2021 Sagan Exoplanet Summer Workshop, NExSci/Caltech

Observations of young planets at different evolutionary stages

Trevor David

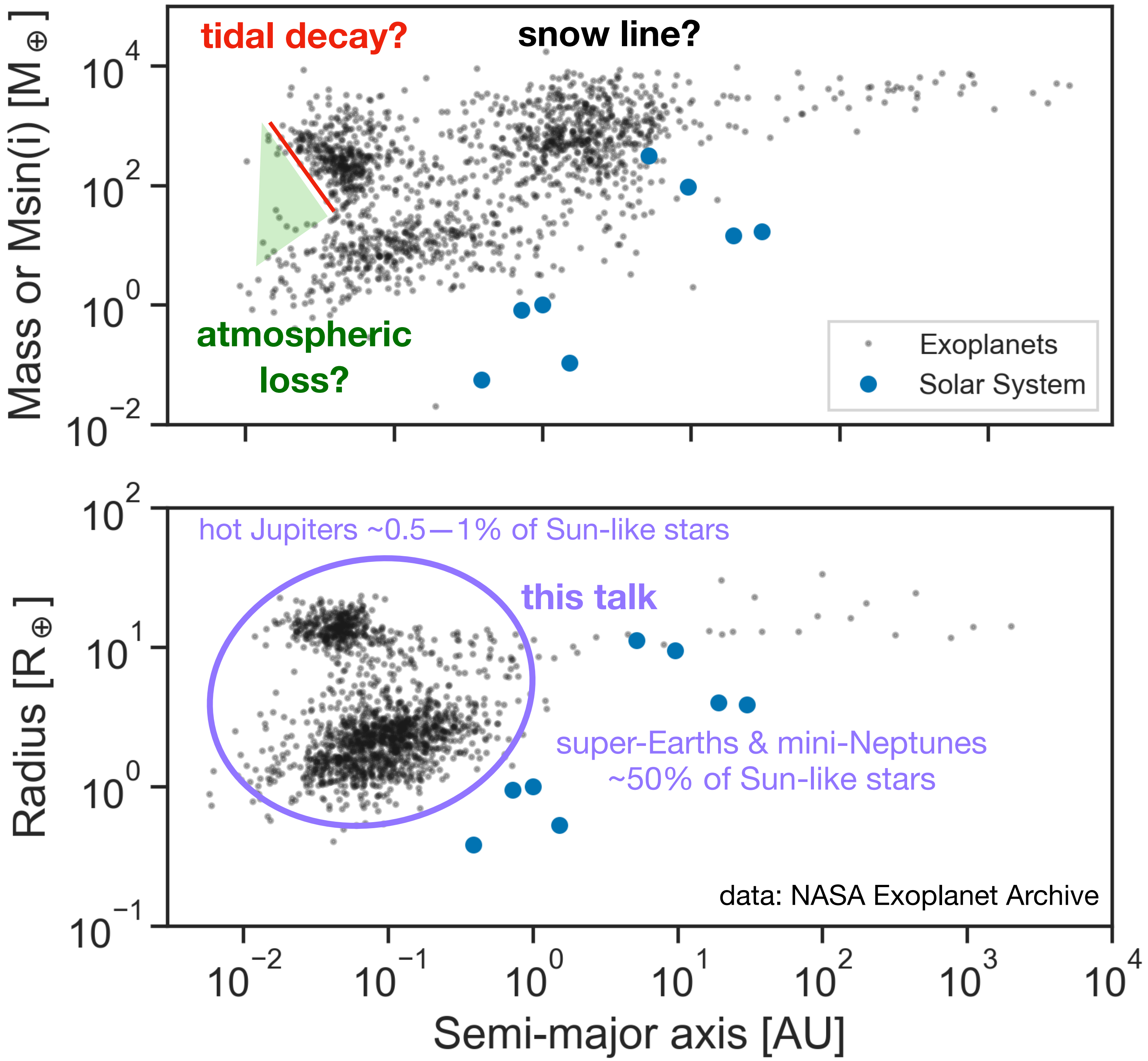
Flatiron Research Fellow
Center for Computational Astrophysics
Flatiron Institute

FLATIRON INSTITUTE
Center for Computational Astrophysics

1. **background**
2. **radius evolution**
3. **atmospheric evolution**
4. **orbital evolution**
5. **preliminary conclusions**

background

Exoplanet demographics: the result of formation & evolution

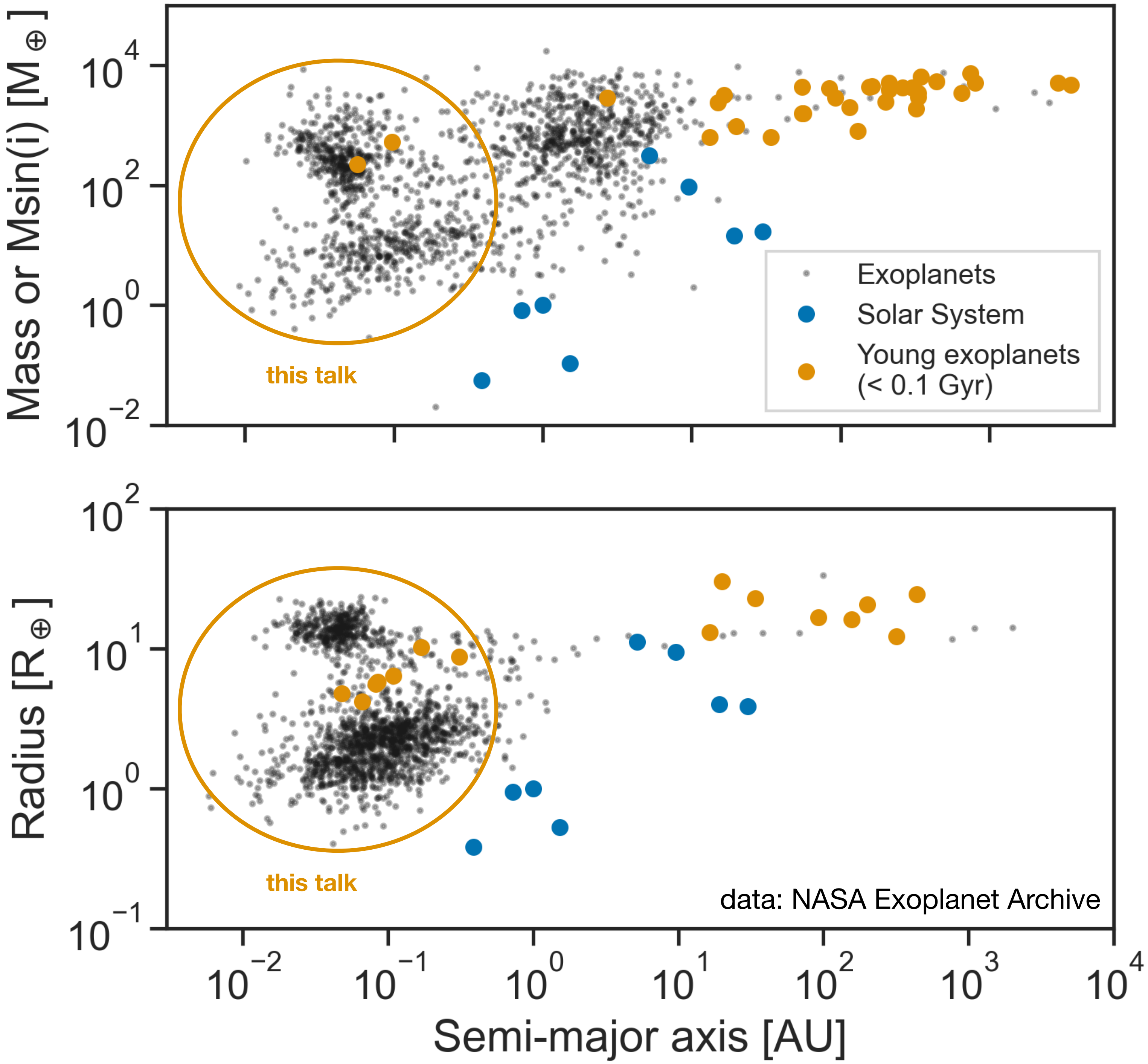


data: NASA Exoplanet Archive

Disentangling signatures of formation and evolution requires studying planets over a broad range of ages

Some relevant processes:
- atmospheric loss
- radial contraction & expansion
- tidal dissipation & orbital migration
- long term dynamical interactions
- ejections & engulfment

A dearth of young exoplanets



data: NASA Exoplanet Archive

50% of planets have published ages

5% of those have ages <1 Gyr

2% have ages <0.1 Gyr

why?

1. small numbers
2. stellar ages are hard
3. detection bias

Inferring exoplanet evolution

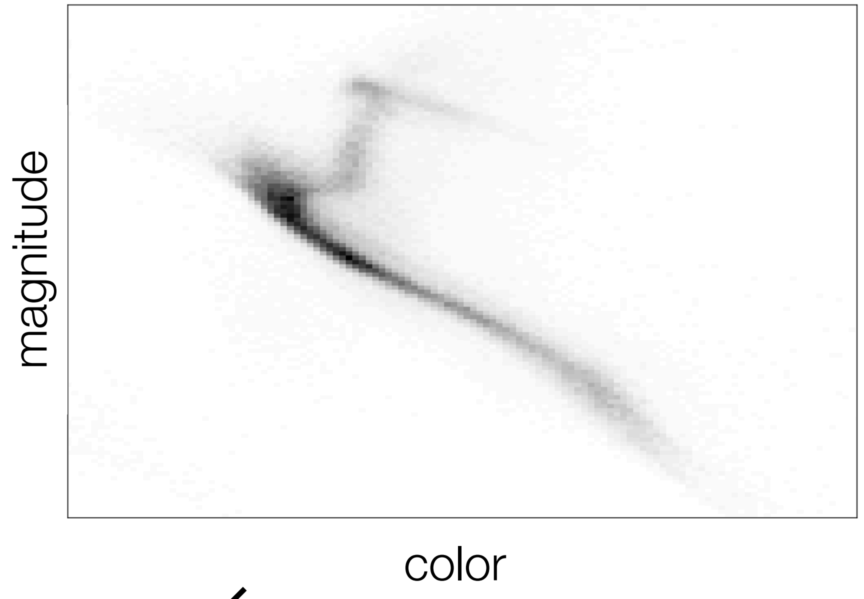
planets in coeval stellar populations

star-forming regions, OB associations, moving groups

young open clusters, dissolving clusters

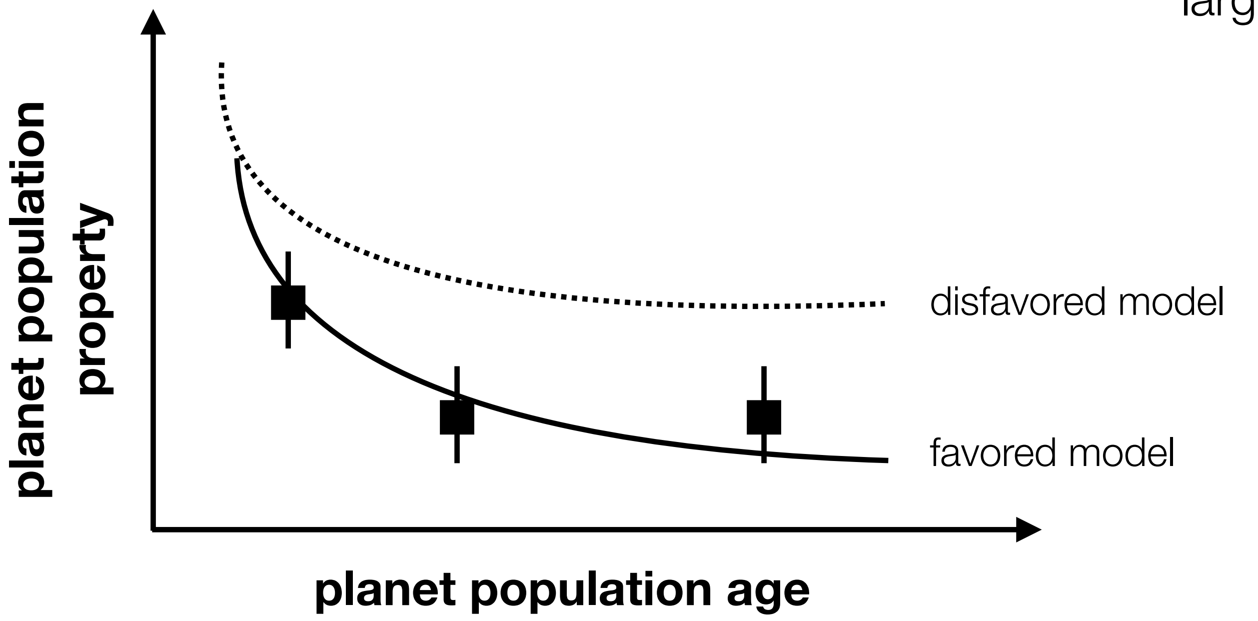
old open clusters, globular clusters

age-dating planet-hosting stars

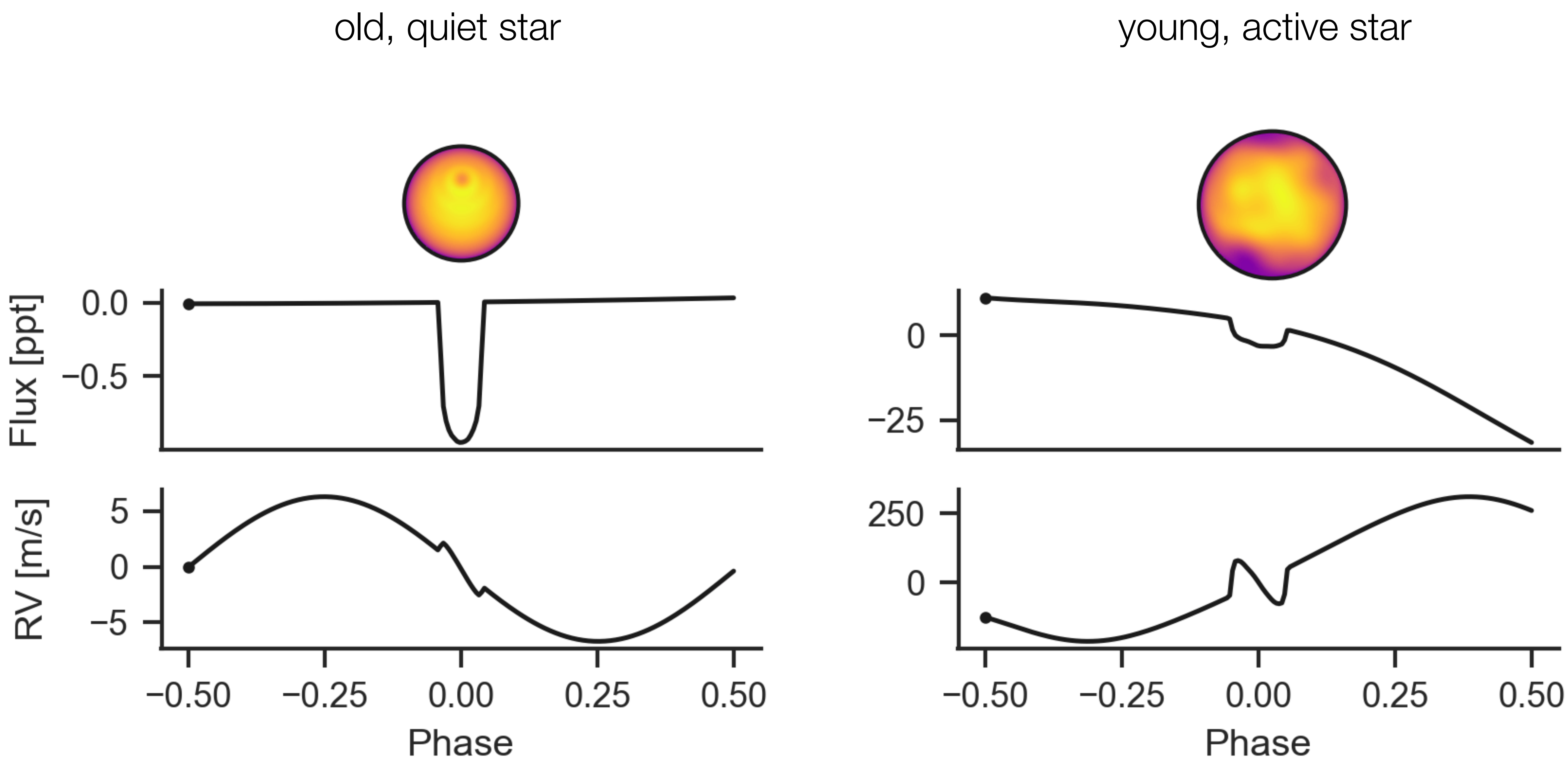


more secure ages at the expense of smaller samples

larger samples at the expense of less secure ages



Impact of stellar activity on transits & radial velocities



old, quiet star

young, active star

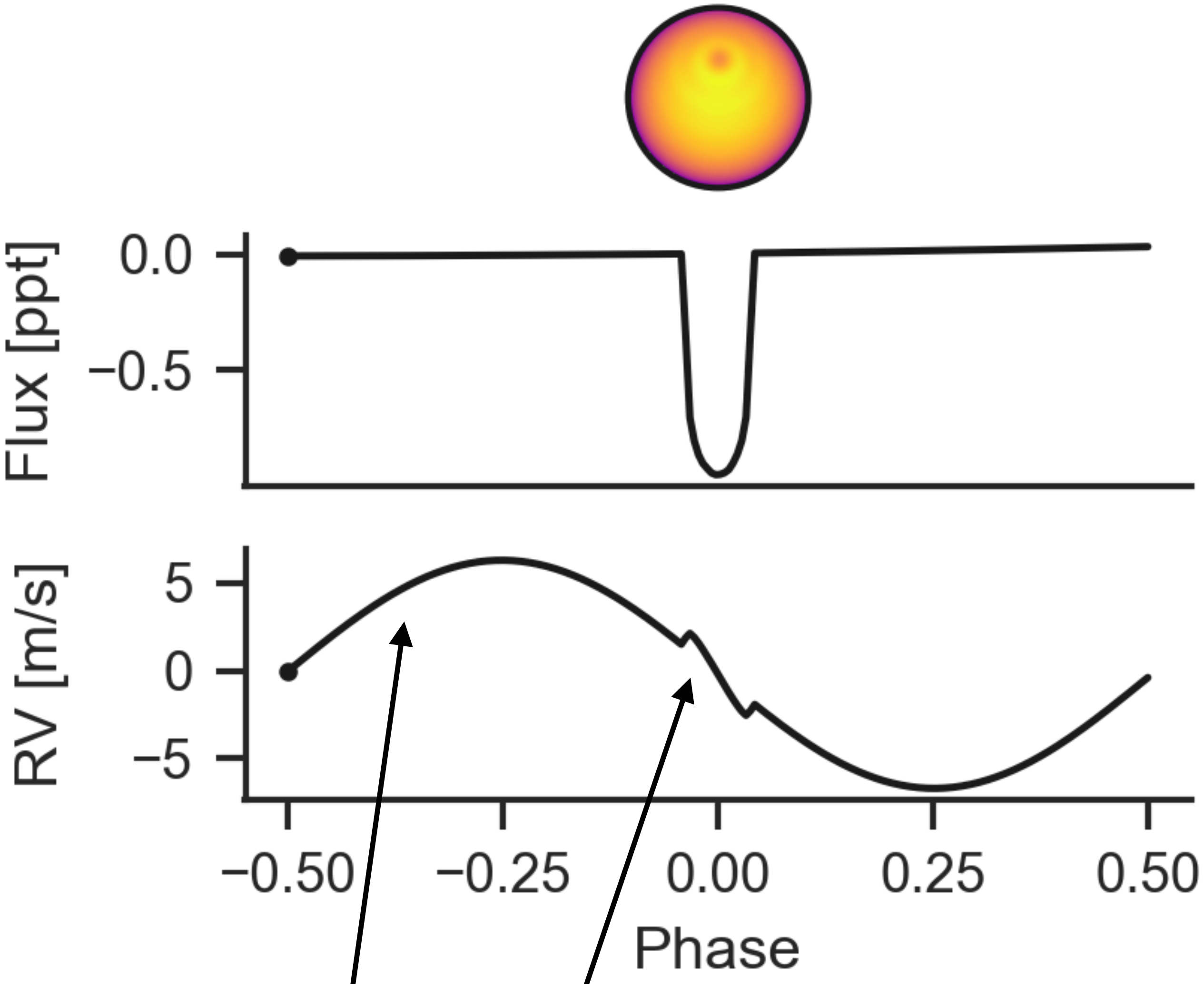
animated with **`starry`** (Luger+ 2019)

https://github.com/rodluger/starry

Impact of stellar activity on transits & radial velocities

old, quiet star

Prot = 30 d

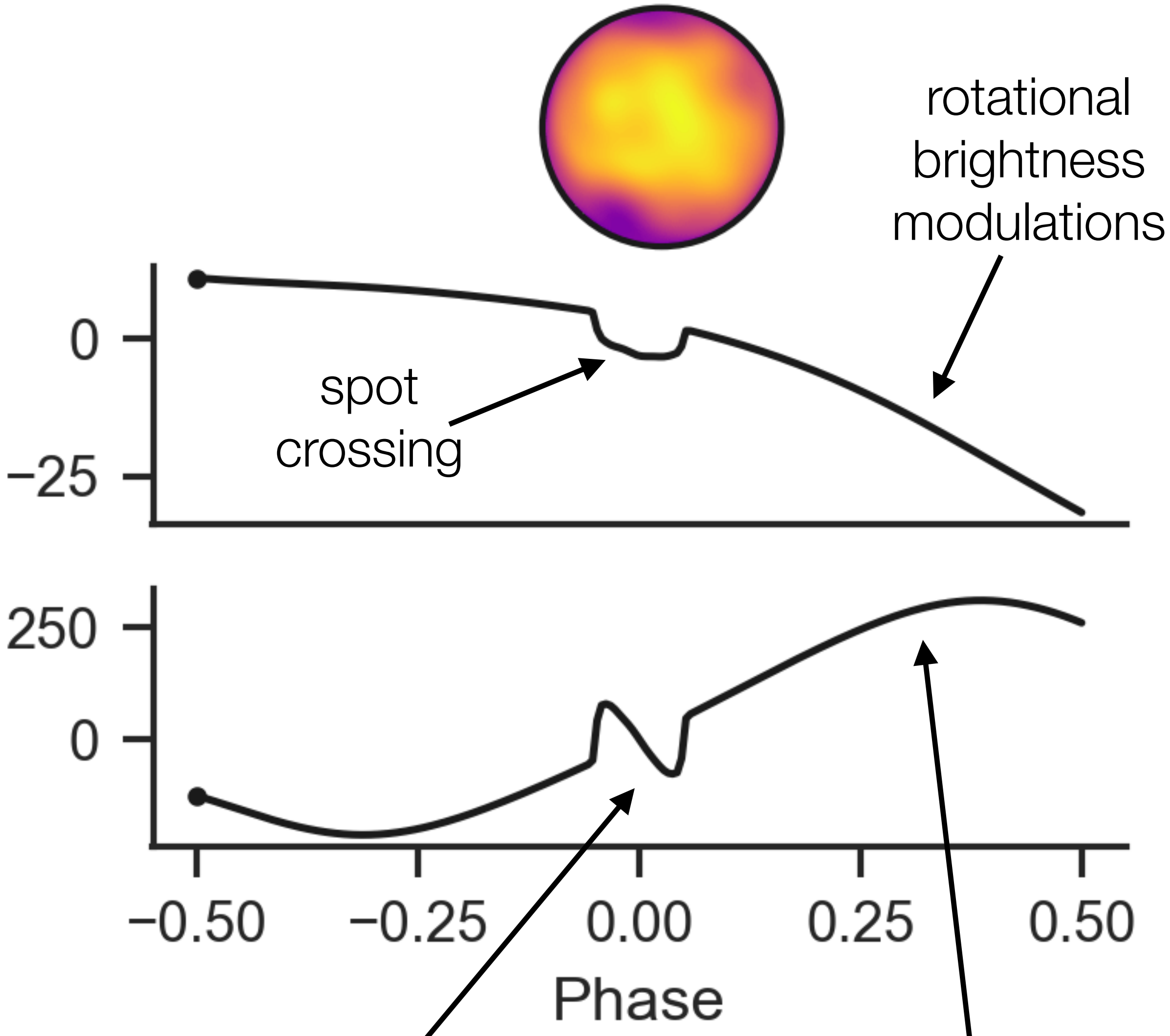


reflex motion

small Rossiter-McLaughlin anomaly

young, active star

Prot = 3 d



rotational brightness modulations

spot crossing

large R-M anomaly

apparent RV shifts from starspots masks reflex motion

radius evolution

Theoretical evolution of a close-in, low-mass planet

Core-accretion:
(e.g. Pollack et al. 1996, Rafikov 2006)

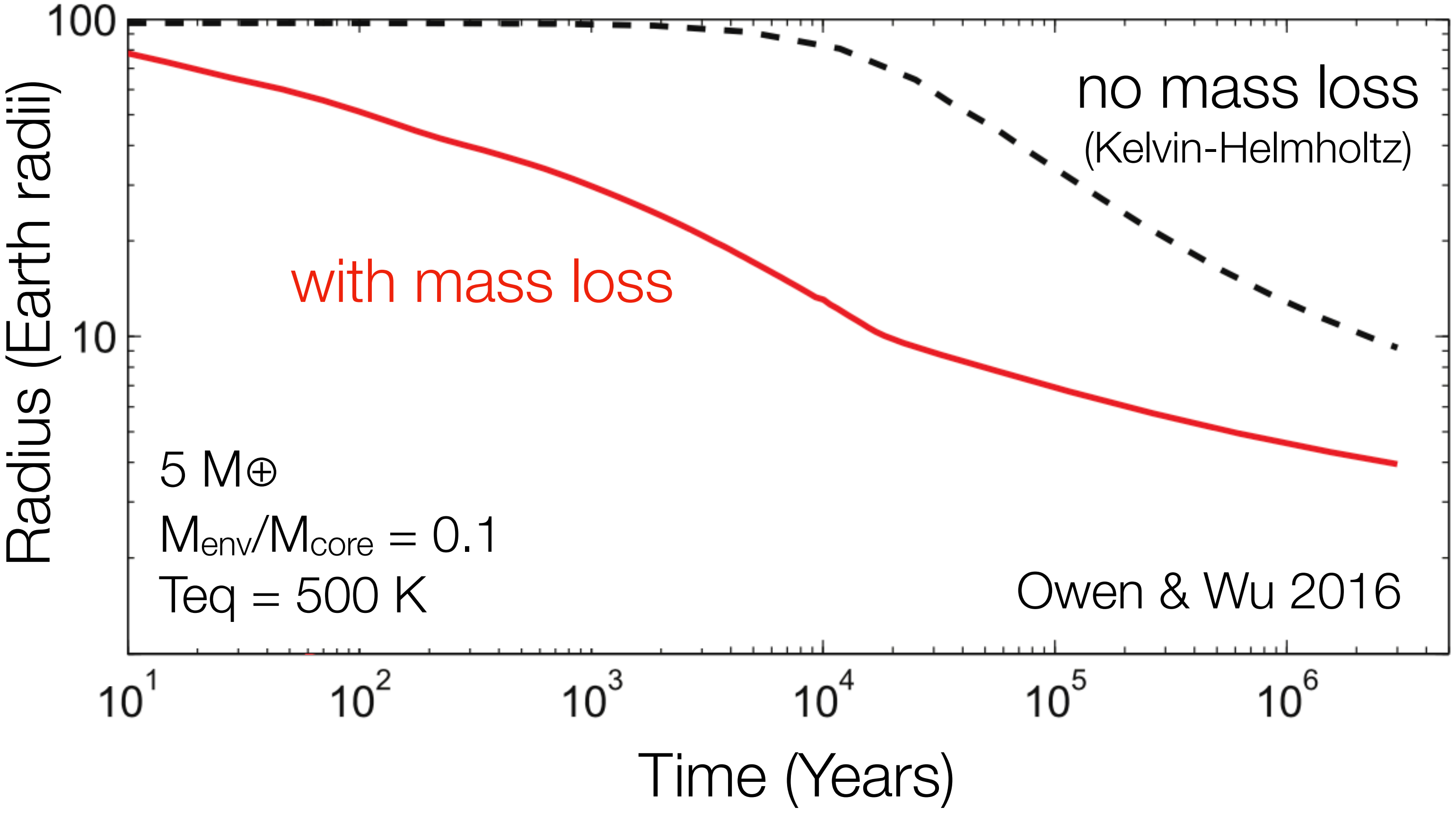
Planet embedded in disk accretes to the Bondi radius, found by:

$$v_{\rm esc} = c_s$$

$$R_B = \frac{GM_P}{2c_s^2}$$

…but this is not the planet's final radius

Core-accretion seems to over-predict envelope mass fractions
(e.g. Lee, Chiang & Ormel 2014)

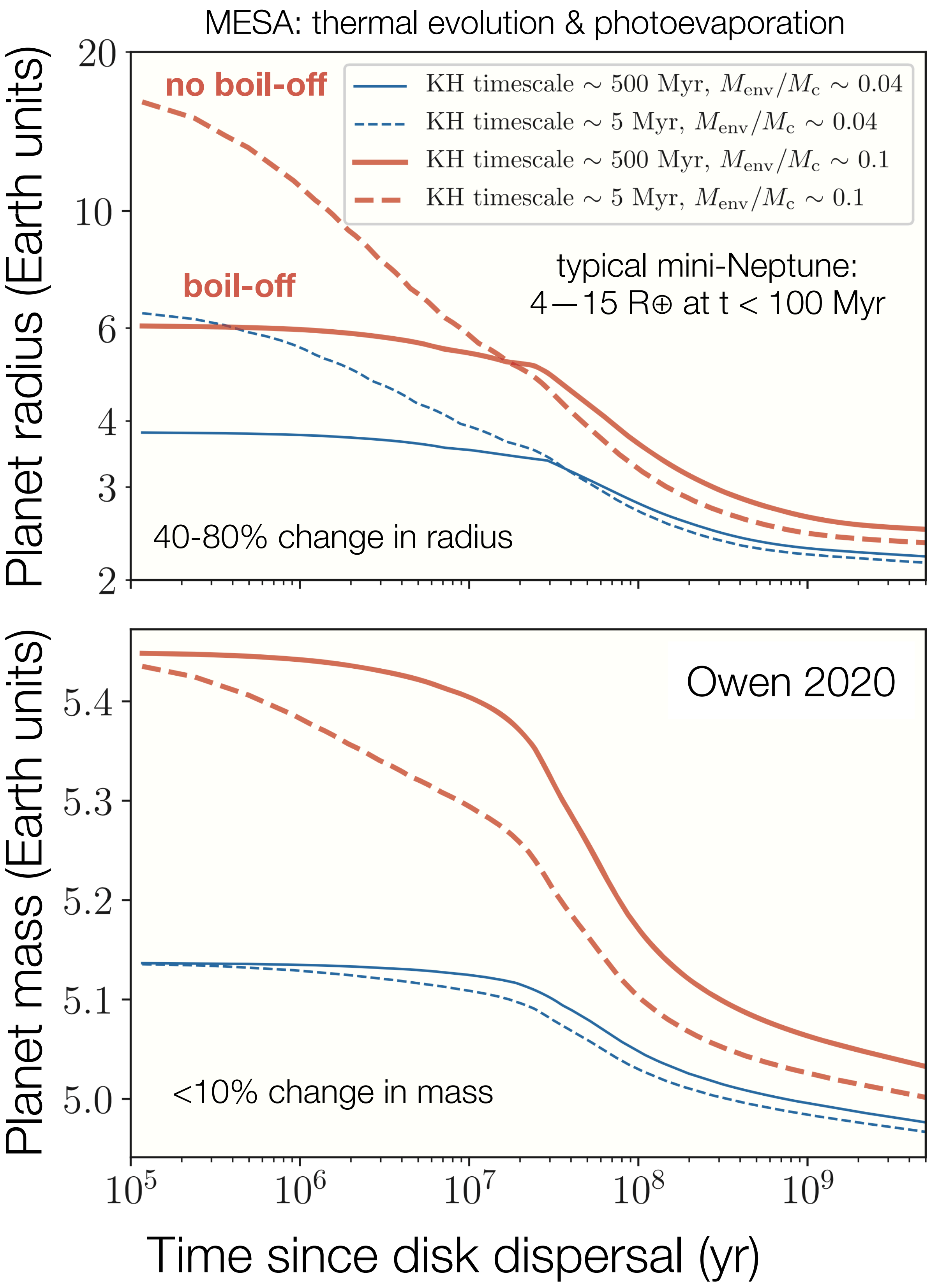


$$t_{\rm disk} \ll t_{\rm cool}$$

"Boil-off"
(Owen & Wu 2016; see also Ikoma & Hori 2012, Ginzburg+ 2016, Misener & Schlichting 2021)

In 10^4 - 10^6 yrs after disk dispersal: planet's internal heat drives mass loss until it contracts to $0.1R_B$, losing up to 90% of its initial envelope mass in the process

Theoretical evolution of a close-in, low-mass planet



MESA: thermal evolution & photoevaporation

Kelvin-Helmholtz timescale:
time it takes to radiate away gravitational binding energy at current luminosity

$$t_{\rm KH} \approx \frac{G M_c M_{\rm env}}{R_p L}$$

If $t_{\rm KH}$ > age, planet must have cooled through some other process, e.g. bulk outflows ('boil-off')

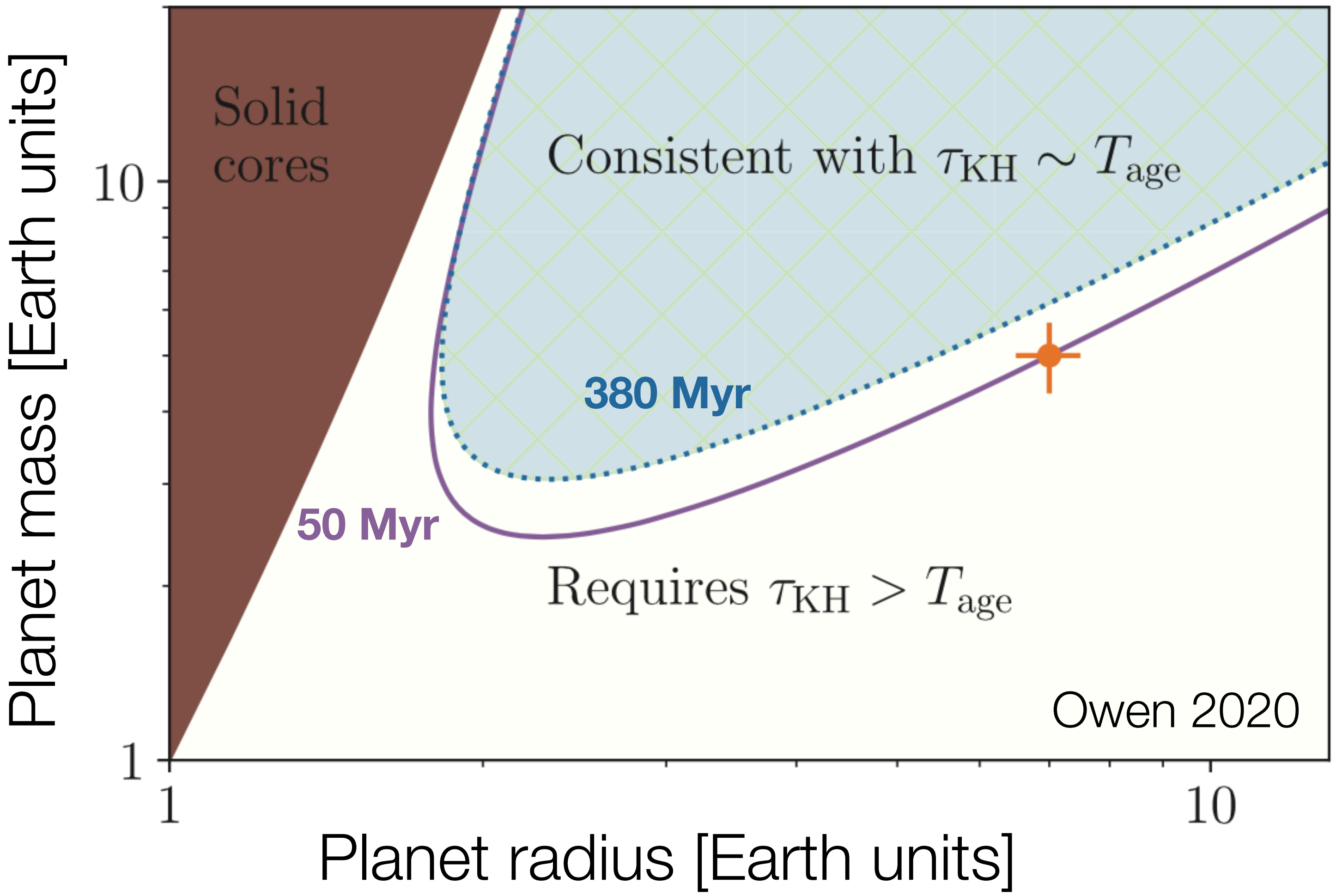
…but we only measure M_P, R_P, age

Two degeneracies:

1. Different M_c + $M_{\rm env}$ combinations can give same M_P, R_P (because we don't know $\rho_{\rm core}$)
2. Even for fixed $\rho_{\rm core}$, $M_{\rm env}$ is degenerate with internal entropy

i.e. a planet with known mass and radius can have more mass in its core and less in its envelope if the envelope is hotter

Theoretical evolution of a close-in, low-mass planet



Solution:

-find young planets which have not had much time to cool

-assume mass-loss through photoevaporation and age < mass-loss timescale

Given M_P, R_p, age: minimum envelope mass stable against photoevaporation

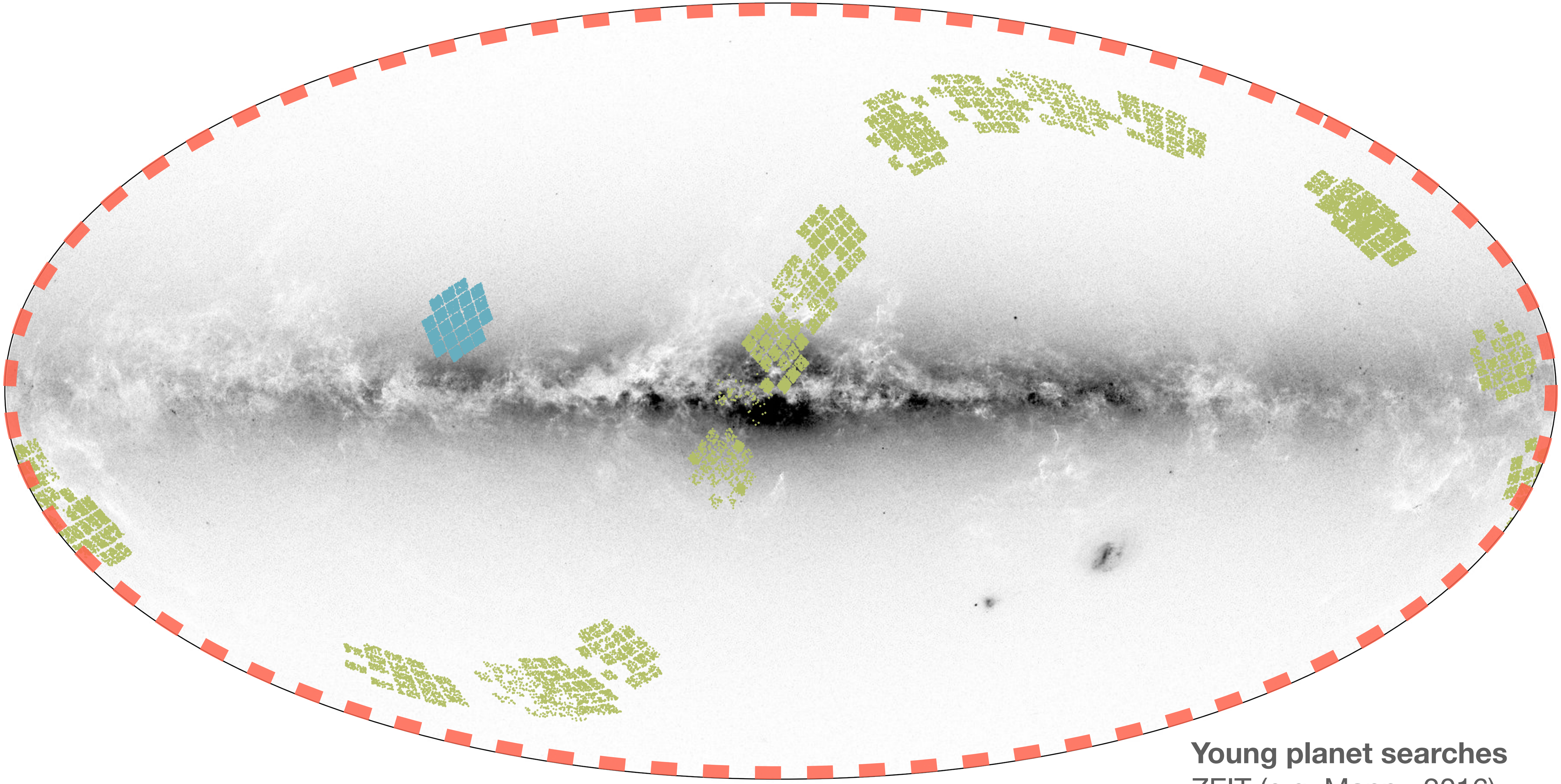
Lower bound on M_{env} translates to upper bound on entropy

Need 10-20% precision in mass, radius, and age to distinguish between these scenarios

Constraining exoplanet evolution with transit surveys

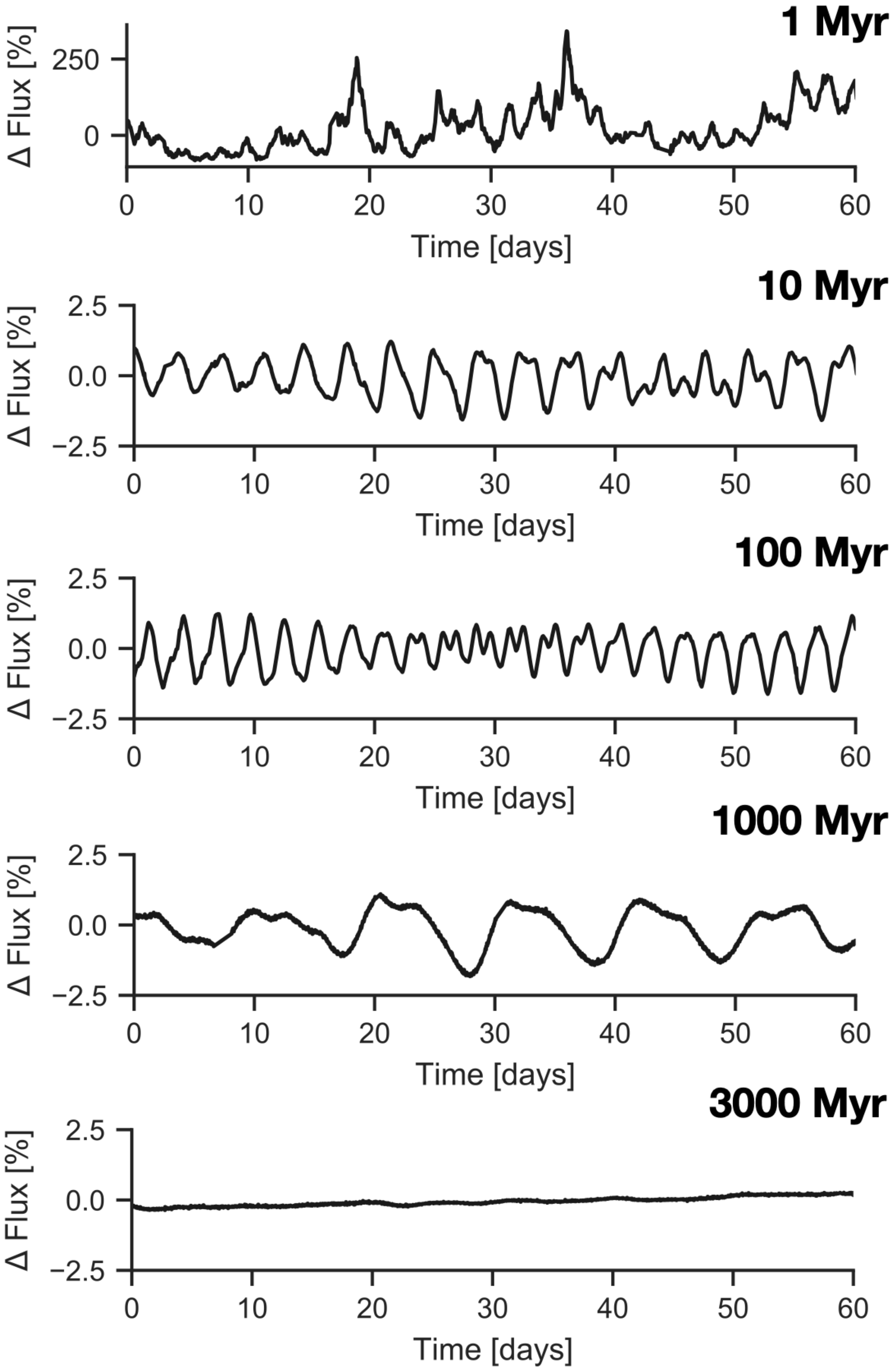
Kepler
-demographic studies
-requires homogeneous
ages for field stars

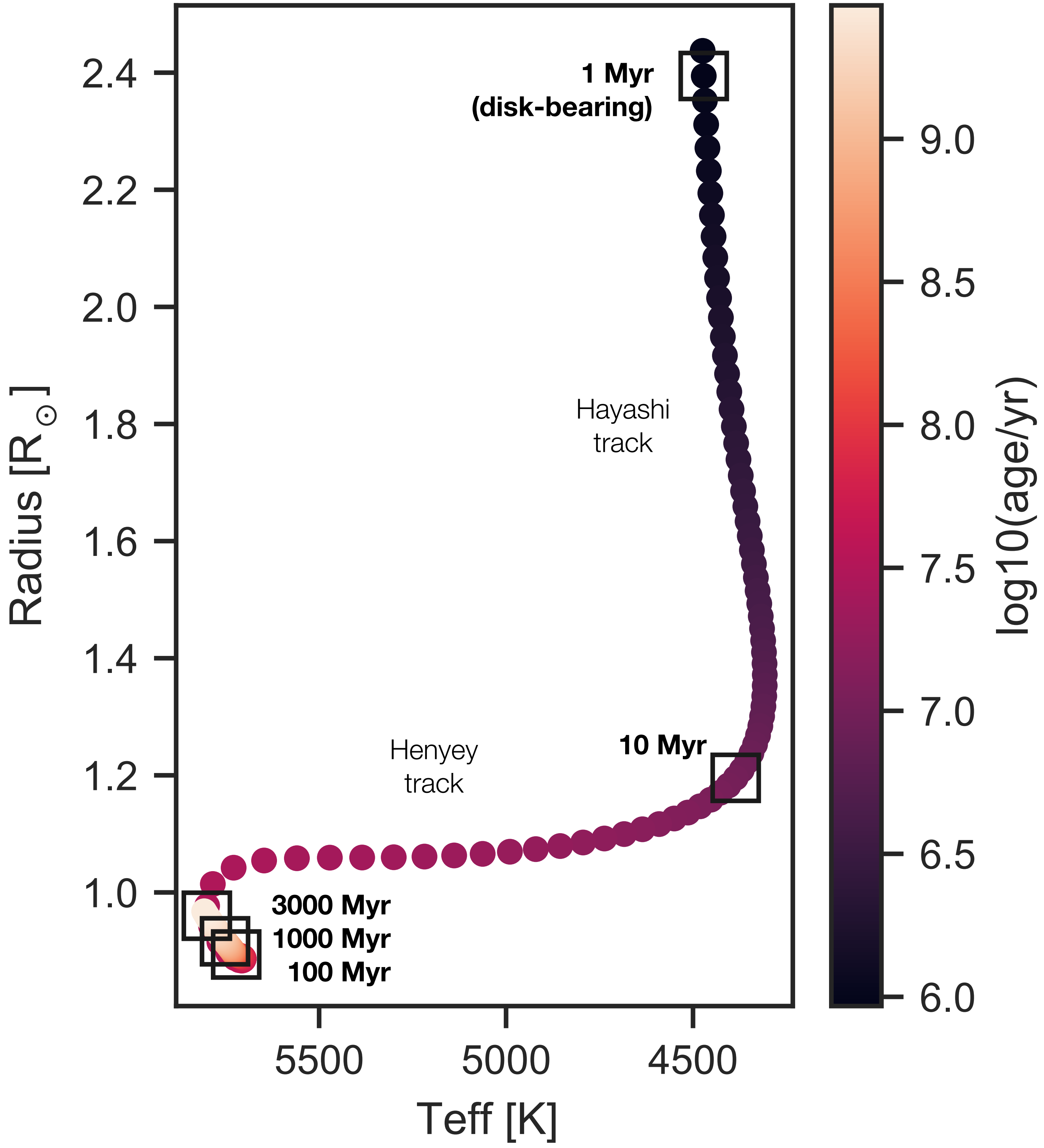
K2 & **TESS**
-observations of clusters
-trends with age
-completeness not well characterized



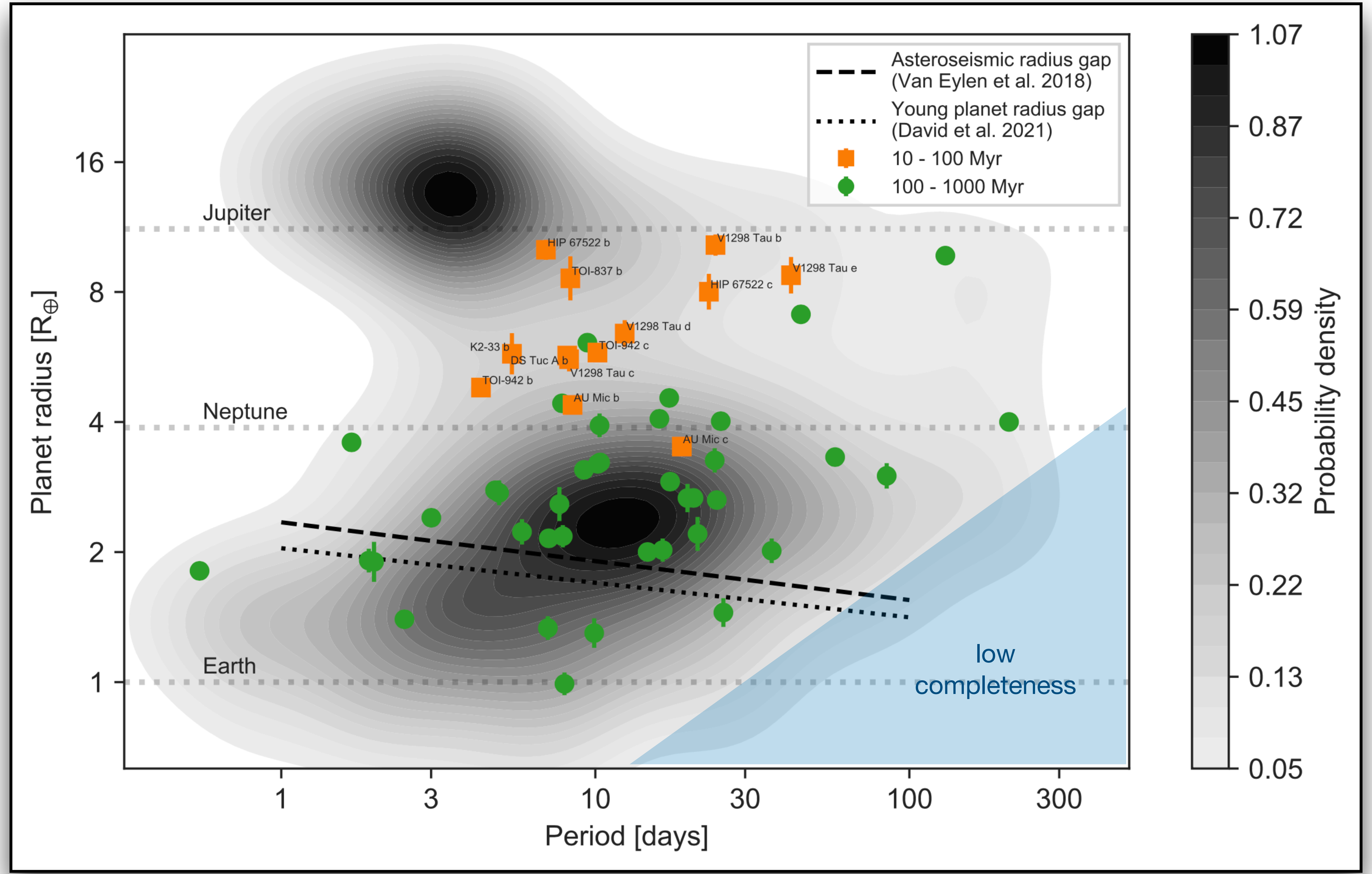
Young planet searches
ZEIT (e.g. Mann+ 2016)
THYME (e.g. Newton+ 2019)
PATHOS (Nardiello+ 2020)
CDIPS (Bouma+ 2020)

Light curve evolution of a solar-mass star



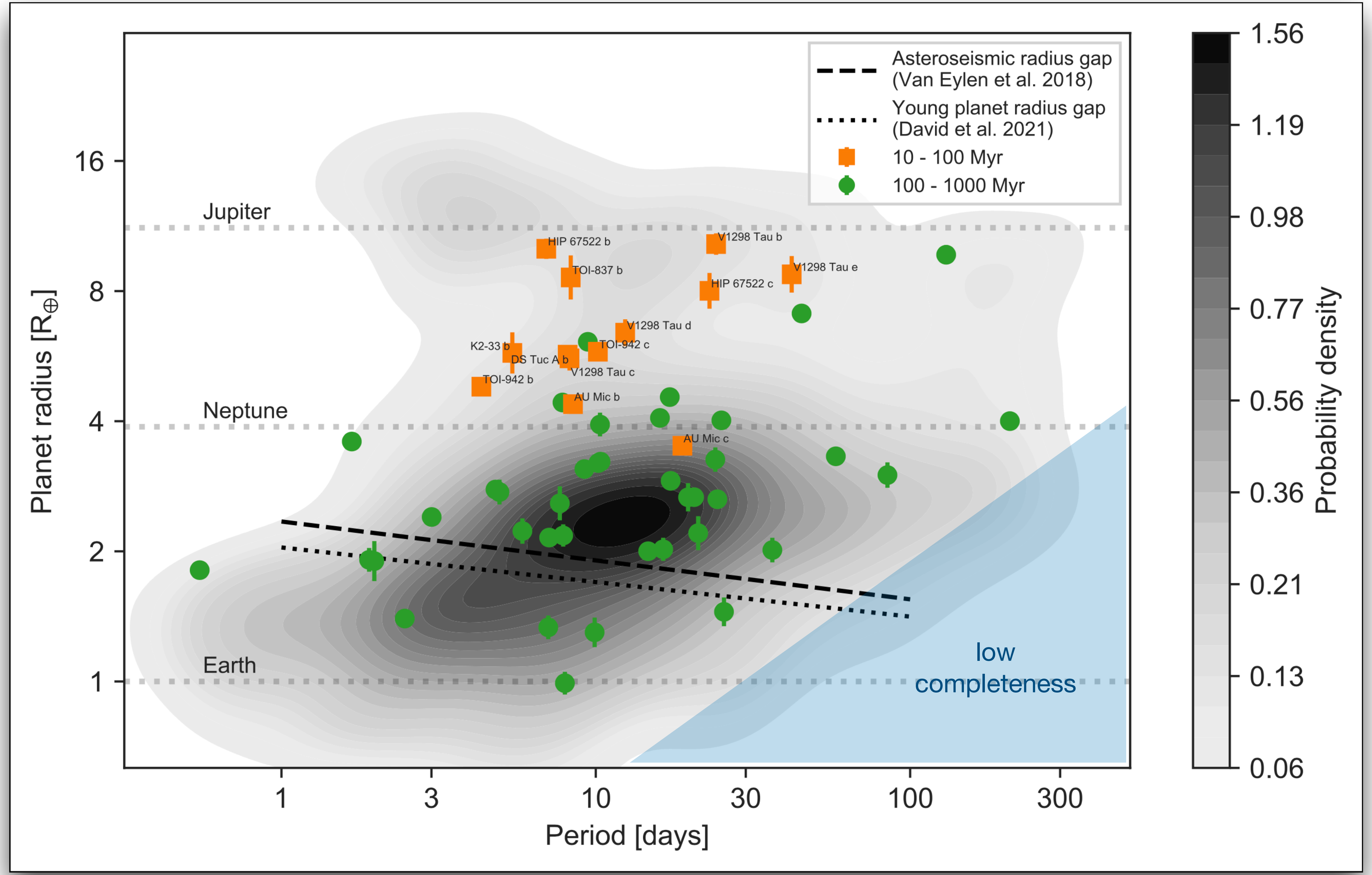


Youngest transiting planets are large



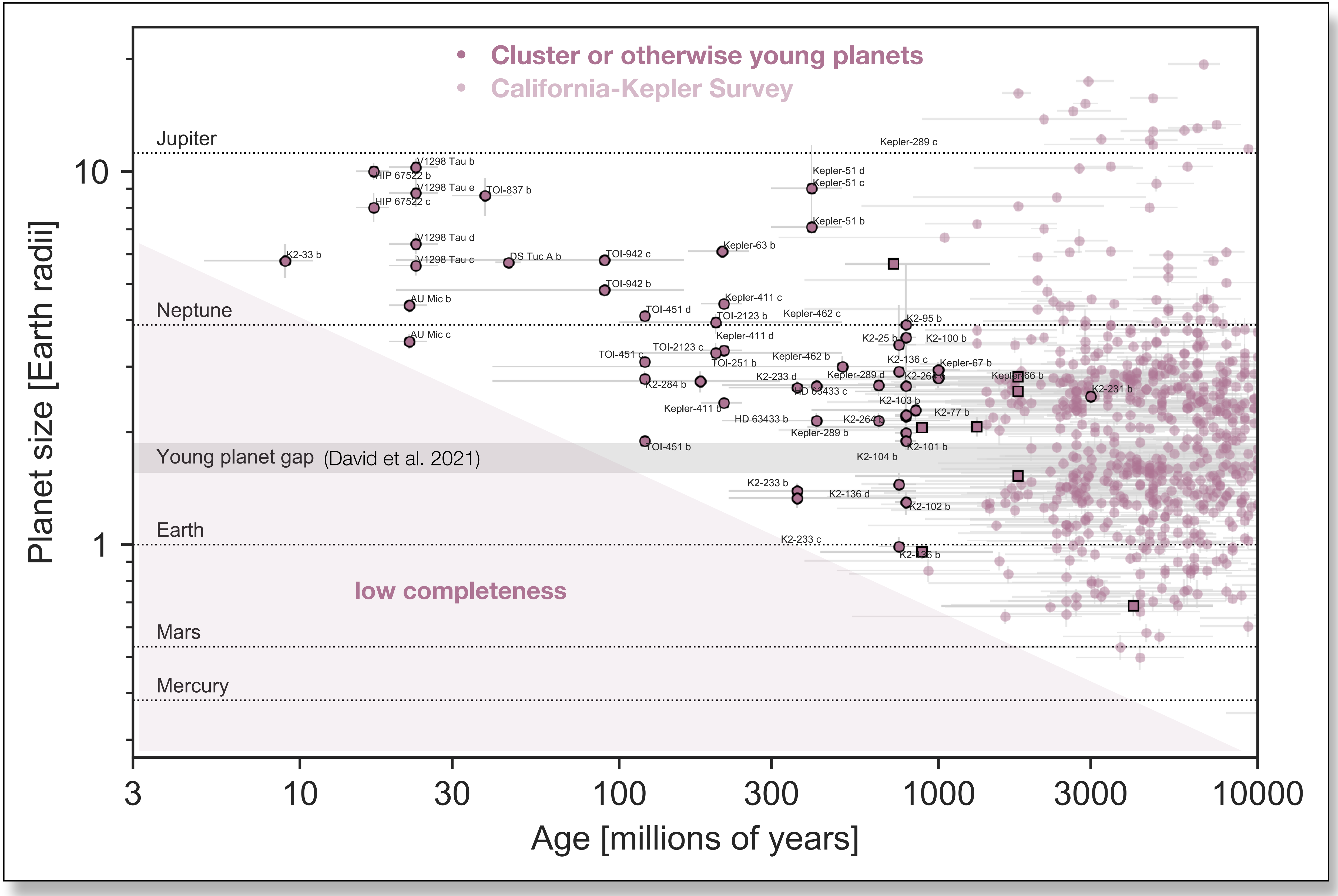
data: NASA Exoplanet Archive

Youngest transiting planets are large

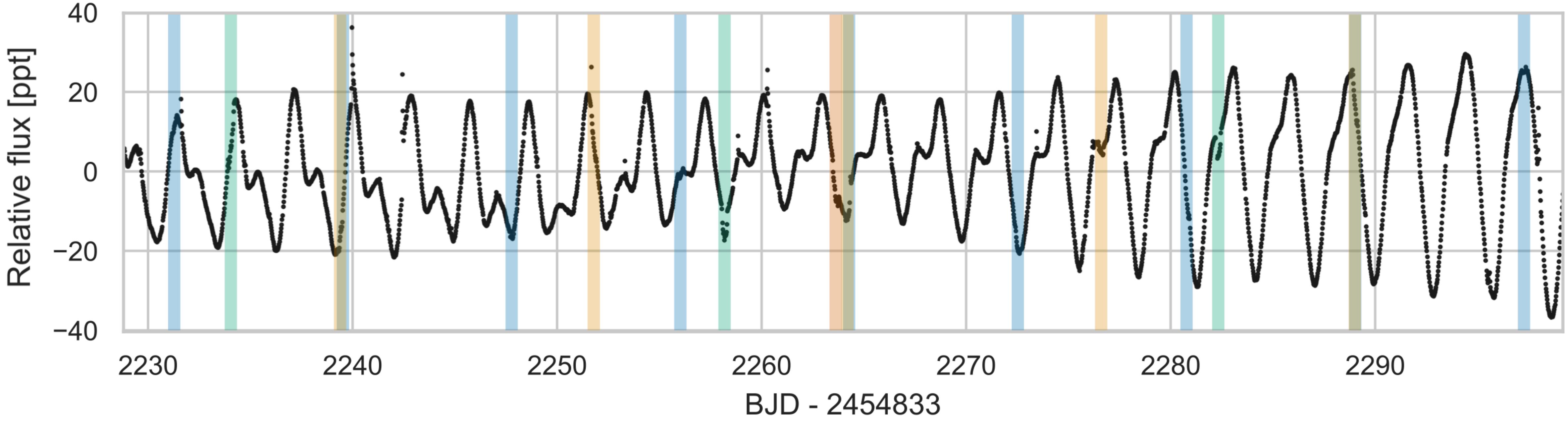


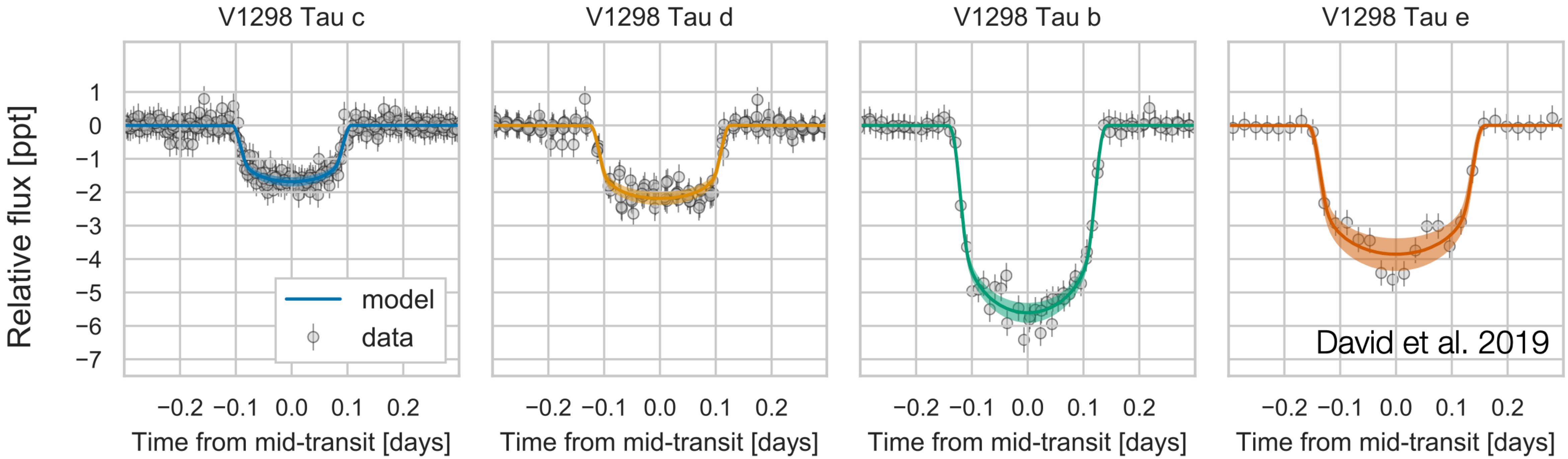
data: NASA Exoplanet Archive

Size evolution of close-in exoplanets



Case study: four newborn planets transiting V1298 Tau





David et al. 2019

$M_\star \sim 1.1\ M_\odot$
$R_\star \sim 1.3\ R_\odot$
Age ~ 20-30 Myr

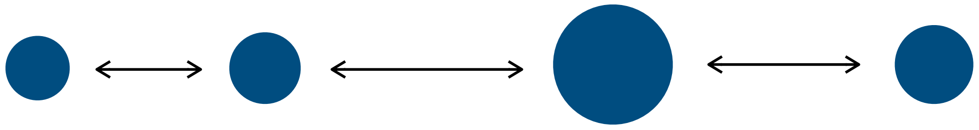
9 transits
P = 8.25 days
$R = 5.6\ R_\oplus$
a = 0.08 au

5 transits
P = 12.40 days
$R = 6.7\ R_\oplus$
a = 0.11 au

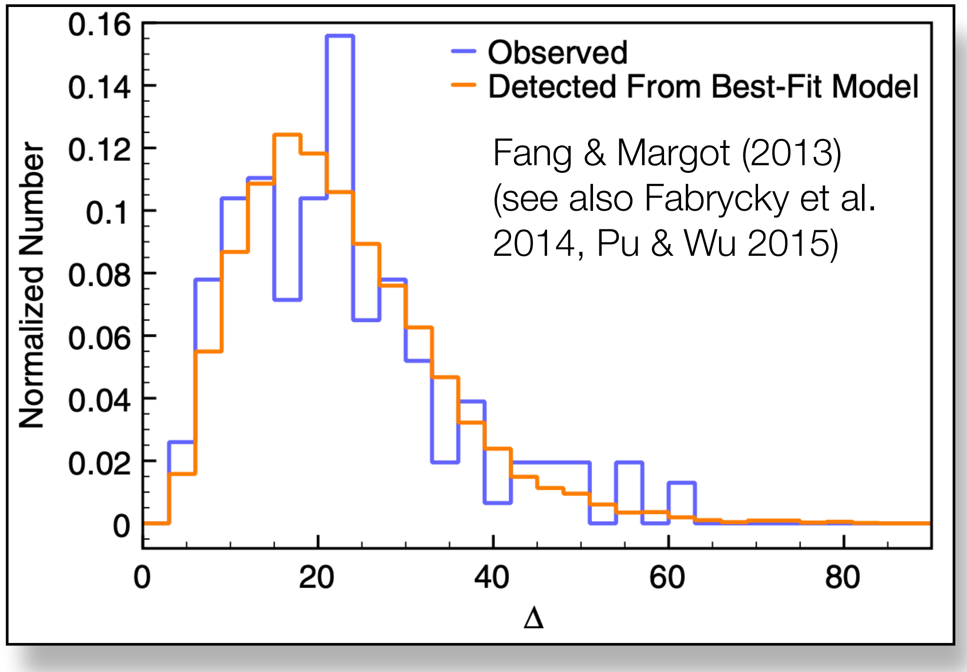
2.5 transits
P = 24.14 days
$R = 10.2\ R_\oplus$
a = 0.17 au

1 transit
P > 36 days
$R = 8.8\ R_\oplus$
a > 0.22 au

Predicting planet masses in the V1298 Tau system



Planet pairs are typically separated by 20 mutual Hill radii

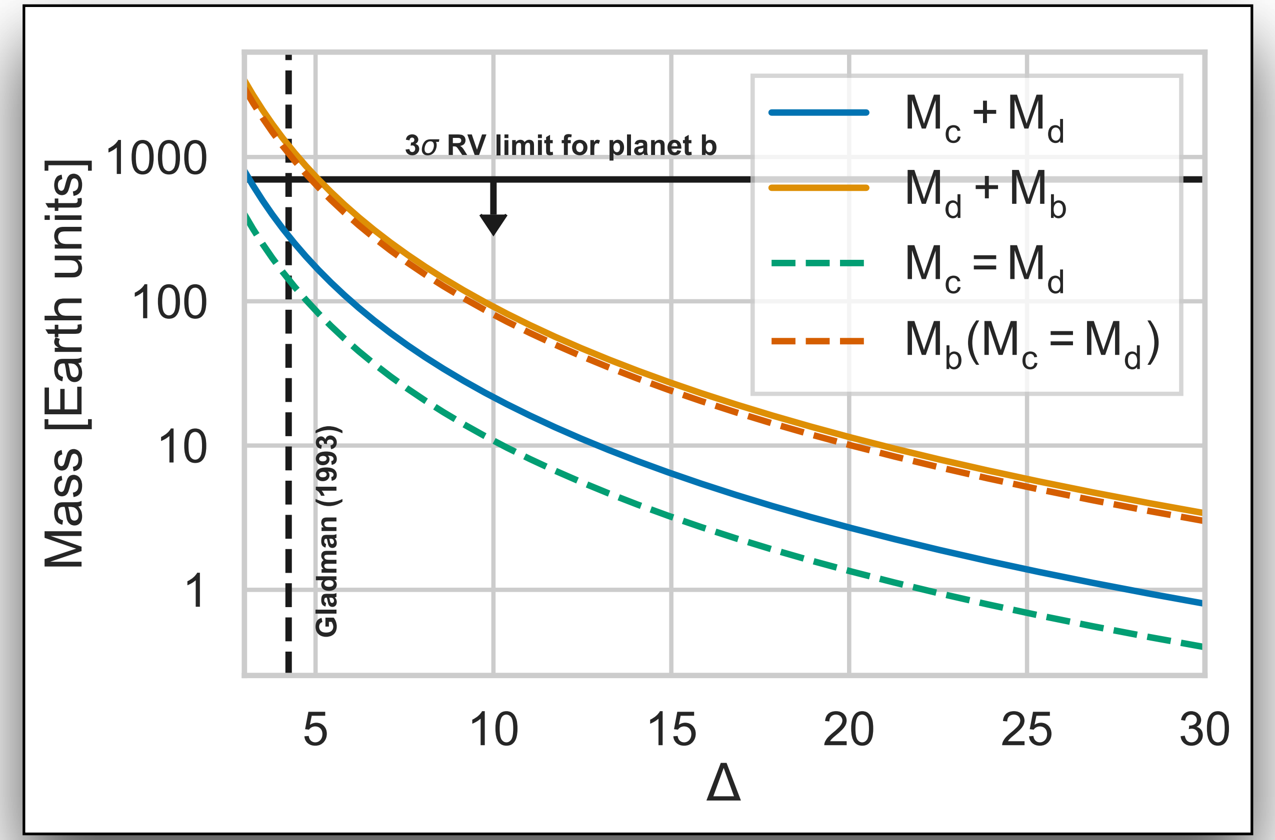


Fang & Margot (2013) (see also Fabrycky et al. 2014, Pu & Wu 2015)

Masses of adjacent planets can be estimated from period ratios, assuming a Hill spacing

$$M_{P,1} + M_{P,2} = 8 \left[\frac{\left(\frac{P_2}{P_1}\right)^{2/3} - 1}{\left(\frac{P_2}{P_1}\right)^{2/3} + 1} \right]^3 \frac{3M_\star}{\Delta^3}$$

David et al. 2019



sum of masses:	individual masses:
Mc + Md ~ 2-30 $M_\oplus$	Mc=Md ~ 1-15 $M_\oplus$
Md + Mb ~ 10-120 $M_\oplus$	Mb ~ 8-90 $M_\oplus$

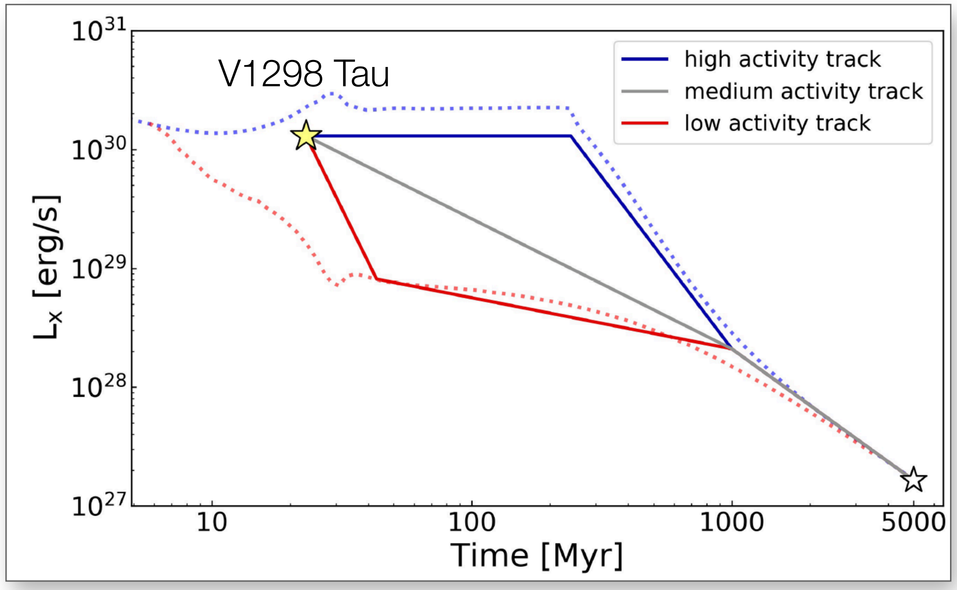
implies contraction of ~40-90% using a mass-radius relation

V1298 Tau: a Kepler multiplanet system precursor?

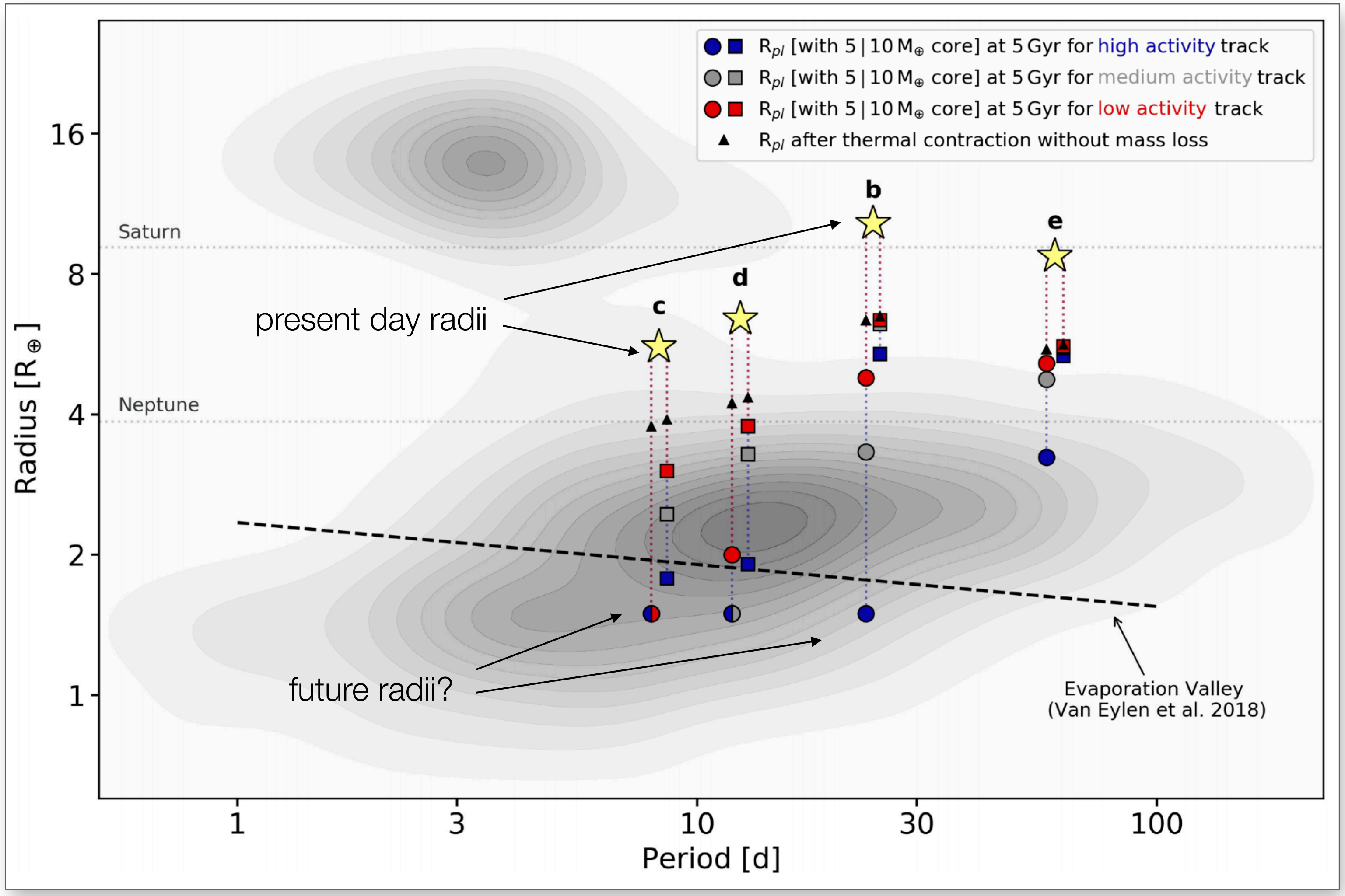
In the energy-limited mass-loss regime, atmospheric loss rate due to photoevaporation depends linearly on the received XUV flux…

$$\dot{M} = \epsilon \frac{\left(\pi R_{\rm XUV}^2\right) F_{\rm XUV}}{K G M_{\rm pl}/R_{\rm pl}}$$

…but the early evolution in high-energy output for a given star is uncertain at the order-of-magnitude level.



Poppenhaeger et al. 2021



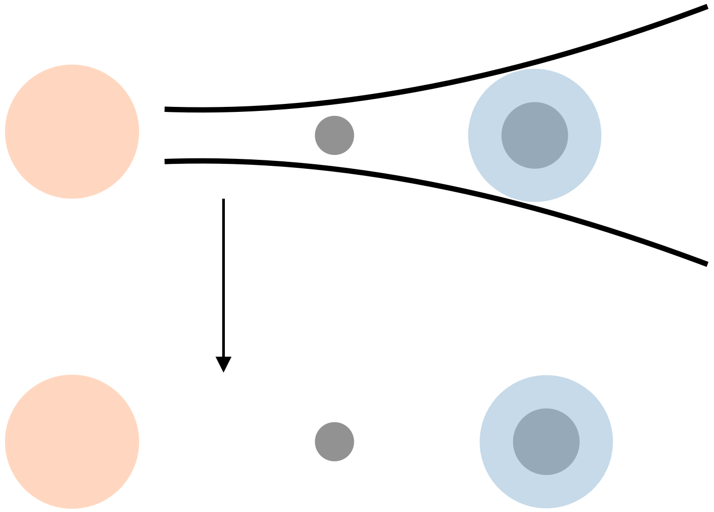
Mass measurements help to constrain future evolution

If core mass of planet c is ≲5 M⊕, planet is evaporated for all plausible activity evolution curves

Planets b, c, d may be stripped, depending on activity track and core masses

Forming the radius gap

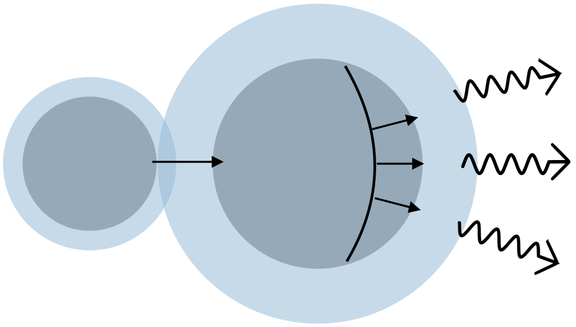
Gas-poor formation



timescale:
0.01 Gyr

Lee et al. 2014, Lee & Chiang 2016, Lopez & Rice 2018,
Lee & Connors 2020

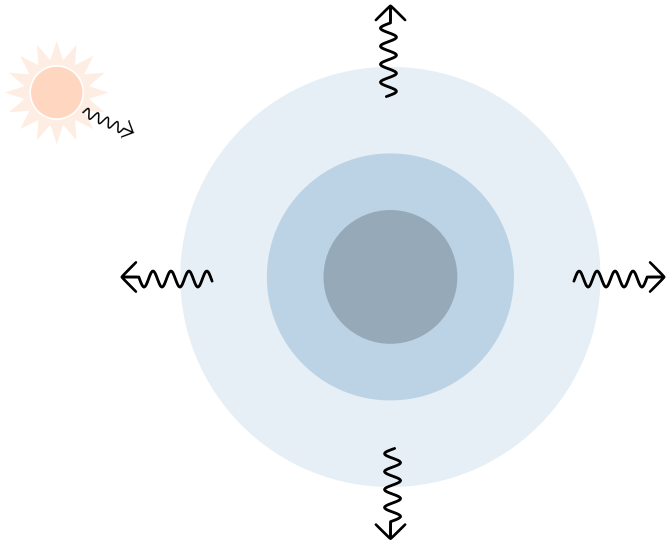
Impact-driven atmospheric loss



timescale:
~0.01-0.1 Gyr

Schlichting et al. 2015, 2016, 2018,
Inamdar & Schlichting 2016, Wyatt et al. 2020

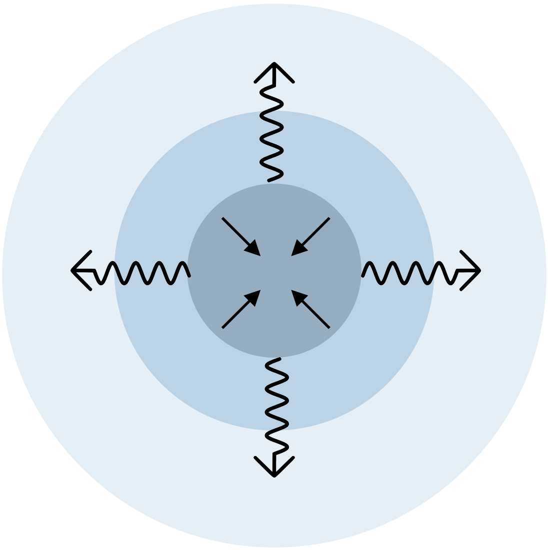
Atmospheric loss via photoevaporation



timescale:
~0.01-1 Gyr

Owen & Wu 2013, Lopez & Fortney 2013, Jin et al.
2014, Chen & Rogers 2016, Rogers & Owen 2020

Core-powered atmospheric loss

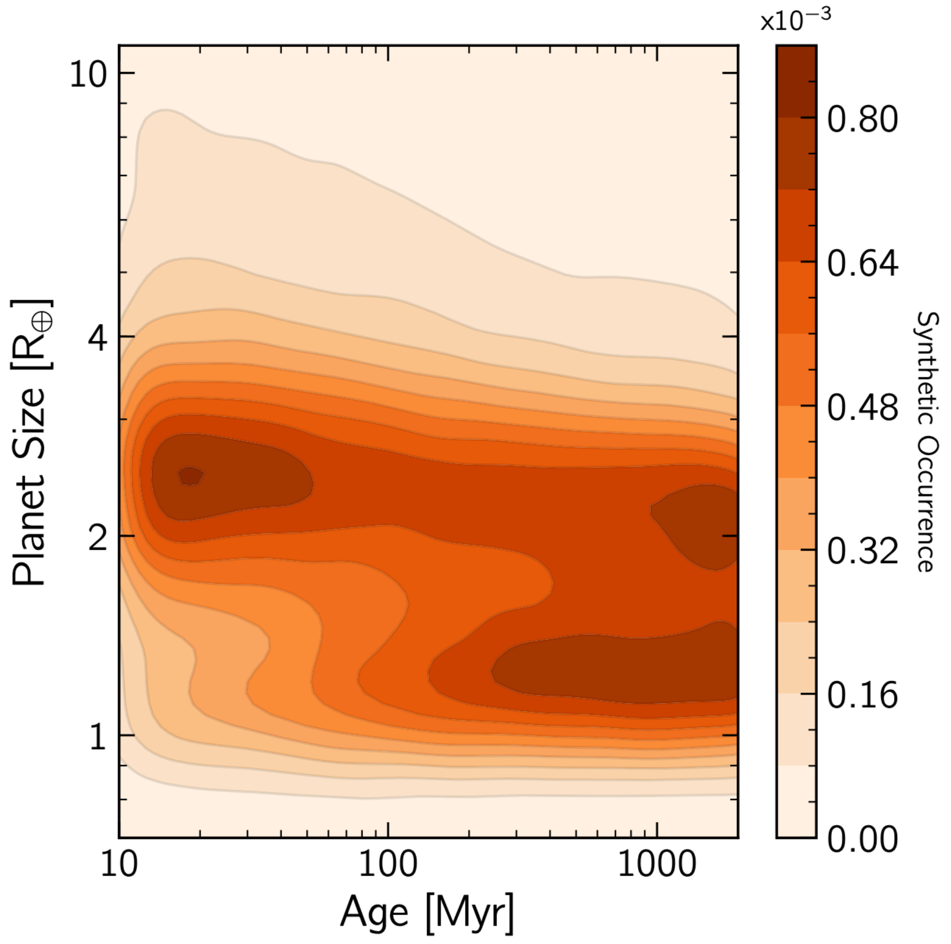


timescale:
≳1 Gyr

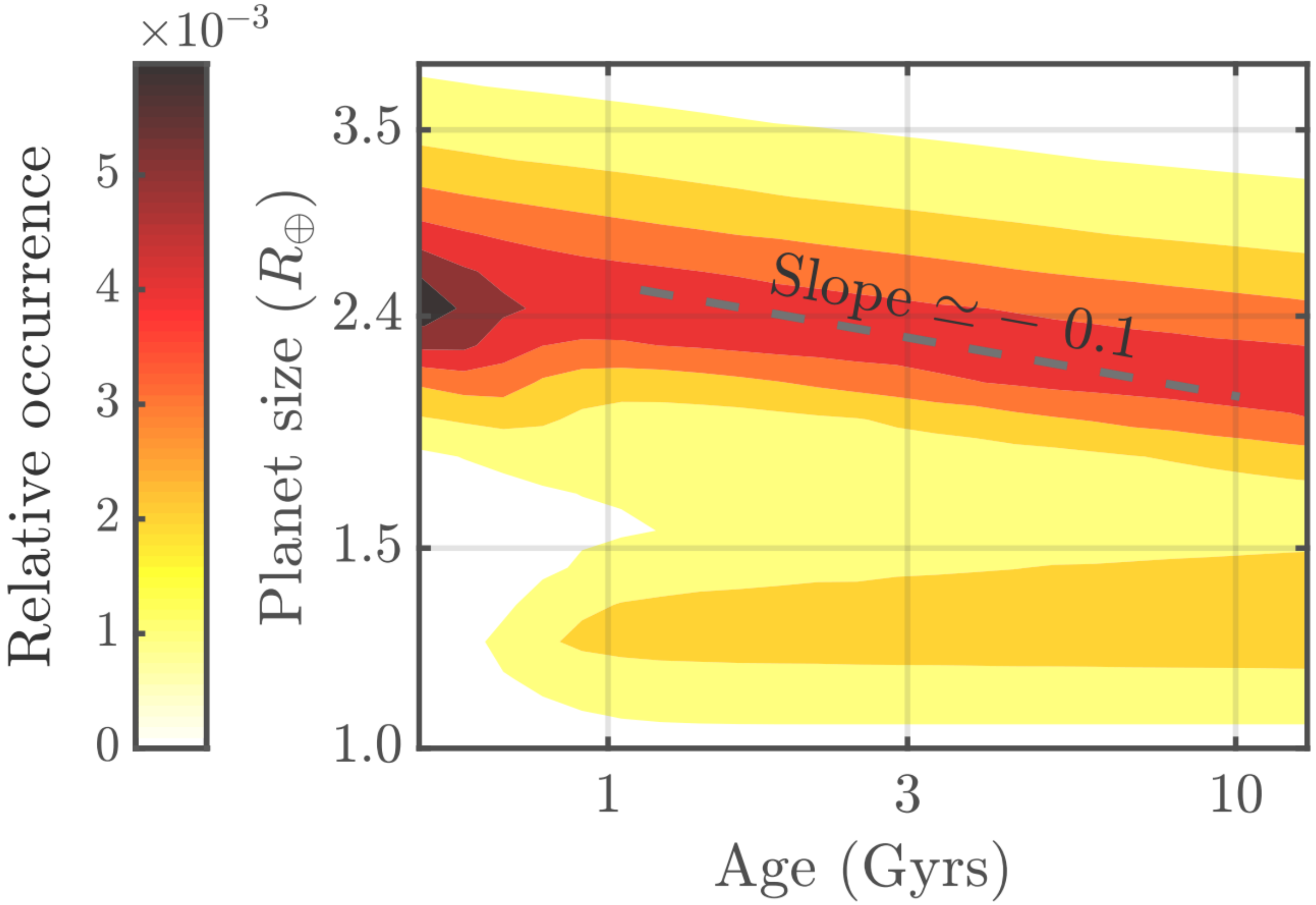
Ginzburg et al. 2018,
Gupta & Schlichting 2019, 2020

Emergence of the radius gap: theory

photoevaporation
(Rogers & Owen 2020)



core-powered mass-loss
(Gupta & Schlichting 2020)



in both models:

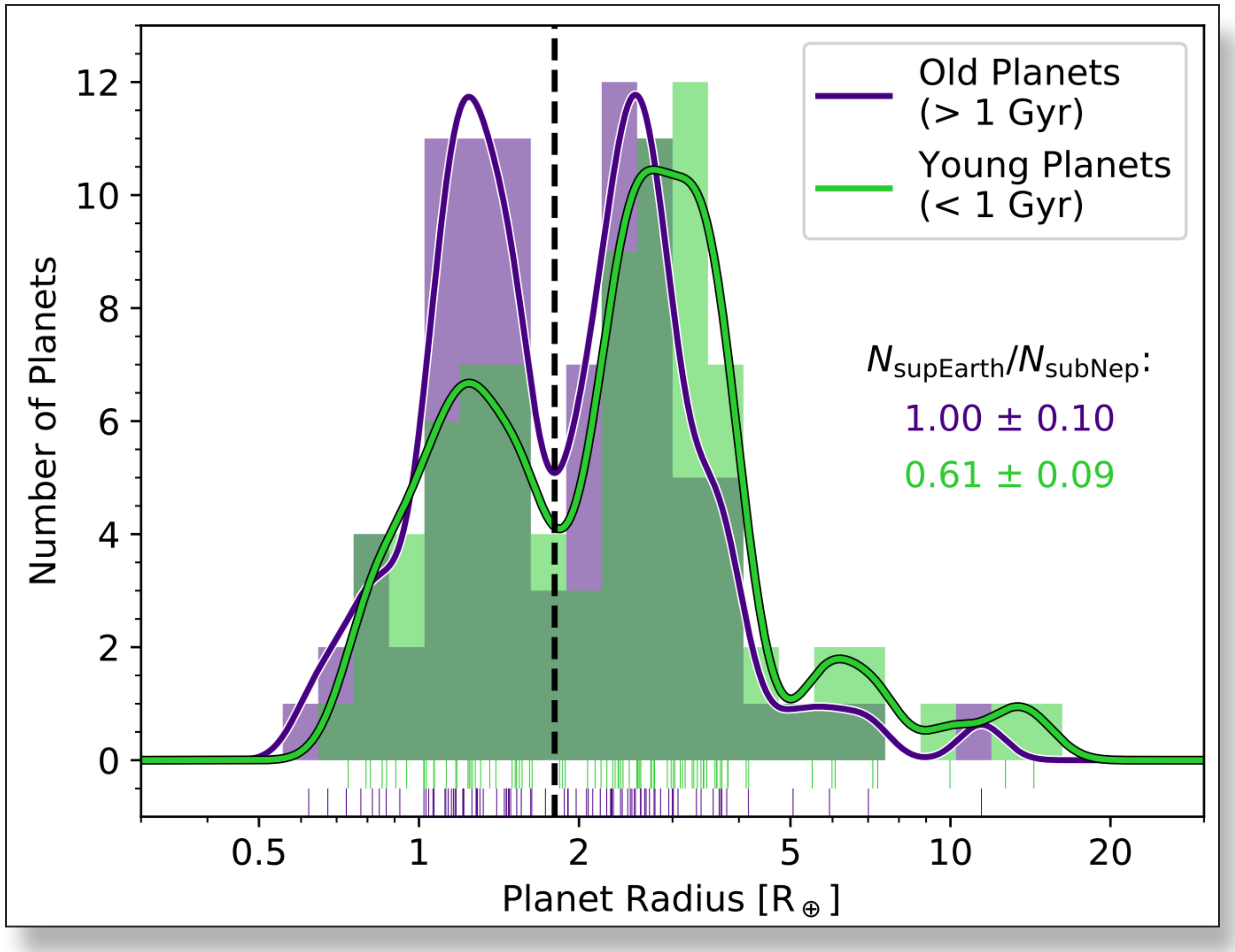
(1) radius gap emerges on ~Gyr timescales

(2) gap is wider at earlier times (due to larger sub-Neptunes and smaller super-Earths)

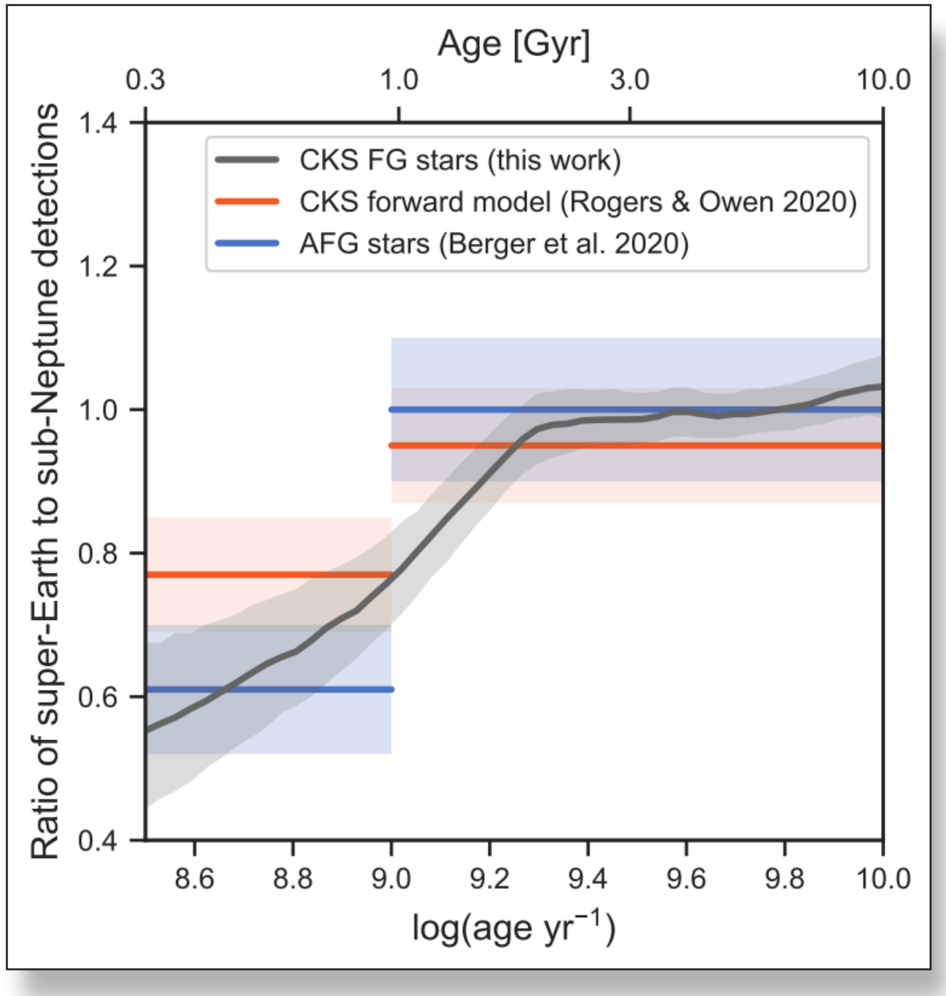
(3) super-Earth population fills in from "bottom up," precise location of the gap shifts higher over time

(4) relative fraction of super-Earths increases with time

Long-term evolution of planet size distribution



Berger et al. 2020



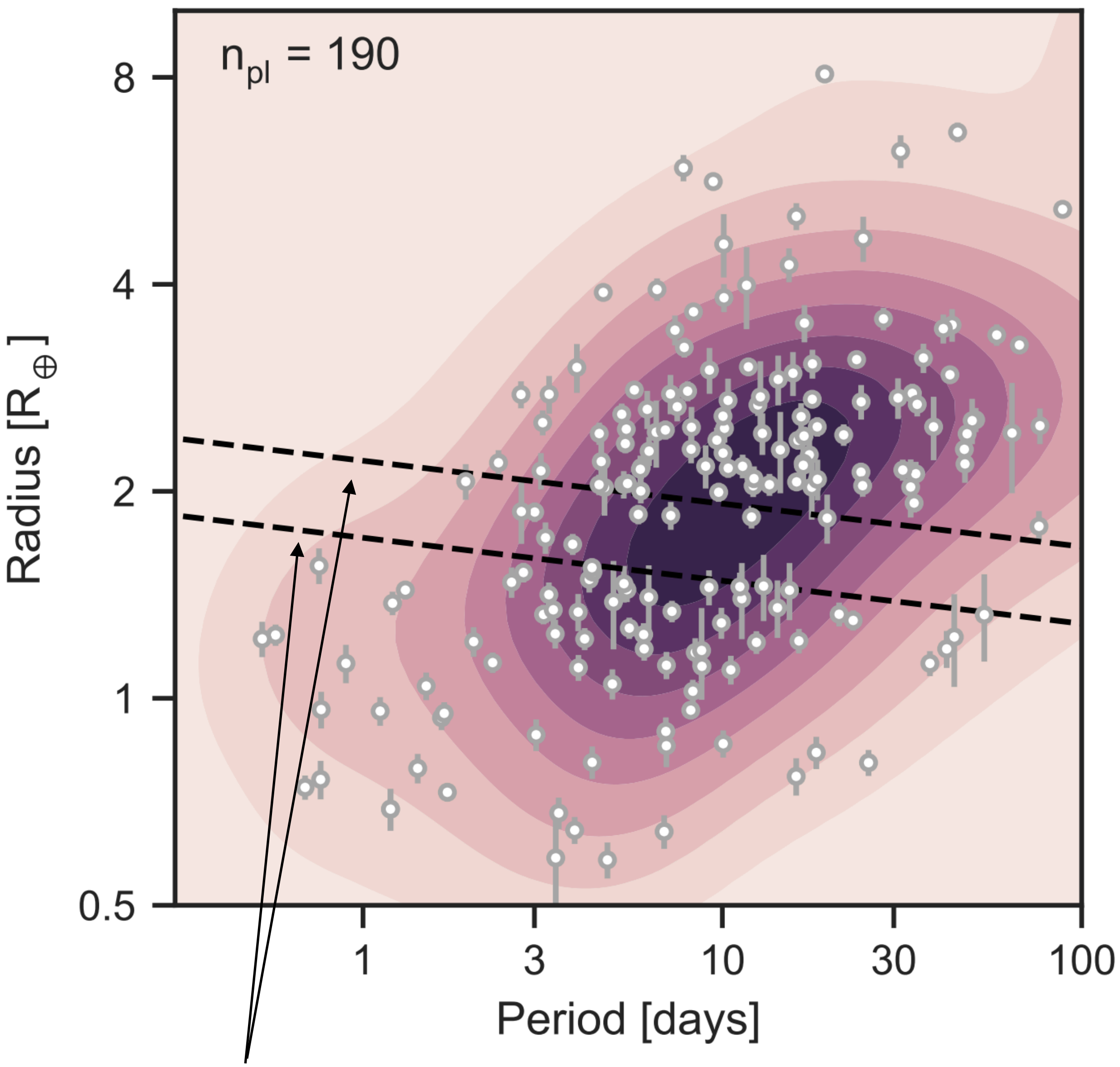
Sandoval, Contardo, & David 2021

for Kepler stars with very similar completeness characteristics, super-Earths appear to be detected more frequently around older stars

possible explanation: some sub-Neptunes may be converted to super-Earths on gigayear timescales

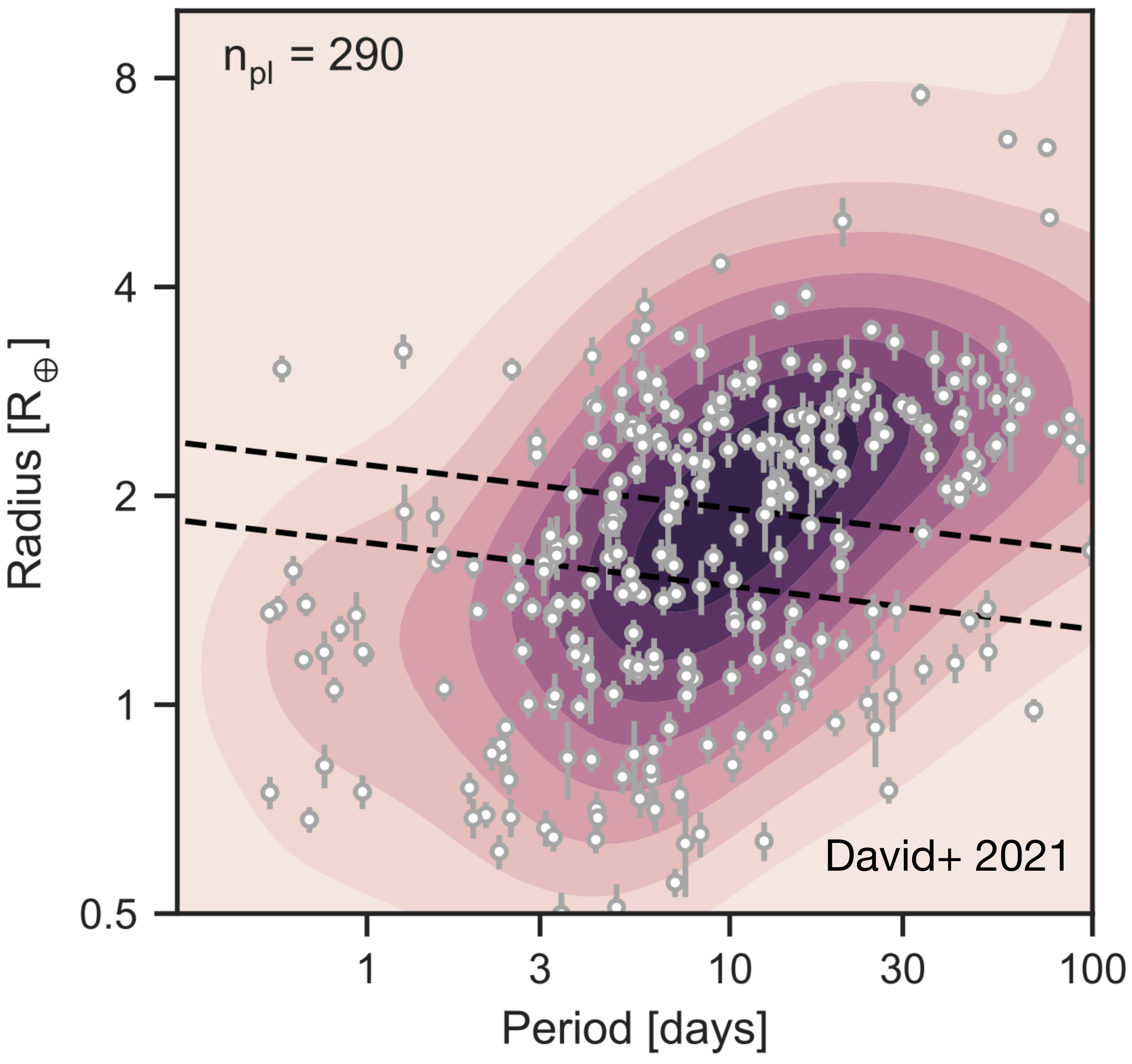
Evolution of the exoplanet radius gap

Planets orbiting fast rotators

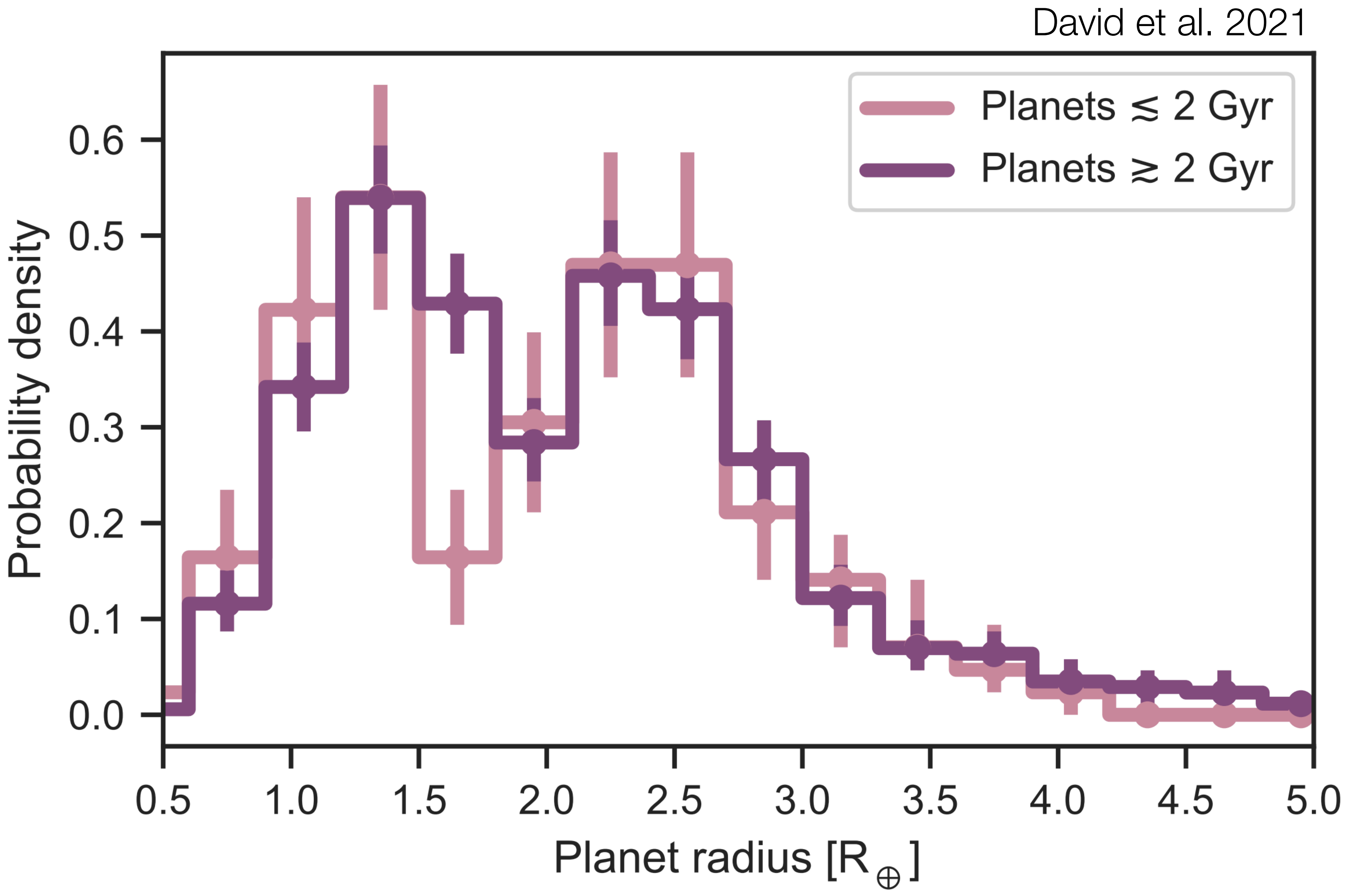


dashed lines derived from an
independently age-selected sample

Planets orbiting slow rotators



Large super-Earths are missing at young ages

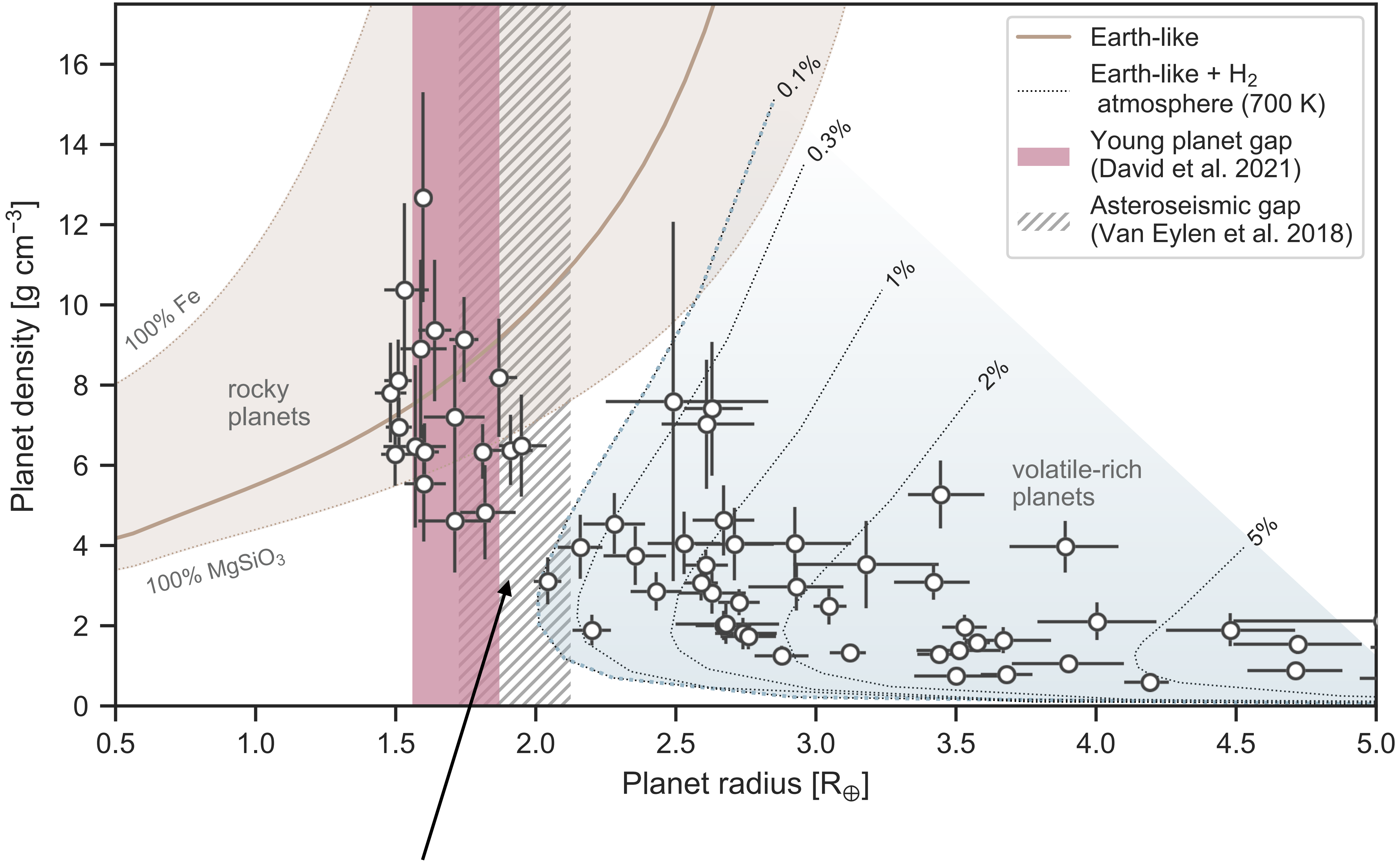


evolution of the planet size distribution is still apparent when considering planets with radii known to 5% or better

the largest cores to experience total atmospheric loss may do so on gigayear timescales

Planets missing at young ages are likely to be rocky

David et al. 2021

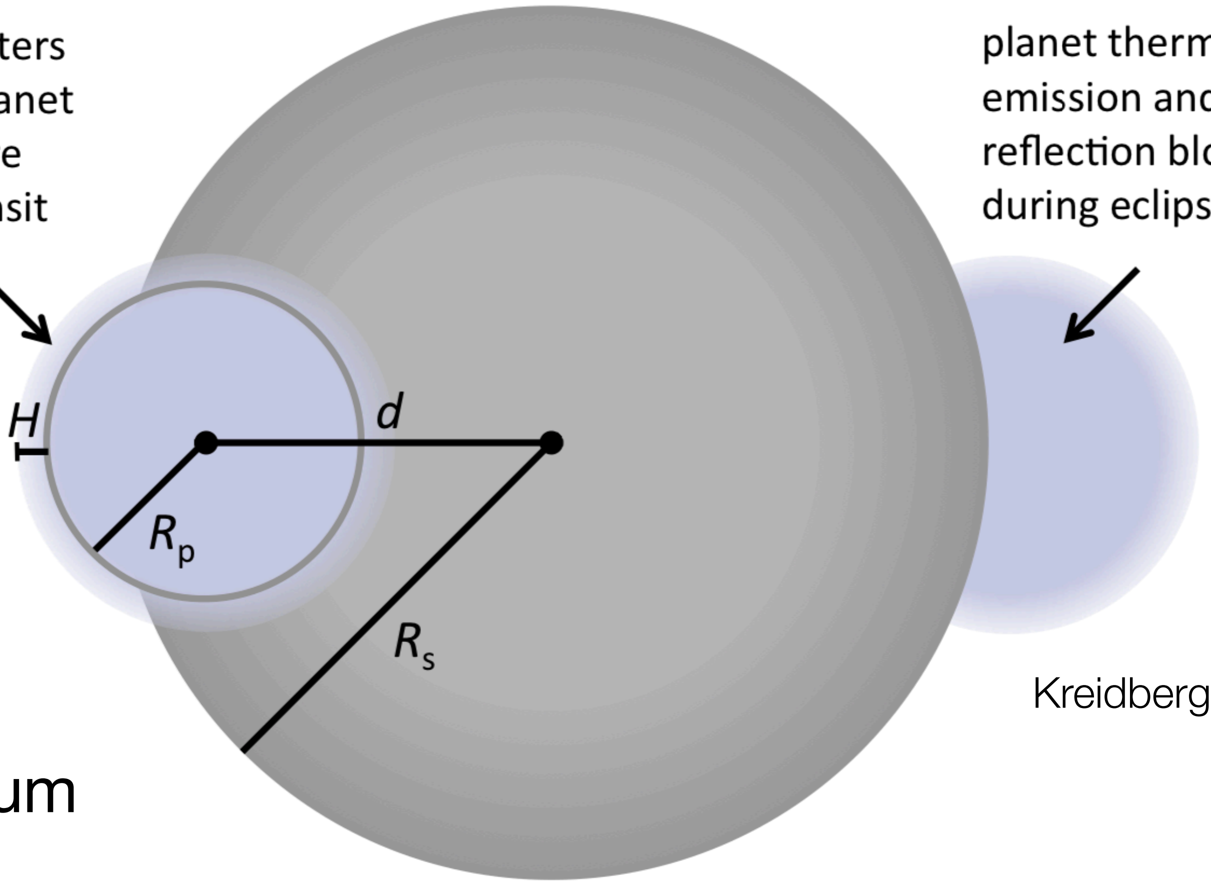


composition gap
(Sinukoff 2018)

composition models
from Zeng et al. 2019

atmospheric evolution

Transmission spectroscopy



starlight filters through planet atmosphere during transit

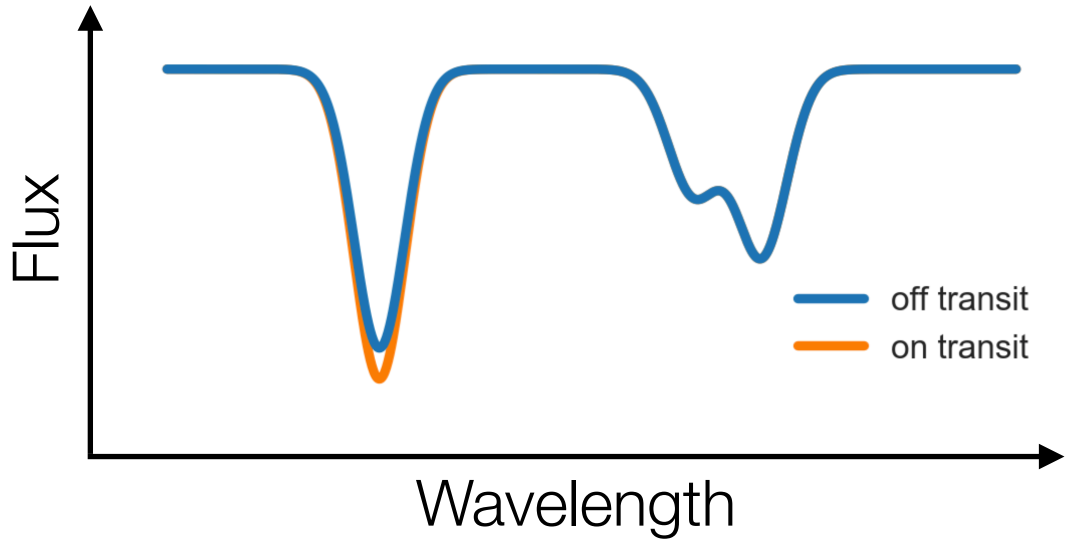
planet thermal emission and reflection blocked during eclipse

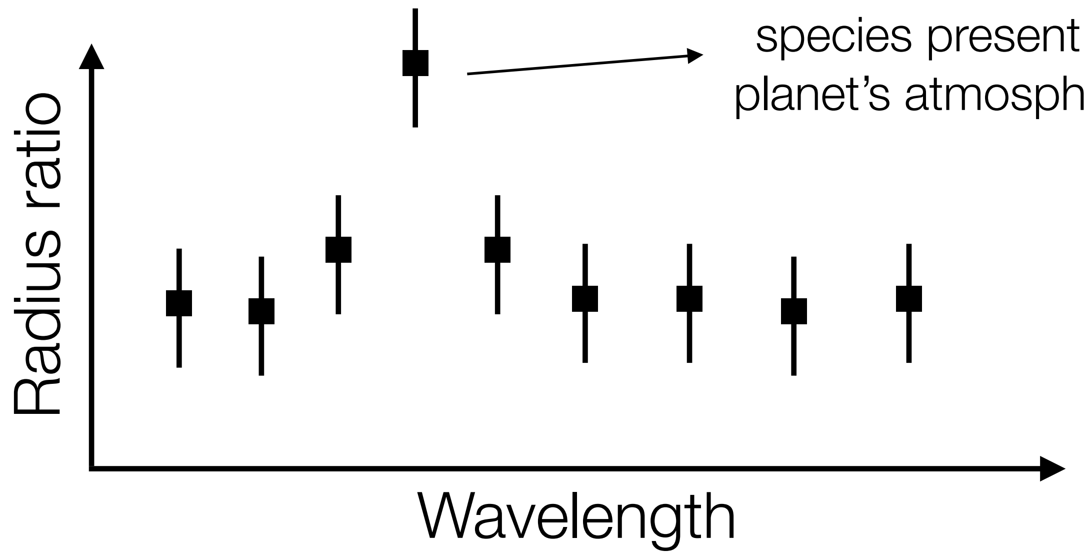
Larger scale heights (extended atmospheres) of young planets should give rise to stronger features in transmission spectra

Kreidberg 2018

Transmission spectrum

$$S_T = F_{in}/F_{out} - 1$$

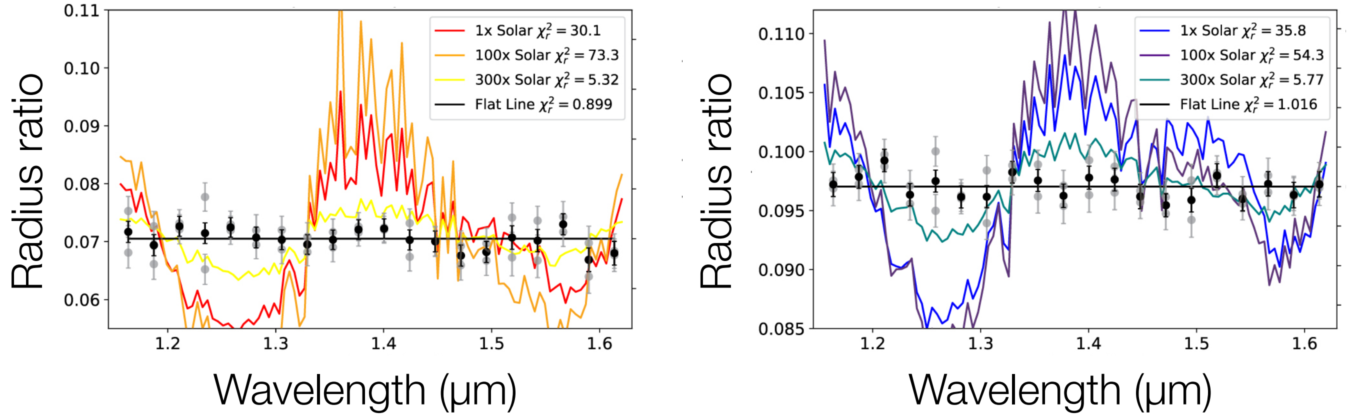




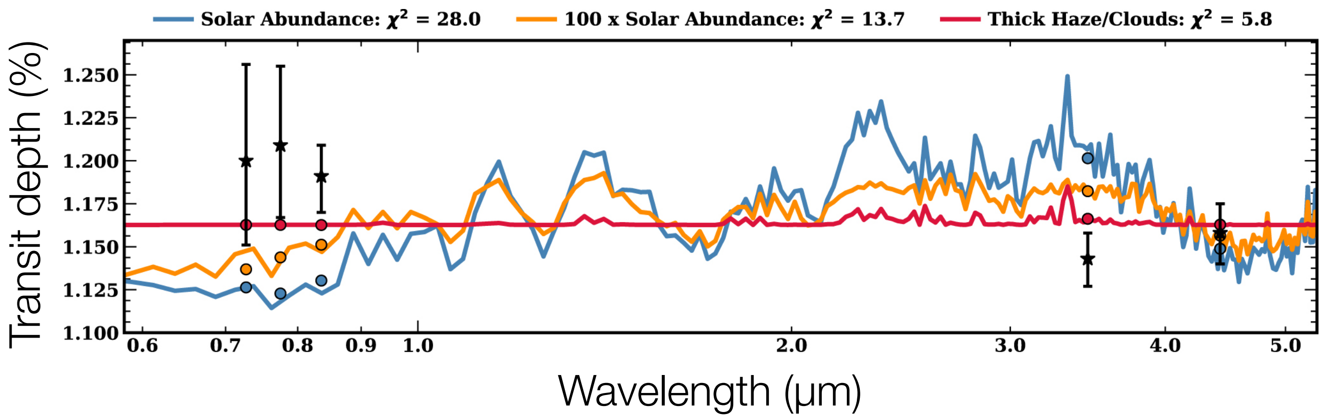
species present in planet’s atmosphere

Flat transmission spectra and dusty outflows?

Kepler 51 b & d (Libby-Roberts+ 2020)



K2-25 b (Thao+ 2020)



Observation:
Flat transmission spectra for young (~300-800 Myr) planets Kepler 51 b & d (Libby-Roberts+ 2020), K2-25 b (Thao+ 2020), possibly V1298 Tau b (Livingston+ in prep.)

Proposed solution:
Dust or high-altitude, aerosol hazes or may be responsible for (1) the apparent radius inflation of young planets, and (2) flat transmission spectra observed to date
(Wang & Dai 2019, Gao & Zhang 2020)

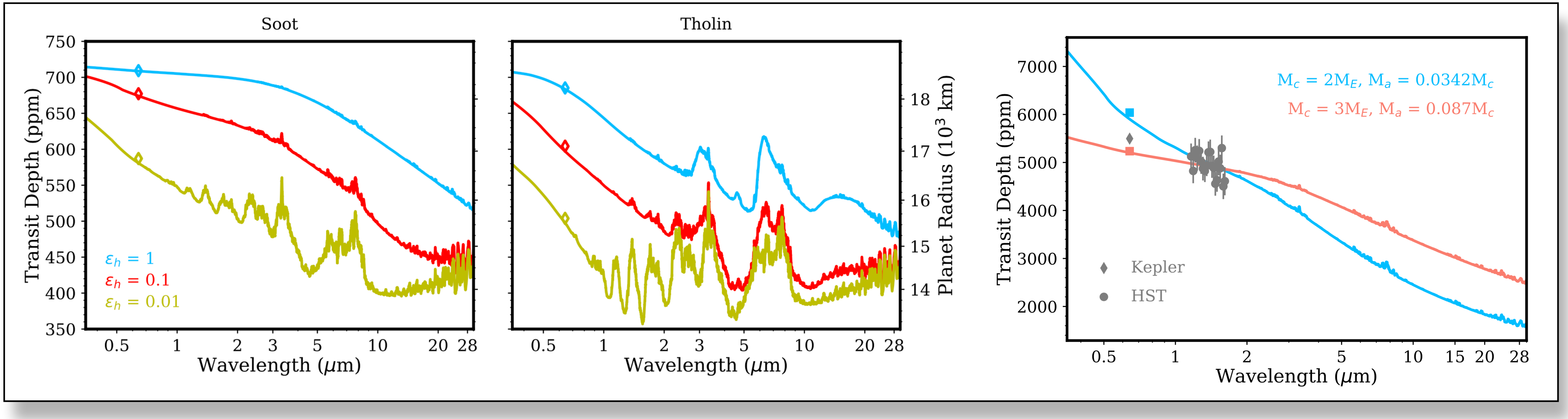
How is the dust advected or created at such high altitudes? Outflows.

Testable prediction:
deeper transits at bluer wavelengths due to scattering, 2x shallower for JWST

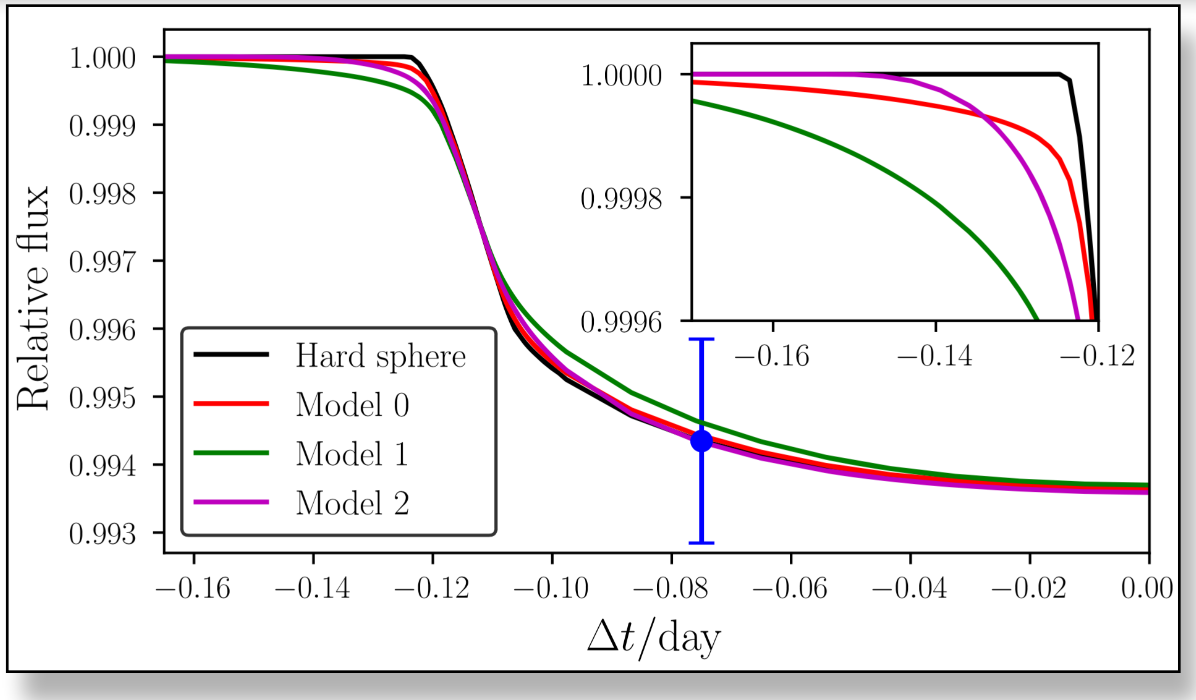
Open questions:
What haze compositions exist? Is this a generic evolutionary stage of low-mass planets?

Flat transmission spectra and dusty outflows?

Gao & Zhang 2020:
spectral shape determined by dust/haze composition, planet mass, envelope mass



Wang & Dai 2019:
dusty outflows produce small changes to transit shape (~200 ppm)



Observing atmospheric escape

Escape is demonstrated if a planet’s radius exceeds its Roche lobe:

$$\delta \geq \left(\frac{R_{\mathrm{Roche}}}{R_*}\right)^2 \approx 0.13 \left(\frac{a}{0.025\ \mathrm{AU}}\right)^2 \left(\frac{M_p}{M_J}\right)^{2/3} \left(\frac{R_*}{R_\odot}\right)^{-2} \left(\frac{M_*}{M_\odot}\right)^{-2/3}$$

1
H

hydrogen

Lyman α

+ large cross-section

- only possible from space

- ISM absorption and geocoronal emission renders the line core unusable

Balmer lines

+ possible from ground

- requires high levels of Lyα and EUV radiation to populate n=2 state

- Hα signatures saturate at ~4%, may not be observable after ~1 Gyr (Allan & Vidotto 2019)

2
He

helium

He I 1083 nm triplet

+ possible from ground

+ less susceptible to stellar activity and ISM absorption

- requires high EUV flux to ionize ground state, but low mid-UV flux to avoid ionizing metastable state

see Oklopčić & Hirata 2018, Oklopčić 2019

6
C

7
N

8
O

metals

several lines

+ good tracer of hydrodynamic flows

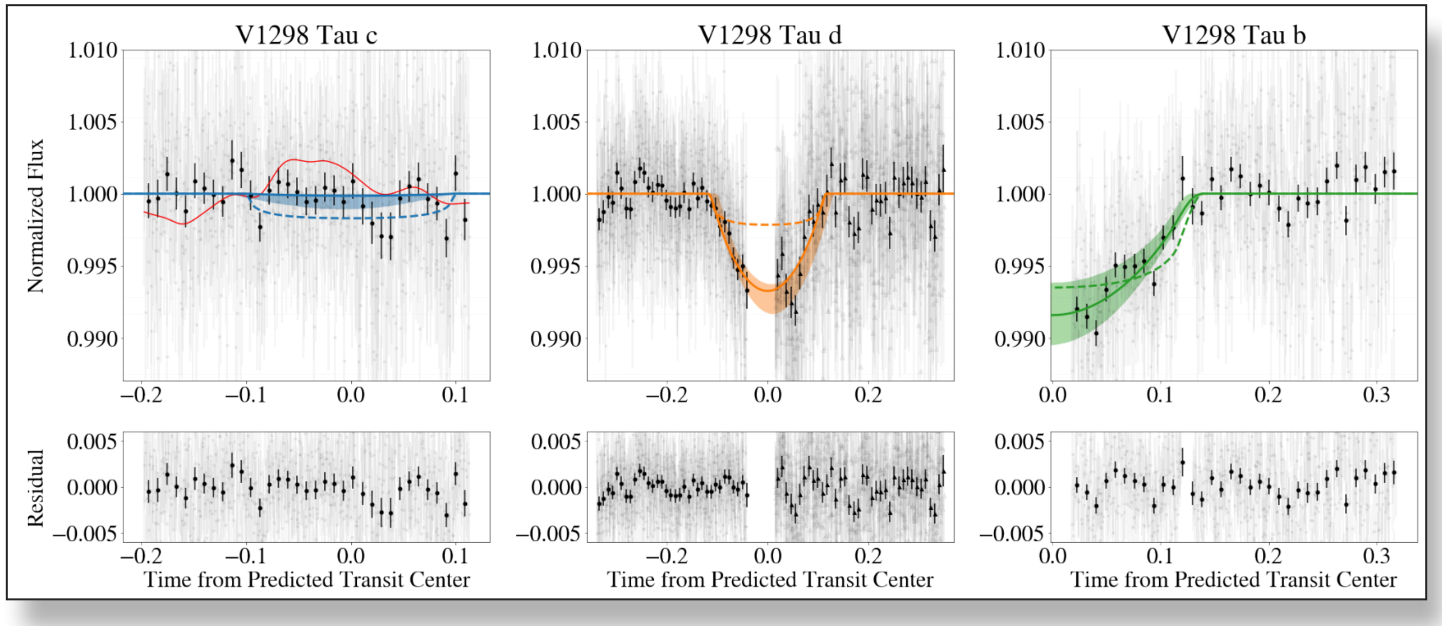
- possible from space with FUV/UV spectroscopy, X-ray

see Owen 2018 for details

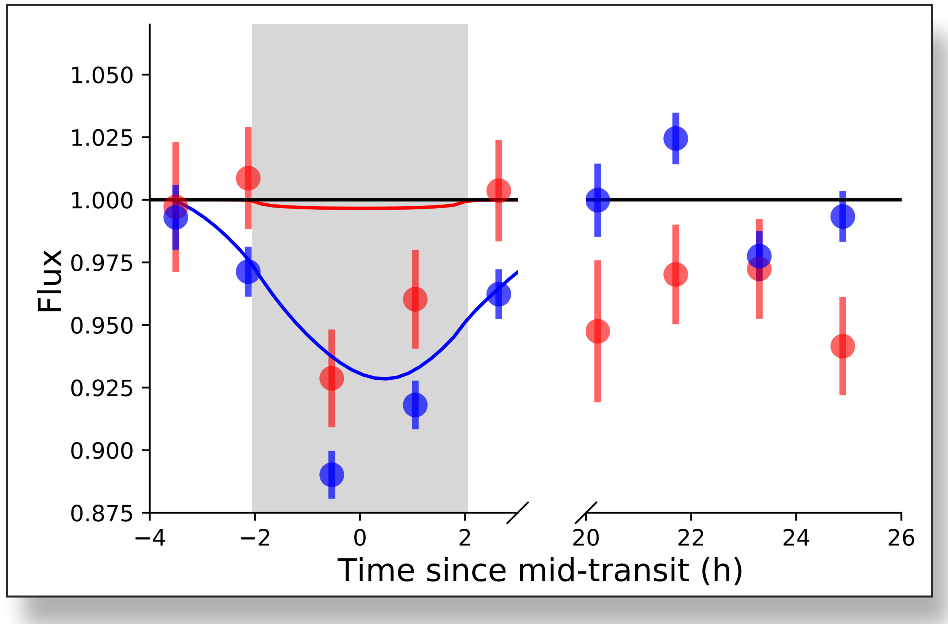
Atmospheric escape in young planets

Planet	Age (Myr)	Host star Sp. type	Radius (Earth units)	Period (days)	Lyα	Hα	He I 1083 nm	Ref.
AU Mic b	20 - 30	M1	4.2	8.5	…	…	X	Hirano+ 2020
V1298 Tau c	20 - 30	K0	5.6	8.3	…	X	X	Feinstein+ submitted, Vissapragada+ submitted
V1298 Tau d	20 - 30	K0	6.4	12.4	…	…	✓	Vissapragada+ submitted
V1298 Tau b	20 - 30	K0	10.3	24.1	…	?	?	Vissapragada+ submitted, David+ in prep.
KELT-9 b	~ 300	A0	21.2	1.5	…	✓	…	Yan & Henning 2018, Cauley+2019, Borsa+ 2019, Wyttenbach+ 2020
HD 63433 b	~ 400	G5	2.2	7.1	X	…	…	Zhang+ 2021
HD 63433 c	~ 400	G5	2.7	20.5	✓	…	…	Zhang+ 2021
K2-100 b	~ 600 - 800	F8	3.6	1.7	…	…	X	Gaidos+ 2020

V1298 Tau at He 1083 nm (Vissapragada+ submitted)

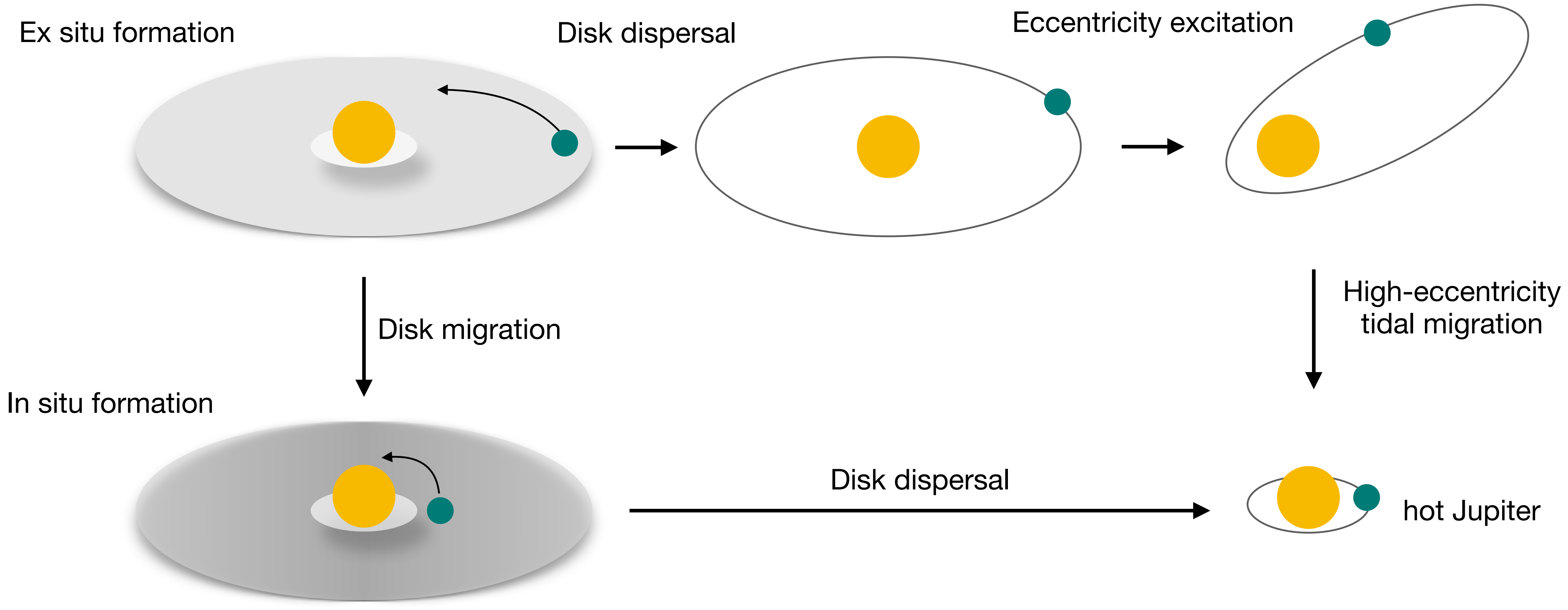


HD 63433 c in Ly*α* (Zhang+ 2021)



orbital evolution

The origins of hot Jupiters



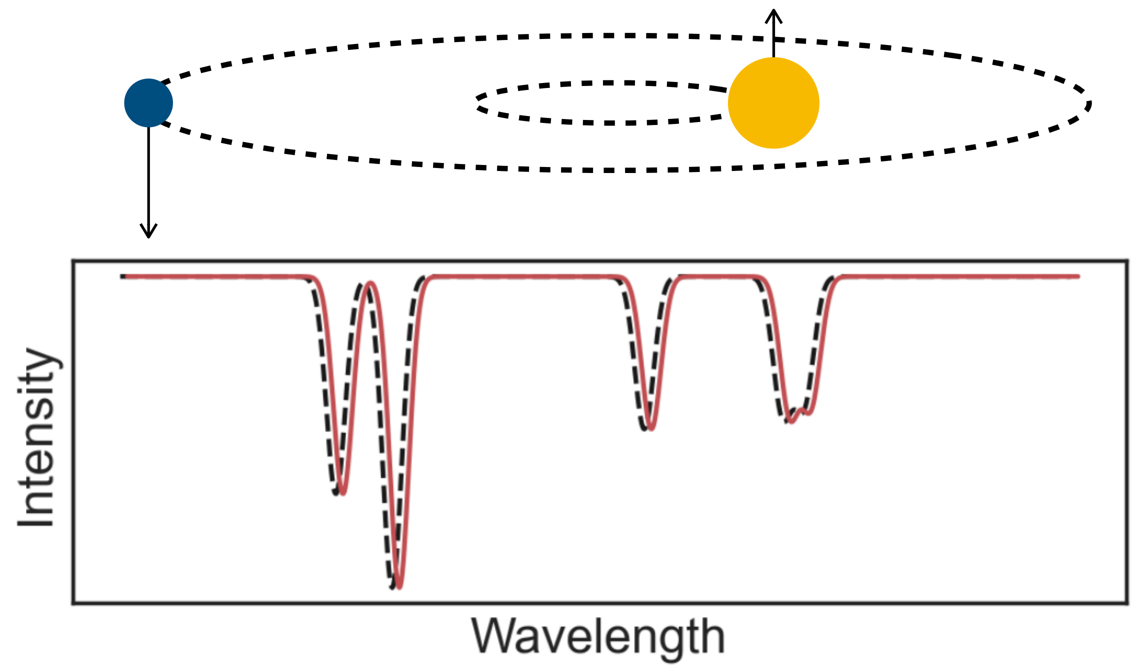
adapted from
Dawson & Johnson 2018

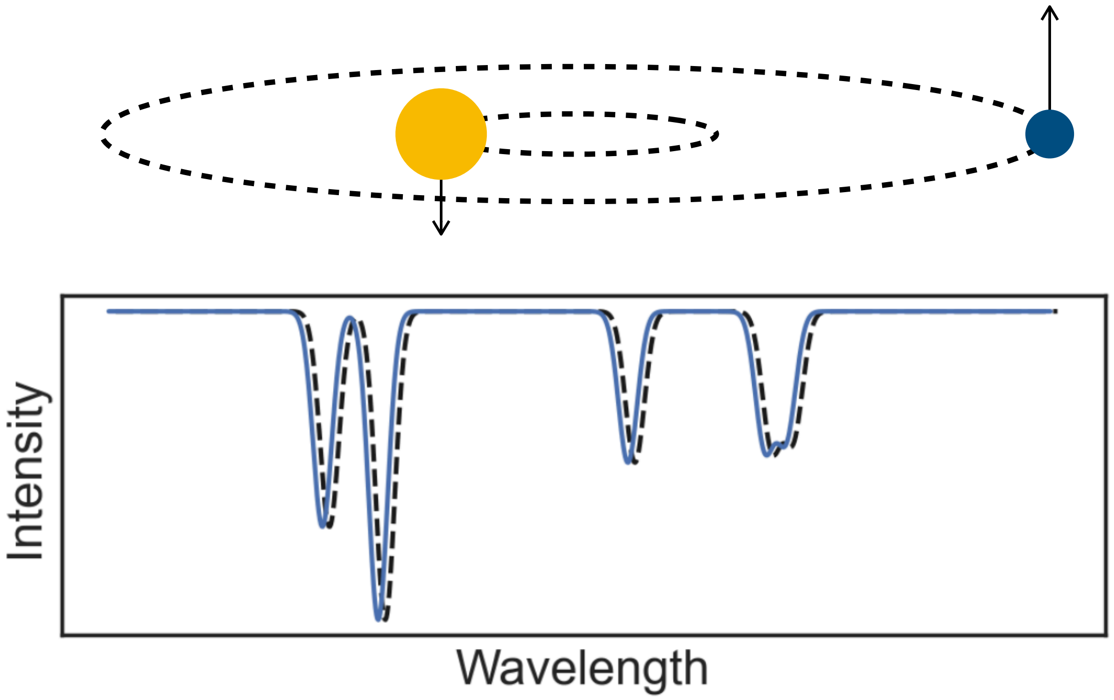
1. In situ formation
2. Ex situ formation + disk migration

→ hot Jupiters in place from end of protoplanetary disk phase (~10 Myr)

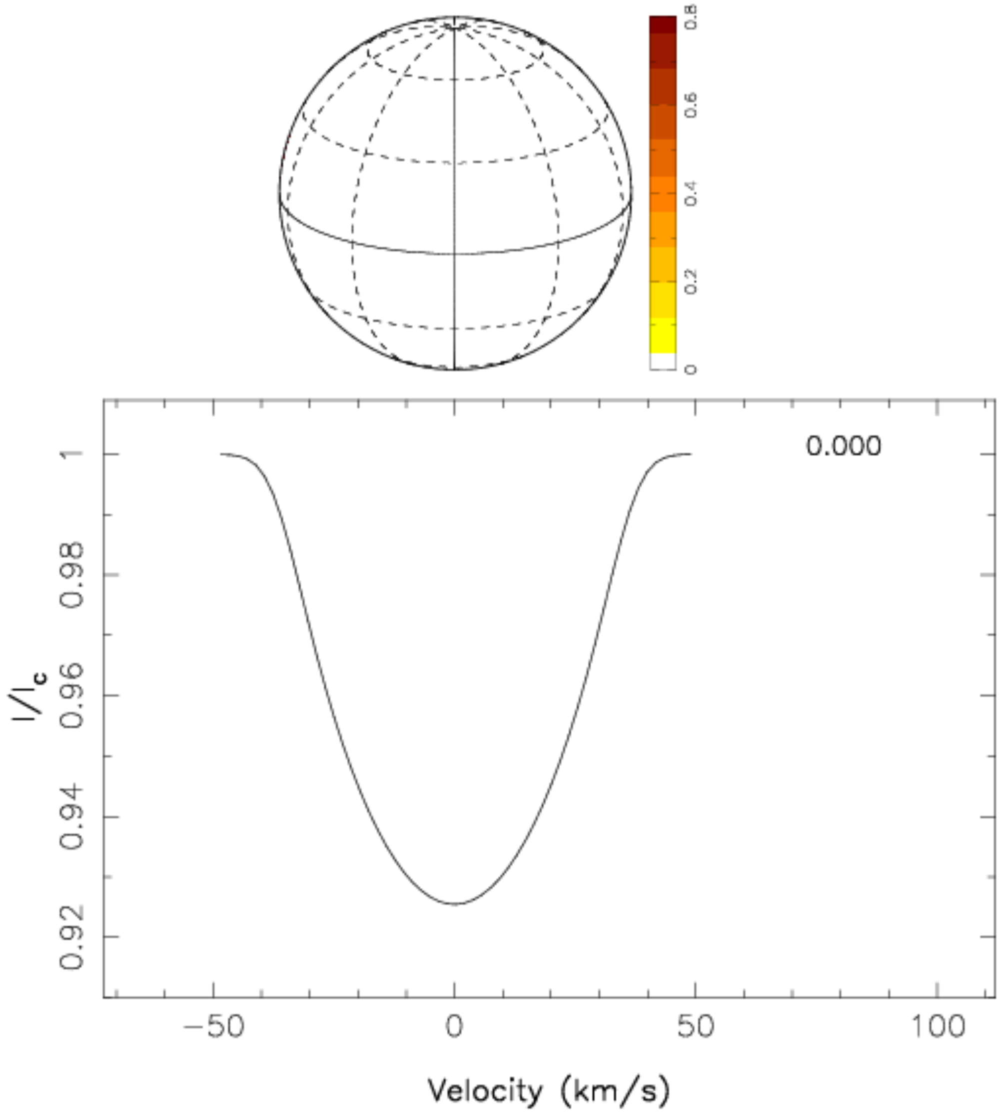
3. Ex situ formation + high-eccentricity migration → hot Jupiters arrive over ~100s to ~1000s of Myr

Real and apparent Doppler shifts





animation by J.F. Donati



Real Doppler shifts are *achromatic*.
Reflex motion has same amplitude regardless of the wavelength you are observing in.

Apparent Doppler shifts from starspots are *chromatic*. Impact of spots on spectral lines is largest at wavelengths where spot-photosphere contrast is highest.

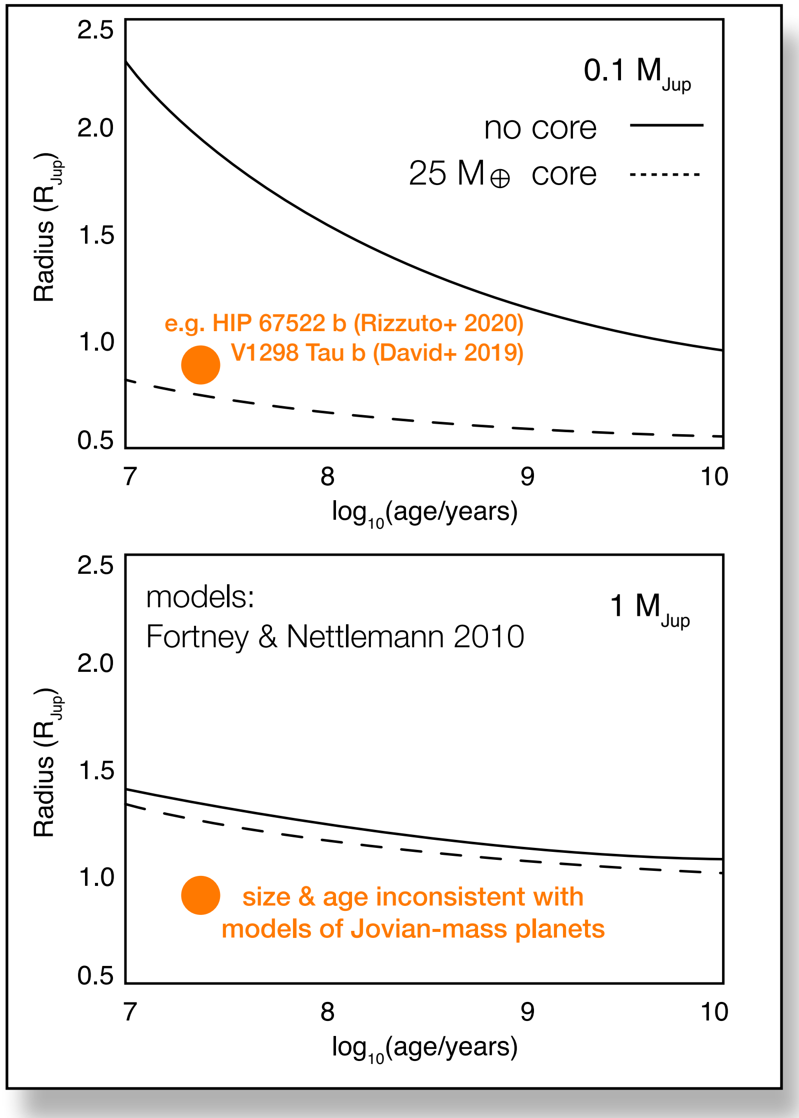
The search for hot Jupiters around young stars

Transit surveys: Jupiter-*sized* planets in multi-transiting systems…but, Jovian-mass planets should be *larger* than Jupiter at ages <100 Myr, and old hot Jupiters are rarely found in multi-transiting systems. These planets may be sub-Neptune progenitors.

KELT & WASP surveys, on the other hand, have confirmed some hot Jupiters transiting young (~300-600 Myr) A-type stars.

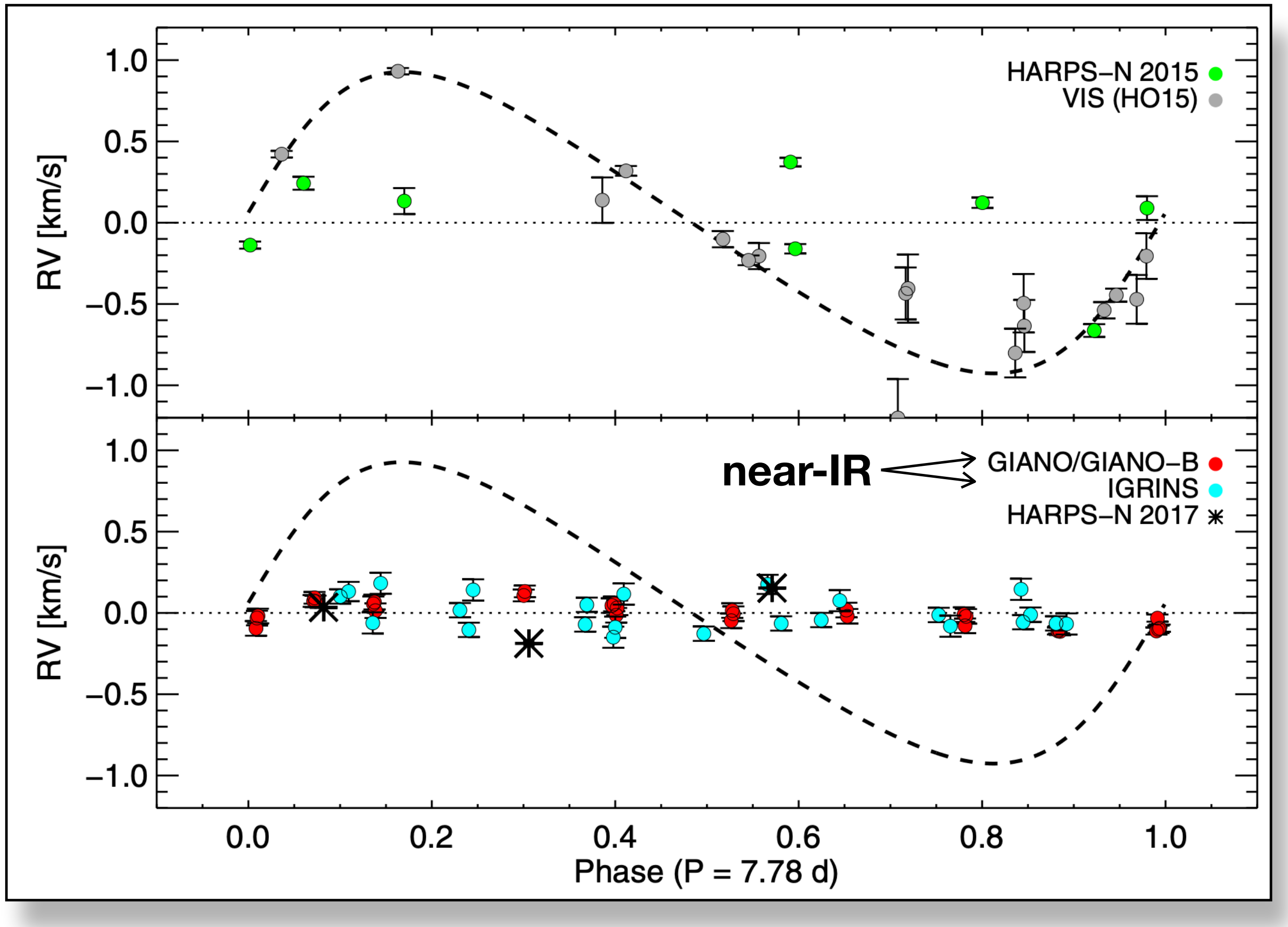
Radial velocity surveys: three hot Jupiters in the ~600-800 Myr Praesepe & Hyades open clusters (Quinn et al. 2012, 2014).

Other hot Jupiters have been claimed around <100 Myr stars, including some that have been refuted. Disentangling stellar activity from reflex motions is a challenge. Stellar surface maps may change quickly, and should not be assumed static over weeks or longer timescales.



BD+20 1790

Carleo et al. 2018



The search for hot Jupiters around young stars

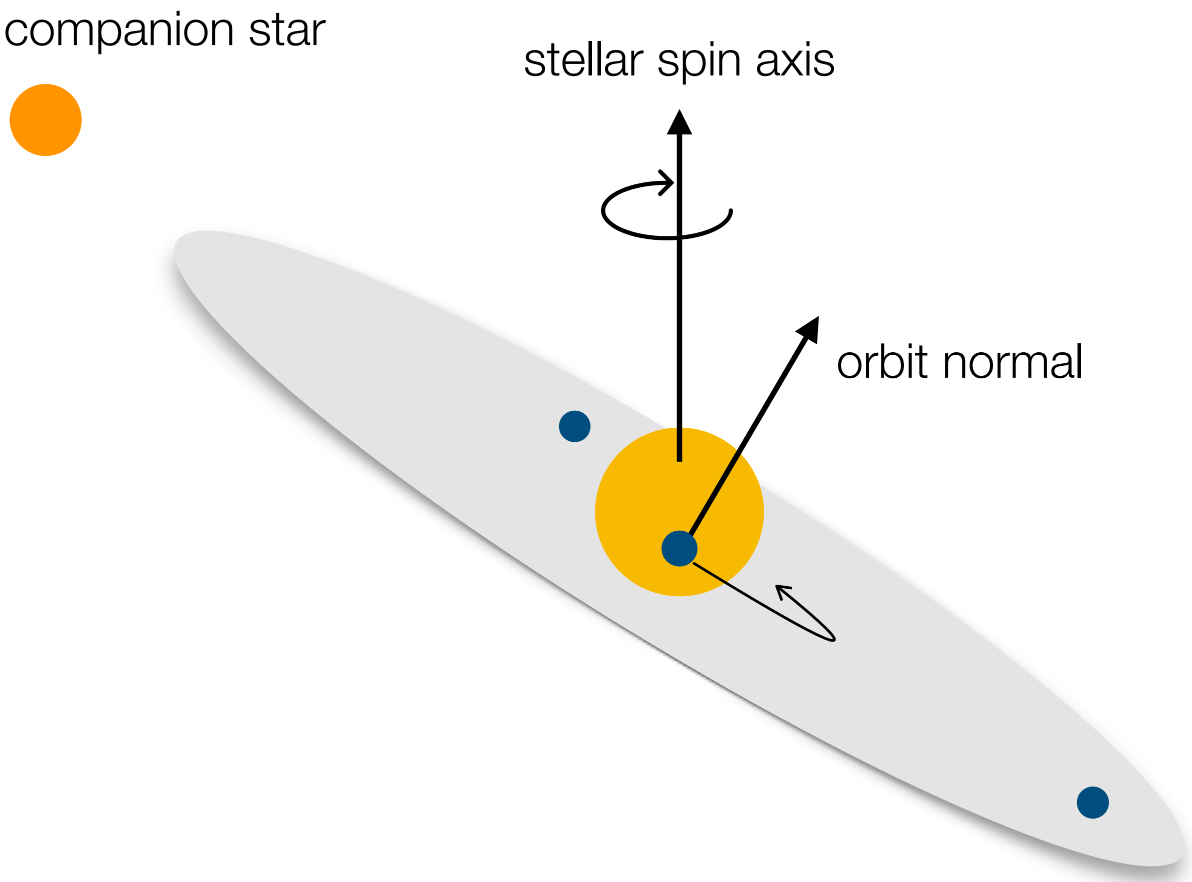
Planet	Method	Discovery	Age (Myr)	Stellar mass (Earth)	Doppler amplitude (m/s)	Orbital period (days)	Rotation period (days)	Independent confirmation	Ref.
TW Hya b*	RV	Setiawan+ 2008	8	0.7	200	3.6	3.6	X	Huélamo+ 2008
BD+20 1790 b	RV	Hernan-Obispo+ 2010, 2015	35-80	0.6	900	7.8	2.8	X	Figueira+ 2010, Carleo+ 2018
PTFO 8-8695	Transit	Van Eyken+ 2012	3	0.4	—	0.45	0.45	X	Yu+ 2015, Bouma+ 2020
Pr0201 b	RV	Quinn+ 2012	600–800	1.2	60	4.4	—	…	…
Pr0211 b	RV	Quinn+ 2012	600–800	1.0	300	2.1	—	…	…
HD 285507 b	RV	Quinn+ 2014	600–800	0.7	125	6.1	12.0	✓	Carleo+ 2020
CI Tau b*	RV	Johns-Krull+ 2016	2	0.9	1000	9.0	9.0	X	Donati+ 2020
KELT 9 b	Transit	Gaudi+ 2017	300	2.5	—	1.5	—	✓	several
V830 Tau b	RV	Donati+ 2016	2	1.0	75	4.9	2.7	X	Damasso+ 2020
TAP 26 b	RV	Yu+ 2017	17	1.0	150	10.8	0.7	…	…
AD Leo b	RV	Tuomi+ 2018	25-300	0.4	20	2.2	2.2	X	Carleo+ 2020
HIP 67522 b	Transit	Rizzuto+ 2020	17	1.2	—	7.0	1.4	…	…

* disk-bearing

Solar-type stars: while some hot Jupiters are observed by ~600-800 Myr, evidence at younger ages is mixed

High-mass stars: some hot Jupiters observed around stars as young as 300 Myr (e.g. KELT 9 b)

Origins of spin-orbit misalignments



disk torque
stellar torque
planet-star dynamics
planet-planet dynamics

Torquing of the protoplanetary disk by a distant companion or nearby star, or other gas aggregation in the birth cluster (Heller 1993, Thies et al. 2011, Batygin et al. 2011, 2020, Batygin 2012, Spalding & Batygin 2014)

Asymmetric, variable or turbulent accretion, particularly in the outer disk (Tremaine 1991, Bate et al. 2010, Fielding et al. 2015)

Magnetic star-disk interactions (Lai et al. 2011, Foucart & Lai 2011, Batygin & Adams 2013, Lai et al. 2014, Spalding & Batygin 2014, 2015)

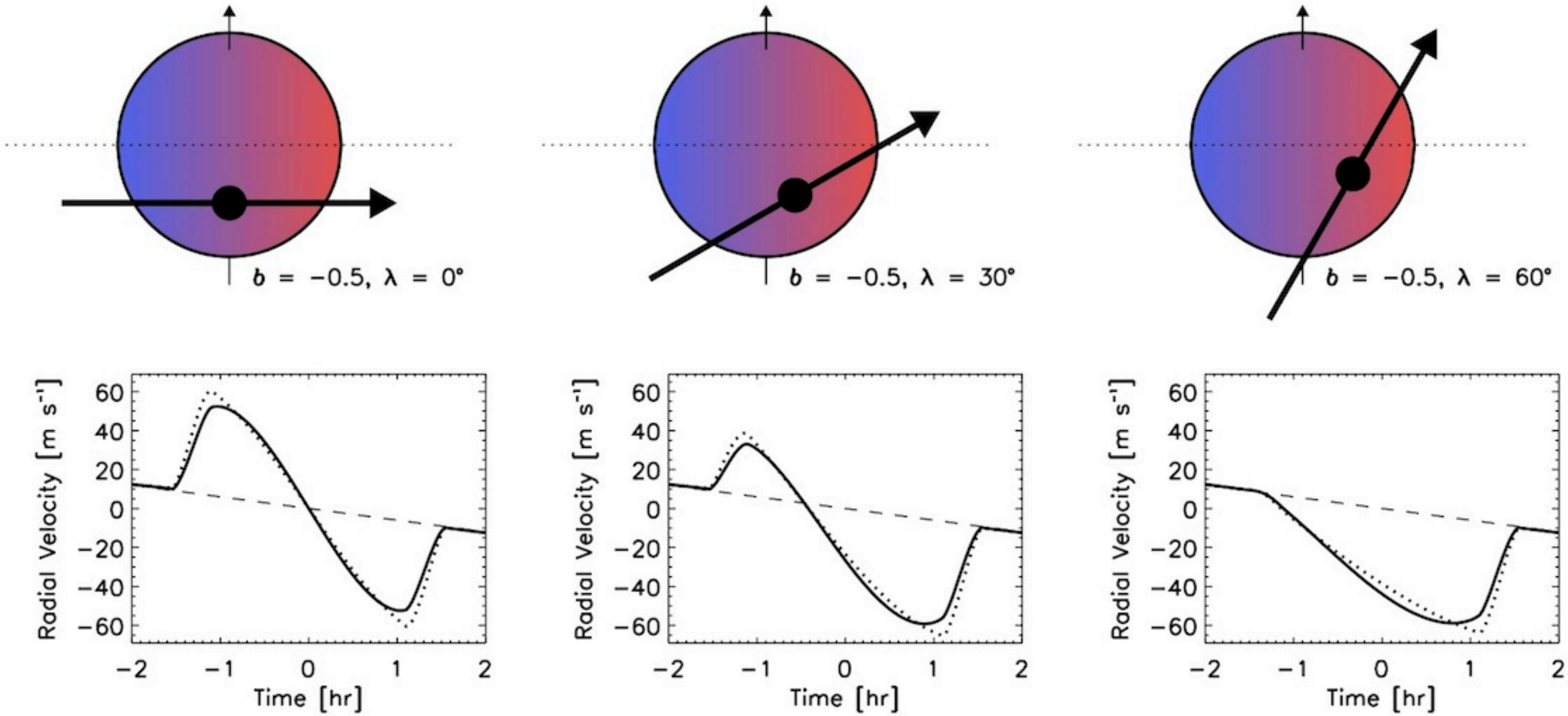
Misalignment between the stellar spin and mean stellar wind axes (Spalding 2019)

Planet-disk interactions (Millholland et al. 2019, Su & Lai 2020)

Dynamical interactions with other planets or a companion star (Fabrycky & Tremaine 2007, Wu 2007, Storch et al. 2014)

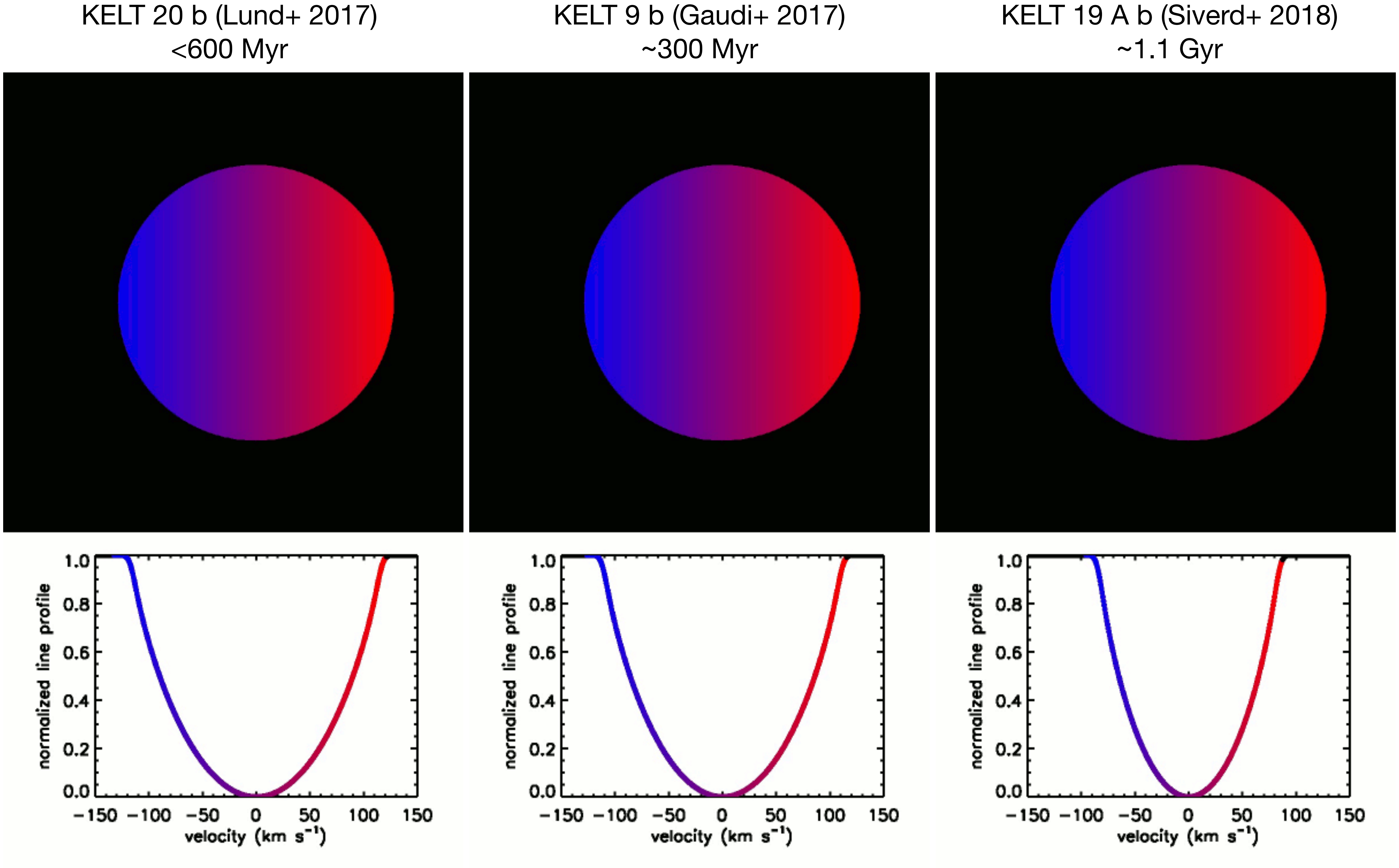
Measuring spin-orbit angles with Rossiter-McLaughlin effect

aligned **misaligned** **misaligned**



Gaudi & Winn 2017

Measuring spin-orbit angles with Doppler tomography



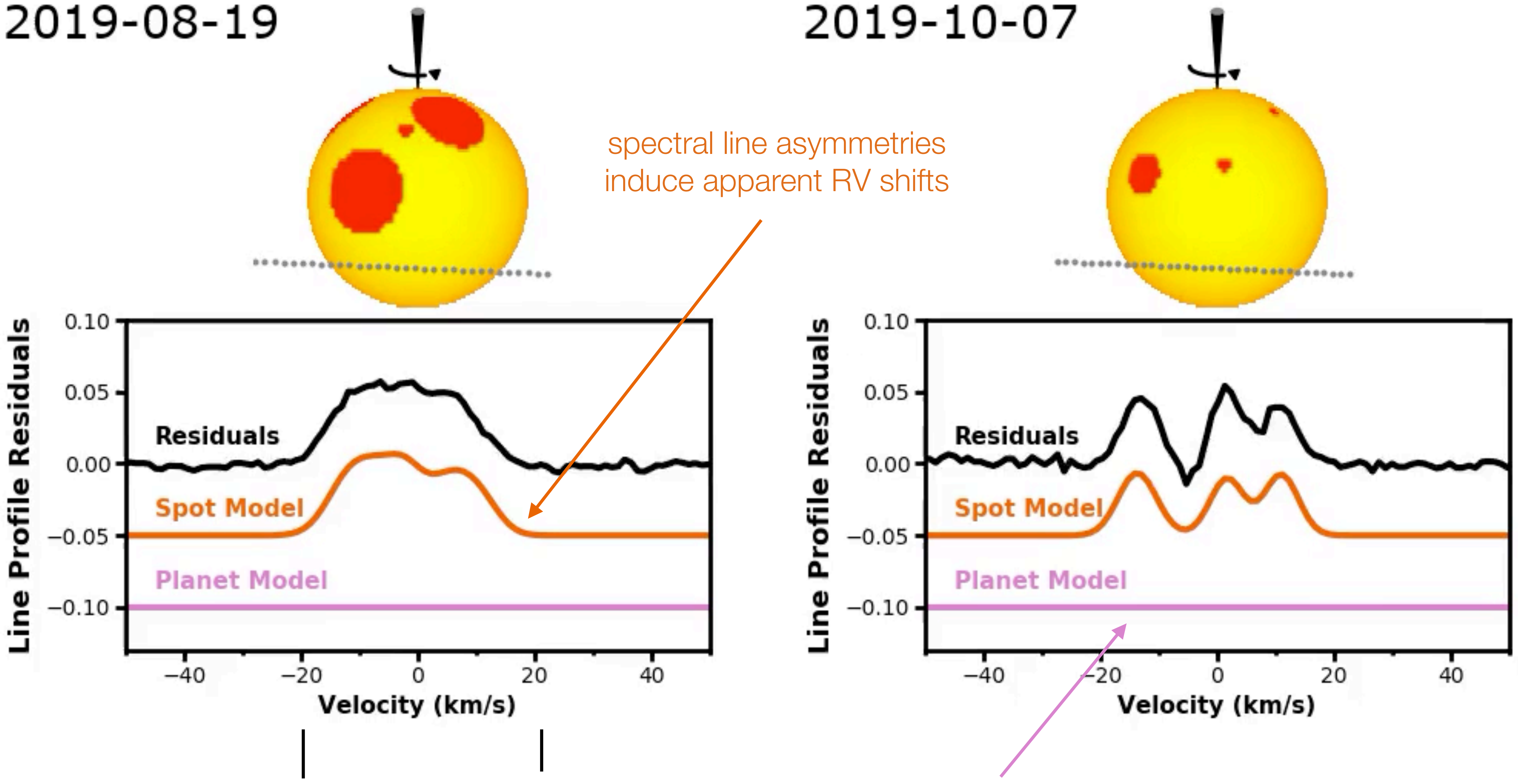
KELT 20 b (Lund+ 2017)
<600 Myr

KELT 9 b (Gaudi+ 2017)
~300 Myr

KELT 19 A b (Siverd+ 2018)
~1.1 Gyr

Doppler tomography animations by Marshall Johnson

Case study: spin-orbit alignment of DS Tuc A b



spectral line asymmetries induce apparent RV shifts

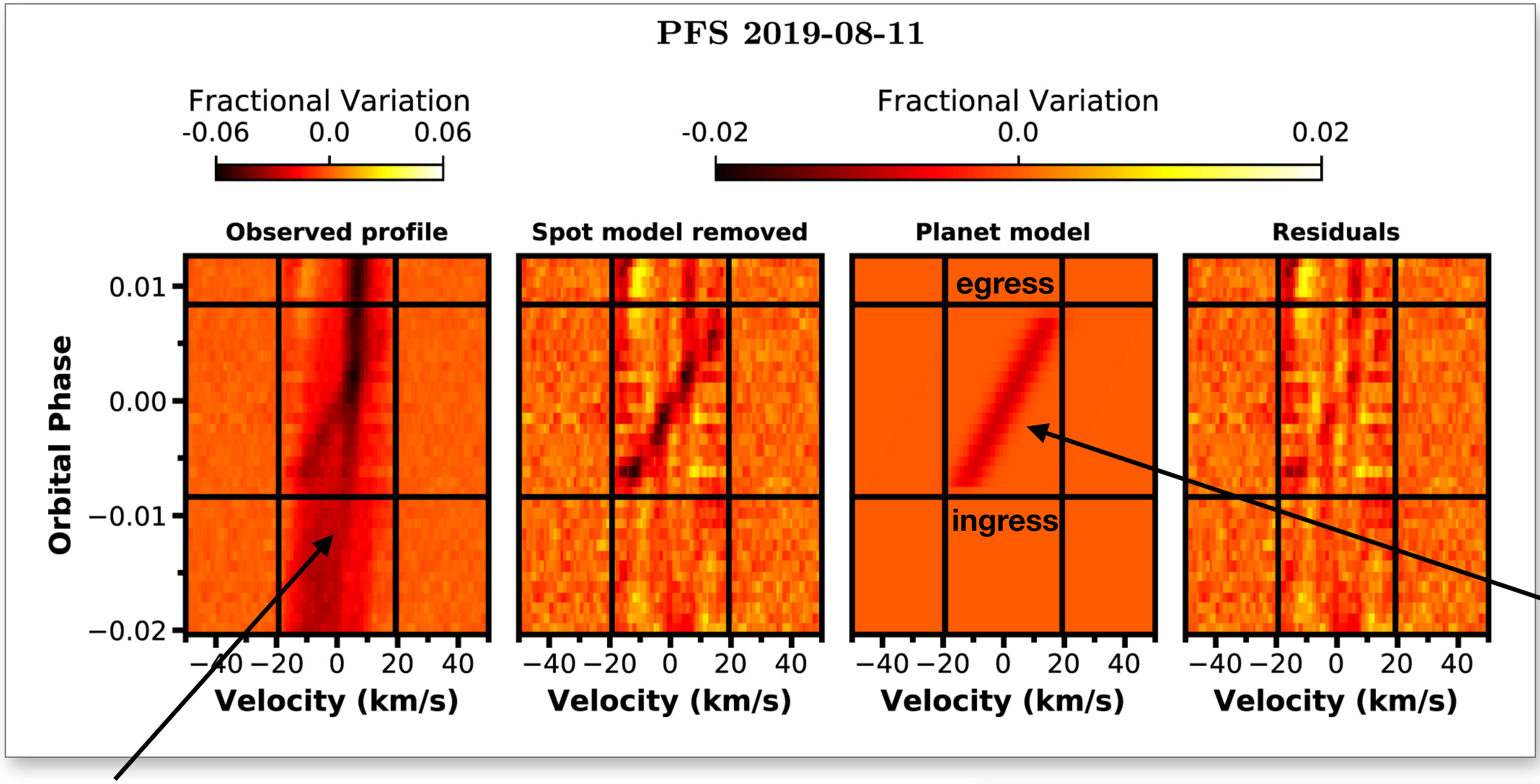
-vsin(i)

+vsin(i)

“Doppler shadow”

Zhou et al. 2020

Case study: spin-orbit alignment of DS Tuc A b



Doppler tomography / imaging

Zhou et al. 2020
λ = 2.5 ± 1 deg

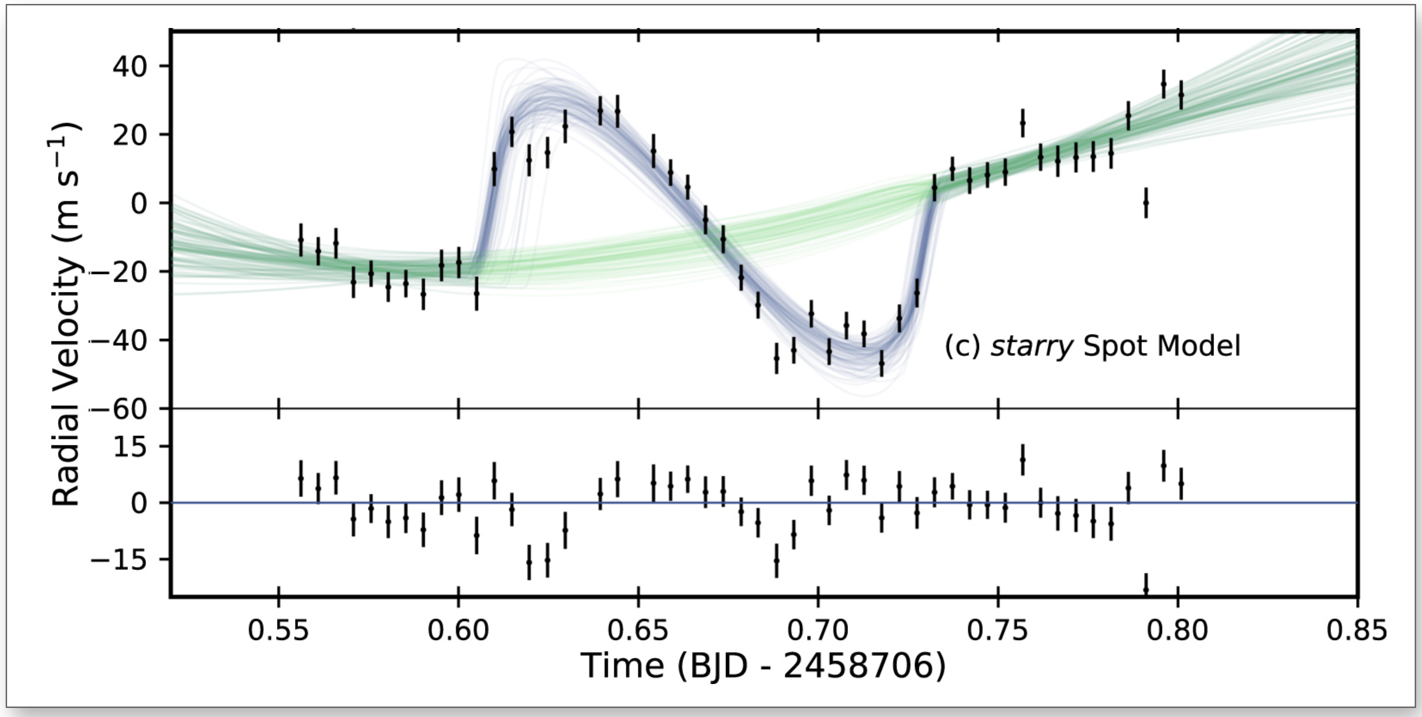
slope determines (projected) spin-orbit angle

starspots

DS Tuc A

45 Myr solar-type star with binary companion at separation of ~180 AU, aligned within 15 deg of stellar spin and planet's orbital axis (Newton+ 2019)

Montet et al. 2020
λ = 12 ± 13 deg

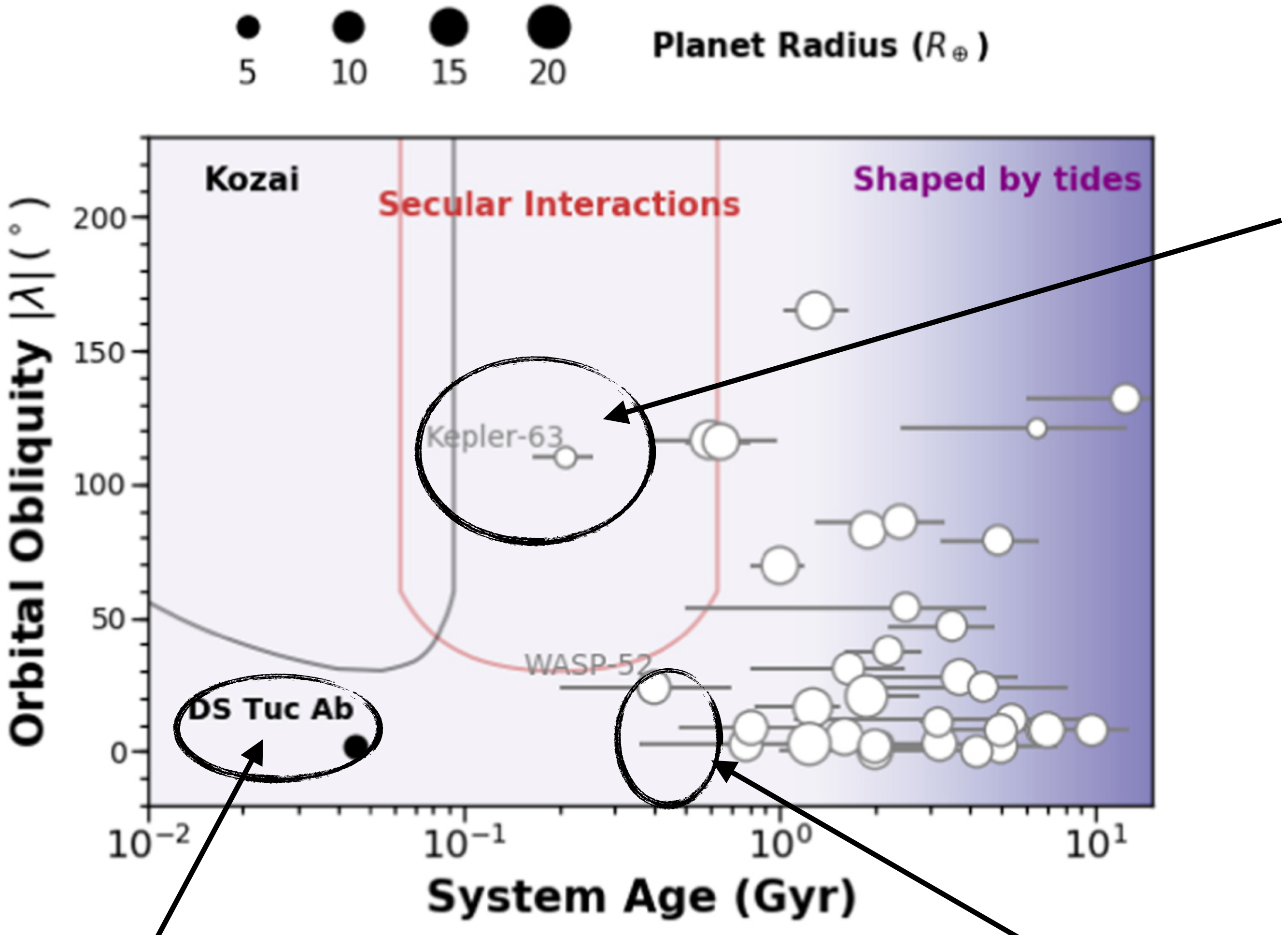


Spin-orbit alignment of young planets

Some spin-orbit misalignments are observed by ~200 Myr

At younger ages, observed planets so far appear aligned

Zhou et al. 2020

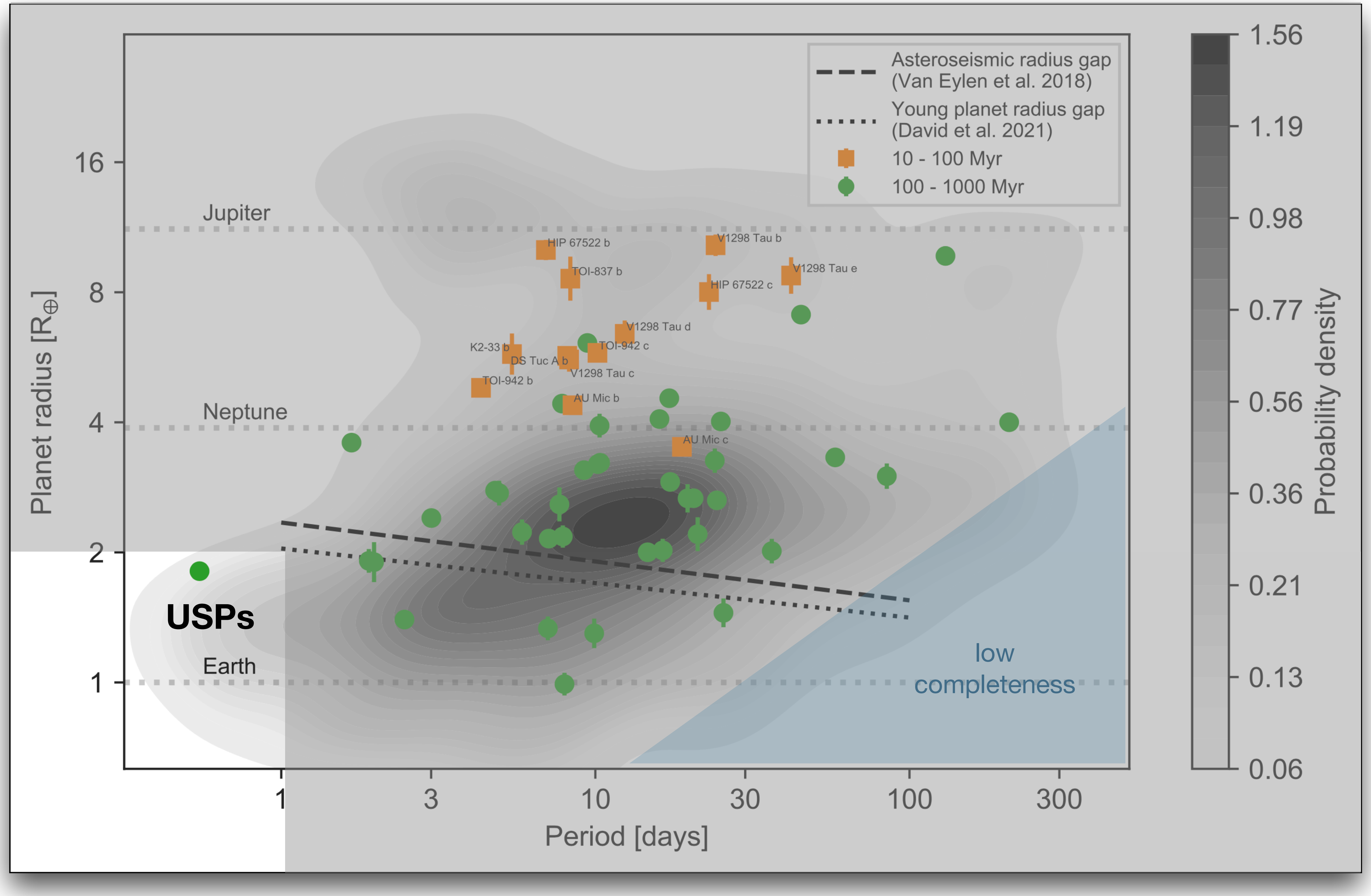


also:
KELT 9 b
(Gaudi+ 2017,
Ahlers+ 2020)

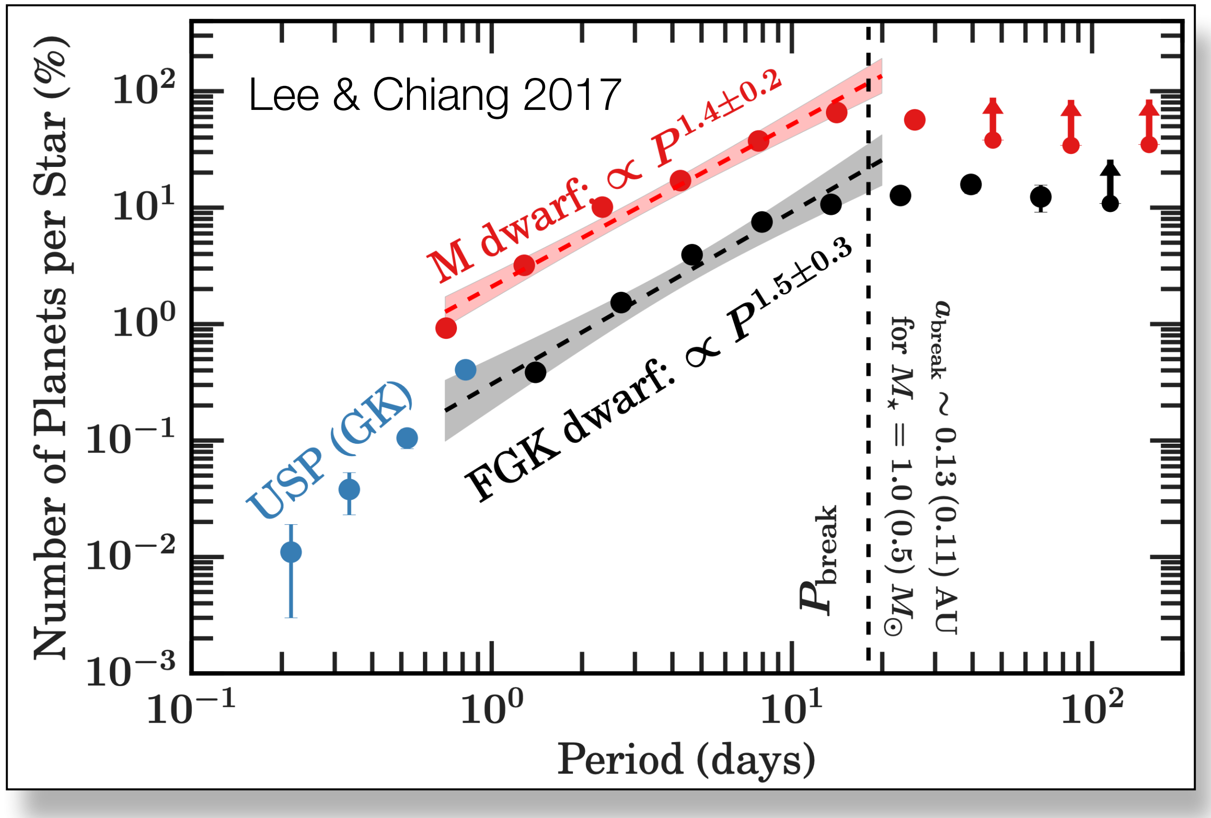
also:
V1298 Tau b (Johnson+ in prep.)
V1298 Tau c (Feinstein+ submitted)
AU Mic b (Hirano et al. 2020, Martioli et al. 2020, Palle et al. 2020, Addison et al. 2020)
TOI-942 b (Wirth+ 2021)

HD 63433 c (Mann+ 2020)

The origins of ultra-short period planets



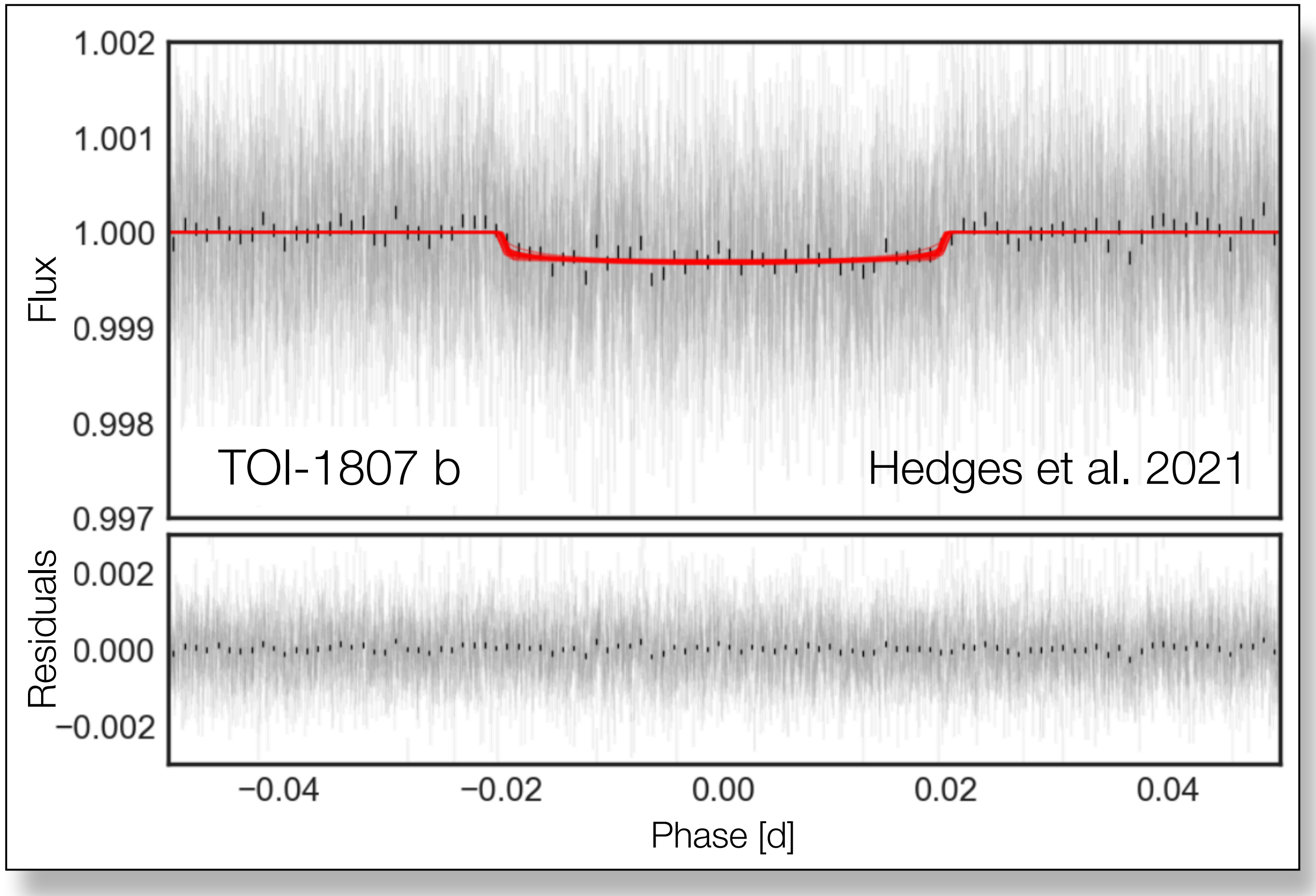
The origins of ultra-short period planets



- rare (~0.5-1% of GK-type stars)
- more common around lower-mass stars
- no strong metallicity preference
- occur in multiplanet systems
- have wide period ratios, large mutual inclinations
- smaller than $2R_\oplus$, rocky in composition
- exist interior to dust sublimation radius
- break in occurrence-period space

see: Sanchis-Ojeda+ 2014, Steffen & Coughlin 2014, Winn+ 2017, 2018, Dai+ 2018, 2019, Adams+ 2020

TOI-1807 b: an USP orbiting a ~100-200 Myr star



Galactic velocities of USP hosts also favor fast formation channel (Hamer & Schlaufman 2020)

Observations of young planets: some early conclusions

1. sizes of the youngest planets are inflated; dramatic size evolution occurs in the first ~100 Myr after disk dispersal
2. evolution of the planet size distribution, and the radius gap, continues beyond ~1 Gyr
3. atmospheric loss explains features of the close-in exoplanet population well
4. evidence for ongoing atmospheric escape in young planets has (largely) been inconclusive
5. transmission spectra of young transiting planets are, so far, featureless; dust/hazes may explain both the flat spectra and inflated radii of young planets
6. spin-orbit misalignments arise early (≳200 Myr) in some cases, but the youngest planets (<100 Myr) so far appear to be fairly aligned
7. some rocky worlds, including at least one USP, are present by ~100 Myr
8. some hot Jupiters are found around ~300–800 Myr stars, while more evidence is required for younger systems (<10 Myr)