Stellar Evolution in Planetary Systems: How White Dwarf Formation Kicks can Reshape Orbital Architectures

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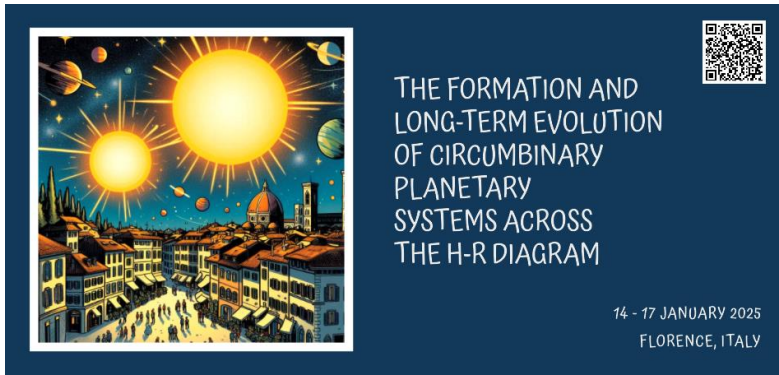
Main Collaborators: David V. Martin, Smadar Naoz, Cheyanne Shariat

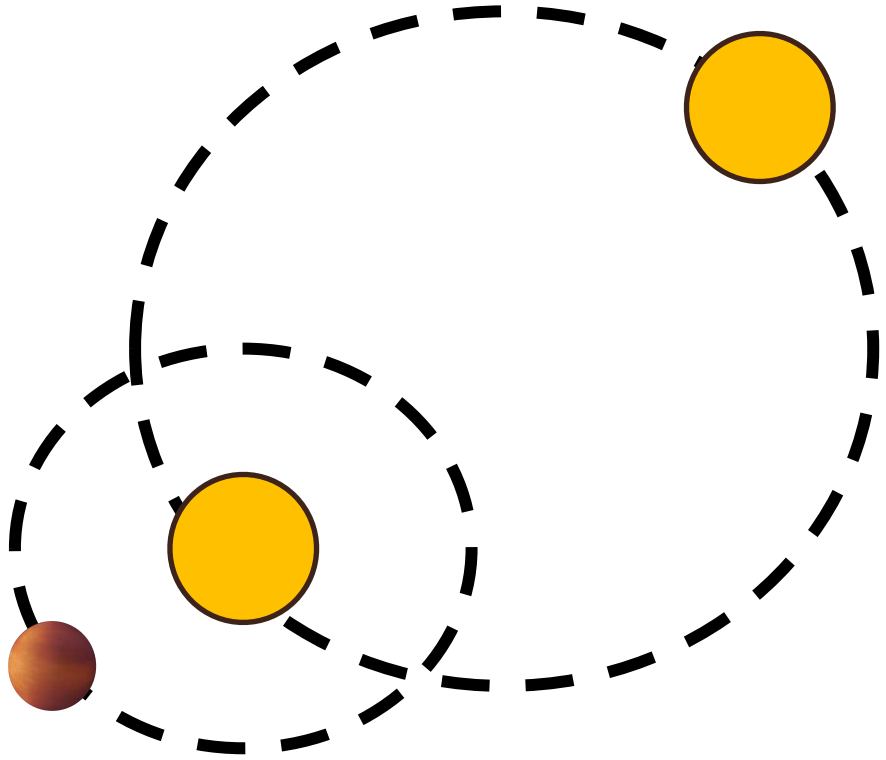
The formation and long-term evolution of circumbinary planetary systems across the H-R diagram
Florence, Italy

Jan. 16th, 2025

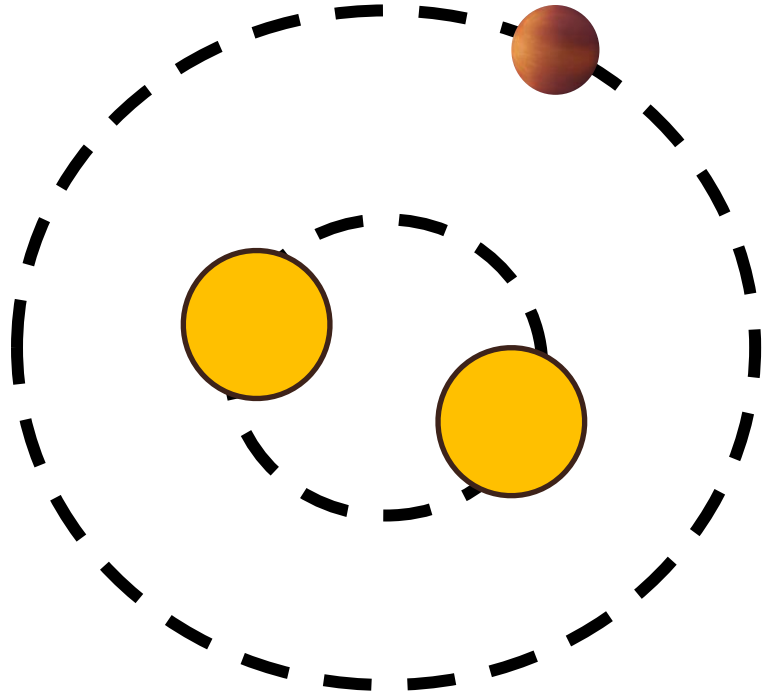


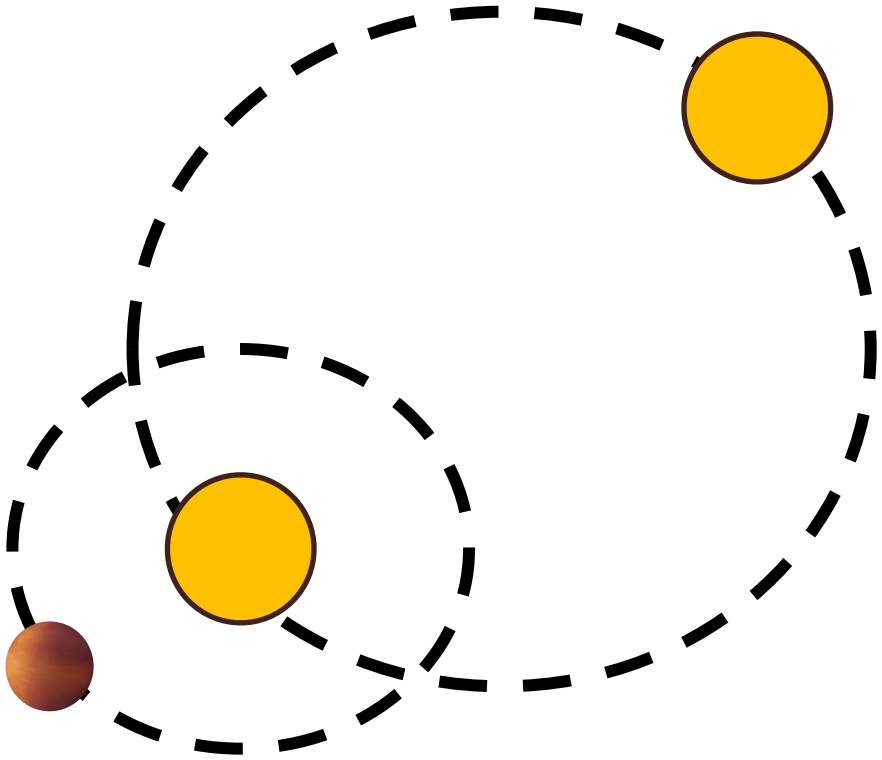
VANDERBILT UNIVERSITY

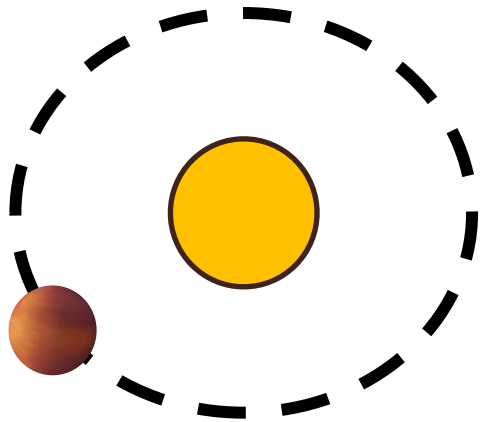
Circumstellar Planets in Binaries (S-type)

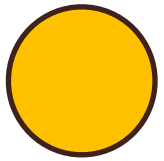


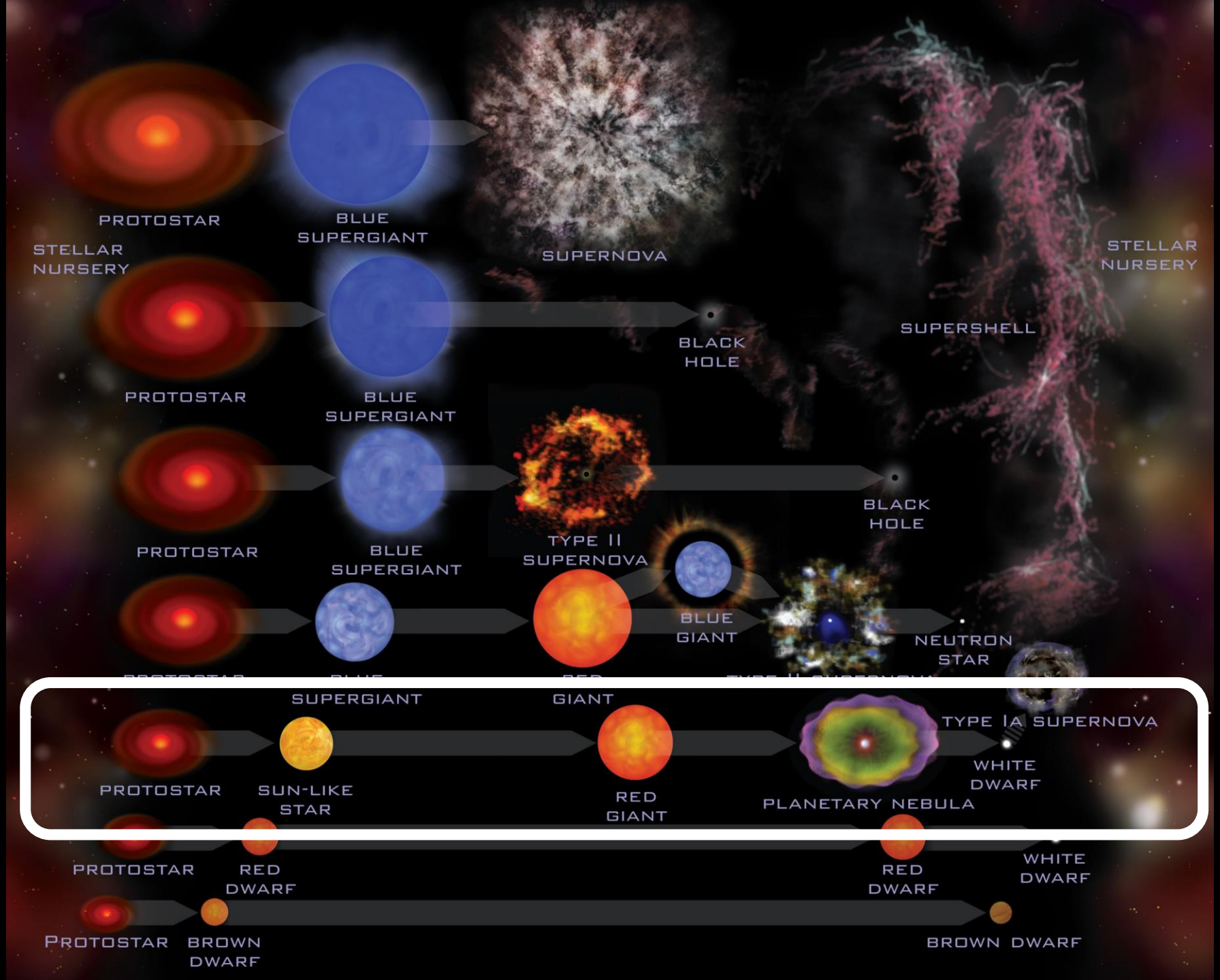
Circumbinary Planets (P-type)










PROTOSTAR
BLUE SUPERGIANT
SUPERNOVA
STELLAR NURSERY
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
BLUE GIANT
NEUTRON STAR
SUPERGIANT
GIANT
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
WHITE DWARF
PLANETARY NEBULA
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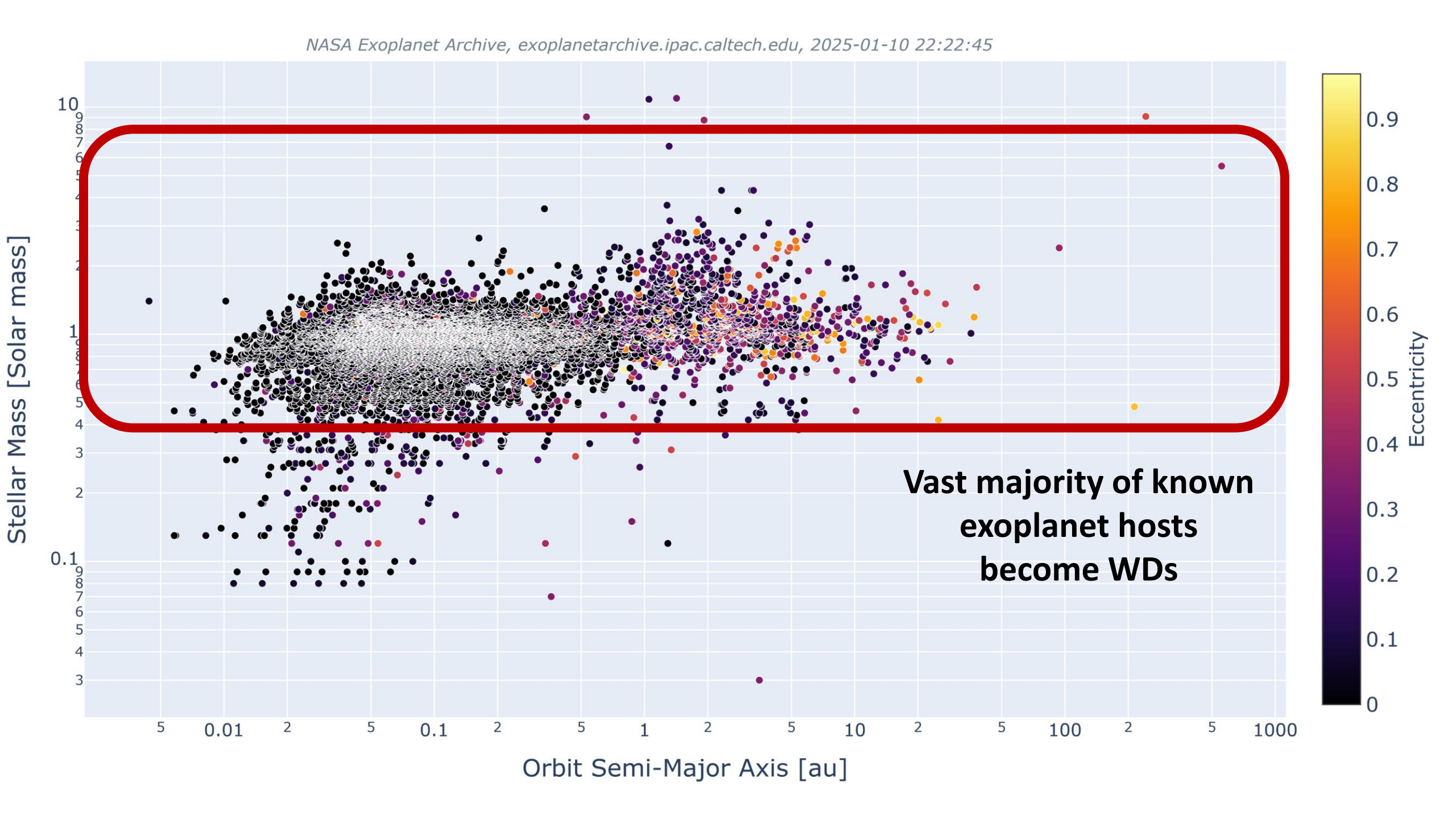
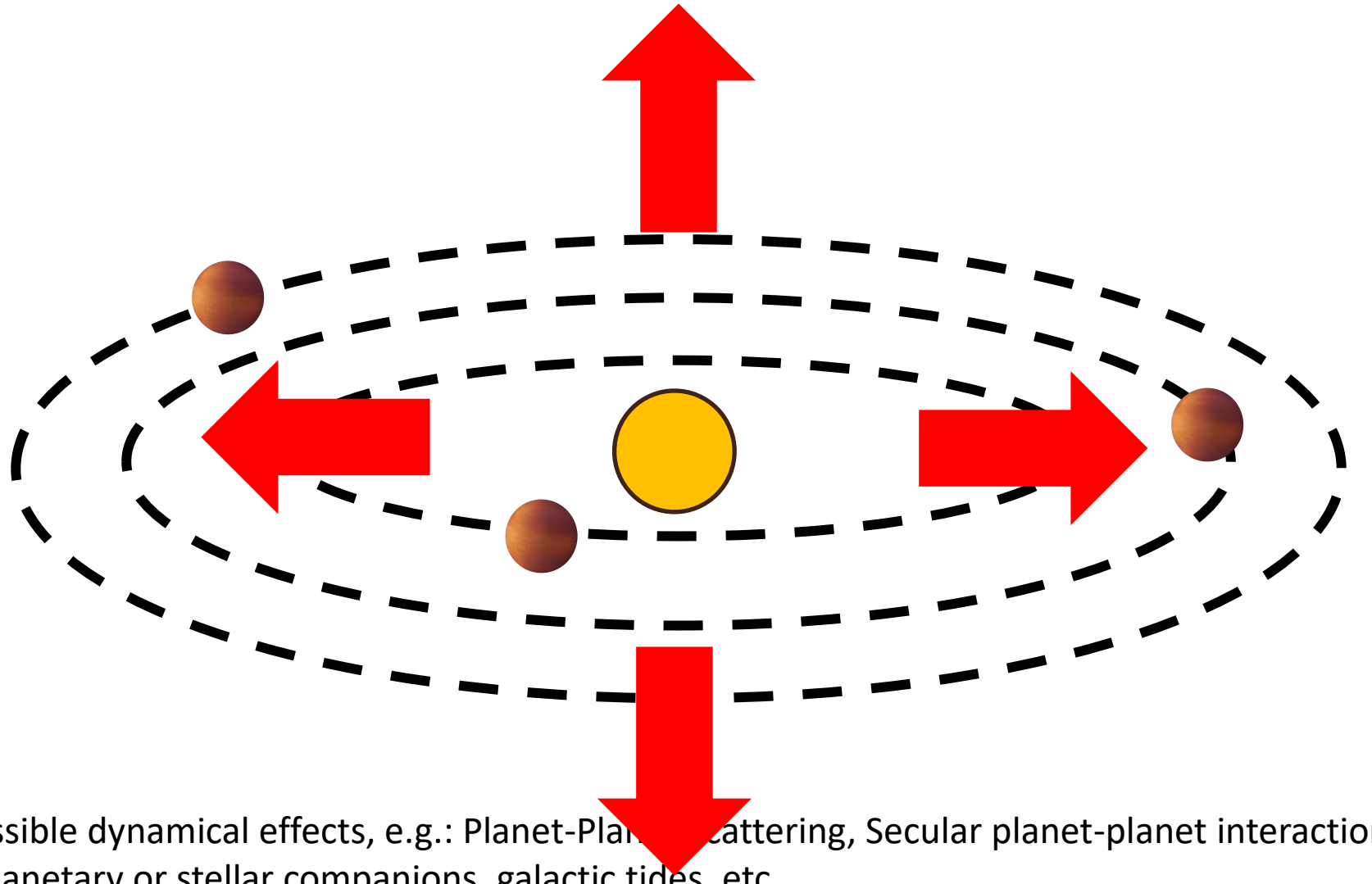
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

NASA JPL

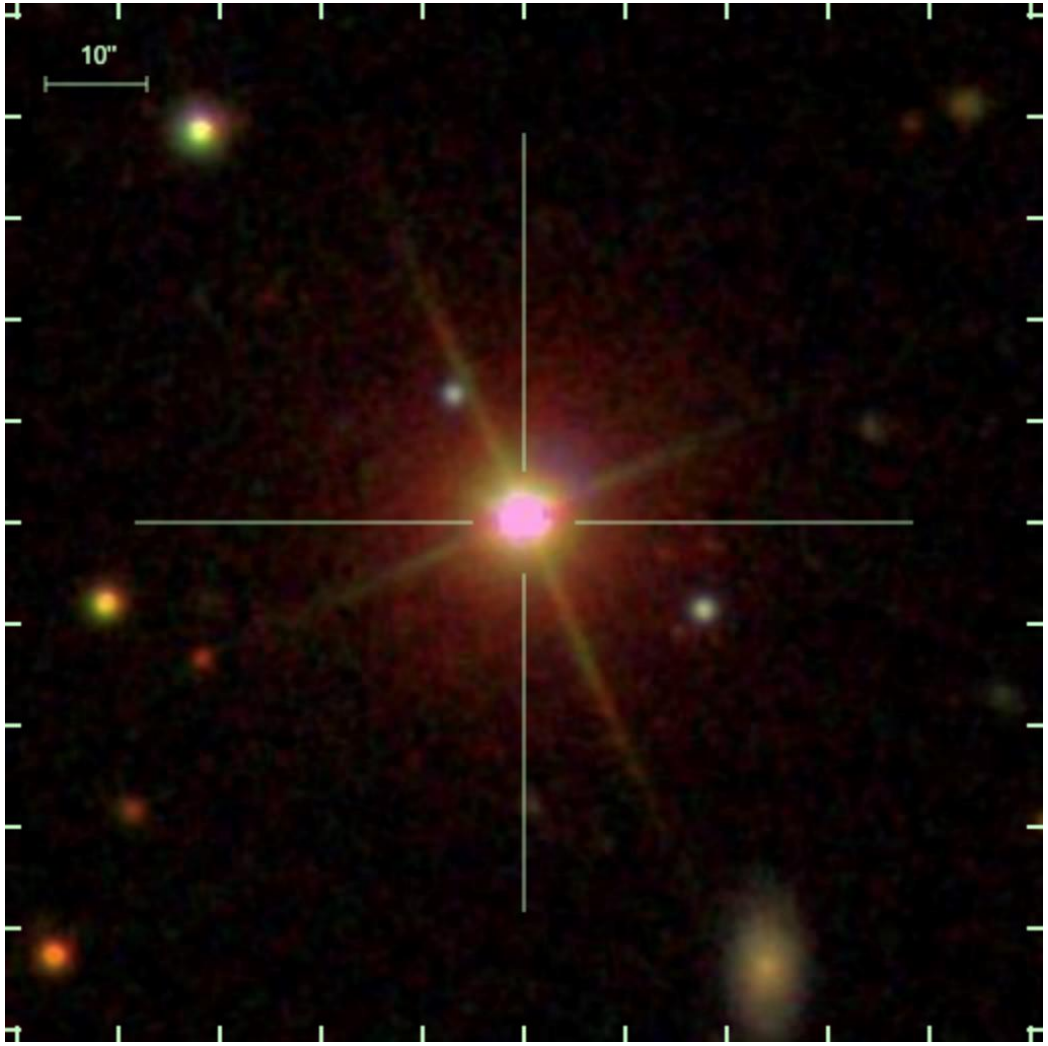

NASA Exoplanet Archive, exoplanetarchive.ipac.caltech.edu, 2025-01-10 22:22:45
Stellar Mass [Solar mass]
Orbit Semi-Major Axis [au]
Eccentricity
Vast majority of known exoplanet hosts become WDs

Classical View of Orbital Evolution due to WDs



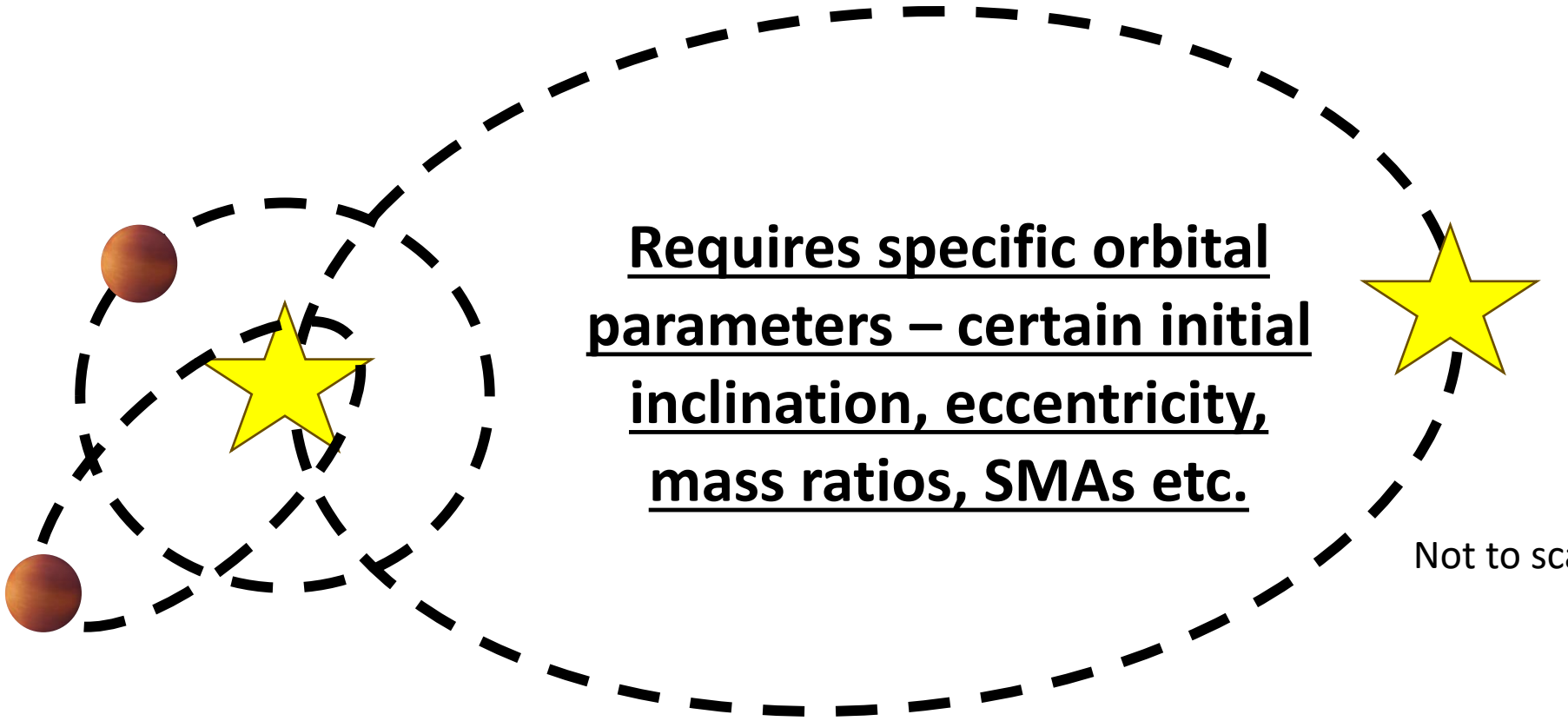
Vast number of possible dynamical effects, e.g.: Planet-Planet scattering, Secular planet-planet interactions, Kozai-Lidov interactions with planetary or stellar companions, galactic tides, etc.

Planets in Evolving Wide Binaries



TOI-1259

High eccentricity migration via Kozai-Lidov

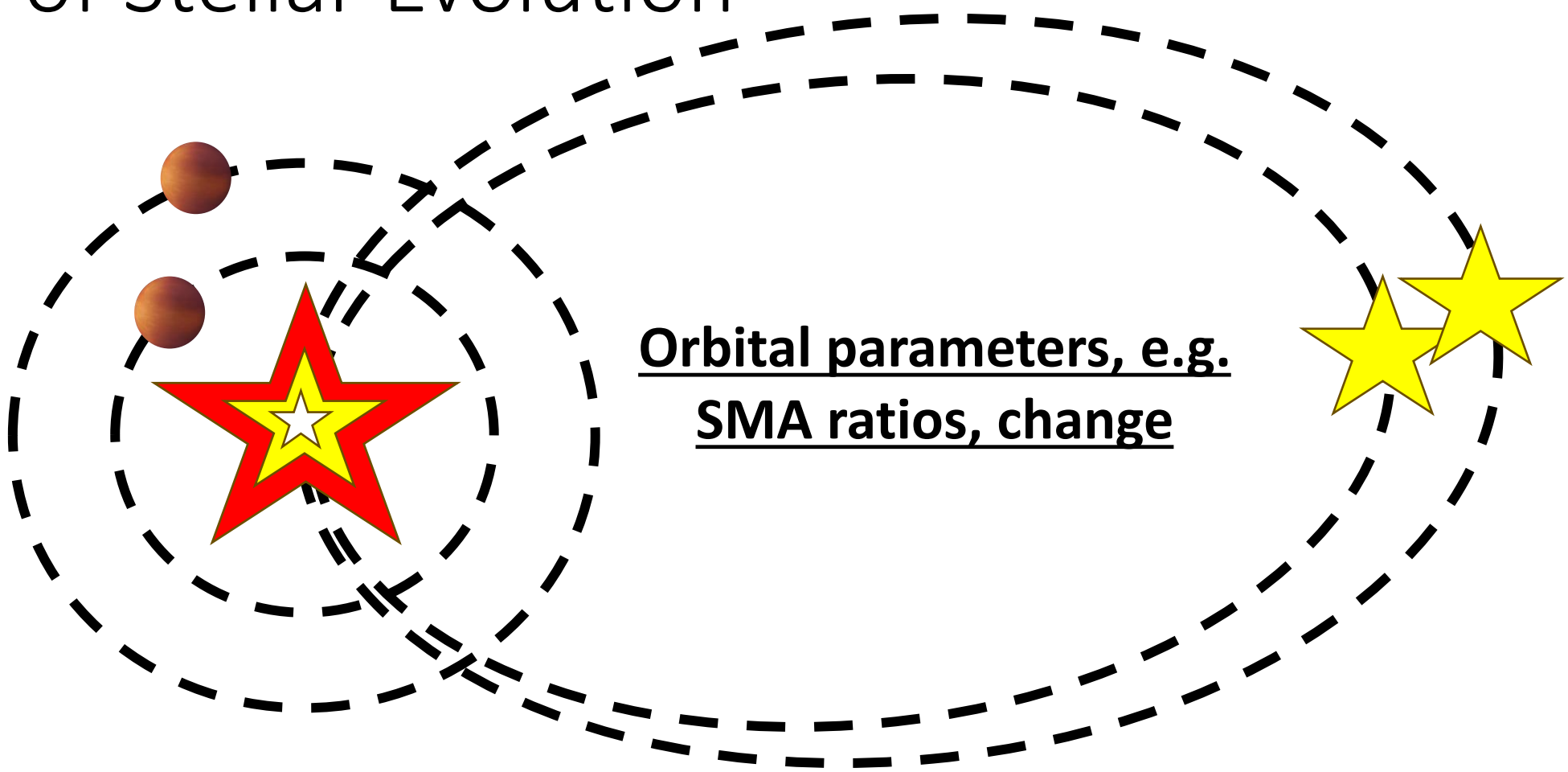


Requires specific orbital parameters – certain initial inclination, eccentricity, mass ratios, SMAs etc.

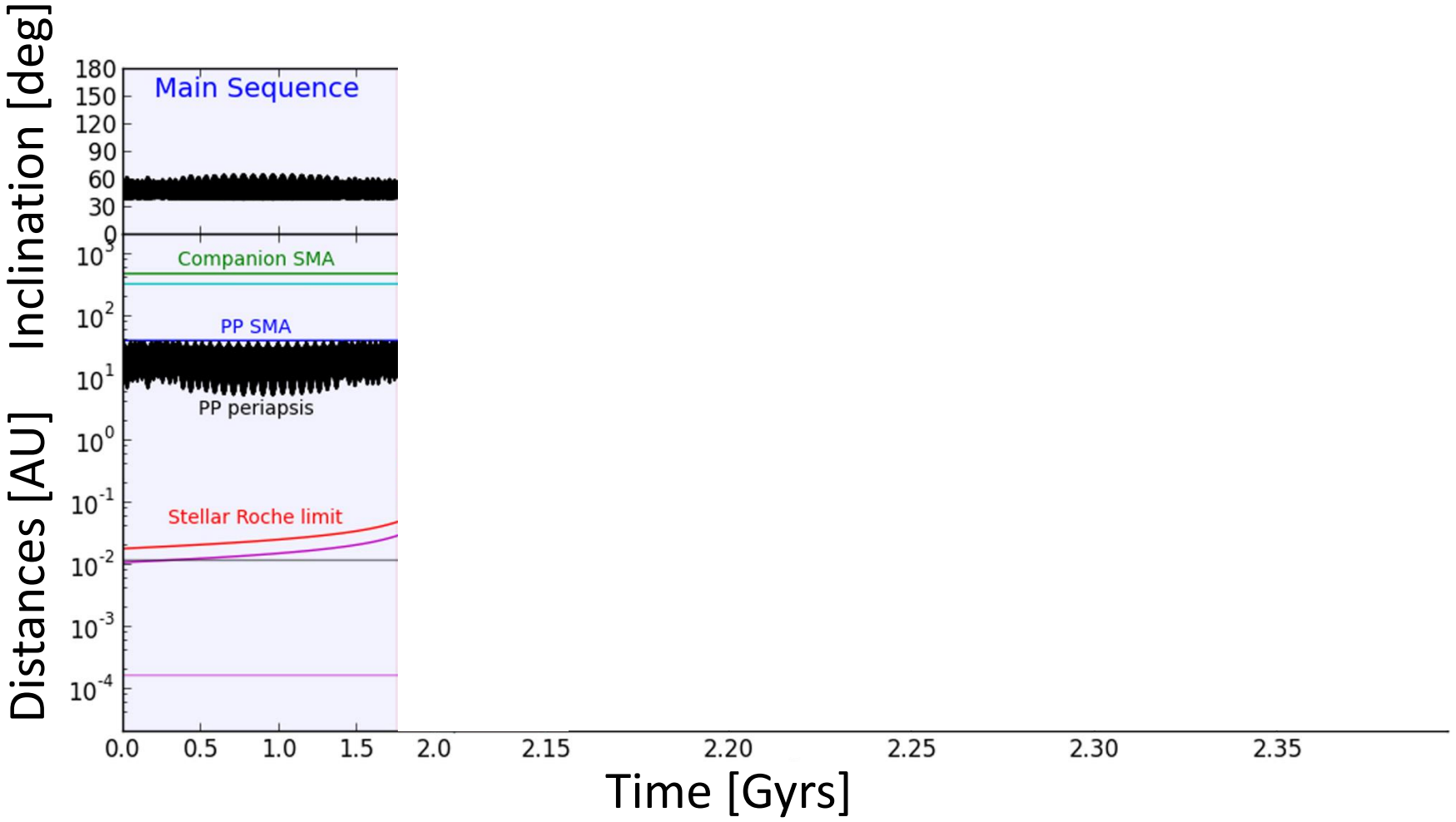
Not to scale

See Kozai 1962, Lidov 1962, Fabrycky & Tremaine 2007, Naoz 2016, Naoz et al. 2011, 2012, 2013, etc., Petrovich 2015, etc.

Impact of Stellar Evolution



Impact of Stellar Evolution

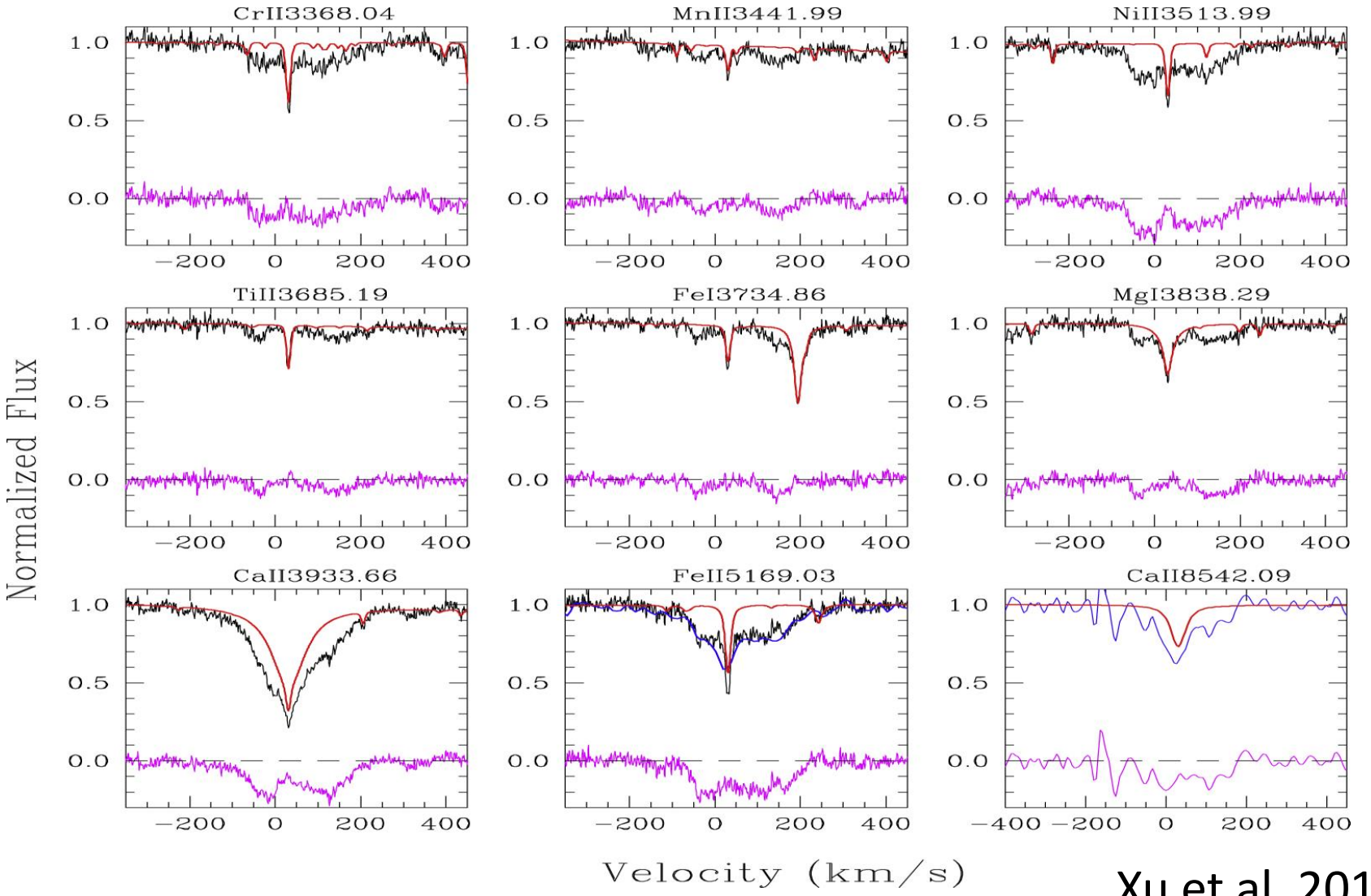


Stephan et al. 2017

<u>Stellar evolution can trigger or enhance Kozai-Lidov evolution</u>

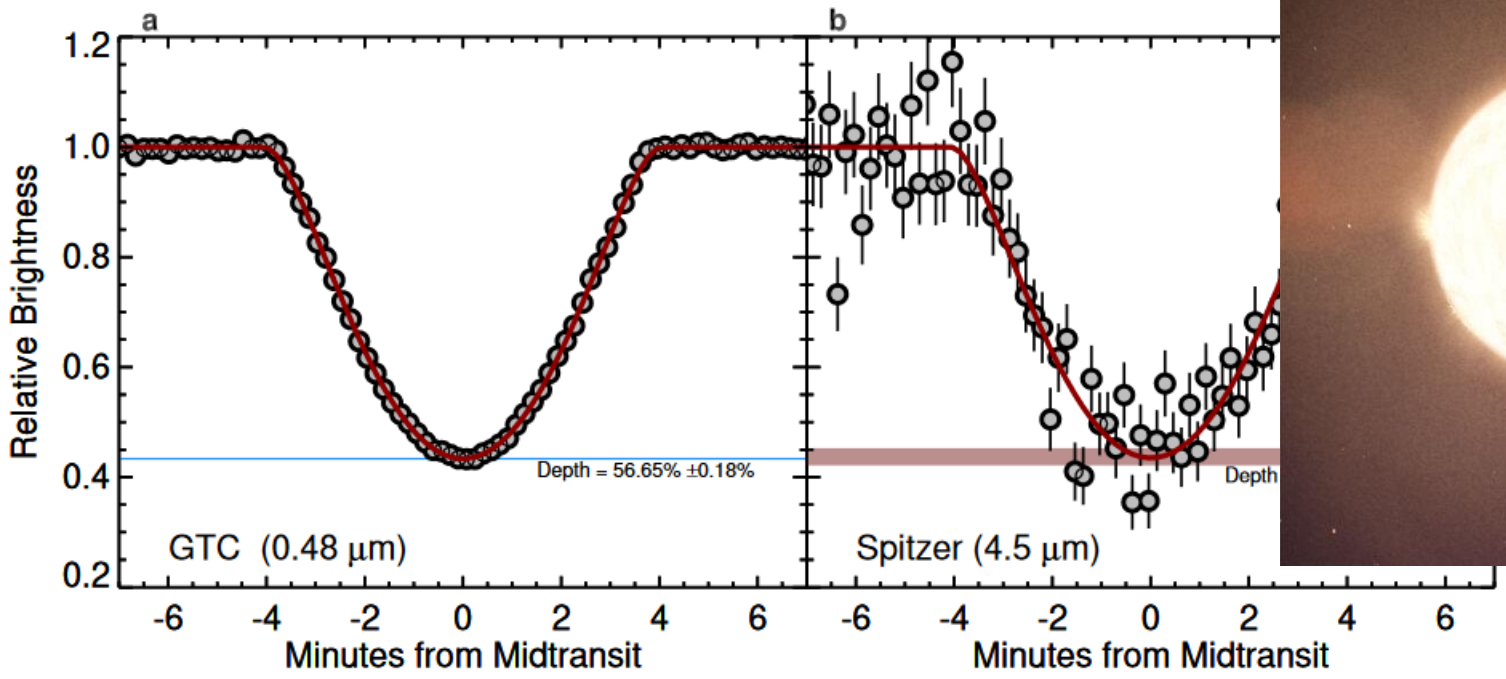
See also Shappee & Thompson 2013, **Stephan et al. 2016**, Hamers & Portegies-Zwart 2016, Vanderburg et al. 2020, Muñoz & Petrovich 2020, **Stephan et al. 2021**, O'Connor et al. 2021, etc.

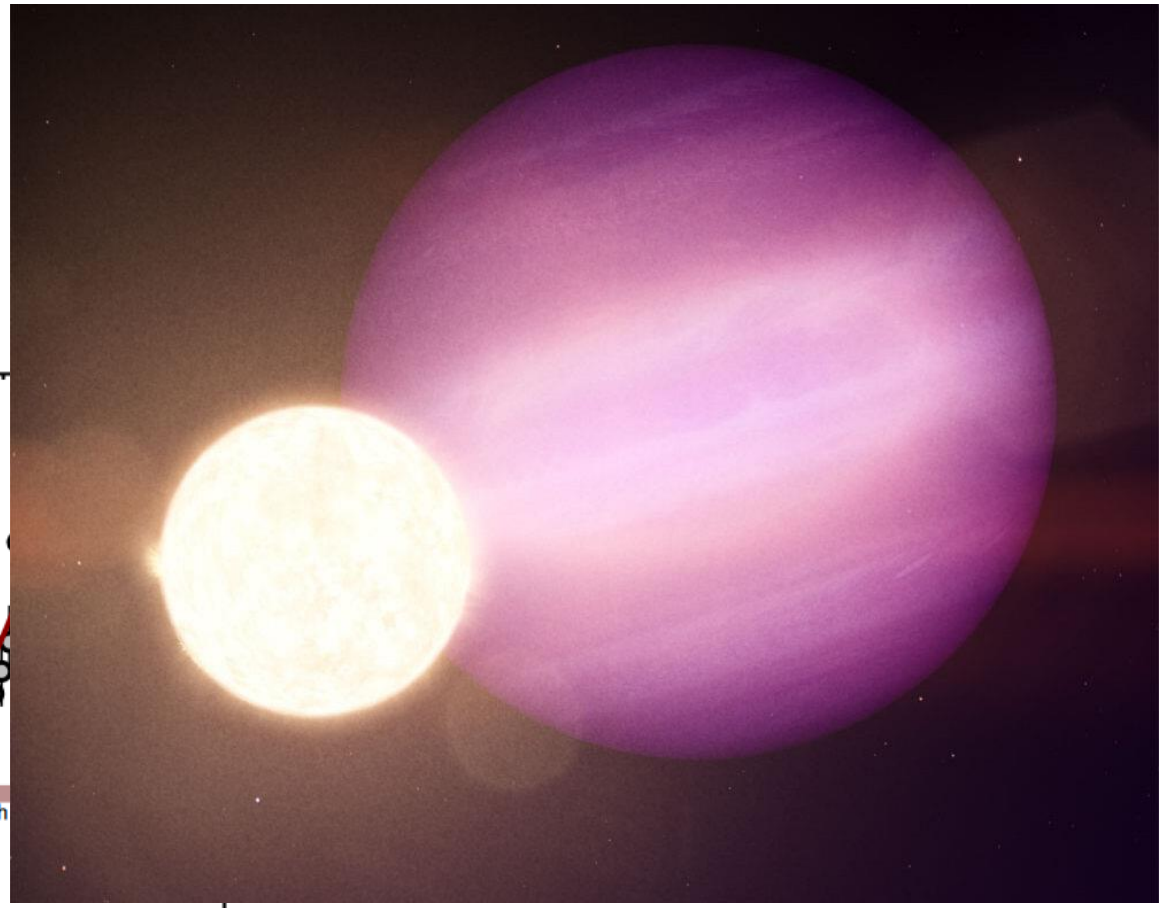
White Dwarf Pollution



Xu et al. 2016

White Dwarf Planet - WD 1856+534

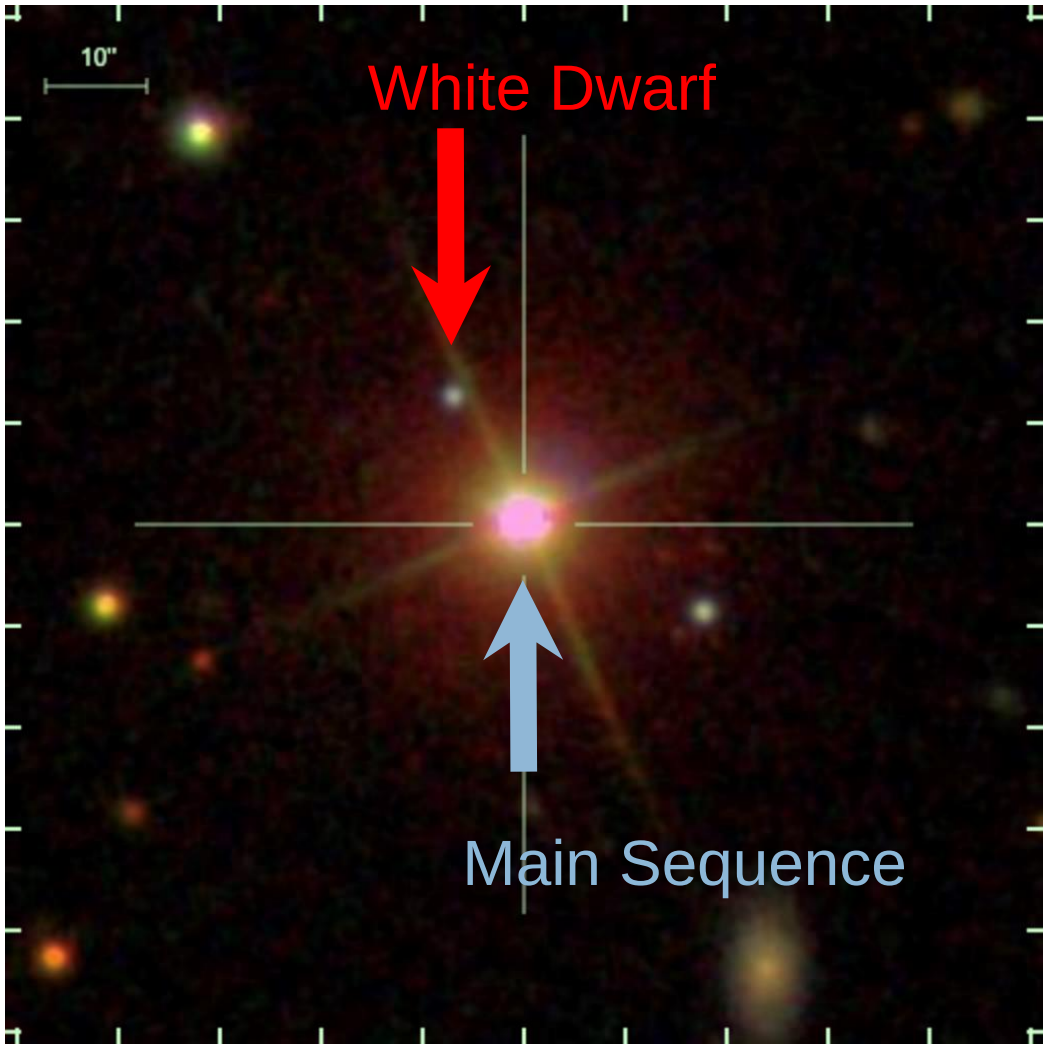




Vanderburg et al. 2020

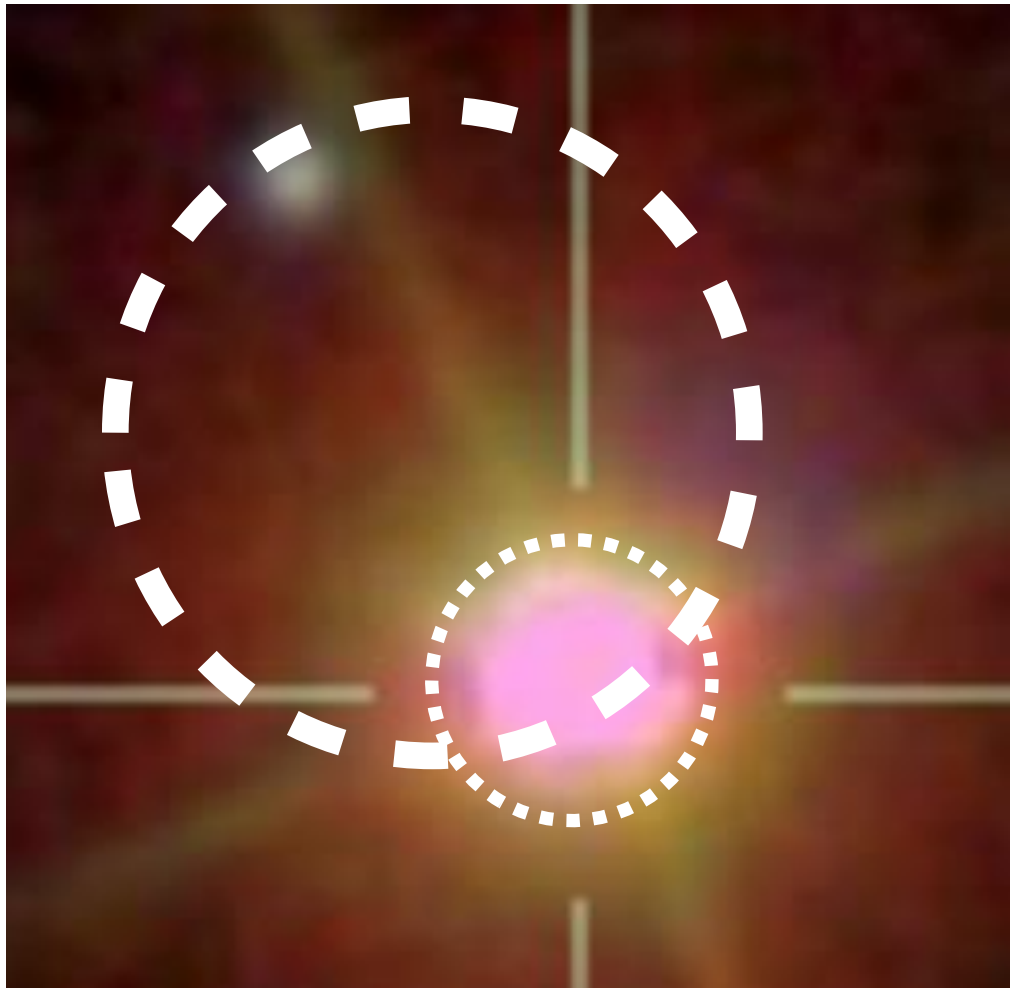
Stellar Evolution of a Companion

TOI-1259



Stellar Evolution of a Companion

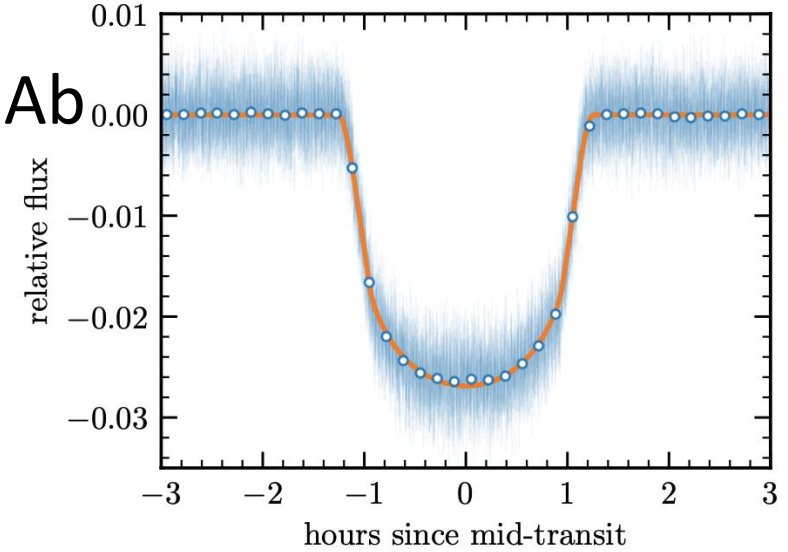
WD orbit:
1648 AU



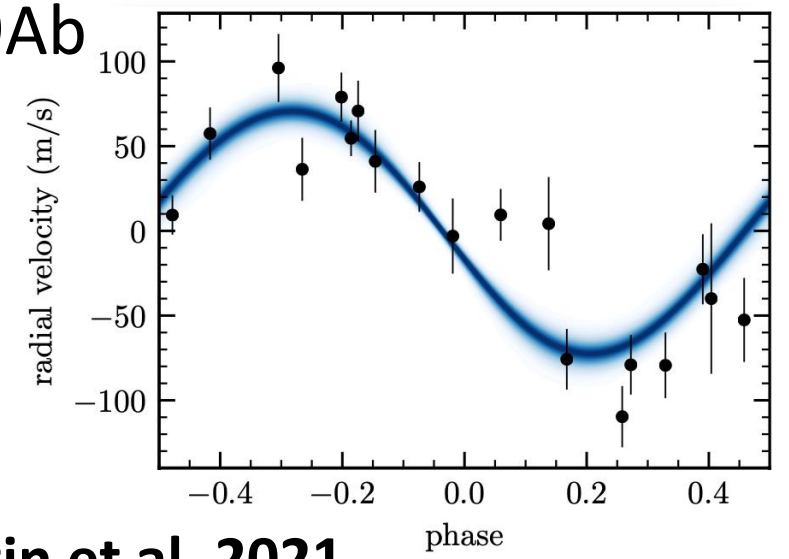
TOI-1259

HJ orbit: 0.04 AU

TOI-1259Ab
Transit



TOI-1259Ab
RVs



Martin et al. 2021

Stellar Evolution of a Companion

WD orbit:
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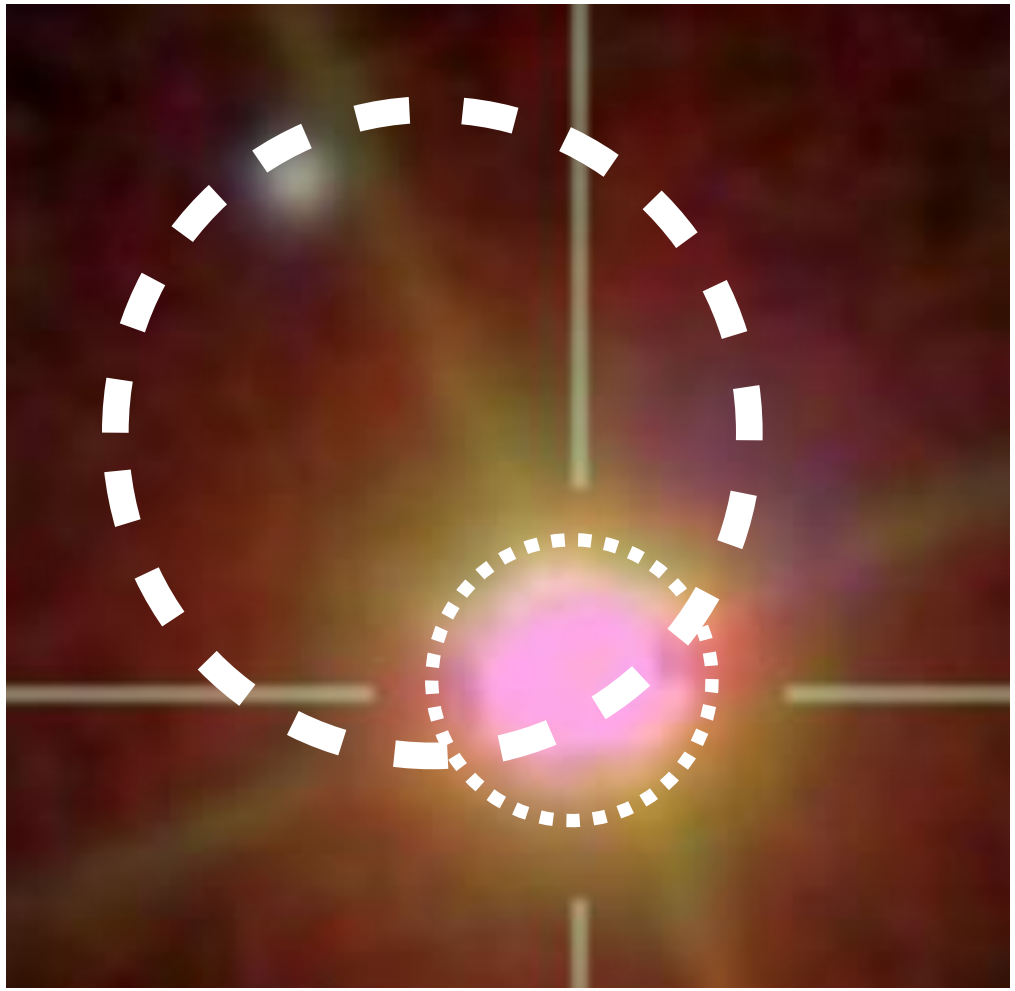

TOI-1259

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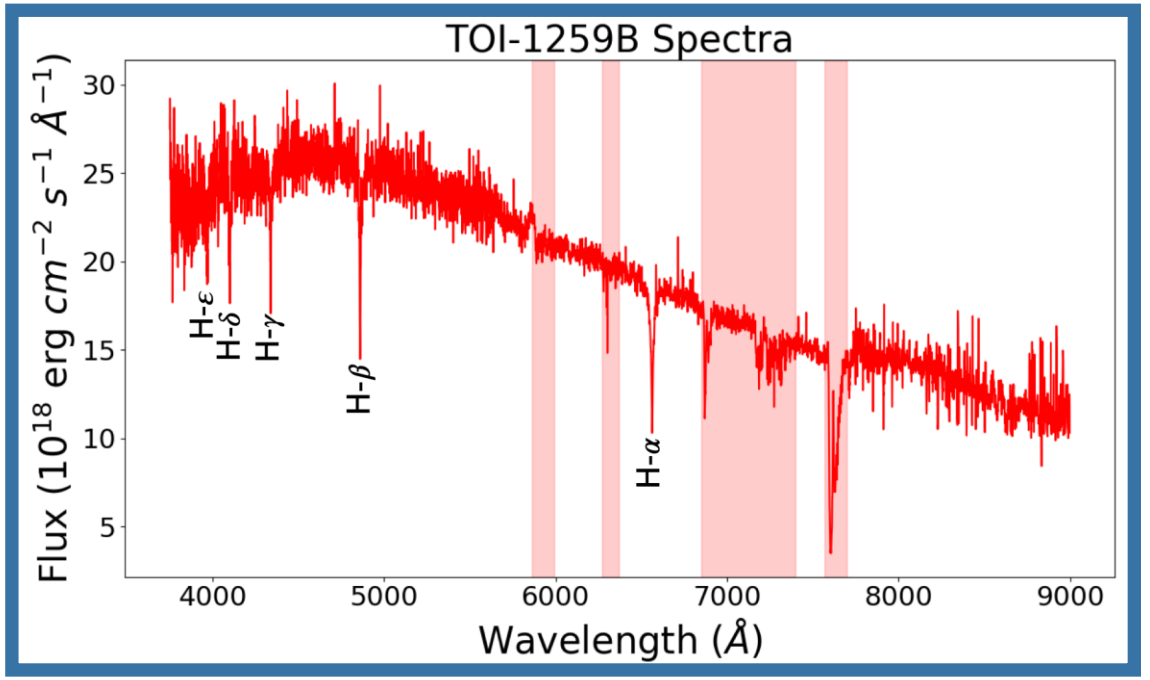
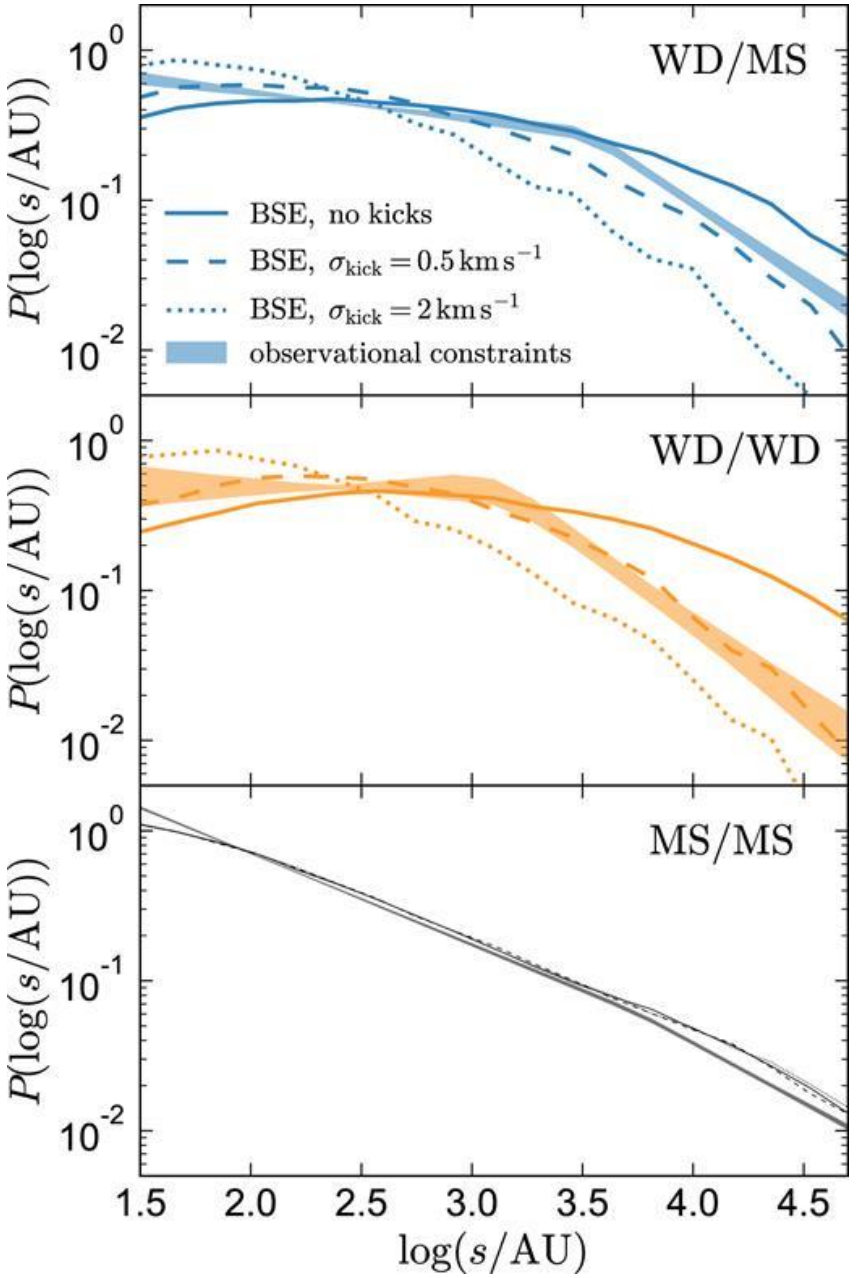


Fitzmaurice et al. 2023

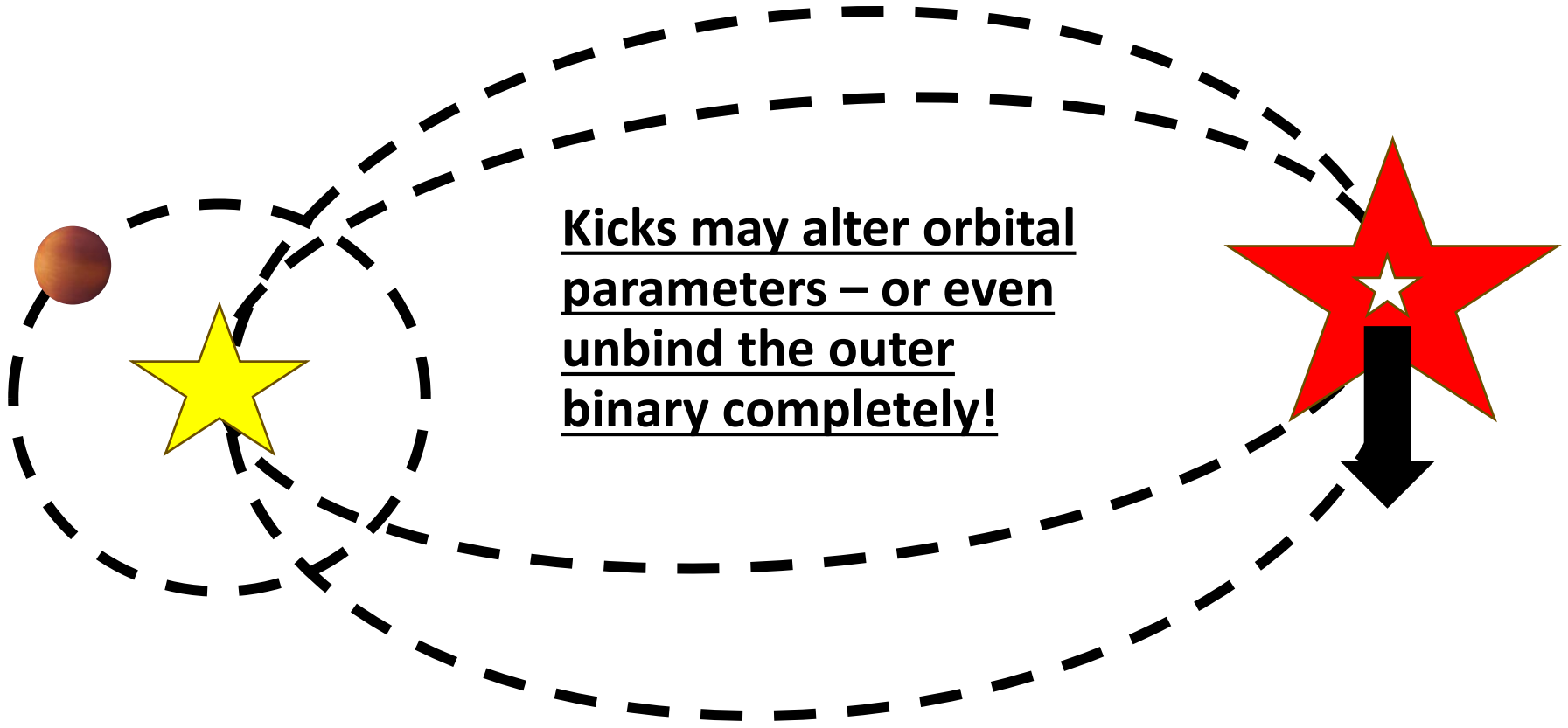
White Dwarf Kicks

- El-Badry & Rix 2018 showed that WD formation seems to come with a kick of ~0.75 km/sec
- Also supported by previous observations of dynamics of stellar clusters and similar systems



El-Badry & Rix 2018

White Dwarf Kick Impact

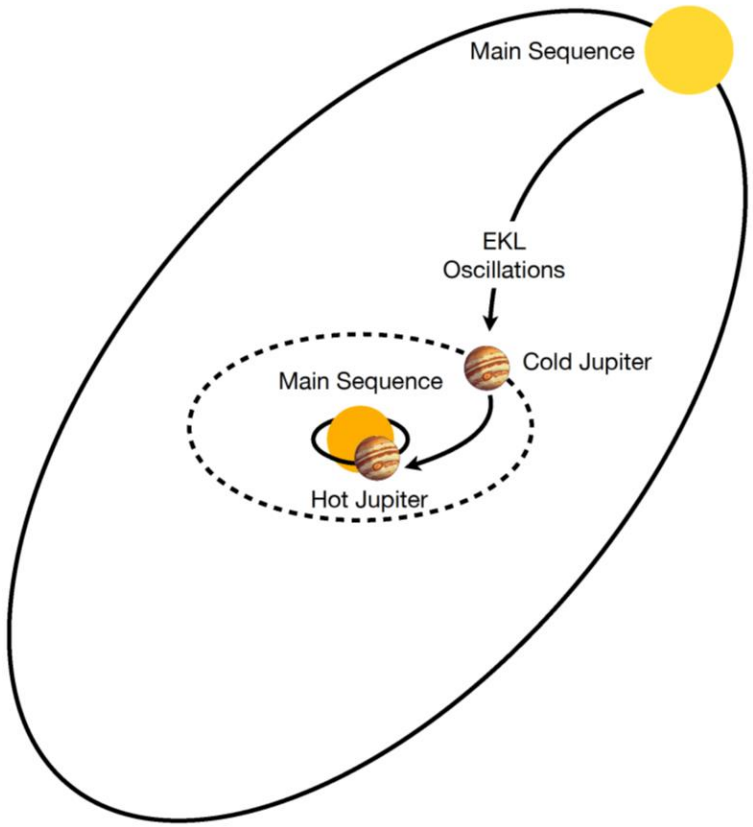


Kicks may alter orbital parameters – or even unbind the outer binary completely!

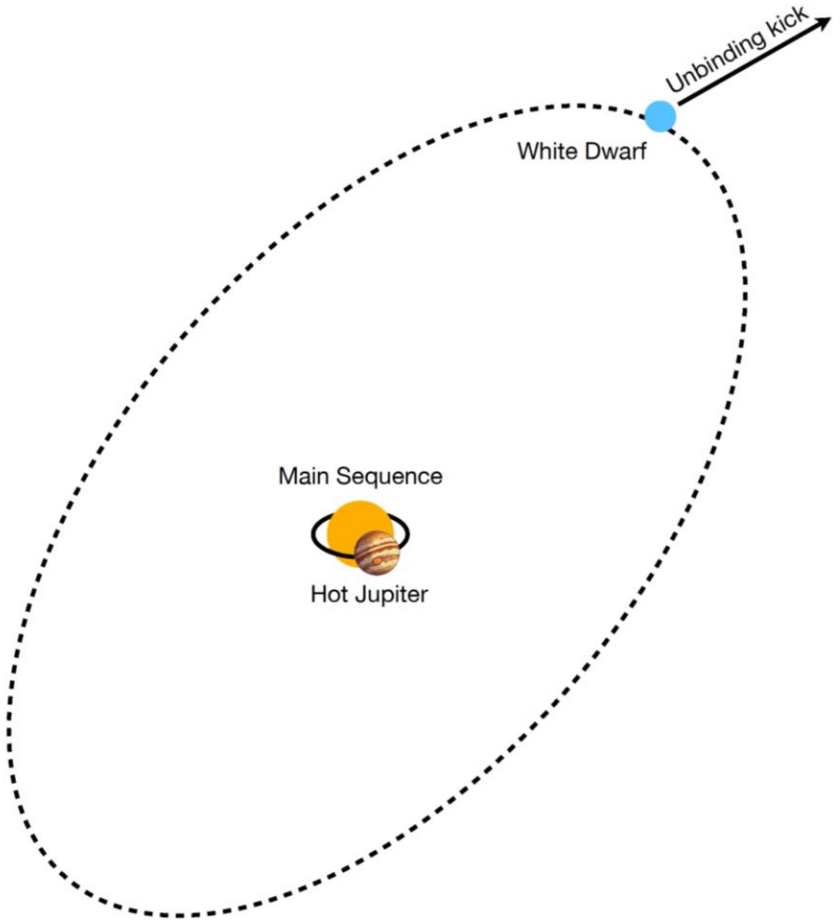
See also **Shariat et al. 2023**

Pathway 1

Step 1: Hot Jupiter formation in a misaligned main sequence binary

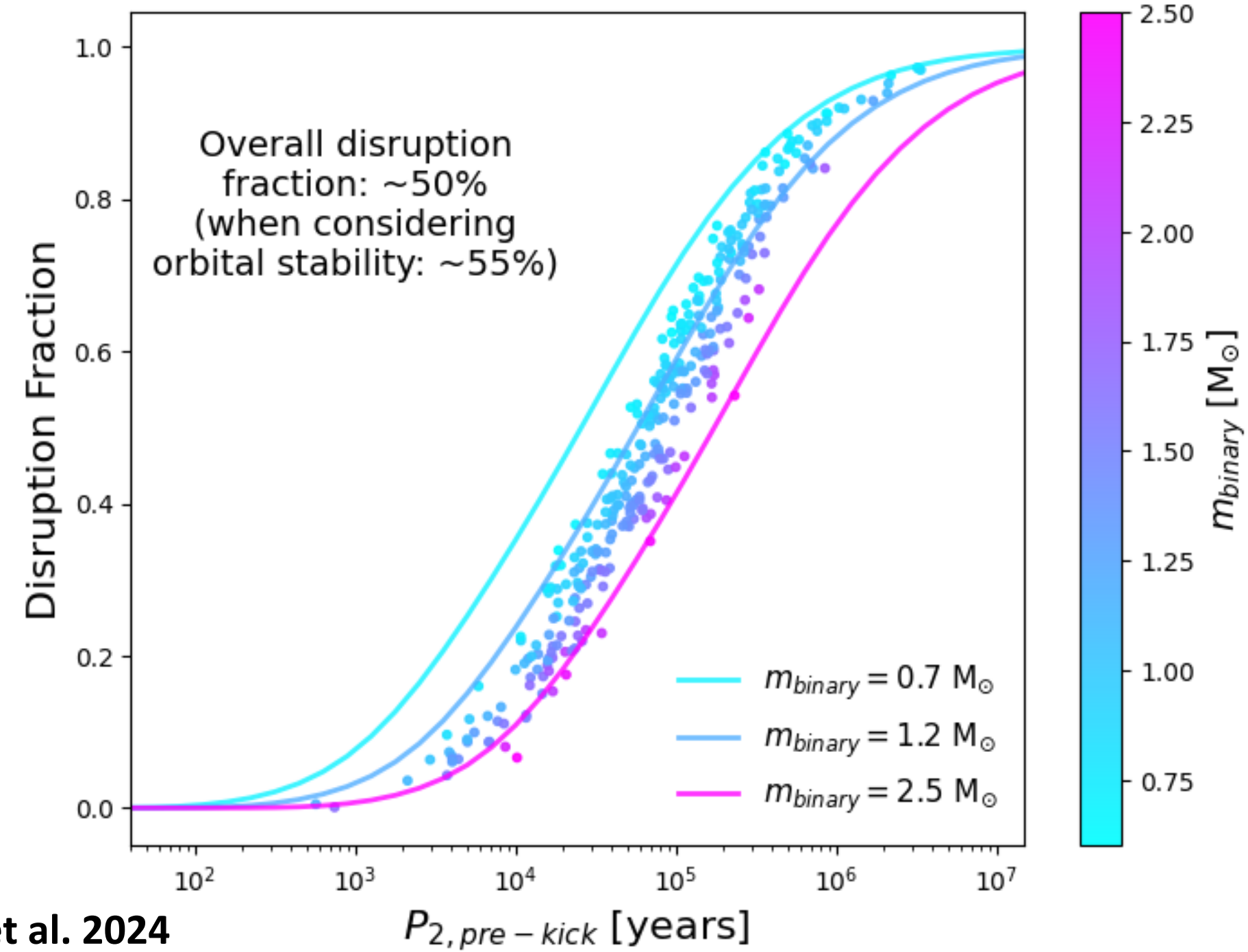


Step 2: Outer star evolves into a white dwarf and experiences a kick which unbinds the binary



End Result: Hot Jupiter around a single main sequence star

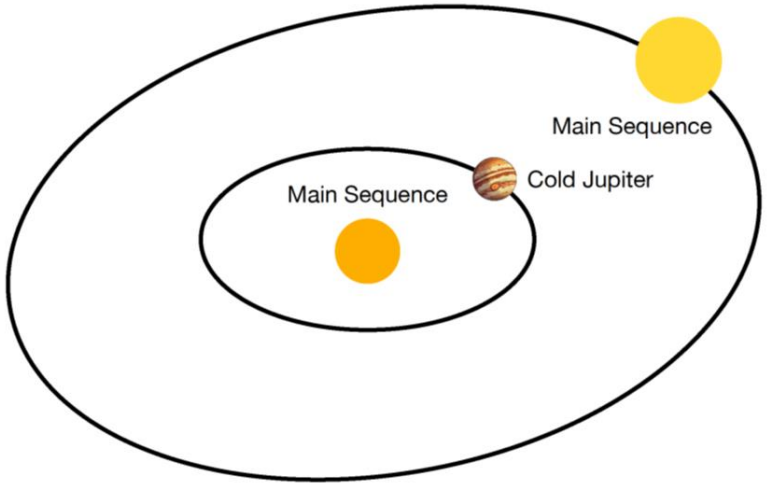
Stephan et al. 2024



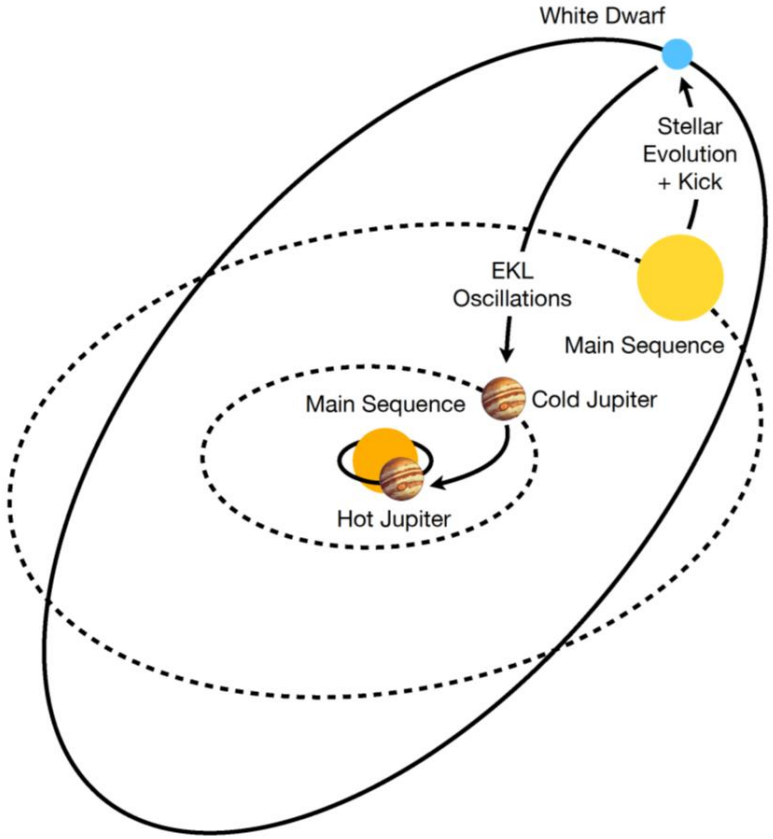
Stephan et al. 2024

Pathway 2

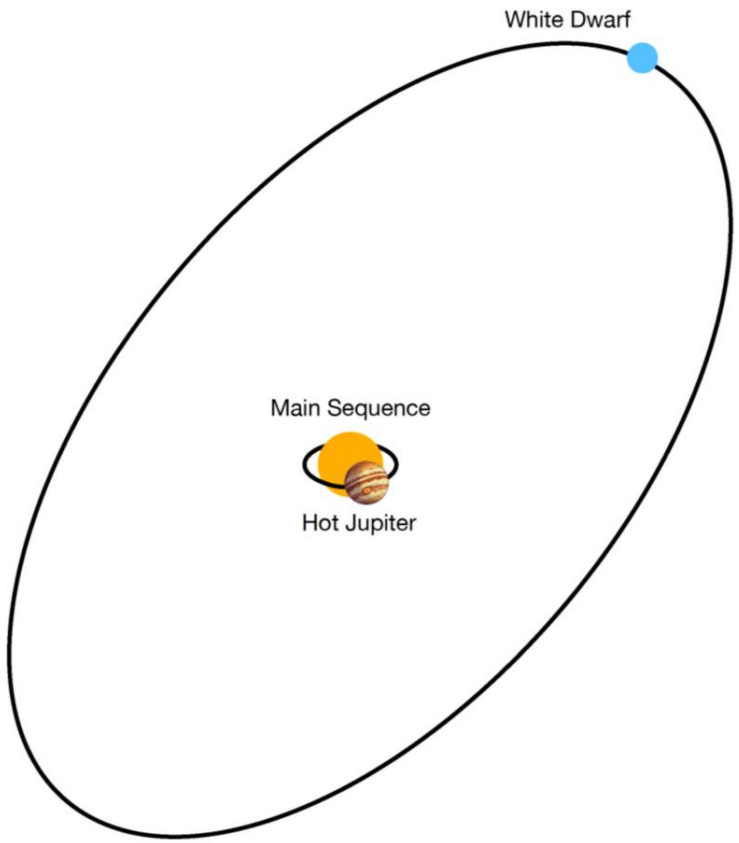
Step 1: Cold Jupiter in a wide binary with no EKL Oscillations



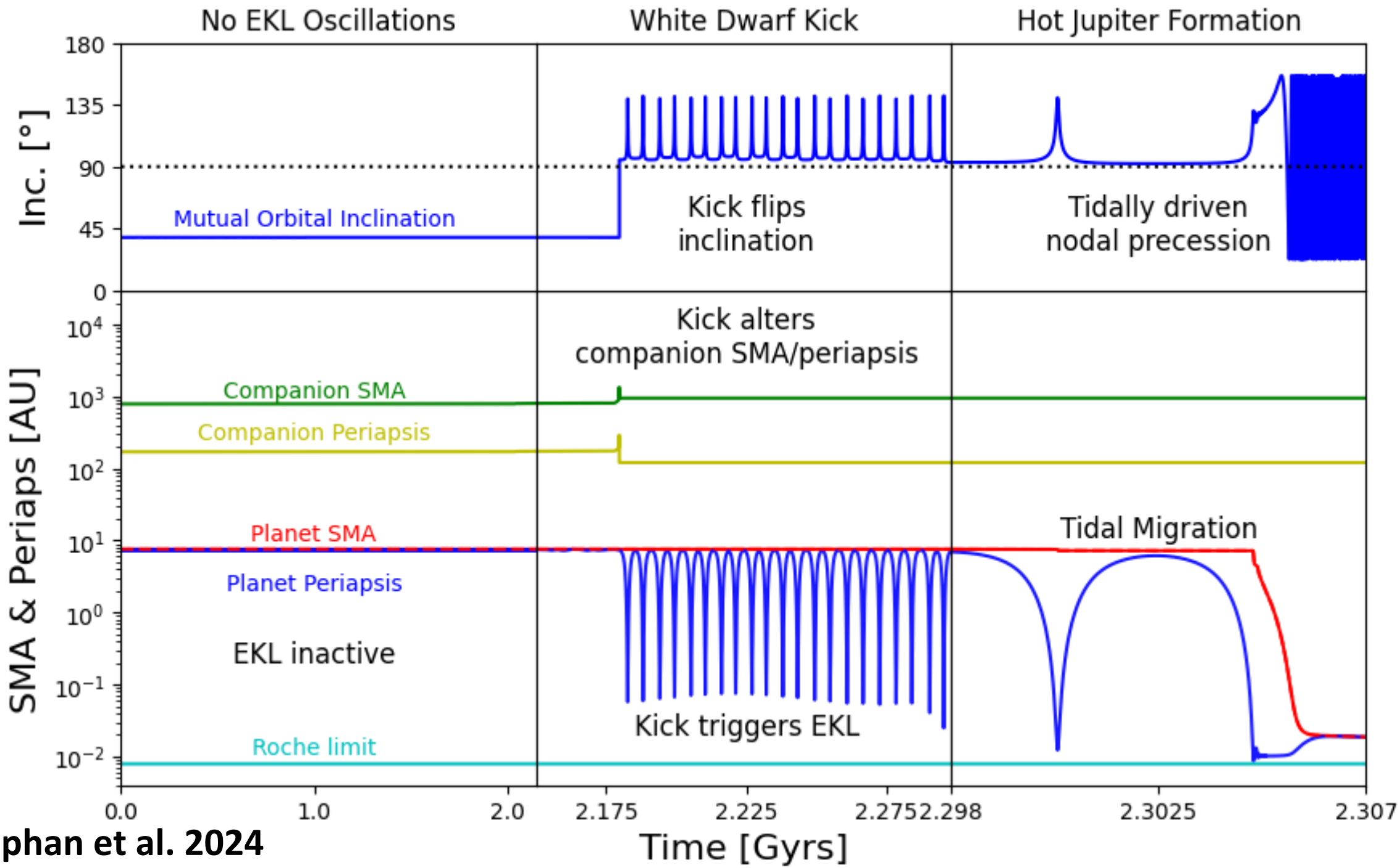
Step 2: Outer star evolves into a white dwarf and experiences a kick which misaligns the binary and causes EKL Oscillations to commence



End Result: Hot Jupiter orbiting a main sequence star in a wide binary with an outer white dwarf

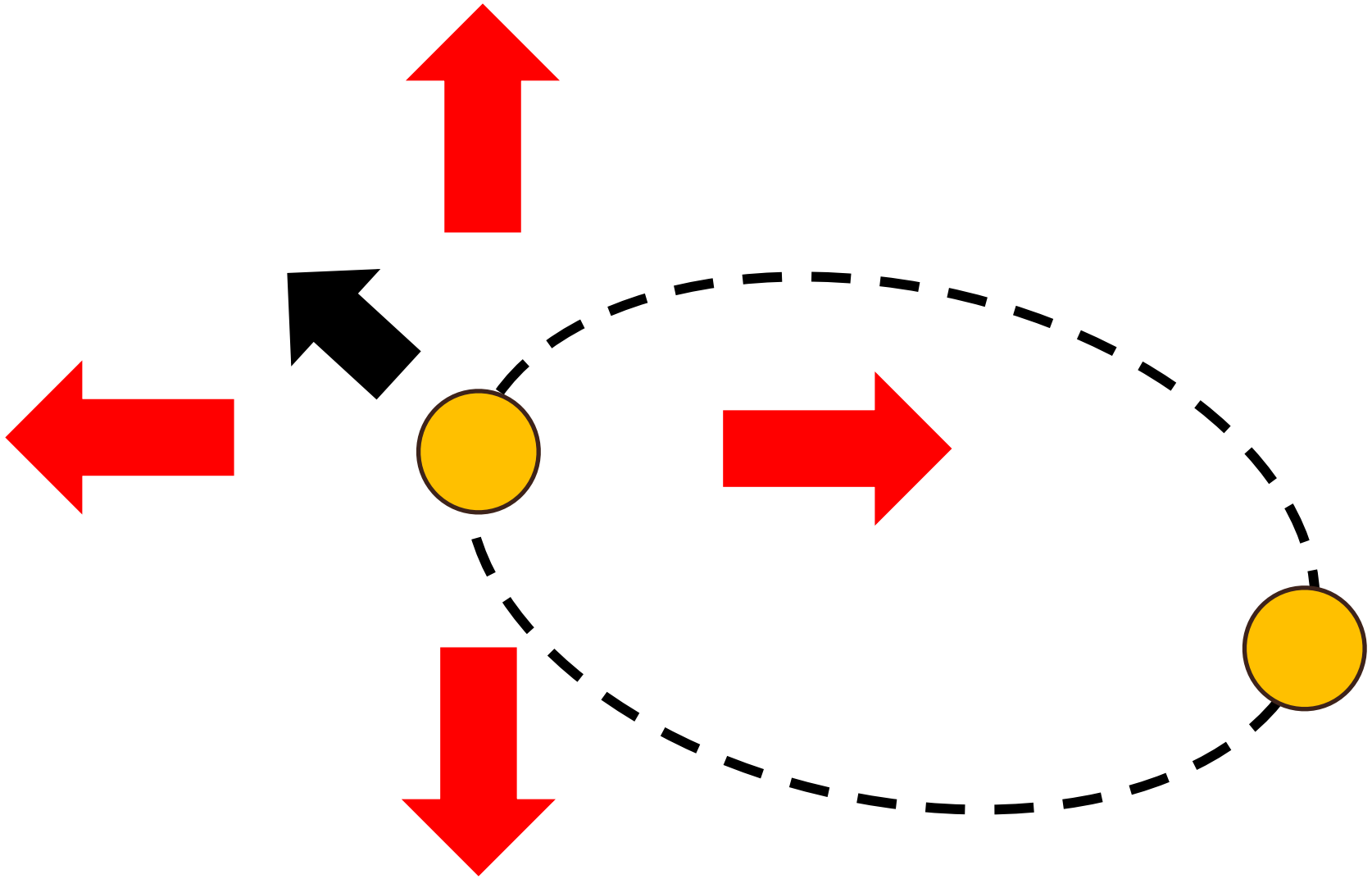


Stephan et al. 2024



Stephan et al. 2024

But… what is this “kick” really?



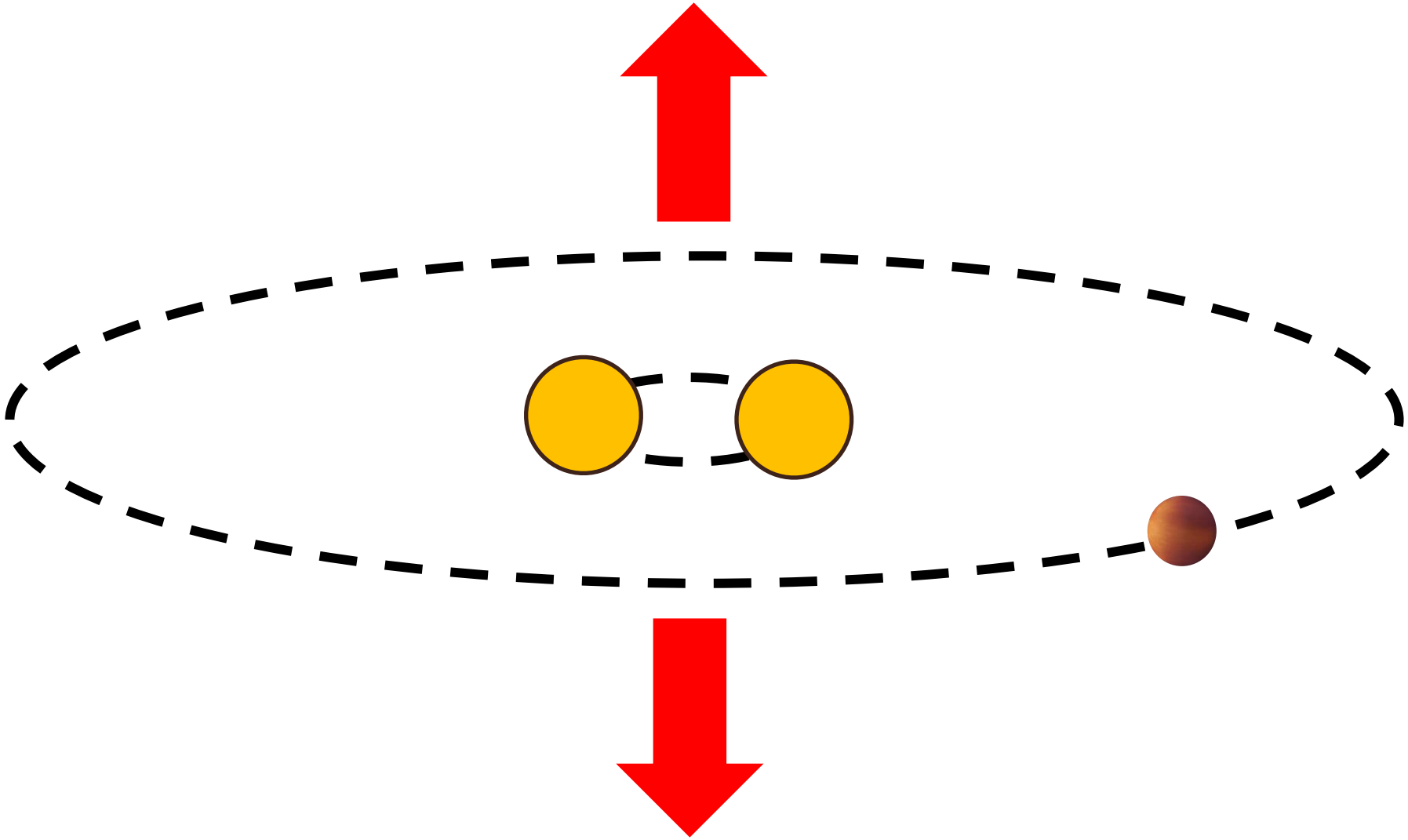
Asymmetric Wind Dynamics

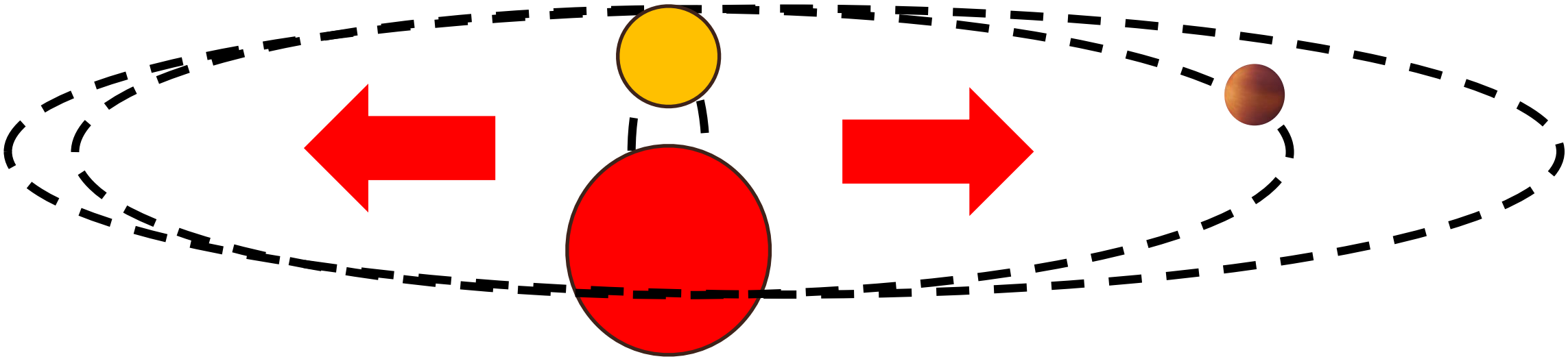
- Asymmetric winds can change eccentricity and inclination over secular timescales (see Veras, Hadjidemetriou & Tout 2013, Dosopoulou & Kalogera 2016a,b)

- Previously assumed to be insignificant, but El-Badry & Rix 2018 kick statistics may imply greater importance

- May be important specifically for CBPs with CE Binary evolution


Credit: R. Sahai (JPL) et al., Hubble Heritage Team, ESA, NASA

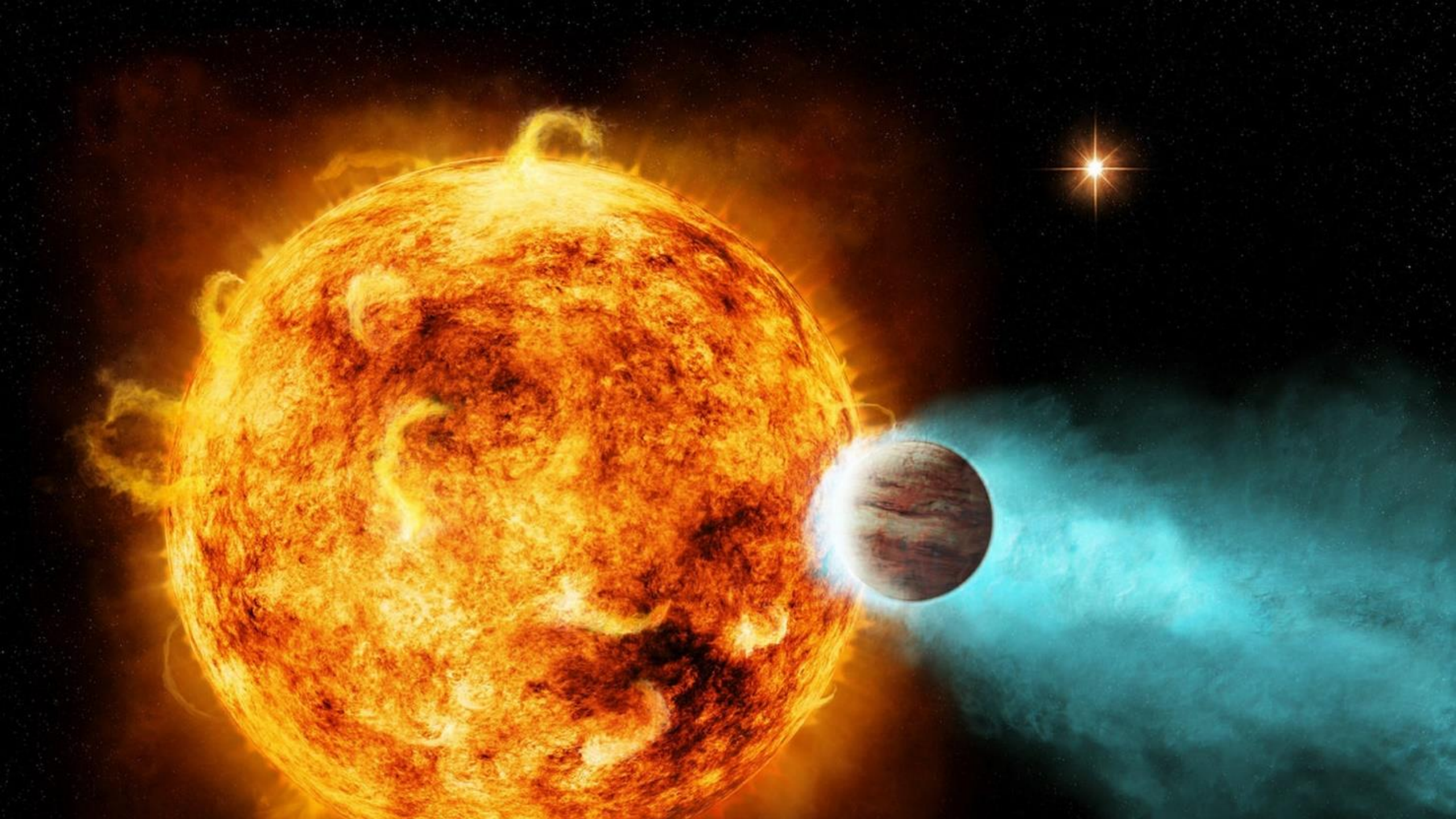


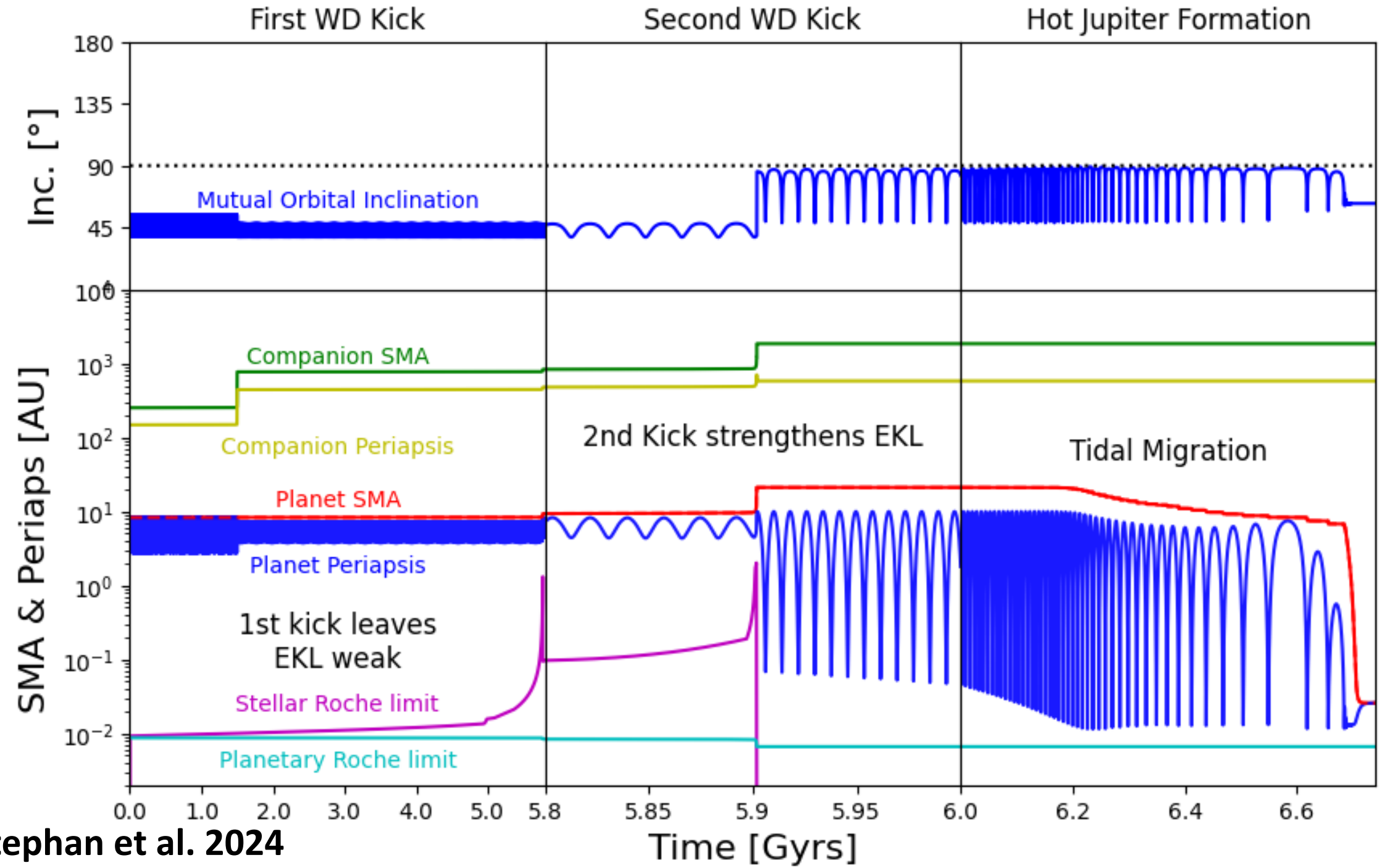


Summary

- Nearly every system we observe is a **snapshot** of a particular stage in a much longer and often complicated evolution
- Some processes can **erase** signatures of past events and evolutionary stages (for example stellar obliquity realignment)
- Stellar binaries can radically change their orbits or separate via stellar evolution and kicks, potentially leading to **mischaracterization** of the dynamical history of observed exoplanets
- Circumbinary planets may eventually also become subject of asymmetric stellar mass loss dynamics, which may inform eventual searches of exoplanets around evolved compact binaries and stellar merger products

Bonus slides



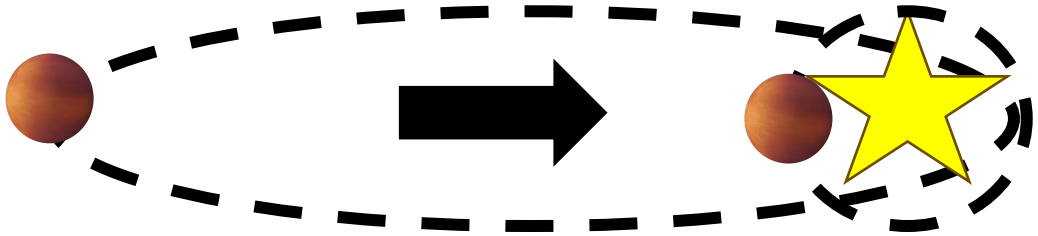


Stephan et al. 2024

Hot Jupiter Formation – A contentious topic

1. In situ/Disk Migration

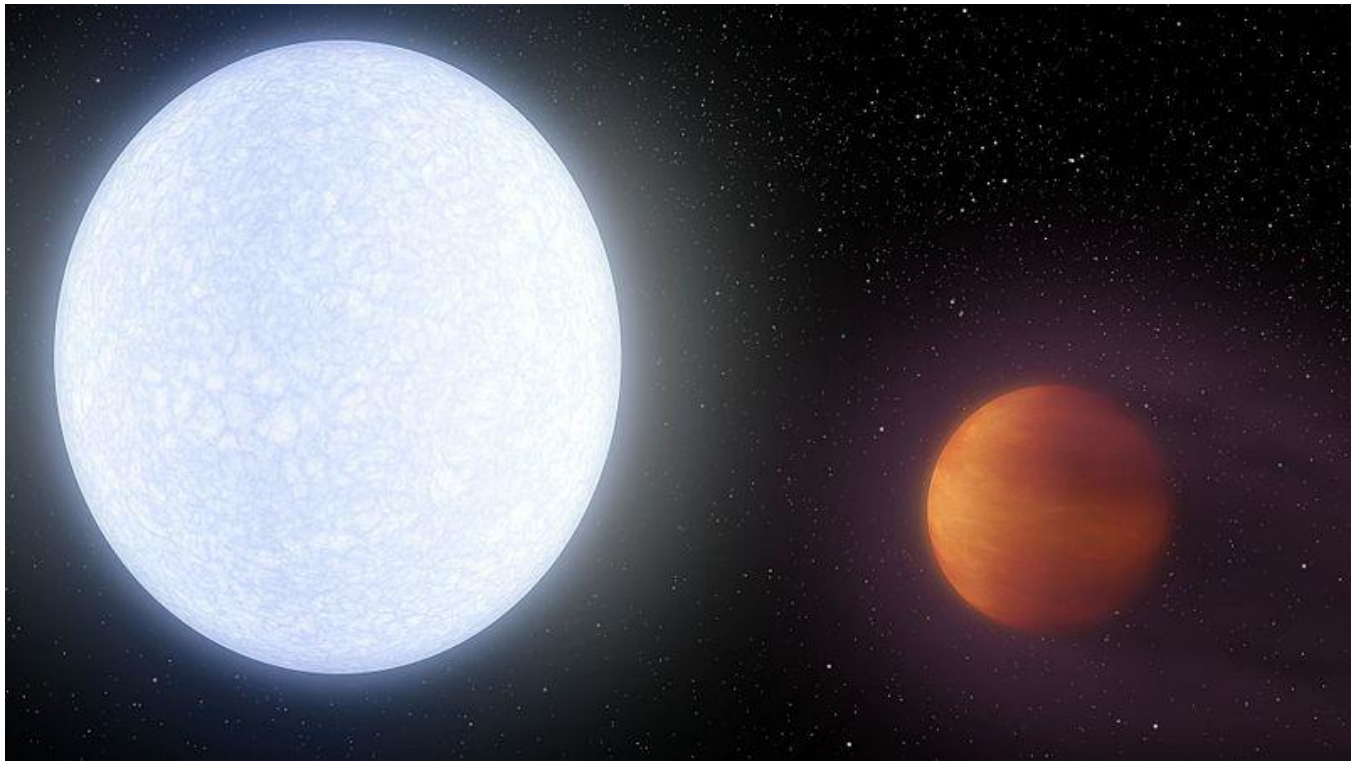
2. High eccentricity migration

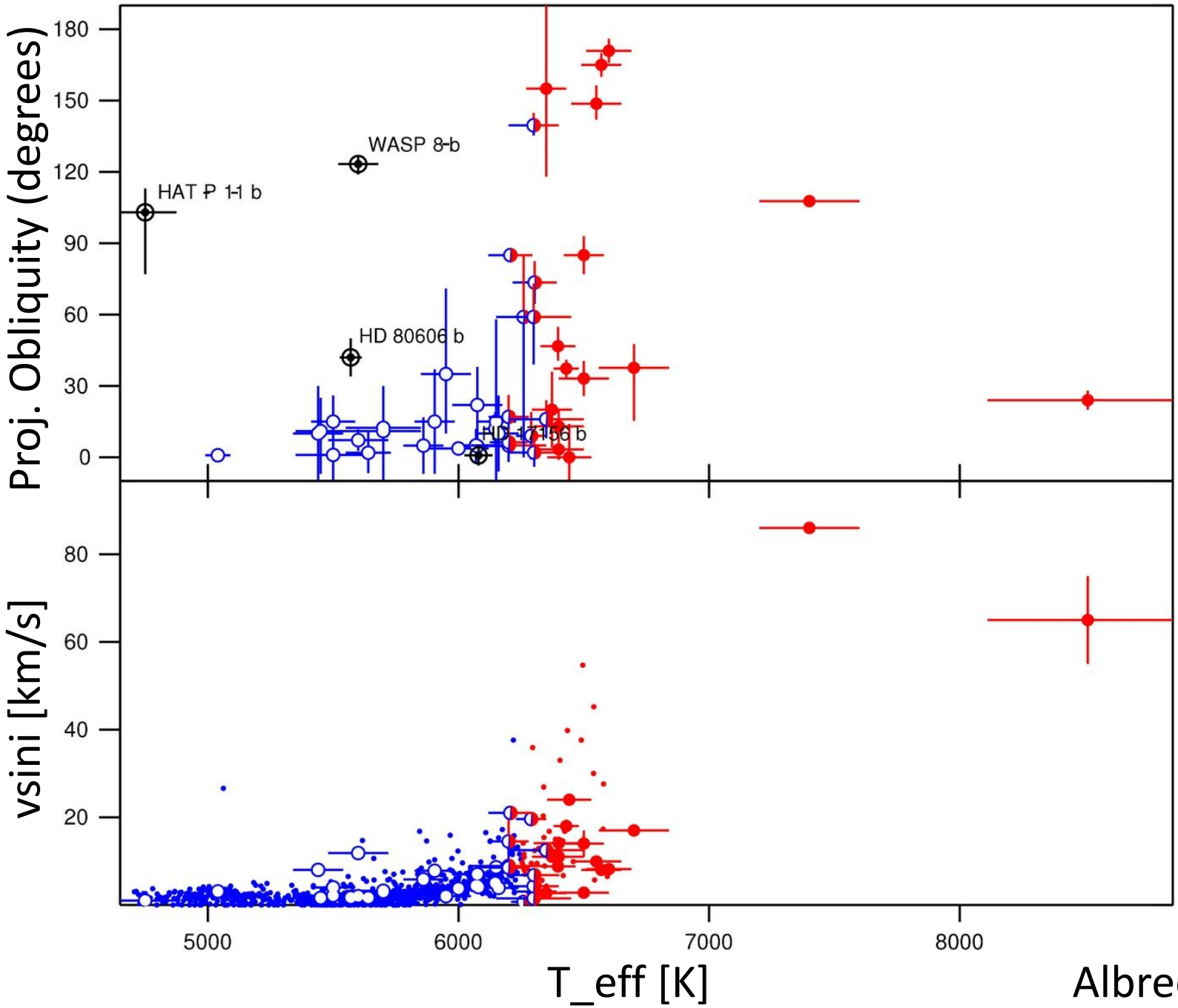


- Kozai-Lidov?
- Planet-Planet scattering?
- Other resonances?

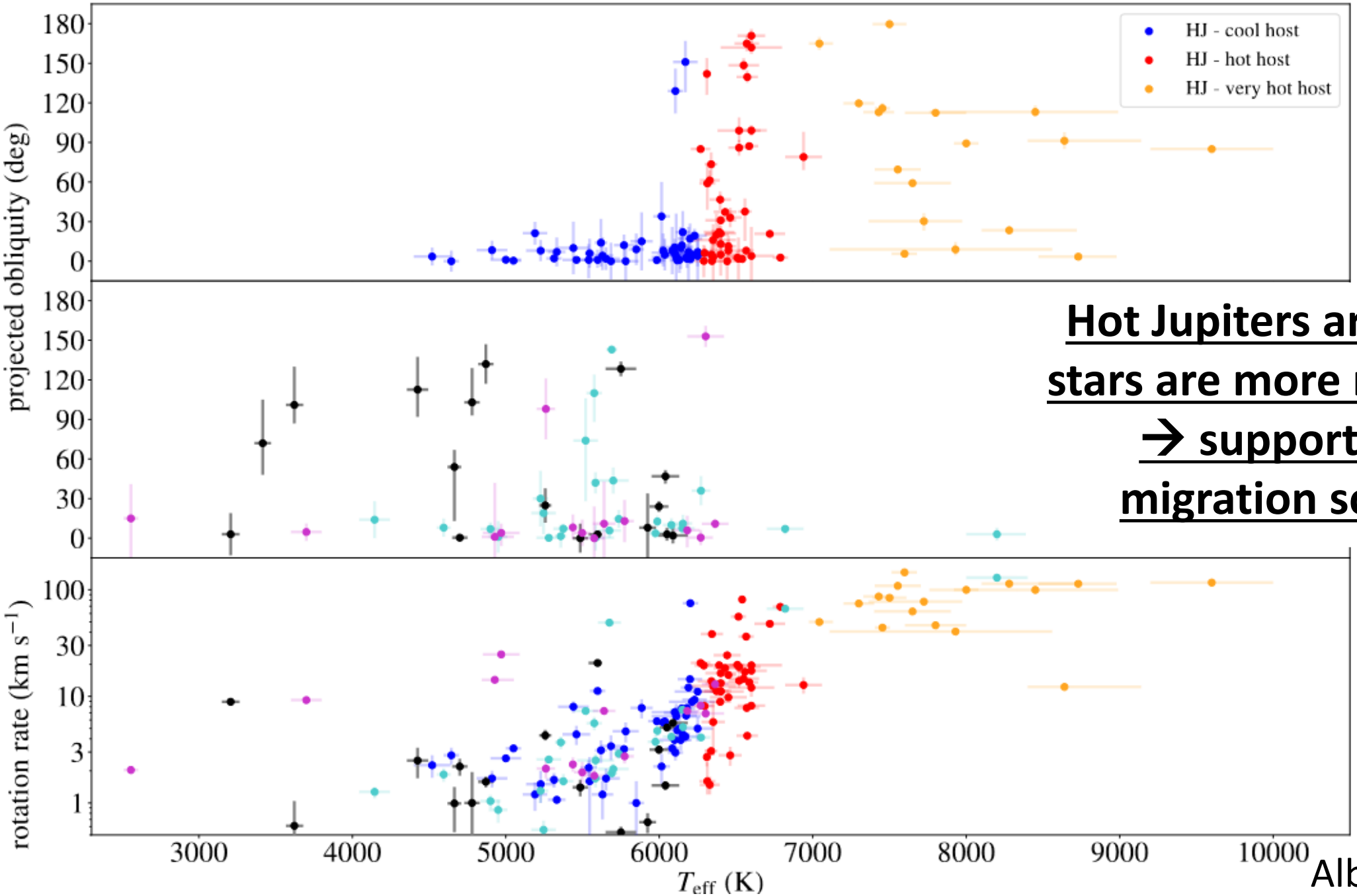
Hot Jupiters

- Gas Giants on short (<10 days) orbits
- Easy to detect via transits, relatively common (~1 % occurrence rate)
- Ideal targets for atmospheric characterization (JWST and future instruments)





Albrecht et al. 2012



Hot Jupiters around Hot stars are more misaligned → supports tidal migration scenario

Albrecht et al. 2022