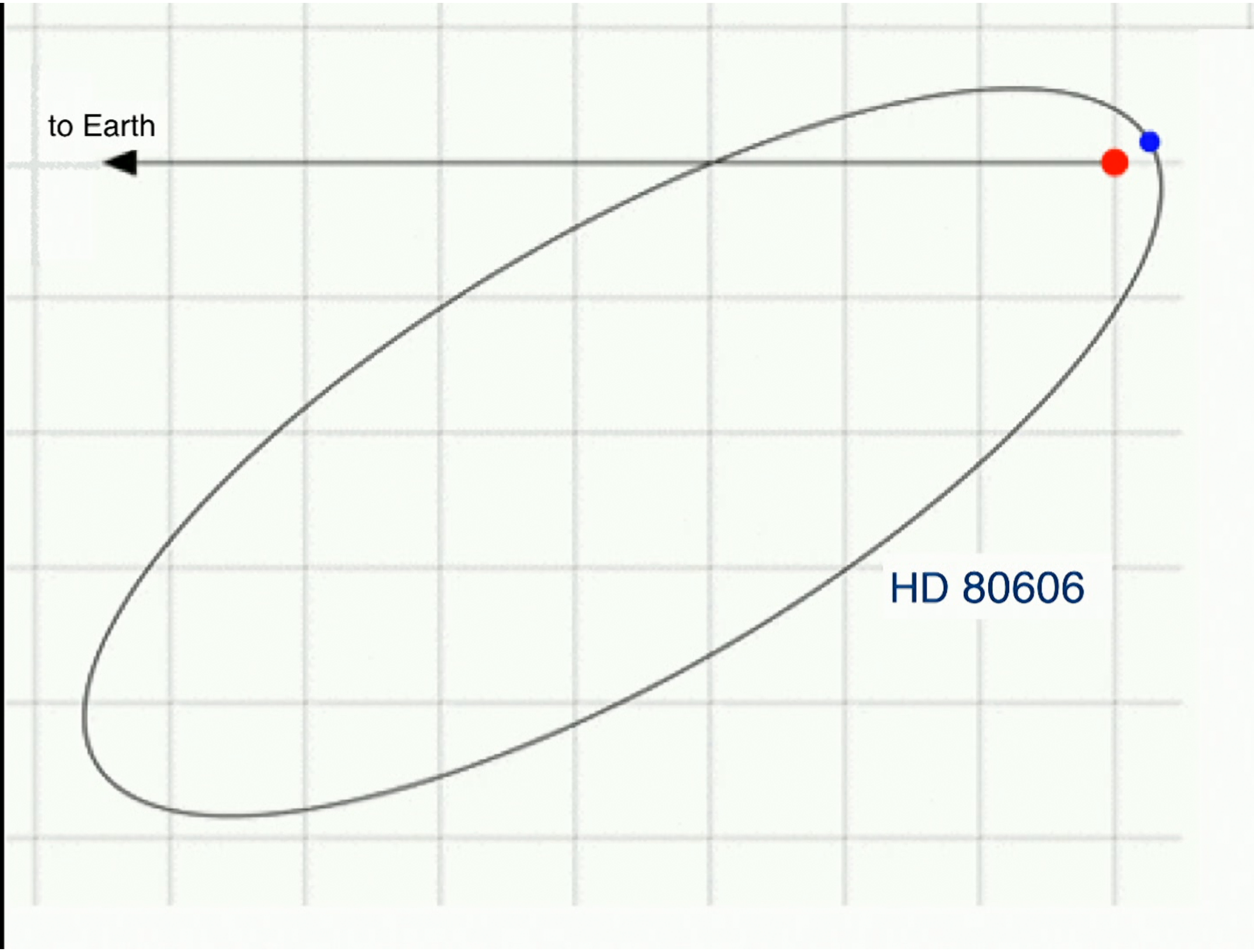


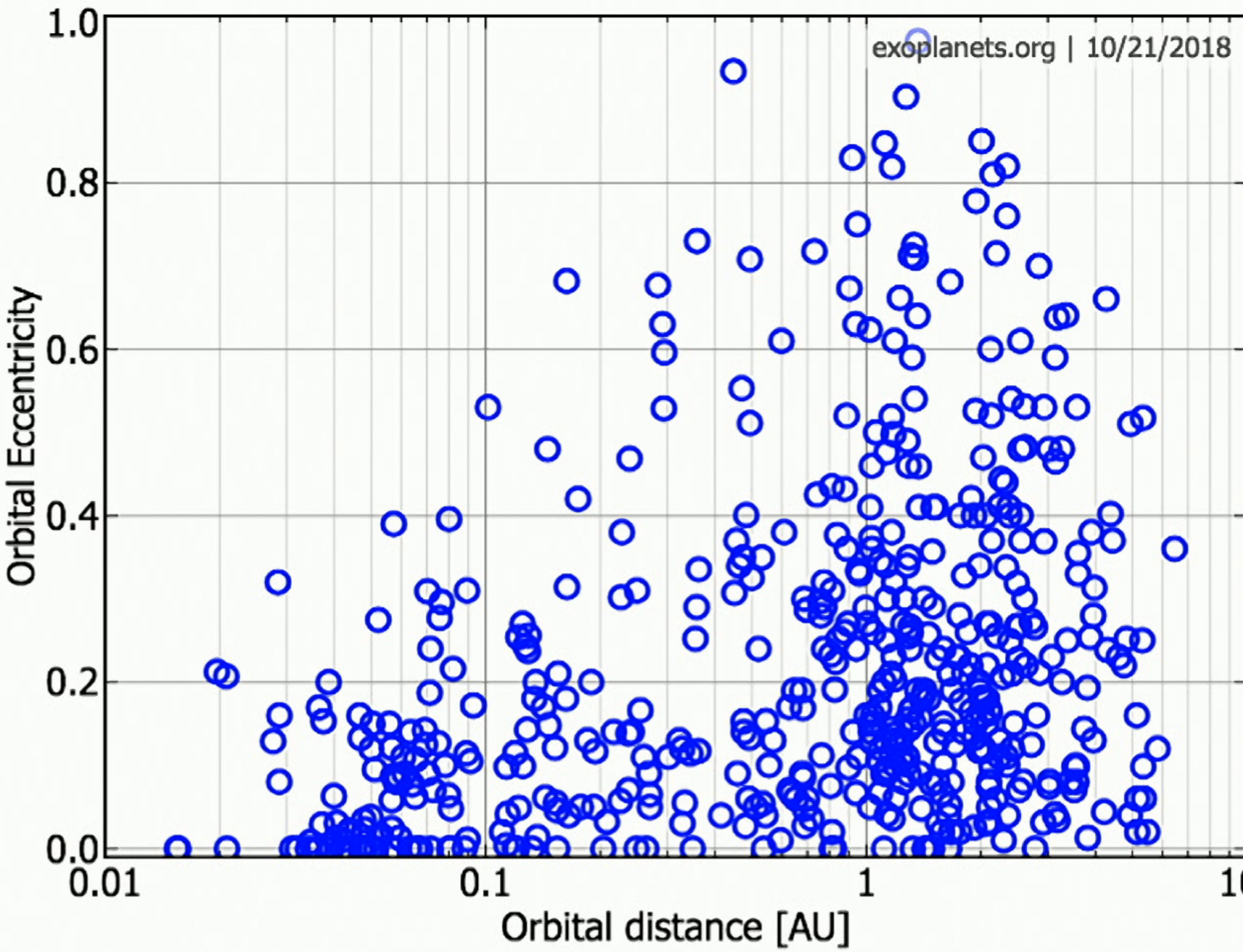
Dawson & Johnson (2018)



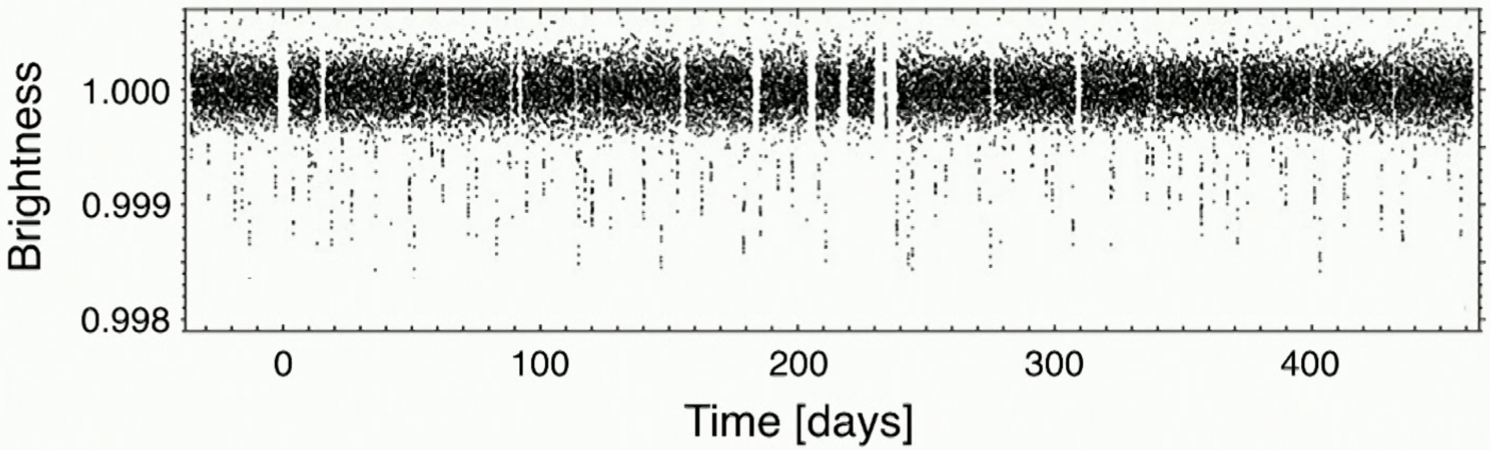
Dawson & Johnson (2018)

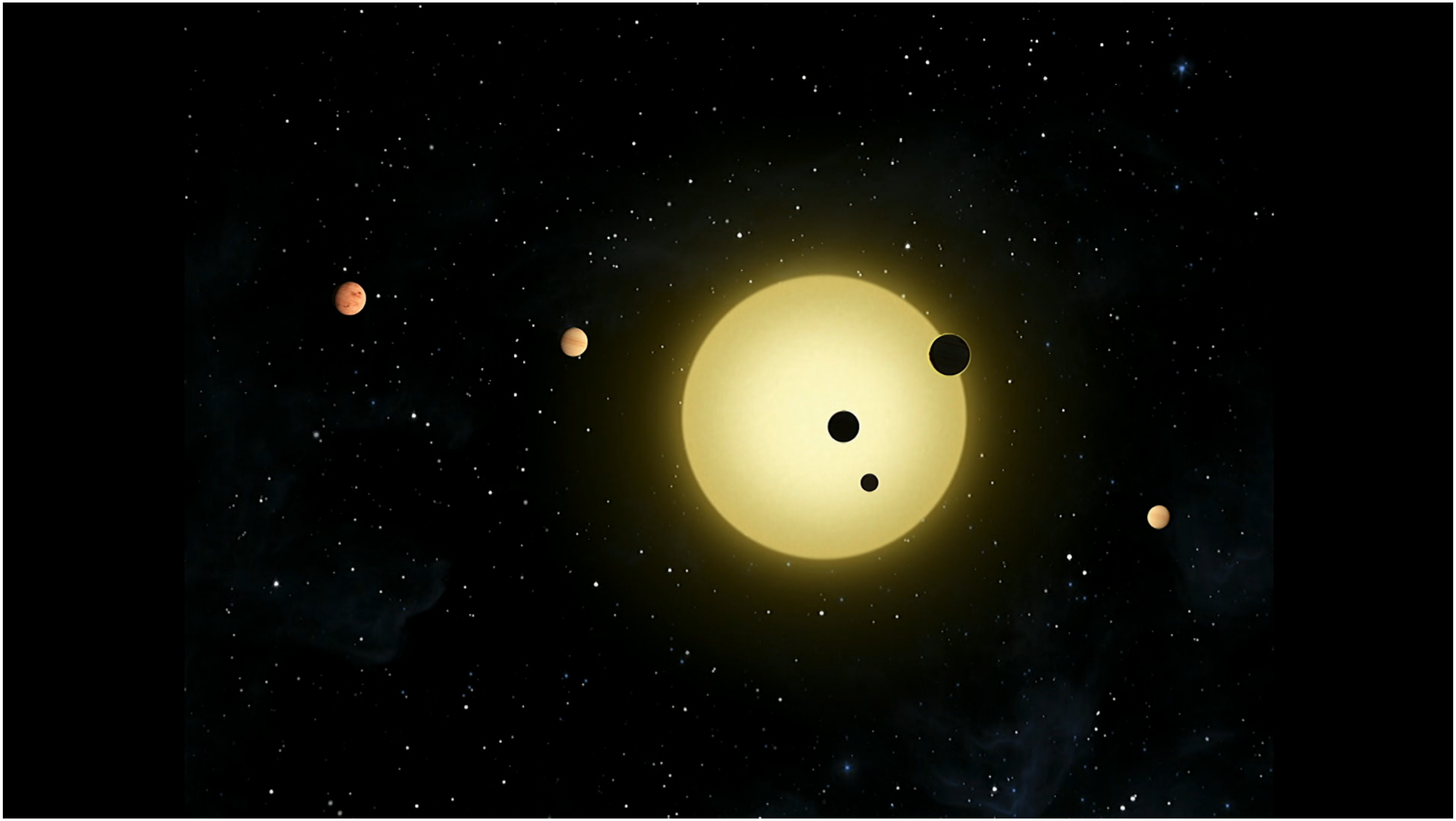

800
600
400
200
0
−200
−400
Speed [m/s]
0
25
50
75
100
Time [days]

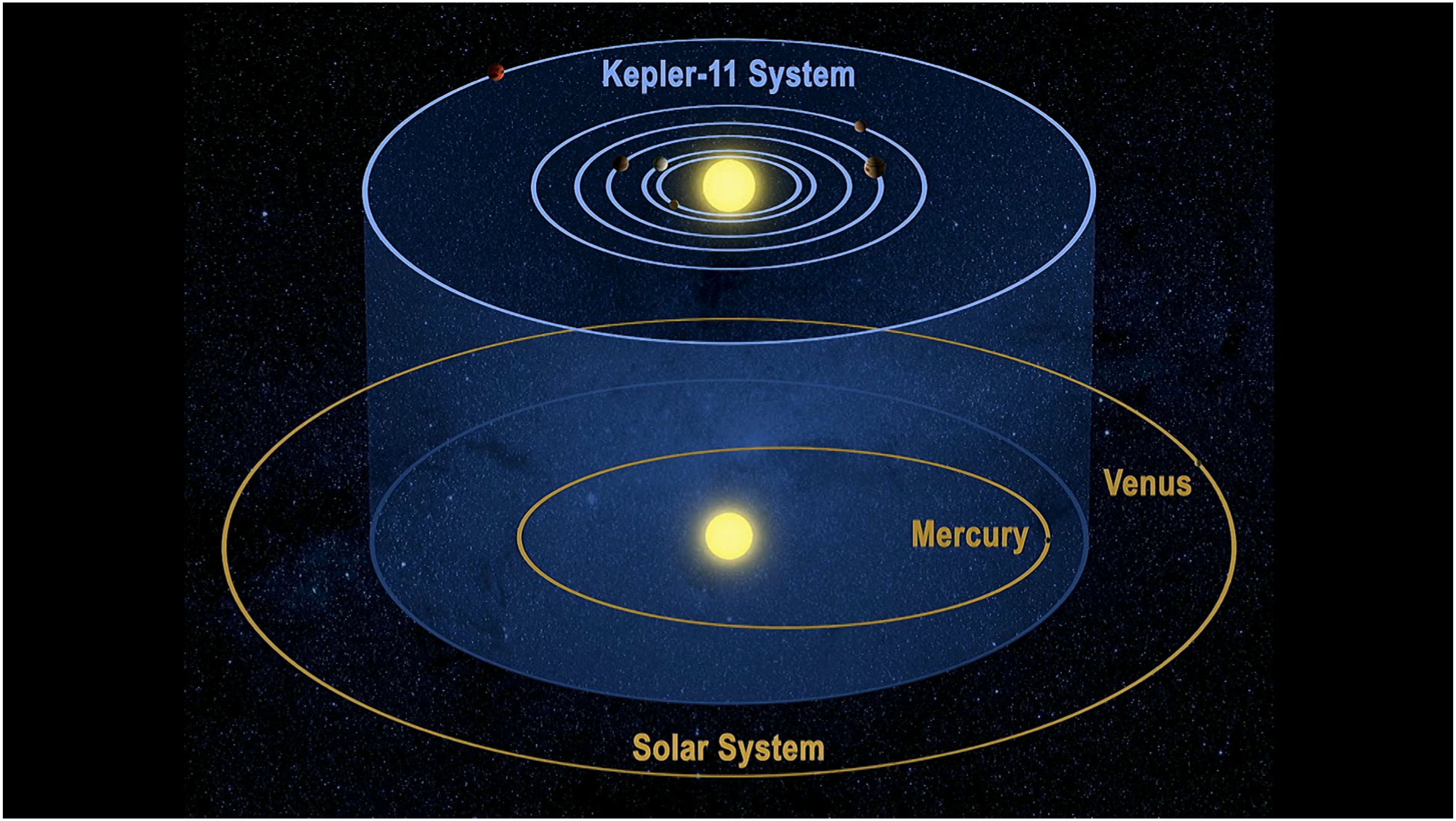

to Earth
HD 80606

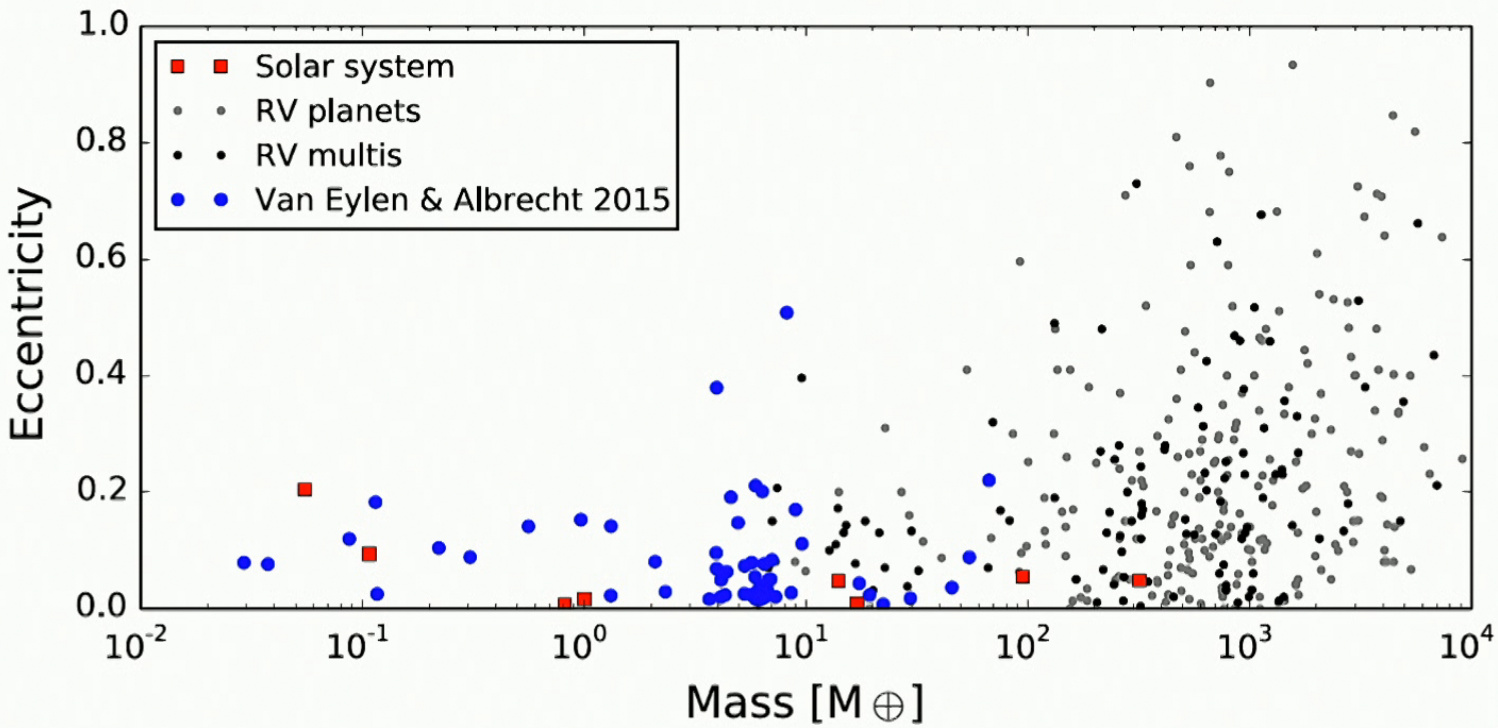

exoplanets.org | 10/21/2018
Orbital Eccentricity
Orbital distance [AU]
1.0
0.8
0.6
0.4
0.2
0.0
0.01
0.1
1
10

Kepler-11

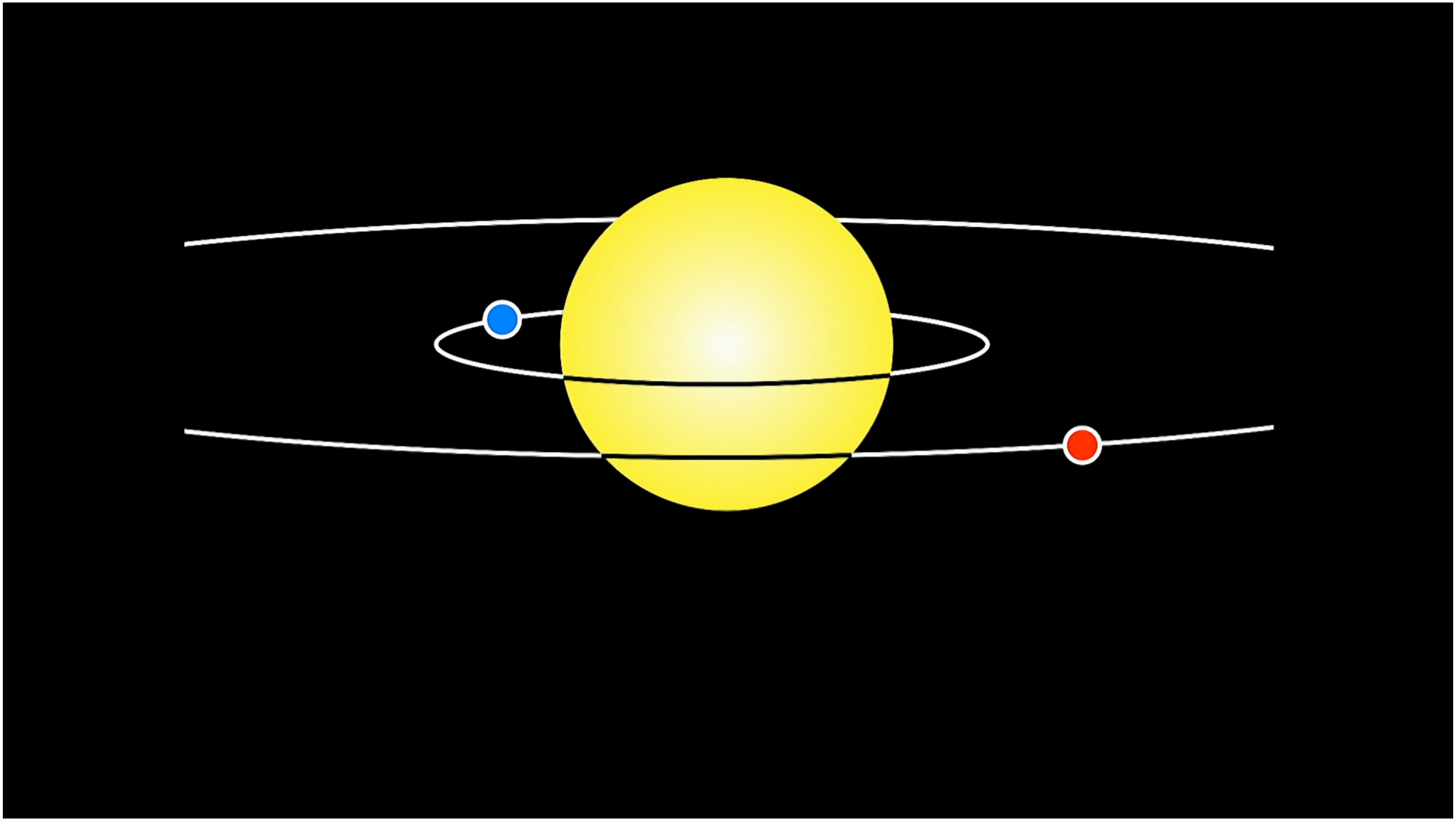


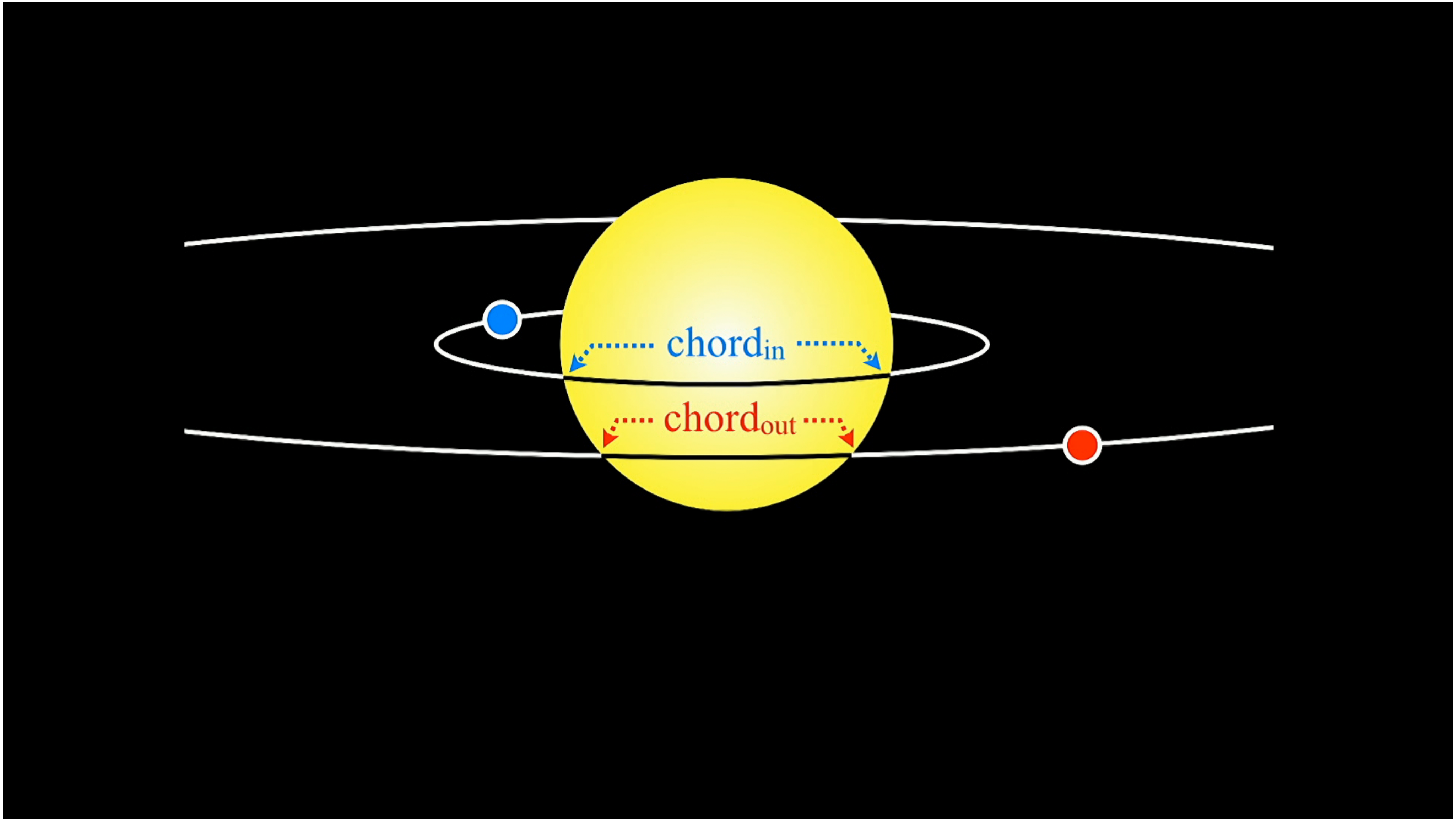



Kepler-11 System
Venus
Mercury
Solar System

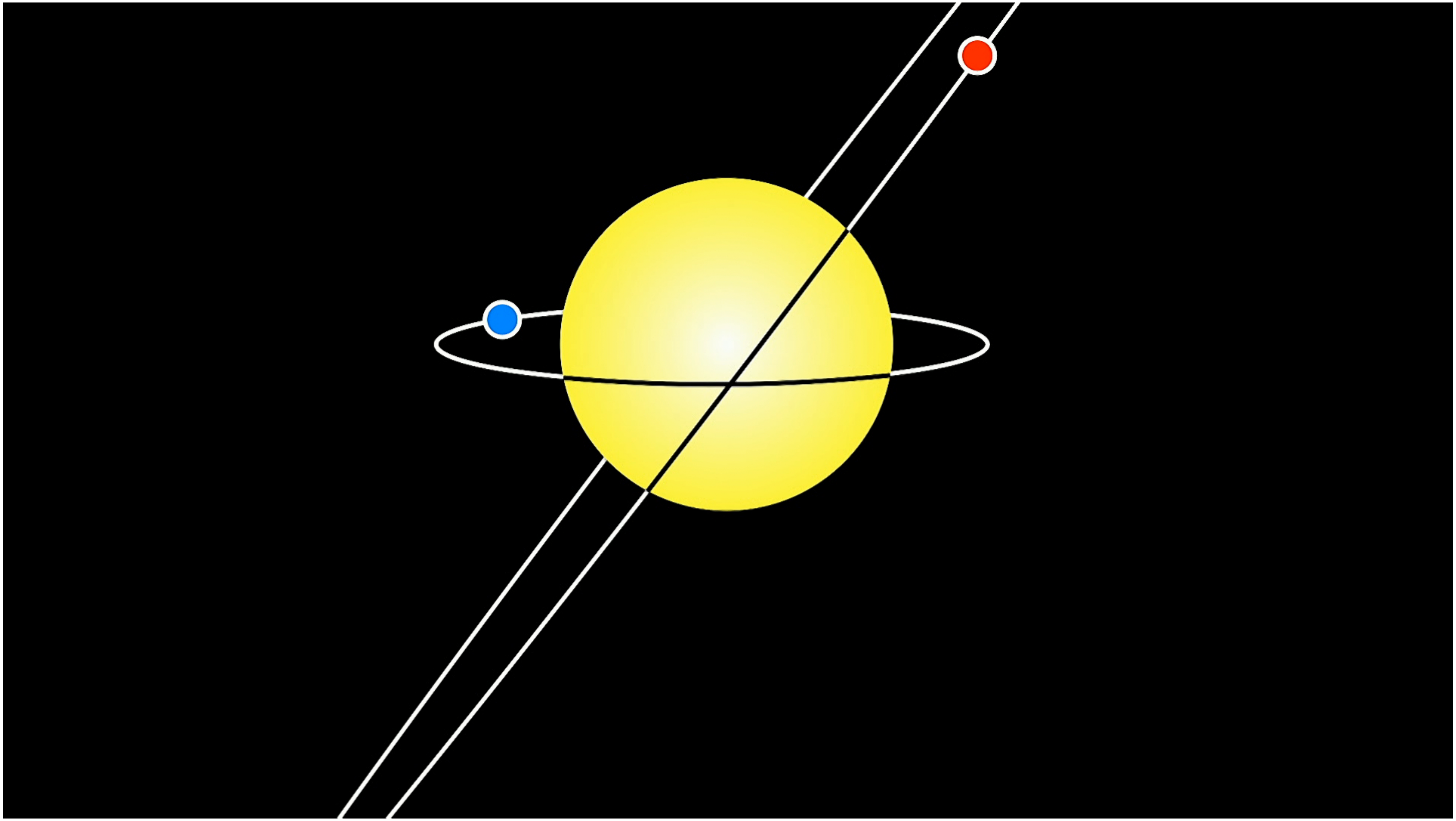


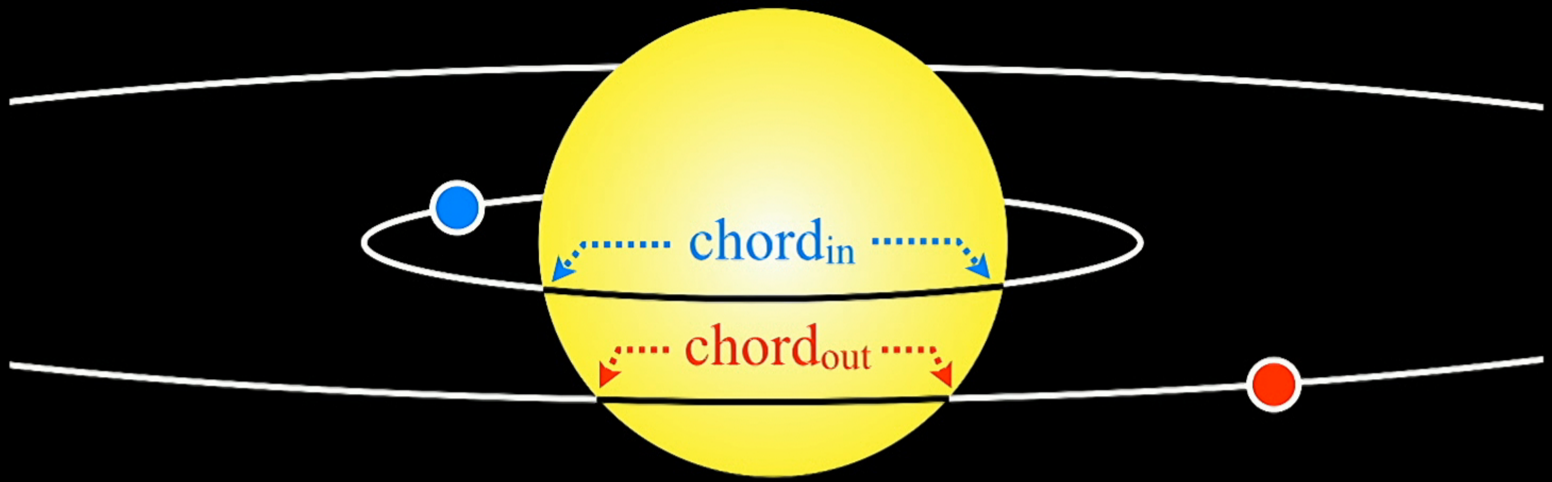
Solar system
RV planets
RV multis
Van Eylen & Albrecht 2015
Eccentricity
1.0
0.8
0.6
0.4
0.2
0.0
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Mass [M⊕]



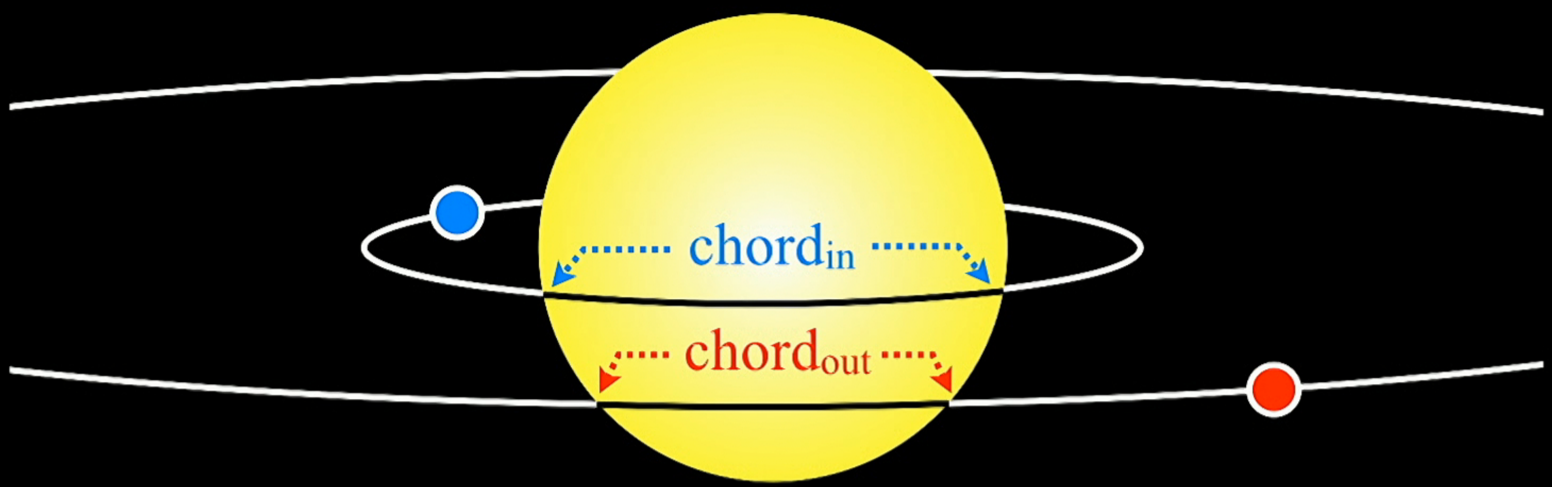


chord$_{in}$
chord$_{out}$

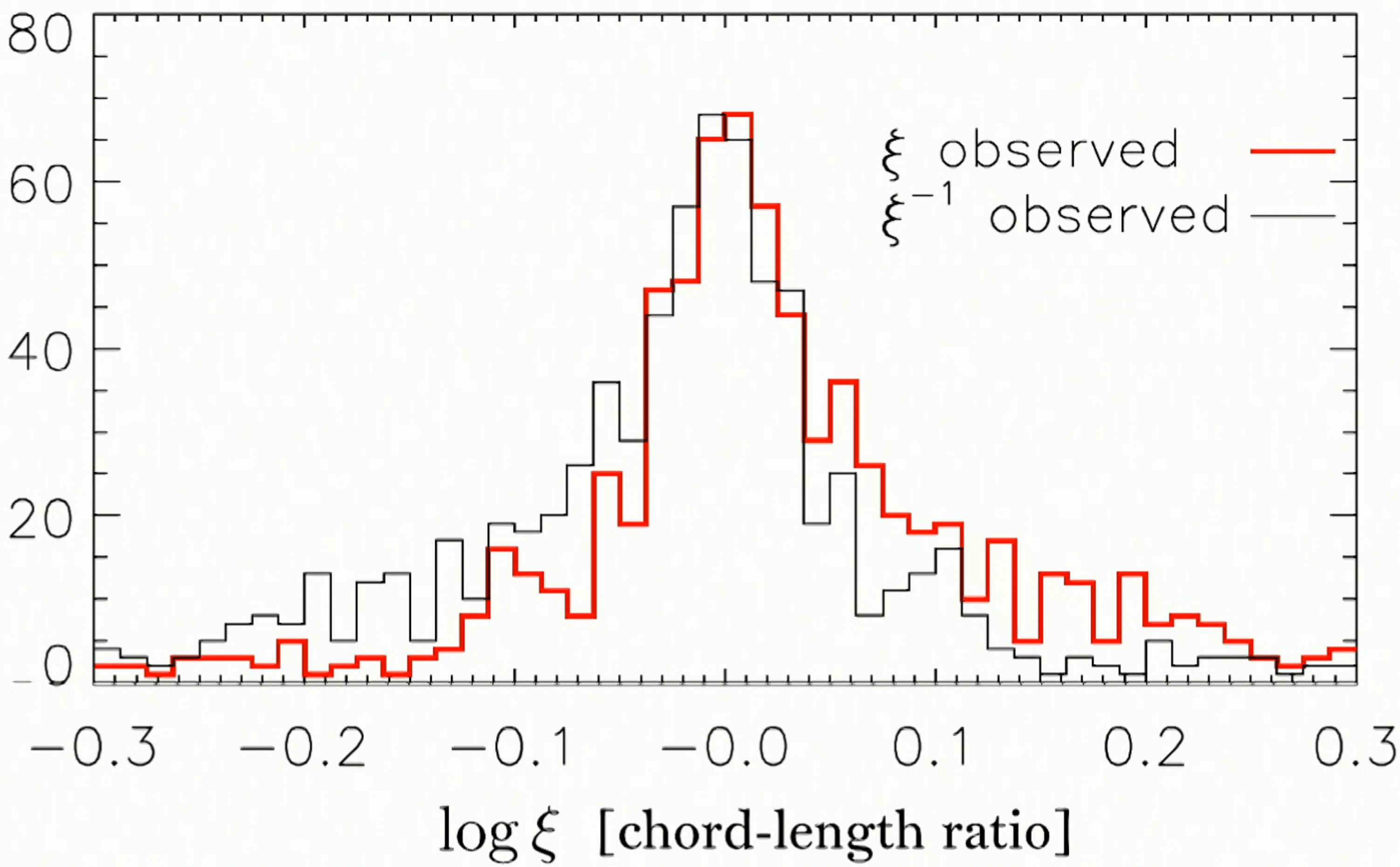




$$\xi \equiv \frac{\mathrm{chord}_{\mathrm{in}}}{\mathrm{chord}_{\mathrm{out}}}$$



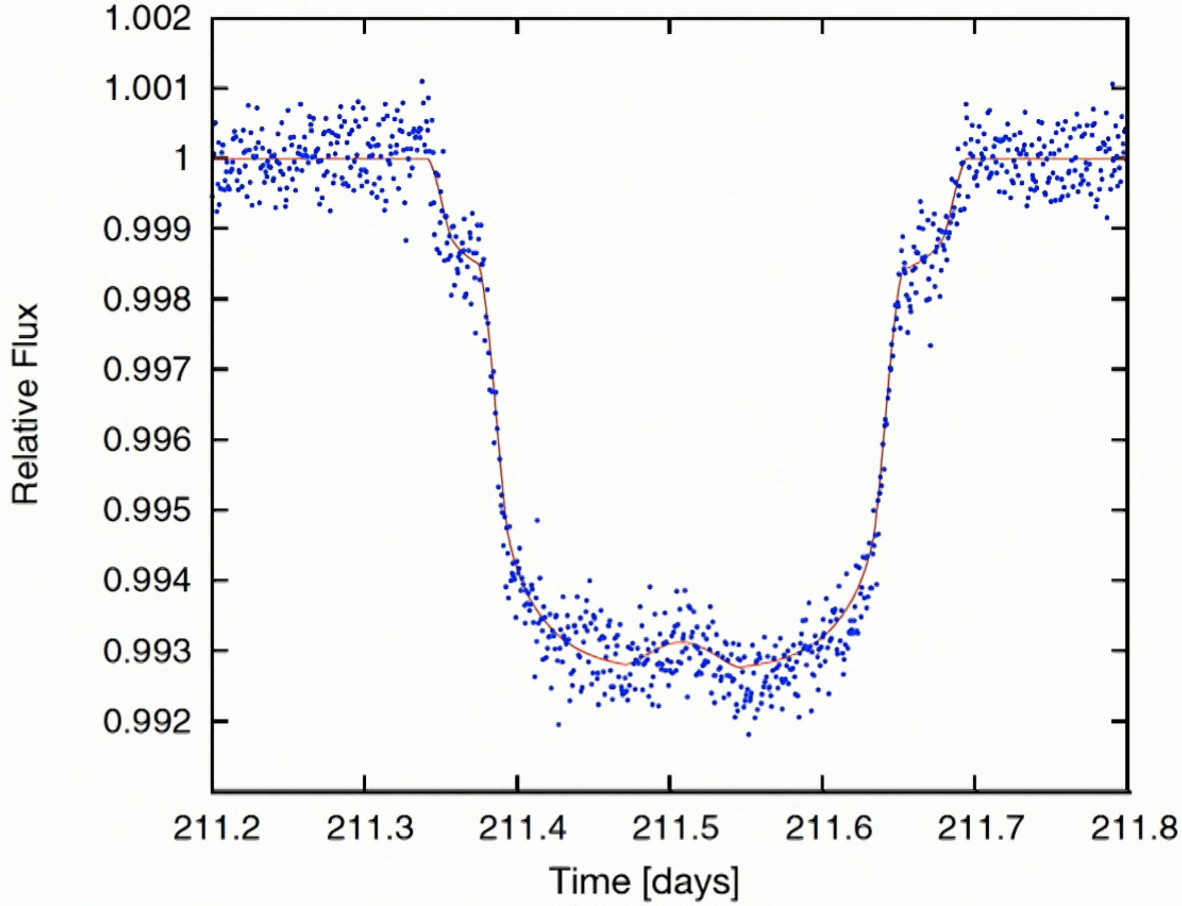
$$\xi \equiv \frac{\text{chord}_{\text{in}}}{\text{chord}_{\text{out}}} = \frac{(T/P^{1/3})_{\text{in}}}{(T/P^{1/3})_{\text{out}}}$$



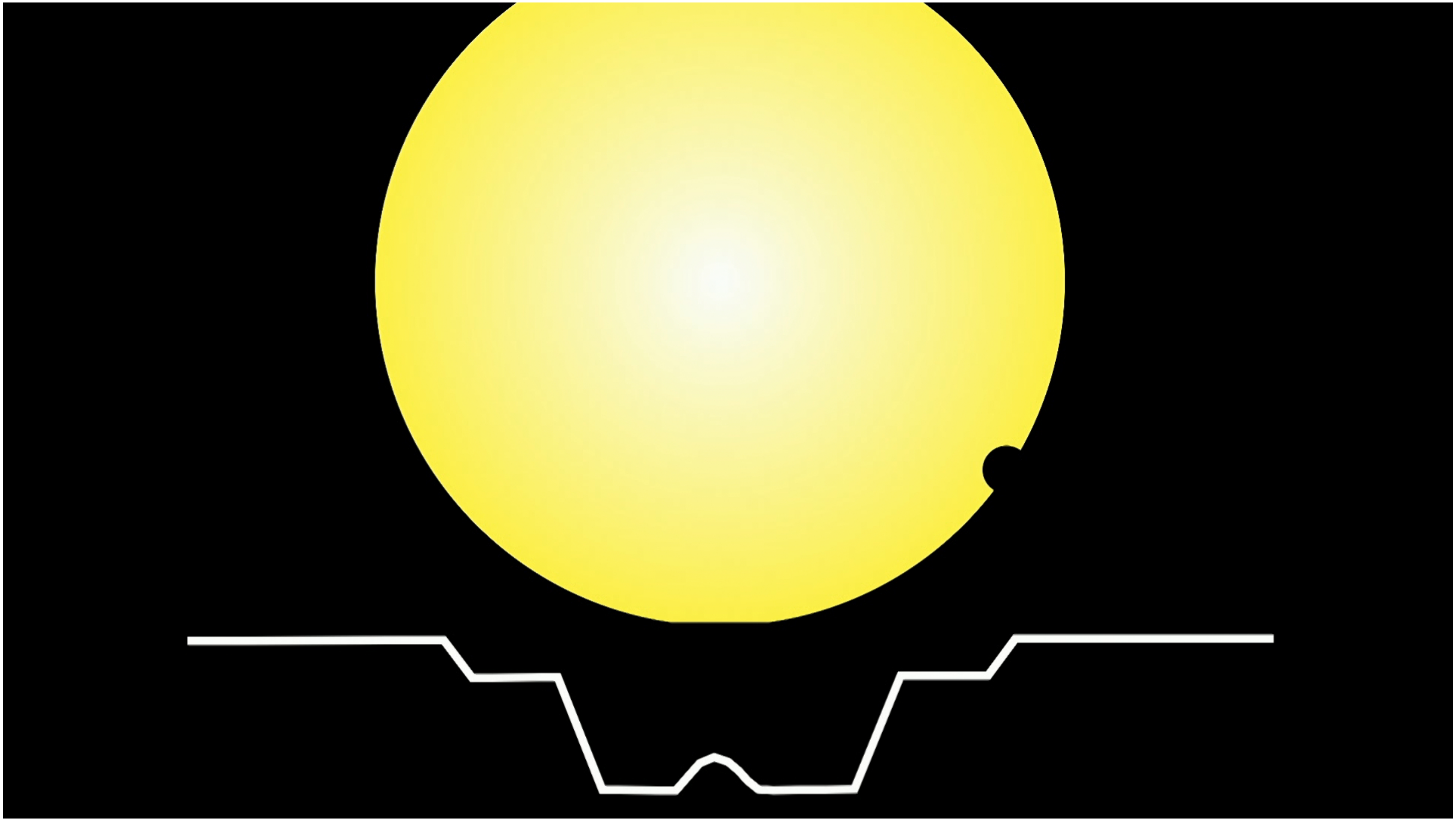
Fabrycky et al. (2014)

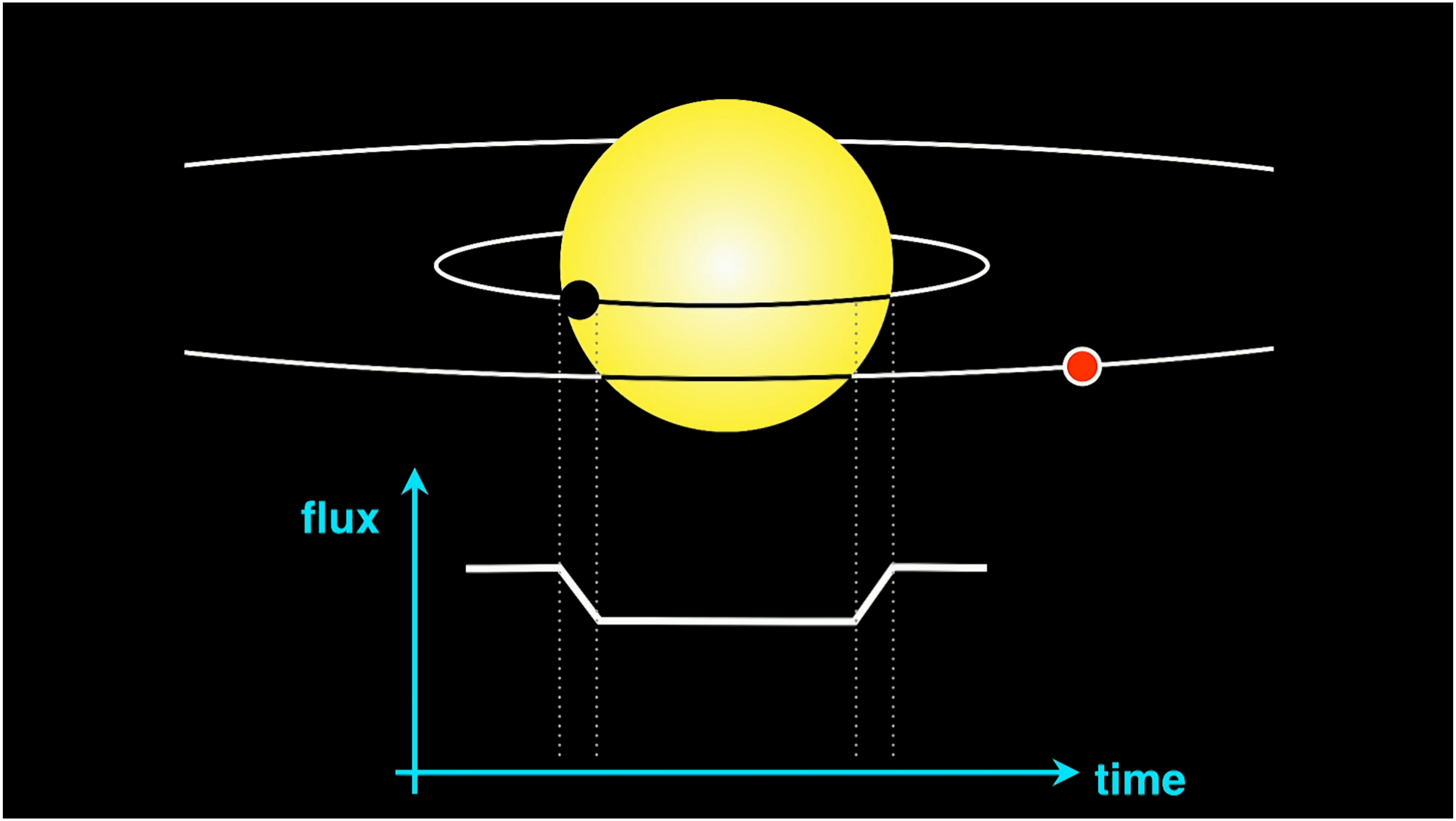
see also Fang & Margot (2012), Figueira et al. (2012)

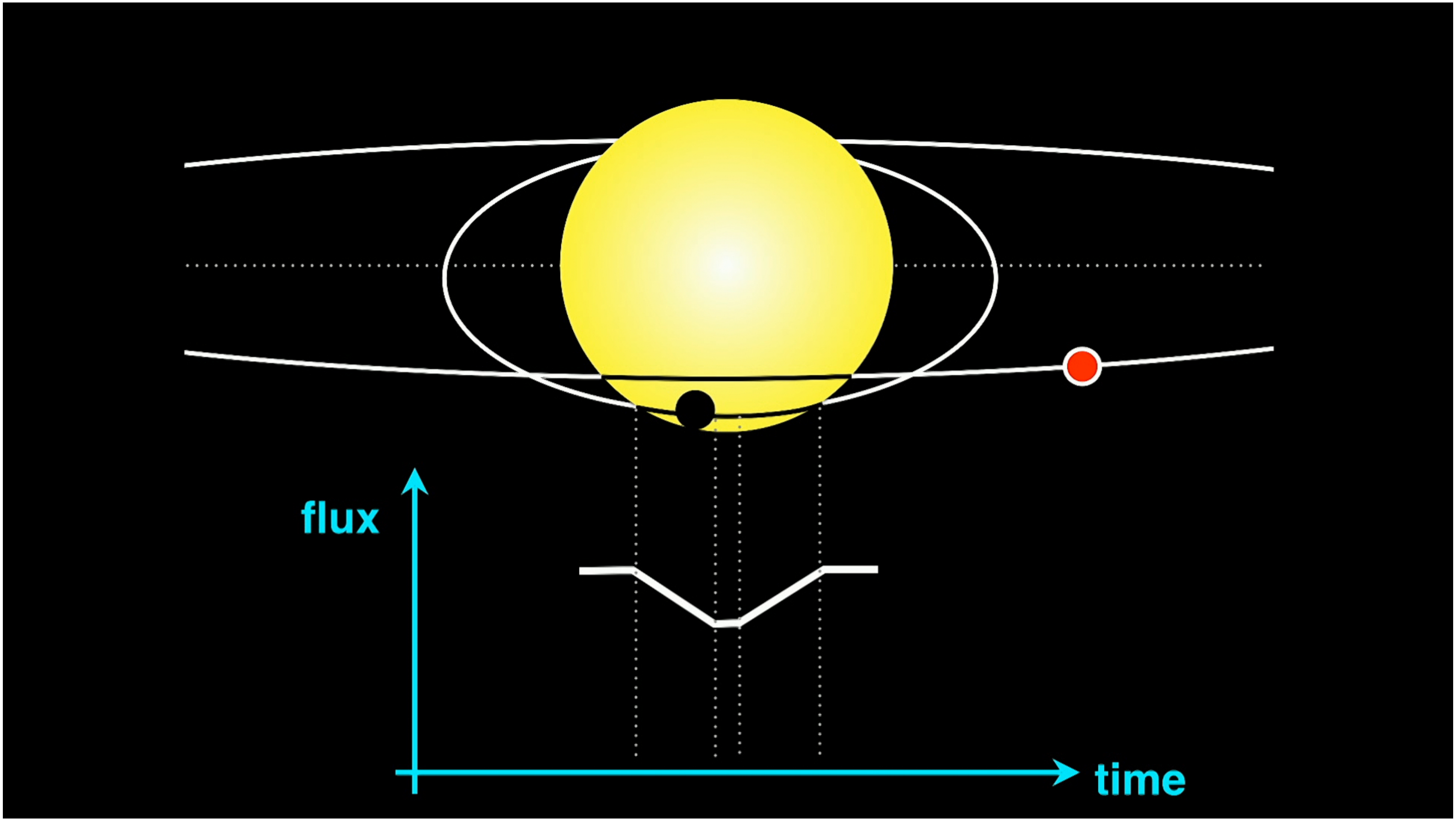
Kepler-94

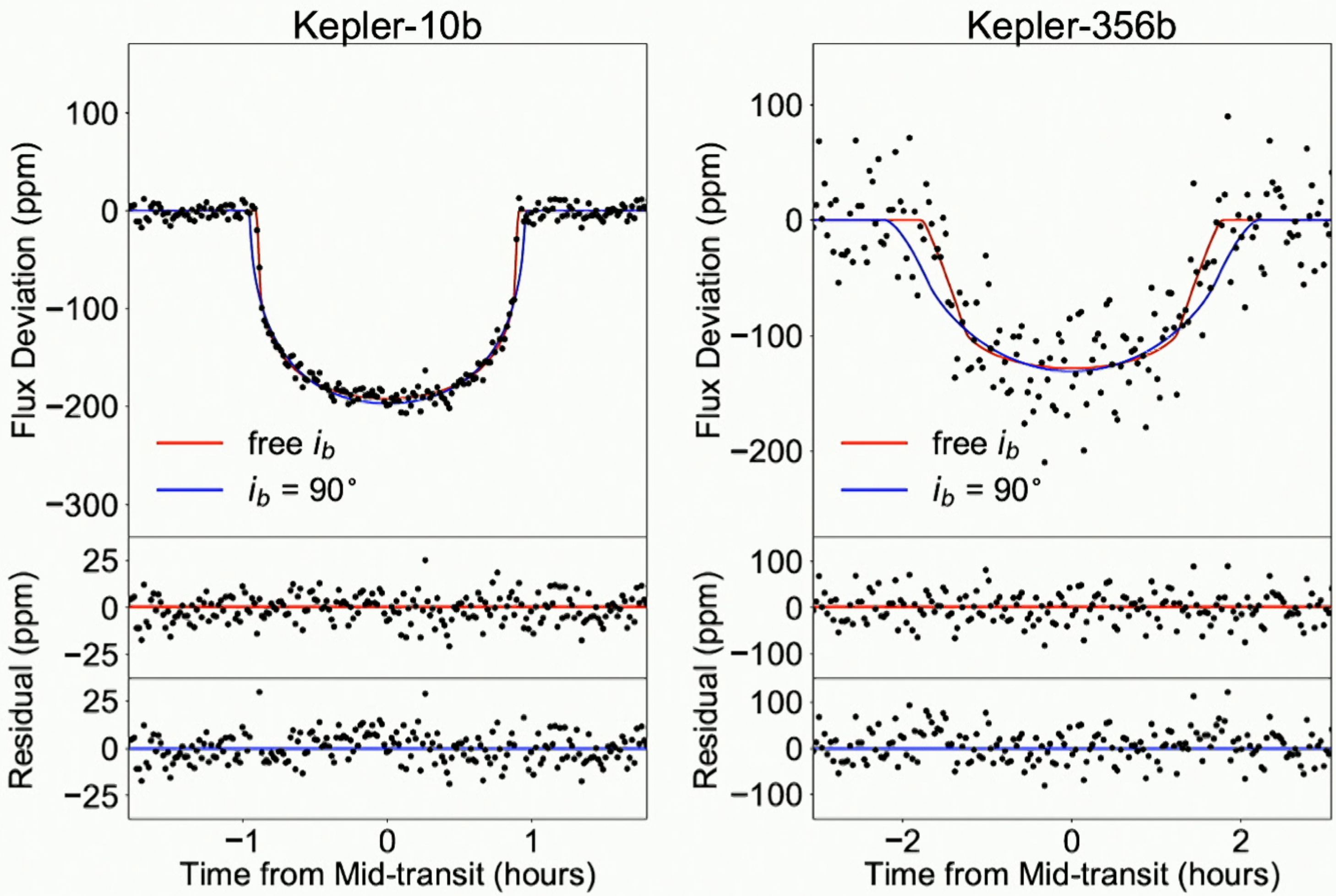


Hirano et al. (2012)

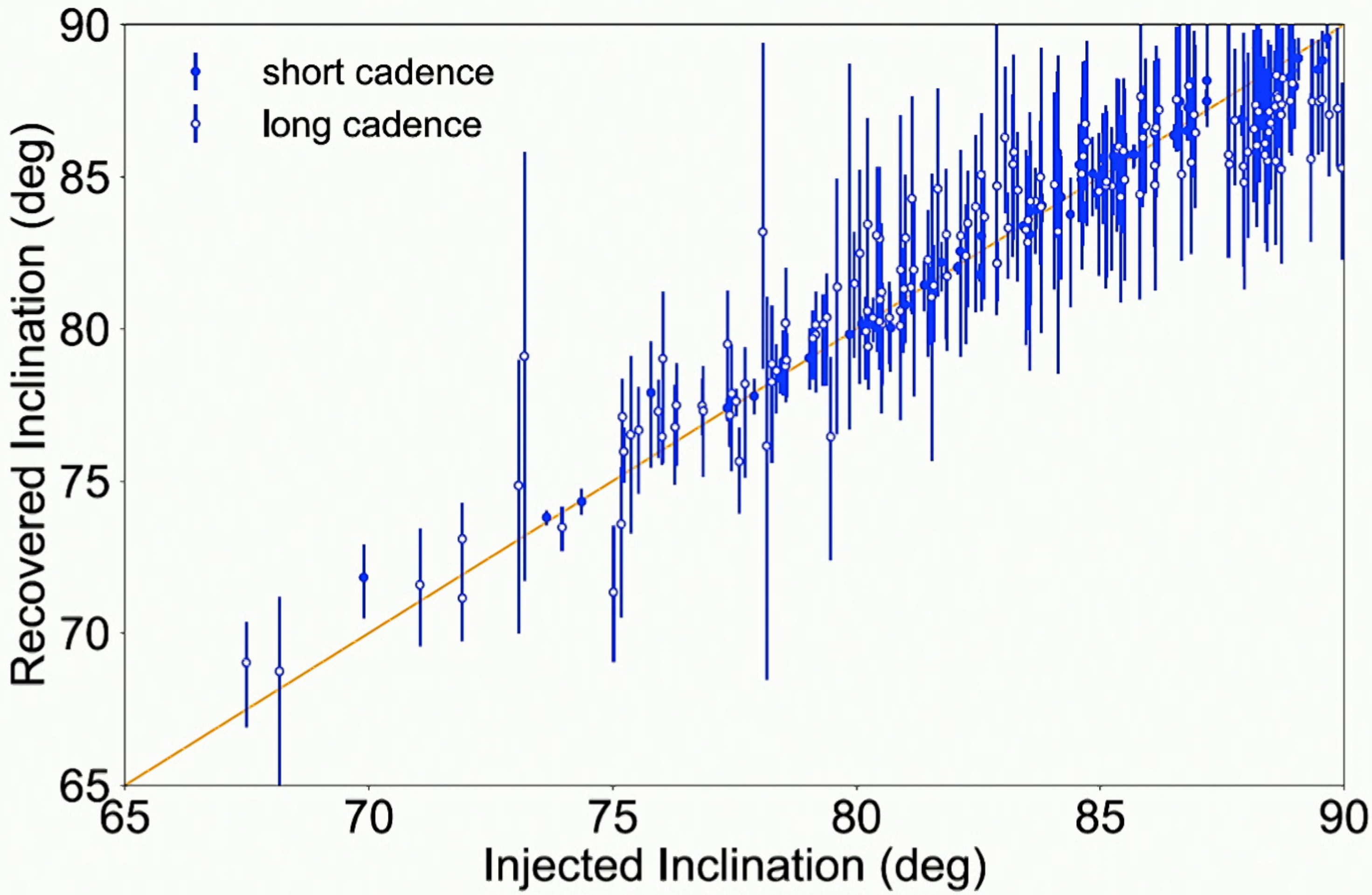



flux
time

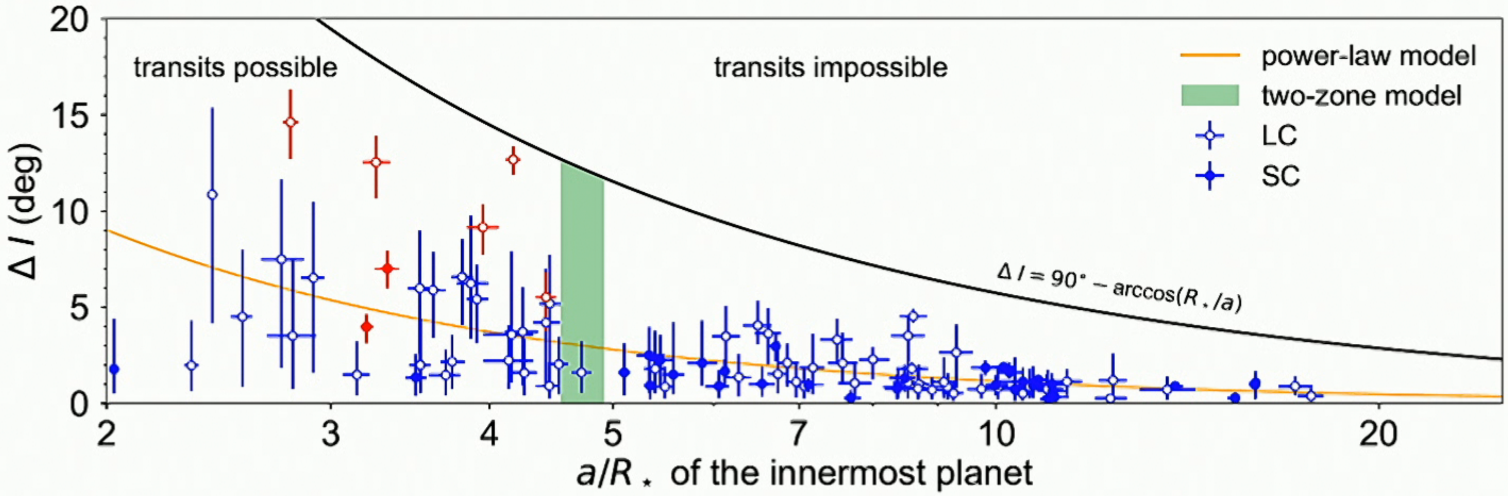

flux
time



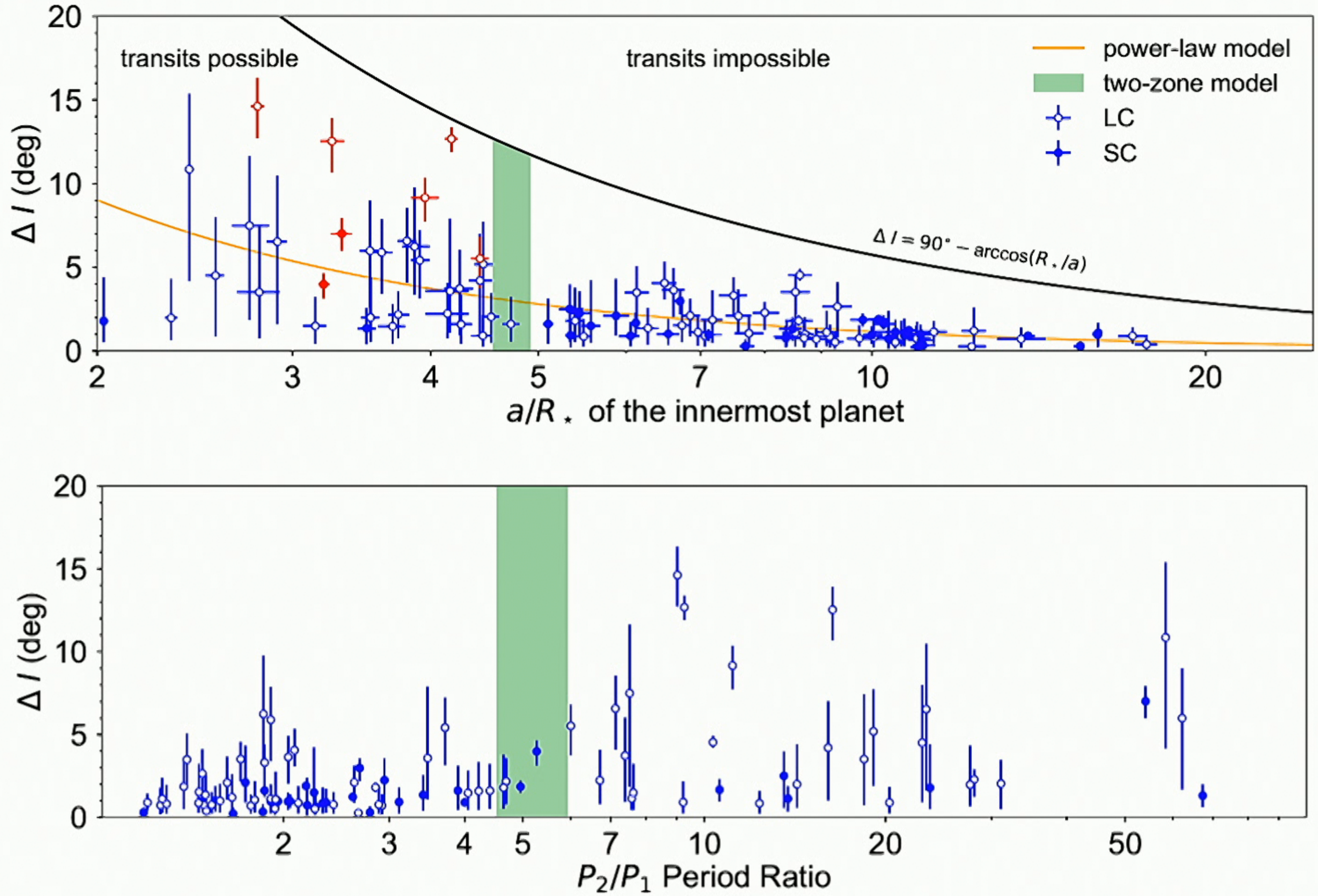
Dai, Winn, & Masuda (2018)



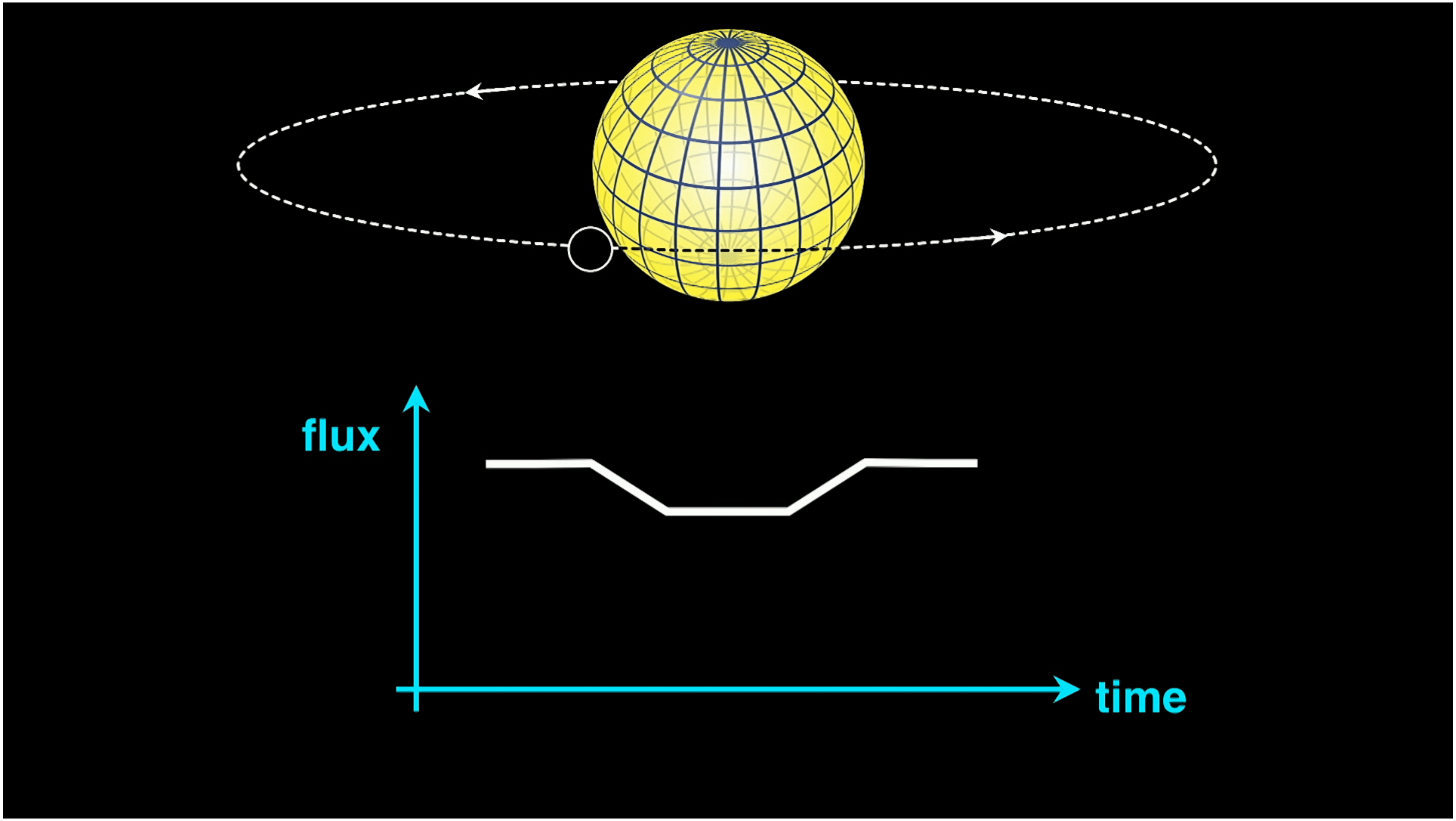
Dai, Winn, & Masuda (2018)

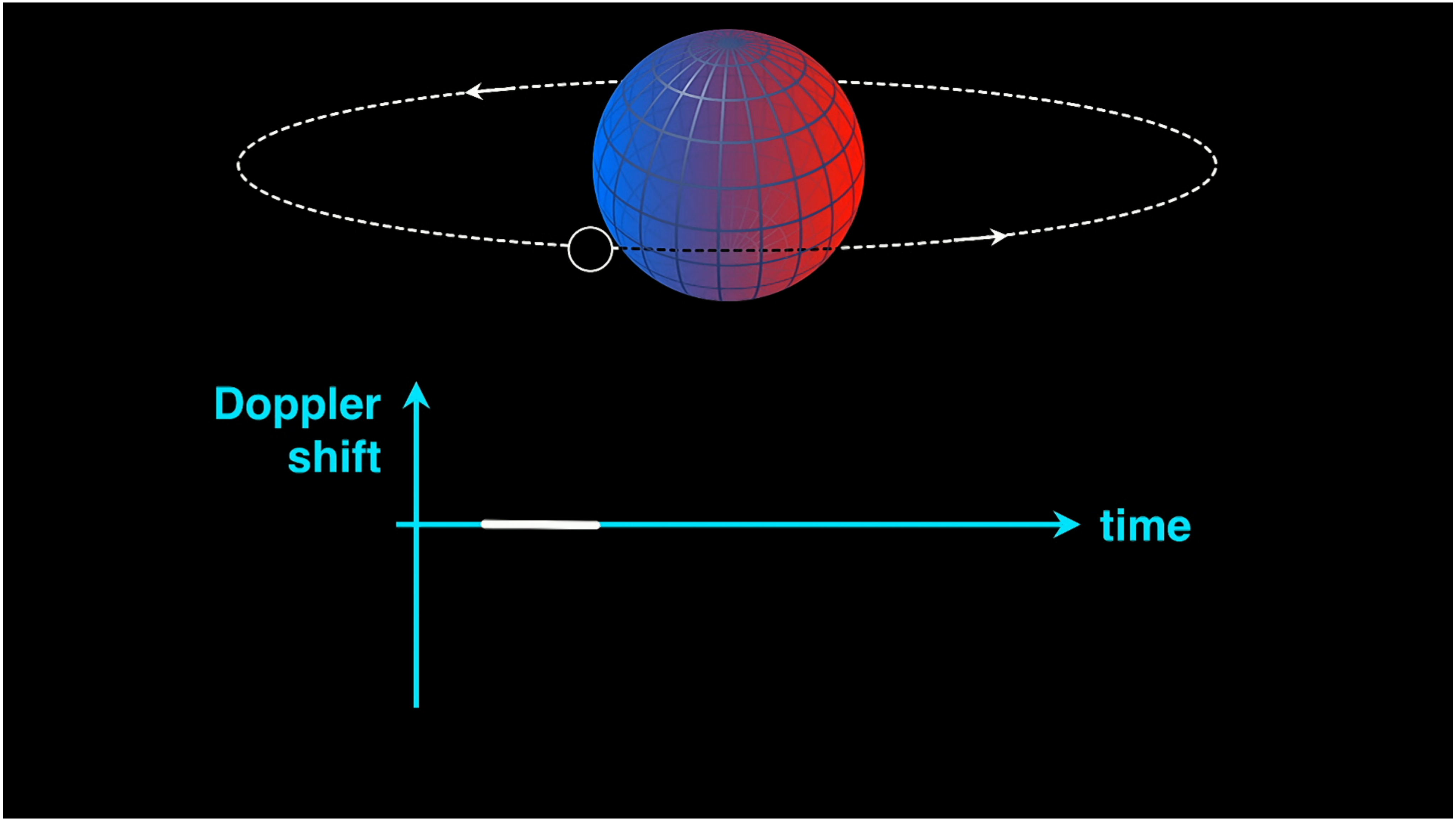


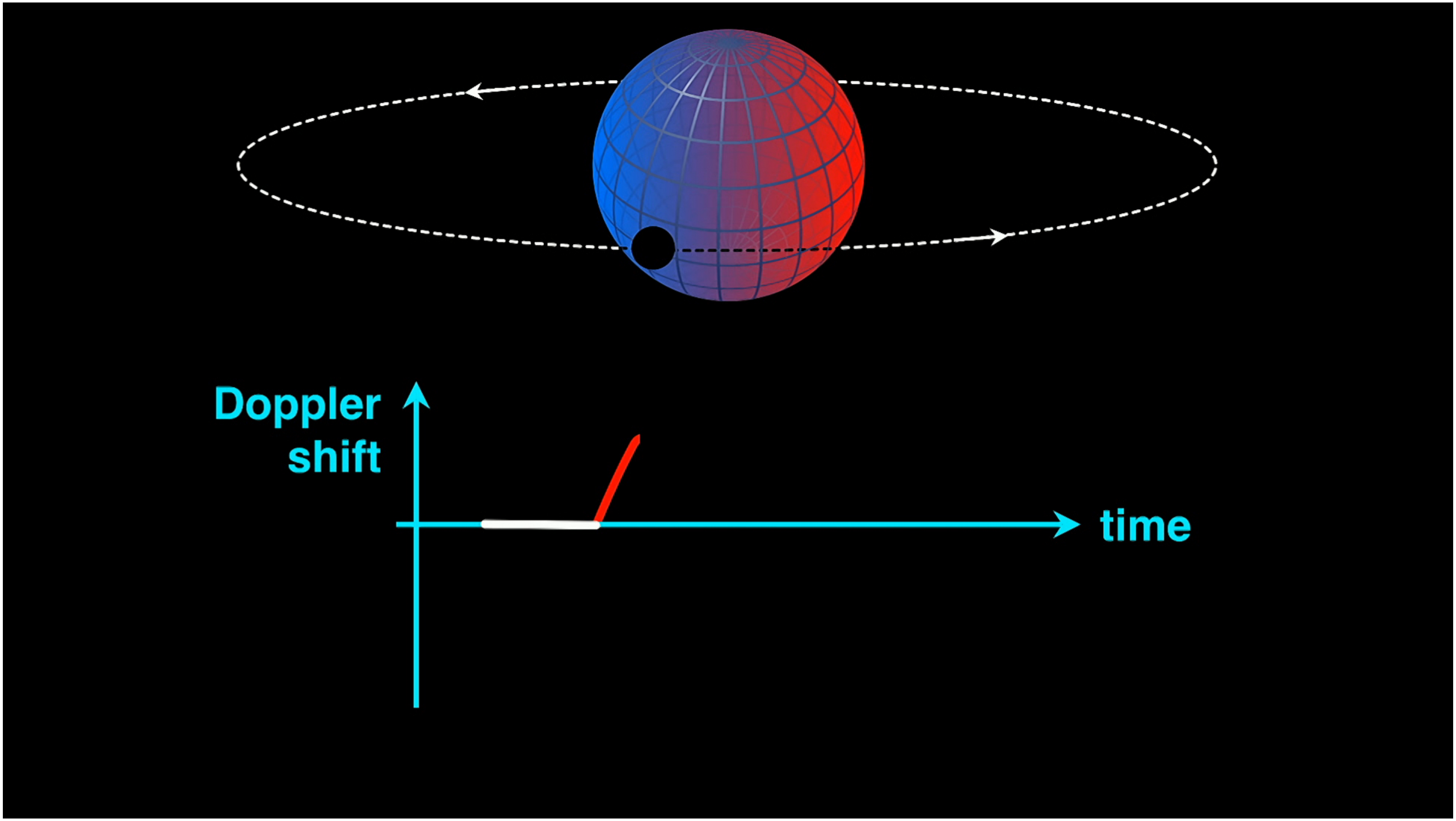
Dai, Winn, & Masuda (2018)

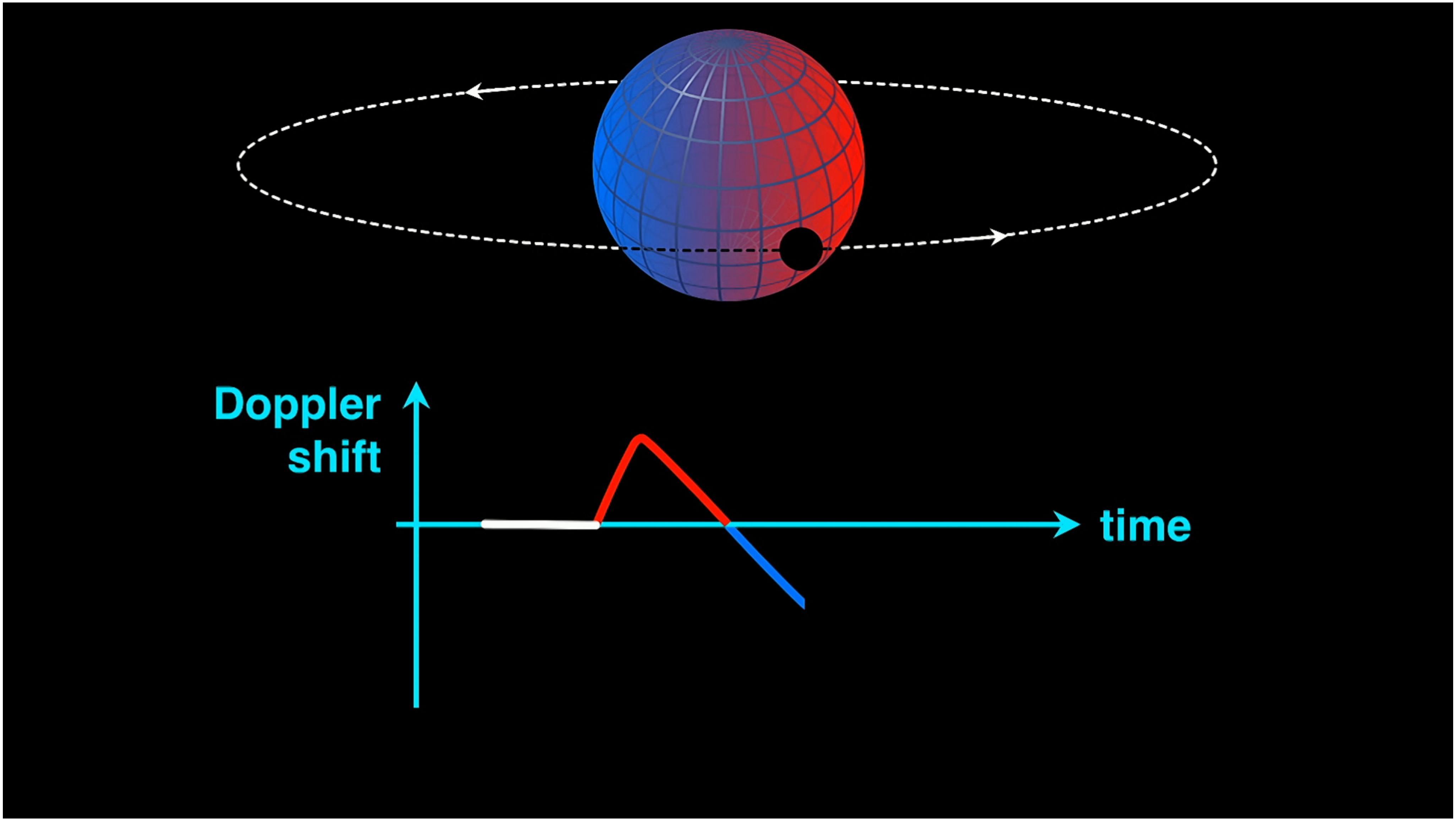


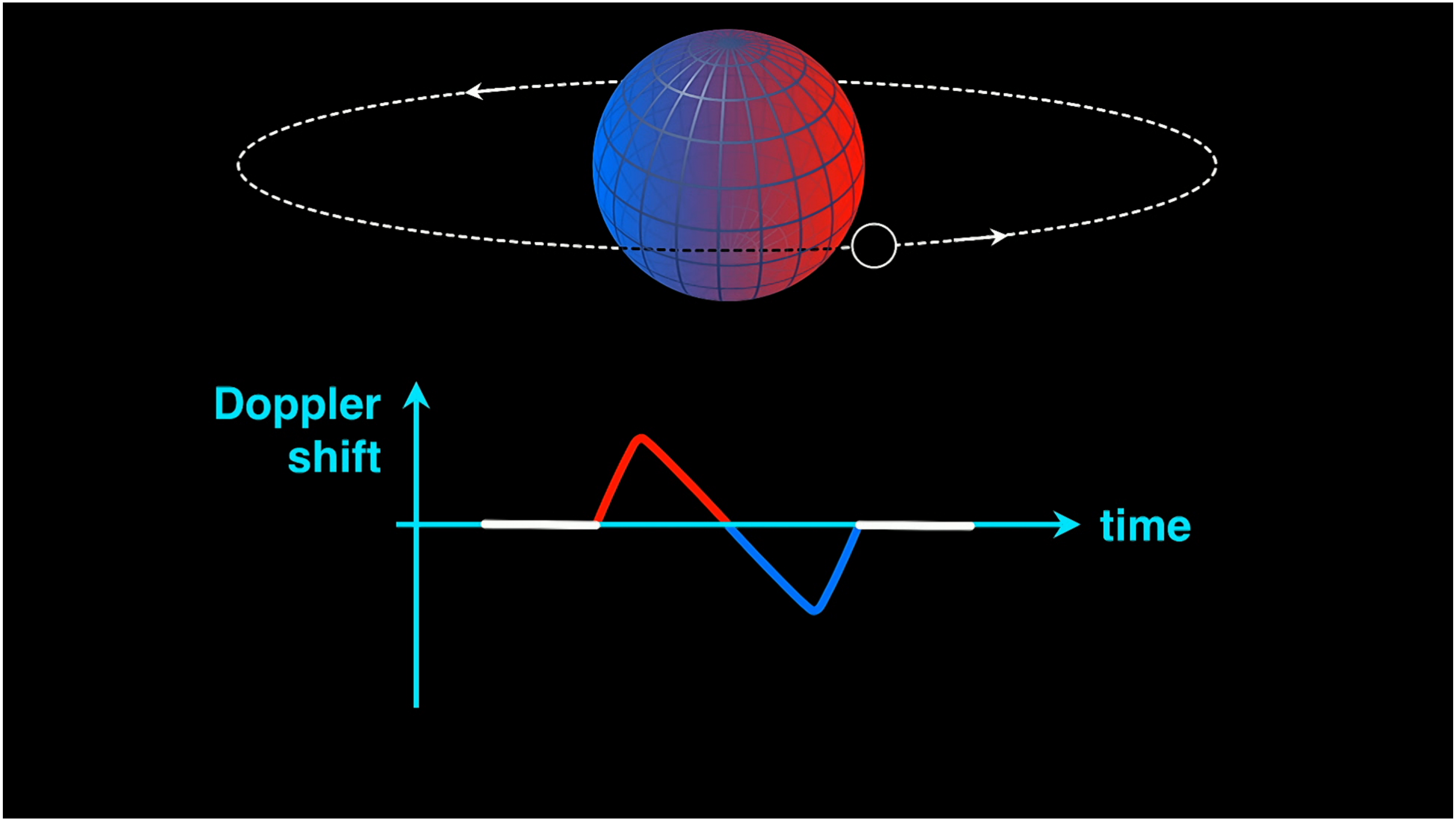
Dai, Winn, & Masuda (2018)

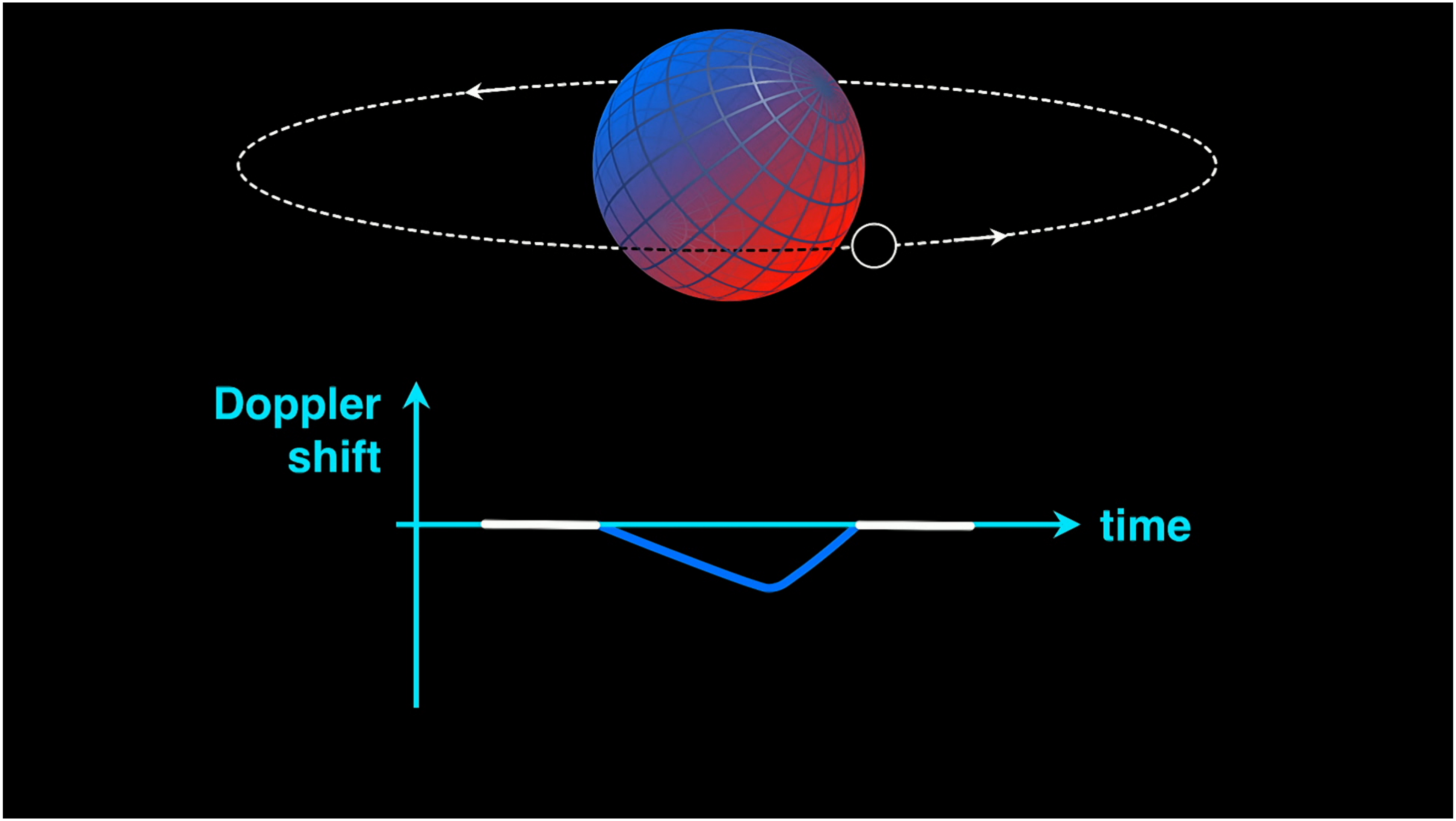

flux
time

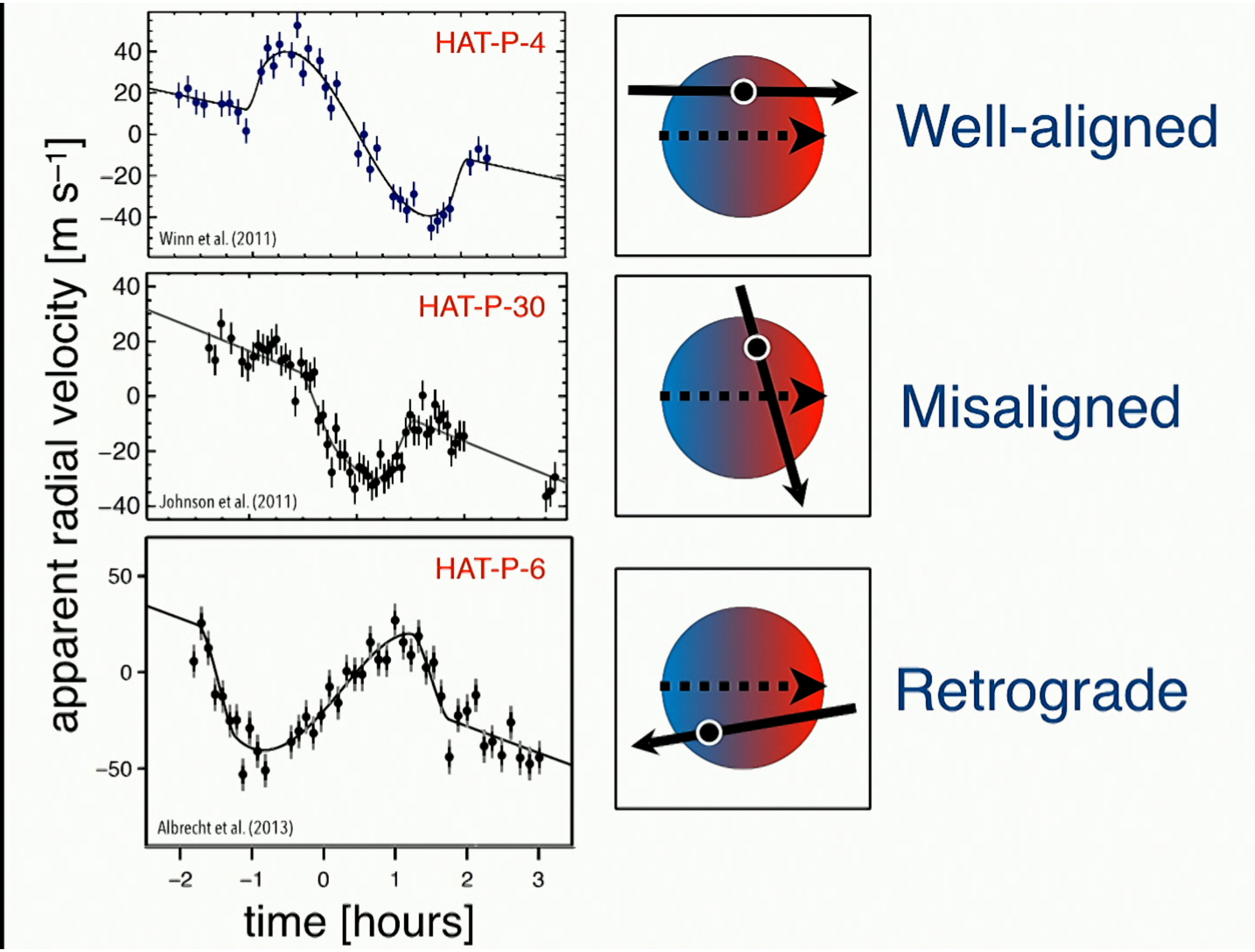

Doppler
shift
time


Doppler
shift
time

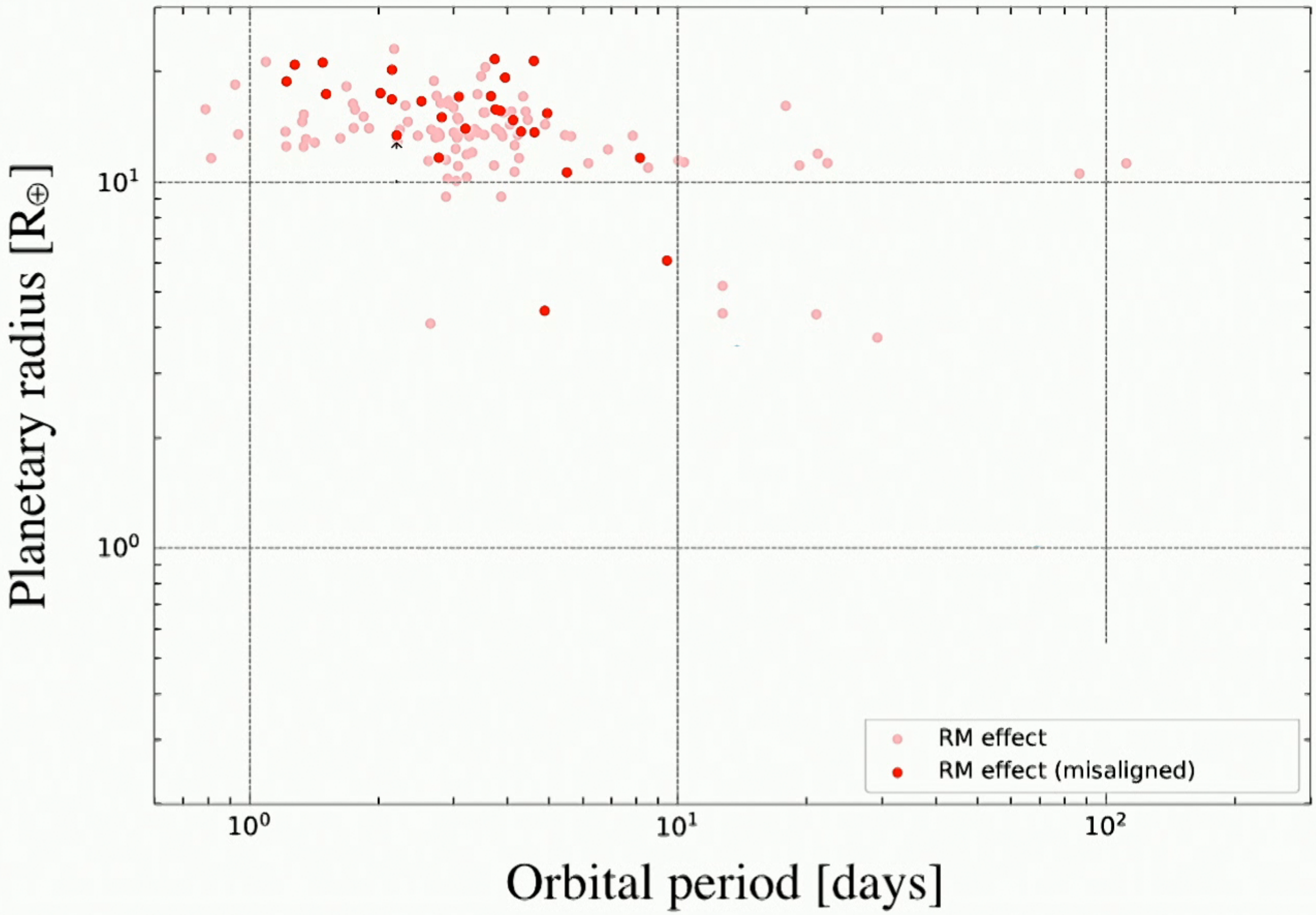

Doppler shift
time


Doppler
shift
time

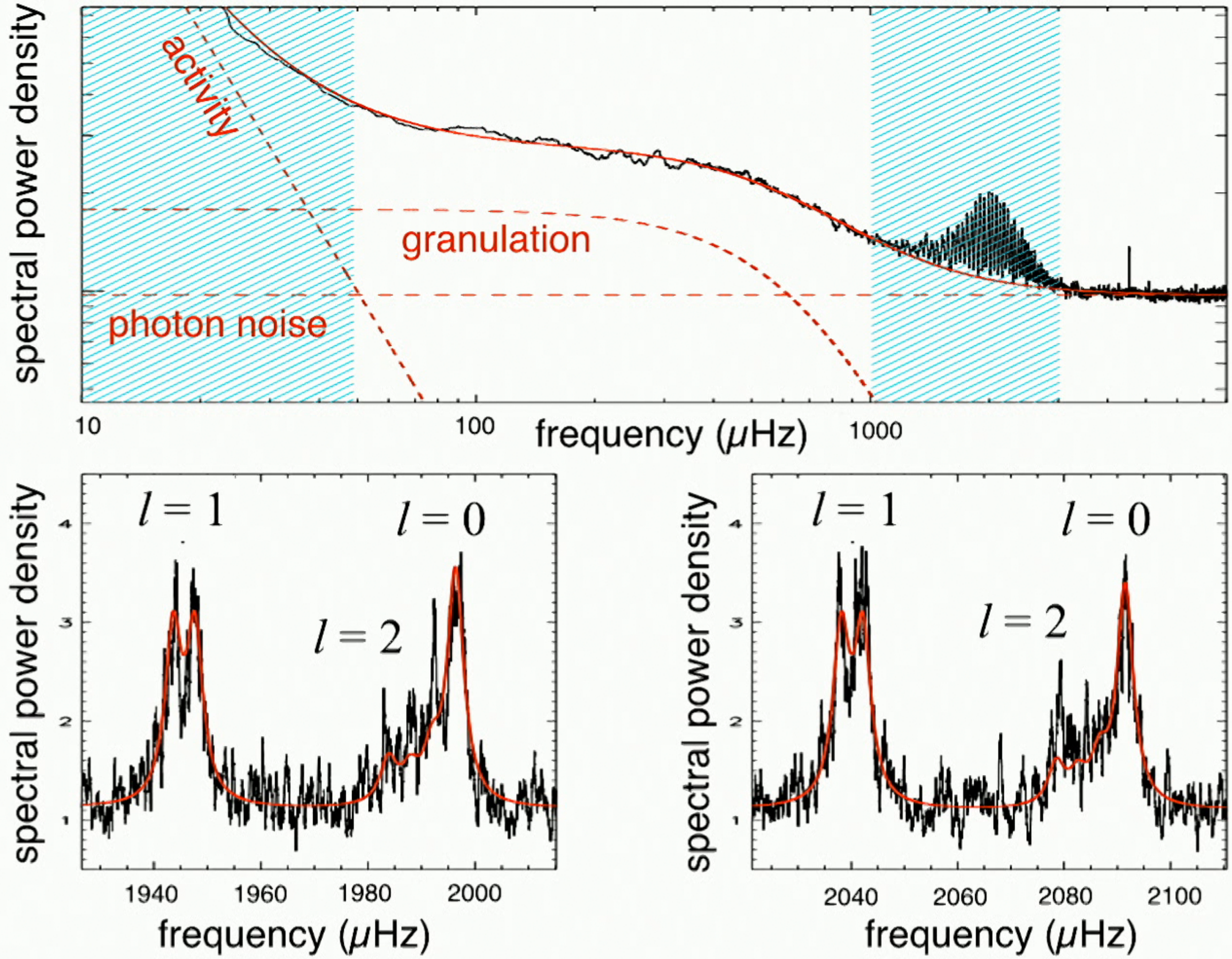

Doppler
shift
time



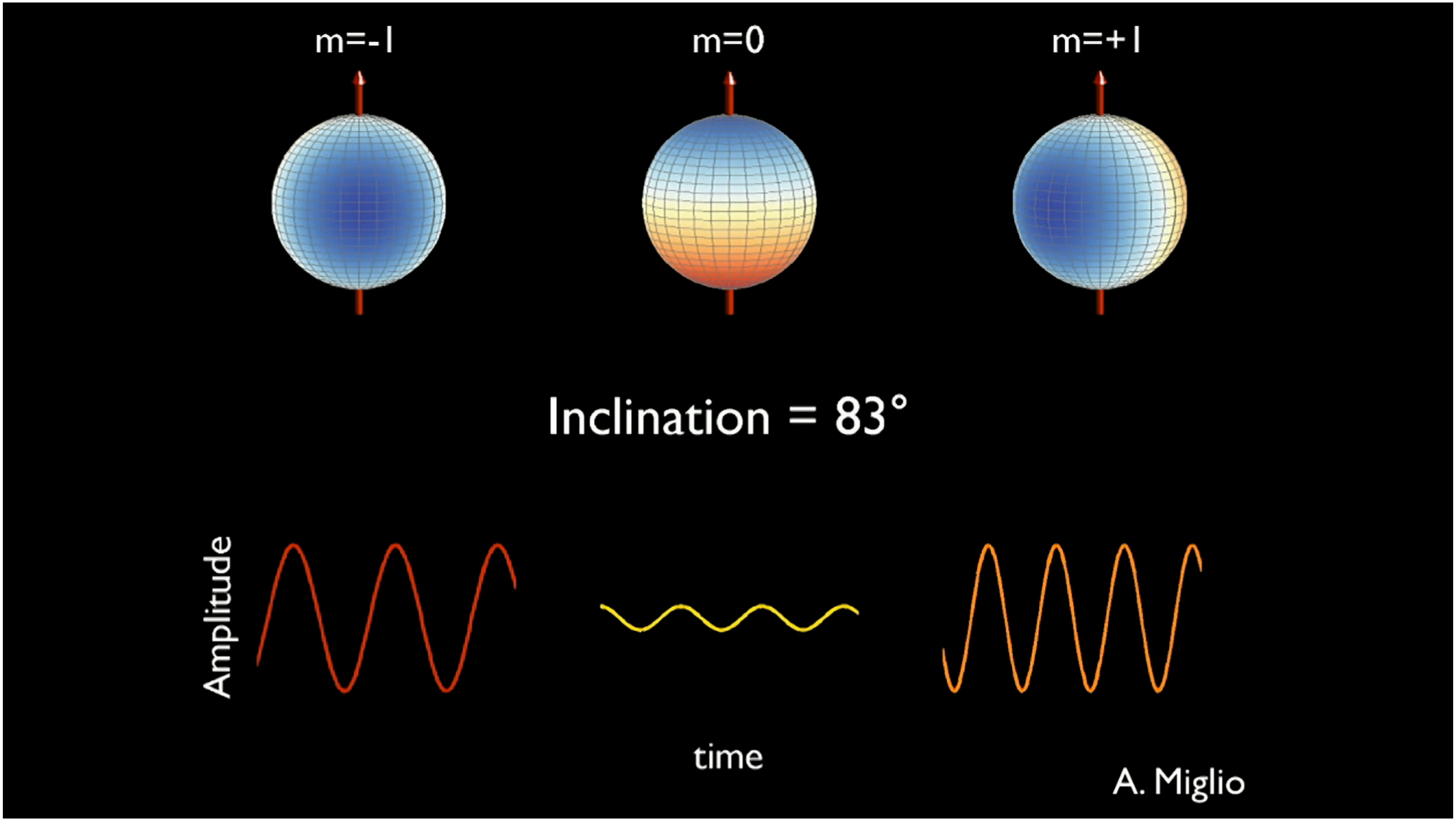
apparent radial velocity [m s⁻¹]
HAT-P-4
Winn et al. (2011)
HAT-P-30
Johnson et al. (2011)
HAT-P-6
Albrecht et al. (2013)
time [hours]
Well-aligned
Misaligned
Retrograde

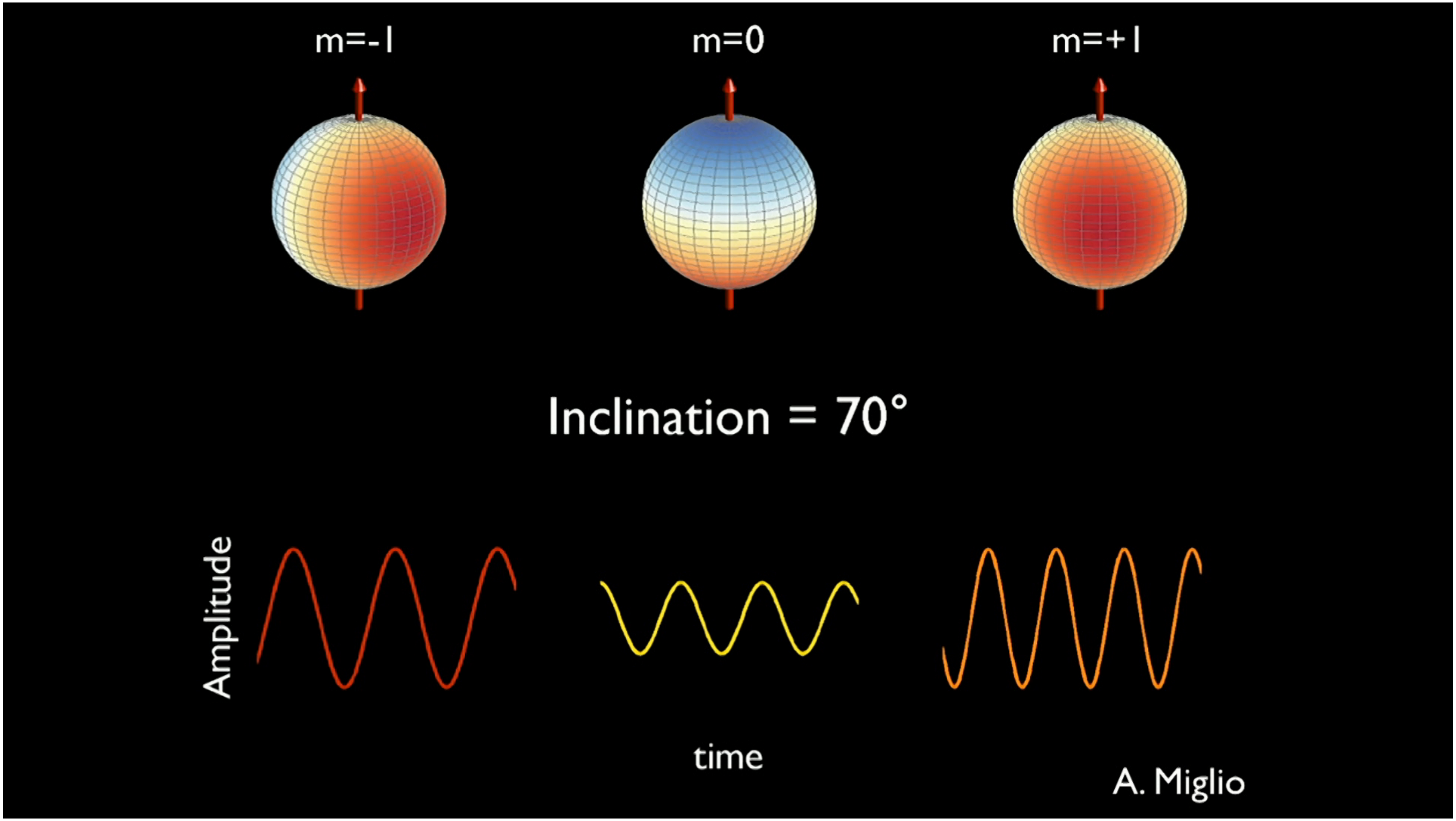


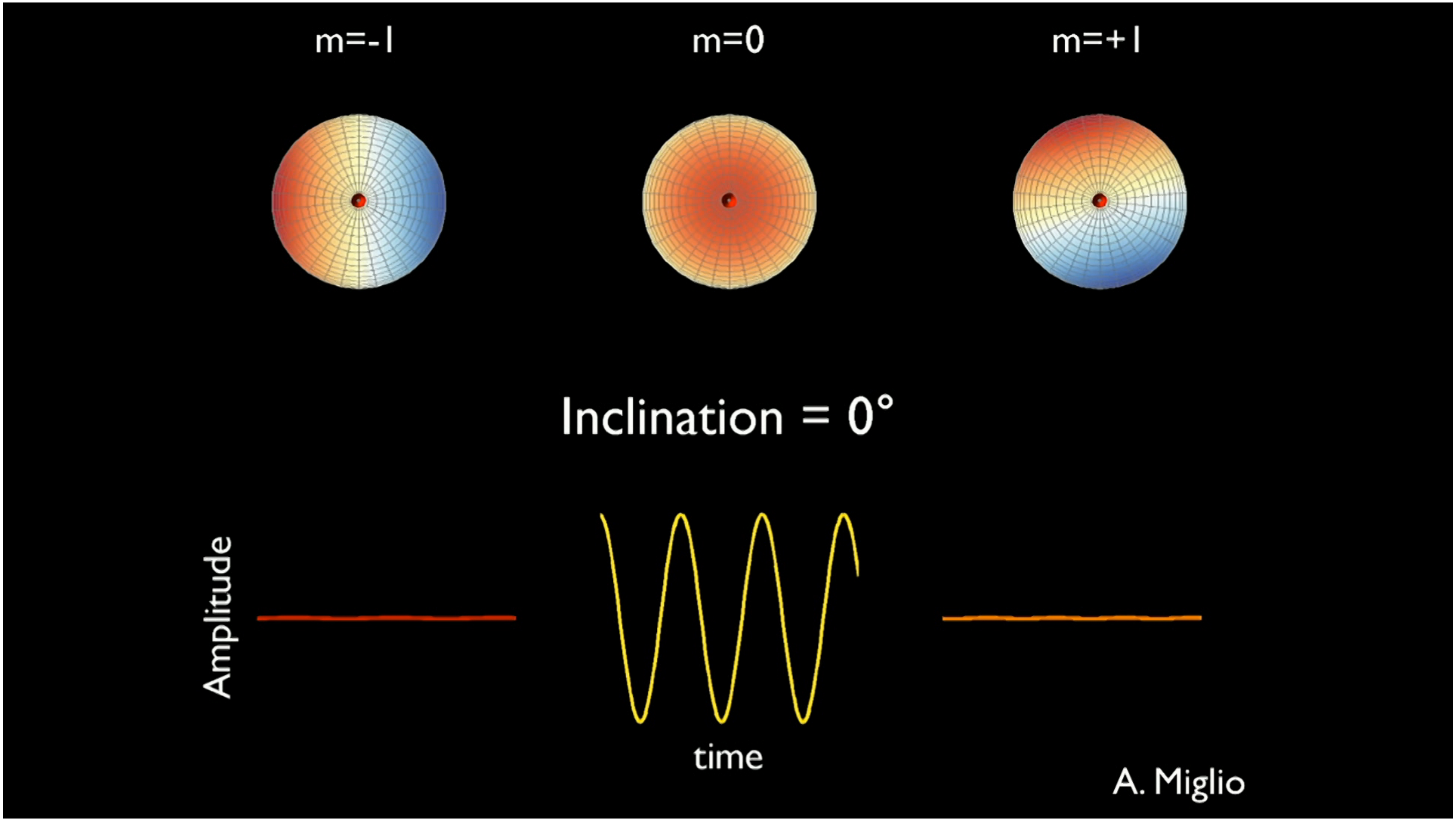
Kamiaka, Benomar, Suto, et al., submitted

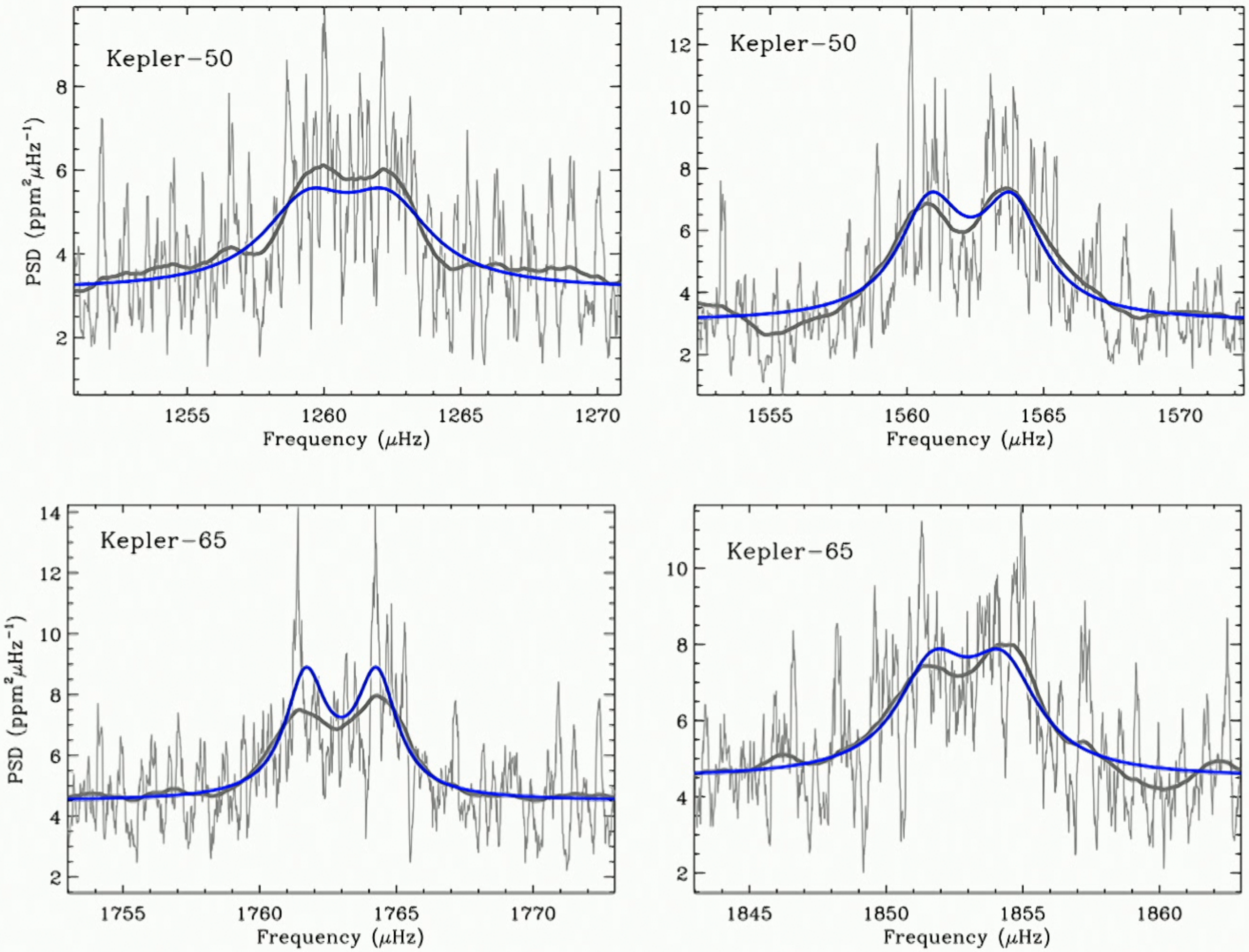


Campante, Lund, Kuszlewicz, et al. (2016)

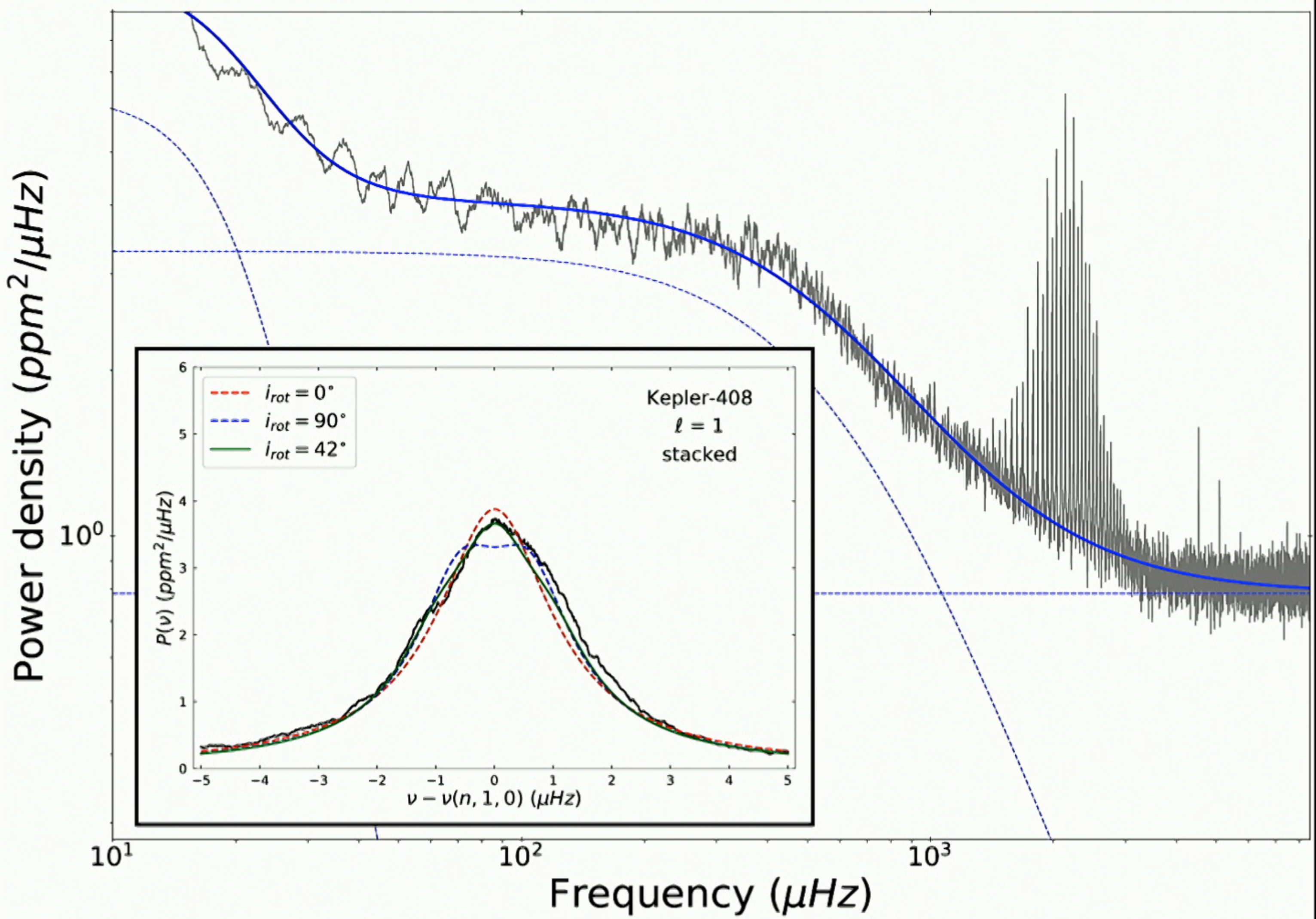

m=-1
m=0
m=+1
Inclination = 83°
Amplitude
time
A. Miglio


m=-1
m=0
m=+1
Inclination = 70°
Amplitude
time
A. Miglio

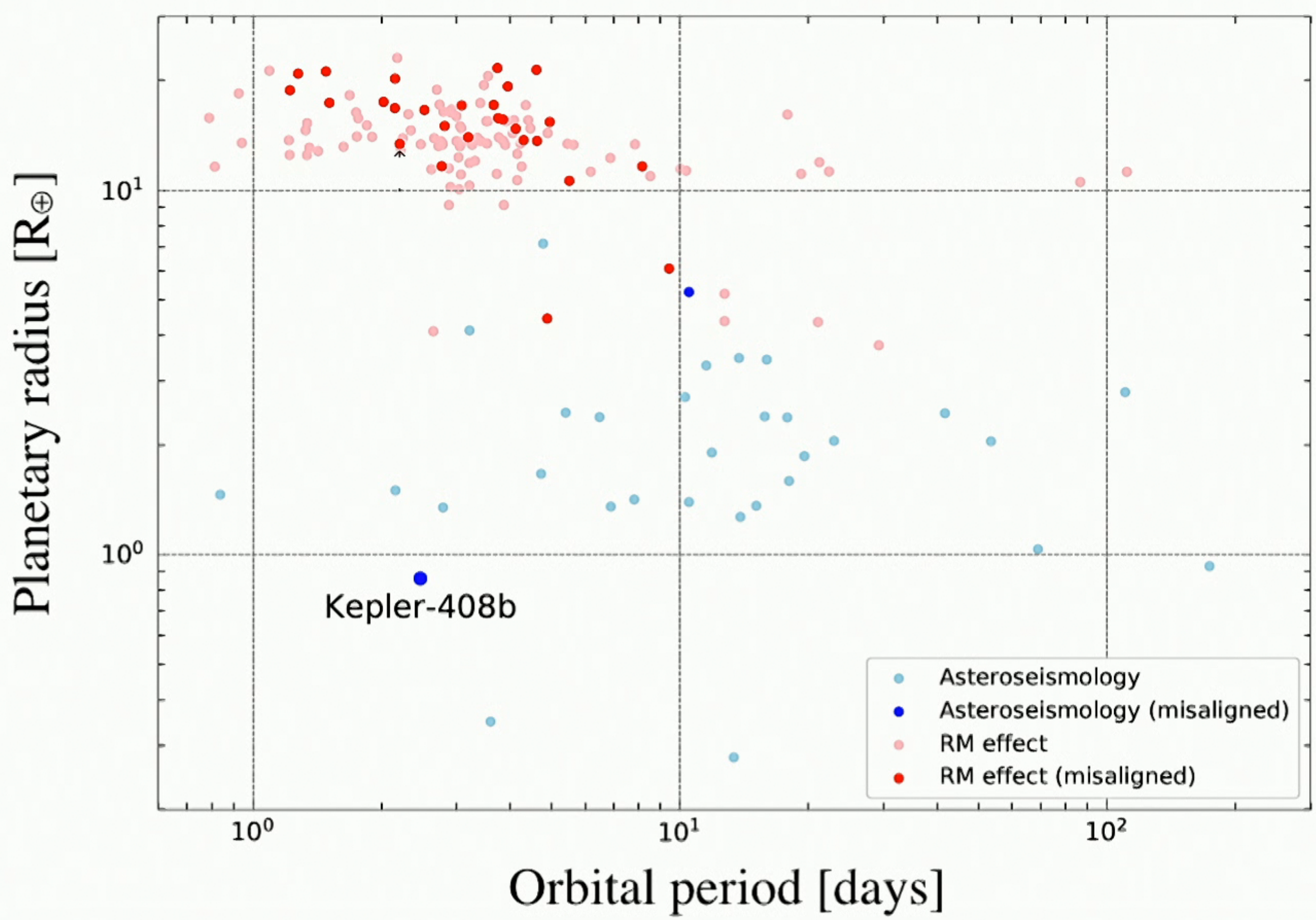

m=-1
m=0
m=+1
Inclination = 0°
Amplitude
time
A. Miglio



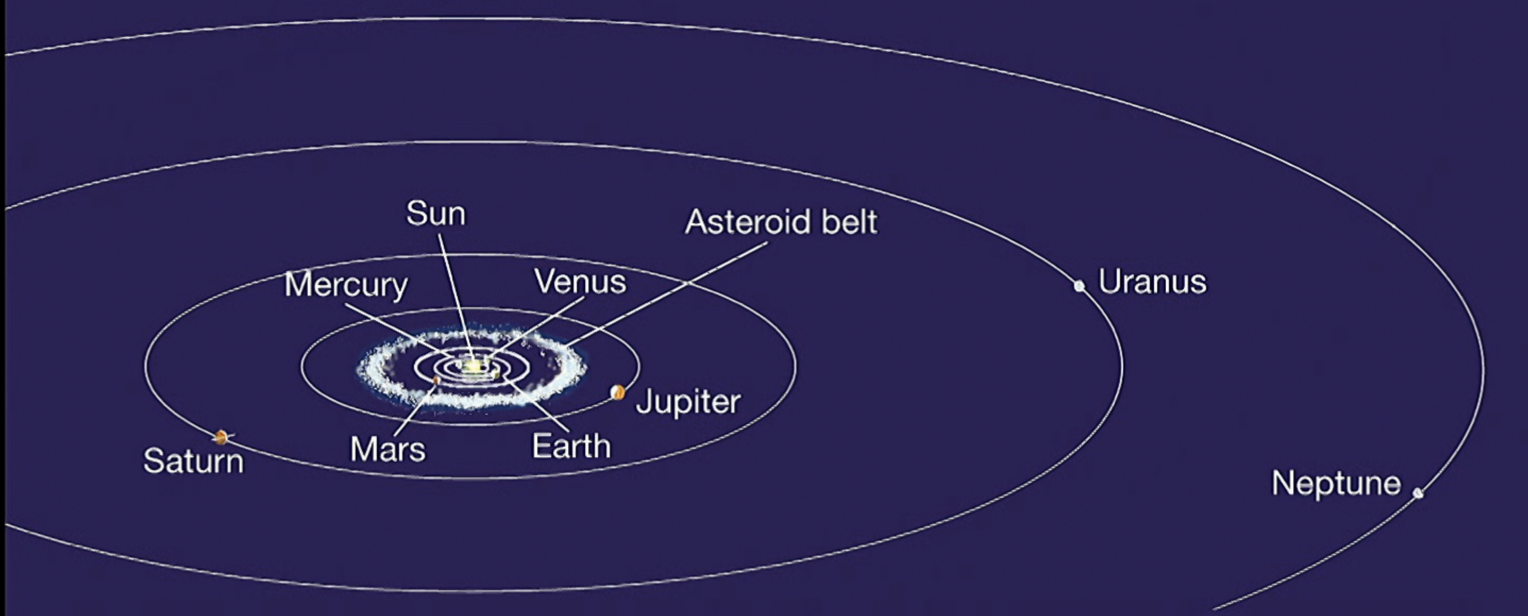
Chaplin, Sanchis-Ojeda, Campante, et al. (2013)



Kamiaka, Benomar, Suto, et al., submitted



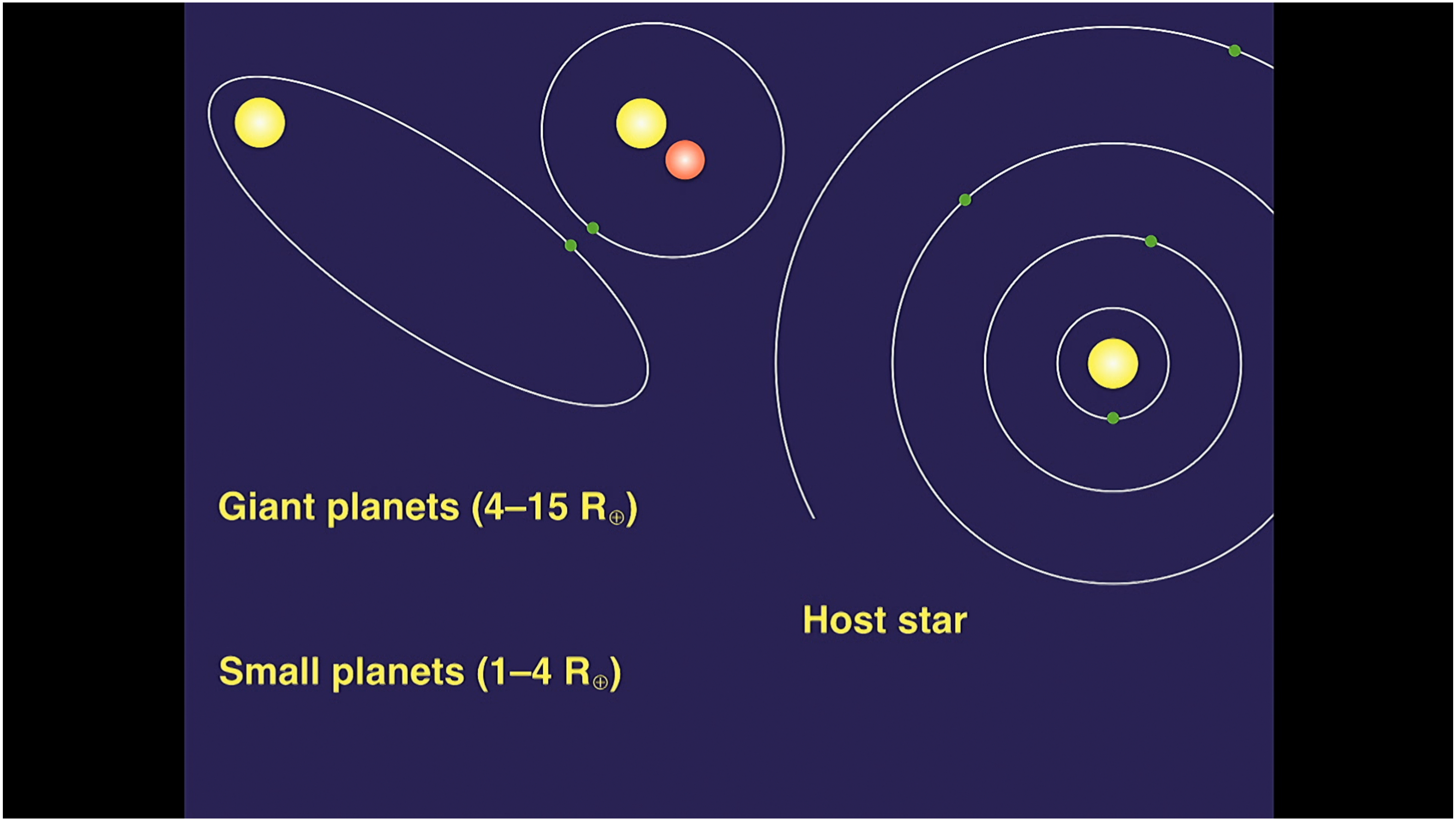
Kamiaka, Benomar, Suto, et al., submitted



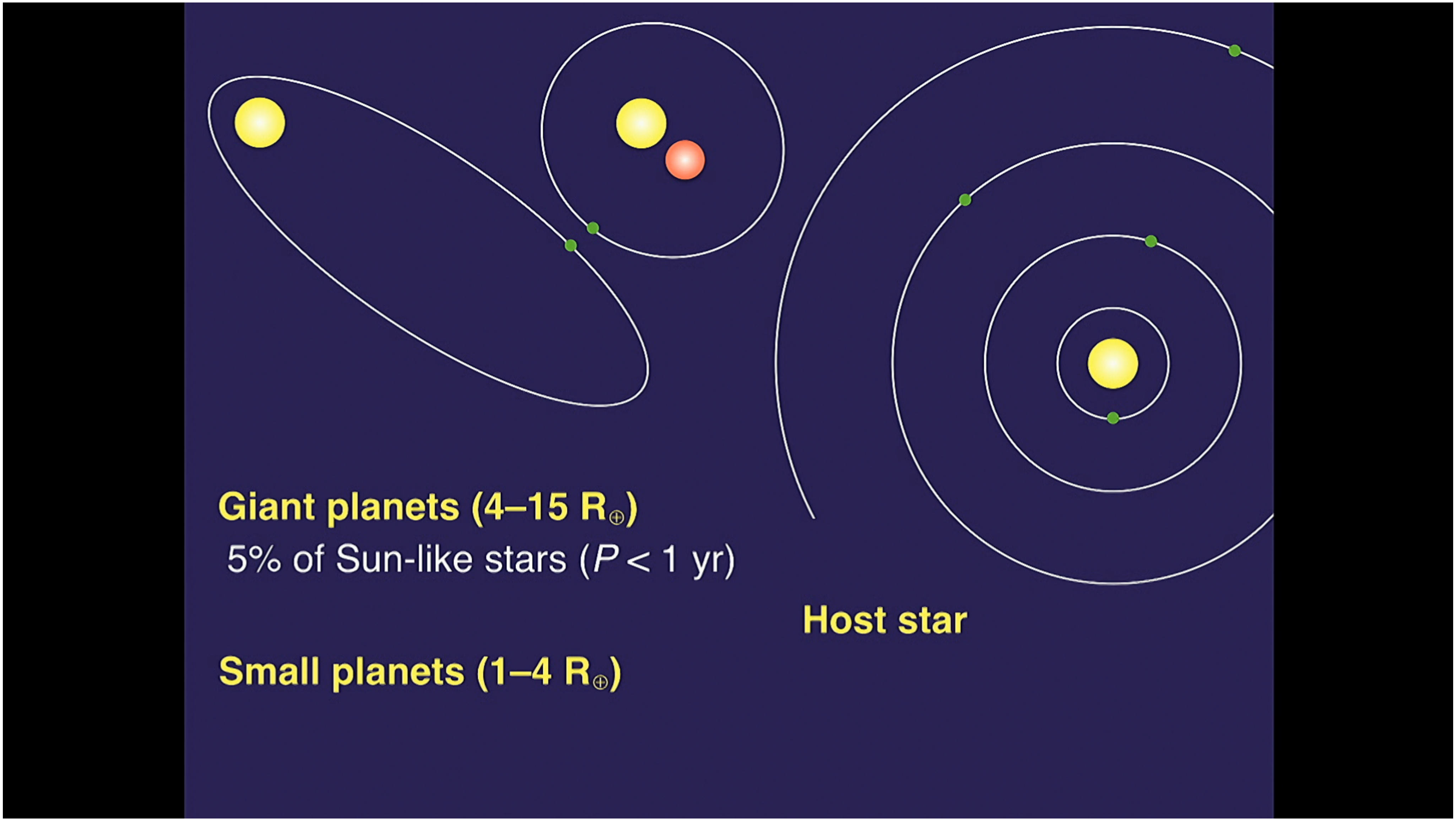
orbits are circular

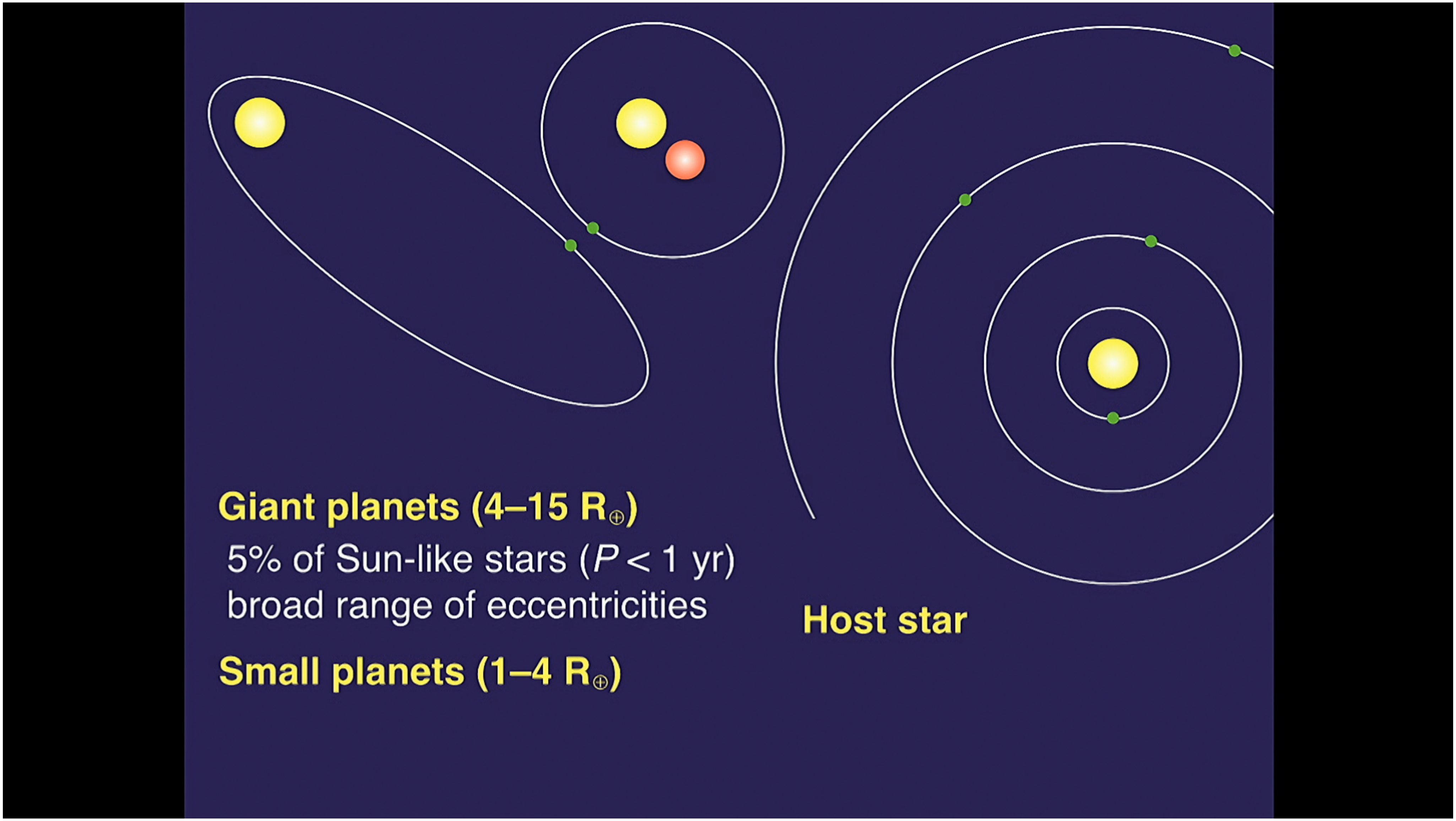
orbits are aligned with each other, and the Sun

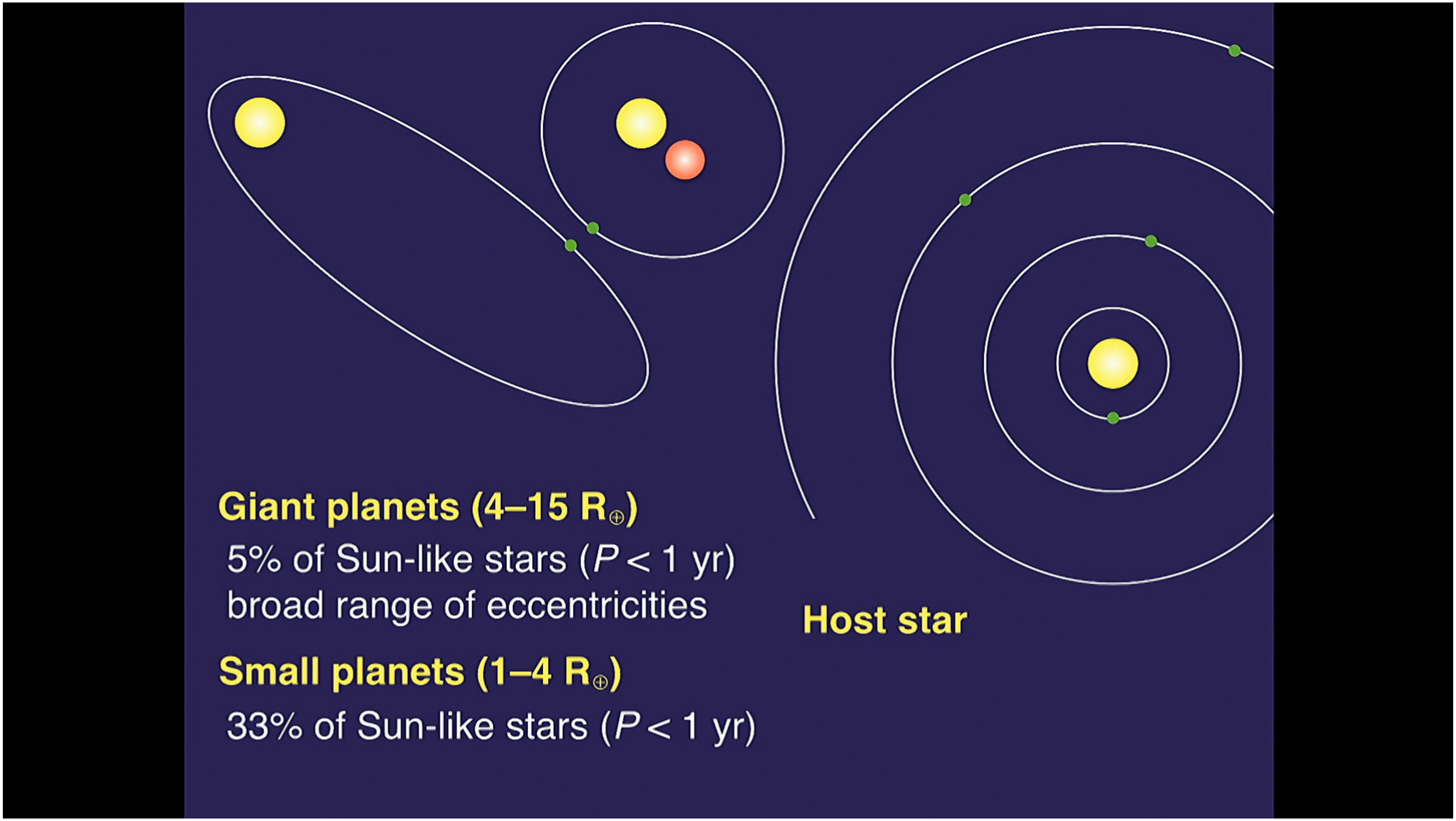
rocky planets 0.3 – 3 AU, giant planets 3 – 30 AU



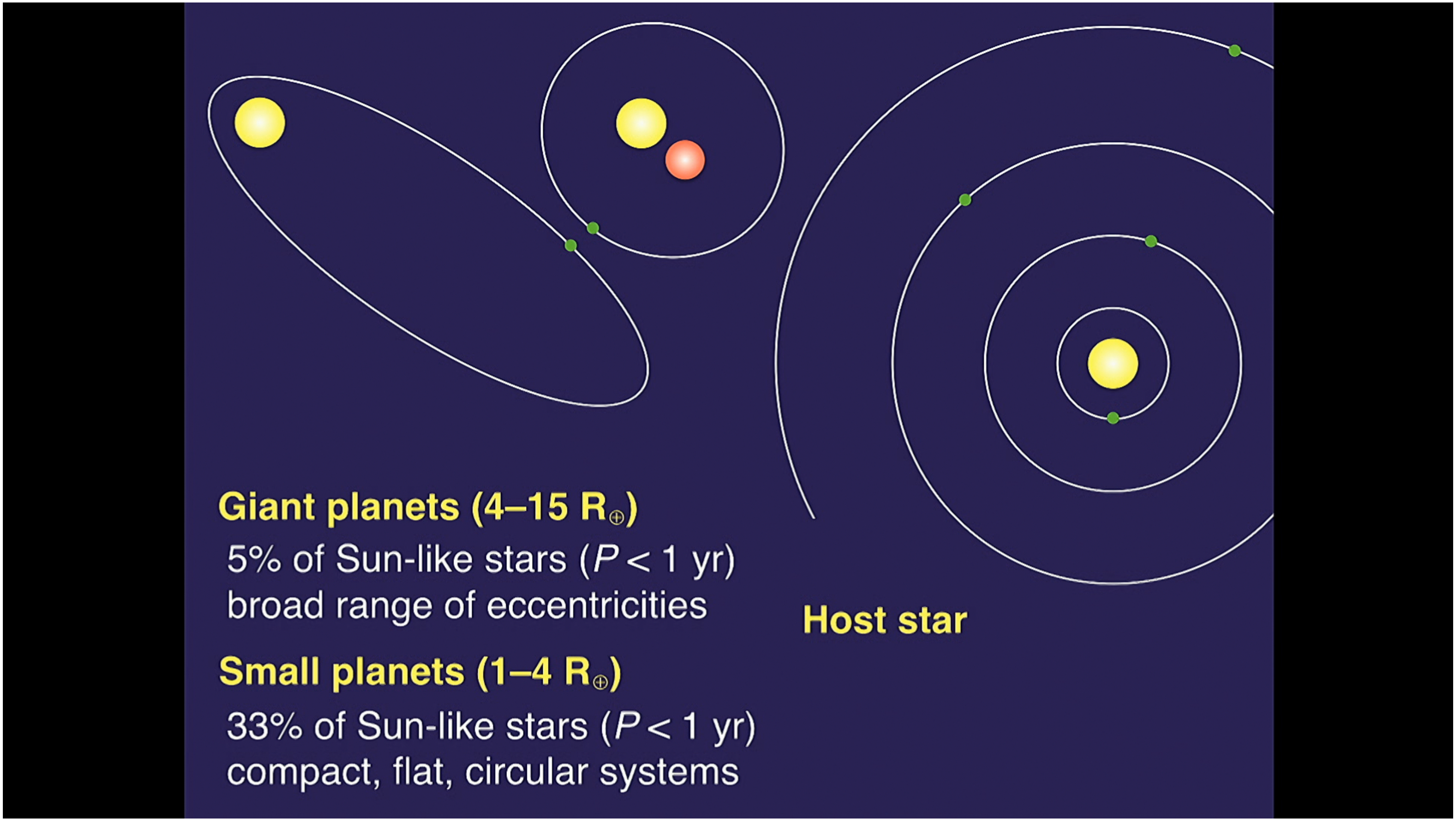
Giant planets (4–15 R⊕)
Host star
Small planets (1–4 R⊕)


Giant planets (4–15 R⊕)
5% of Sun-like stars (P < 1 yr)
Host star
Small planets (1–4 R⊕)

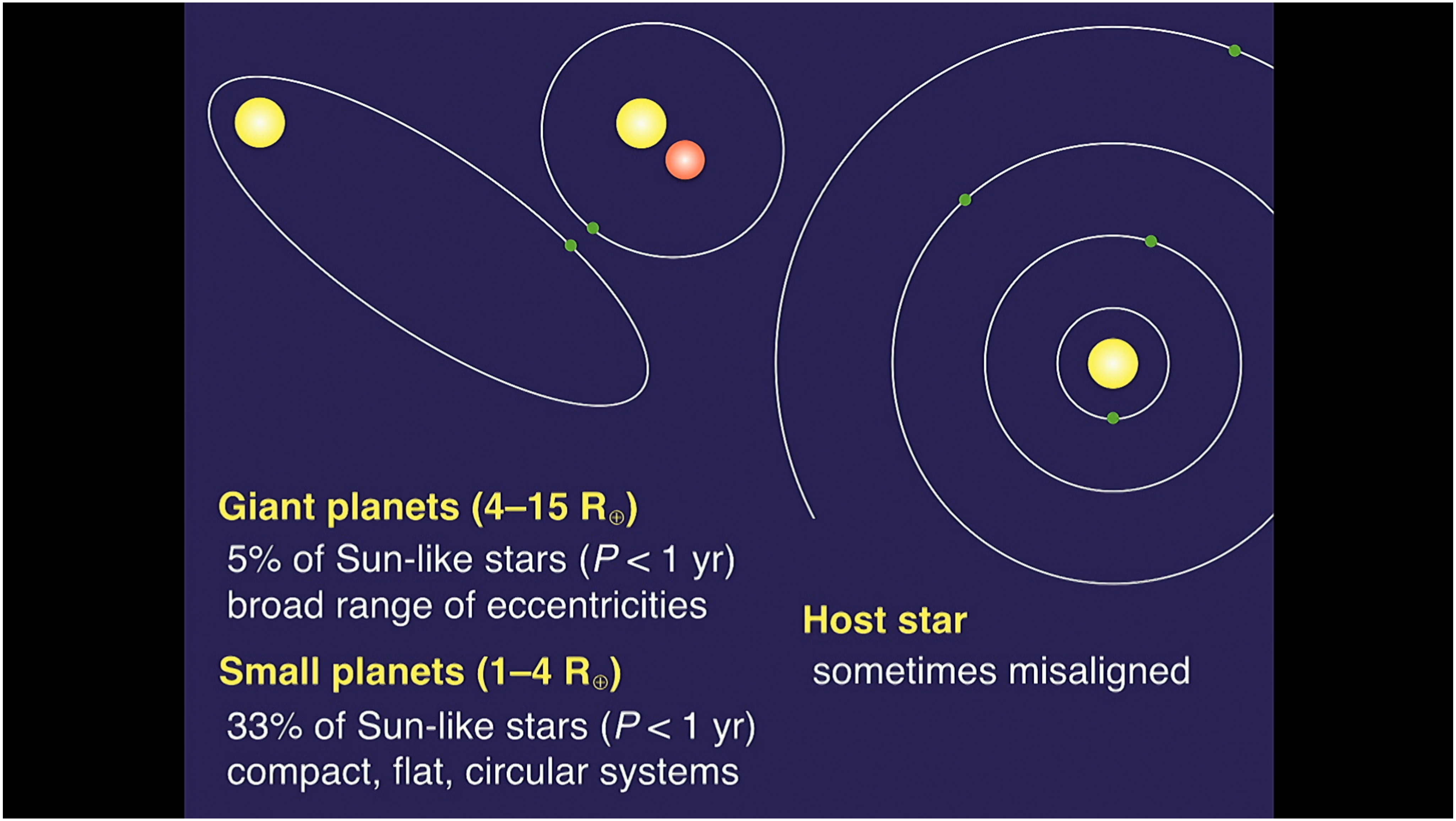

Giant planets (4–15 R⊕)
5% of Sun-like stars (P < 1 yr)
broad range of eccentricities
Host star
Small planets (1–4 R⊕)

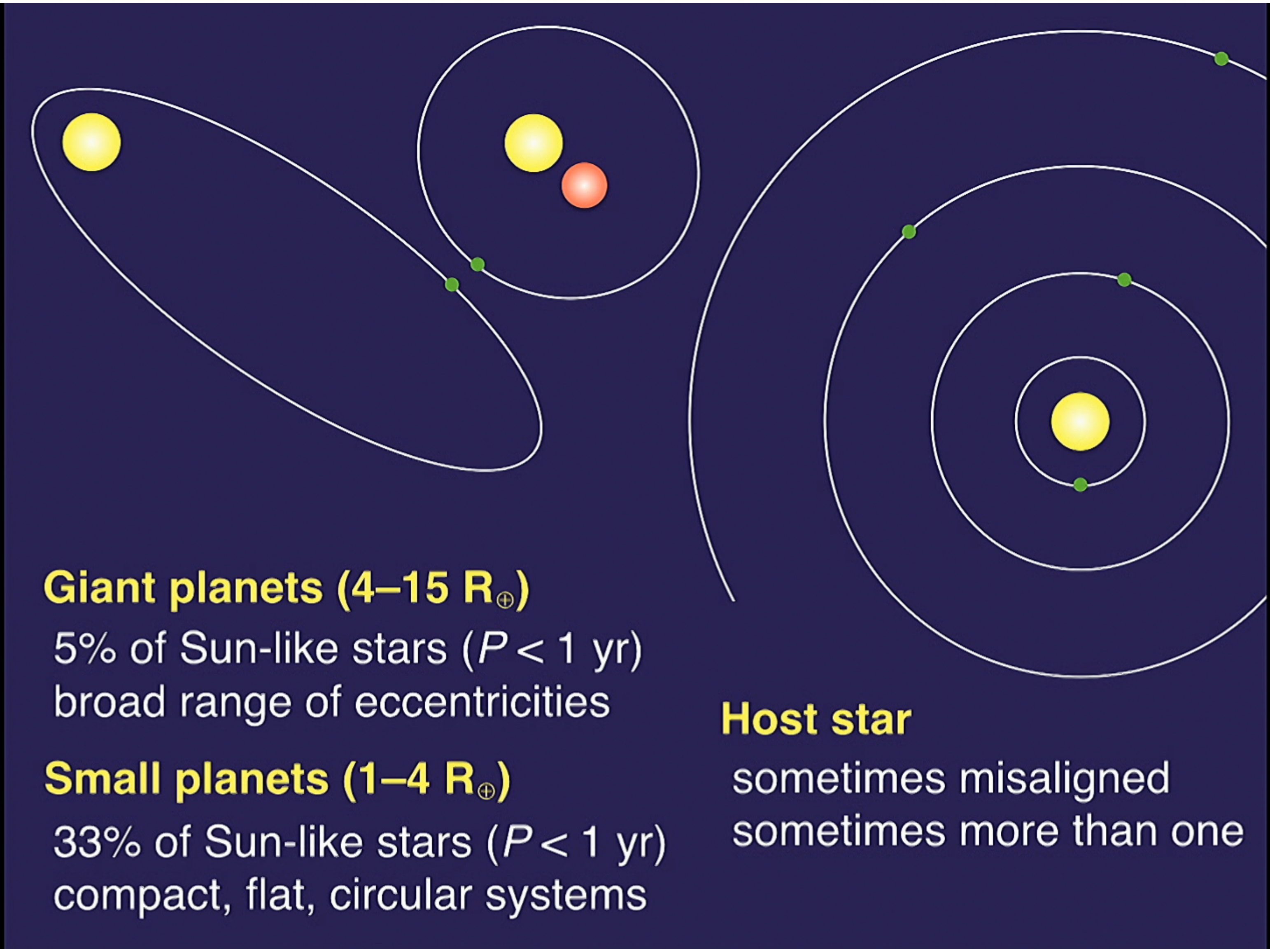


Giant planets (4–15 R⊕)
5% of Sun-like stars (P < 1 yr)
broad range of eccentricities
Small planets (1–4 R⊕)
33% of Sun-like stars (P < 1 yr)
Host star

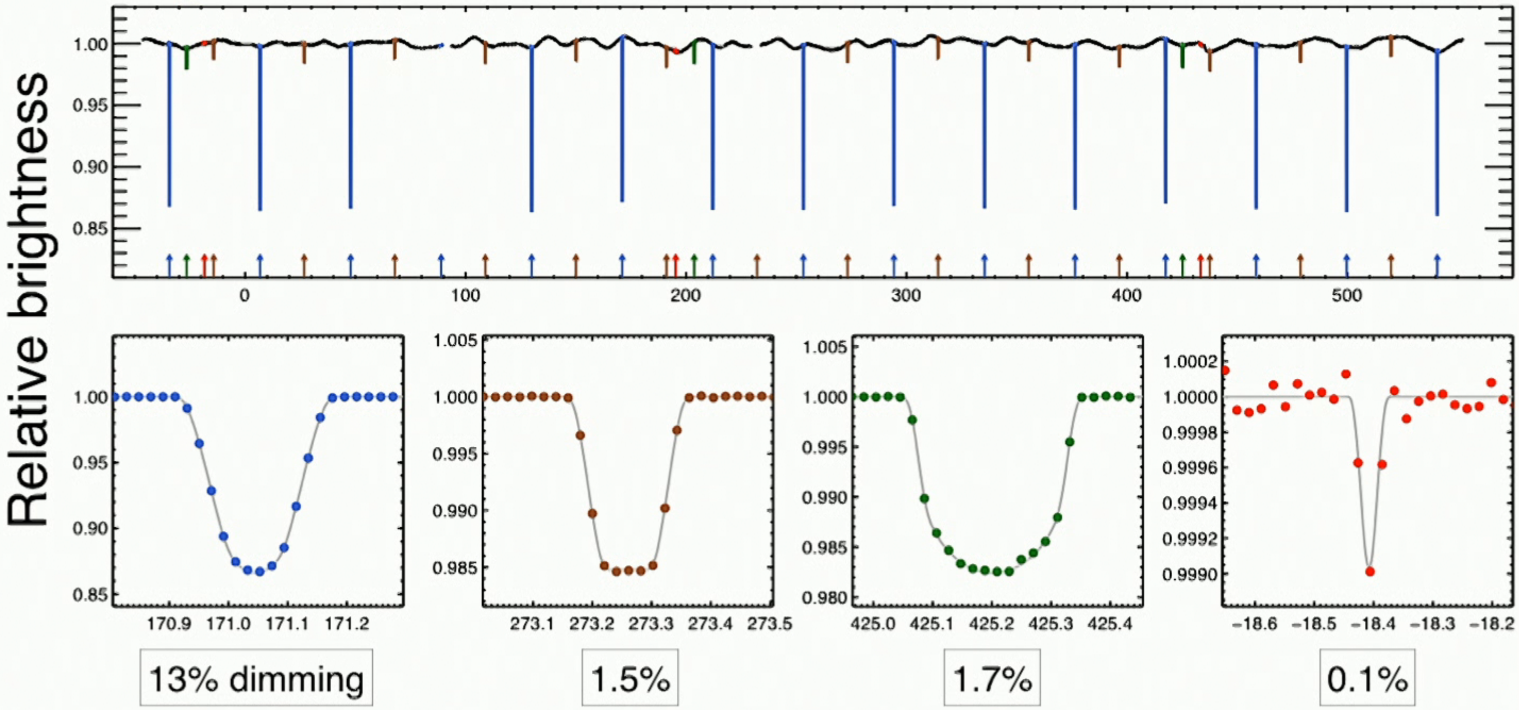


Giant planets (4–15 R⊕)
5% of Sun-like stars (P < 1 yr)
broad range of eccentricities
Host star
Small planets (1–4 R⊕)
33% of Sun-like stars (P < 1 yr)
compact, flat, circular systems

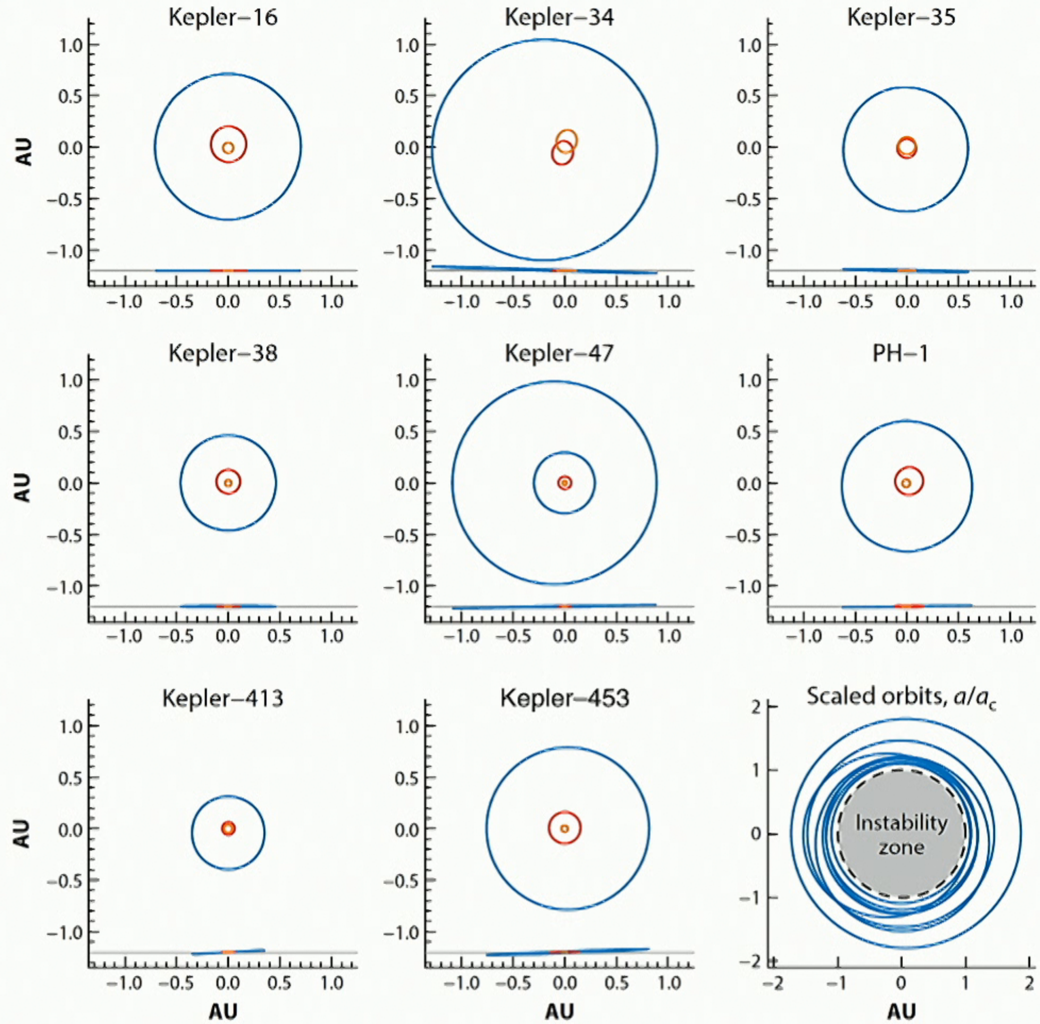

Giant planets (4–15 R⊕)
5% of Sun-like stars (P < 1 yr)
broad range of eccentricities
Small planets (1–4 R⊕)
33% of Sun-like stars (P < 1 yr)
compact, flat, circular systems
Host star
sometimes misaligned


Giant planets (4–15 R⊕)
5% of Sun-like stars (P < 1 yr)
broad range of eccentricities
Small planets (1–4 R⊕)
33% of Sun-like stars (P < 1 yr)
compact, flat, circular systems
Host star
sometimes misaligned
sometimes more than one

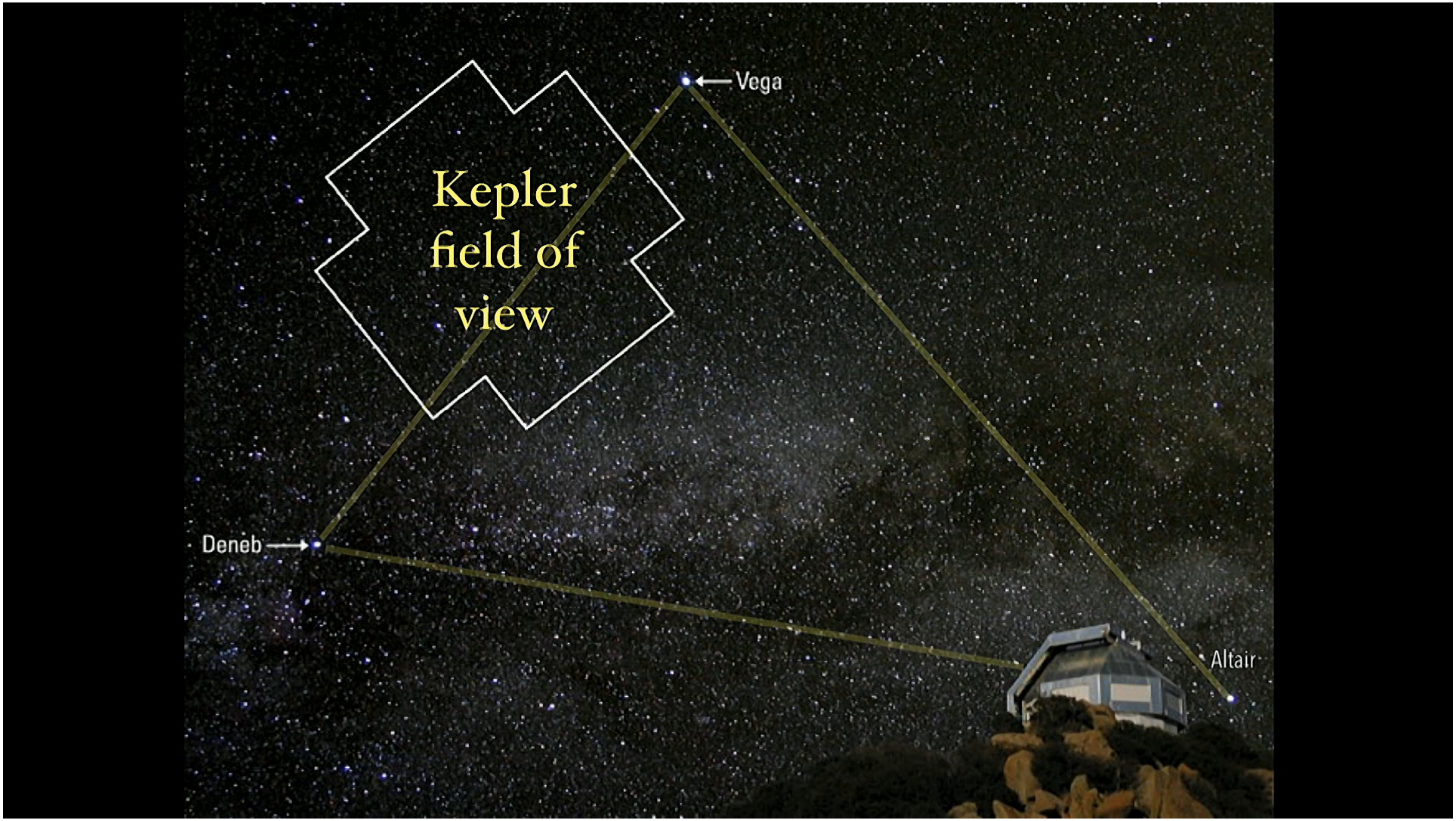
Kepler-16

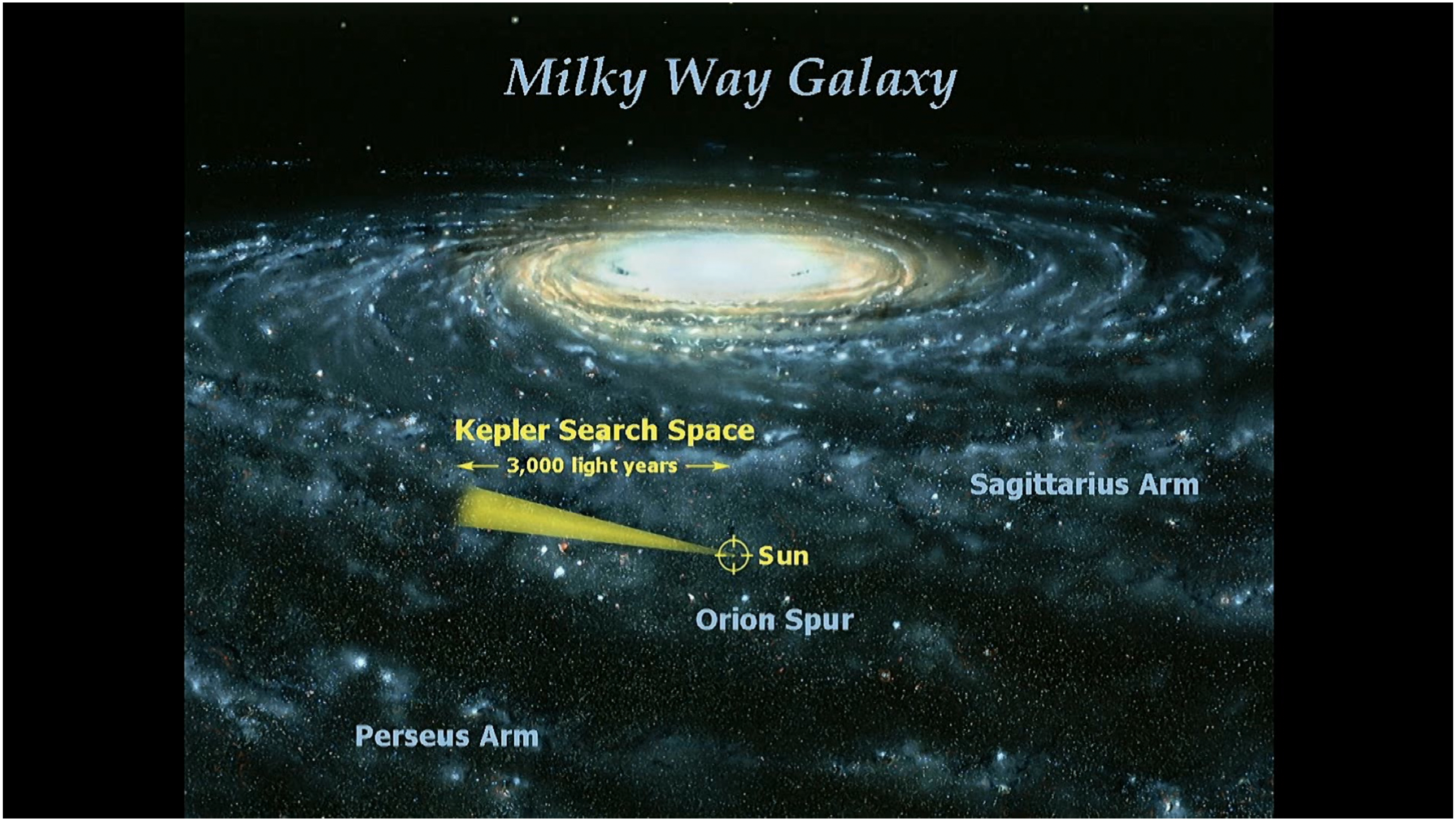


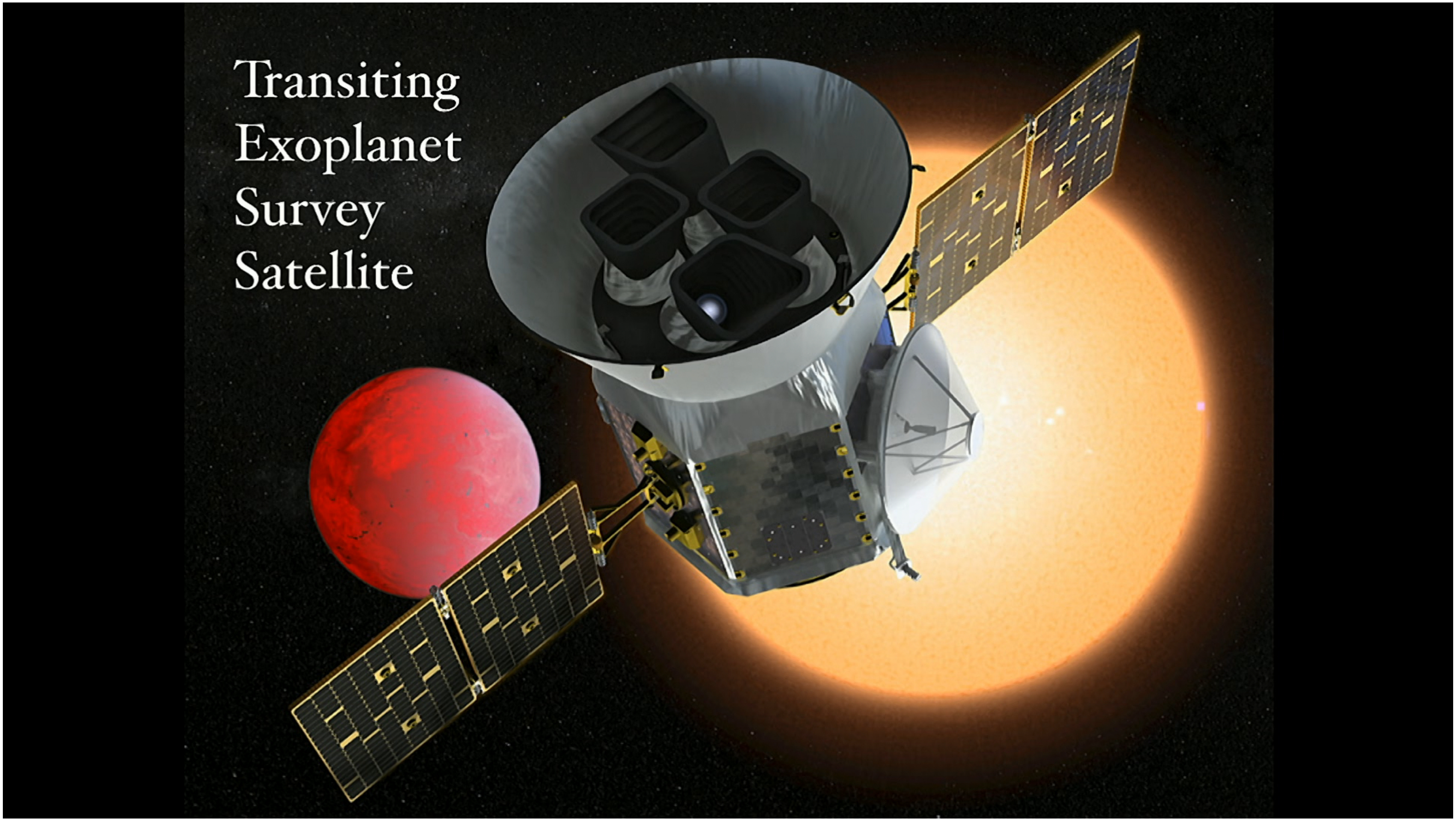
Doyle, Carter, Fabrycky, et al. (2011)



Winn & Fabrycky (2015)


Kepler field of view
Vega
Deneb
Altair


Milky Way Galaxy
Kepler Search Space
3,000 light years
Sagittarius Arm
Sun
Orion Spur
Perseus Arm


Transiting
Exoplanet
Survey
Satellite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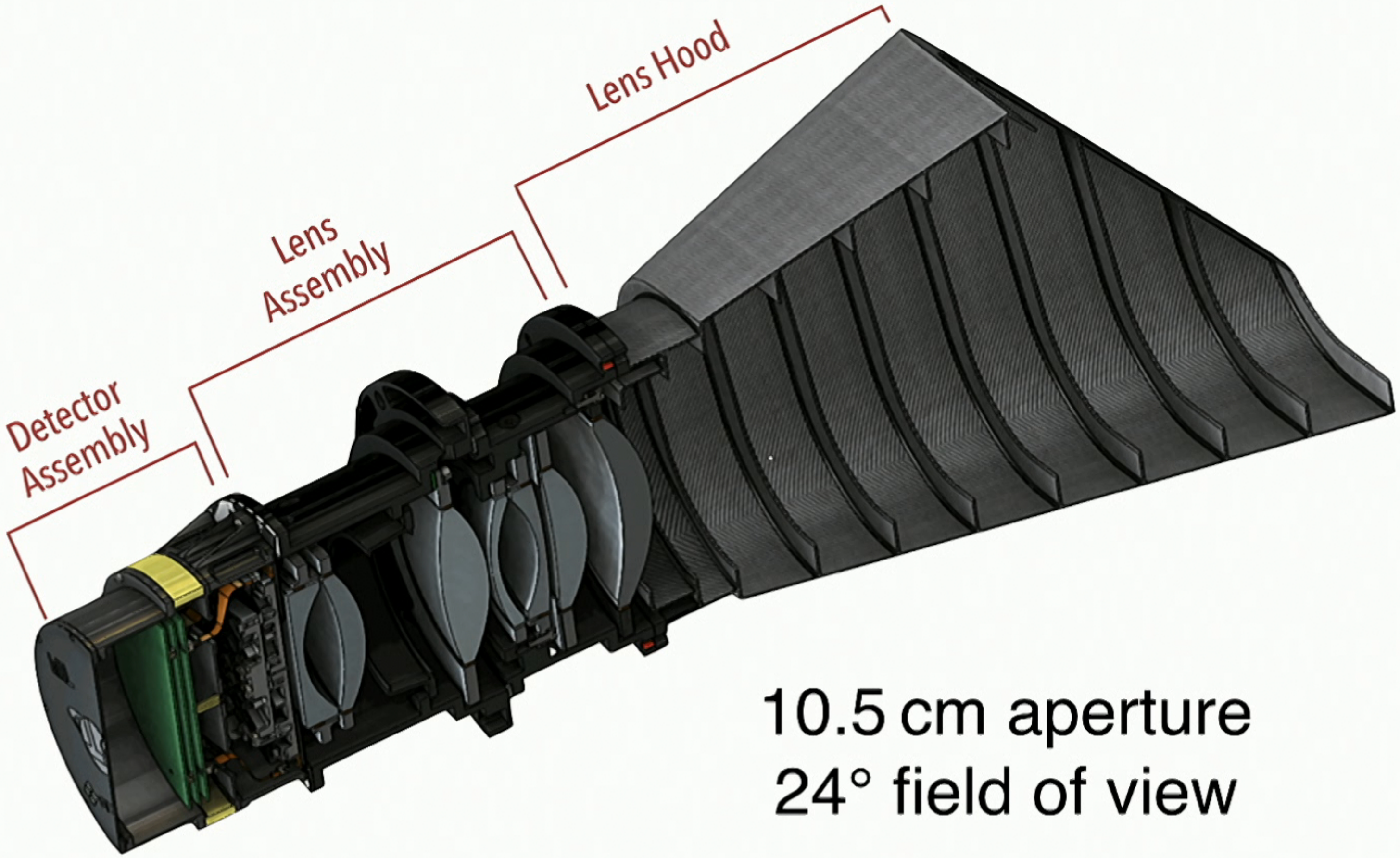
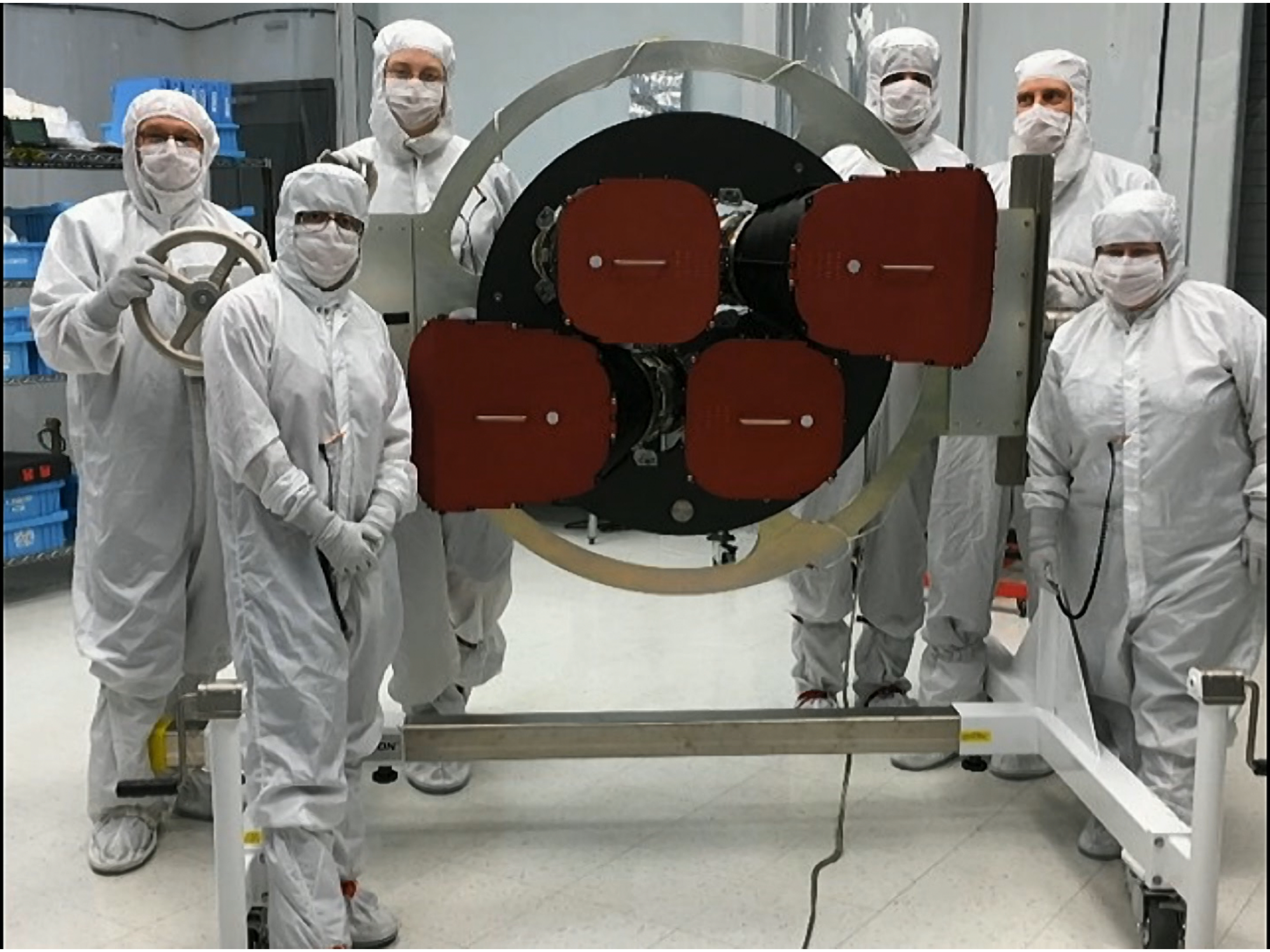
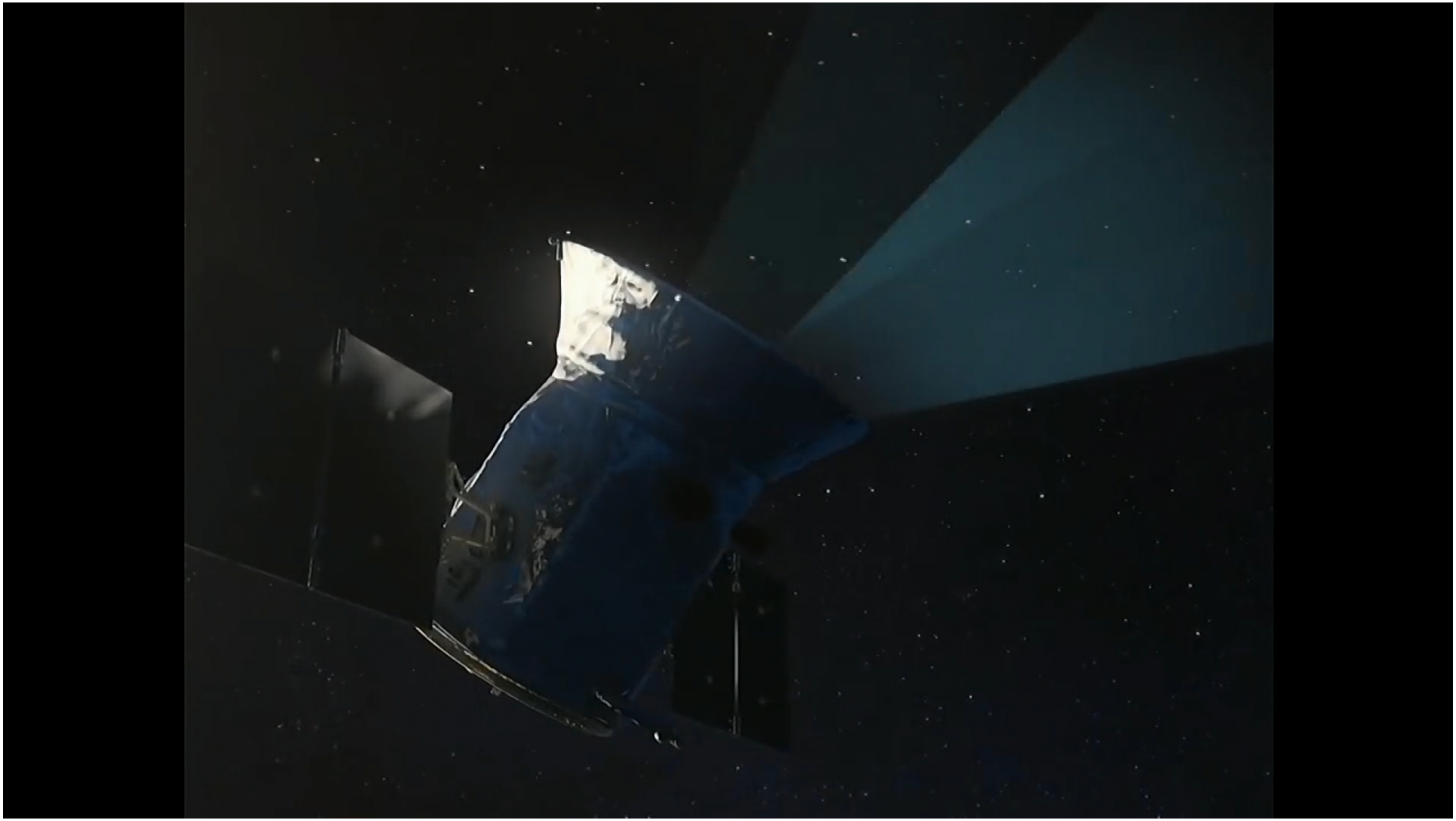
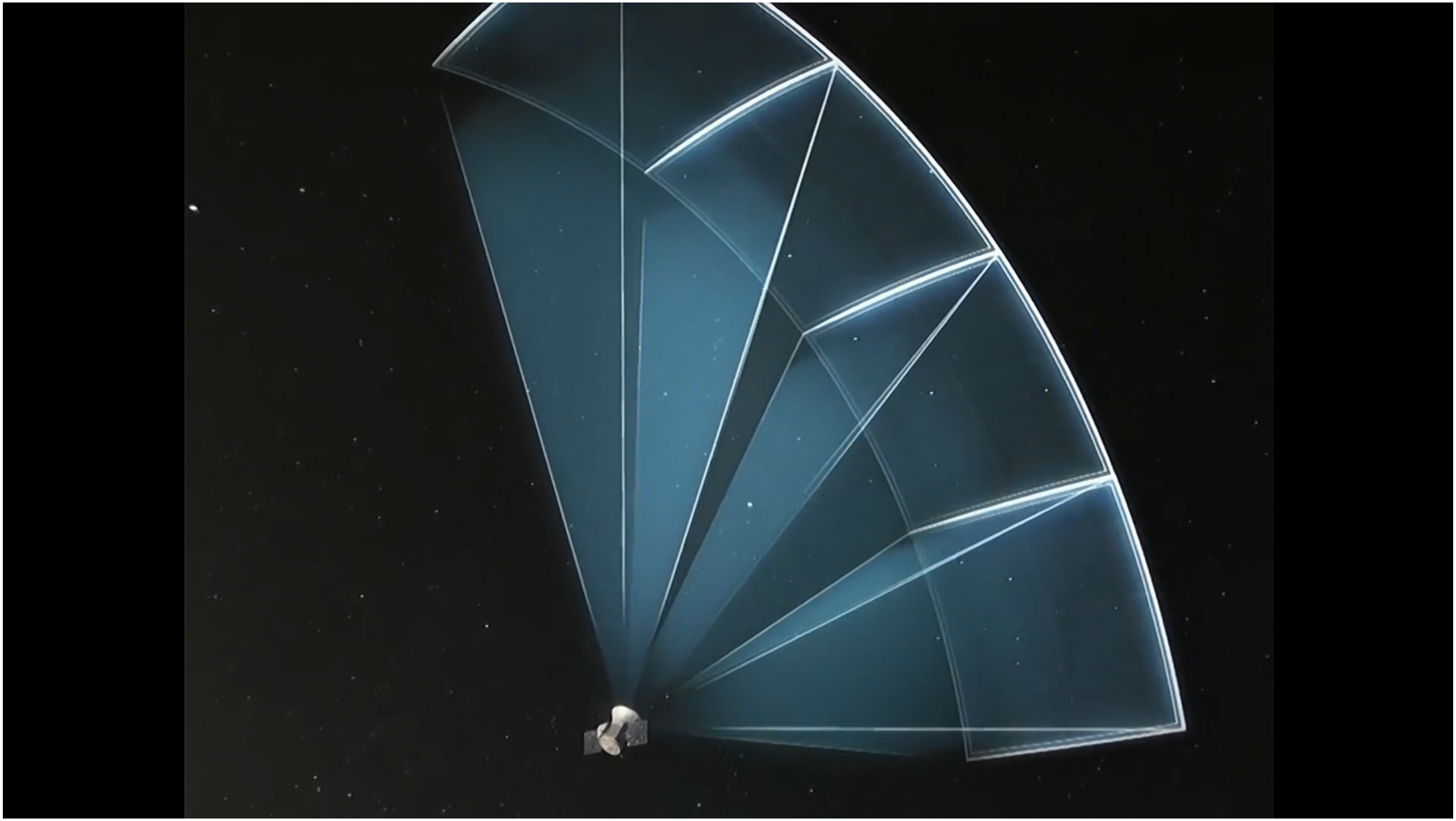


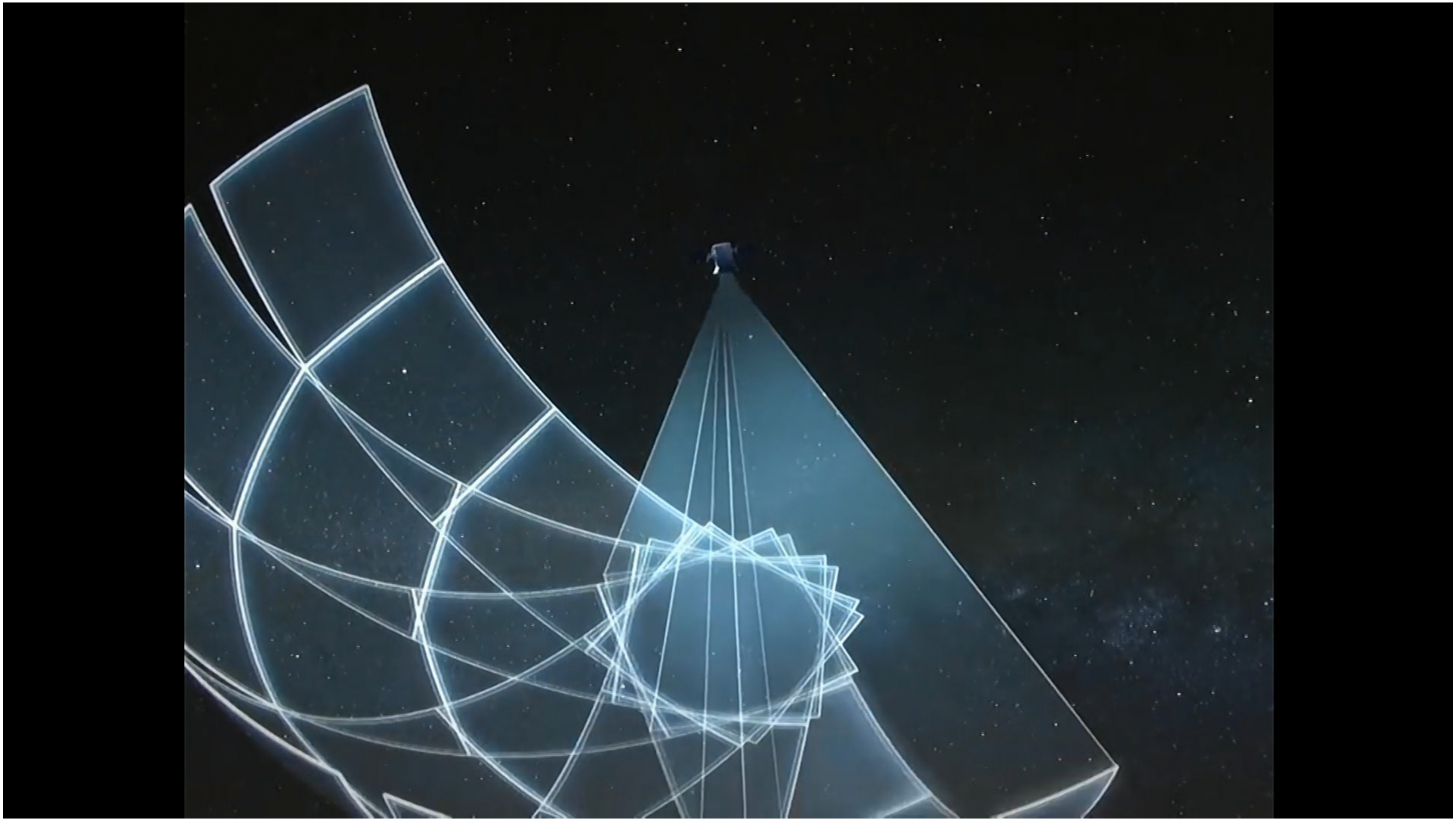
10.5 cm aperture
24° field of view

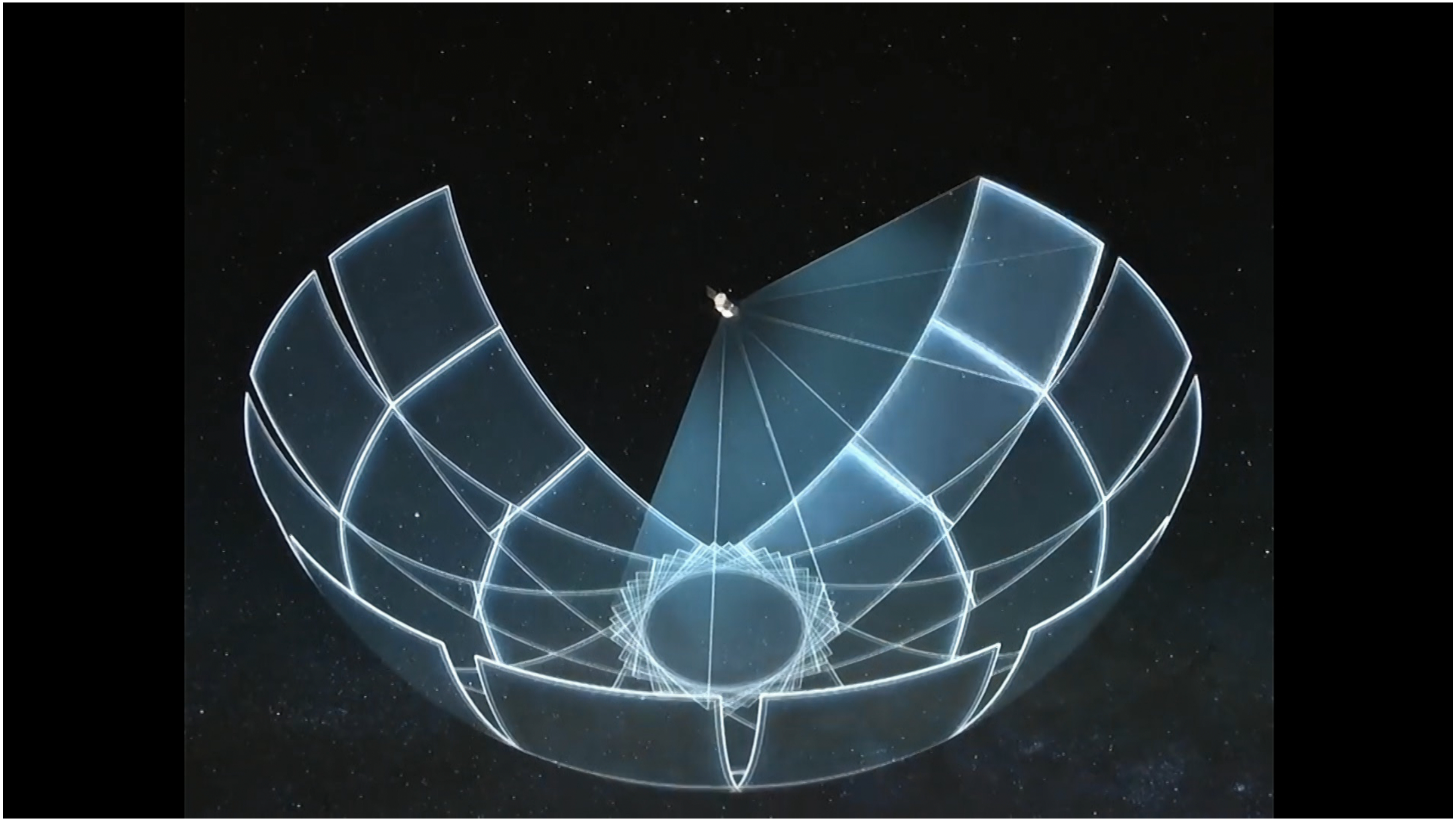
Ricker, Winn, Vanderspek, et al. (2015)

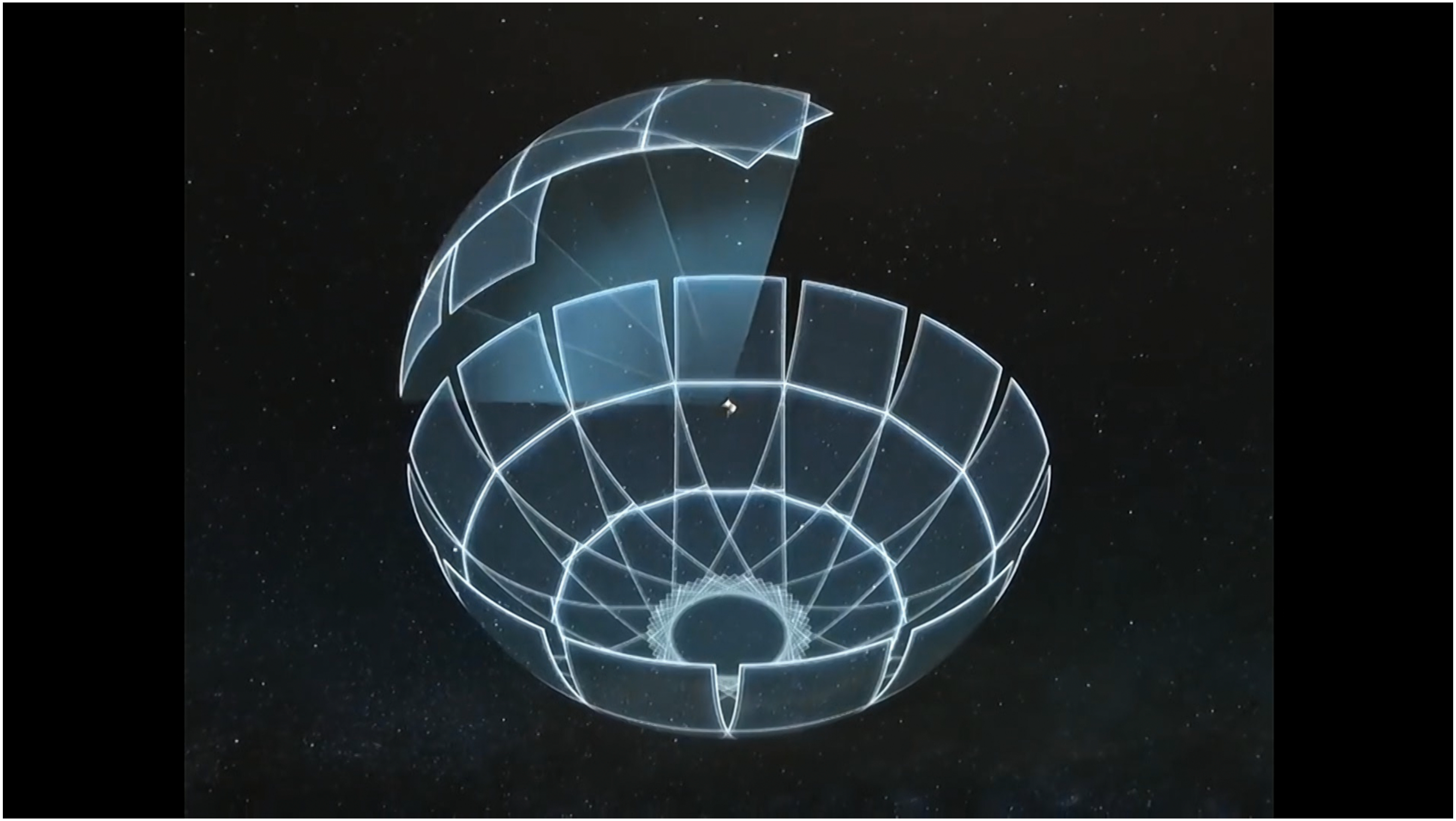


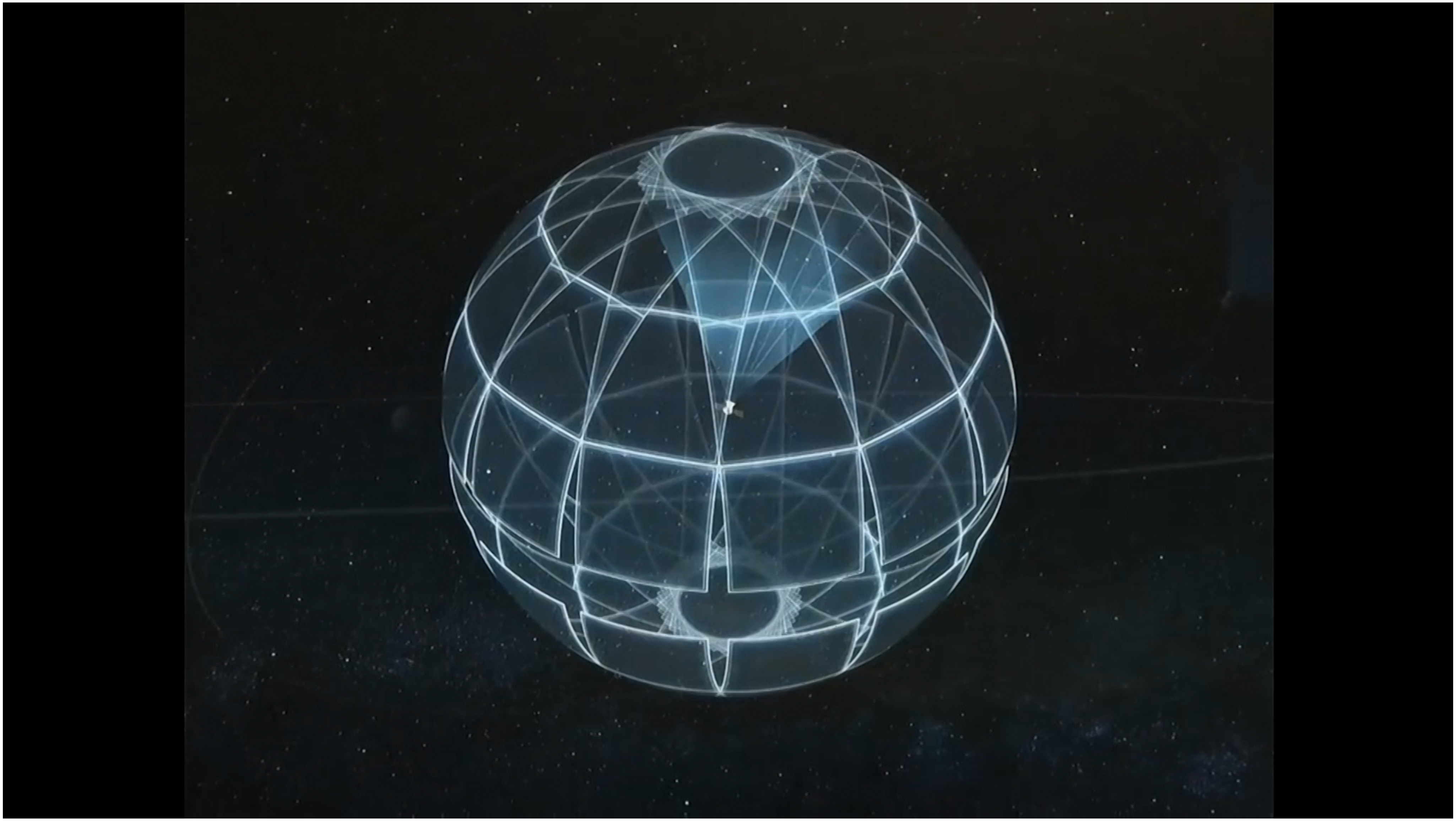


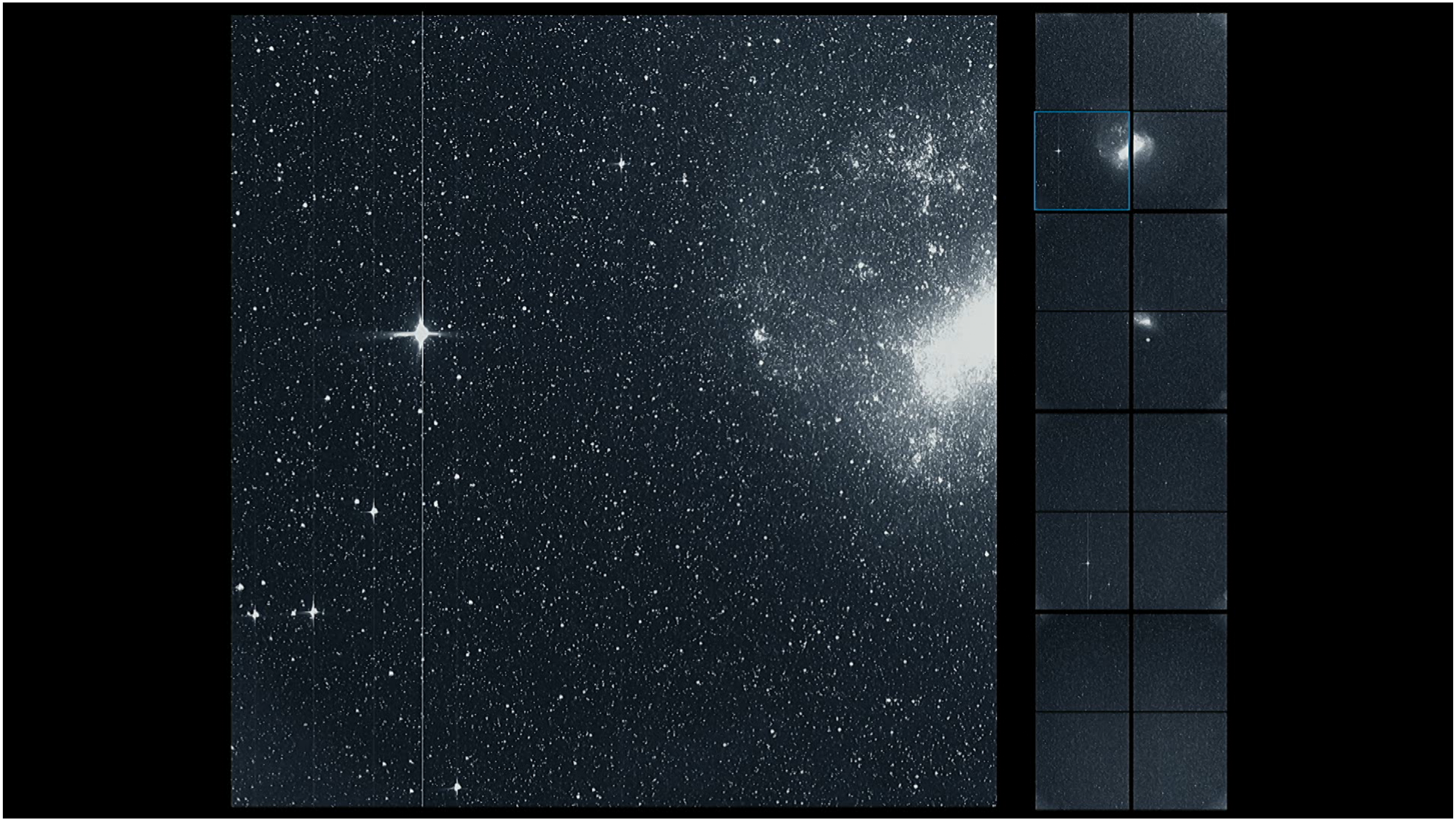




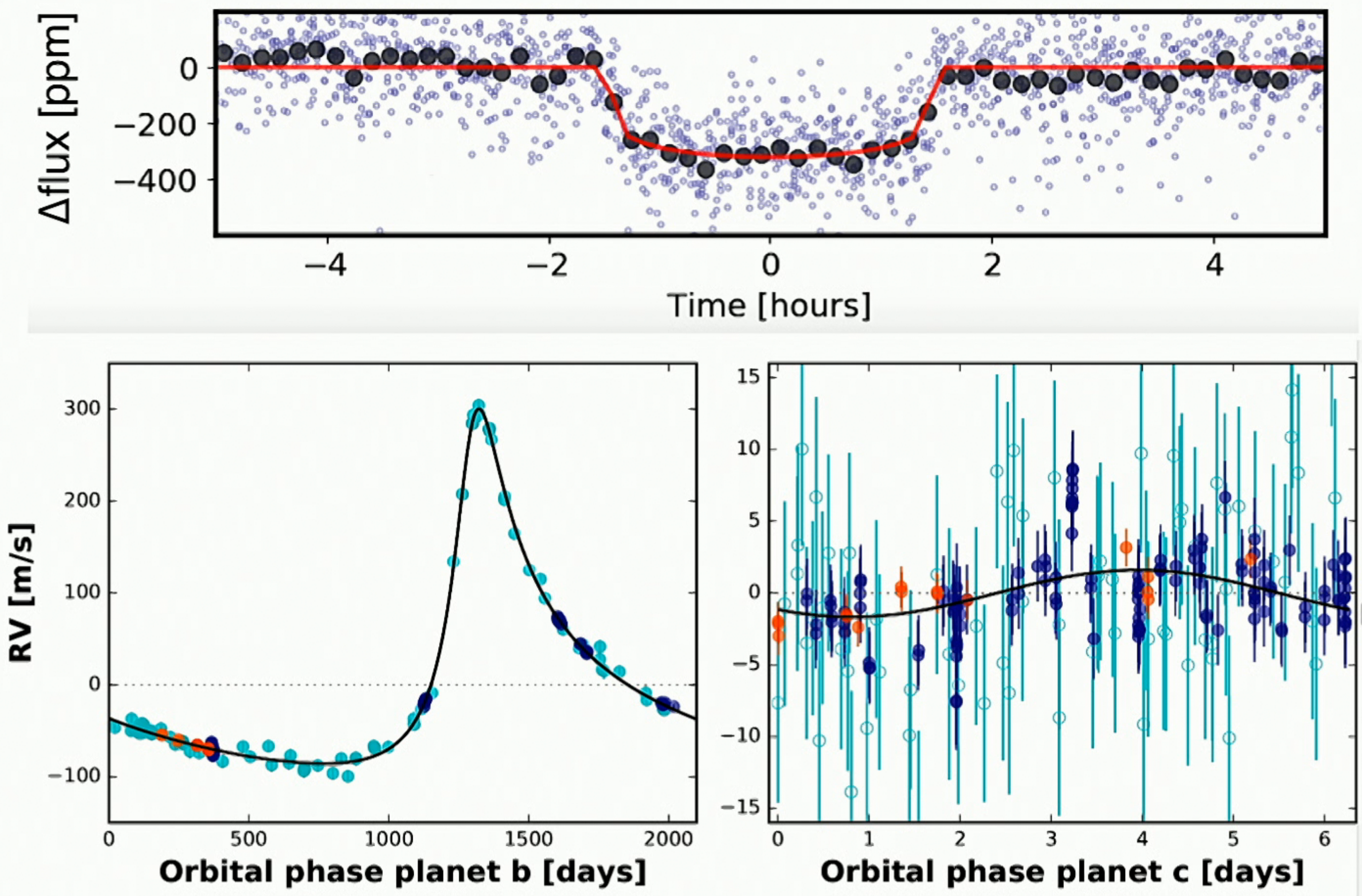




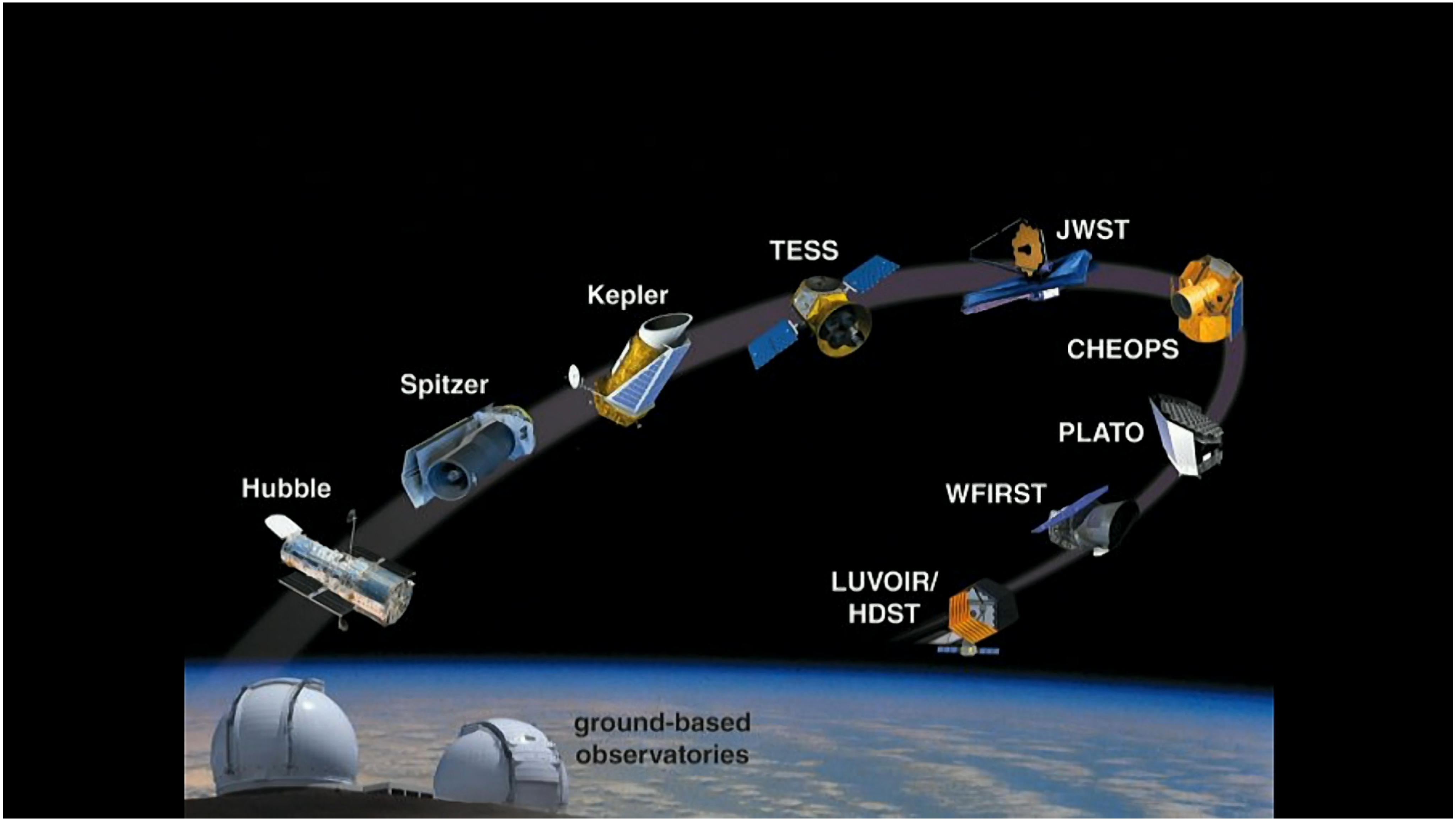





π Mensae



Huang, Burt, Vanderburg, et al., submitted


JWST
TESS
Kepler
CHEOPS
Spitzer
PLATO
Hubble
WFIRST
LUVOIR/
HDST
ground-based
observatories