A Song of Ice and Fire:

The fate of planetary systems after stellar death

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Tsinghua Astronomy Colloquium

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Image: Paradise Edits/Deviant Art

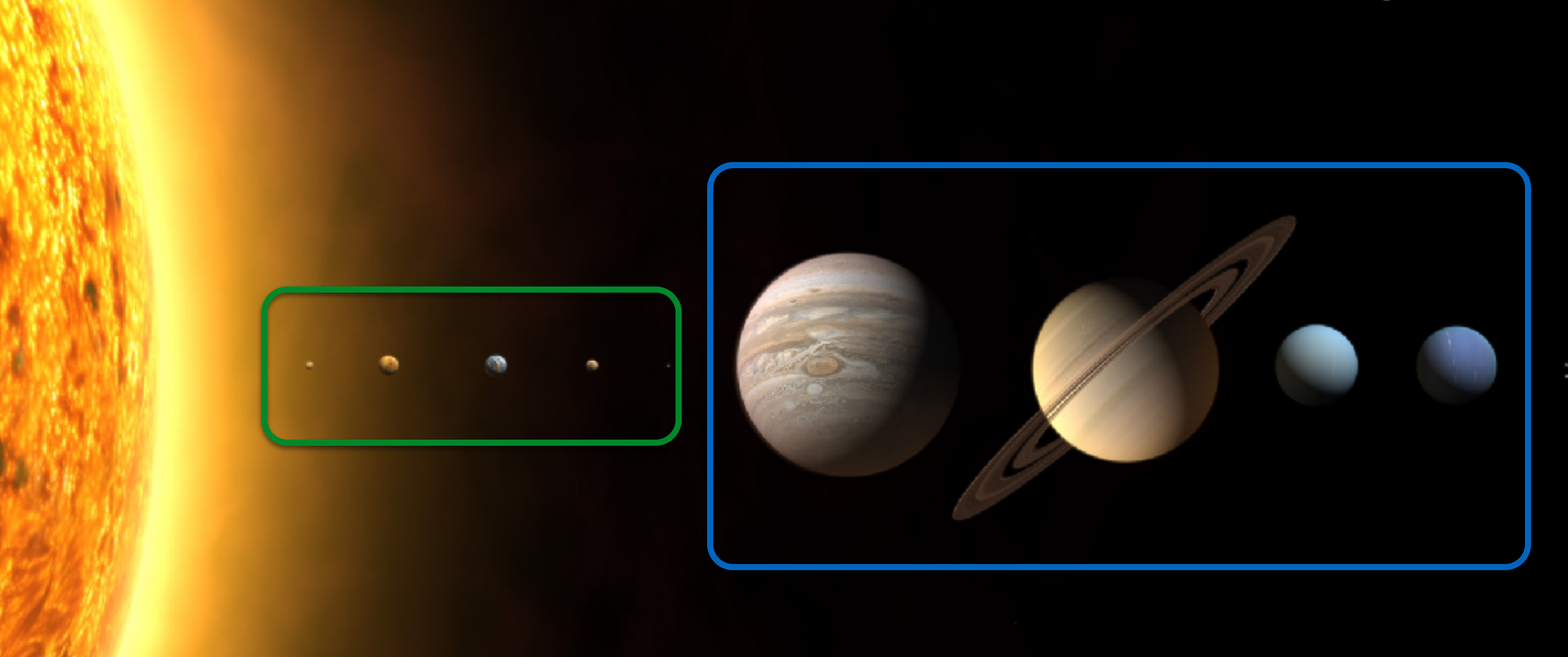
Fred C. Adams, Ruth Angus, Juliette C. Becker, Björn Benneke, David Berardo, Charles Beichman, Allyson Bieryla, Simon Blouin, Warren R. Brown, Lars A. Buchhave, Douglas A. Caldwell, Andreia Carrillo, David R. Ciardi, David Charbonneau, Jessie L. Christiansen, Karen A. Collins, Knicole D. Colón, Ian Crossfield, Tansu Daylan, John Doty, Alexandra E. Doyle, Diana Dragomir, Courtney Dressing, Patrick Dufour, Jason Eastman, Akihiko Fukui, Bruce Gary, Ana Glidden, Varoujan Gorjian, Natalia M. Guerrero, Xueying Guo, Kevin Heng, Andreea I. Henriksen, Chelsea X. Huang, Jonathan Irwin, Jon M. Jenkins, John Asher Johnson Lisa Kaltenegger, Stephen R. Kane, Thomas G. Kaye, David Kipping, Beth Klein, Laura Kreidberg, David W. Latham, John A. Lewis, Jack J. Lissauer, Andrew W. Mann, Nate McCrady, Carl Melis, Farisa Morales, Caroline V. Morley, Brett Morris, Felipe Murgas, Norio Narita, Lorne Nelson, Elisabeth R. Newton, Enric Palle, Hannu Parviainen, Logan A. Pearce, Joshua Pepper, Saul A. Rappaport, George R. Ricker, Mark E. Rose, Laura Schaefer, Sara Seager, Jeffrey C. Smith, Keivan G. Stassun, René Tronsgaard, Roland K. Vanderspek, Joshua N. Winn, Robert A. Wittenmyer, Jason T. Wright, Siyi Xu, Liang Yu, Greg Zeimann, Ben Zuckerman

What is the story of our Solar System?

System/spacings not to scale

Image: Wikimedia

Patterns in the Solar System can teach us about our origins



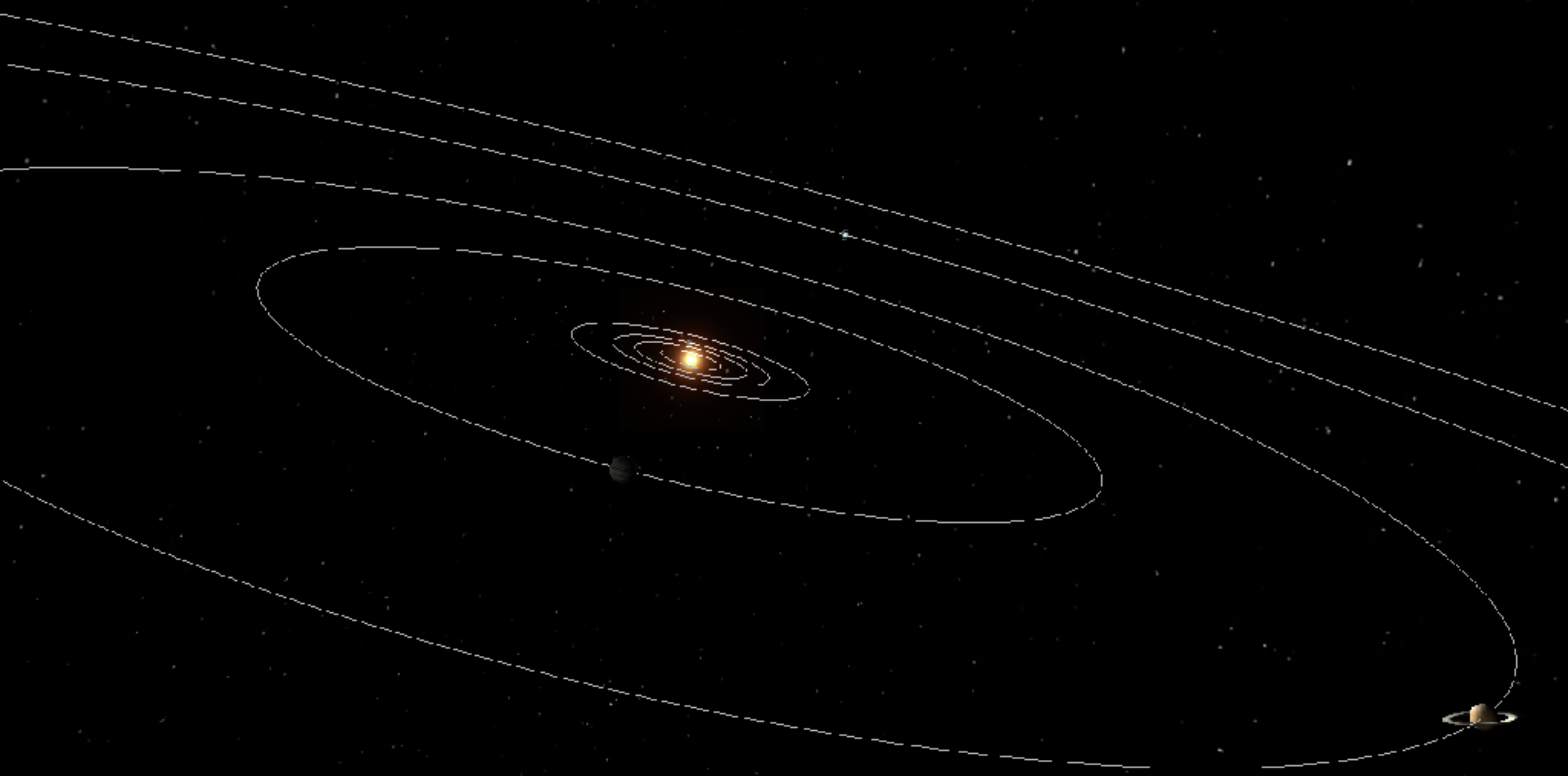
Small, rocky inner planets without thick atmospheres

Large, massive planets with thick gaseous envelopes

System/spacings not to scale

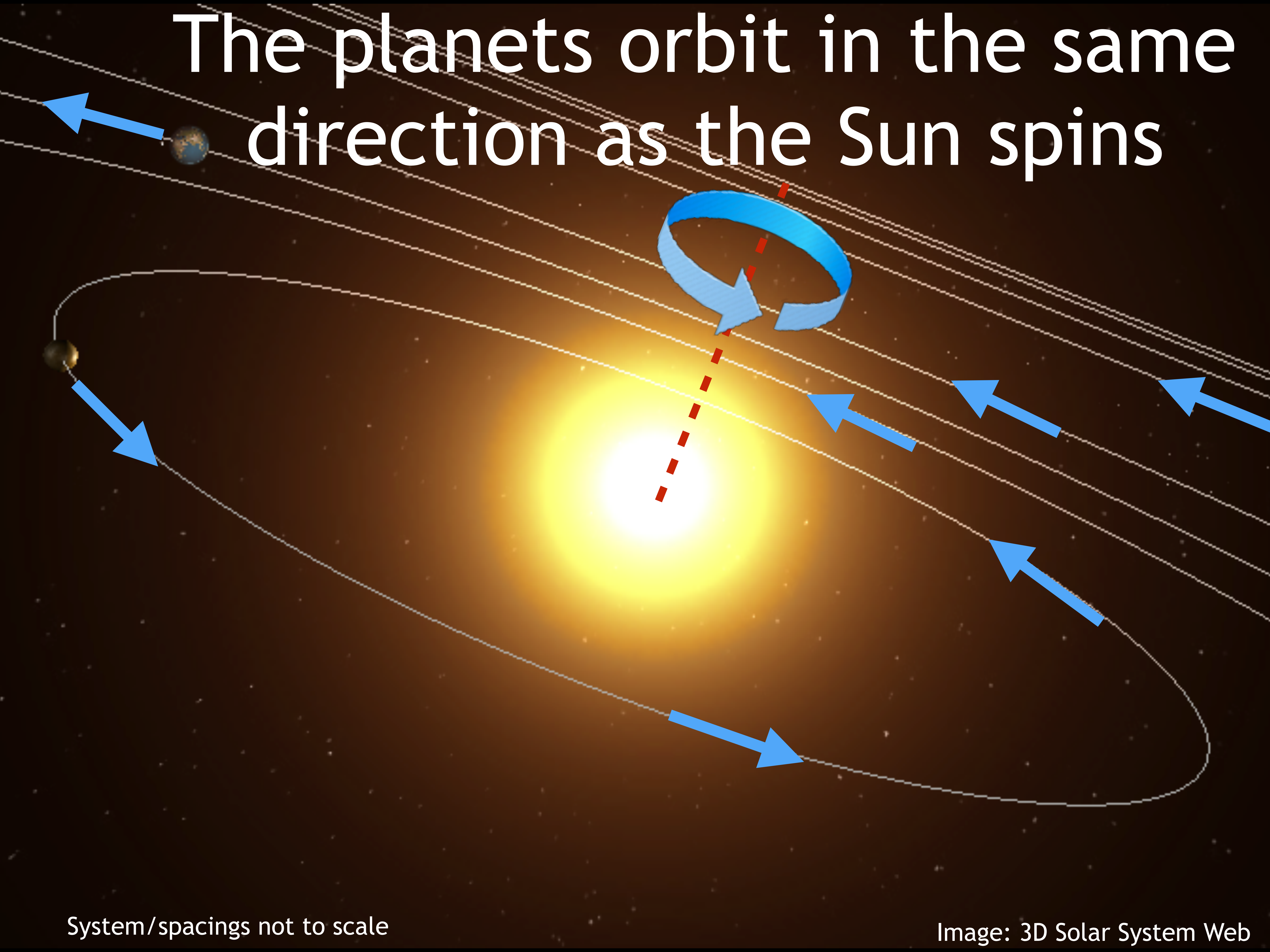
Image: Wikimedia

Flat, orderly architecture

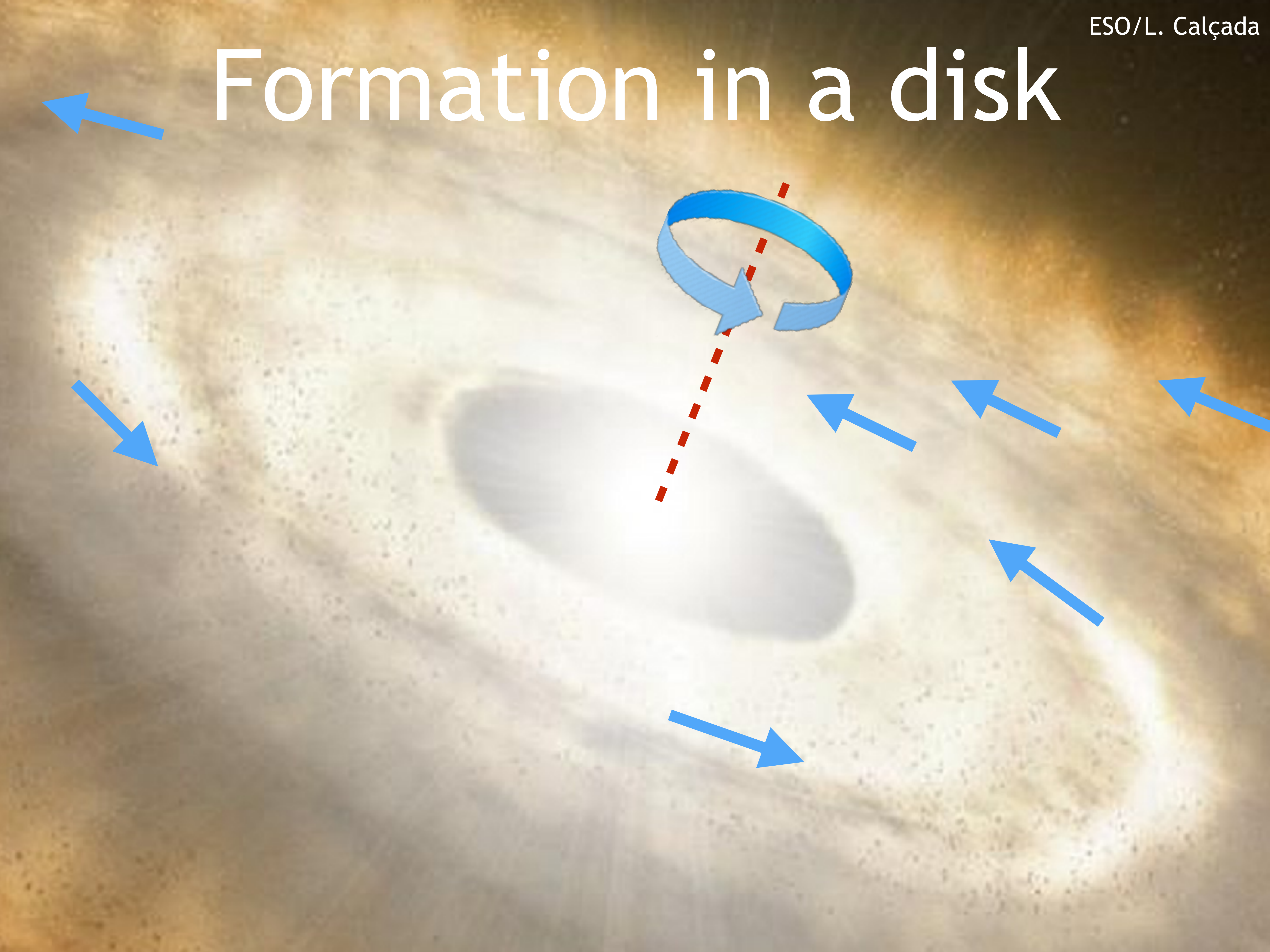


System/spacings not to scale

Image: 3D Solar System Web

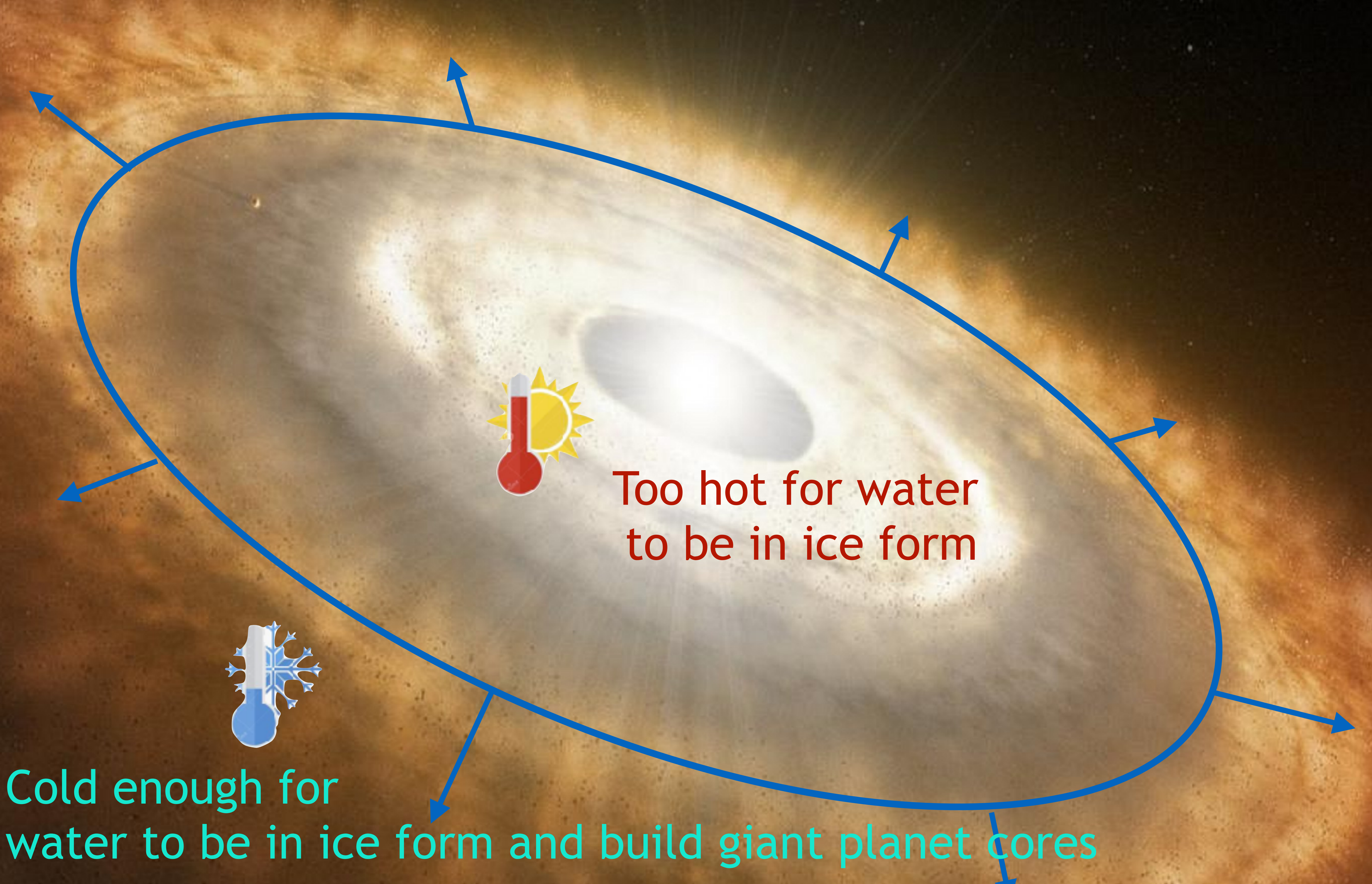

The planets orbit in the same direction as the Sun spins
System/spacings not to scale
Image: 3D Solar System Web

Formation in a disk

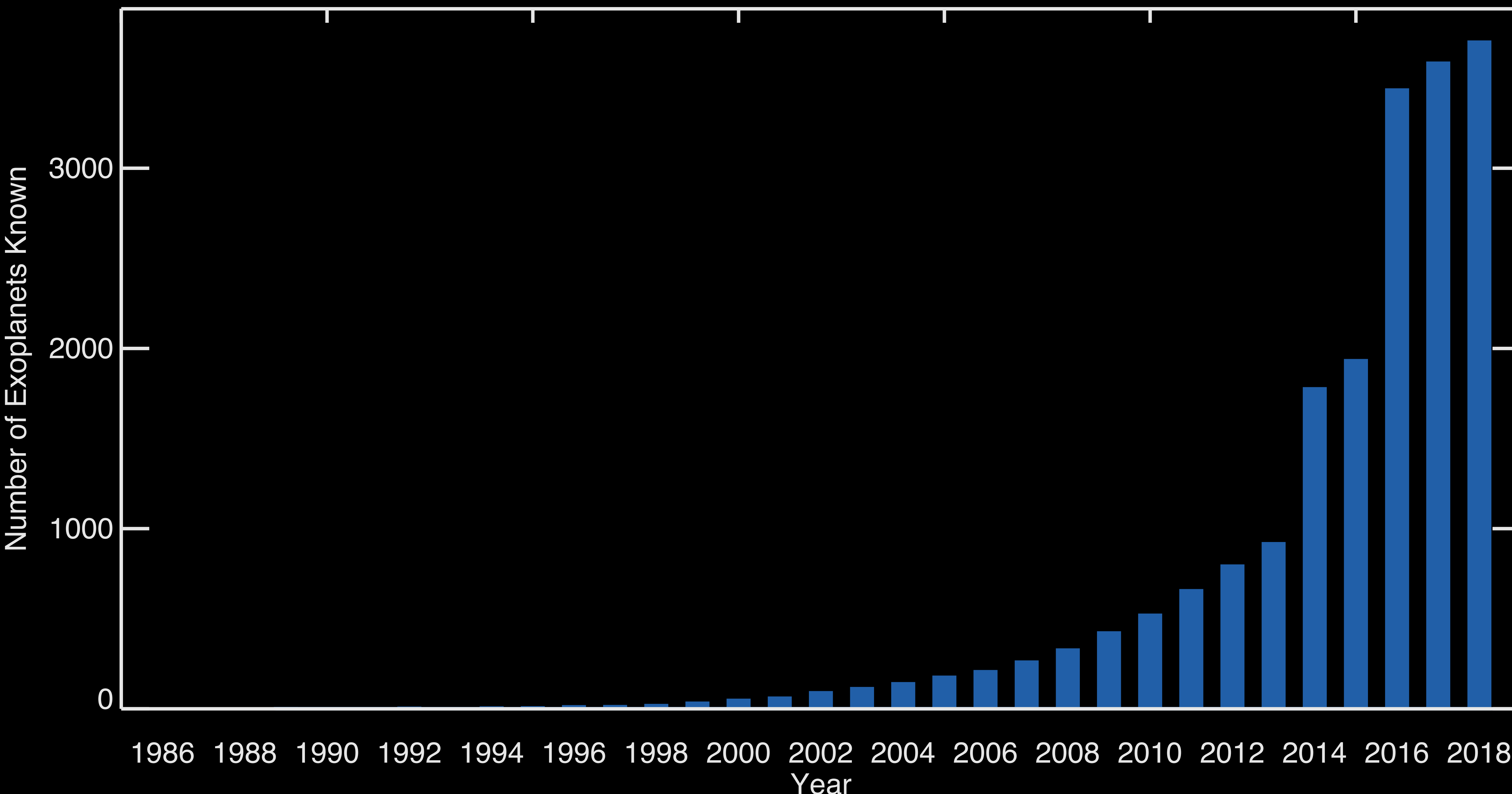


ESO/L. Calçada

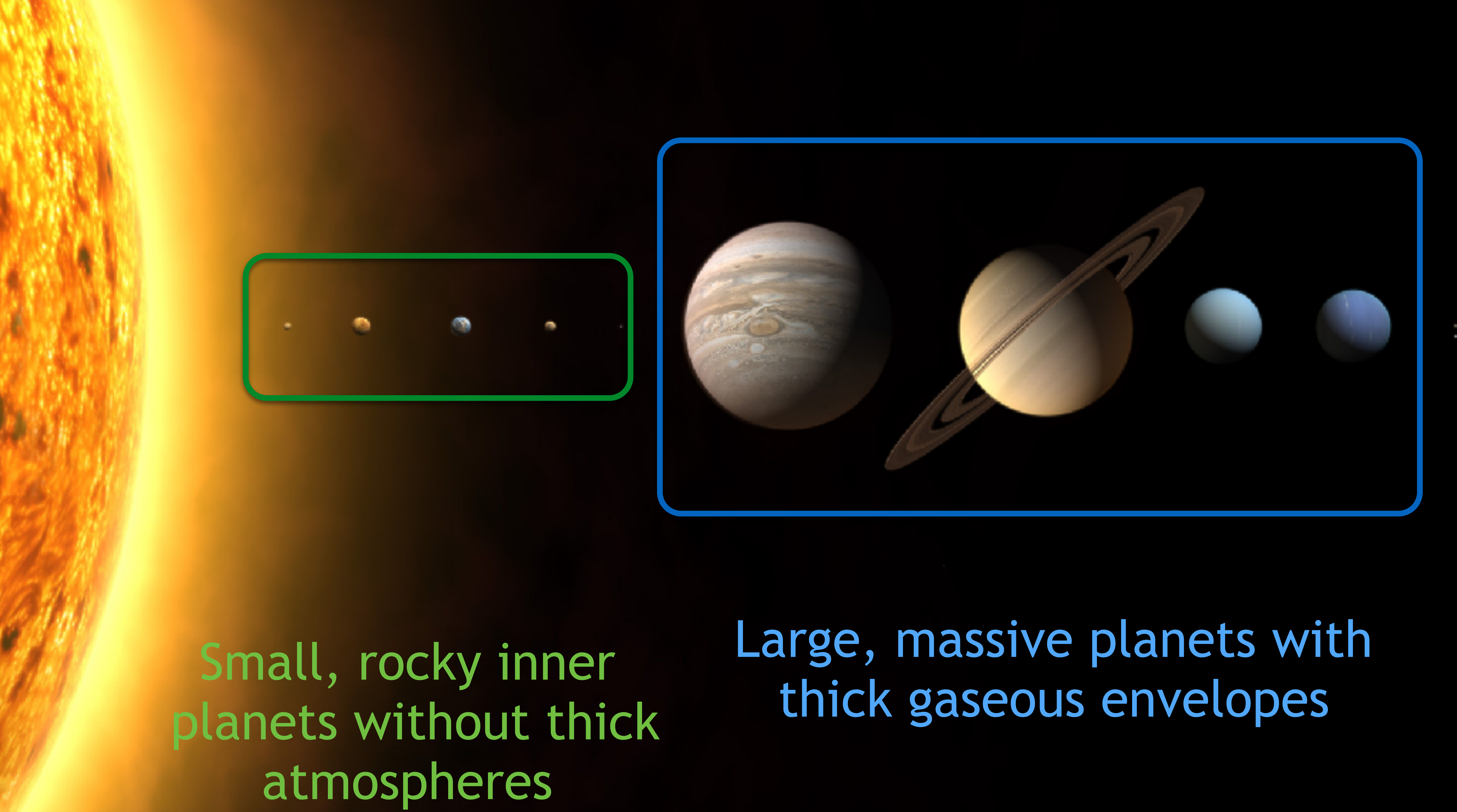
Snow lines


ESO/L. Calçada
Too hot for water
to be in ice form
Cold enough for
water to be in ice form and build giant planet cores

Along the way, the discovery of exoplanets refined our origin story.



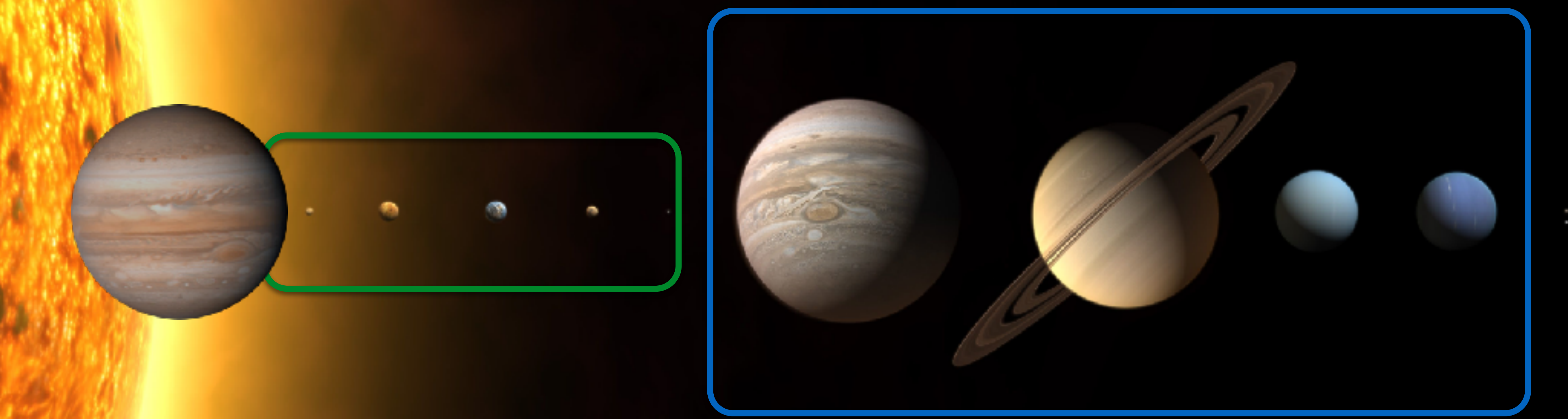
Patterns in the Solar System are not always followed



System/spacings not to scale

Image: Wikimedia

Patterns in the Solar System are not always followed



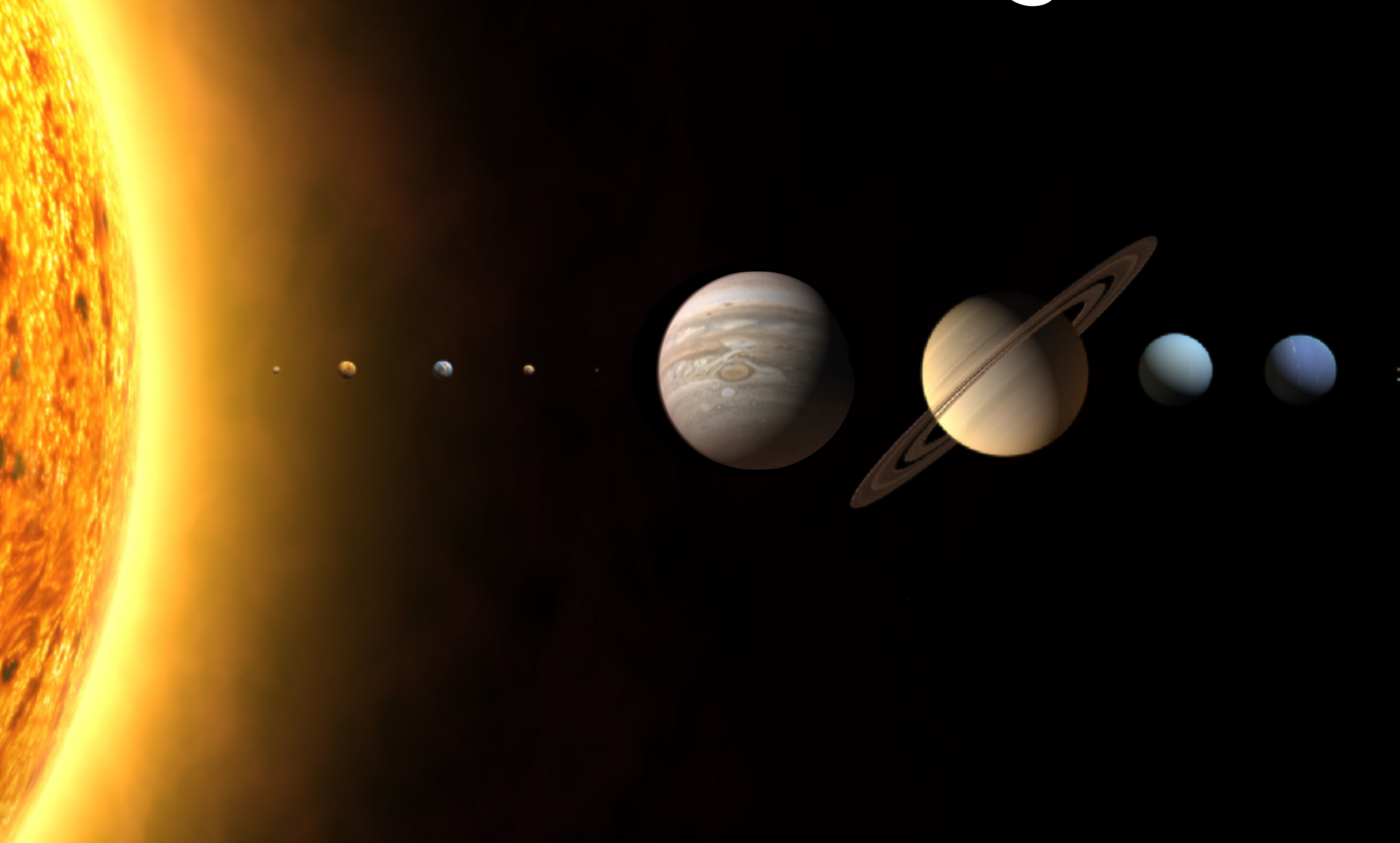
Small, rocky inner planets without thick atmospheres

Large, massive planets with thick gaseous envelopes

System/spacings not to scale

Image: Wikimedia

Planets can migrate



System/spacings not to scale

Image: Wikimedia

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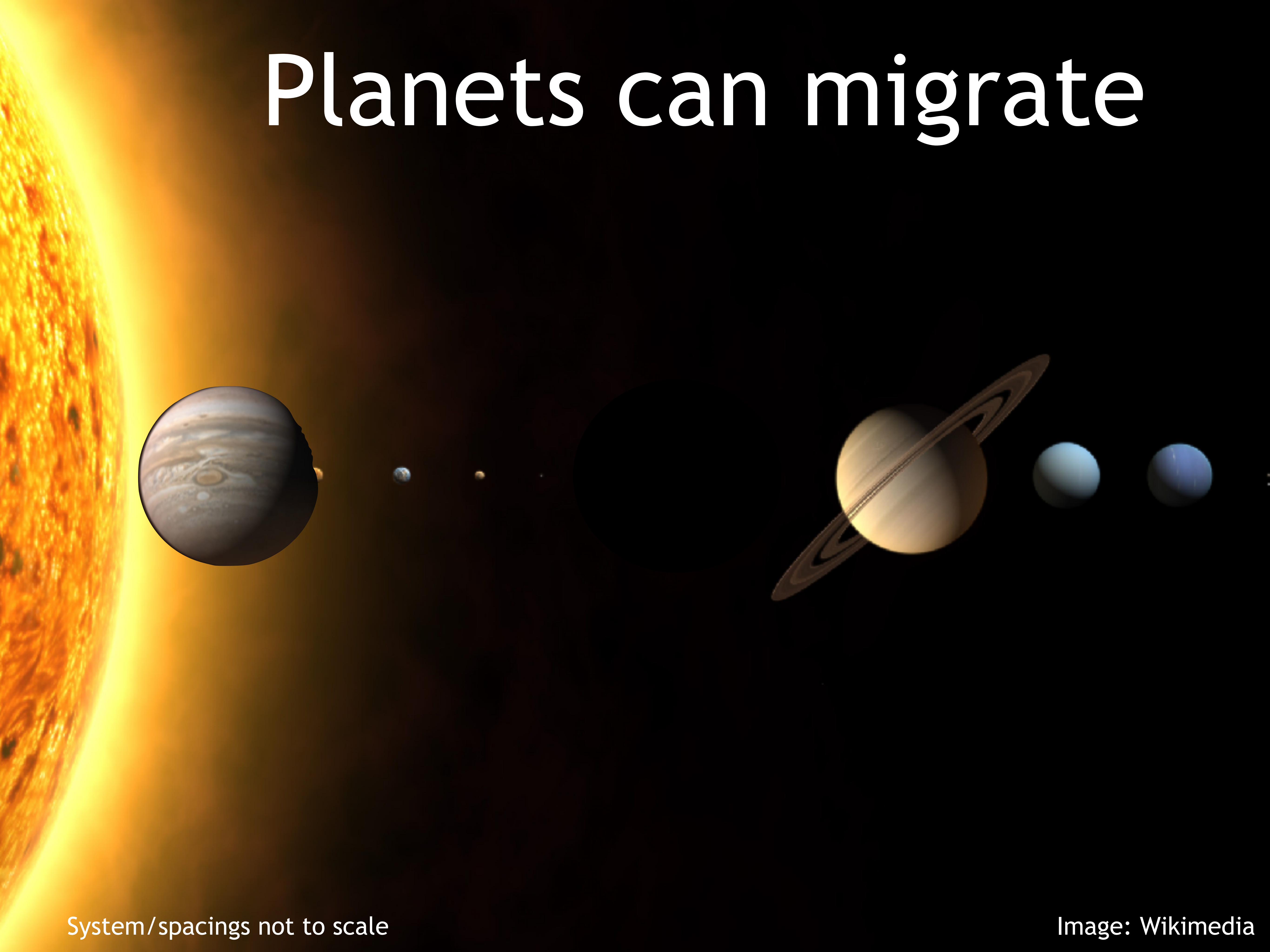
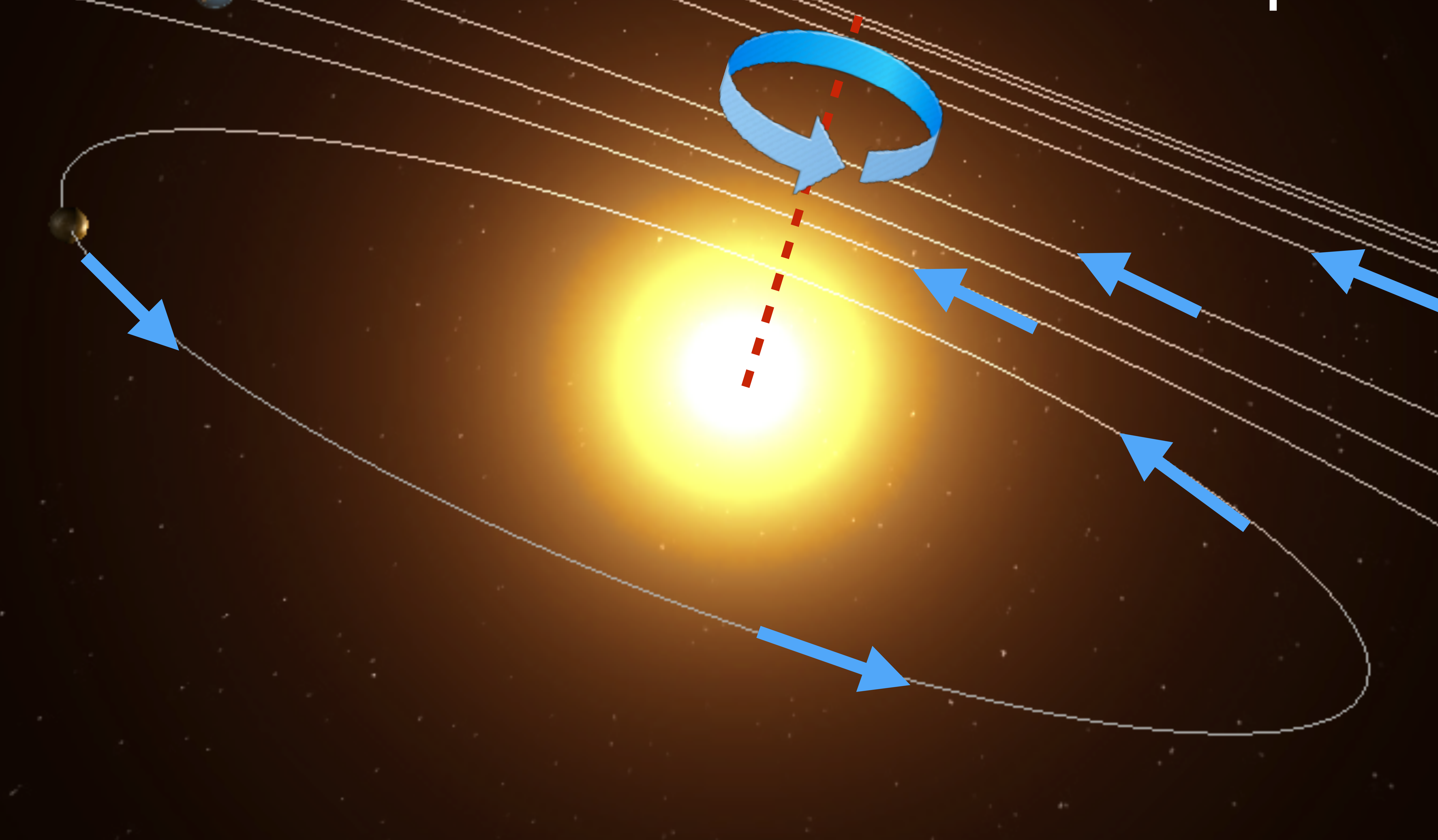


System/spacings not to scale

Image: Wikimedia

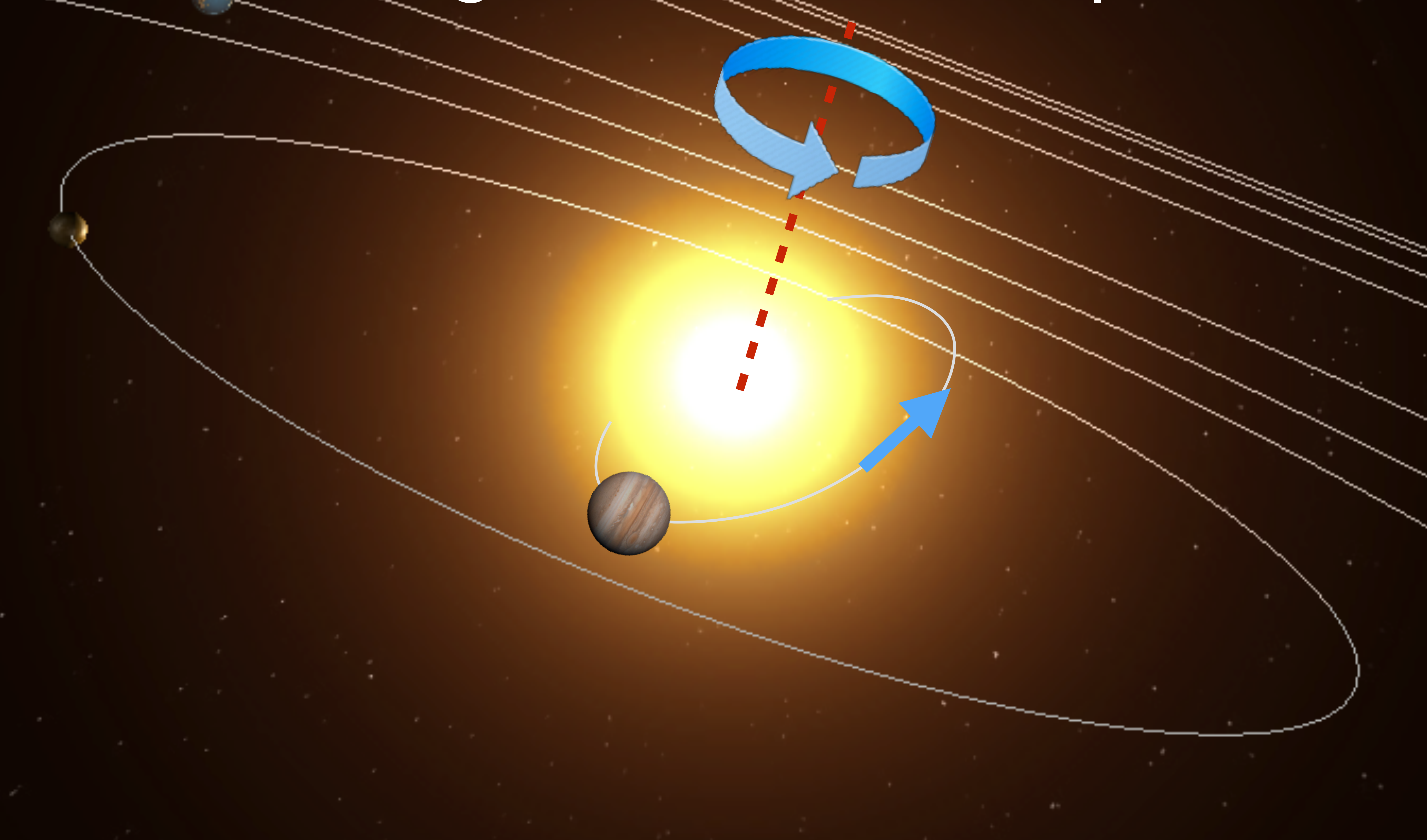
The Solar System planets orbit in the same direction as the Sun spins



System/spacings not to scale

Image: 3D Solar System Web

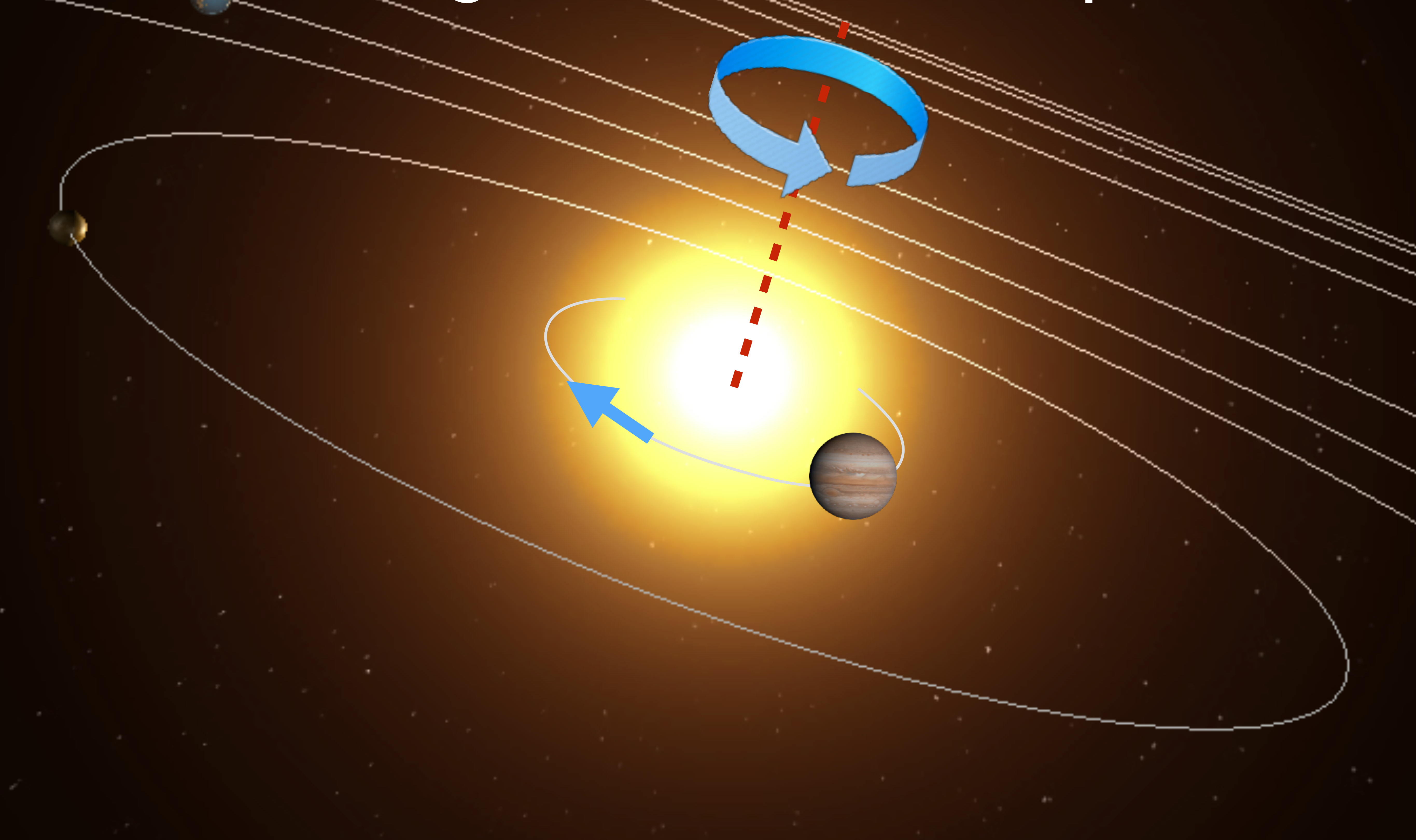
Exoplanet orbits aren't necessarily aligned with stellar spin



System/spacings not to scale

Image: 3D Solar System Web

Exoplanet orbits aren't necessarily aligned with stellar spin



System/spacings not to scale

Image: 3D Solar System Web

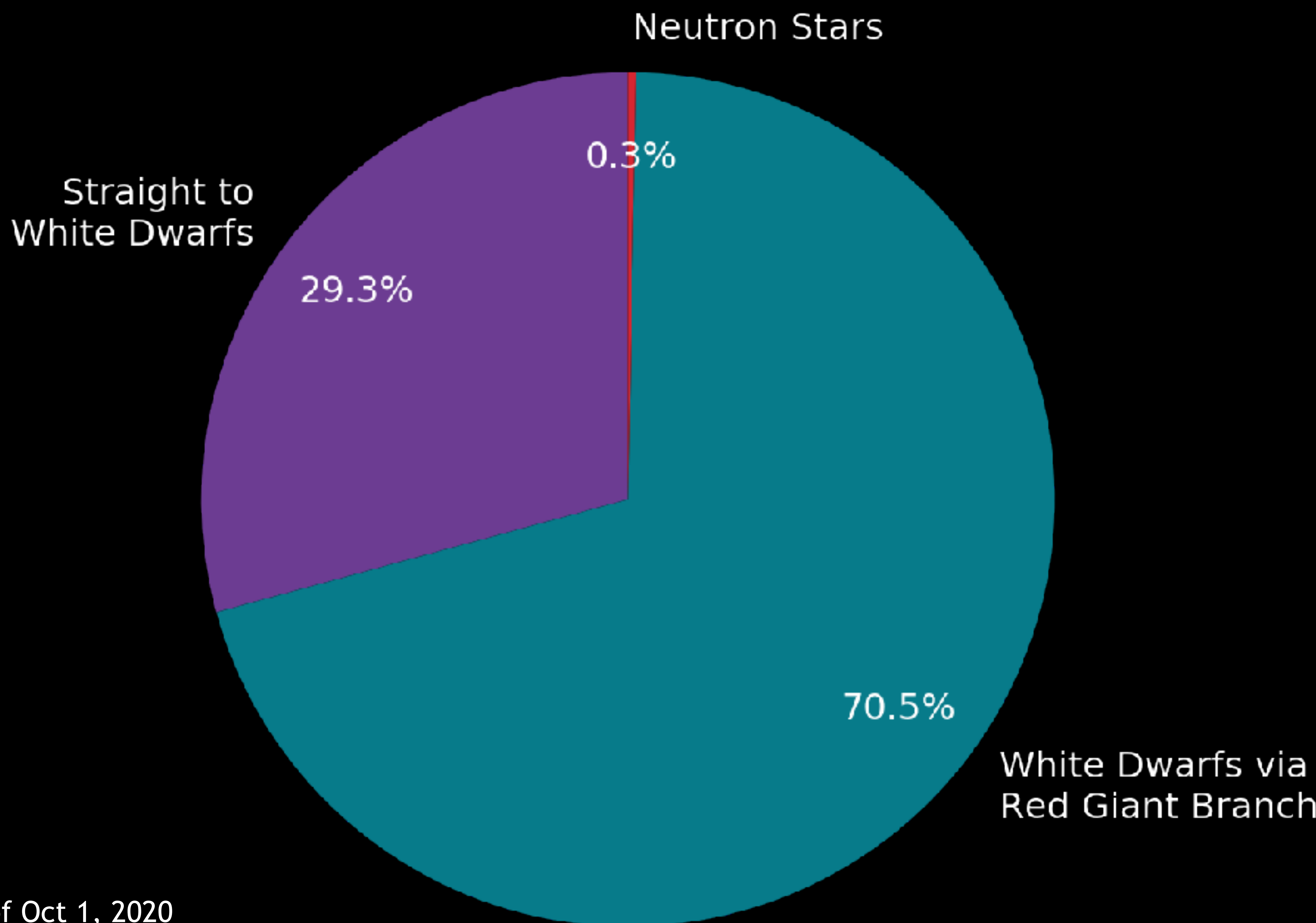
Dynamical interactions between planets must be common

Ford et al. 2005, Trent Schindler, National Science Foundation


We have a basic understanding of how we got here
but what will happen to the Solar System in the future?
System/spacings not to scale
Image: Wikimedia

What happens to planetary systems after the stars run out of hydrogen fuel and leave the main sequence?

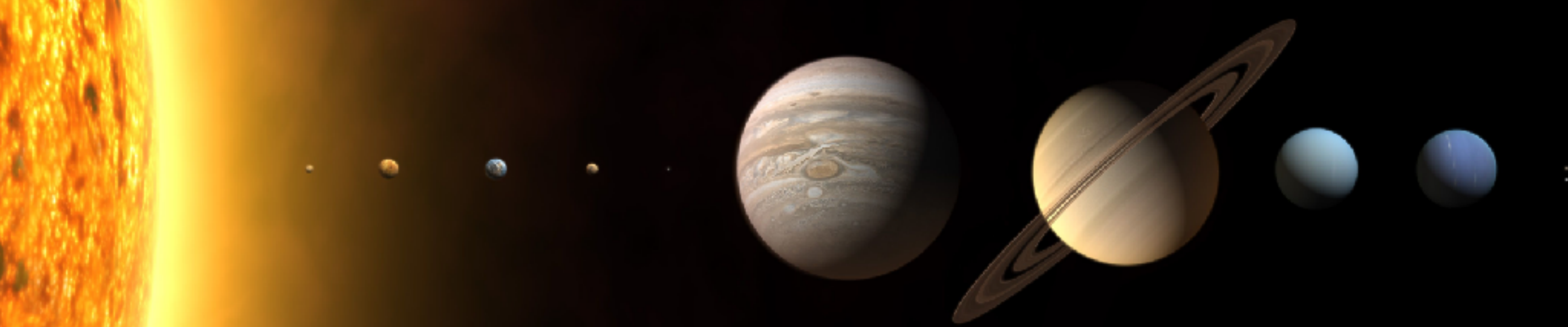
Almost all of the planets we know today orbit stars that will become white dwarfs.



As of Oct 1, 2020

In this talk:

1. What do we know about the fate of planetary systems around white dwarfs?



2. What have we learned from studying two particularly interesting white dwarfs?

3. What might we learn in the future?

System/spacings not to scale

Image: Wikimedia

The Sun Today

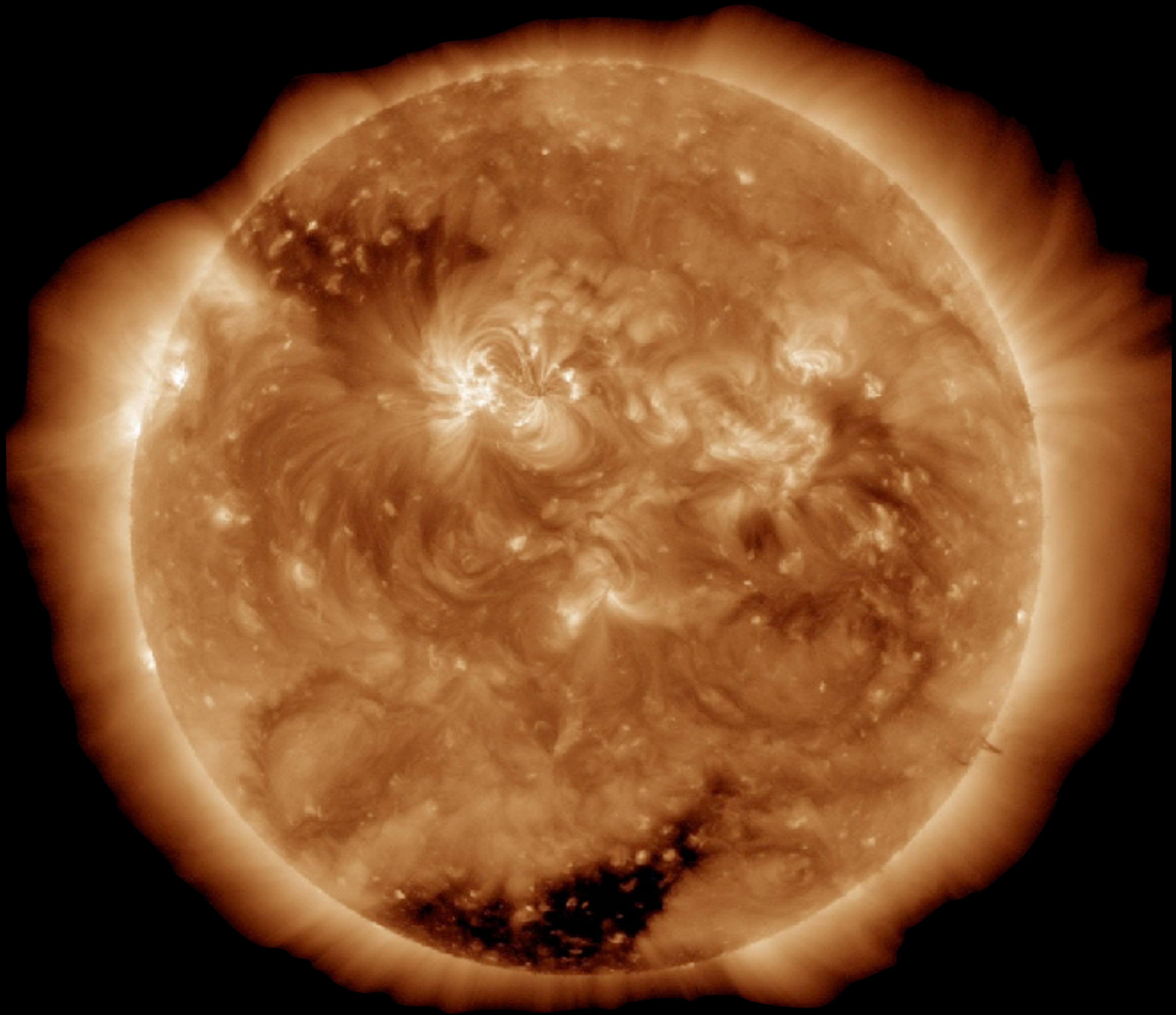


Image: NASA/SDO

The Sun Today

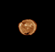
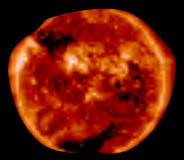


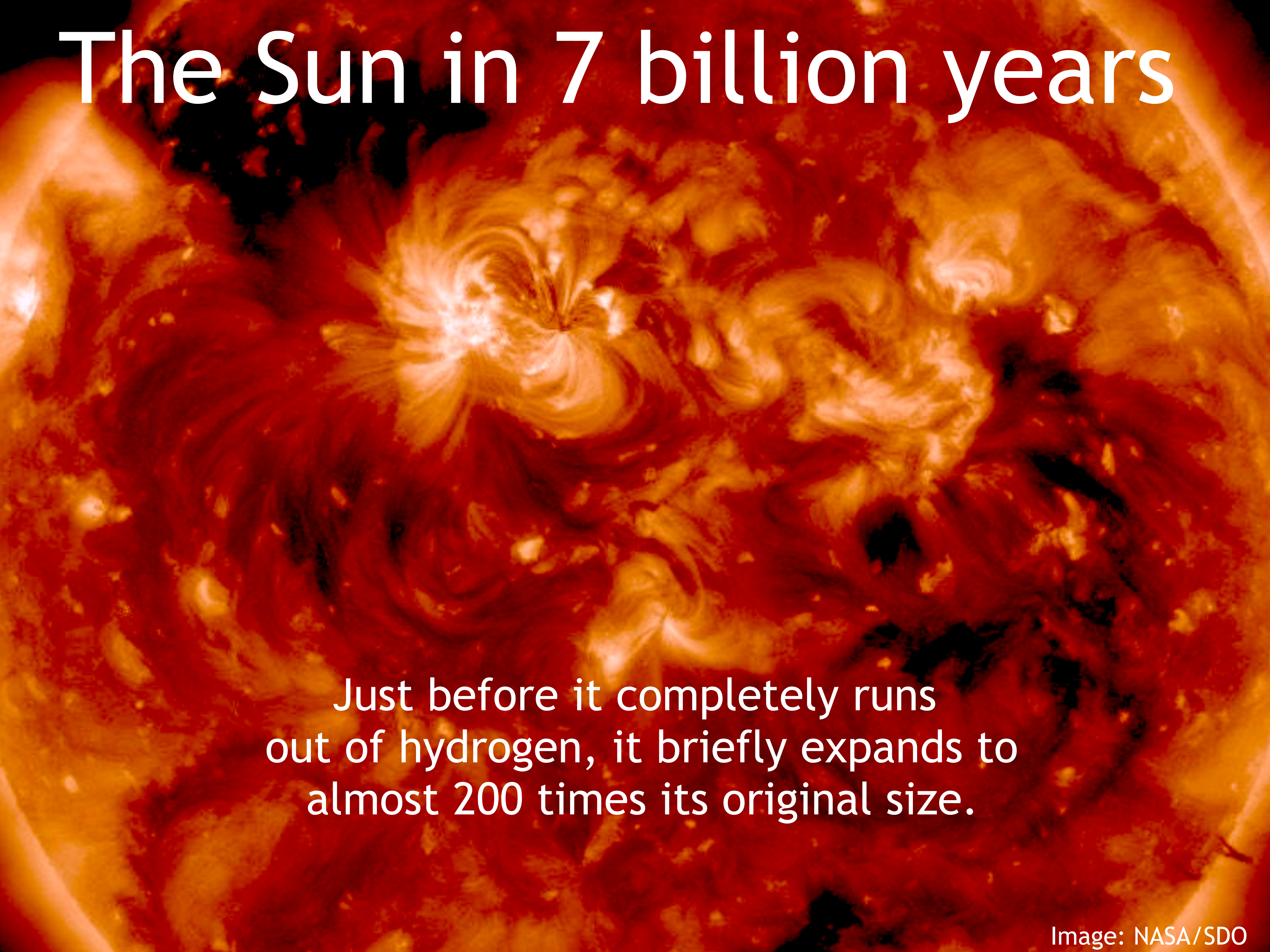
Image: NASA/SDO

The Sun in 7 billion years

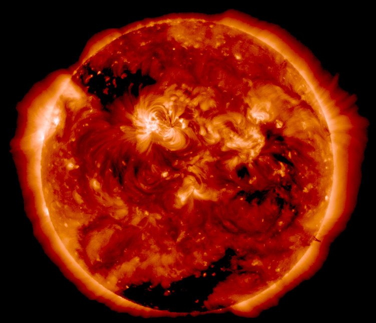


As the sun runs out of hydrogen, it becomes a red giant 10 times its original size.

Image: NASA/SDO

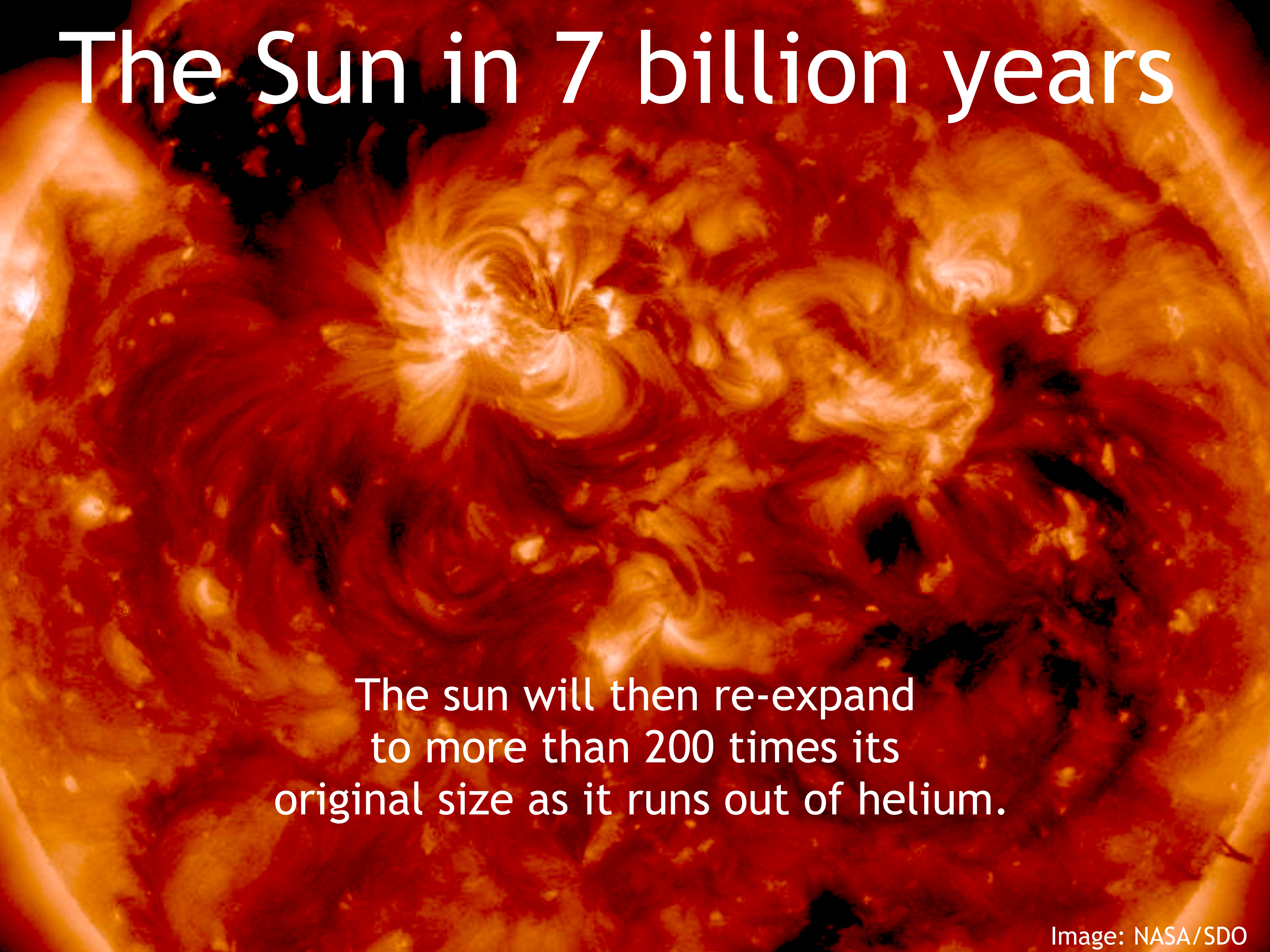

The Sun in 7 billion years
Just before it completely runs out of hydrogen, it briefly expands to almost 200 times its original size.
Image: NASA/SDO

The Sun in 7 billion years



It then collapses to about 20 times its original size and begins burning helium in its core.

Image: NASA/SDO


The Sun in 7 billion years
The sun will then re-expand to more than 200 times its original size as it runs out of helium.
Image: NASA/SDO

The Sun in 7 Billion Years

After helium is exhausted, there is nothing else the sun can burn so it sheds its outer layers and the core begins contracting.

Image: NASA/Walt Feimer

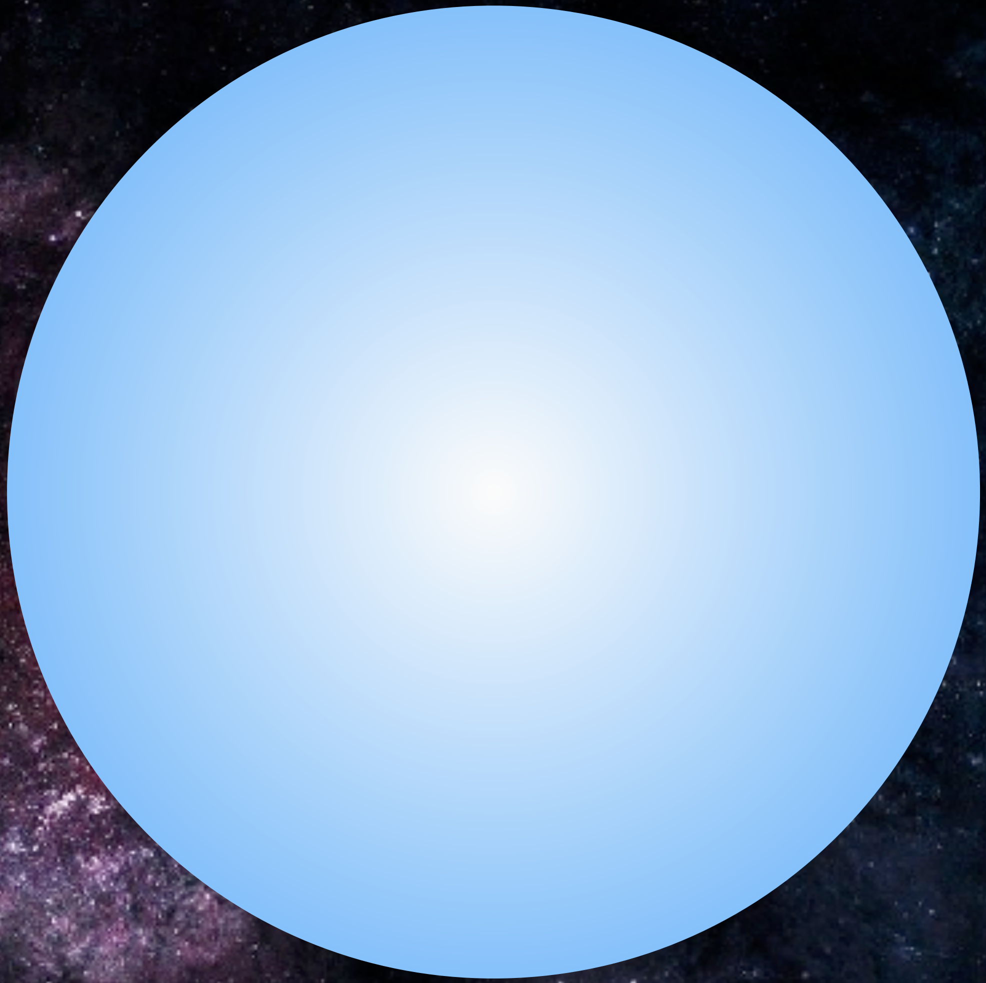
The Sun in 7 Billion Years

After helium is exhausted, there is nothing else the sun can burn so it sheds its outer layers and the core begins contracting.

Image: NASA/Walt Feimer

White Dwarfs

Burnt-out Earth-sized cores of stars like the Sun when they run out of nuclear fuel



Typically half the mass of the sun

300,000 times less massive

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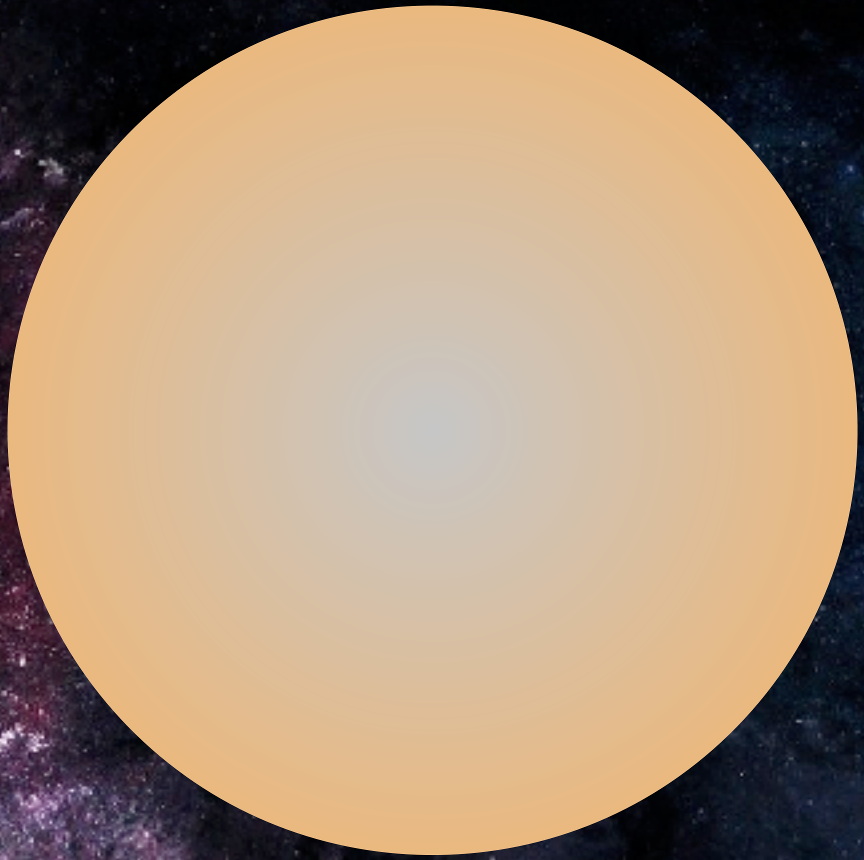

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White Dwarfs

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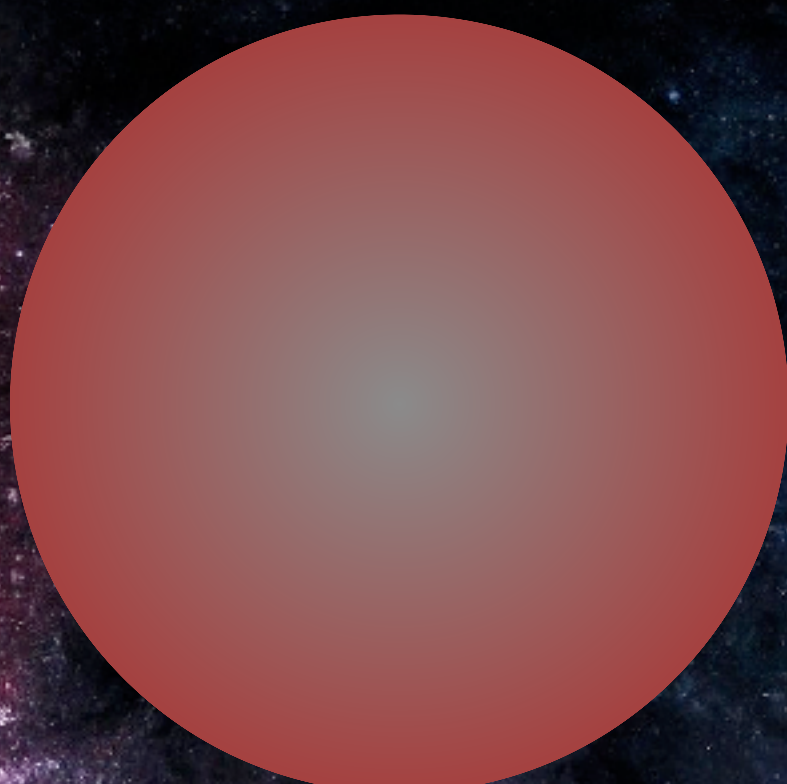

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Burnt-out Earth-sized cores of stars like the Sun when they run out of nuclear fuel

Typically half the mass of the sun

300,000 times less massive

What happens to the planets during this process?

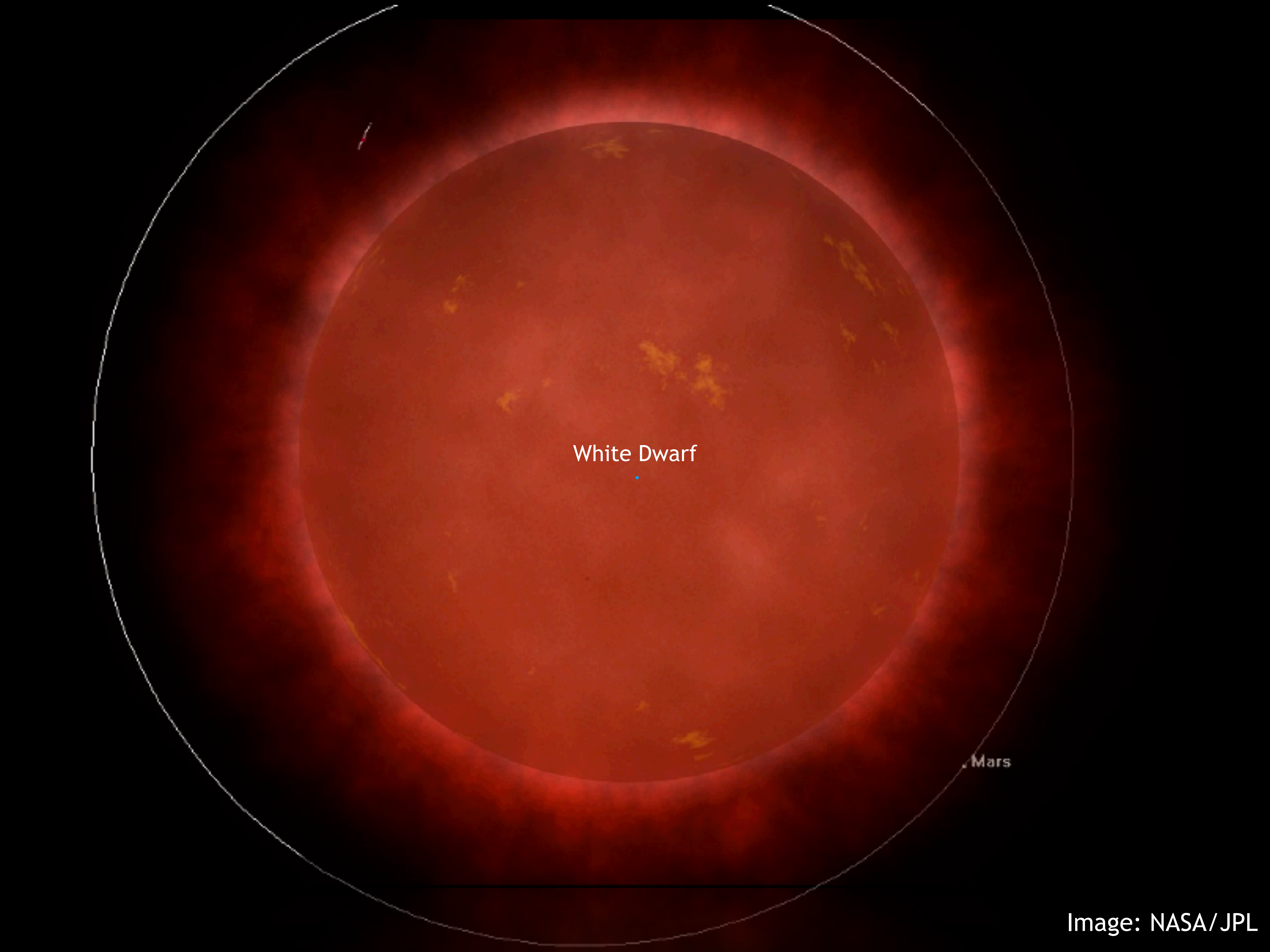
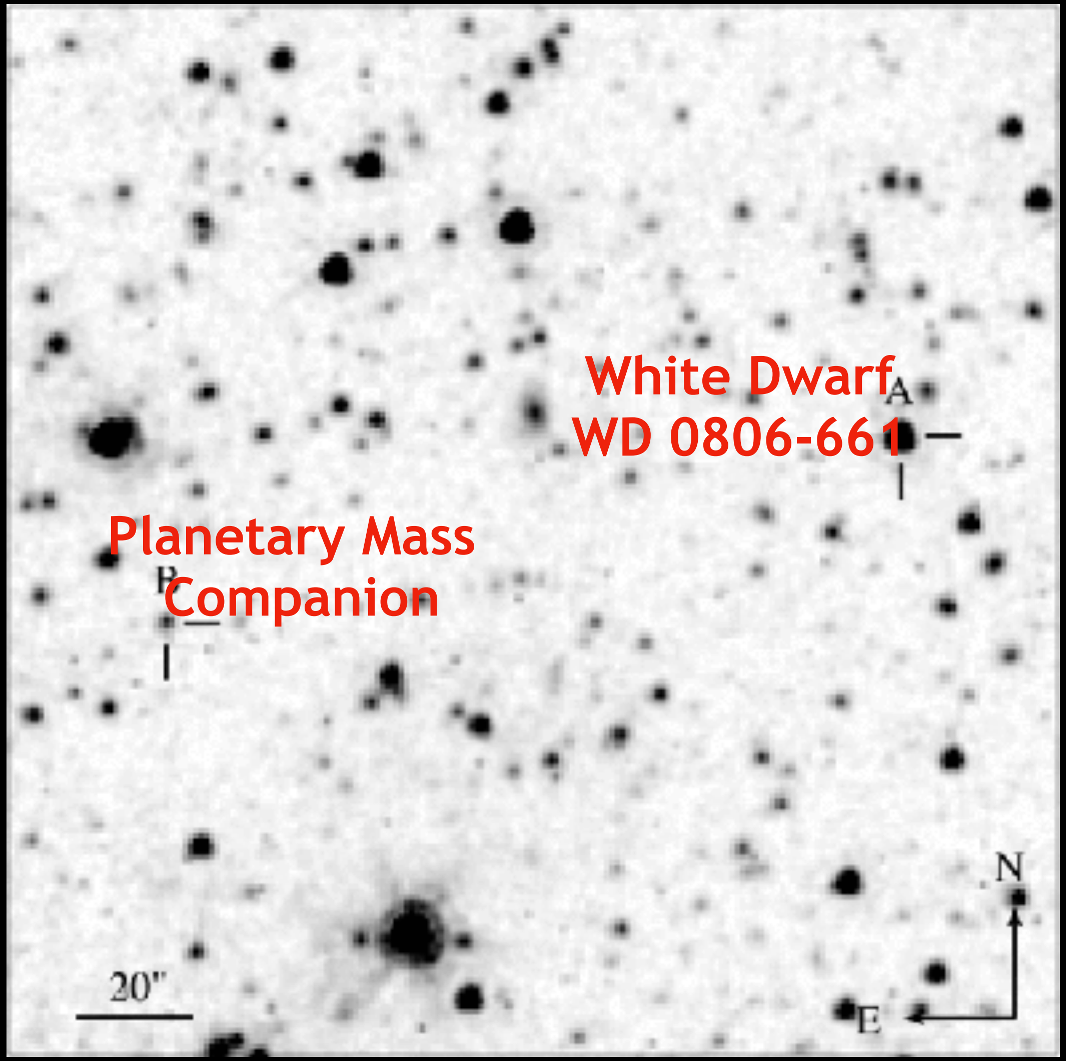
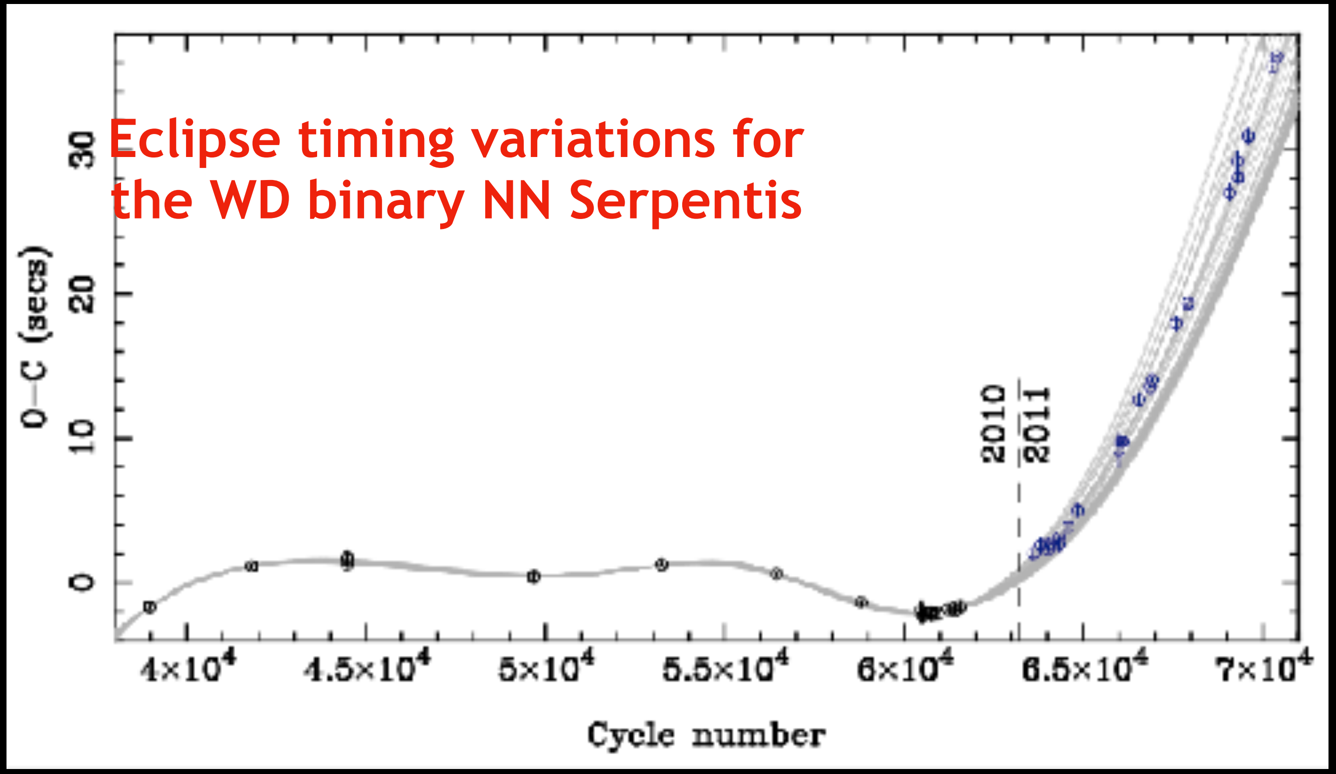


Image: NASA/JPL

Planets orbiting farther than about 1 AU from their stars will survive post-main-sequence evolution



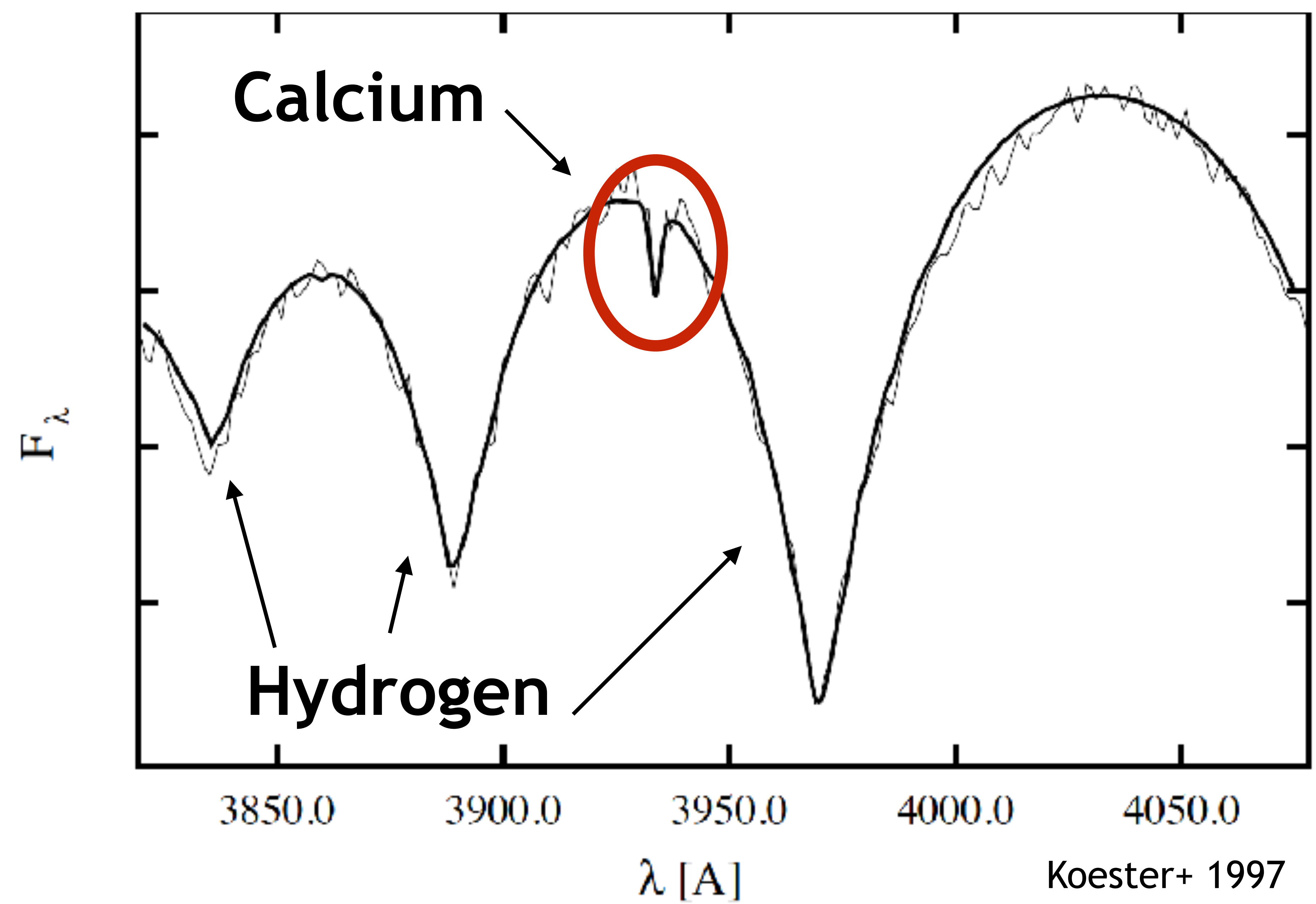
Luhman et al. 2011



Marsh et al. 2013

Do planets ever come back close to the white dwarf after the red giant phase?

Yes: evidence is in white dwarf “metal pollution"



White Dwarfs have strong gravity

$$g = \frac{GM}{R^2}$$

White Dwarfs have strong gravity

$$g = \frac{GM}{R^2}$$

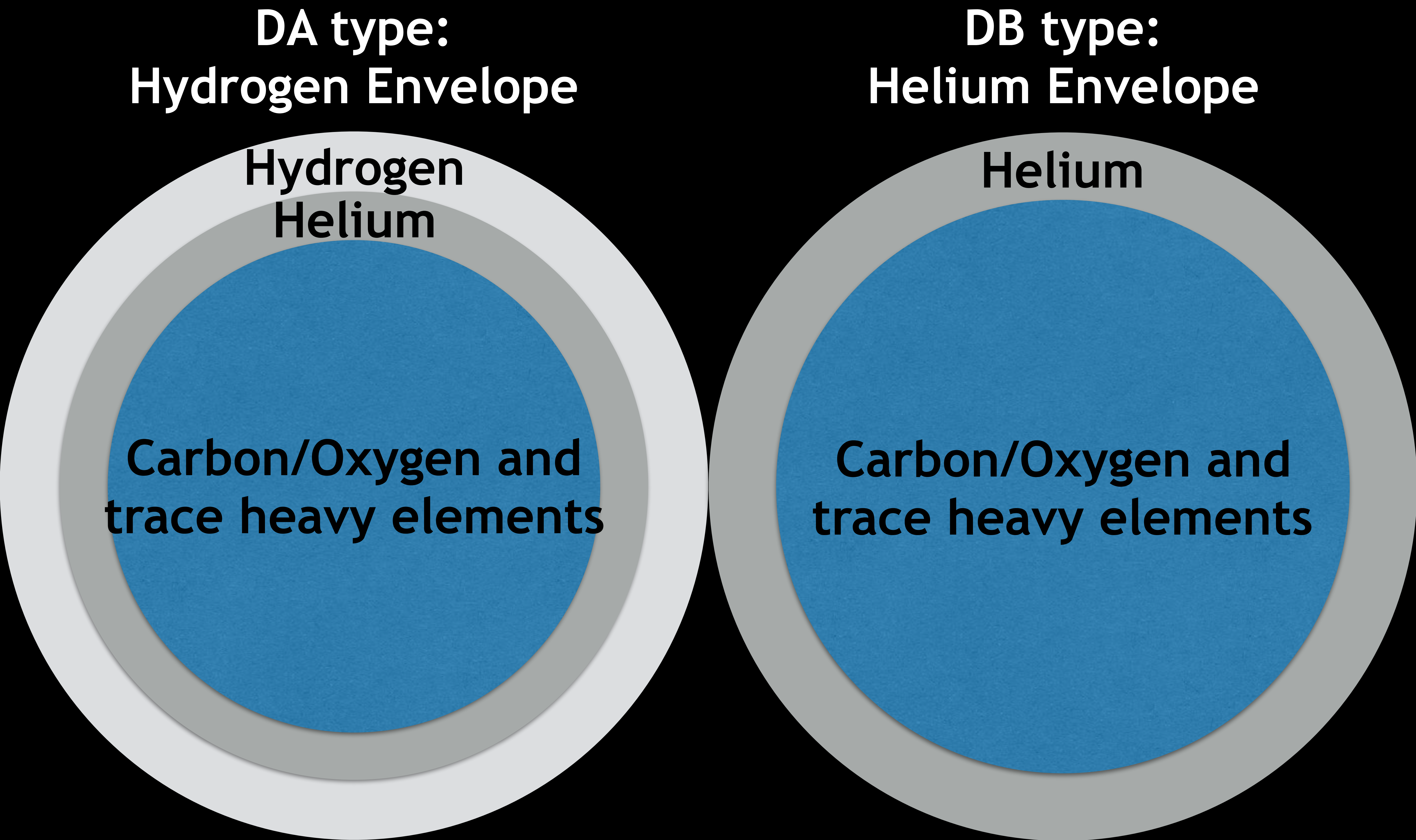
0.5 times the Sun

10^4 times stronger than the Sun

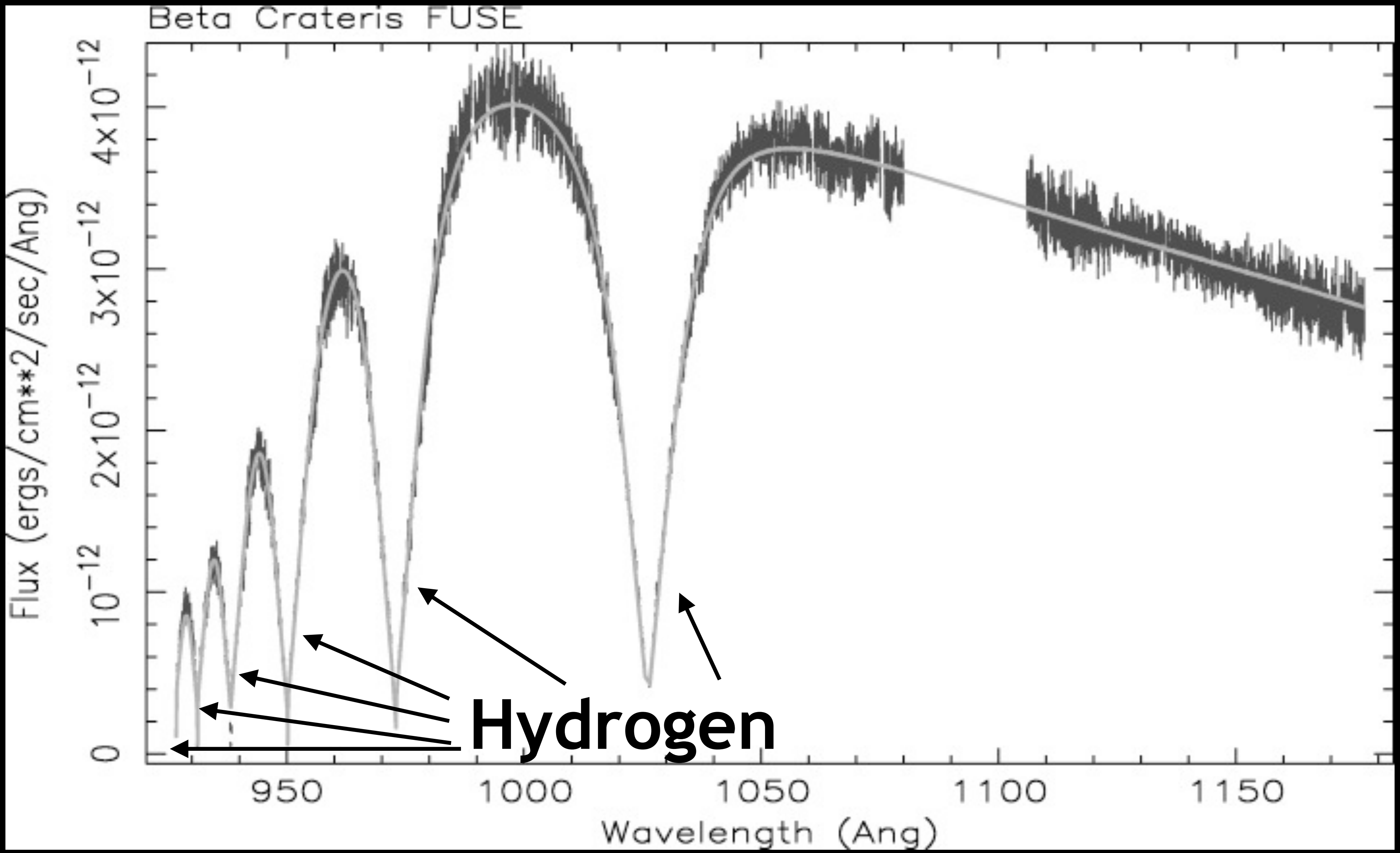
100 times smaller than the Sun

Gravity causes heavy elements to sink down

White Dwarf Structure

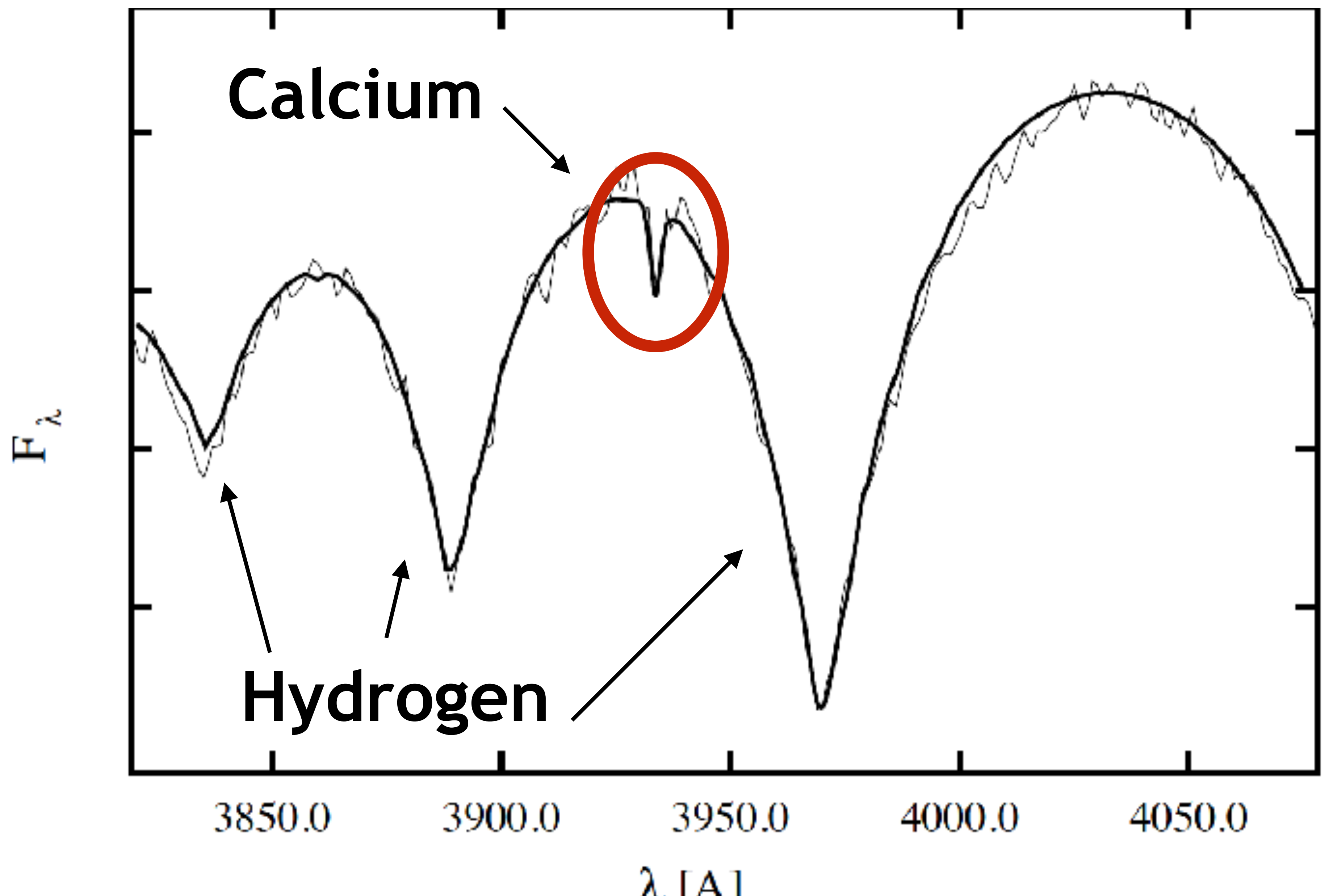


White Dwarf Spectra should only have H and He



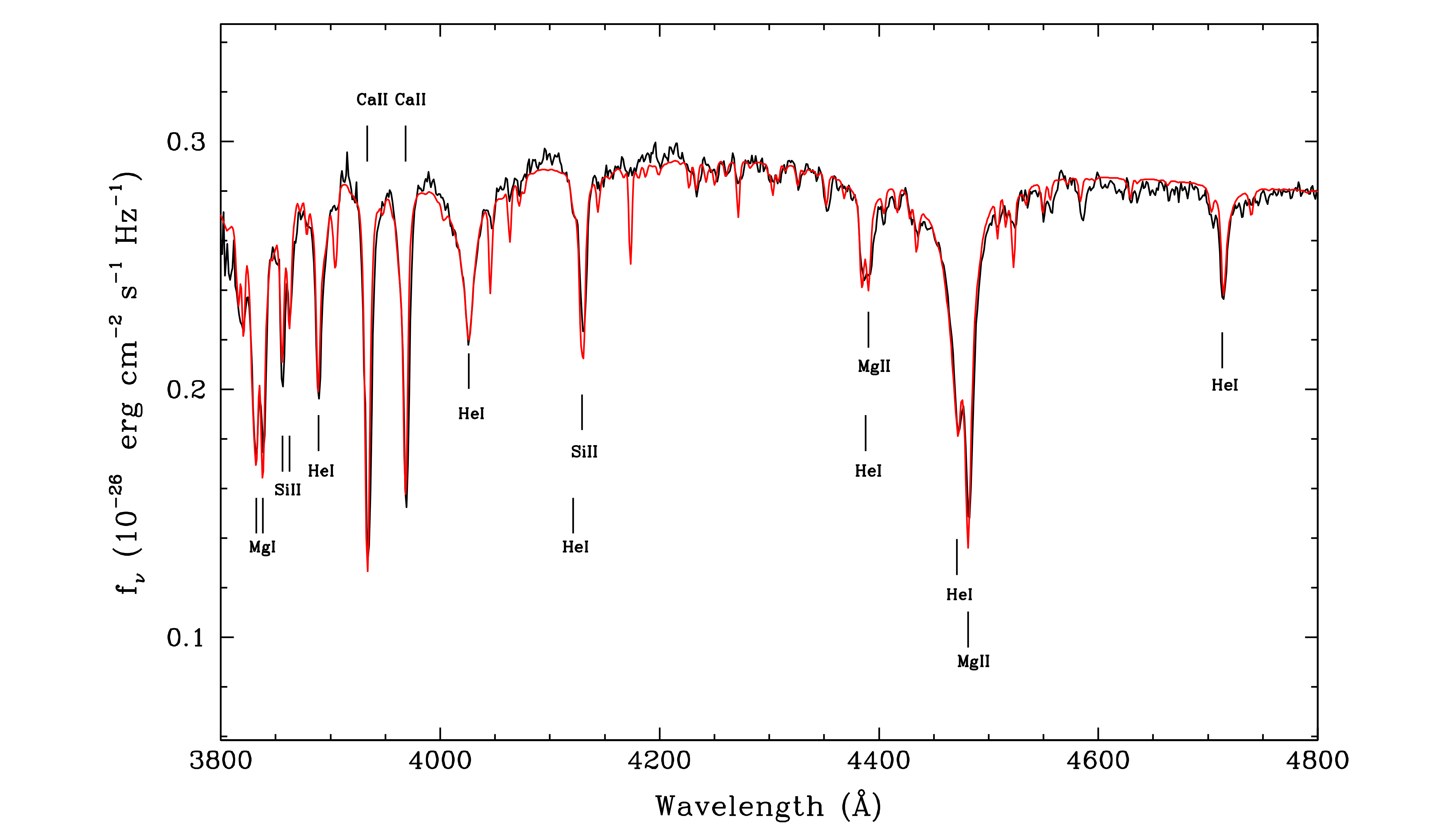
Barstow+ 2001

White dwarfs with heavy element pollution



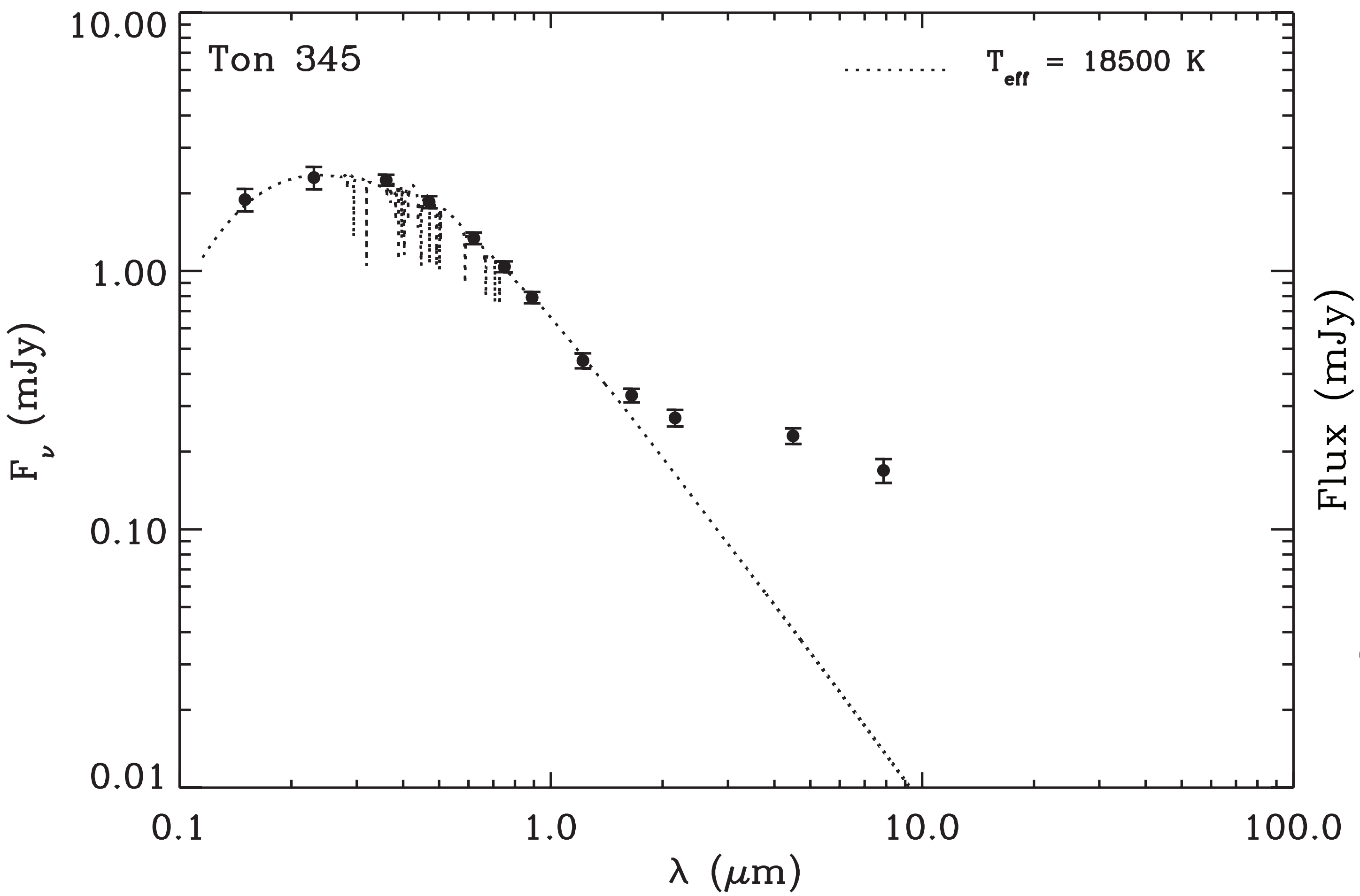
Koester+ 1997

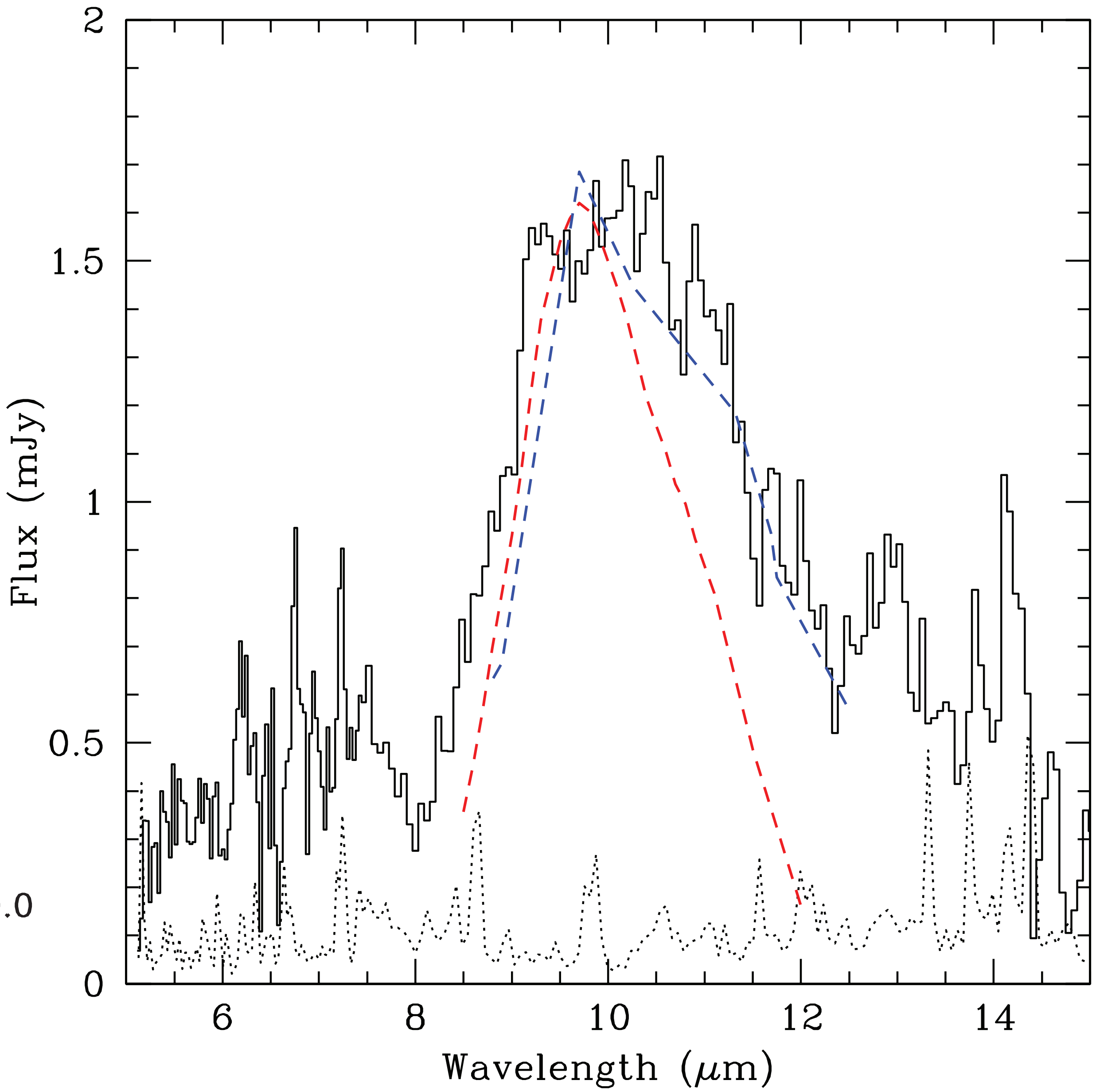
White dwarfs with heavy element pollution



Dufour+ 2010

Dusty disk/metal connection

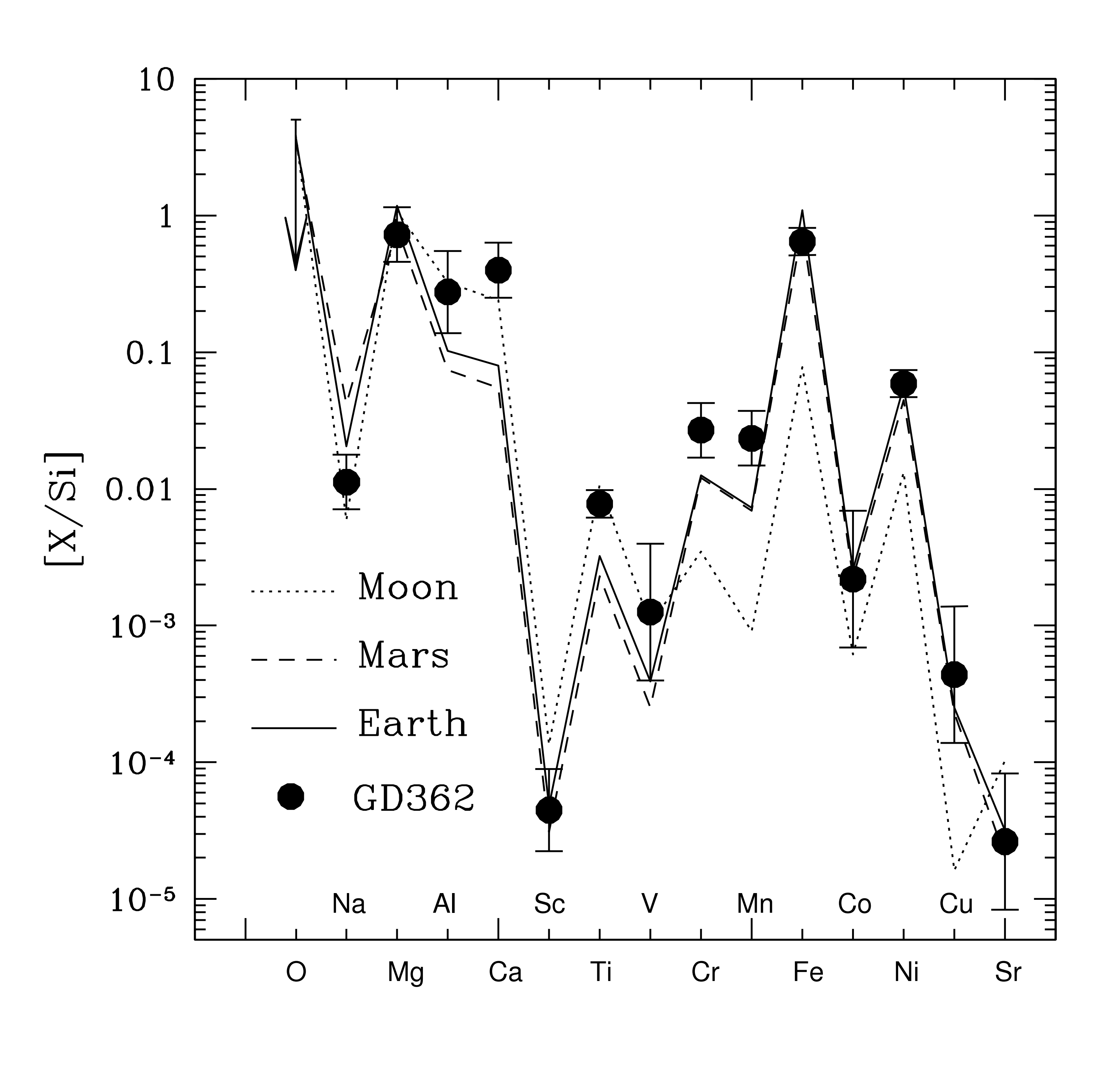




Farihi+ 2010

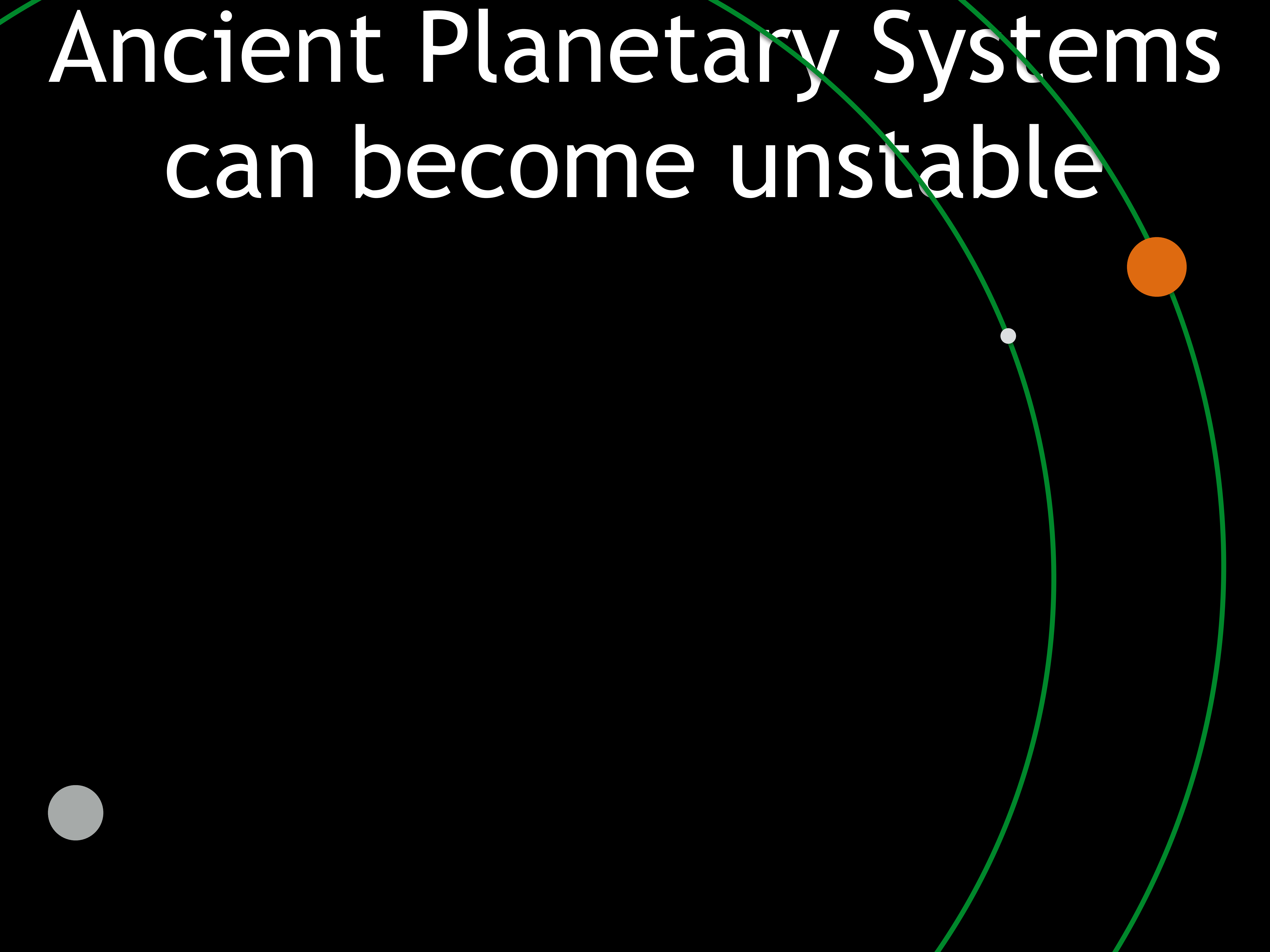
Jura+ 2007

Evidence for accreted planetary material?



Zuckerman+ 2007

Ancient Planetary Systems can become unstable



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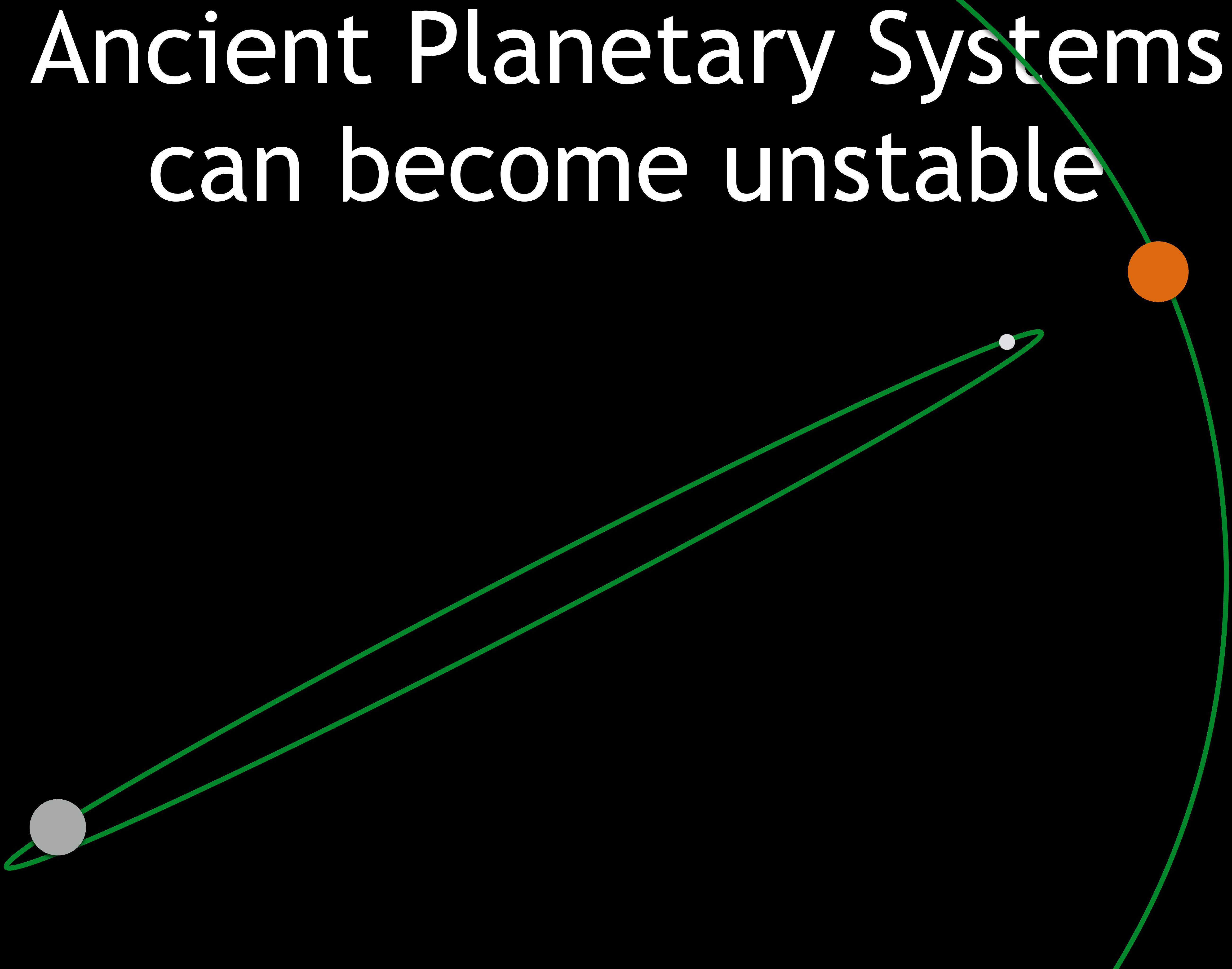
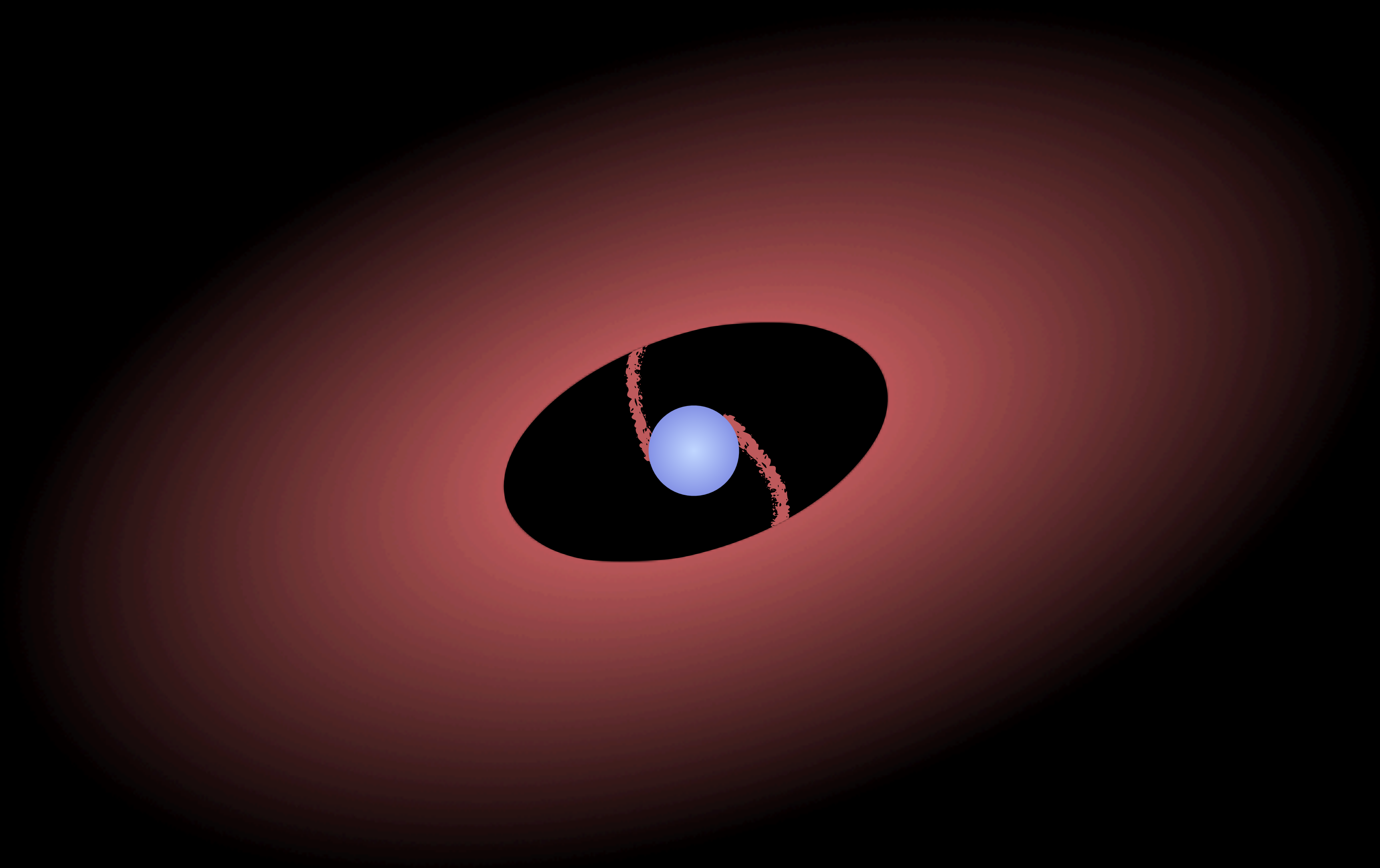


On close passages, objects can be disrupted

esa

www.spacetelescope.org

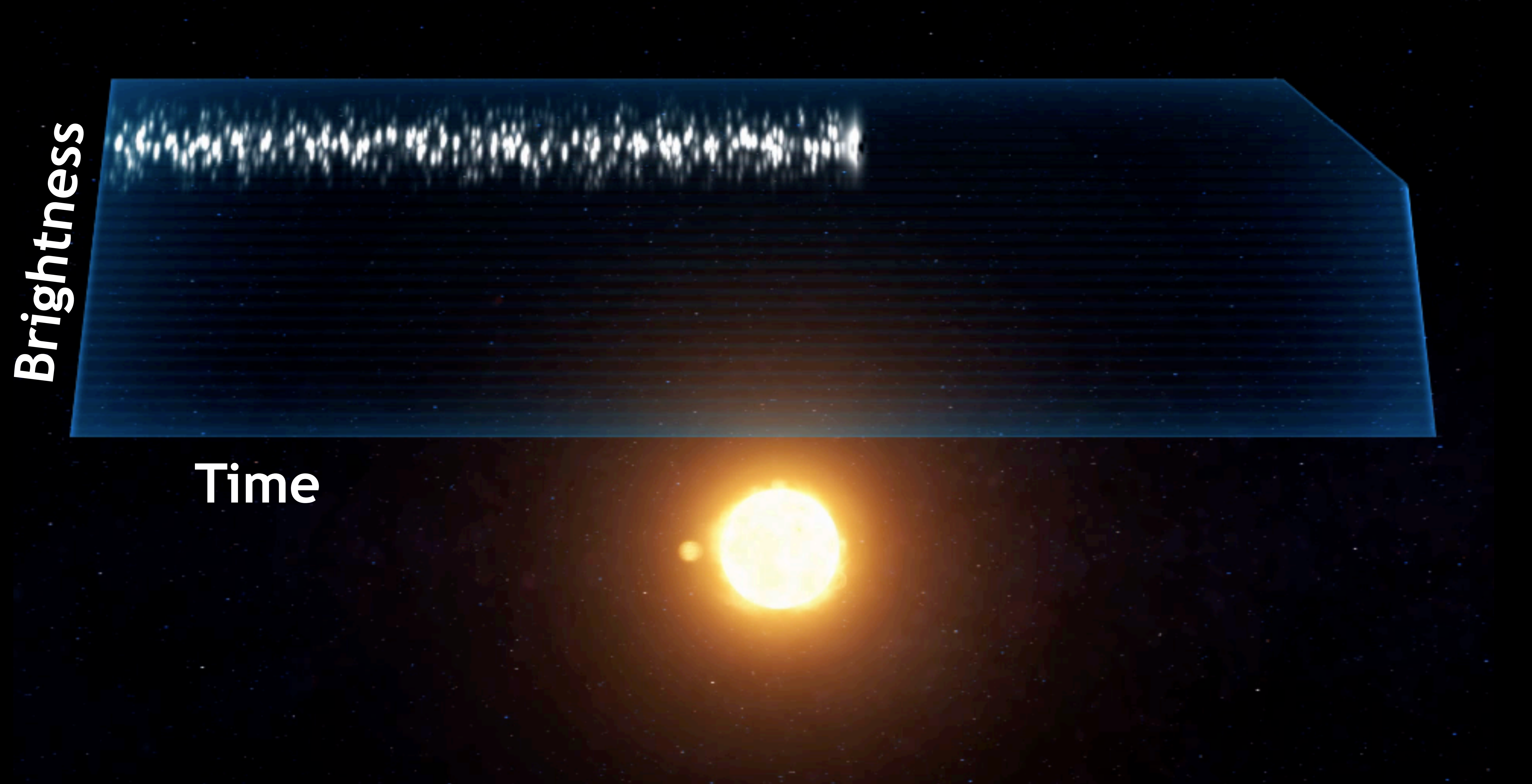
Disrupted material then forms a disk and accretes onto the white dwarf



But how does this process take place?

- Is accretion episodic or steady-state?
- What are the characteristics of the debris? Is it pure dust, or are there larger bodies?
- What is the size of the dust particle?
- Are the accreted objects differentiated (core/mantle)?

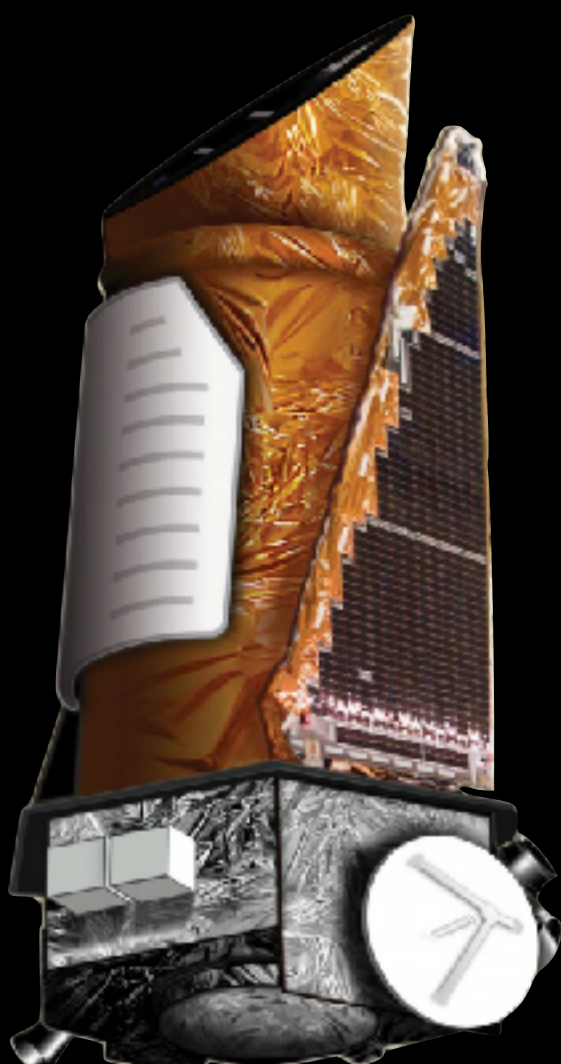
Planets with orbits aligned with our line of sight transit their stars and cause the star's brightness to dim.

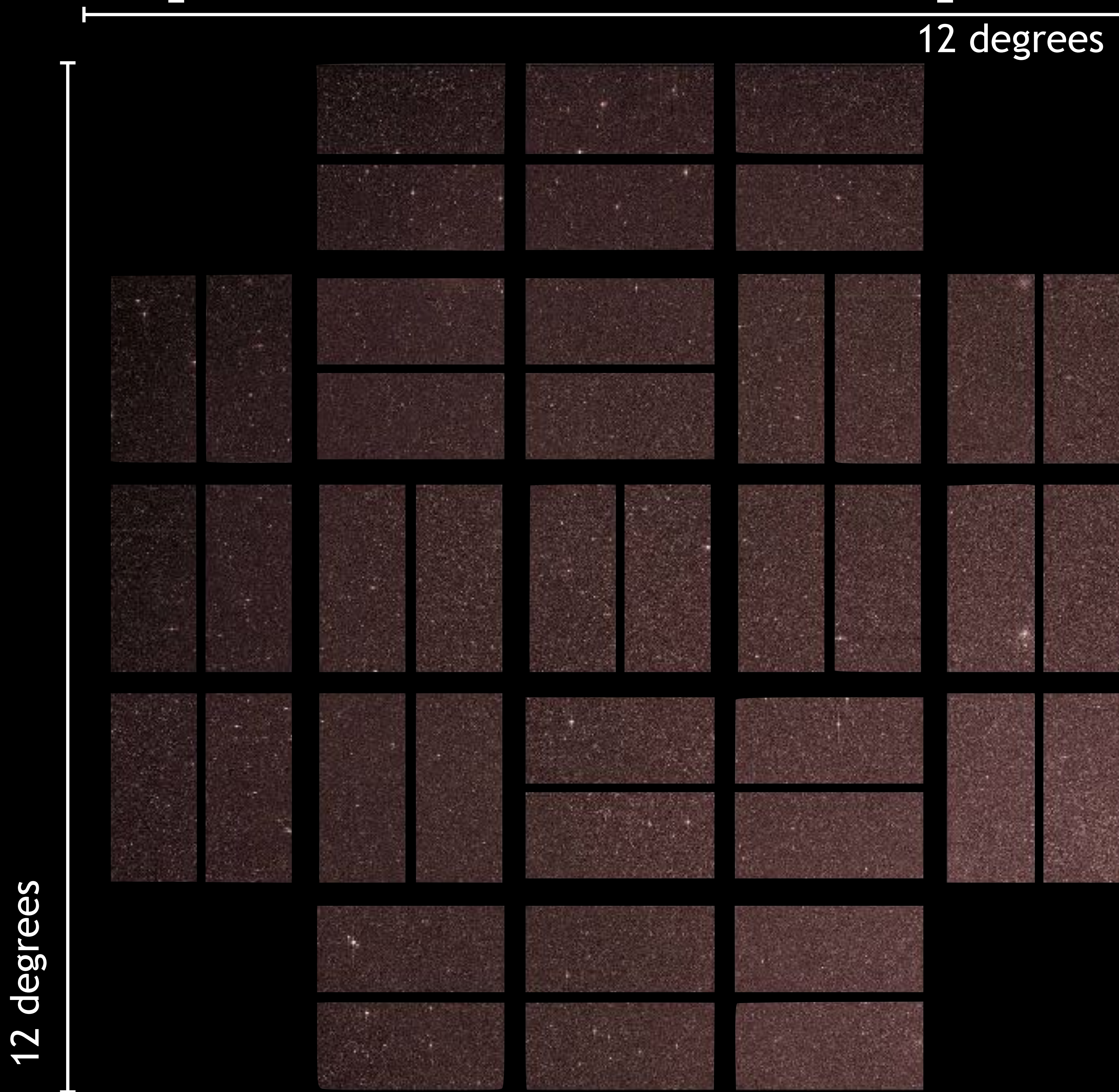


Animation: NOVA

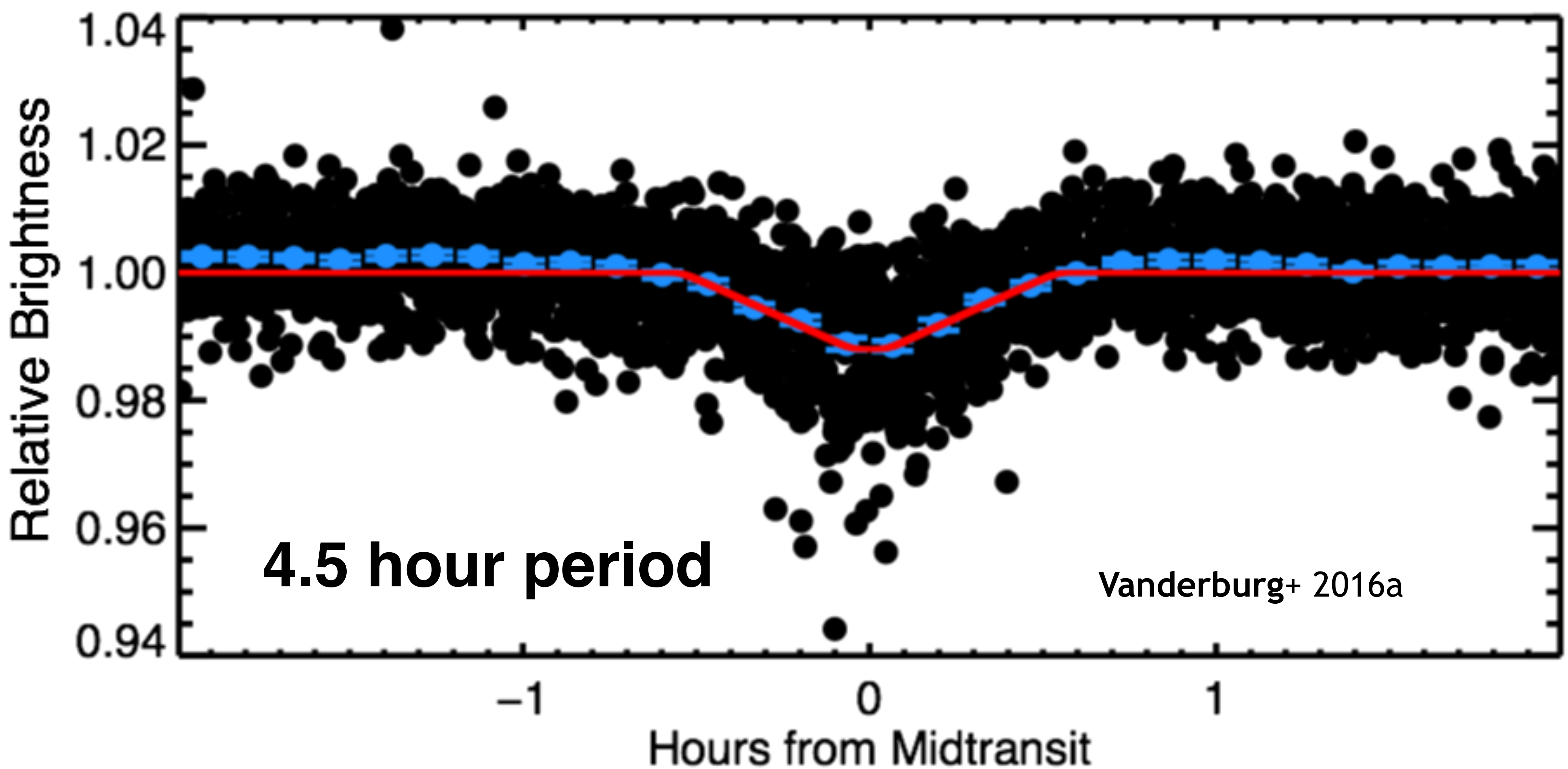
Kepler Space Telescope

0.95 meter diameter
105 square degree FOV
30 minute cadence

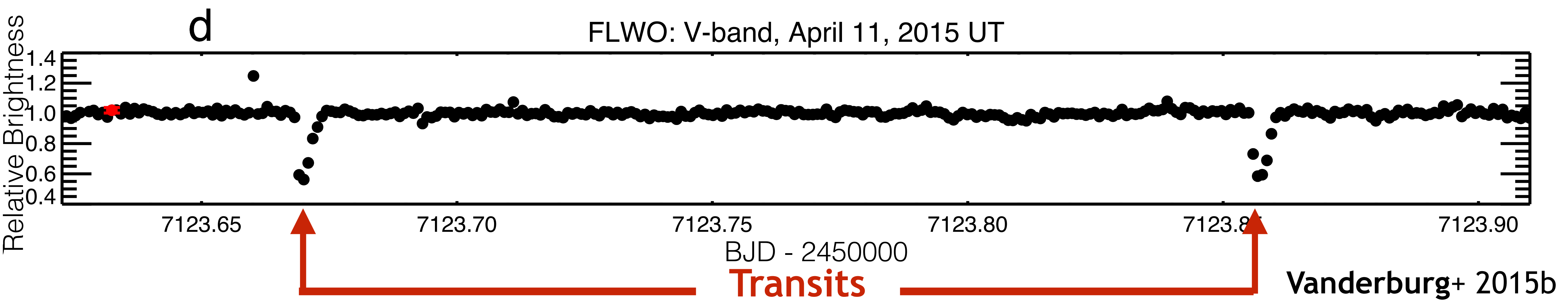




Planet candidate transiting white dwarf WD 1145+017

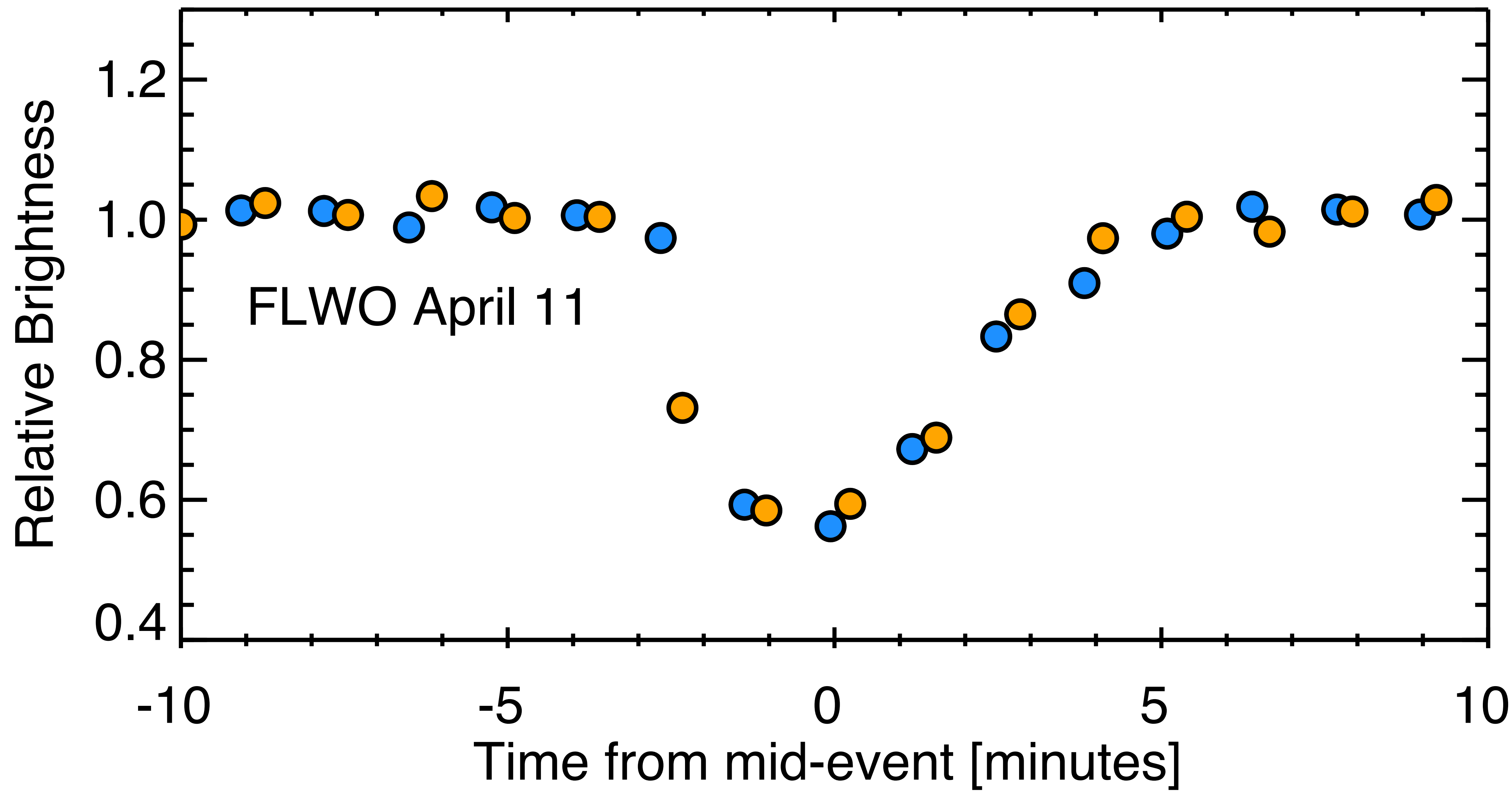


Ground-based follow-up data



Vanderburg+ 2015b

Ground-based follow-up data



Vanderburg+ 2015b

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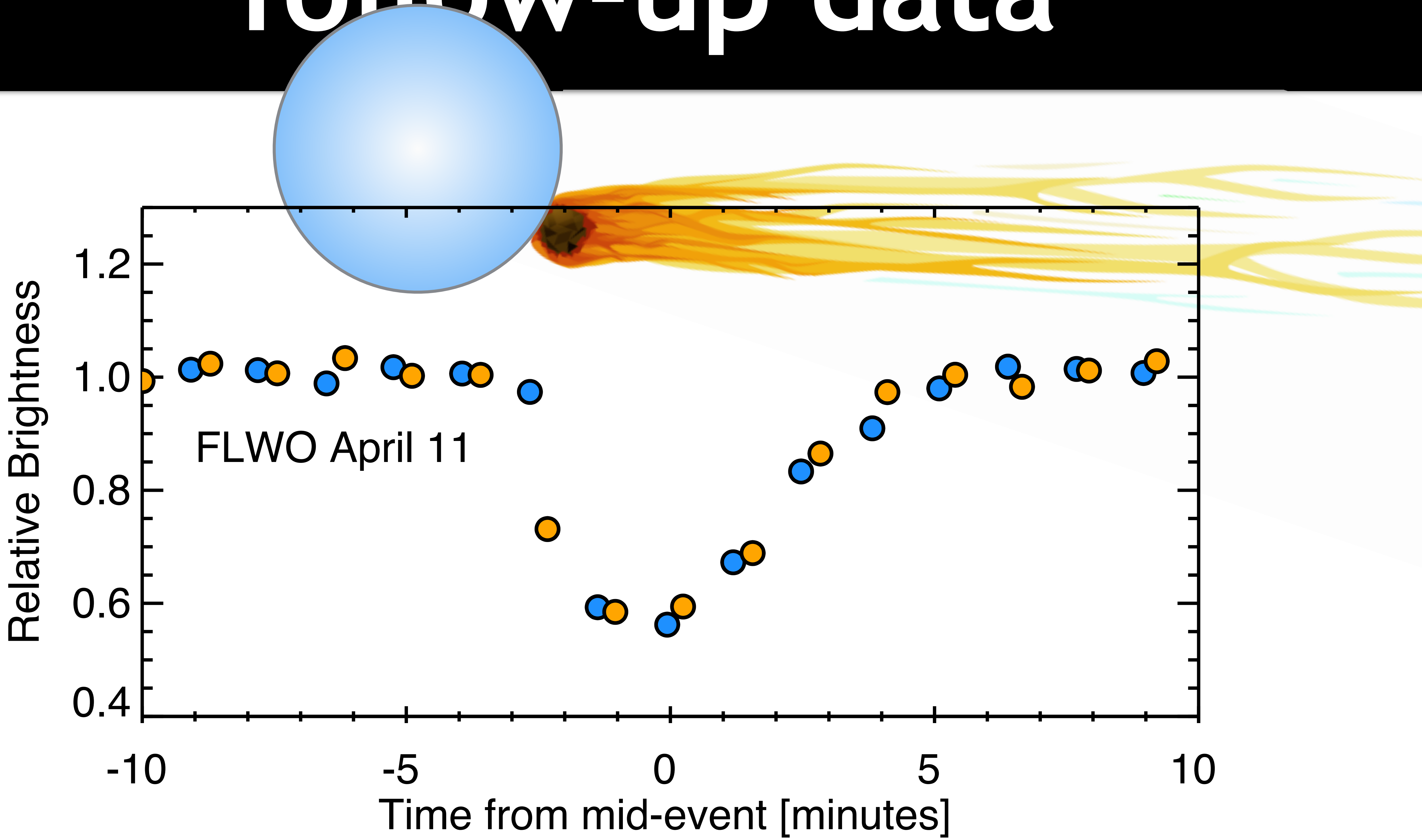
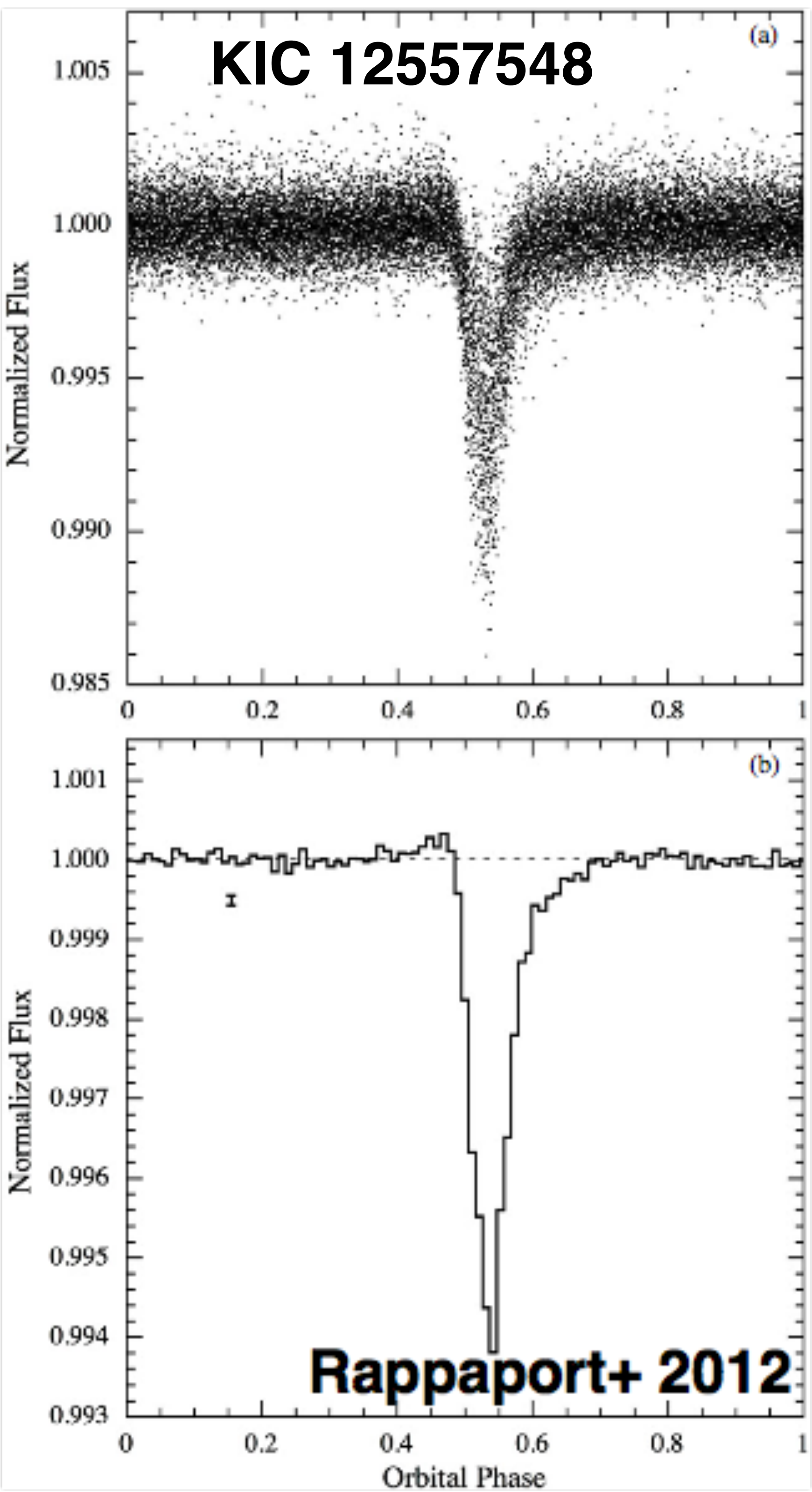
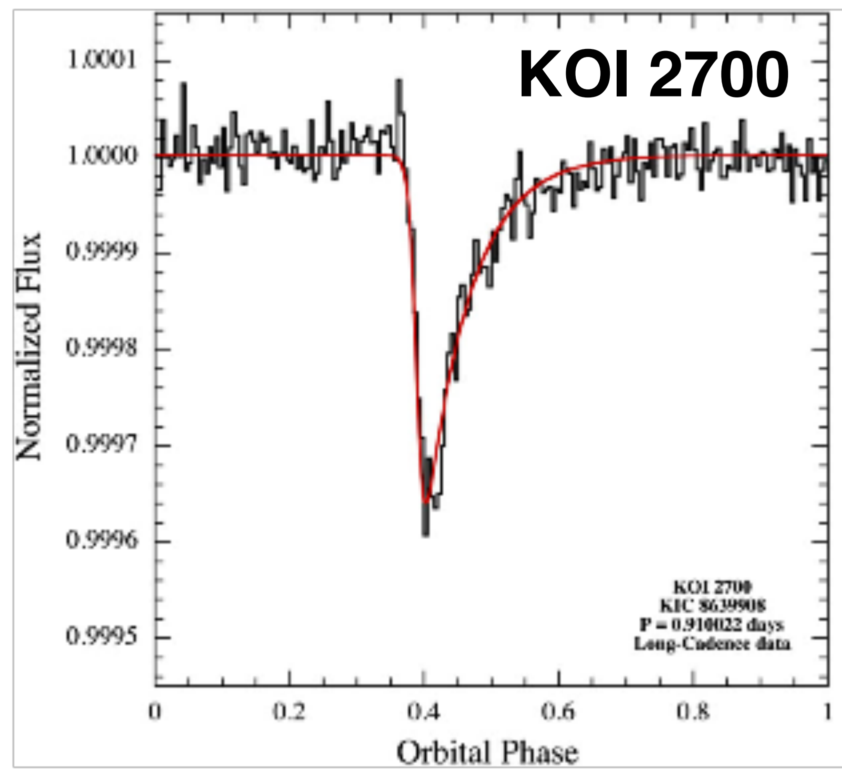


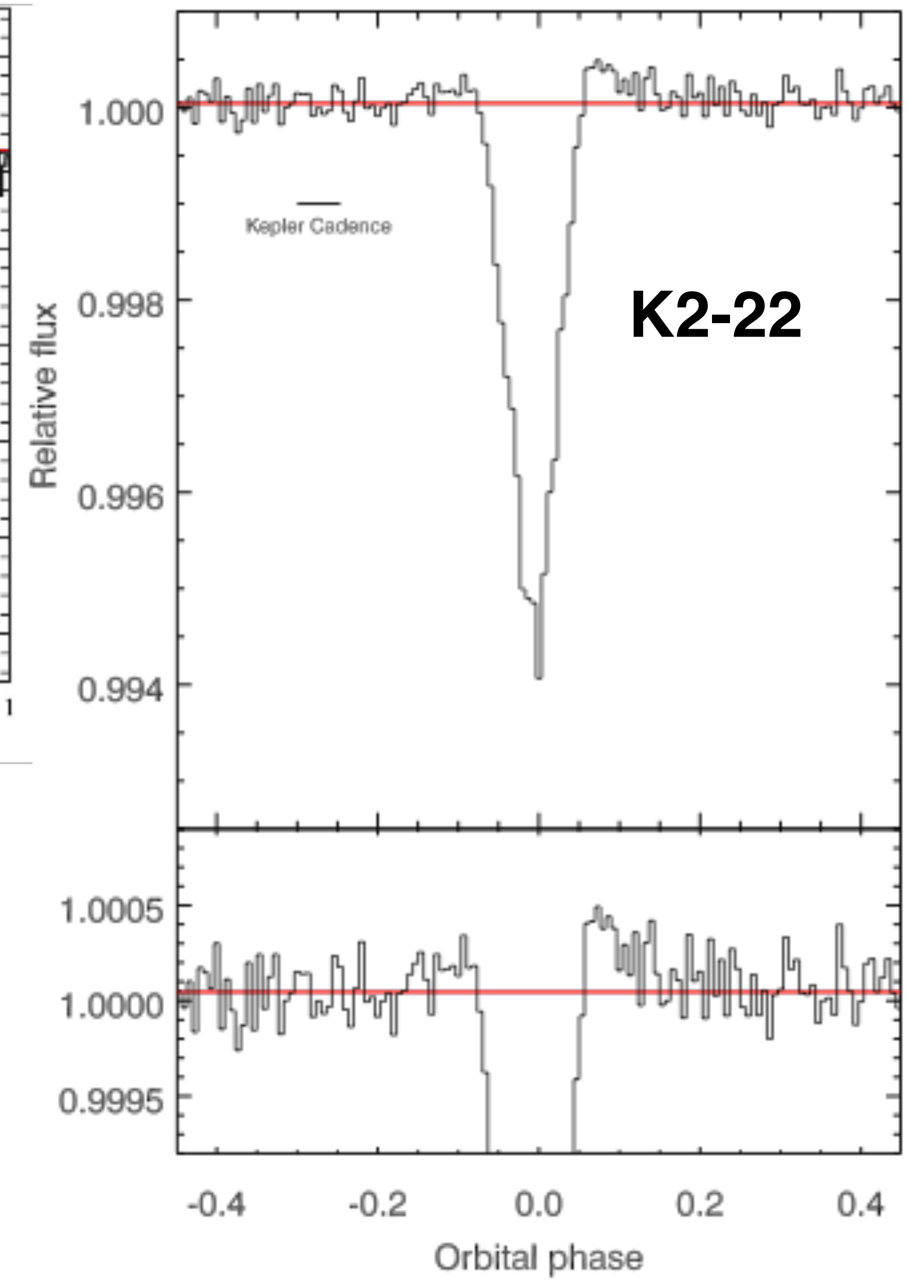
Vanderburg+ 2015b

Disintegrating Planets



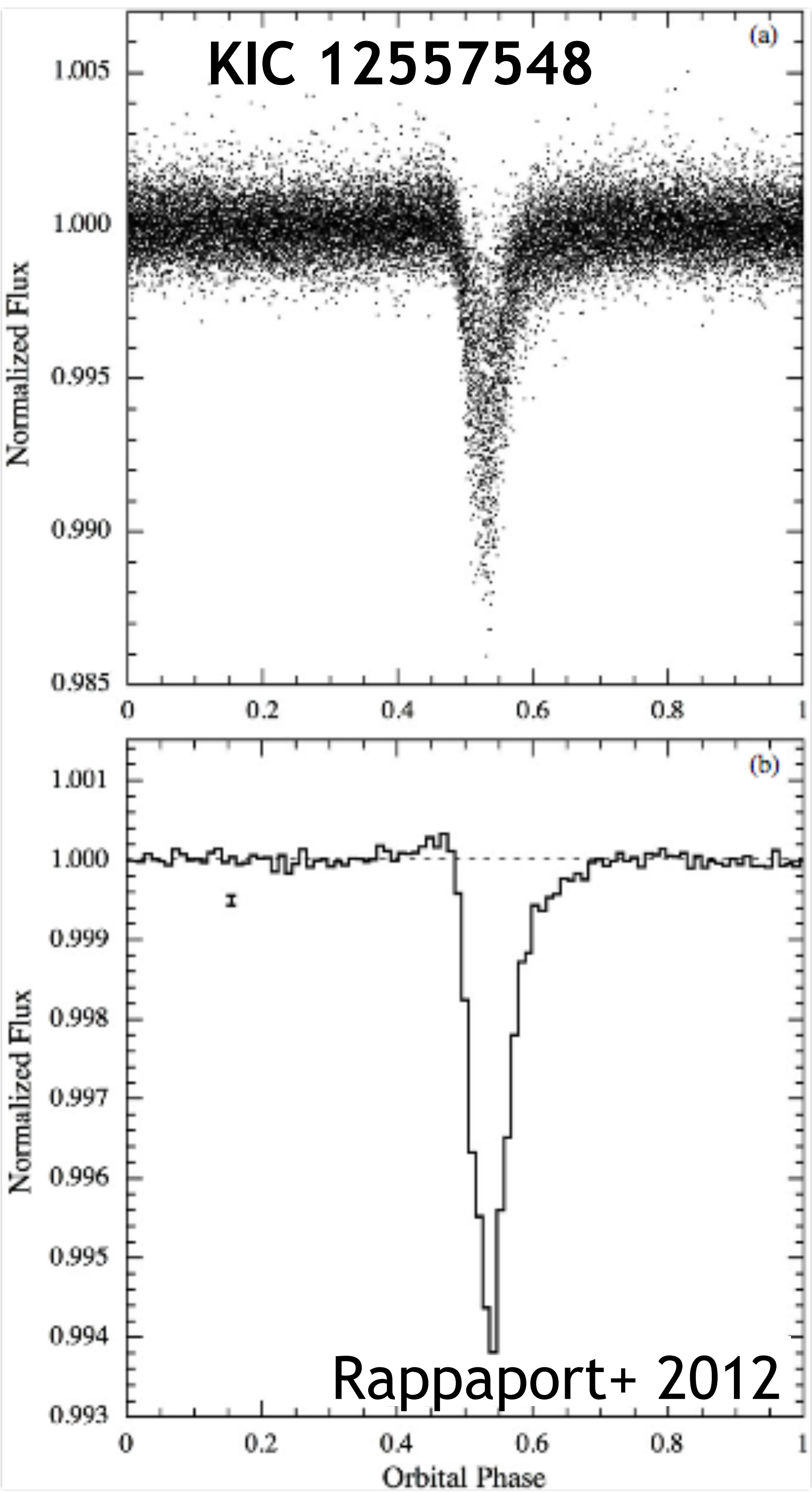


Rappaport+ 2014

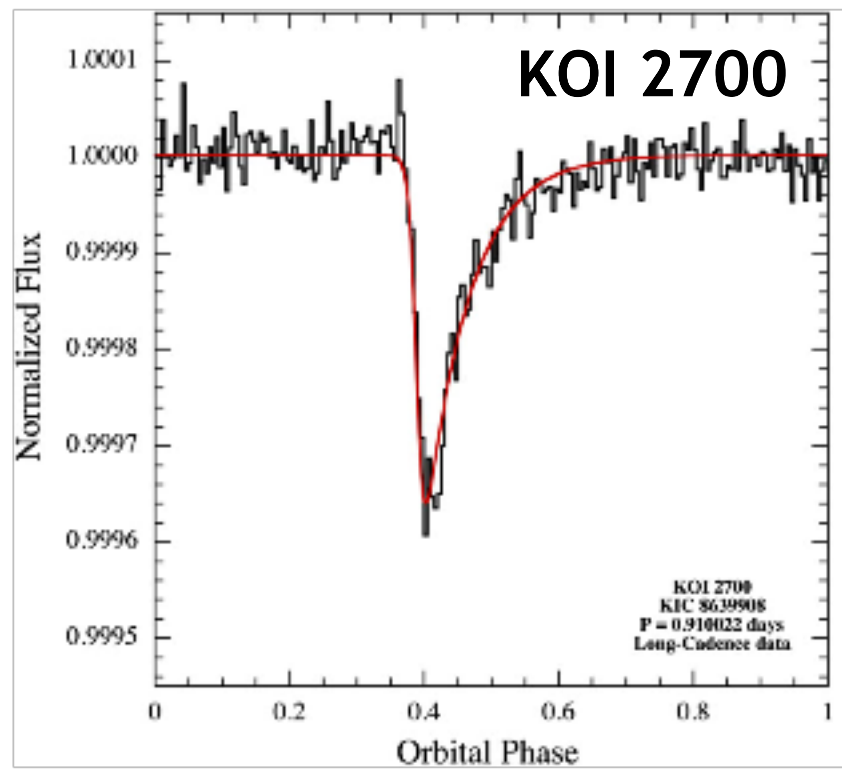


Sanchis-Ojeda+ 2015

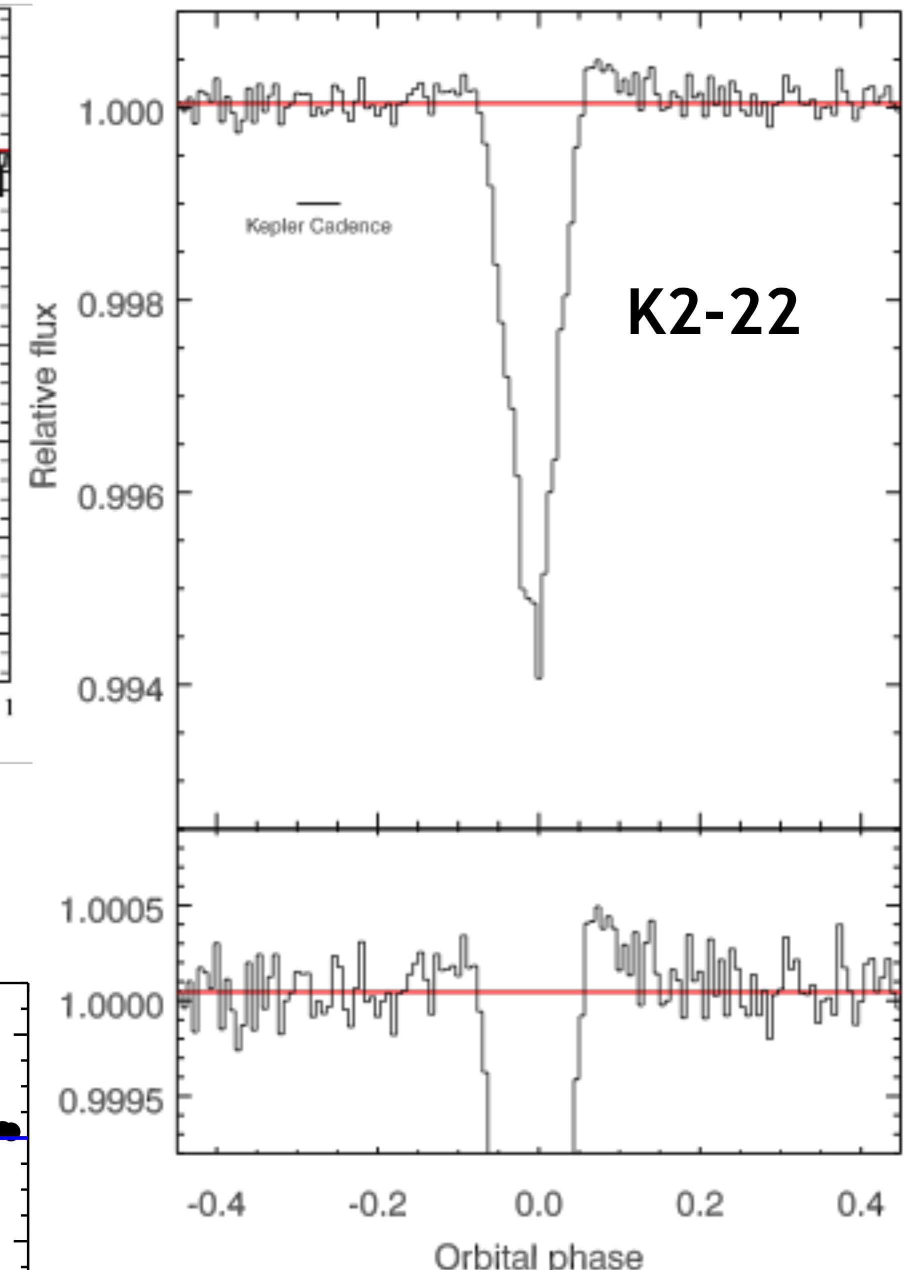
Disintegrating Planets



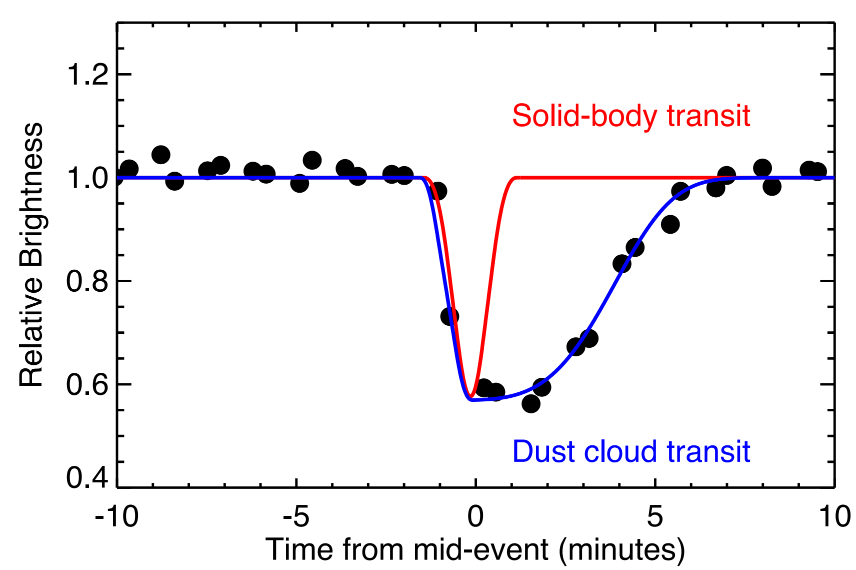
Rappaport+ 2012



Rappaport+ 2014



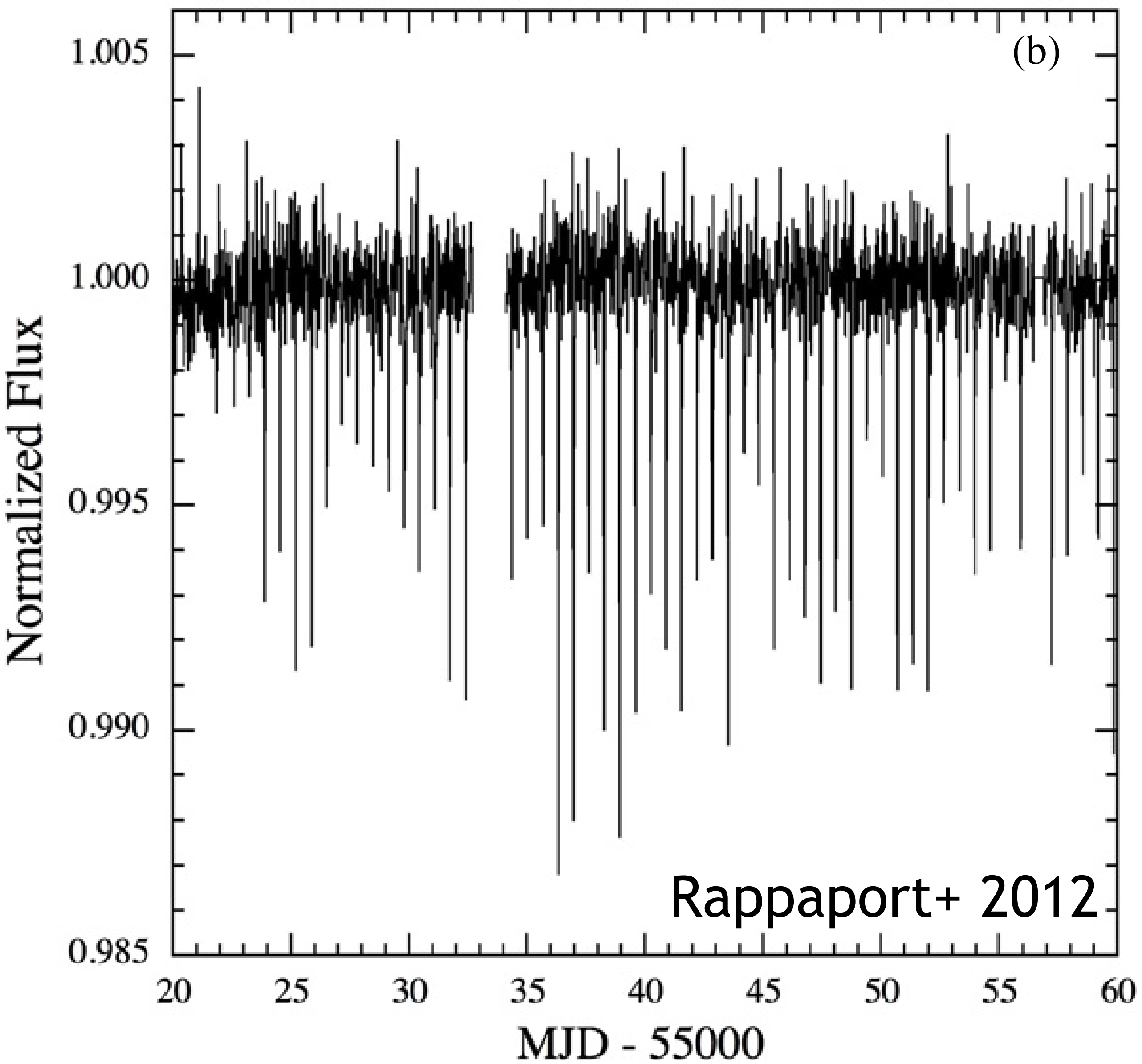
Sanchis-Ojeda+ 2015



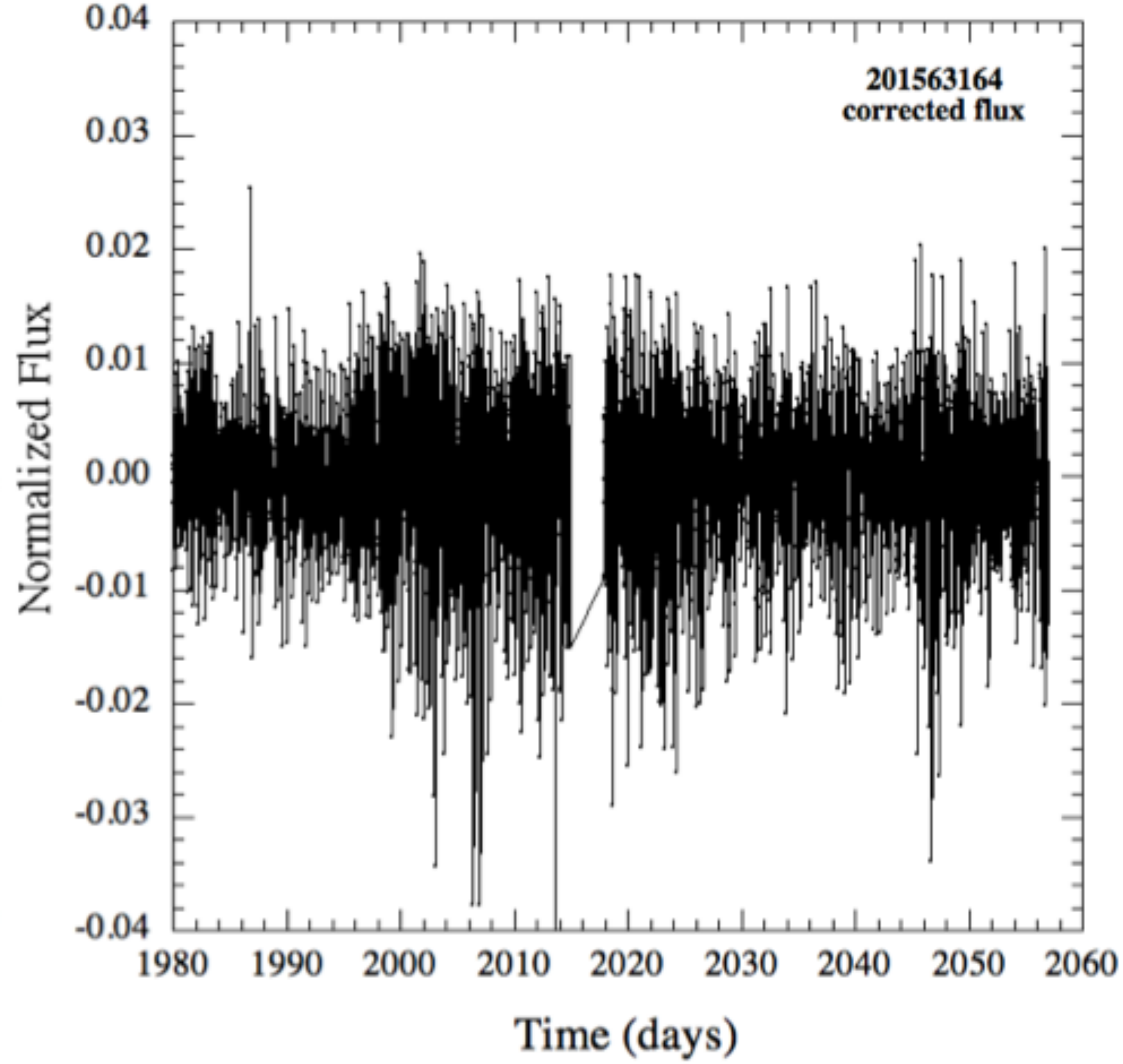
Vanderburg+ 2015b

Transit Depth Variations

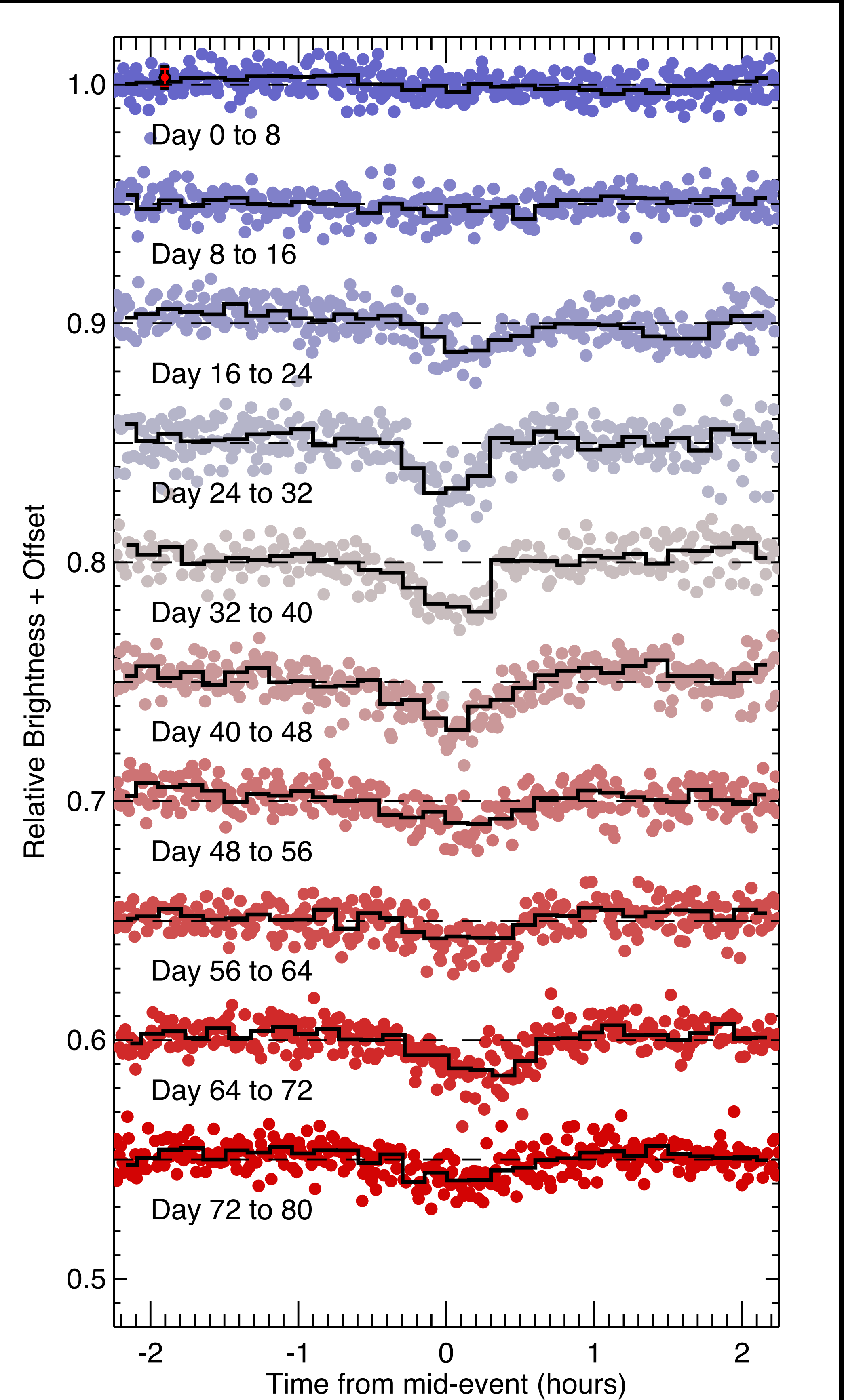
KIC 12557548



WD 1145+017

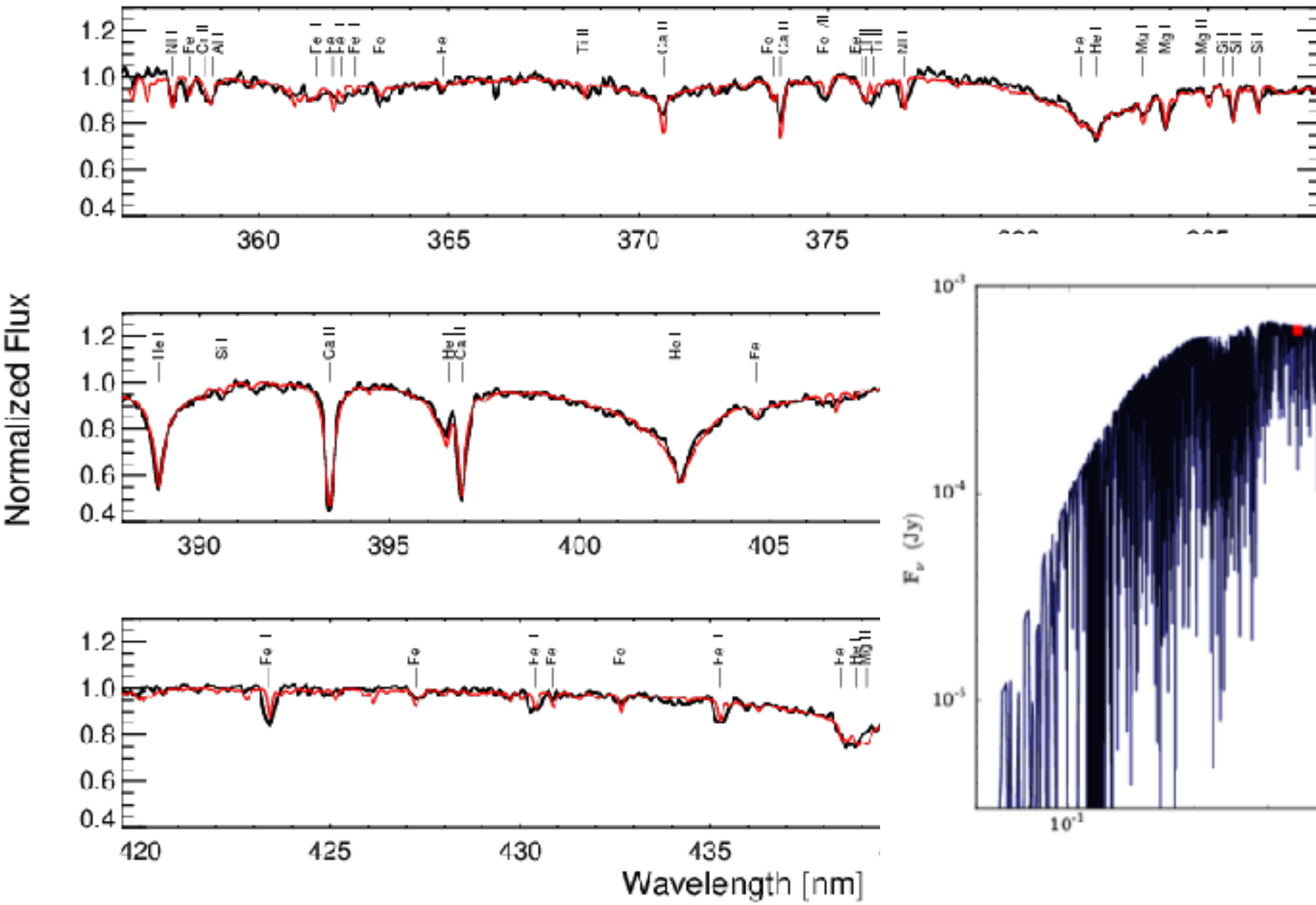


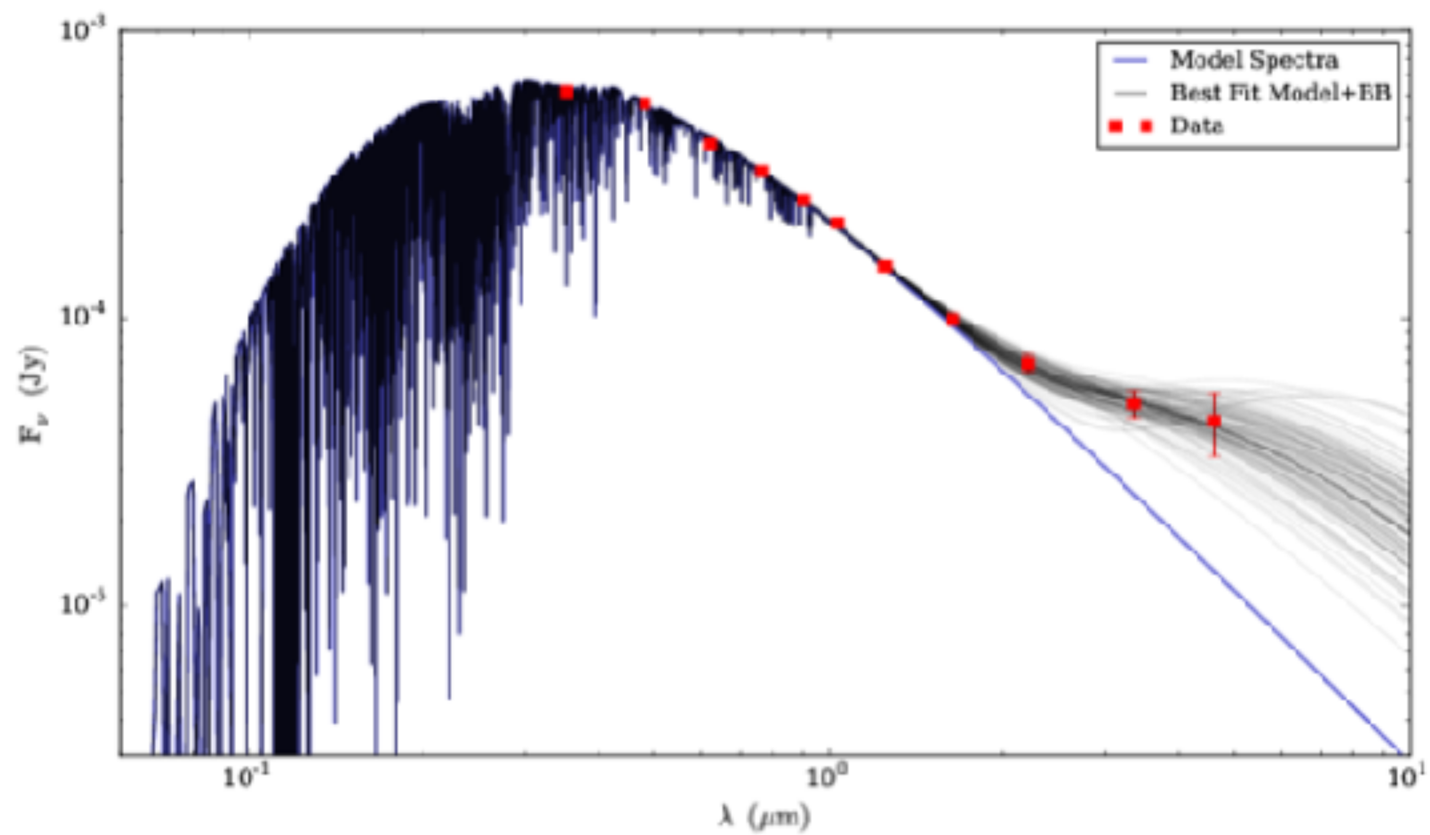
Transit Depth Variations



Vanderburg+ 2015b

WD 1145+017 is a metal-rich WD with a disk



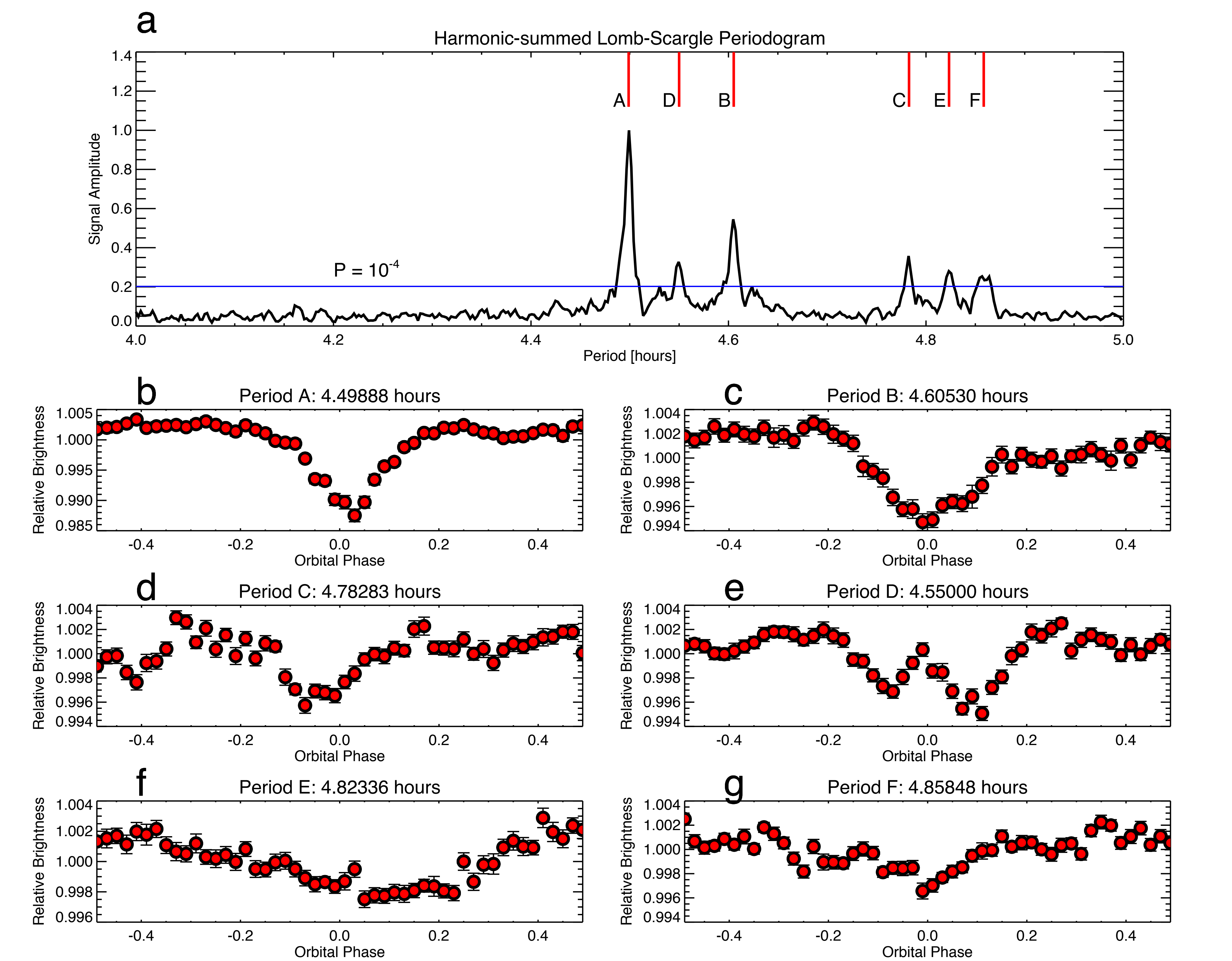


Vanderburg+ 2015b

We are watching the disruption of a minor planet in real time.

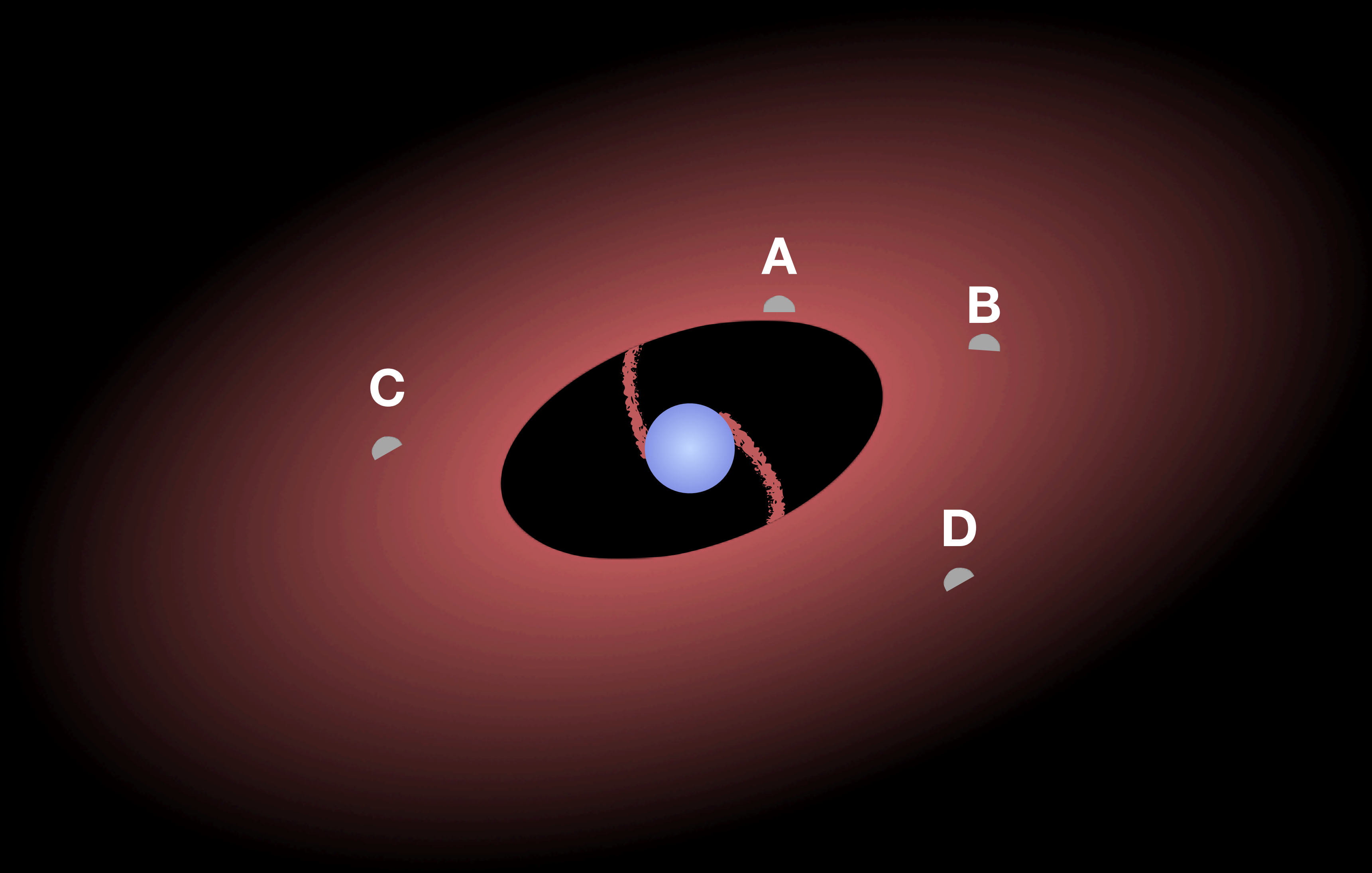
Image: Mark A. Garlick

Additional Stable Periods in K2-multiple bodies?

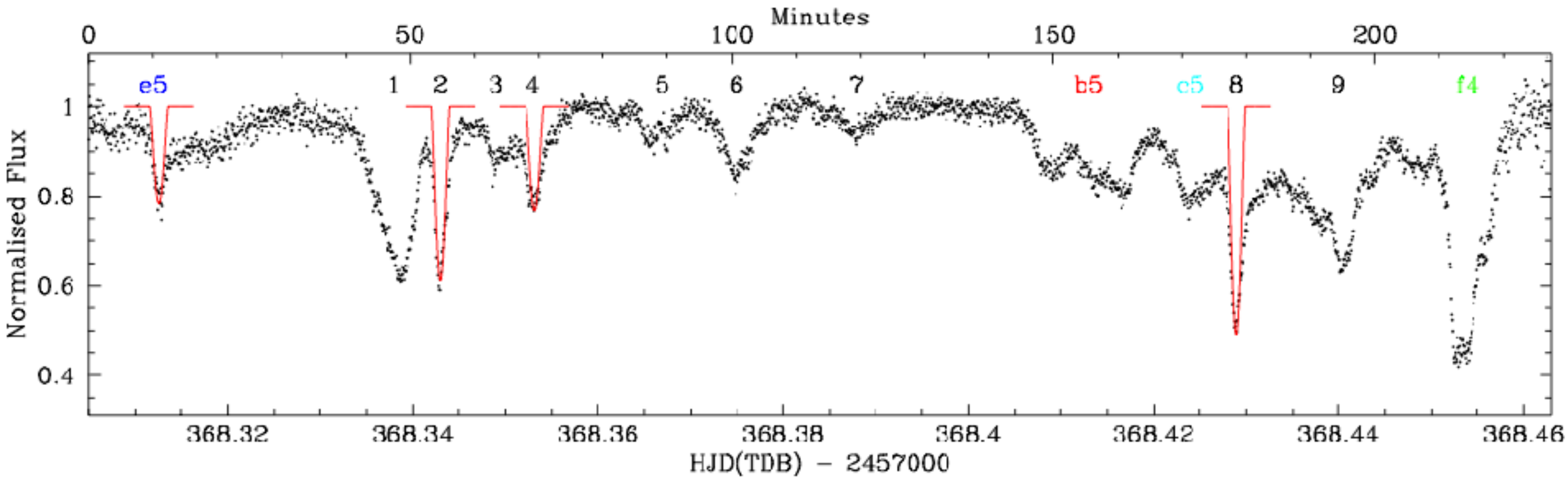


Vanderburg+ 2015b

Periods are stable for months-years — implies massive bodies/fragments



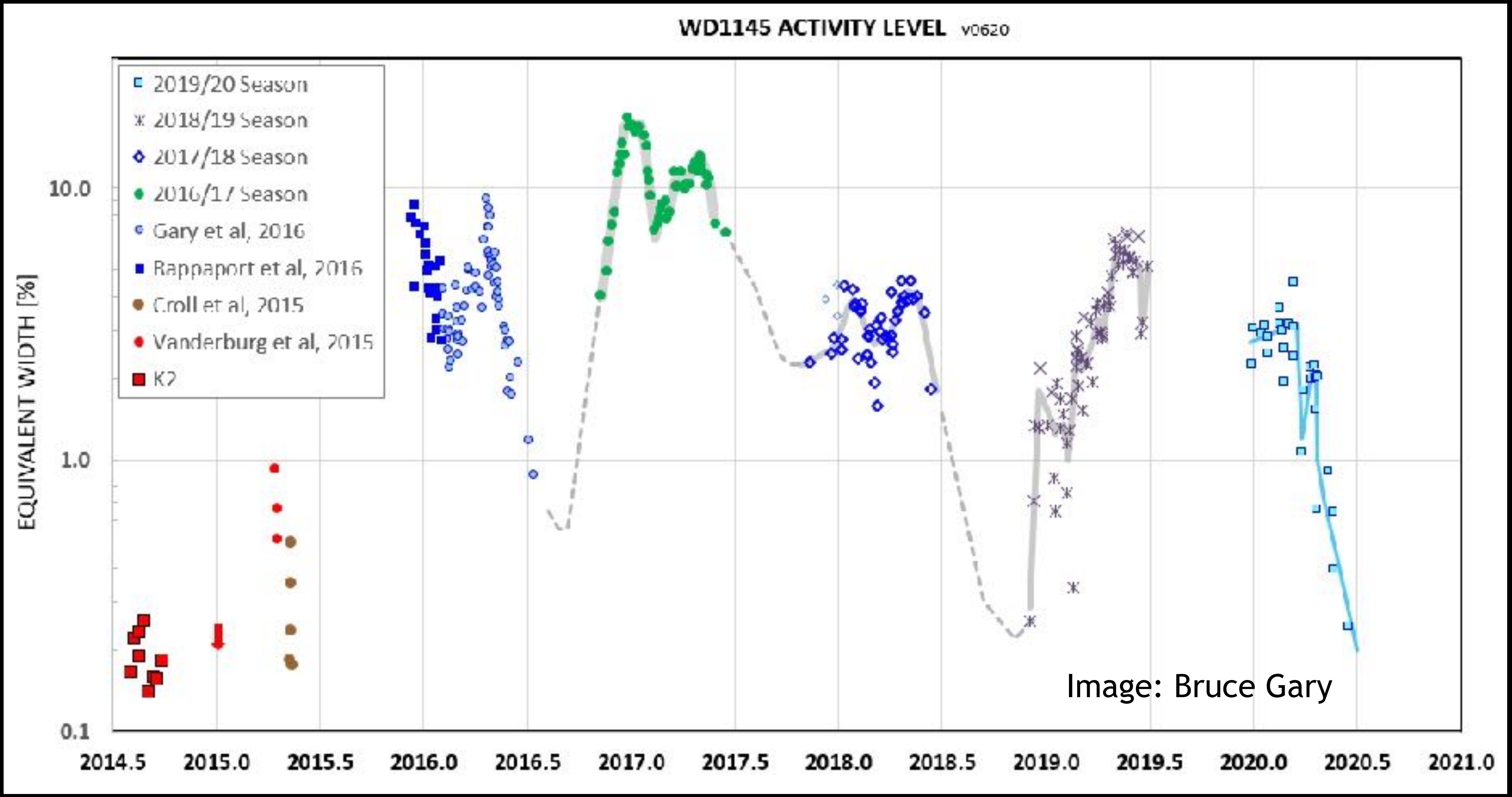
Observations of WD 1145+017 six months later



Gaensicke+ 2016

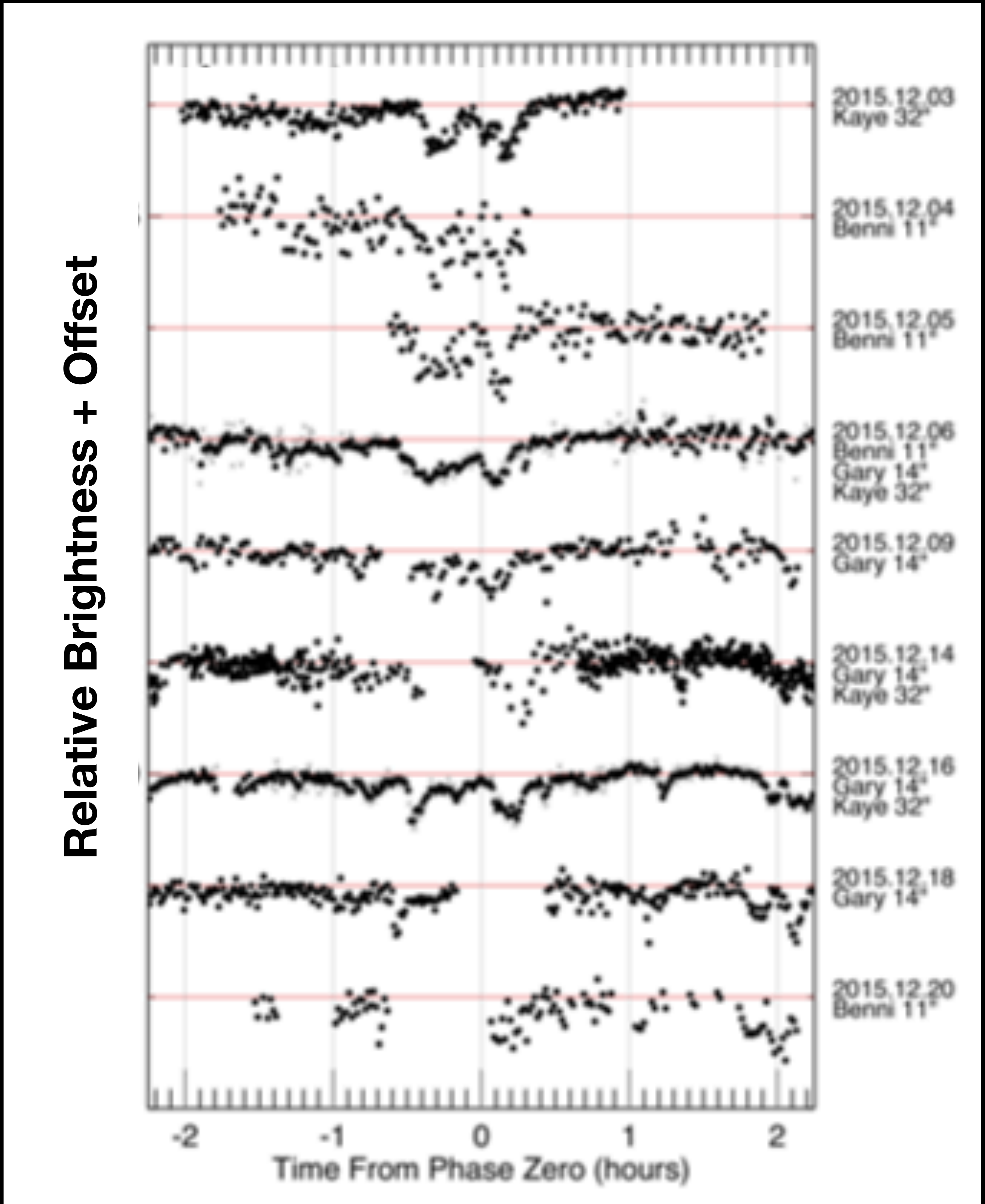
Rapid evolution: 10x increase in transit activity

Large changes in transit depth/dust production



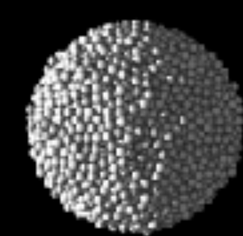
Episodic accretion, not steady state?

Multiple transits spread throughout the orbit



Rappaport et al. 2016
(including **Vanderburg**)

One large asteroid releasing fragments?

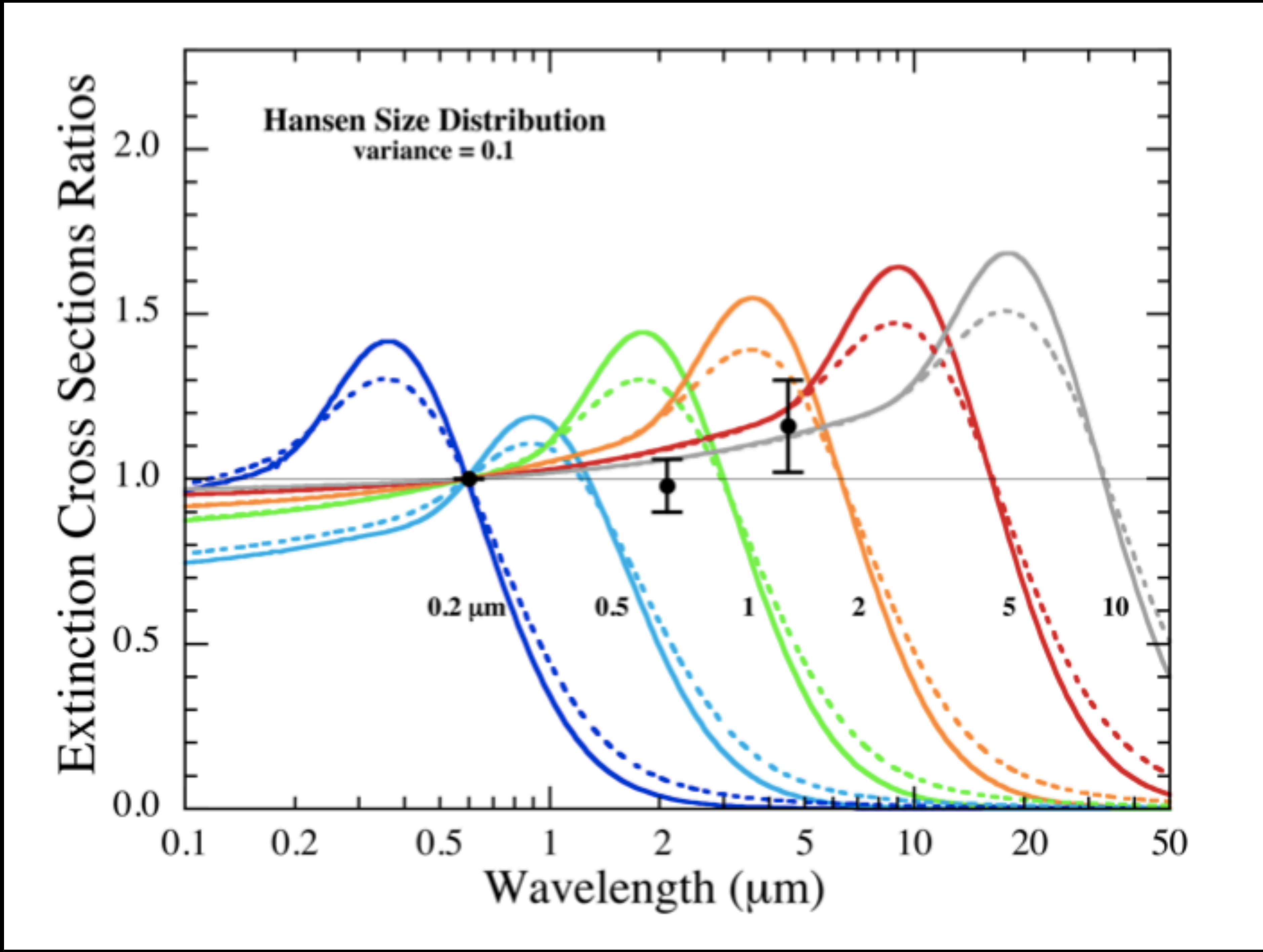


Disruption of a differentiated asteroid seems to match transit behavior

2000 km

Veras+ 2016

Simultaneous Multi-wavelength Transits show the same transit depth



Xu et al. 2018
(including **Vanderburg**)

Particles larger than ~1 micron

Is WD 1145+017 unusual or typical?

Can we use WD 1145-like objects to make general inferences about white dwarf planet accretion?

Transiting Exoplanet Survey Satellite (TESS)

Four 0.105 meter diameter cameras
2304 square degree FOV
10 minute cadence for the whole sky
2 minute or 20s for selected targets

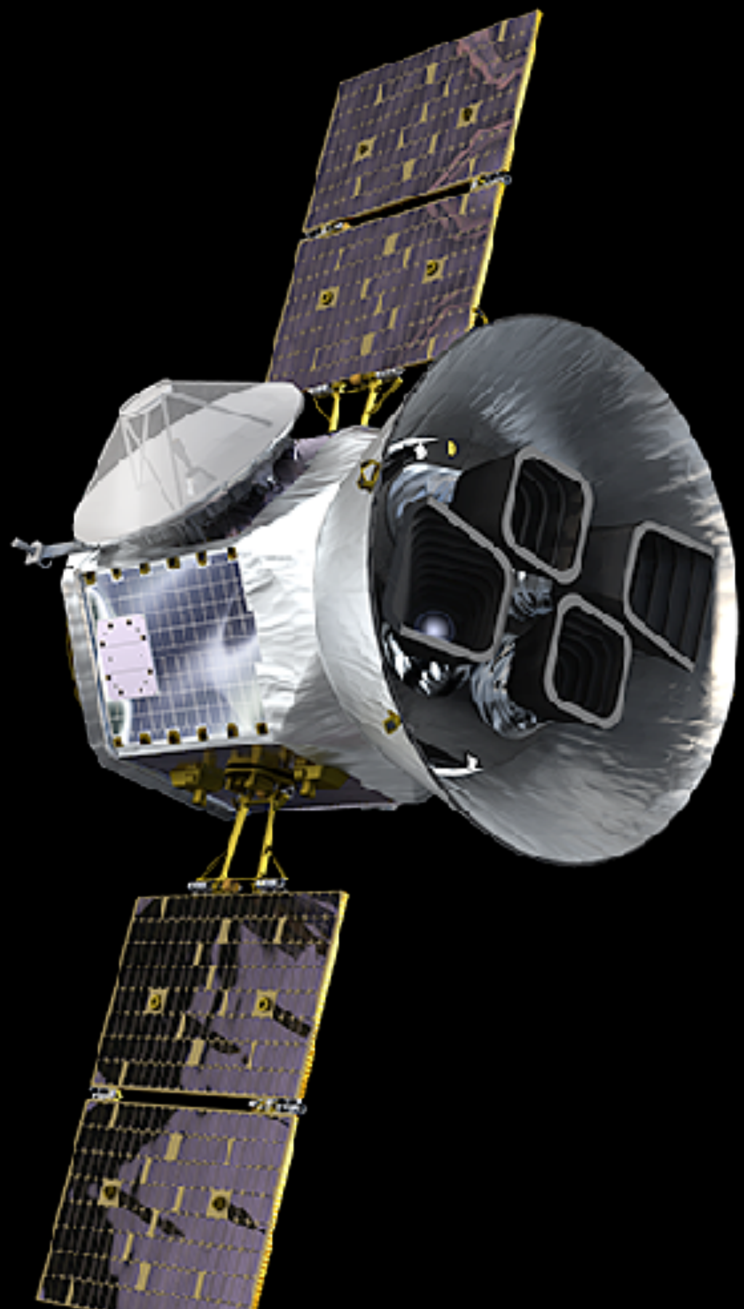
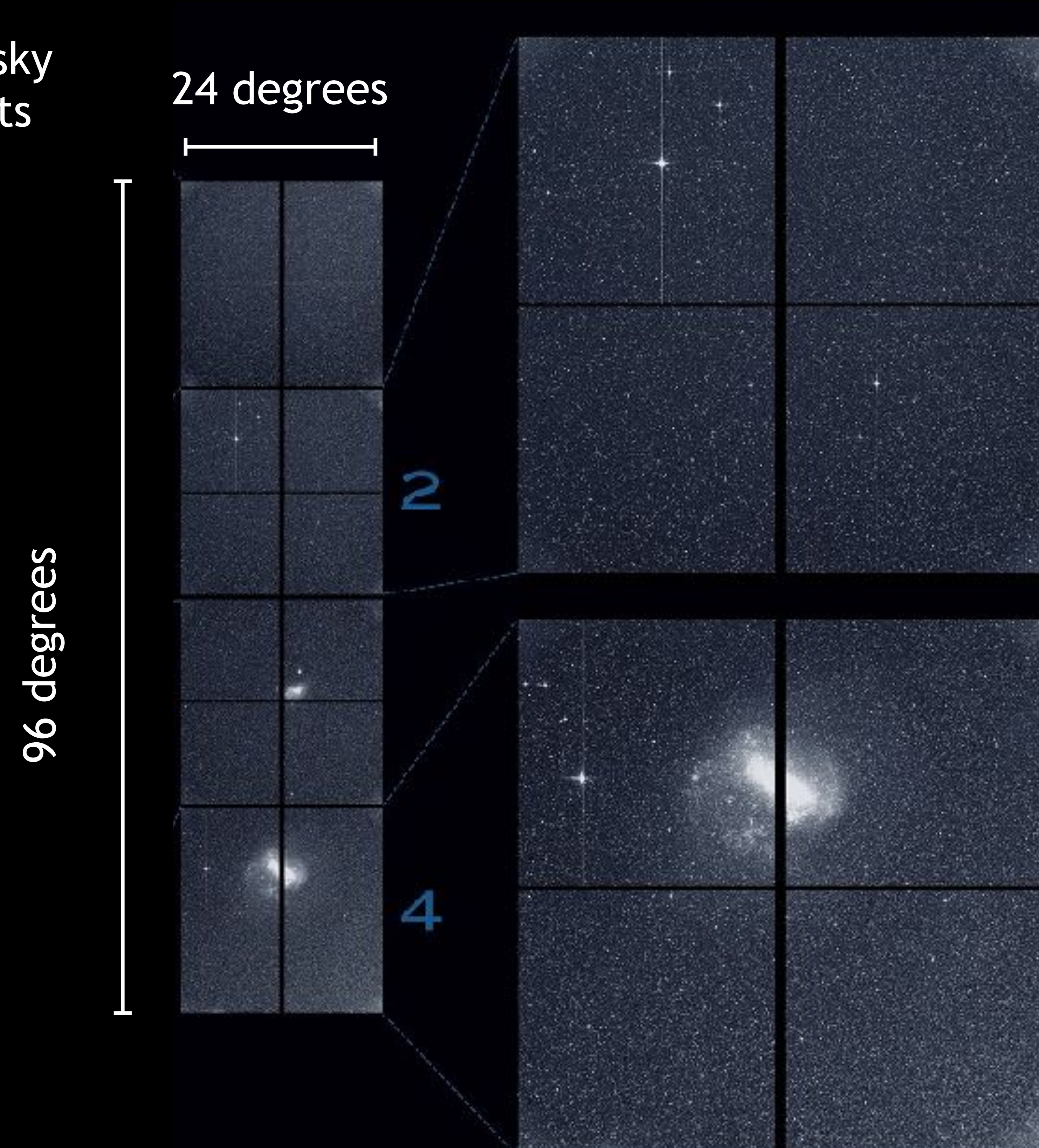
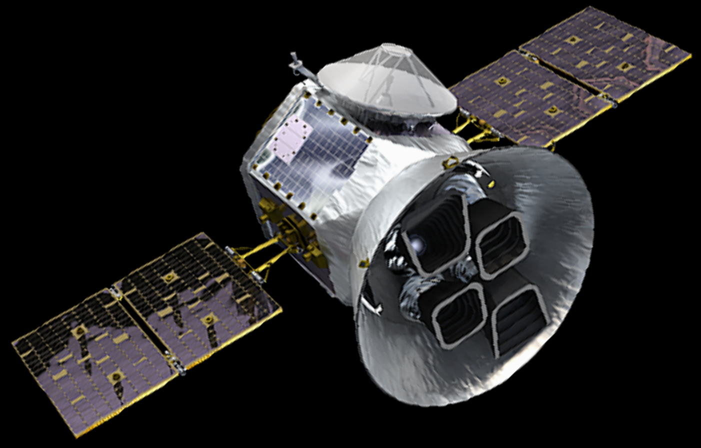
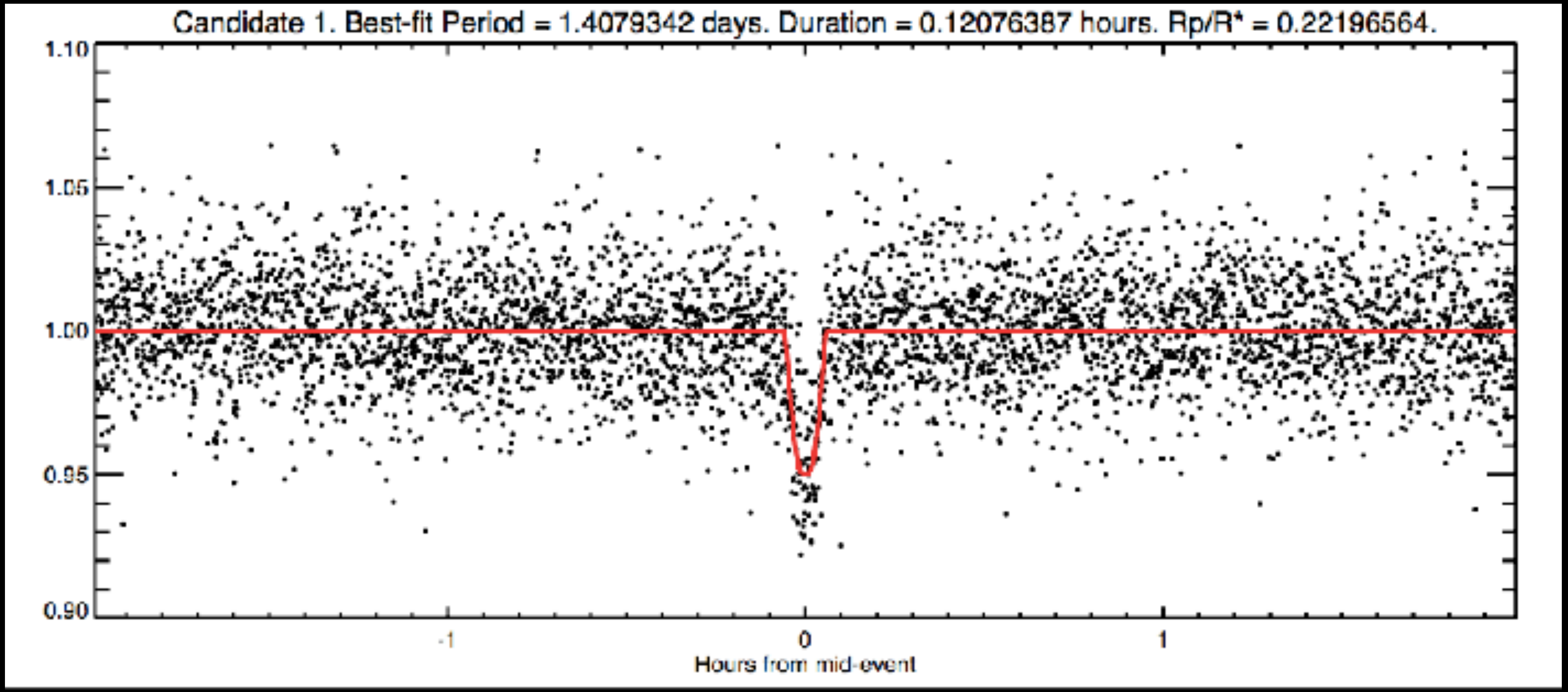


Image: NASA



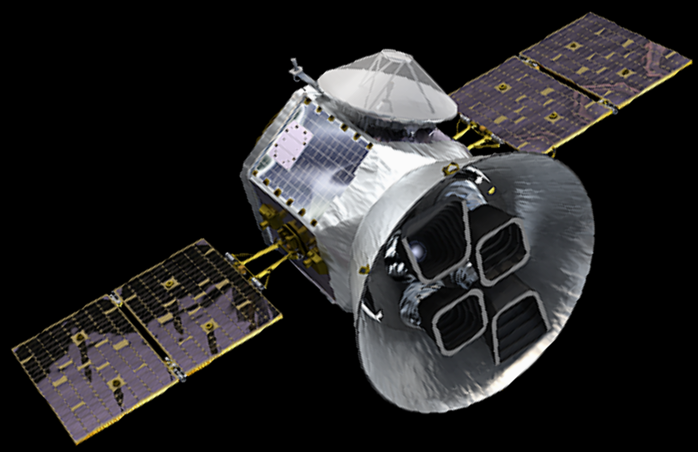
TESS detects transits of a white dwarf



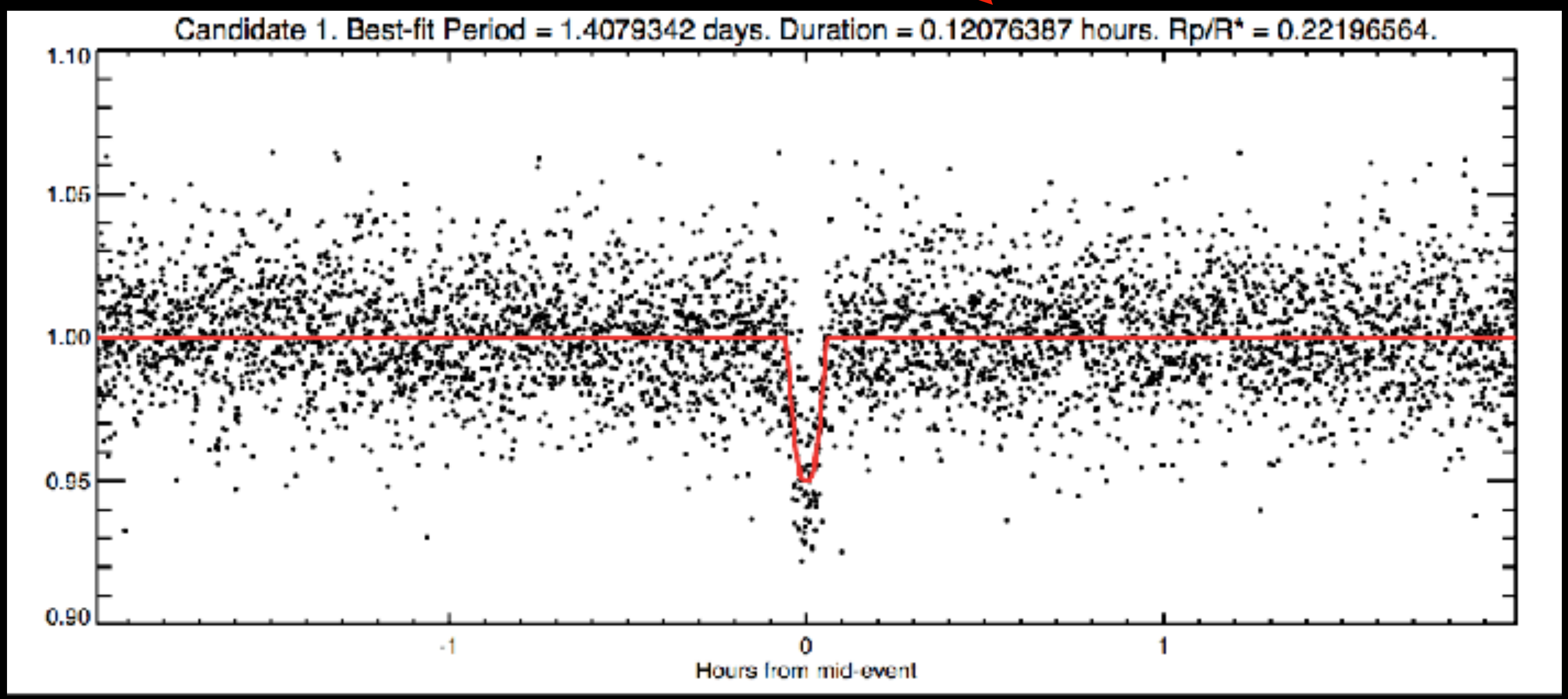


Vanderburg et al. 2020

TESS detects transits of a white dwarf

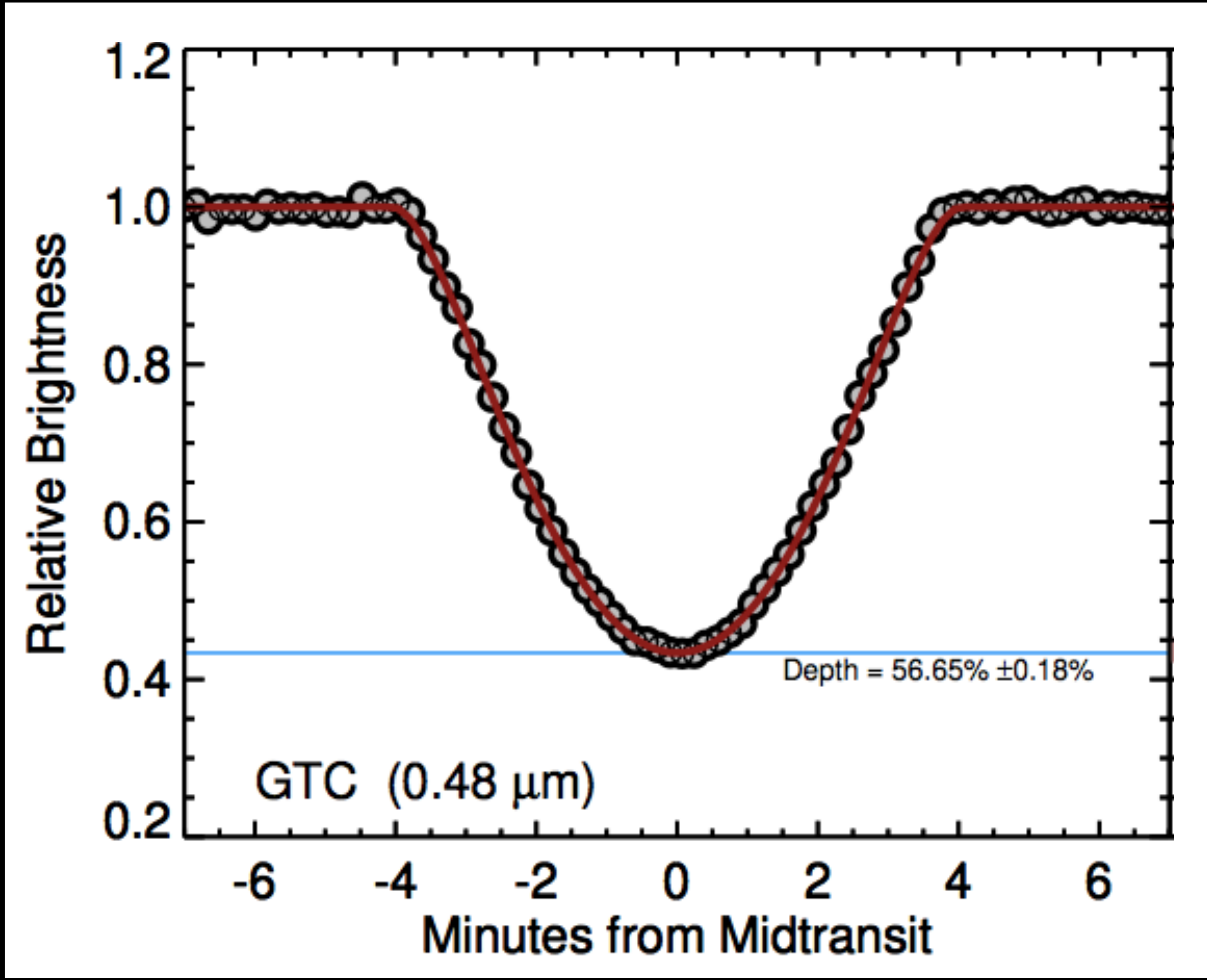


~7 minute transit duration
consistent with WD host



Vanderburg et al. 2020

Ground-based observations reveal a Jupiter-sized companion, and no asymmetry. An intact planet?



Vanderburg et al. 2020

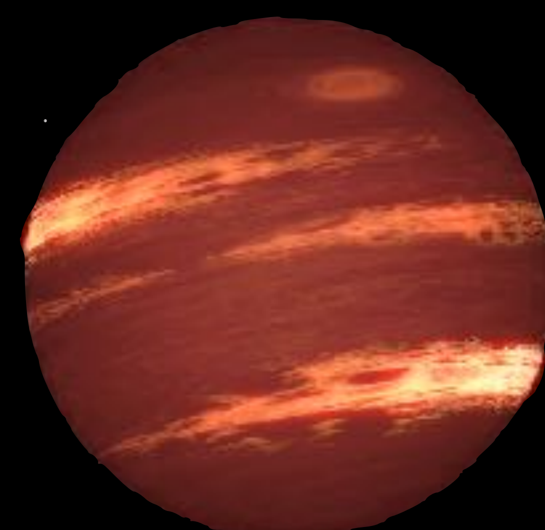
What is the object's mass?

Giant Planet

Mass: $\approx$0.25-13 $M_{Jupiter}$
Radius: $\approx$1 $R_{Jupiter}$

Image: NASA

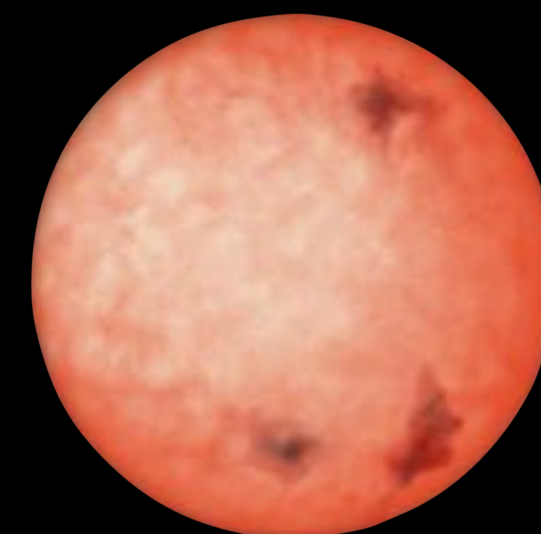
Brown Dwarf



Mass: $\approx$13-80 $M_{Jupiter}$
Radius: $\approx$1 $R_{Jupiter}$

Image: NASA

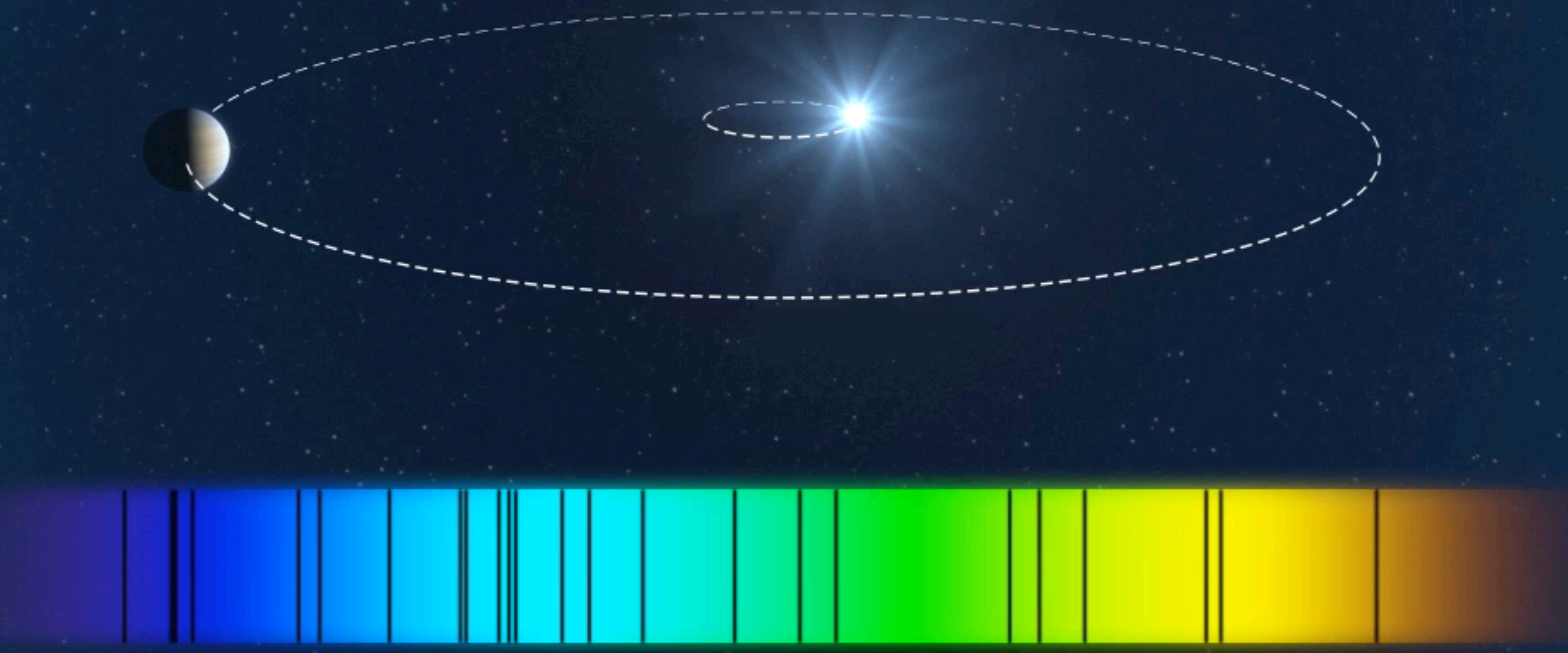
Low-mass Star



Mass: $\gtrsim$80 $M_{Jupiter}$
Radius: $\approx$1 $R_{Jupiter}$

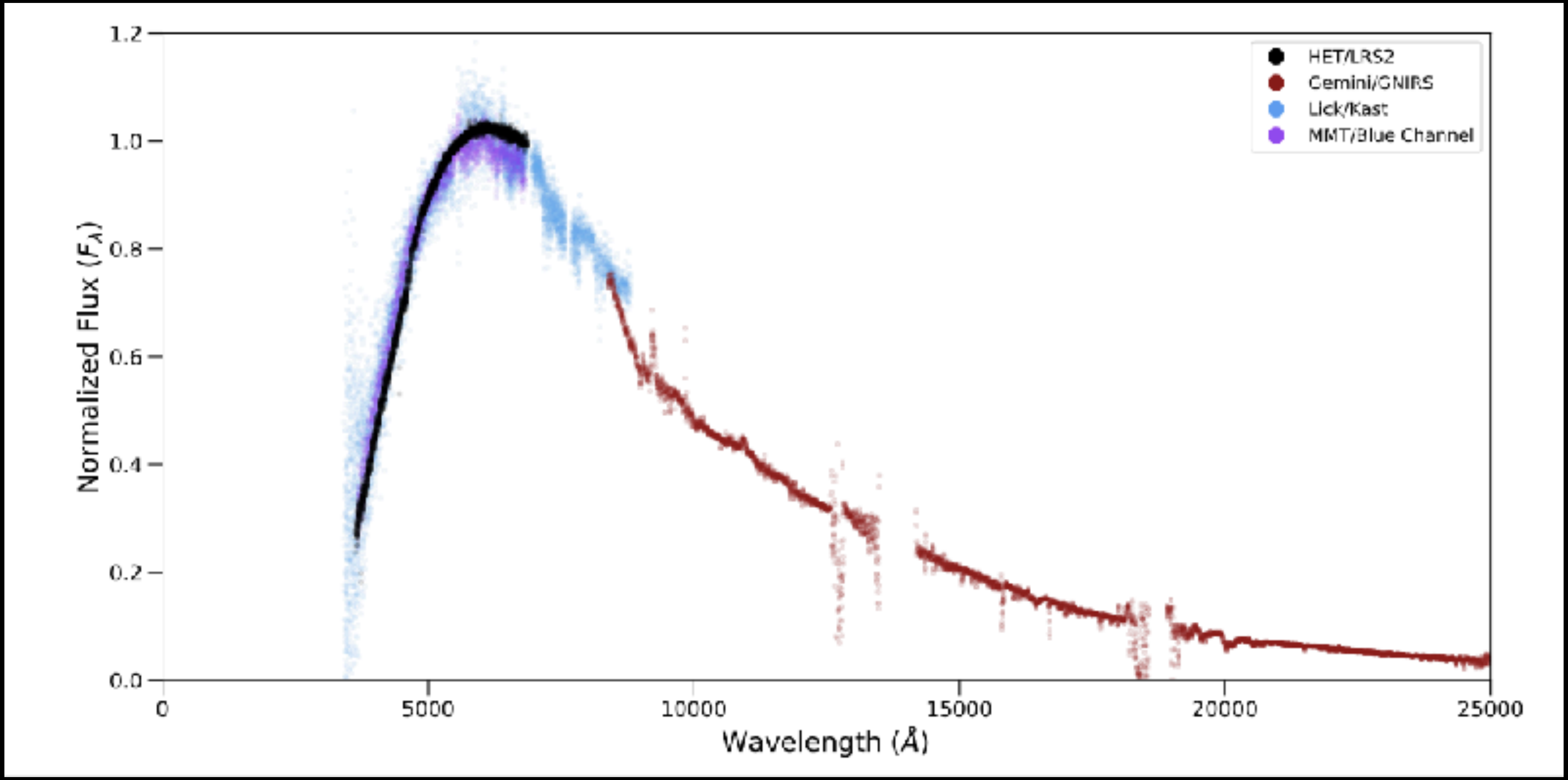
Image: J Pinfield

Usually, we determine masses by measuring the Doppler shift of the star due to the orbiting companion



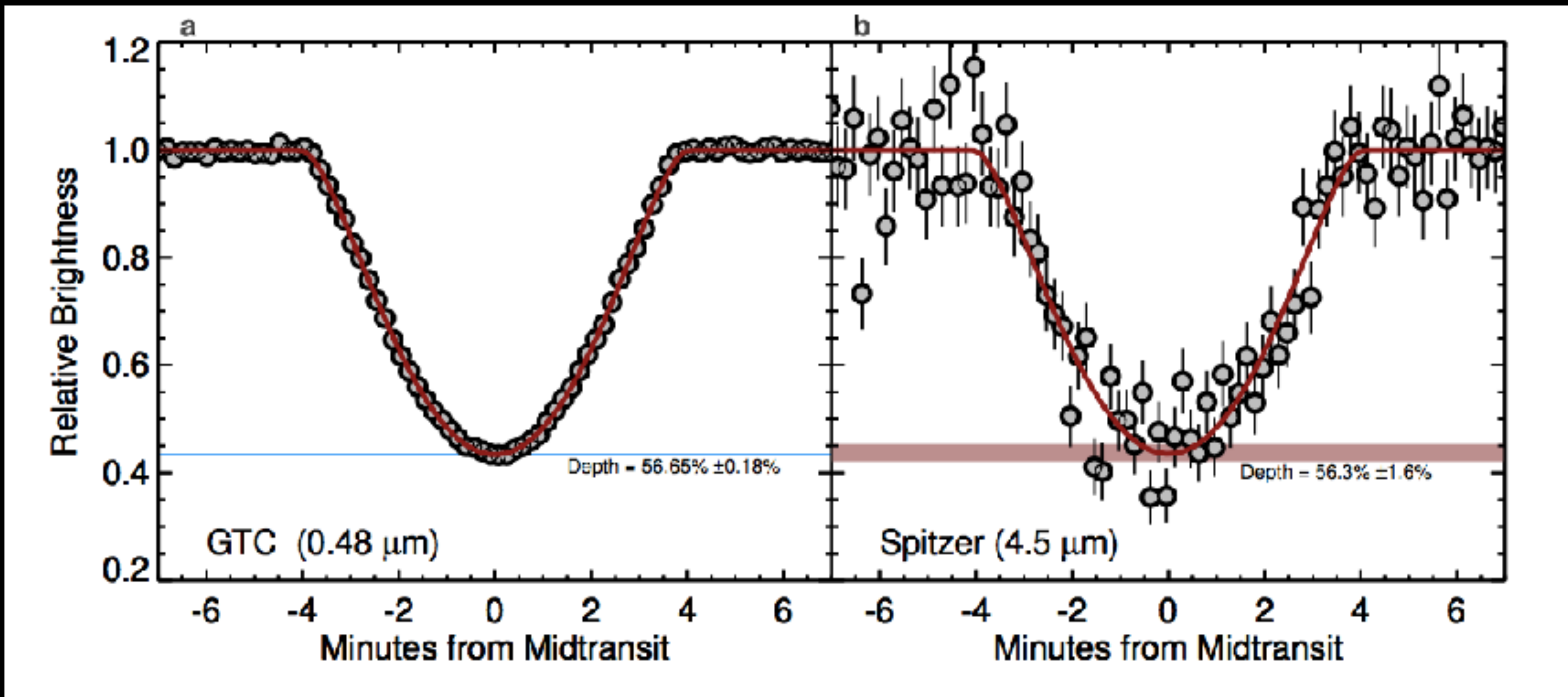
Animation: ESO

The white dwarf is old (≈6 Gyr), cold (4700 K), and has no spectral lines, so Doppler measurements are impossible.



Vanderburg et al. 2020

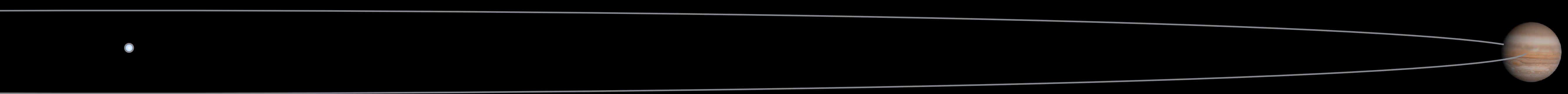
Instead, constrain mass with Spitzer: same transit depth in optical/IR data implies mass less than 11.7 M_J.(95% confidence)



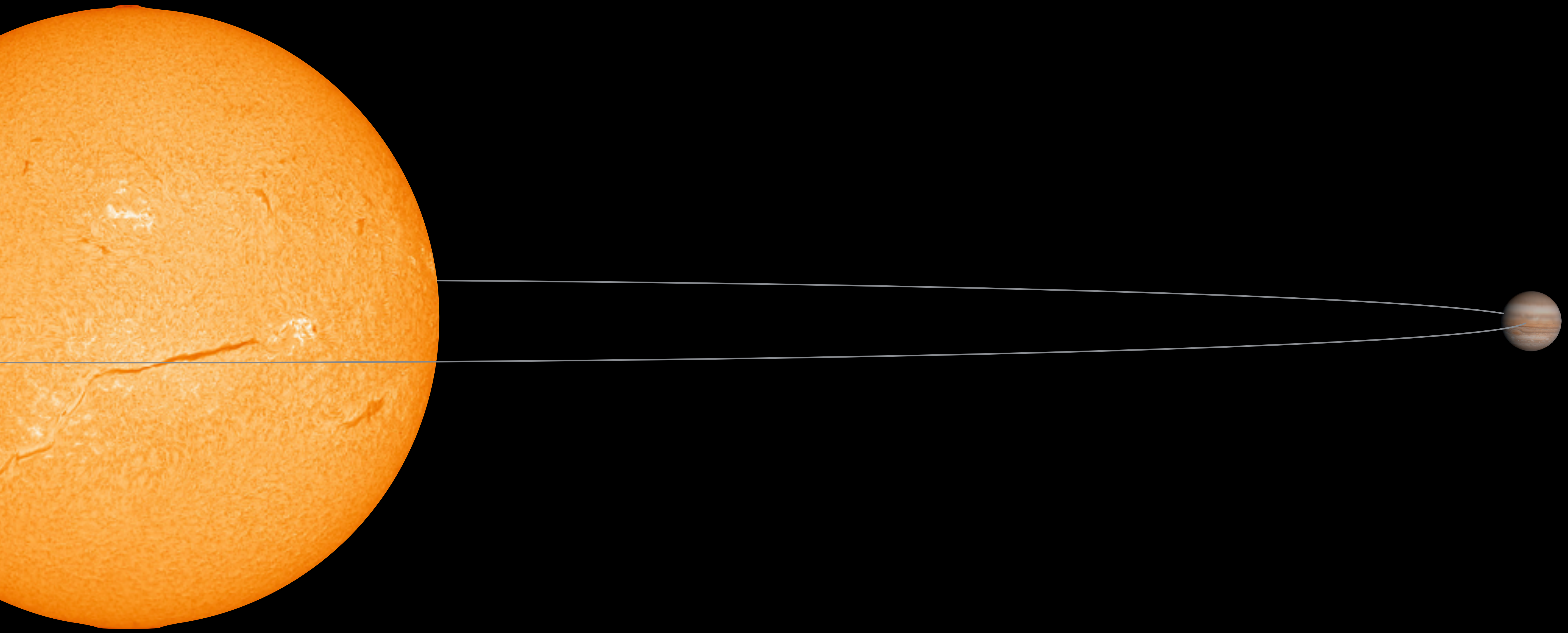
Vanderburg et al. 2020

So, this is very likely a giant planet orbiting close to a white dwarf star. We call it WD 1856 b.

The system to scale

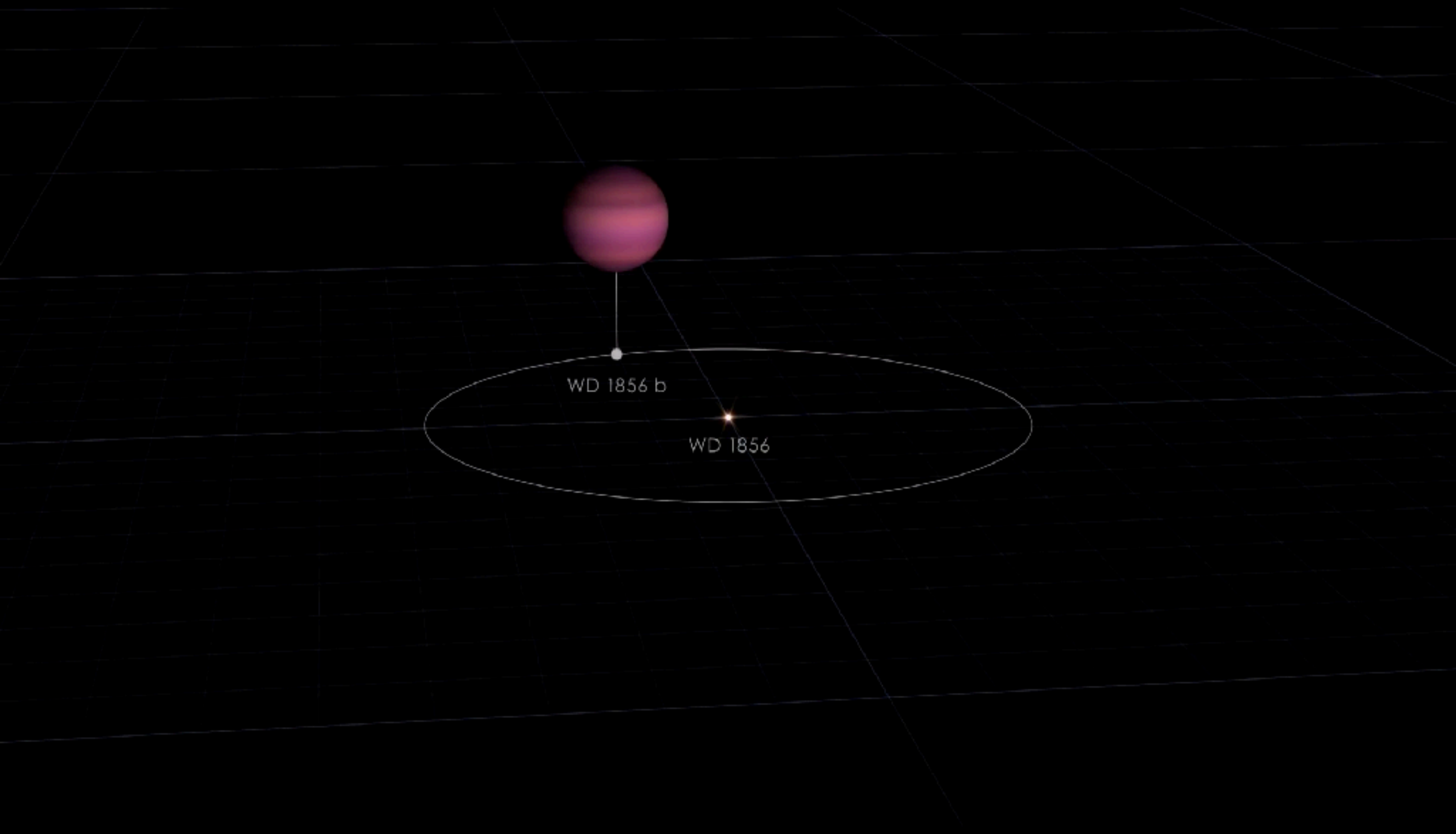


The system to scale

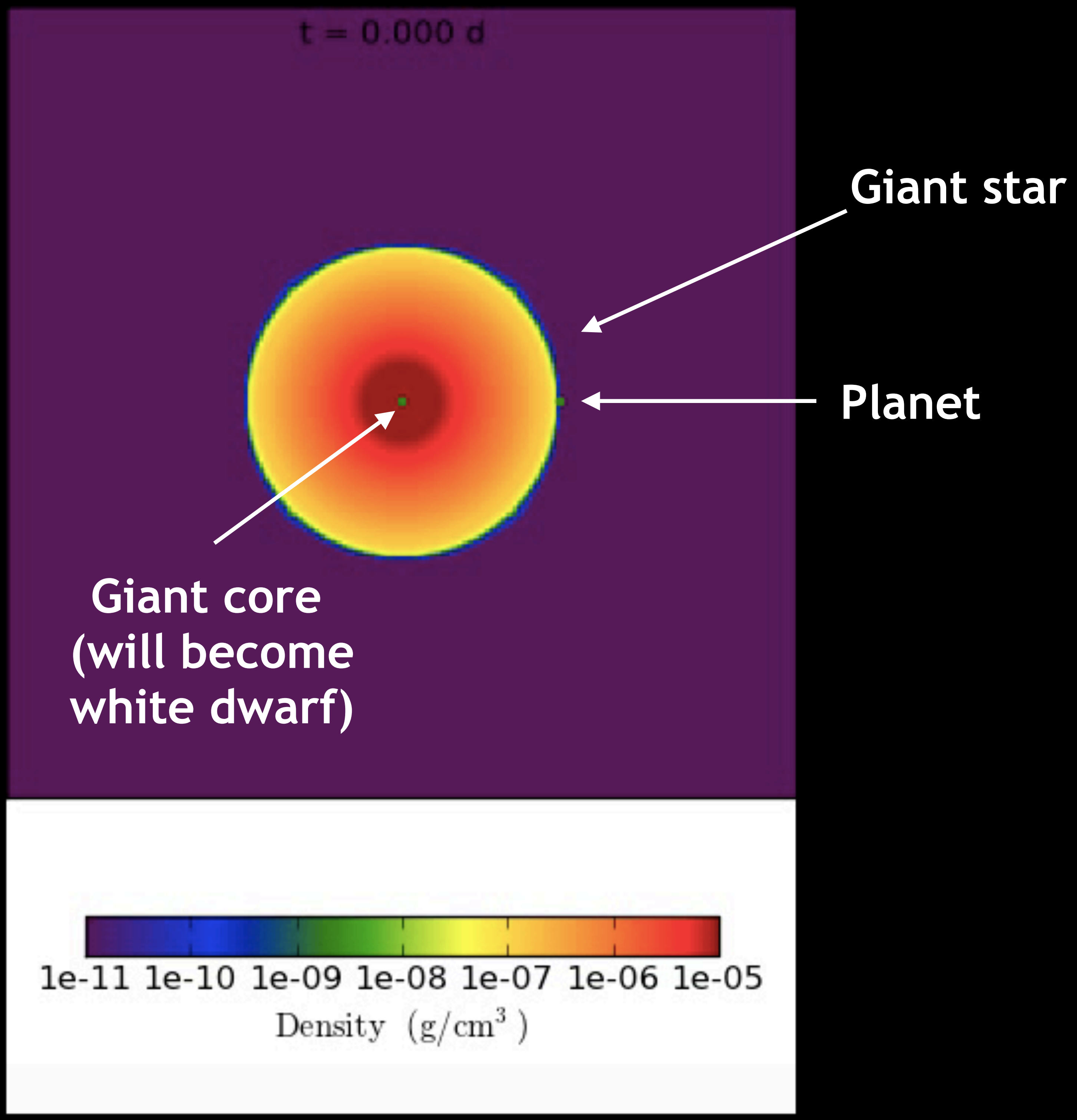


The system to scale

WD 1856 b must have originally orbited outside about 1 AU and migrated inwards

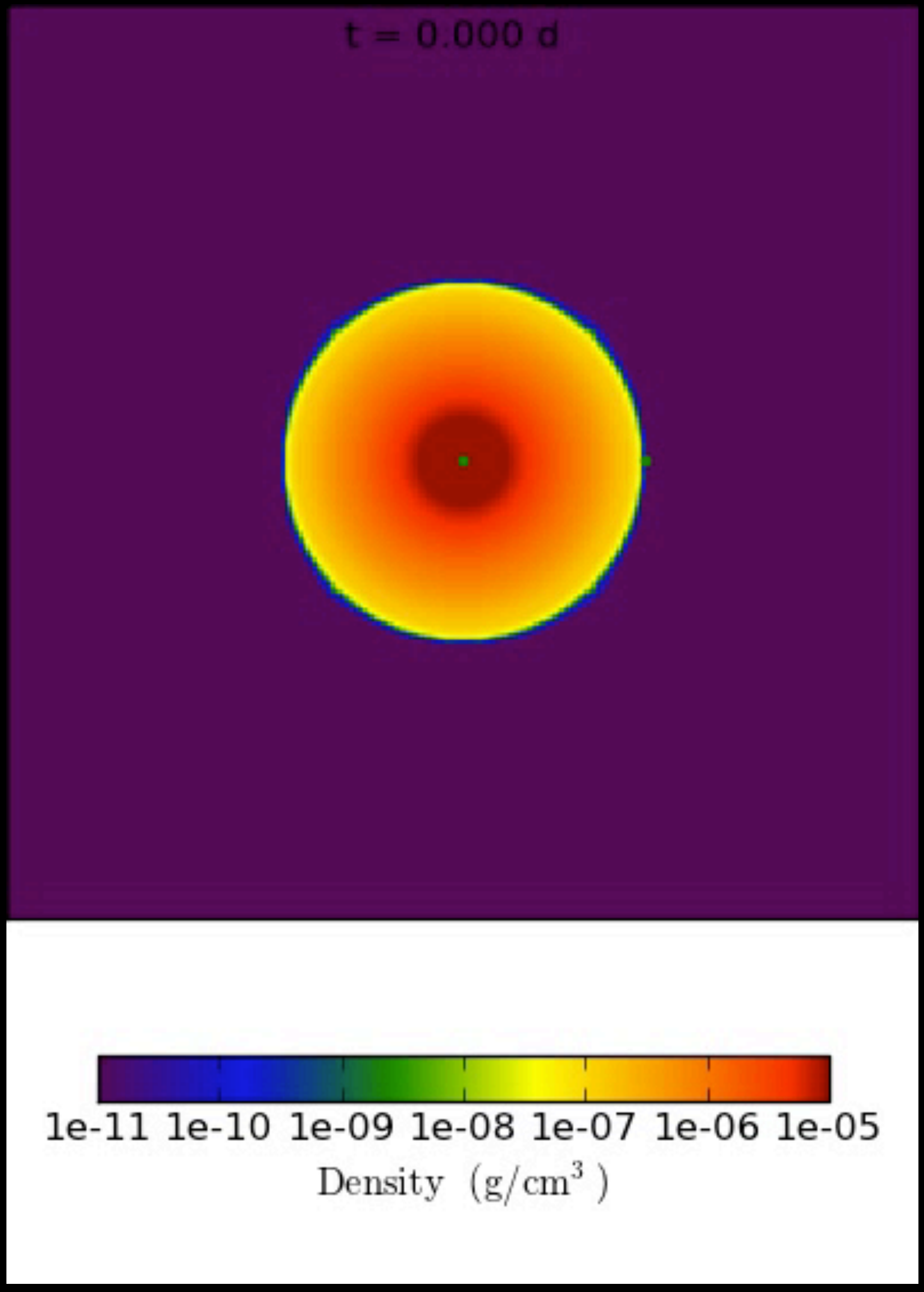


How could the planet migrate? Common Envelope Evolution



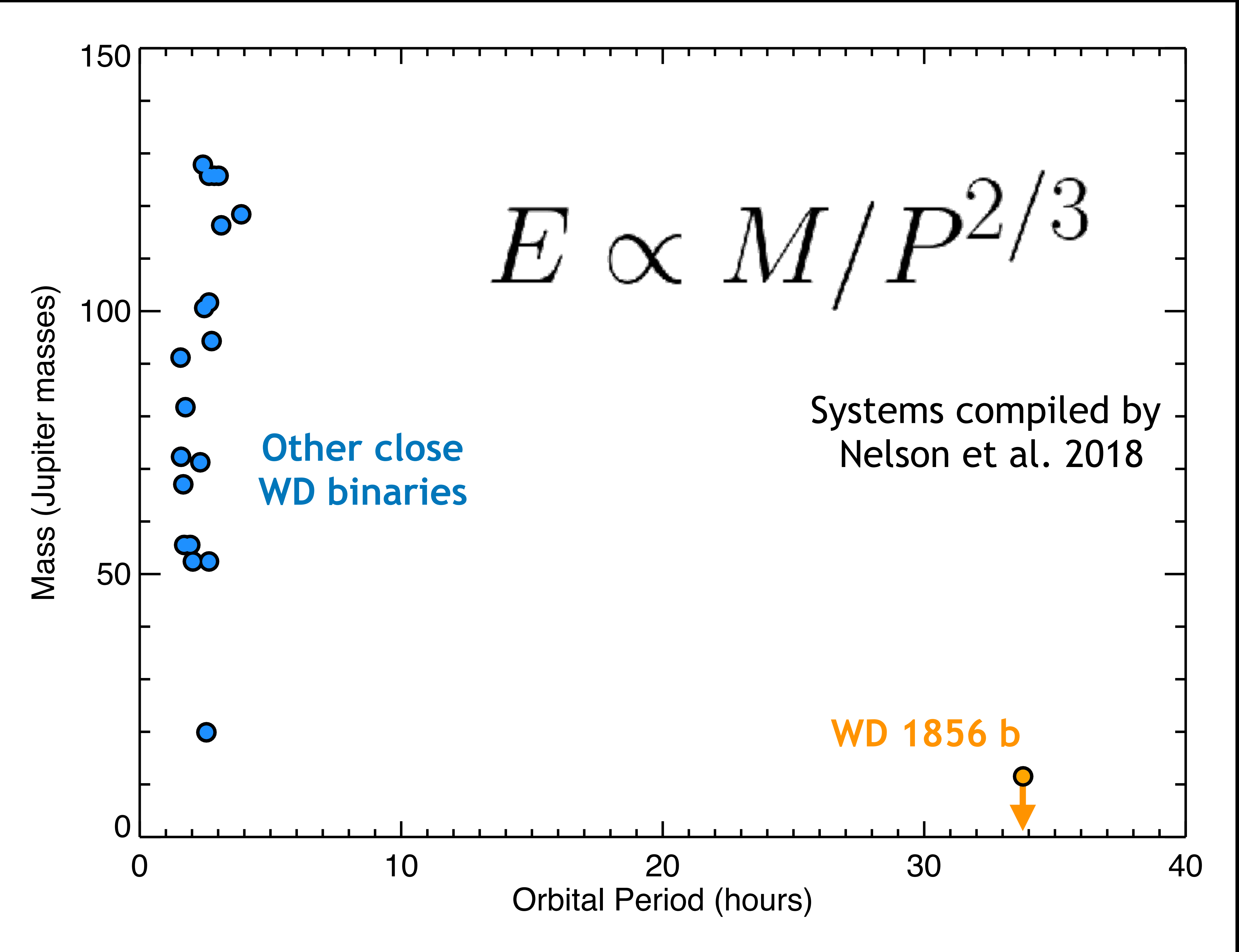
Passy et al. (2012).

How could the planet migrate? Common Envelope Evolution

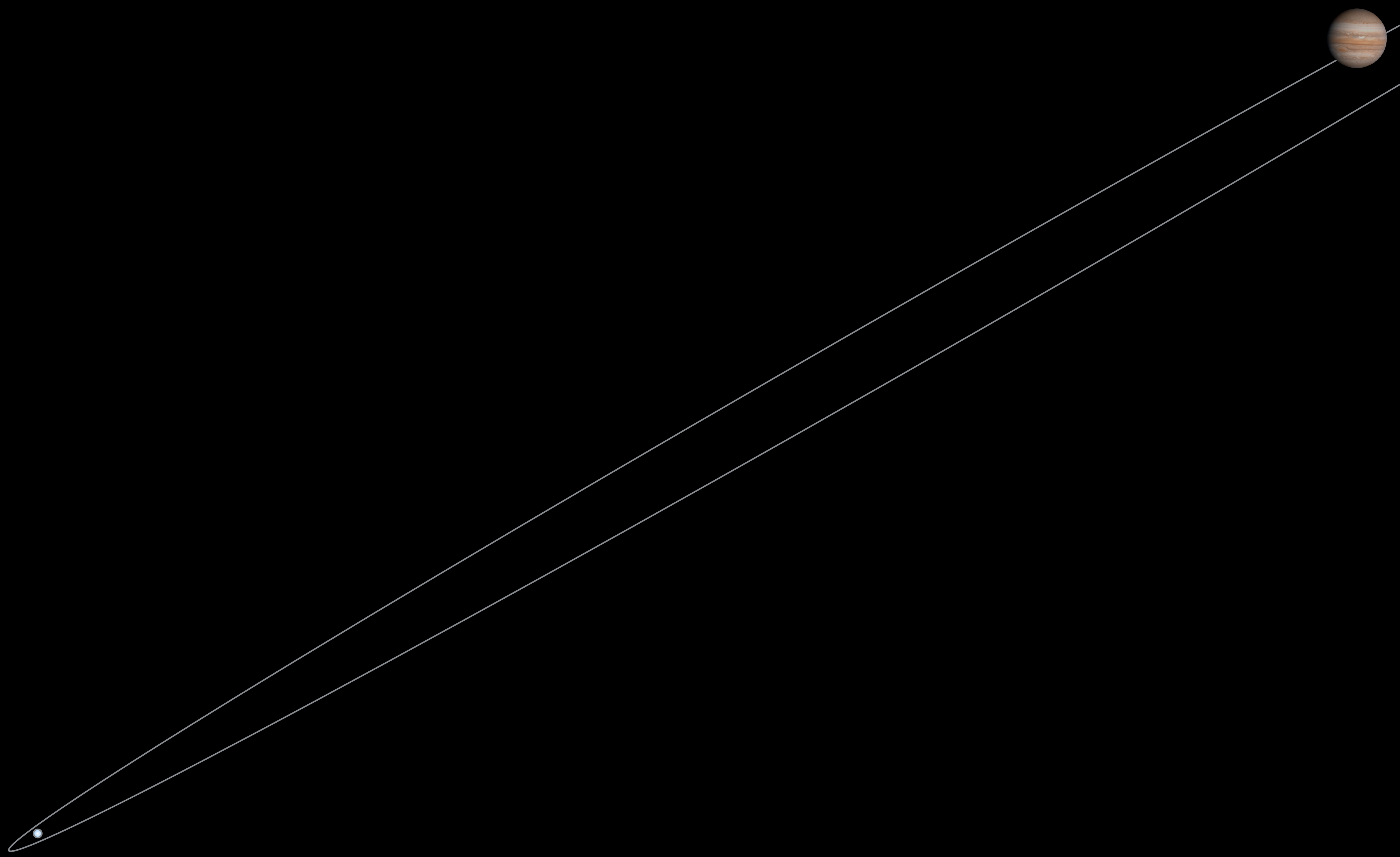


Passy et al. (2012).

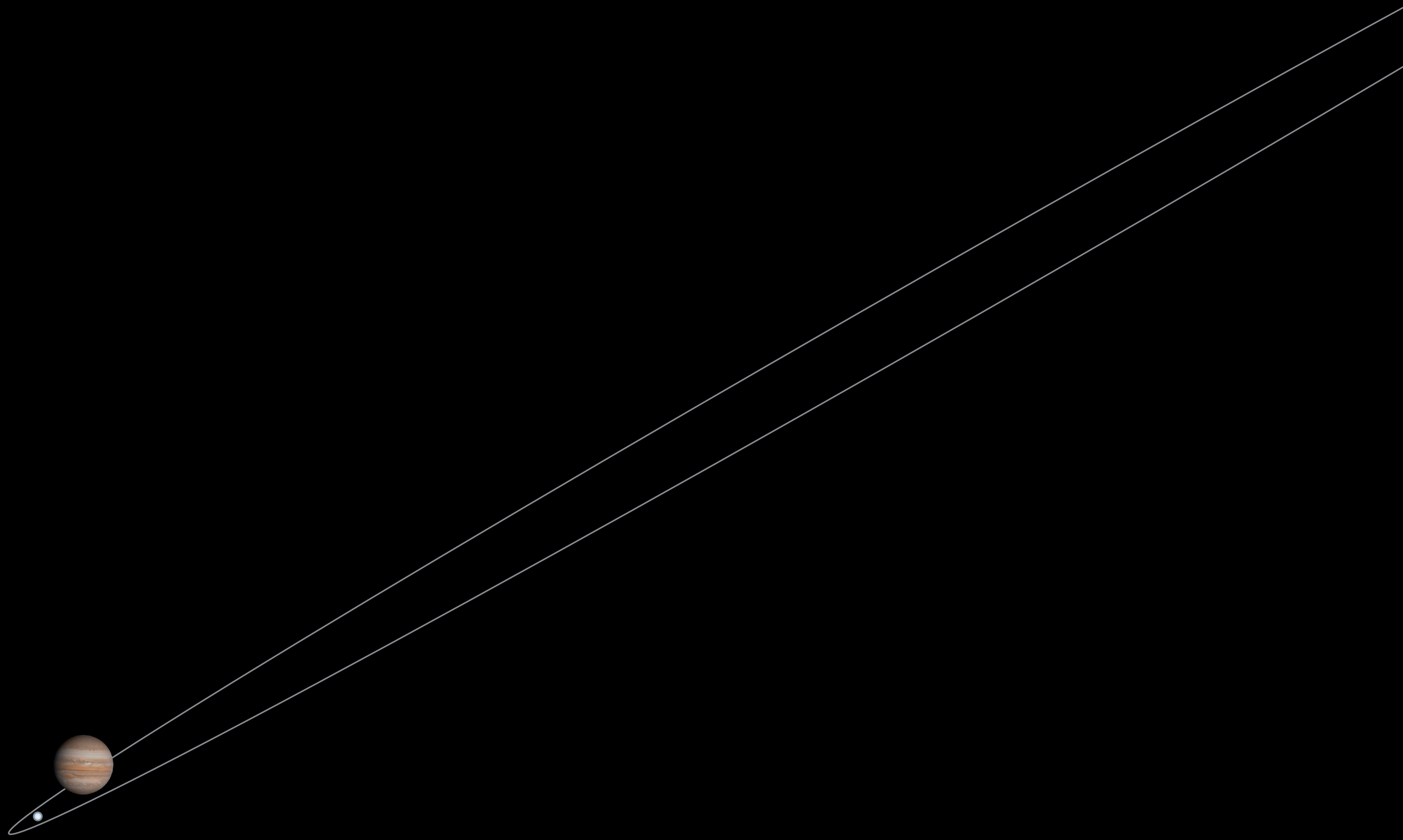
Does WD 1856 b have enough mass to eject the envelope?



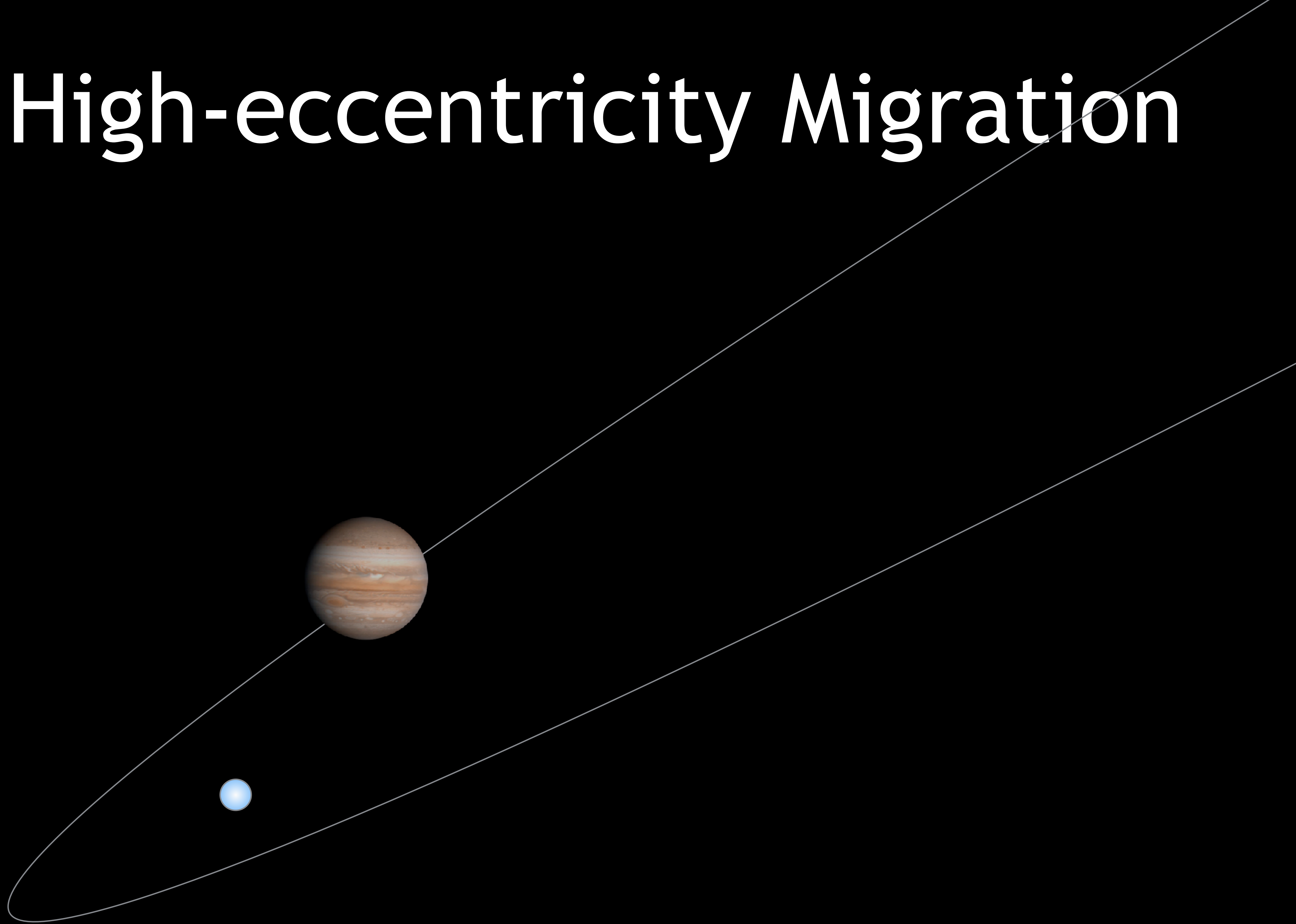
High-eccentricity Migration



High-eccentricity Migration

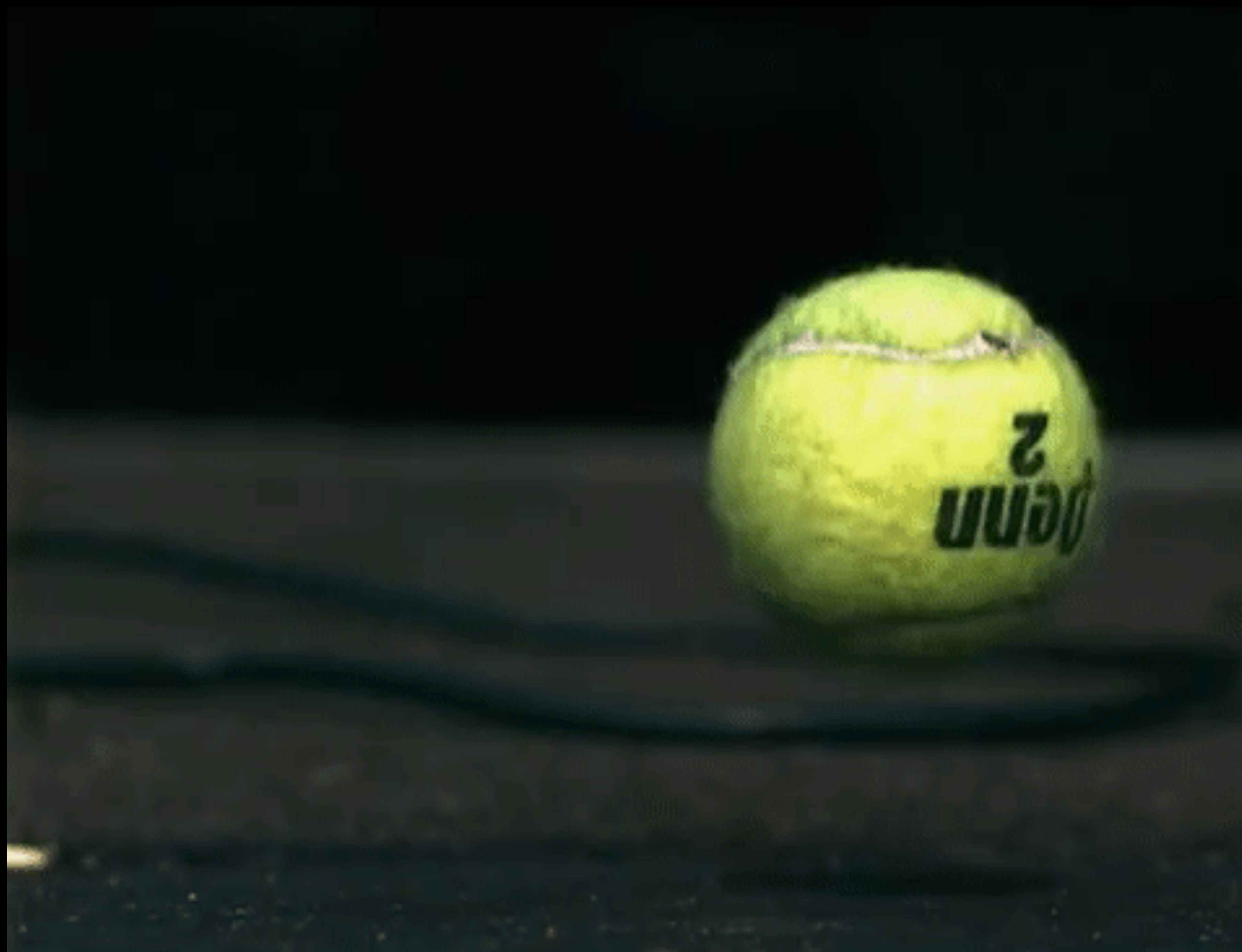


High-eccentricity Migration



High-eccentricity Migration

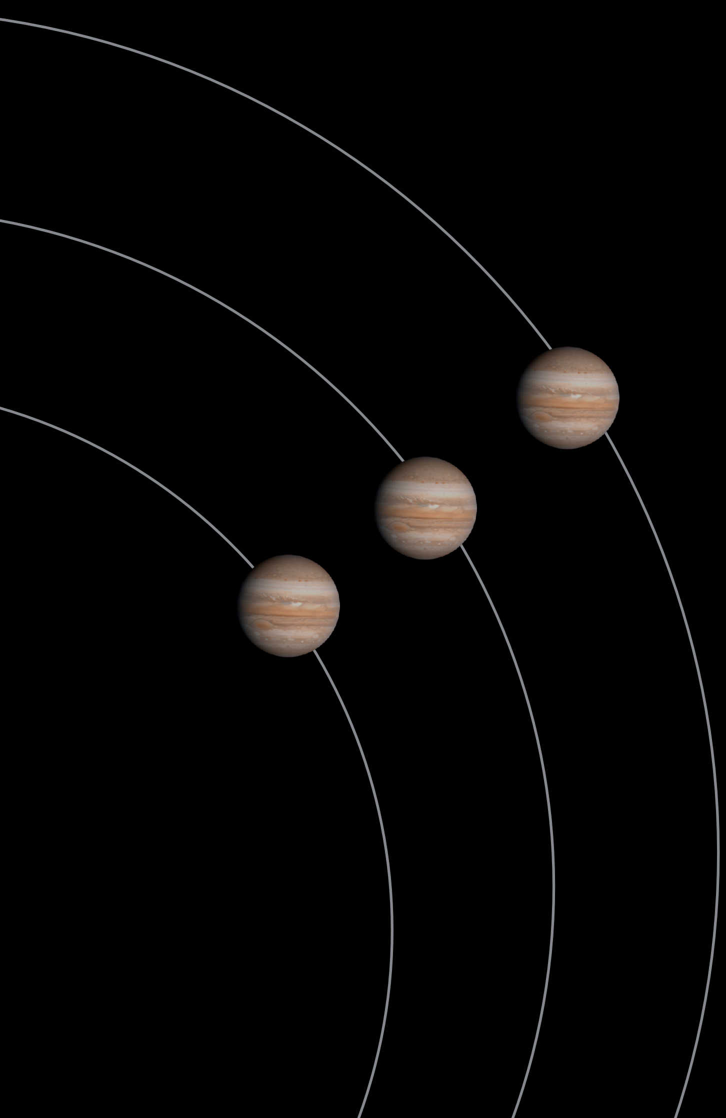
Like how tennis balls don’t bounce as high each successive time, the planet doesn’t return to same semimajor axis and circularizes



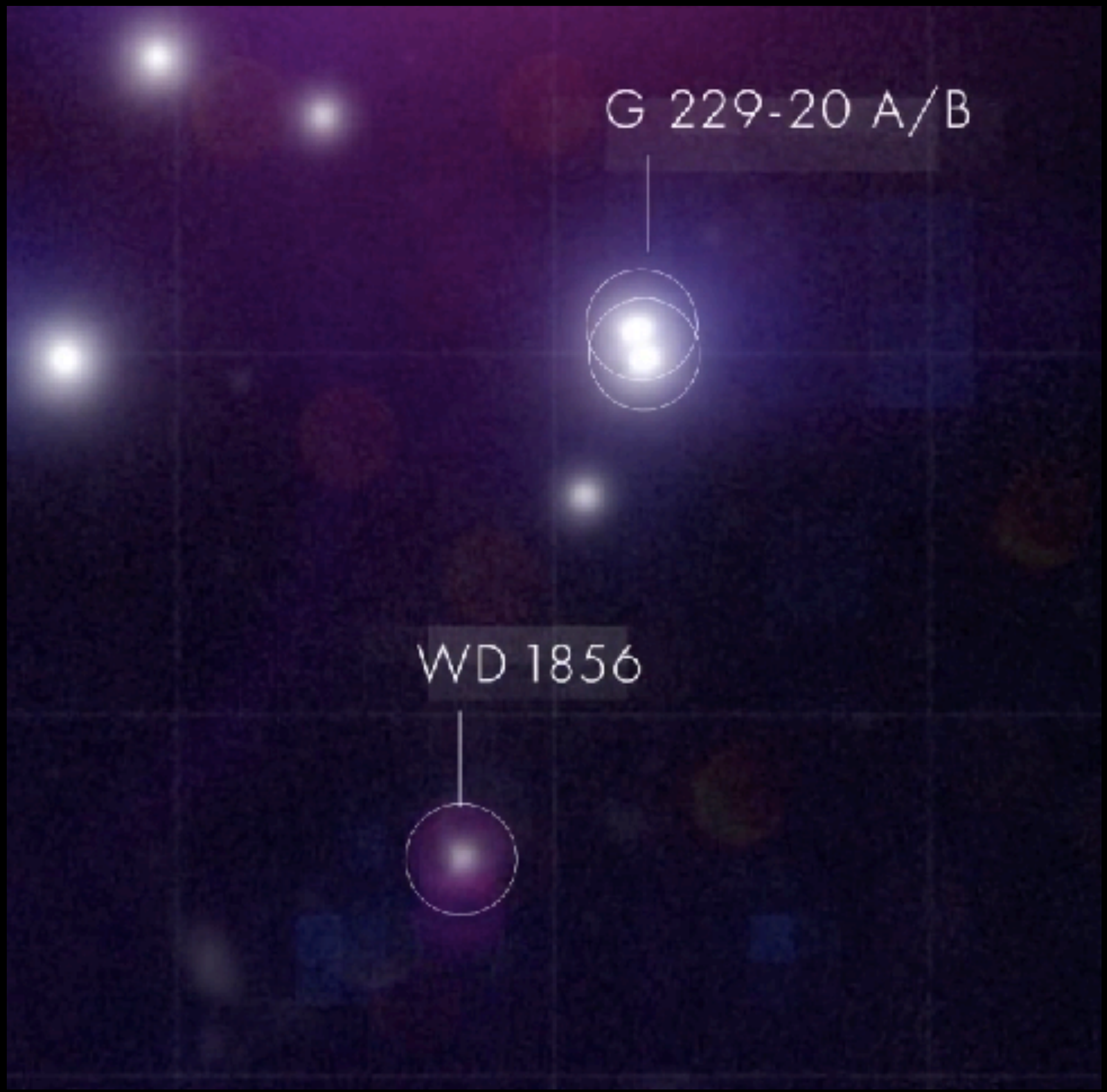
https://gfycat.com/ko/vaguelimpingbuzzard

How does the planet get such high eccentricity?

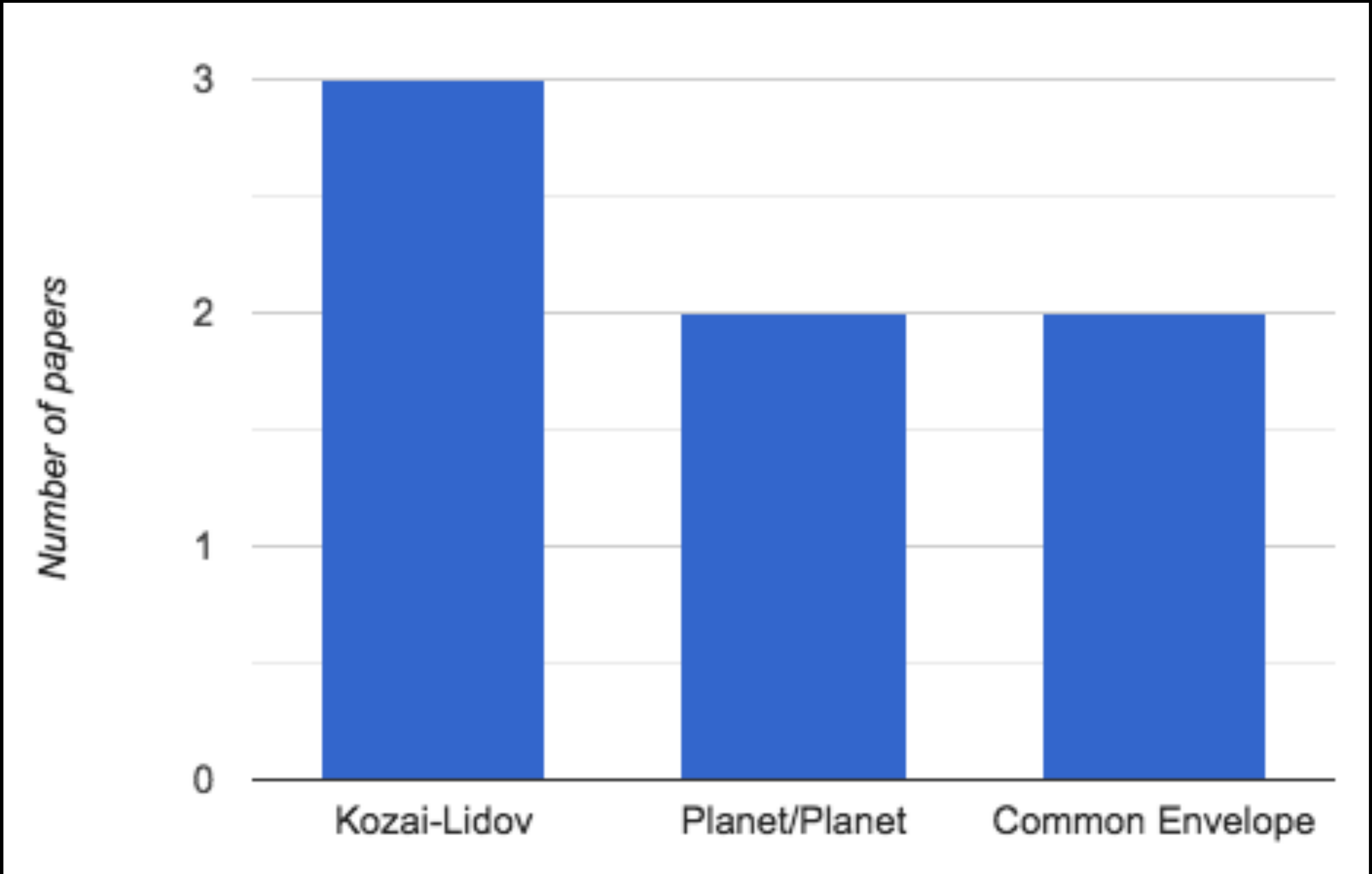
Planet/Planet scattering



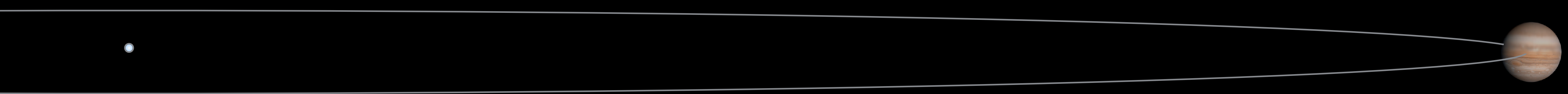
Kozai-Lidov effect



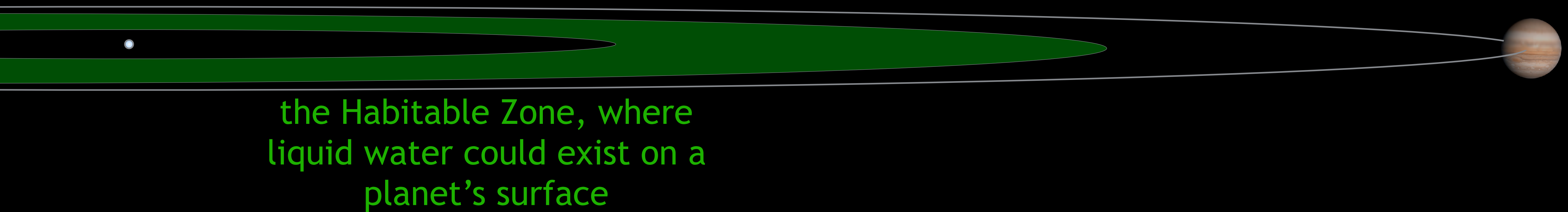
Lots of ideas from the community so far



The system to scale

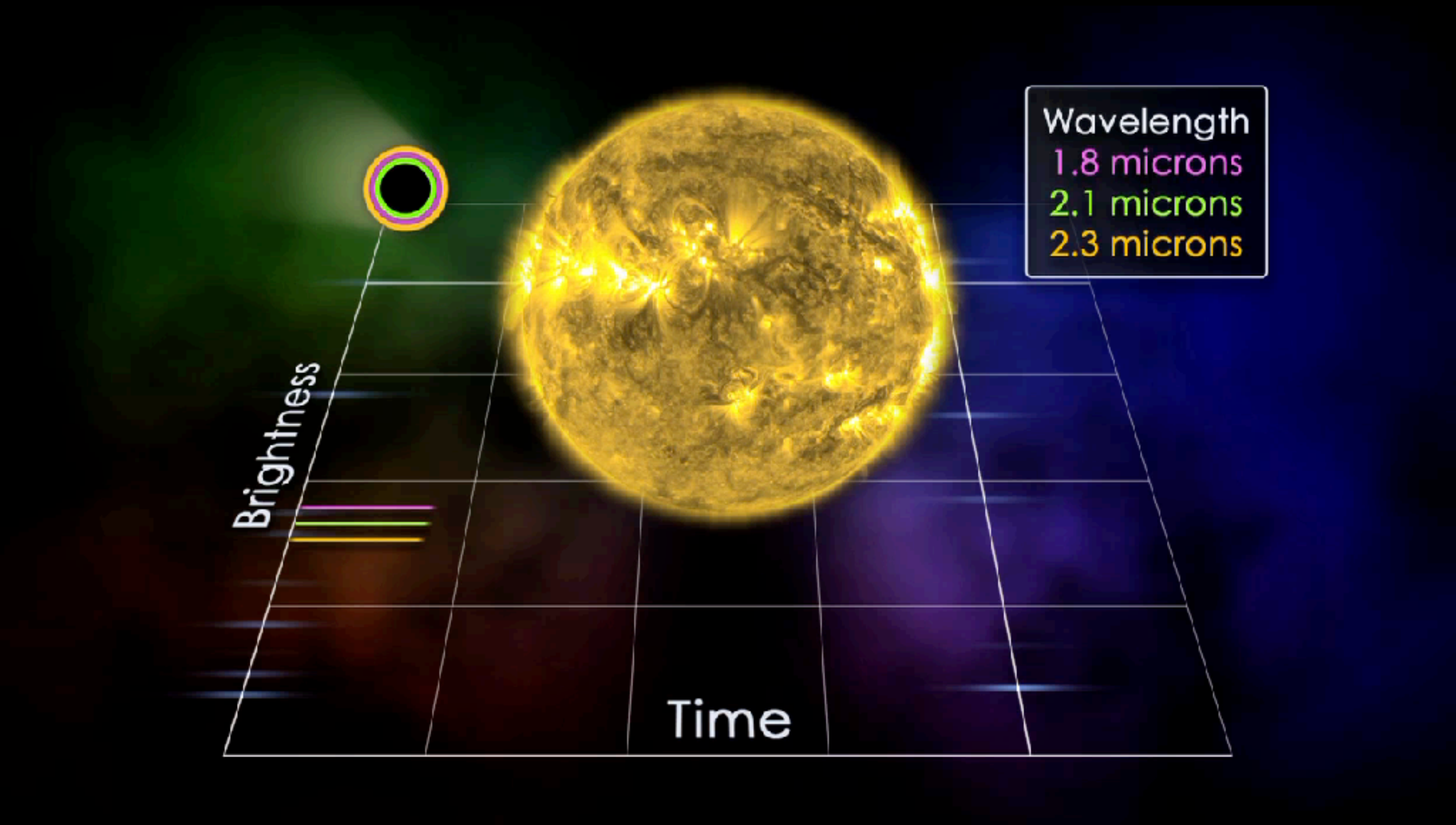


The system to scale



If WD 1856 b could survive the journey close to its star, maybe a smaller (rocky) planet could too.

Transmission spectroscopy



Animation: NASA

Atmospheric Biosignatures

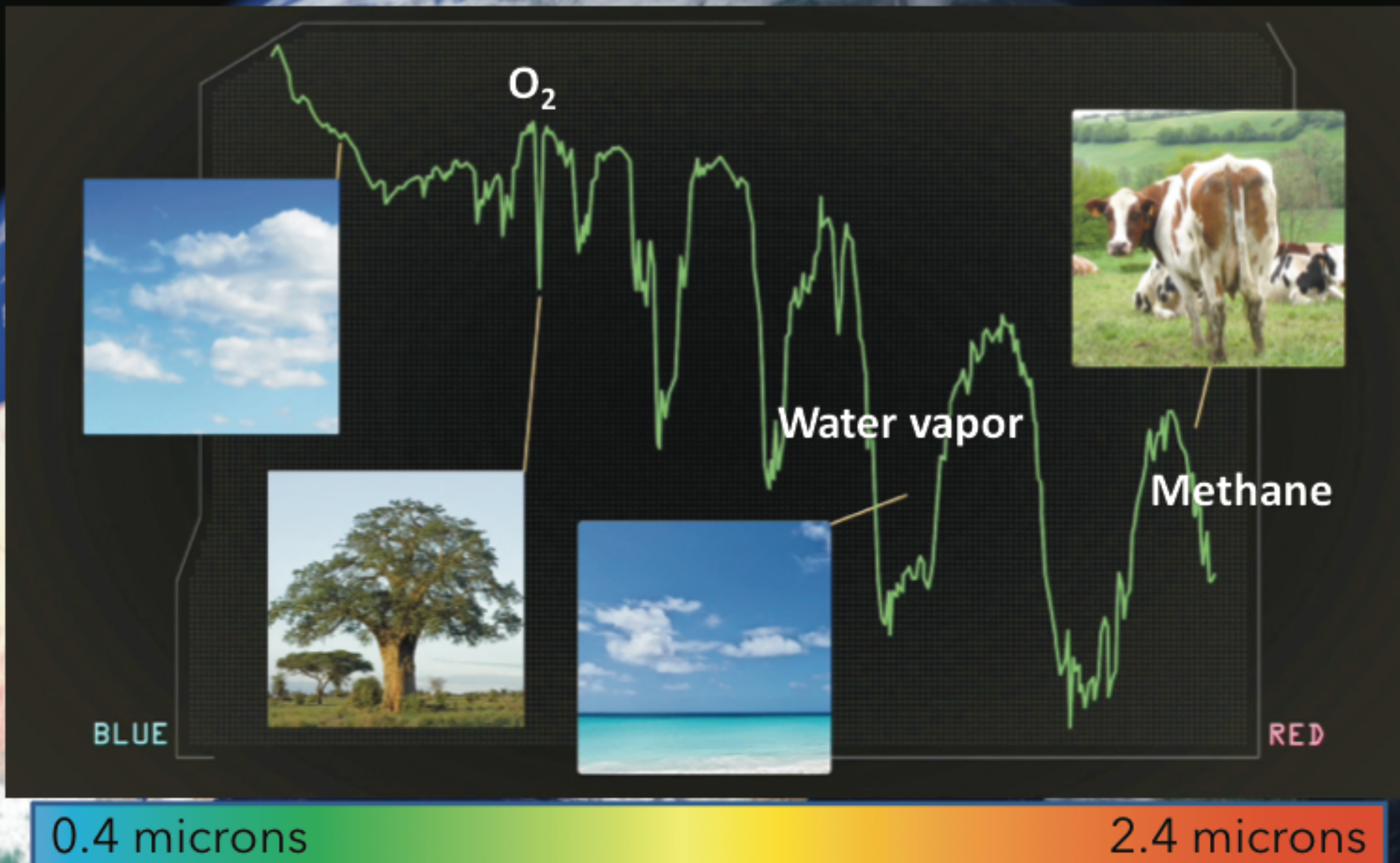
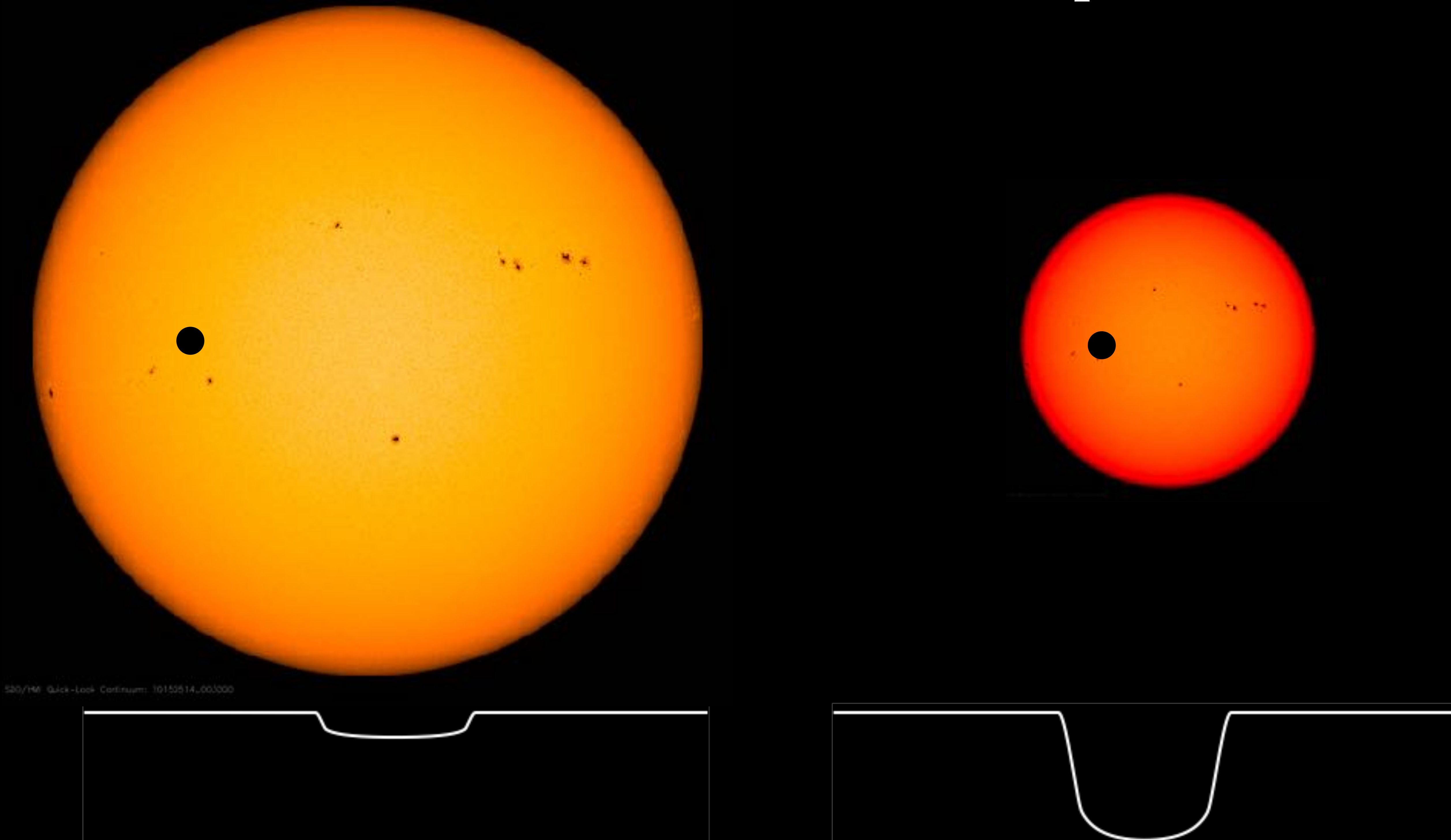


Image: LUVOIR Team

Small Stars are optimal



The same sized planet causes a larger signal on a smaller star

Image: NASA/SDO

White dwarfs take this to an extreme

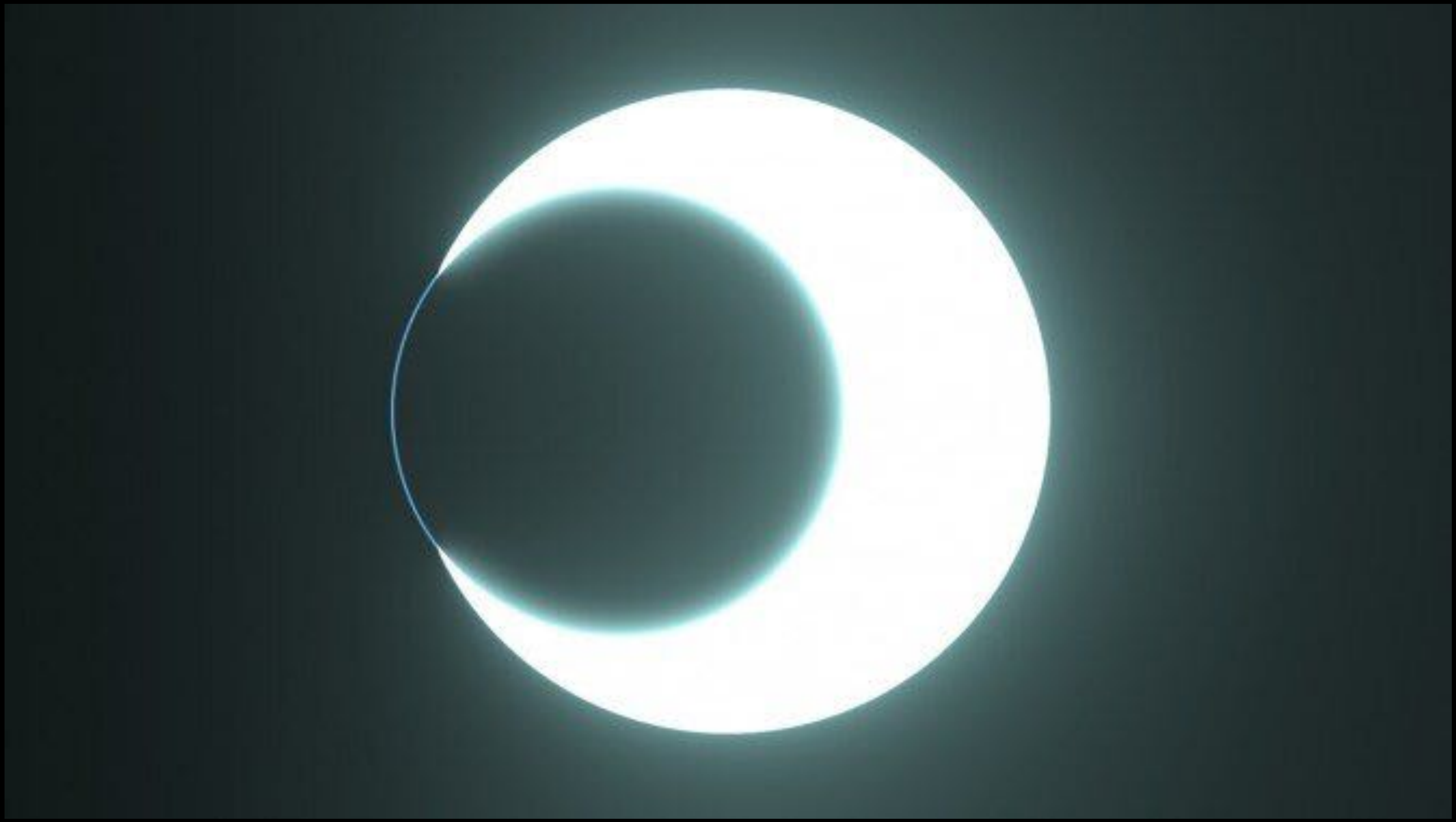
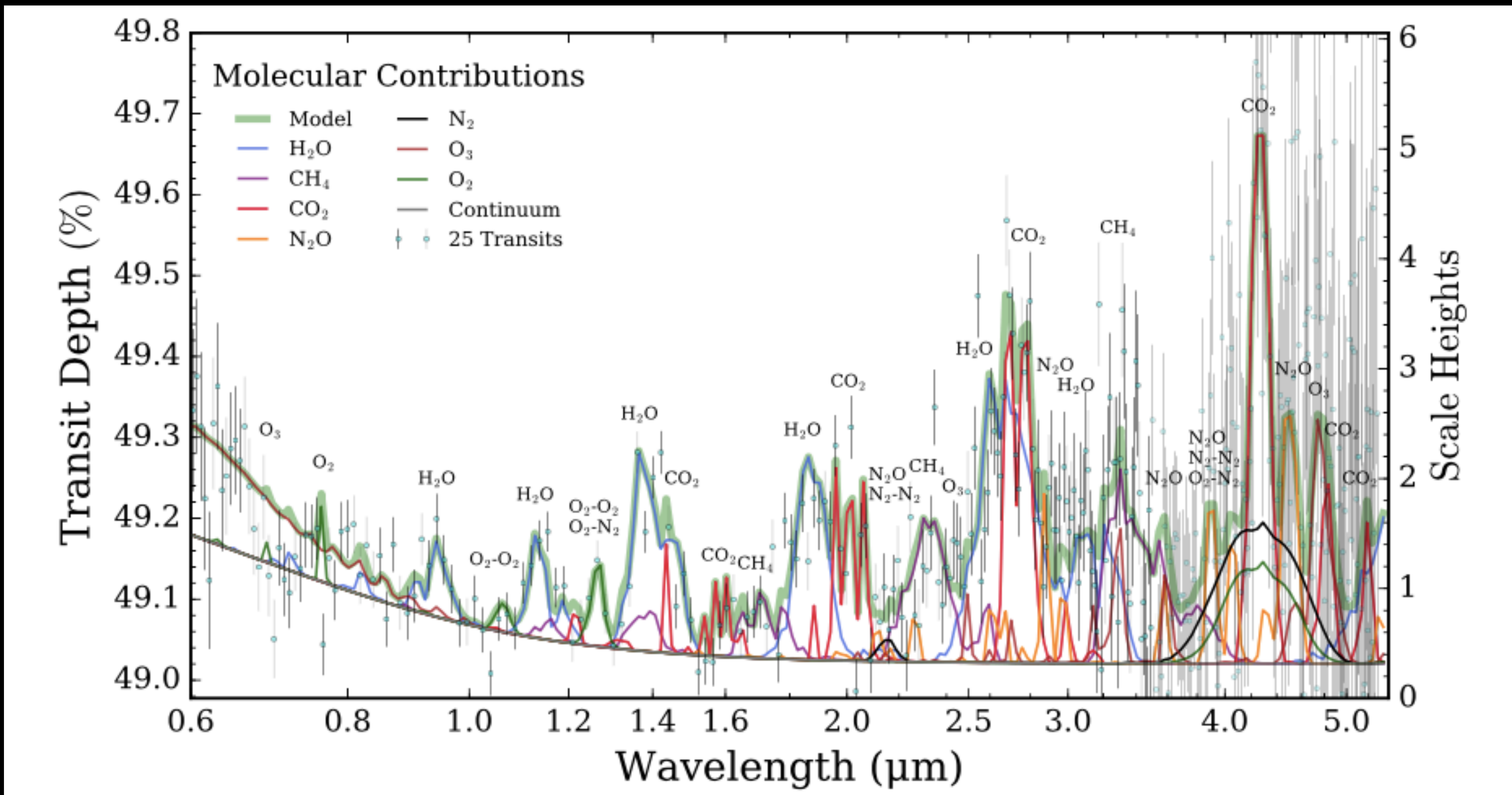


Image: Jack Madden

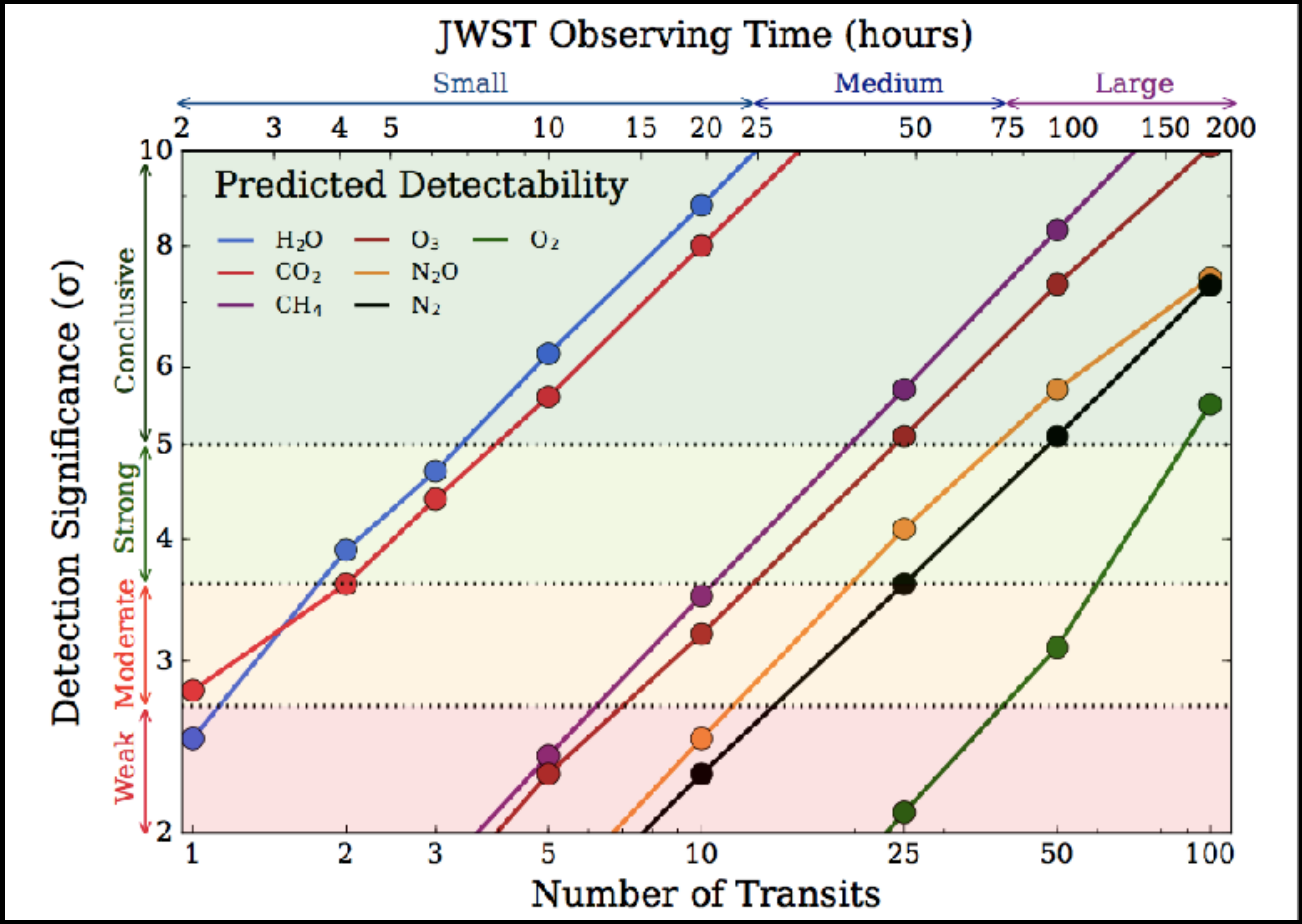
Biosignature gases could be readily detectable with JWST



25 transits - nominal 25 hour program, but only 3 hours of observations

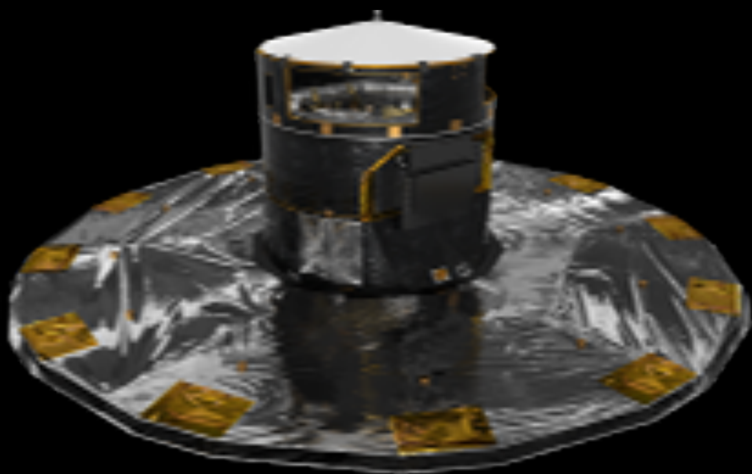
Kaltenegger et al. 2020 (including **Vanderburg**)

Biosignature gases could be readily detectable with JWST

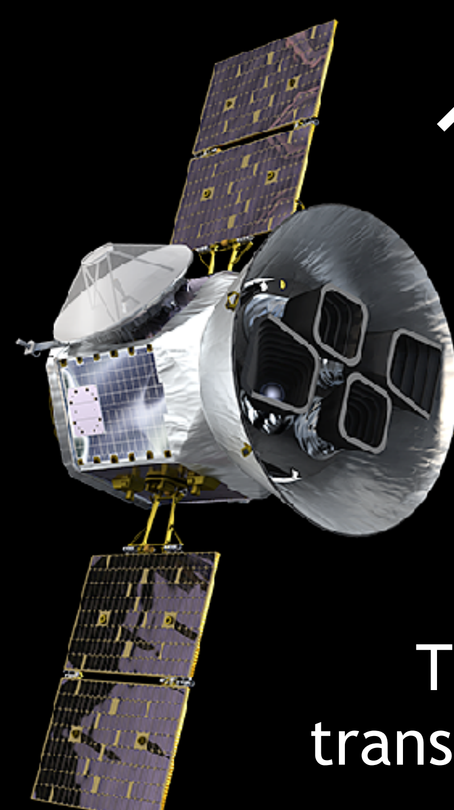


Kaltenegger et al. 2020 (including **Vanderburg**)

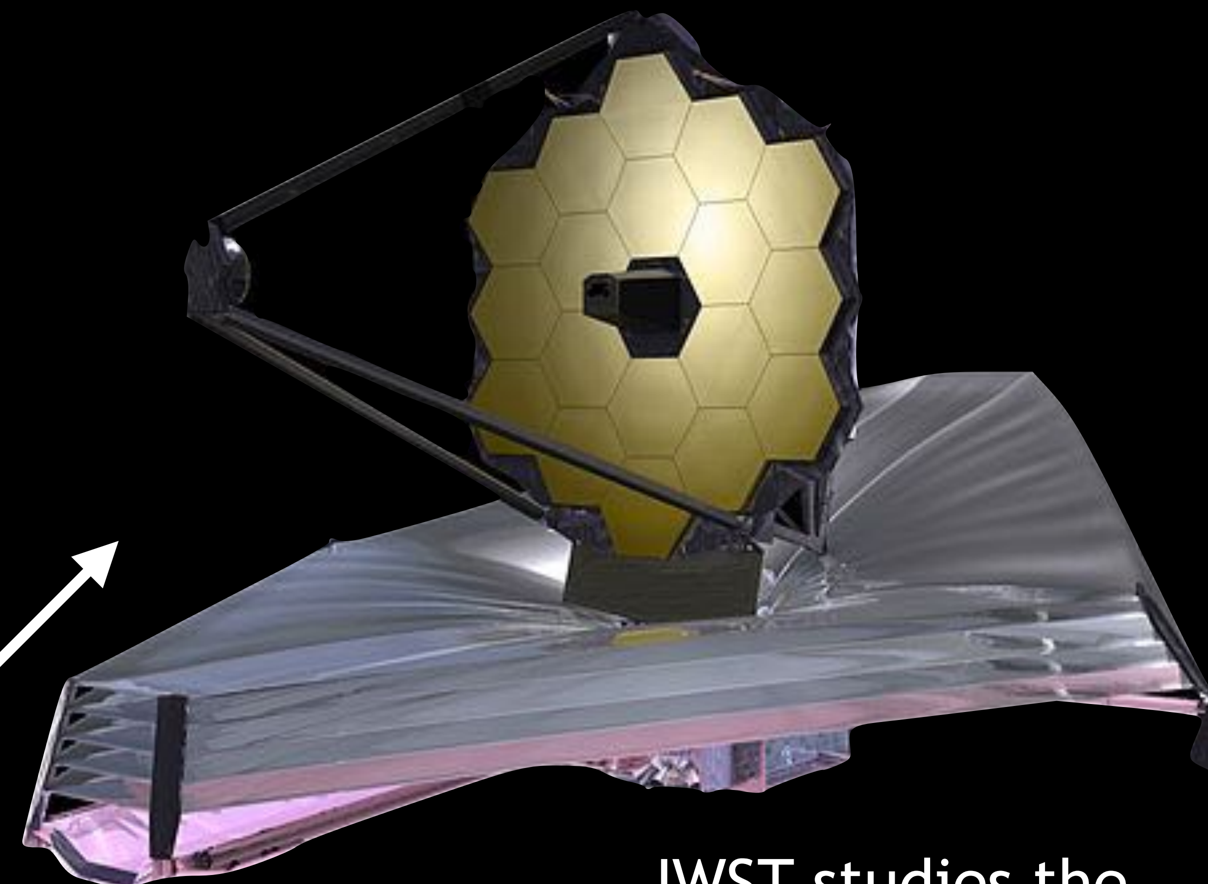
A shortcut to detecting biosignatures?



Gaia identifies white dwarfs



TESS finds transiting planets



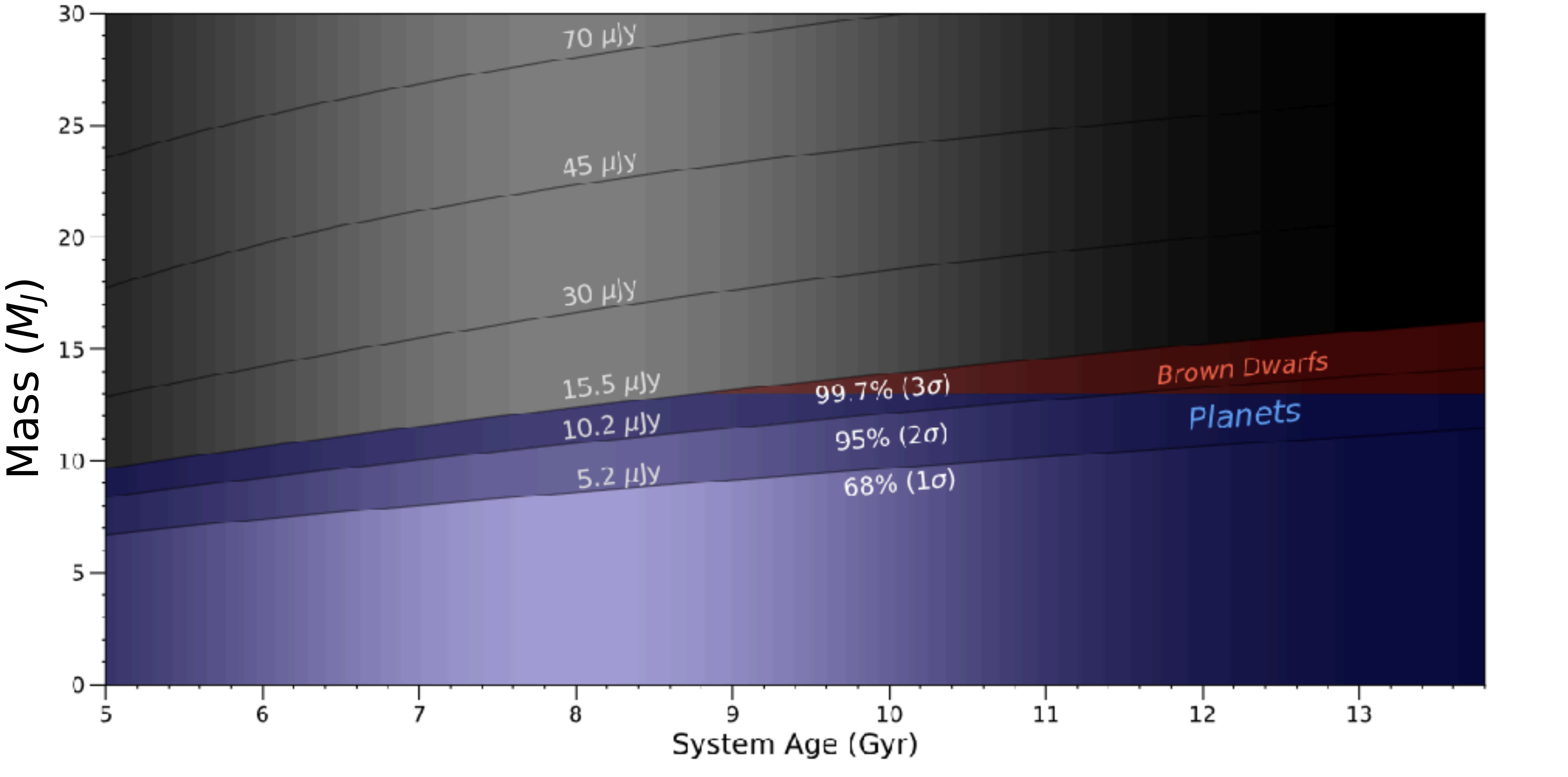
JWST studies the atmospheres

Transiting planets and material around white dwarfs can teach us about post-main-sequence planetary evolution.

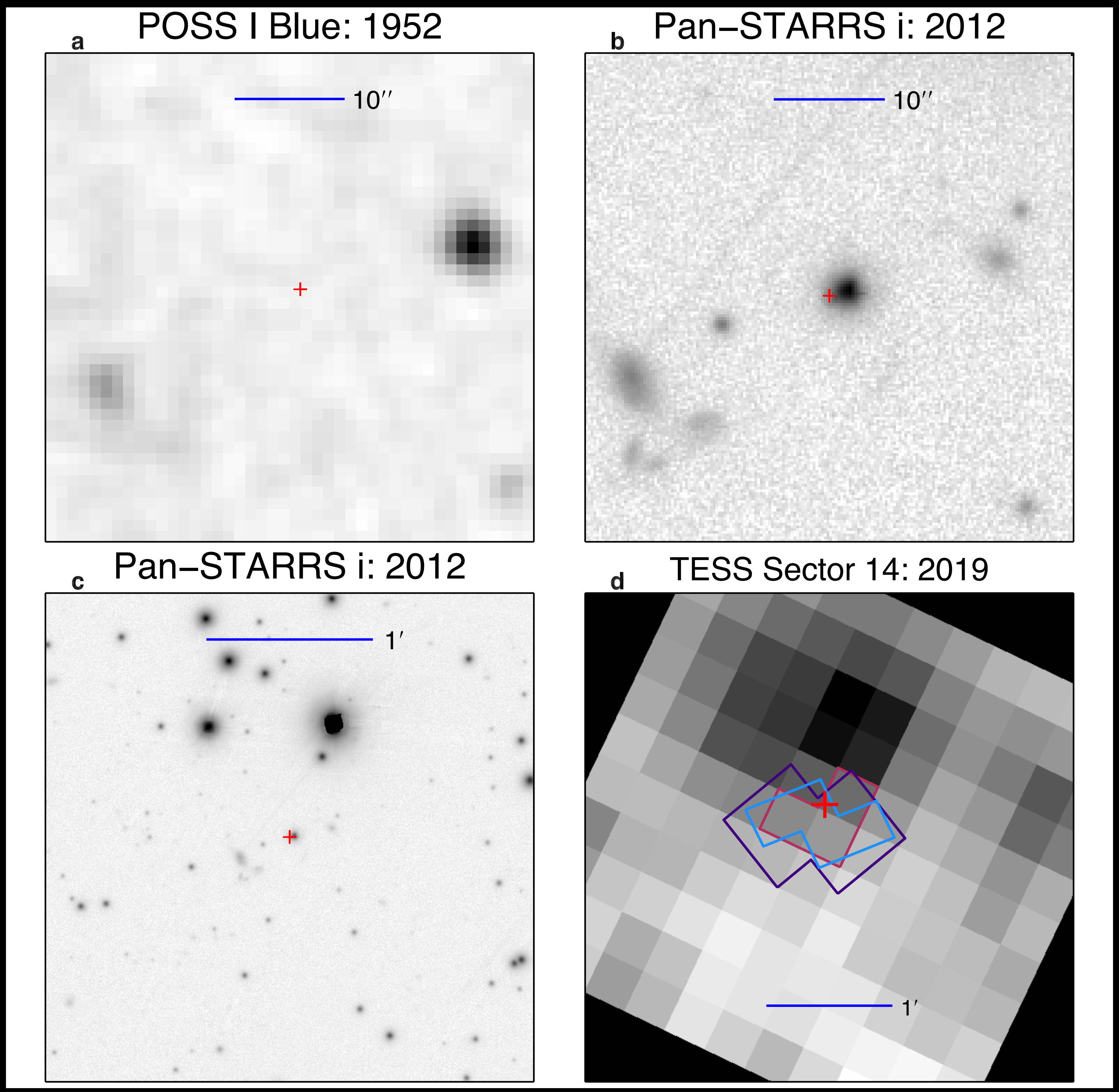
The disintegrating material around WD 1145+017 **has provided new insights into how white dwarfs disrupt and accrete asteroids and minor planets.**

The giant planet candidate around WD 1856+534 demonstrates **large planets can migrate close to white dwarfs and survive the process.**

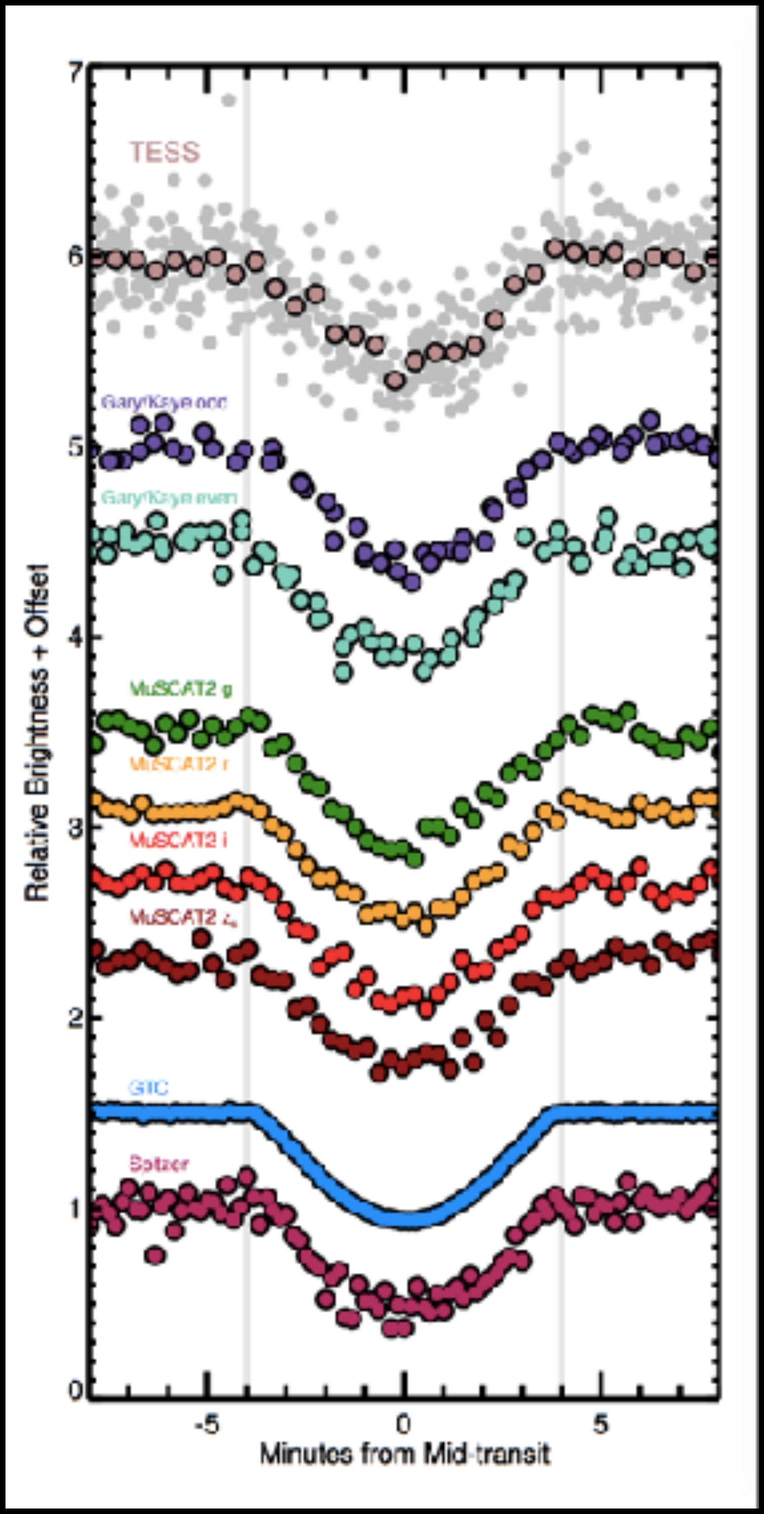
If Earth-sized planets can migrate in a similar way close to white dwarfs, they could end up orbiting in the white dwarf’s habitable zone, **and plausibly support a second generation of life.** If we find such a planet, we could study its atmosphere in detail with JWST.



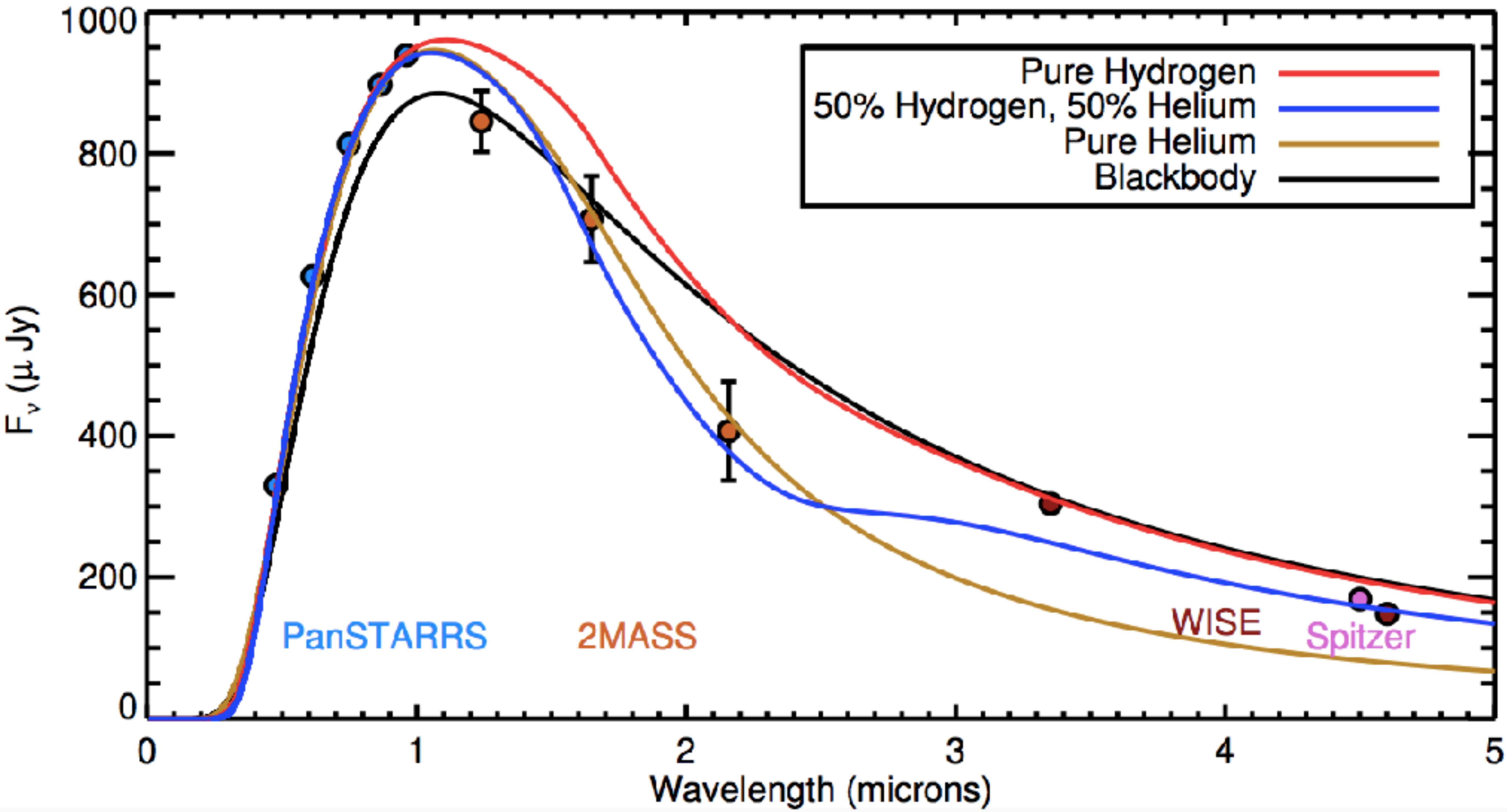
Vanderburg et al. 2020



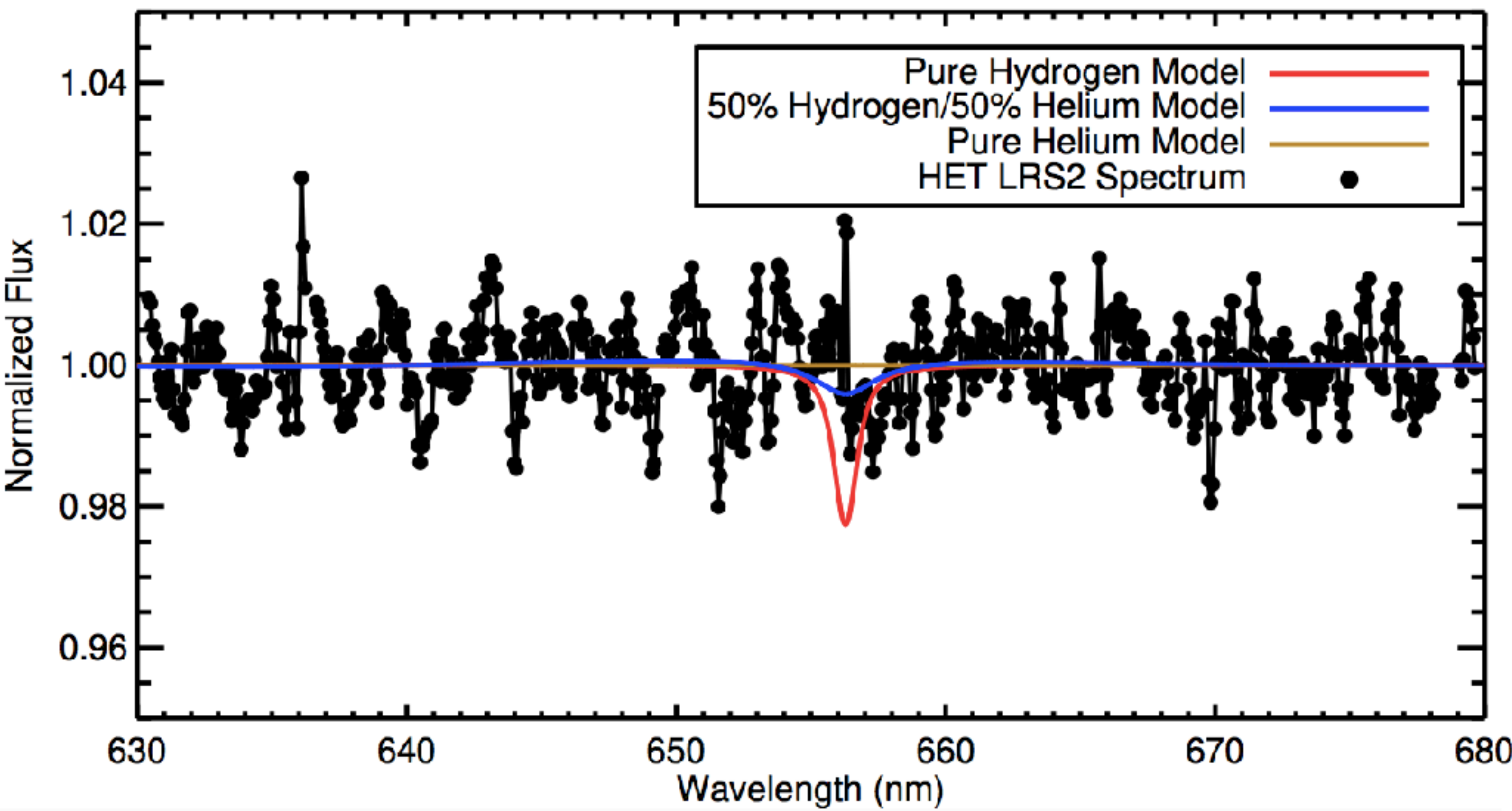
Vanderburg et al. 2020



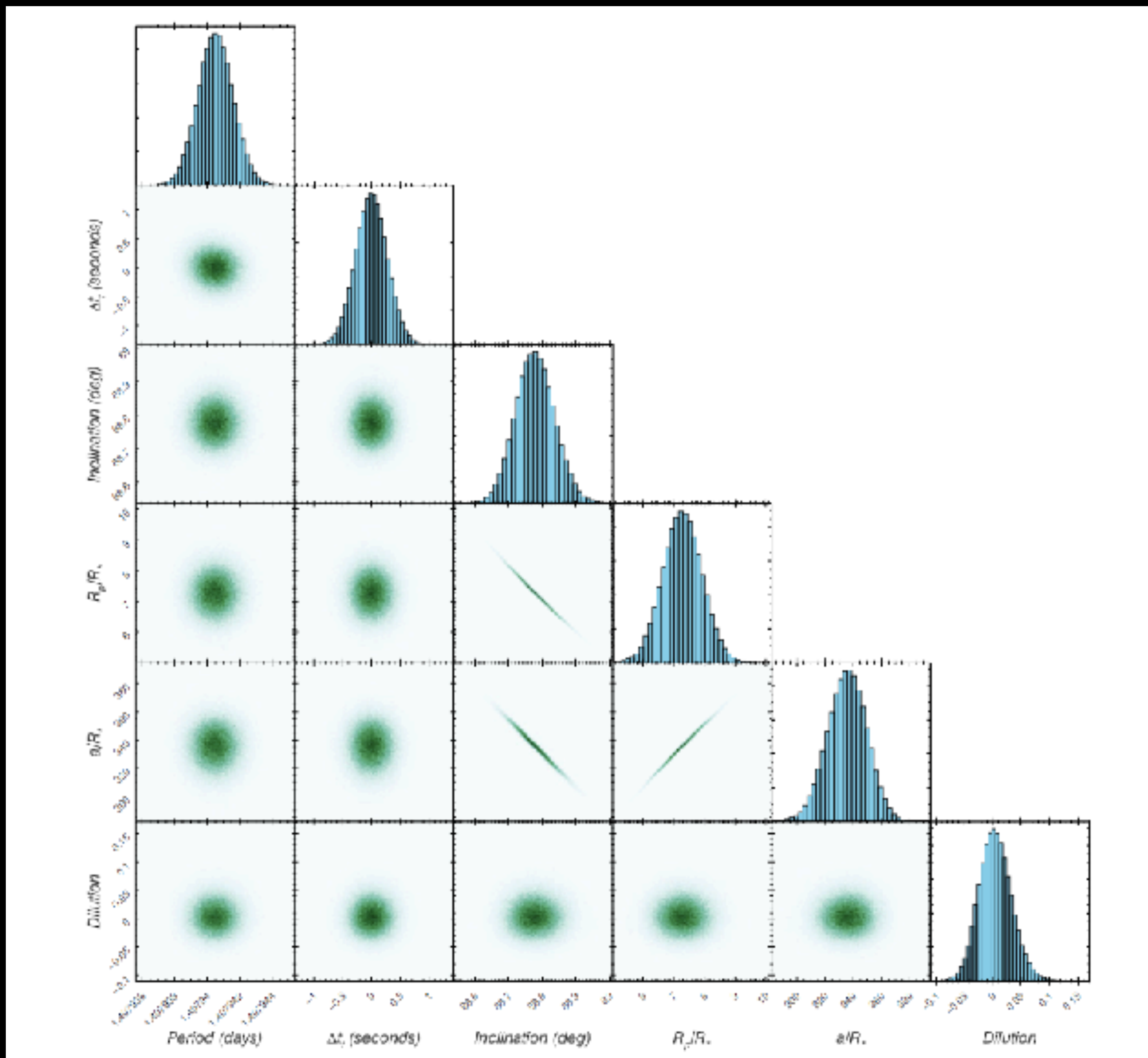
Vanderburg et al. 2020



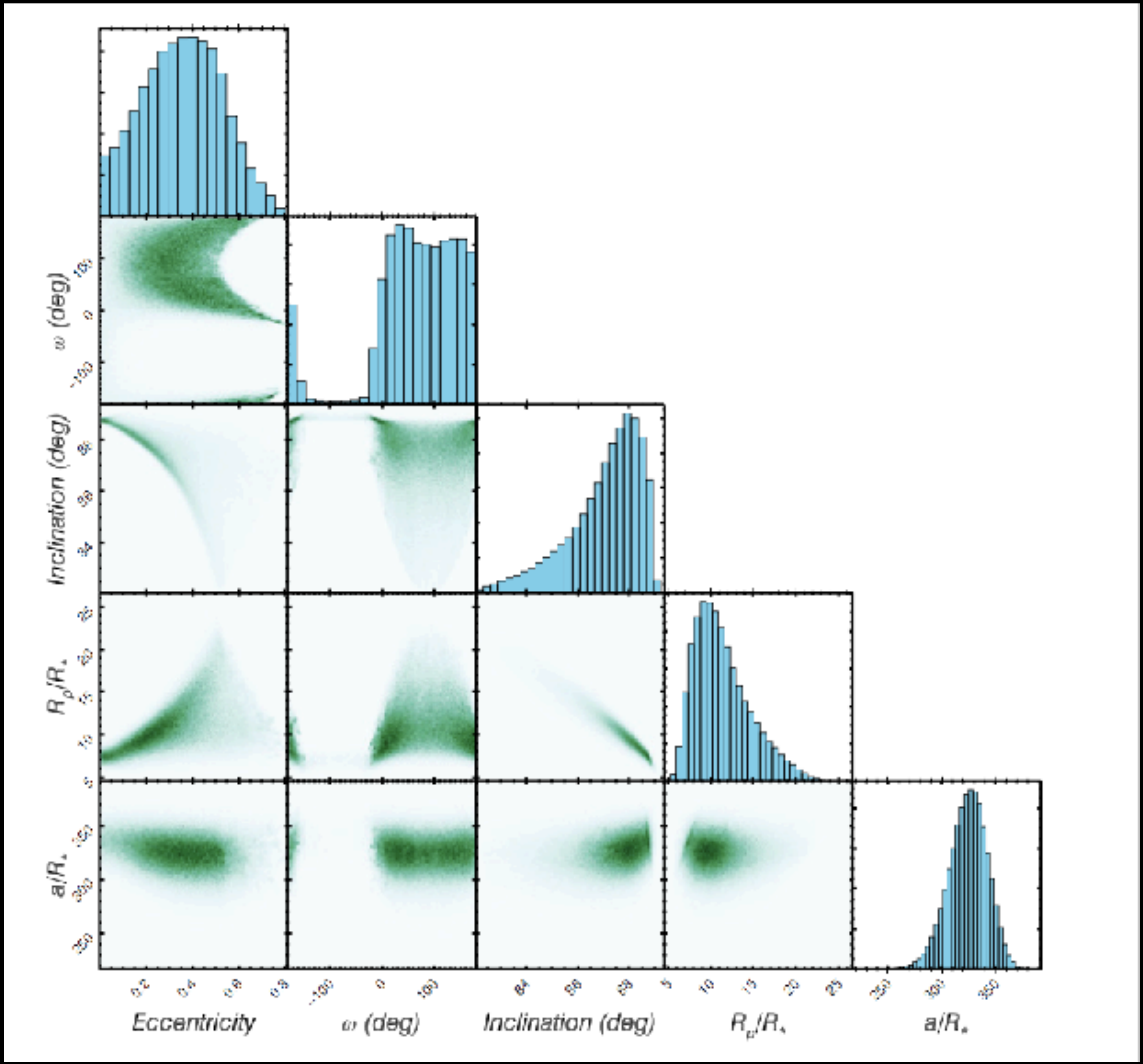
Vanderburg et al. 2020



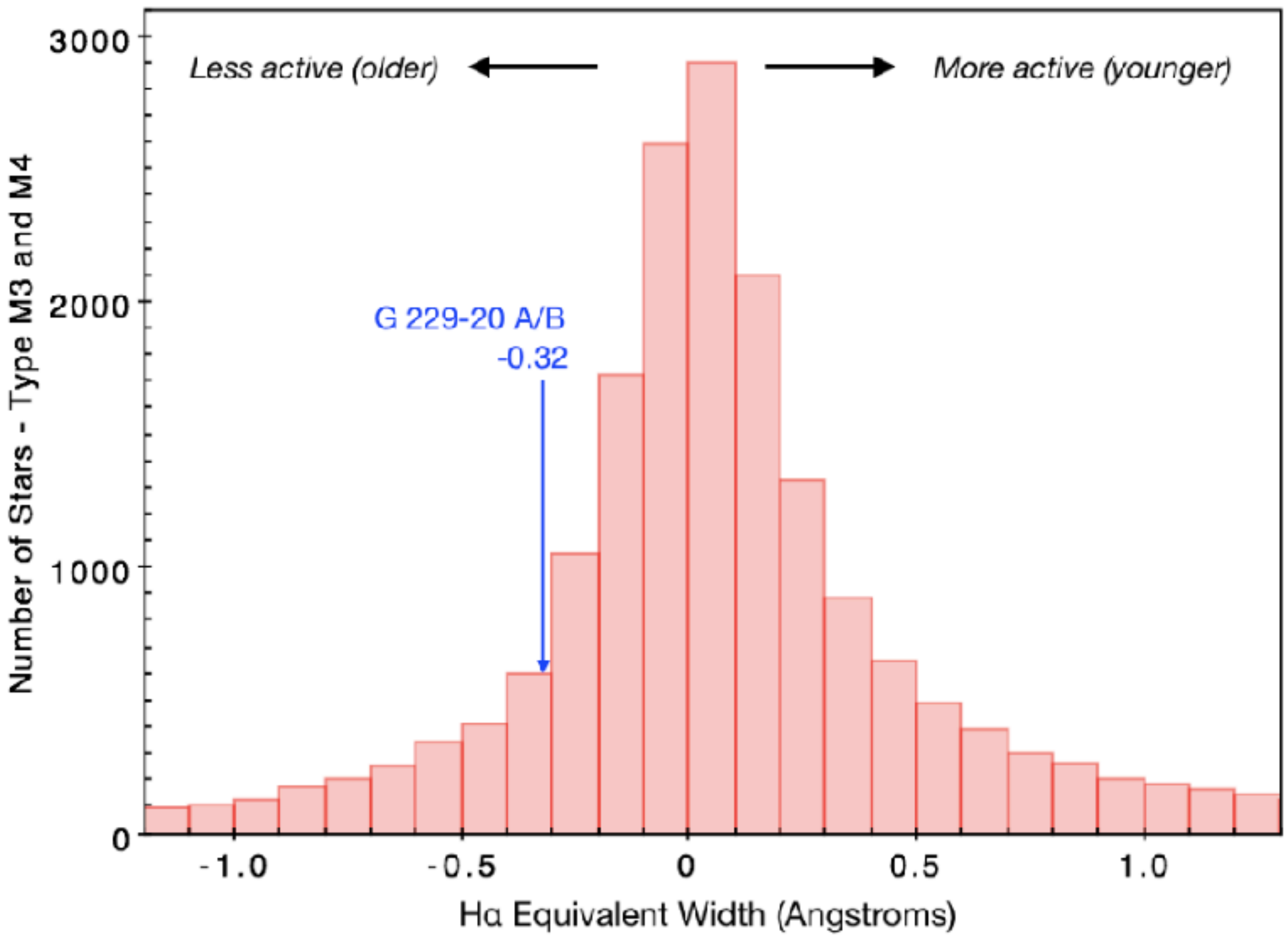
Vanderburg et al. 2020



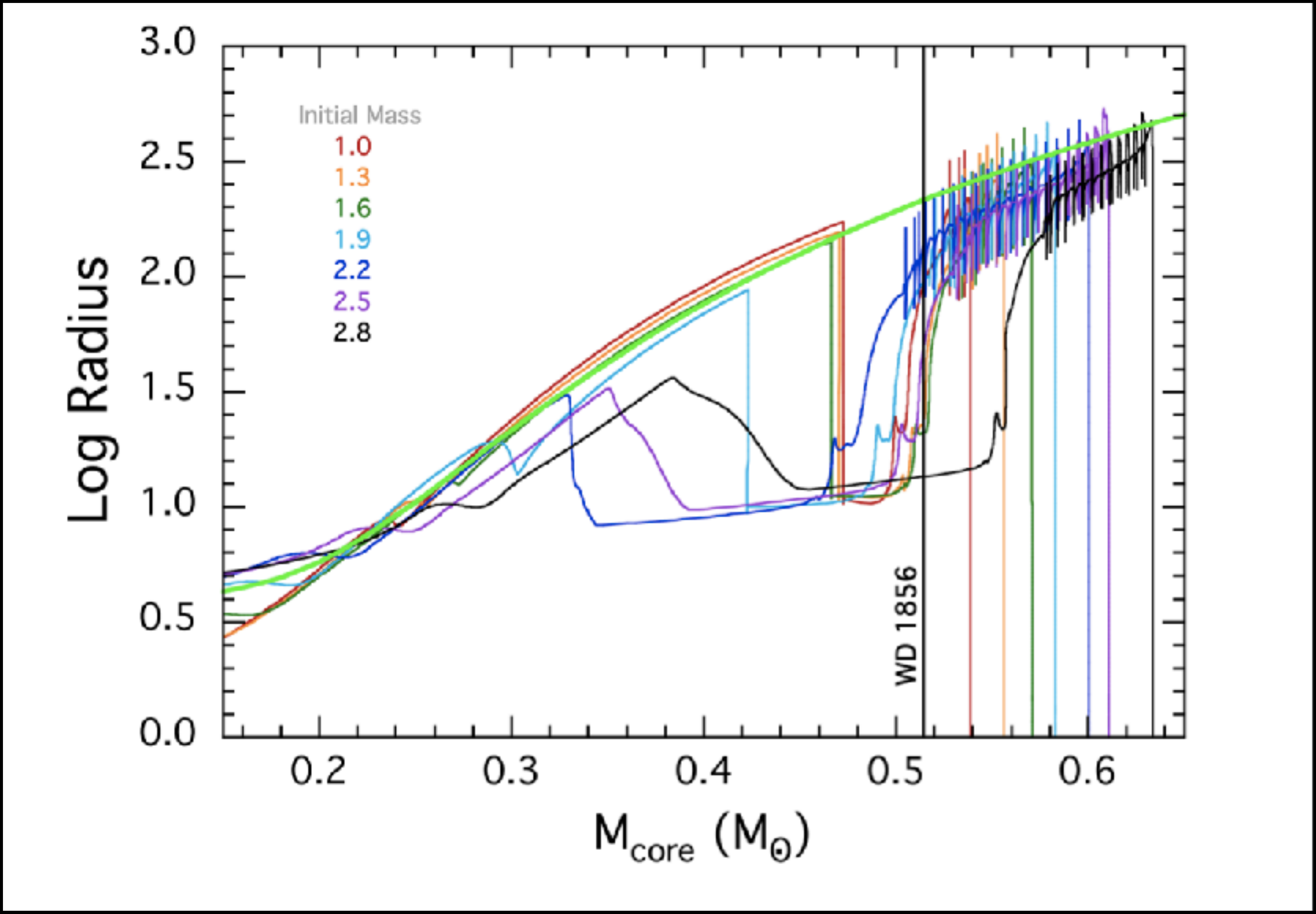
Vanderburg et al. 2020



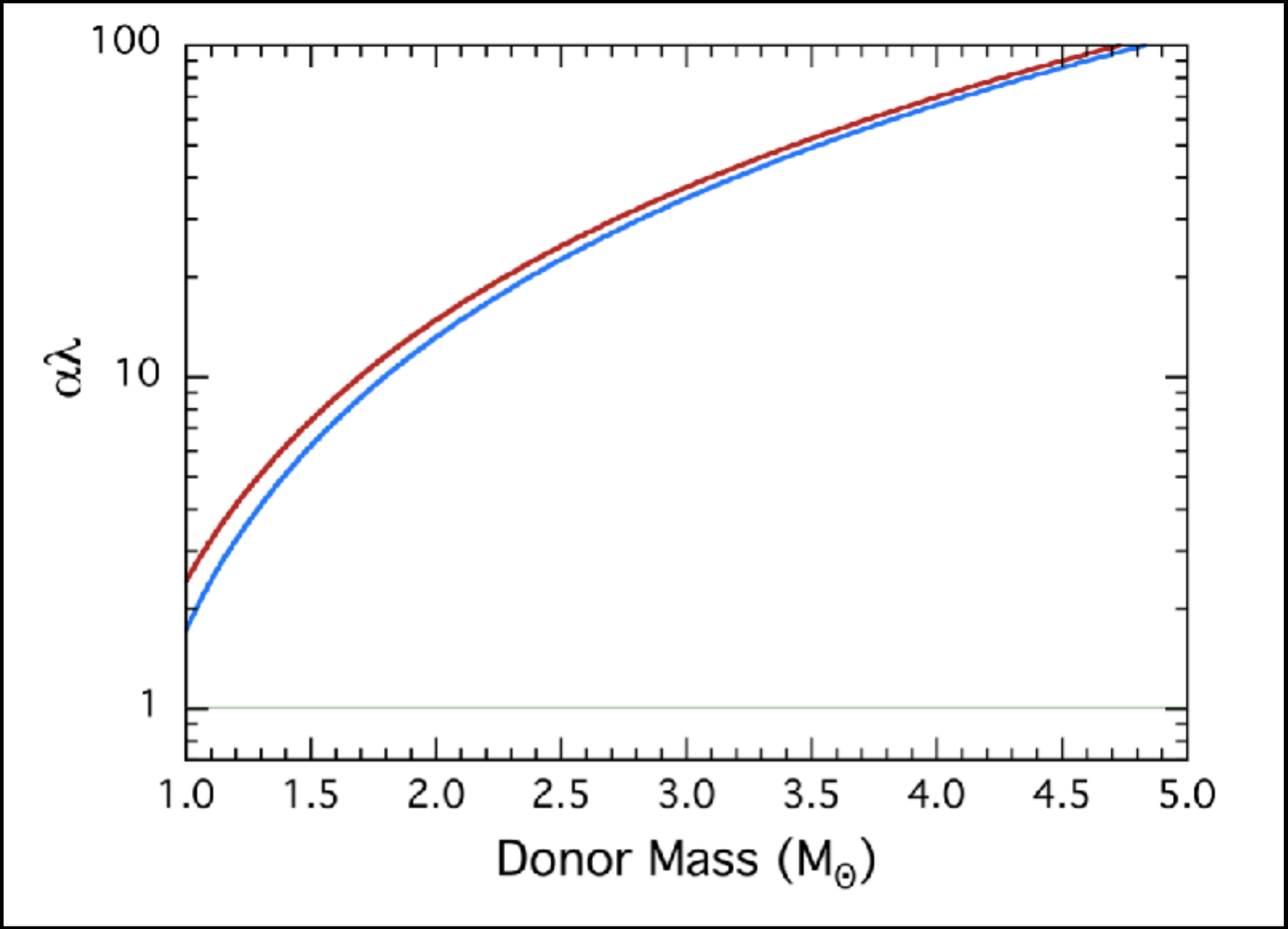
Vanderburg et al. 2020



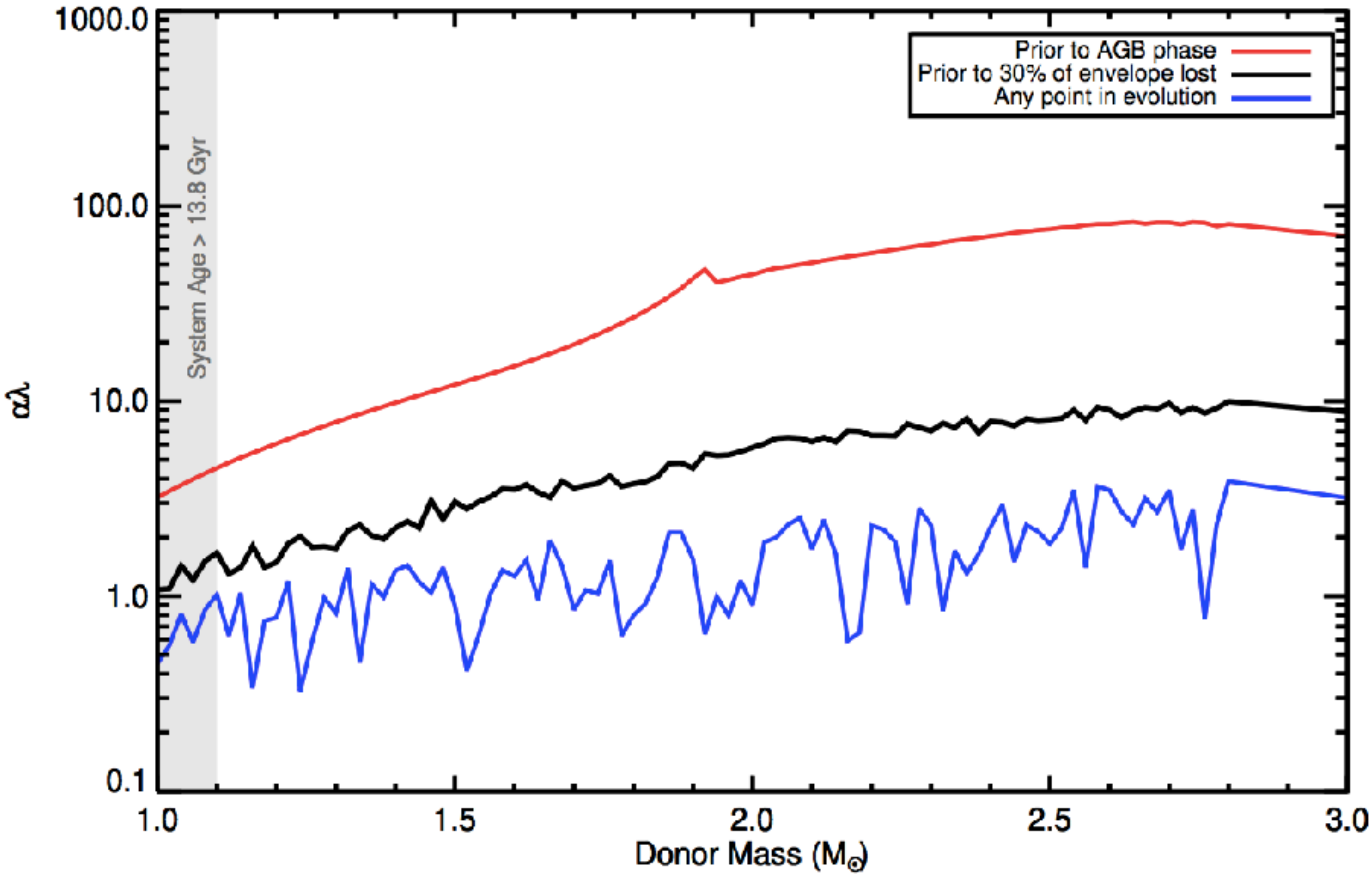
Vanderburg et al. 2020



Vanderburg et al. 2020



Vanderburg et al. 2020



Vanderburg et al. 2020