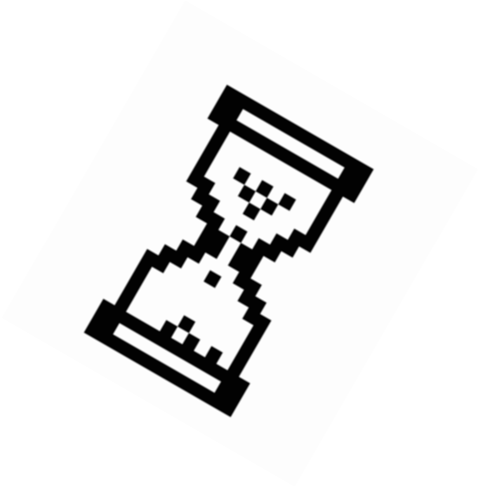
Towards measuring temporal trends in exoplanet properties and occurrence

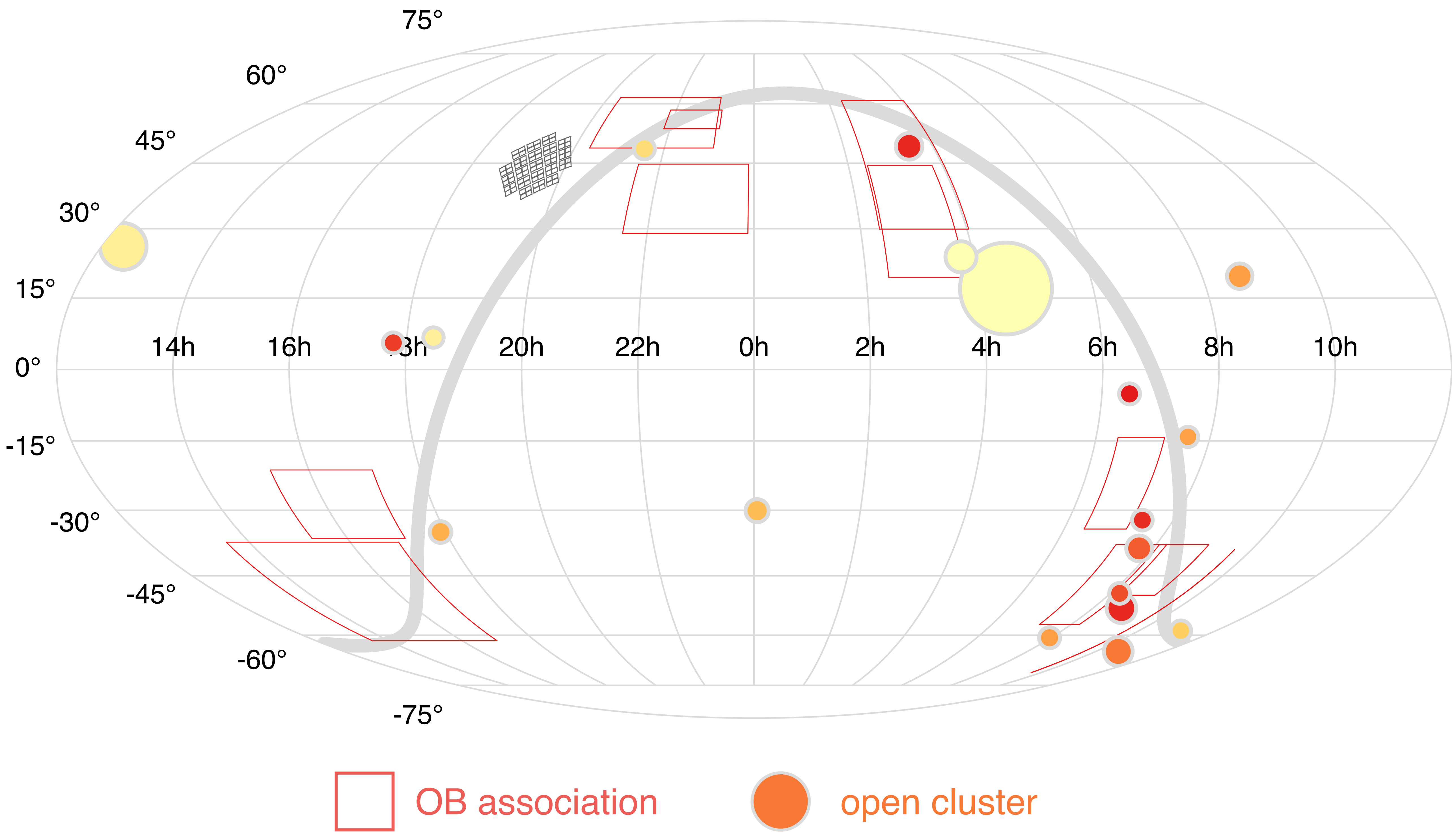


in collaboration with Eric Mamajek, Lynne Hillenbrand,
Erik Petigura, Ed Gillen, Ian Crossfield,
Andrew Howard, Howard Isaacson,
et al.

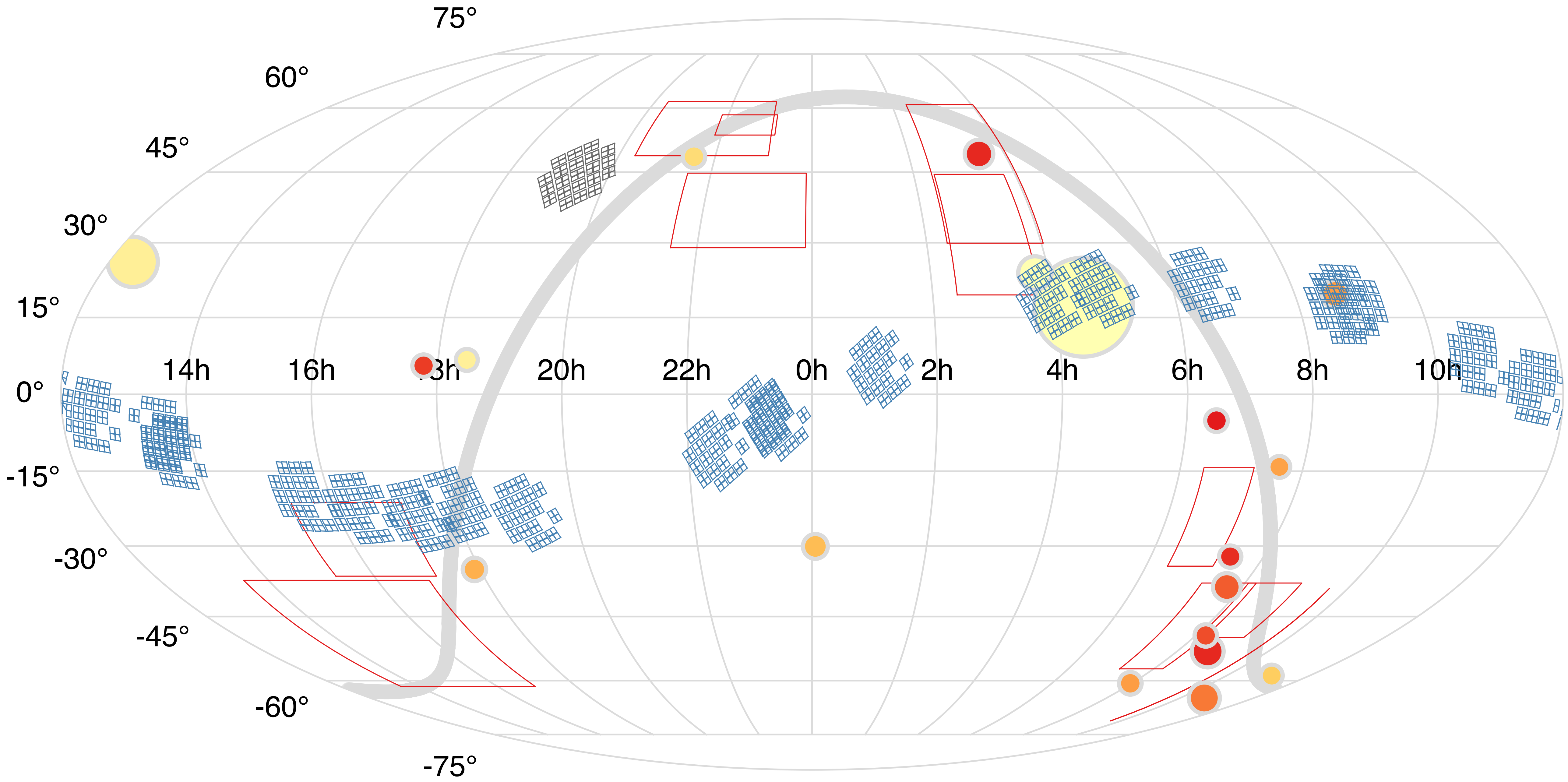
Trevor David
JPL-ESI Postdoc

Jet Propulsion Laboratory
California Institute of Technology

Young clusters as a window into exoplanet evolution

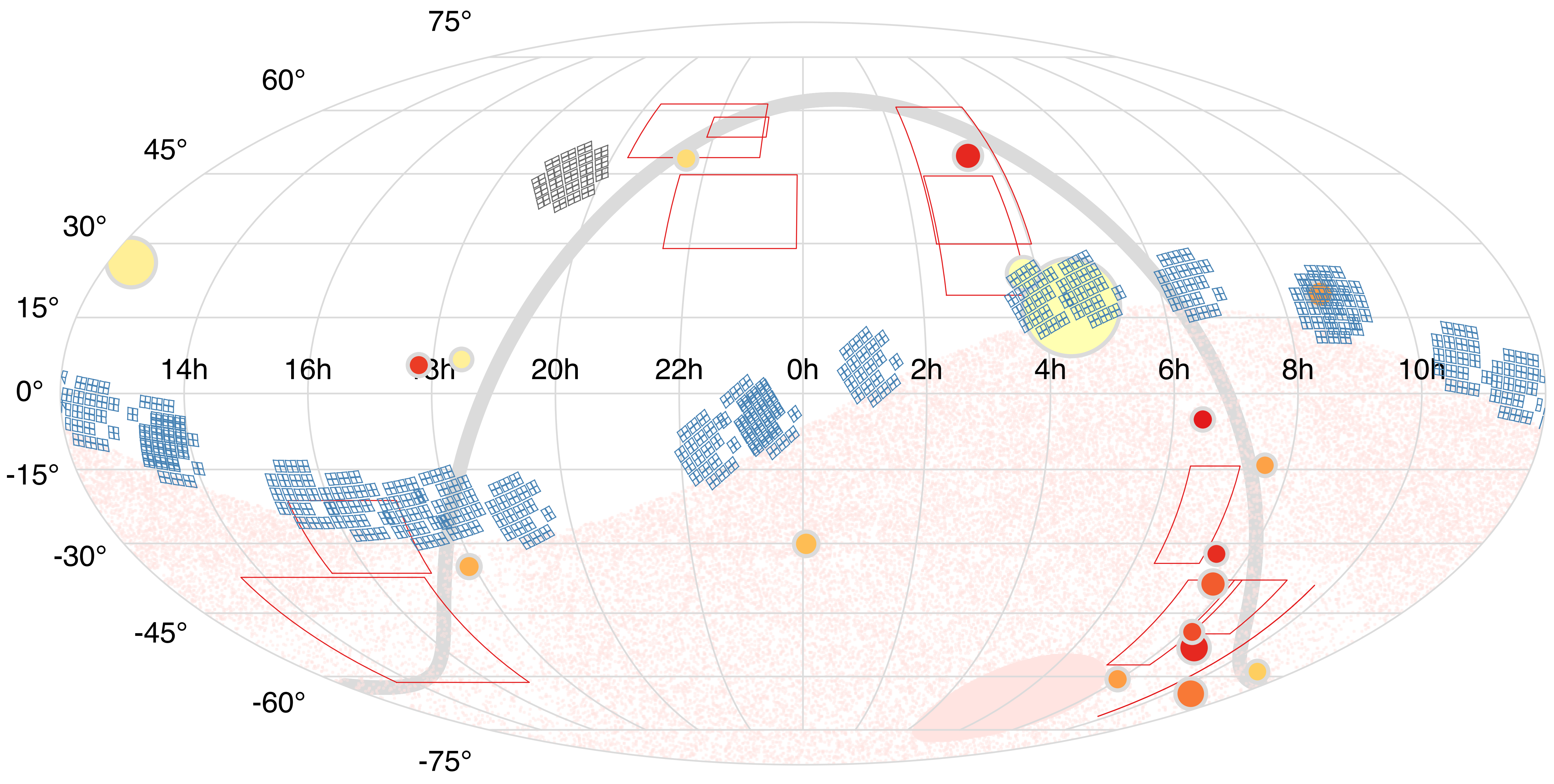


Young clusters as a window into exoplanet evolution



K2: 350,000+ stars
(~80 day baselines at 30-minute cadence)
320+ planets, 490+ candidates
few thousand young stars (1 Myr - 800 Myr)

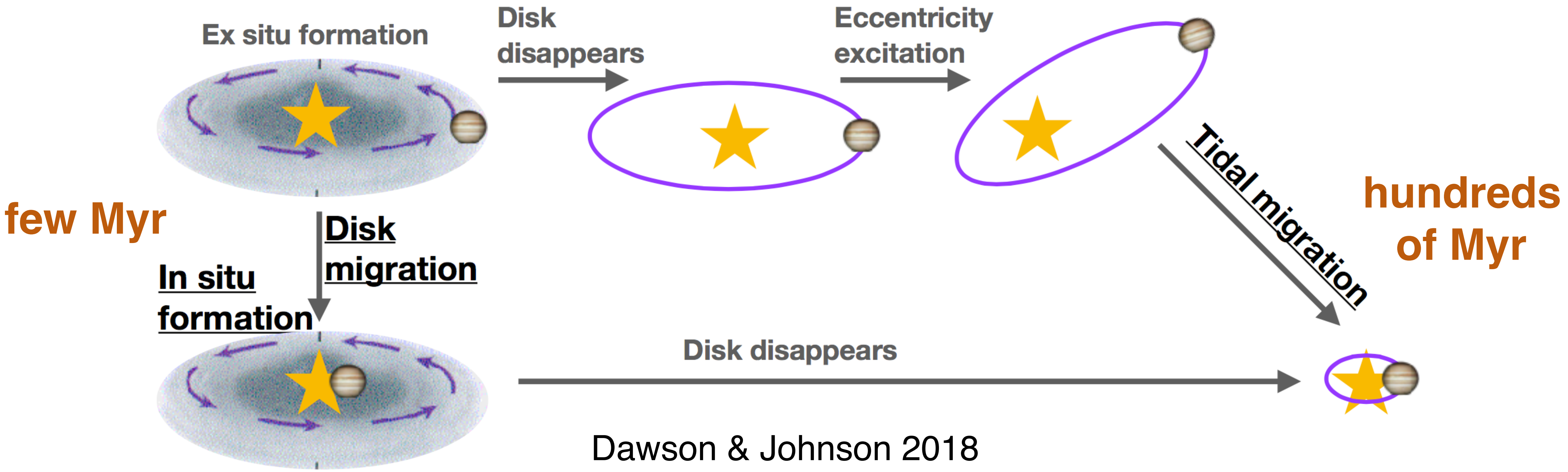
Young clusters as a window into exoplanet evolution



TESS:

Origins of close-in planets

the hot Jupiter paradigm: three possible channels

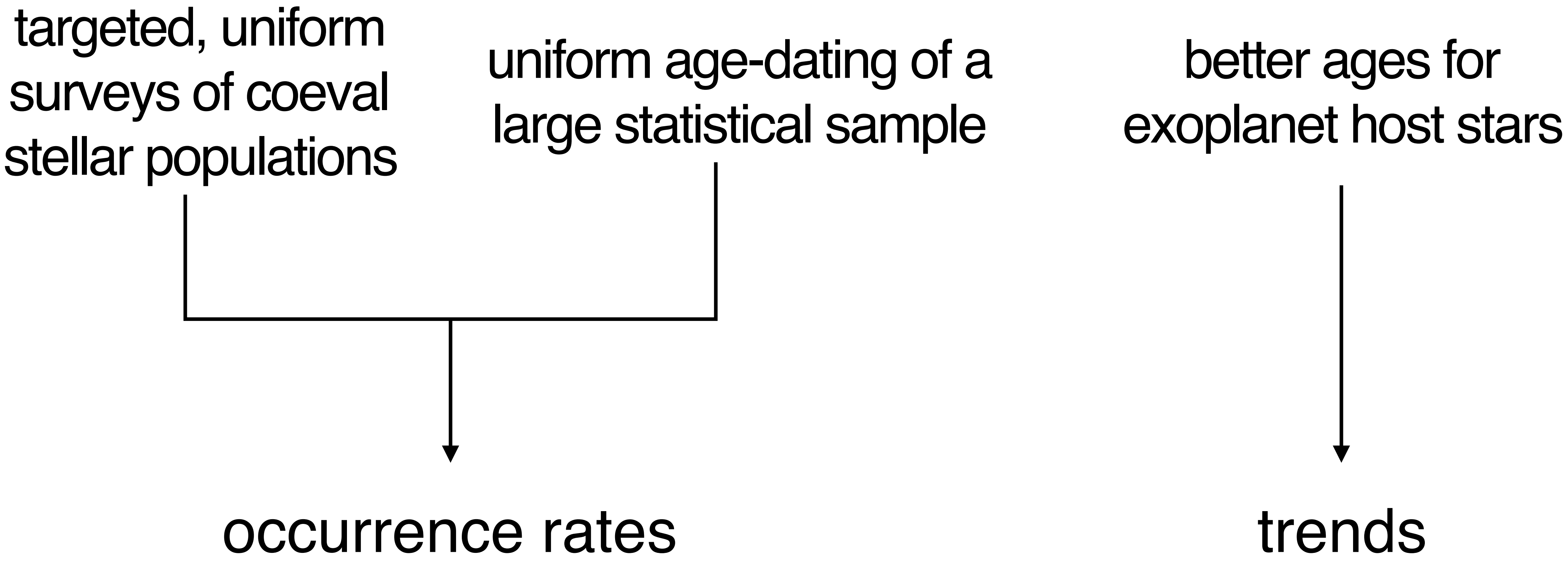


Dawson & Johnson 2018

if all hJs form through tidal migration, **then** a dearth of hJs around young stars is expected
if all hJs form *in situ* or via disk migration, **then** hJ occurrence should be flat with time

hot Neptunes share some similar characteristics to hJs
i.e. tendency to be single and preference for metal-rich stars
(Dong et al. 2018, Petigura et al. 2018)

How does one investigate exoplanet properties across time?



targeted, uniform surveys of coeval stellar populations

uniform age-dating of a large statistical sample

better ages for exoplanet host stars

occurrence rates

trends

Coeval stellar populations are diverse

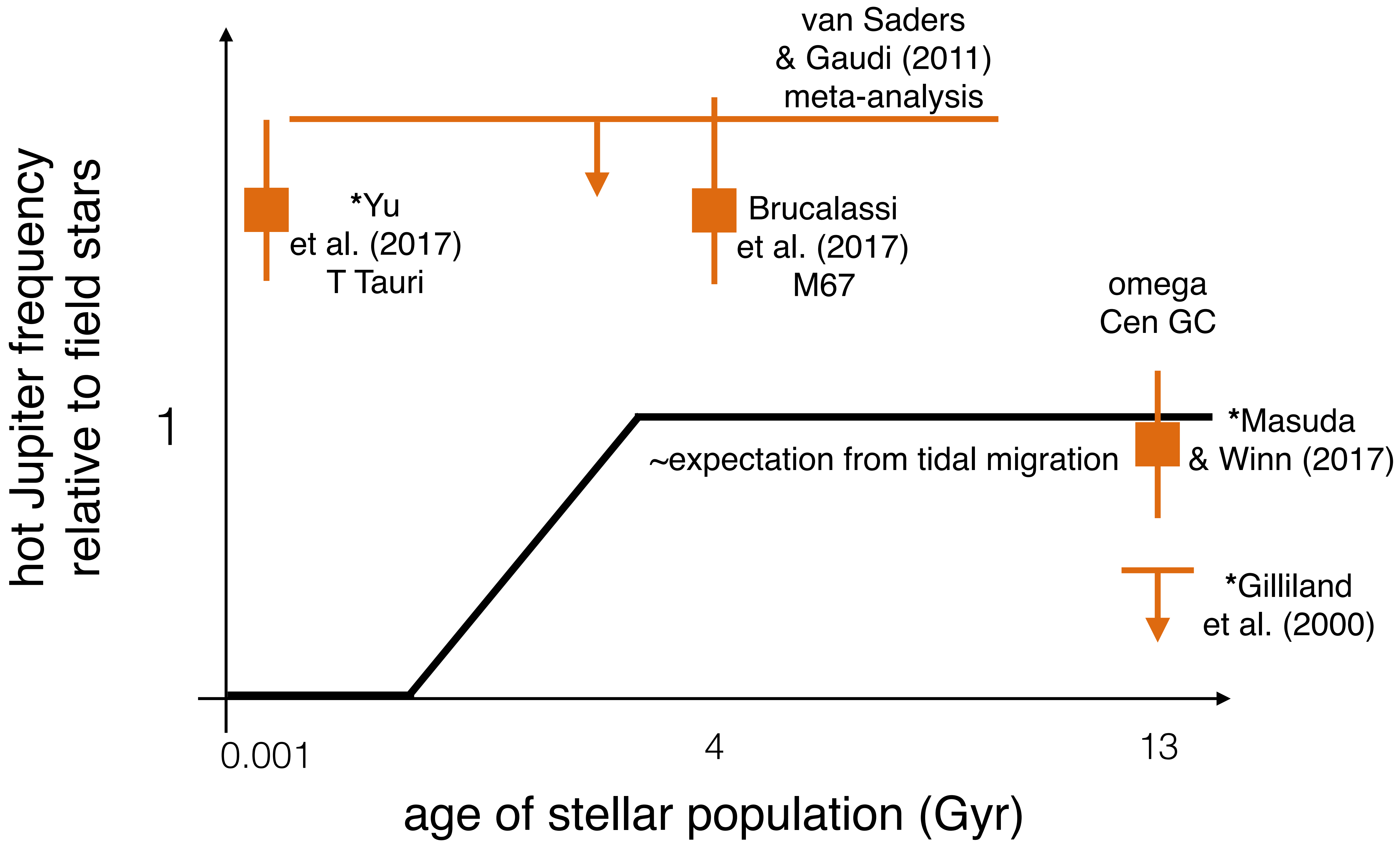
star-forming regions and OB associations
young (<10^7 yr), few nearby,
somewhat populous (10^3),
found near galactic plane,
solar metallicity,
unbound

young moving groups
young (10^7-10^8 yr),
nearby (tens of pcs), sparsely
distributed on the sky (dozens
of members), unbound

open clusters
intermediate age (10^8-10^9 yr),
somewhat populous (10^3-10^4)
some nearby, approximately
solar metallicity,
loosely bound

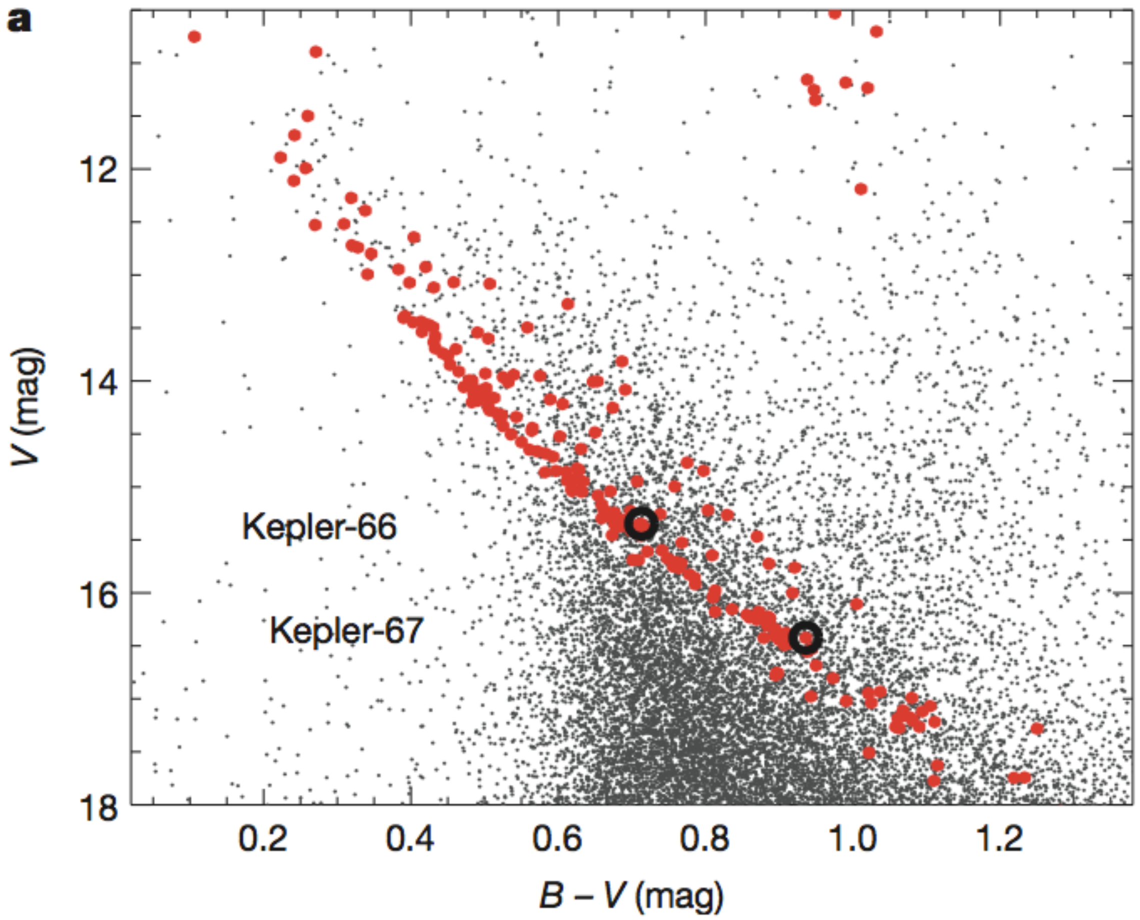
globular clusters
old (10^{10} yr),
populous (10^4-10^5),
distant (kpcs),
metal-poor, bound,
found in galactic halo,
evidence for multiple ages

A brief history of cluster planet searches: hot Jupiters



A brief history of cluster planet searches: small planets

Meibom et al. (2013)
Frequency of sub-Neptunes in a 1 Gyr old cluster is **the same** as the field
(2 planets for 377 stars surveyed)



now, with *K2*, we can study occurrence in nearer and younger clusters
Hyades/Praesepe (~600-800 Myr), Pleiades (125 Myr), Upper Sco (5-10 Myr)

Stages of planet formation observed by K2

planet occurrence as a function of time can directly
measure planet migration / evolution timescales

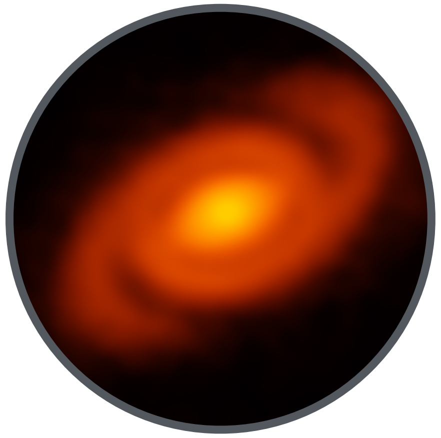
1-3 Myr — 10 Myr — 120 Myr — 600-800 Myr

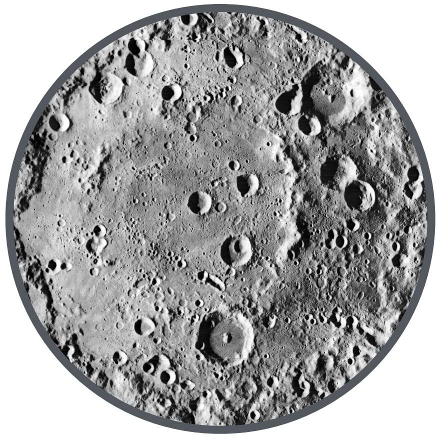
embryo formation

primordial disk dispersal

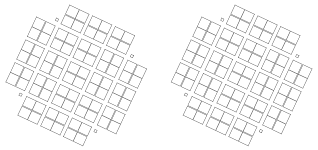
giant impacts

late heavy bombardment, dynamical migration complete?

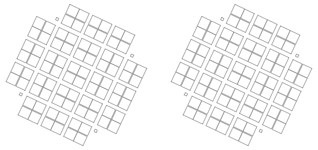




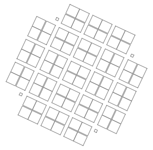
ρ Ophiuchi (C2)
Taurus (C13)



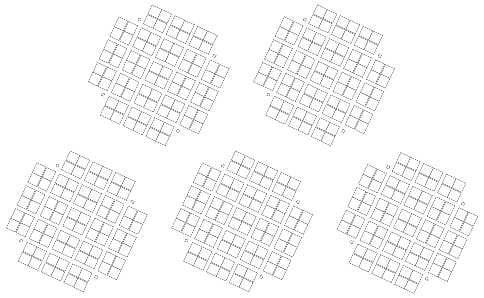
Upper Scorpius
(C2, C15)



Pleiades
(C4)

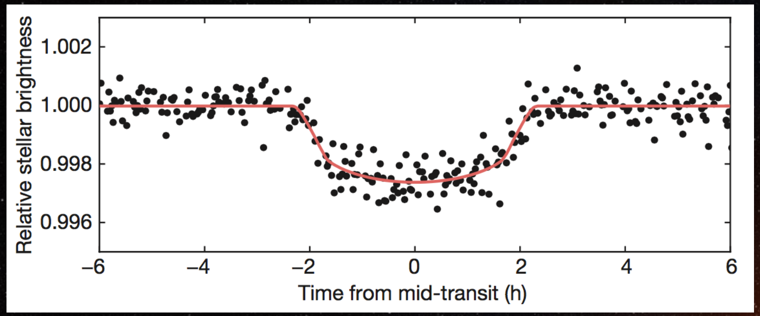


Hyades (C4, C13)
Praesepe (C5, C16, C18)

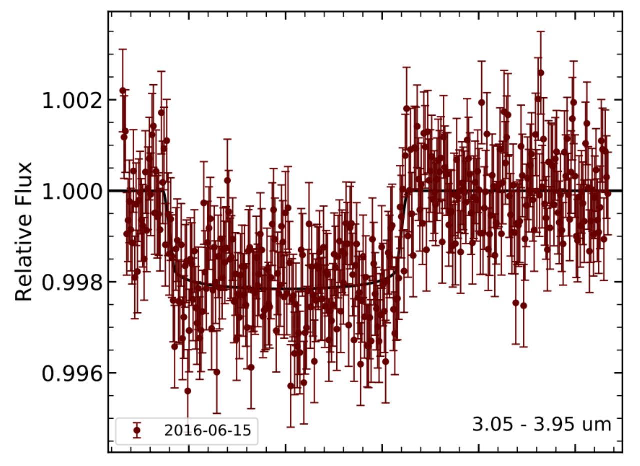


Planet count: 0 — 1 — 0 — 12

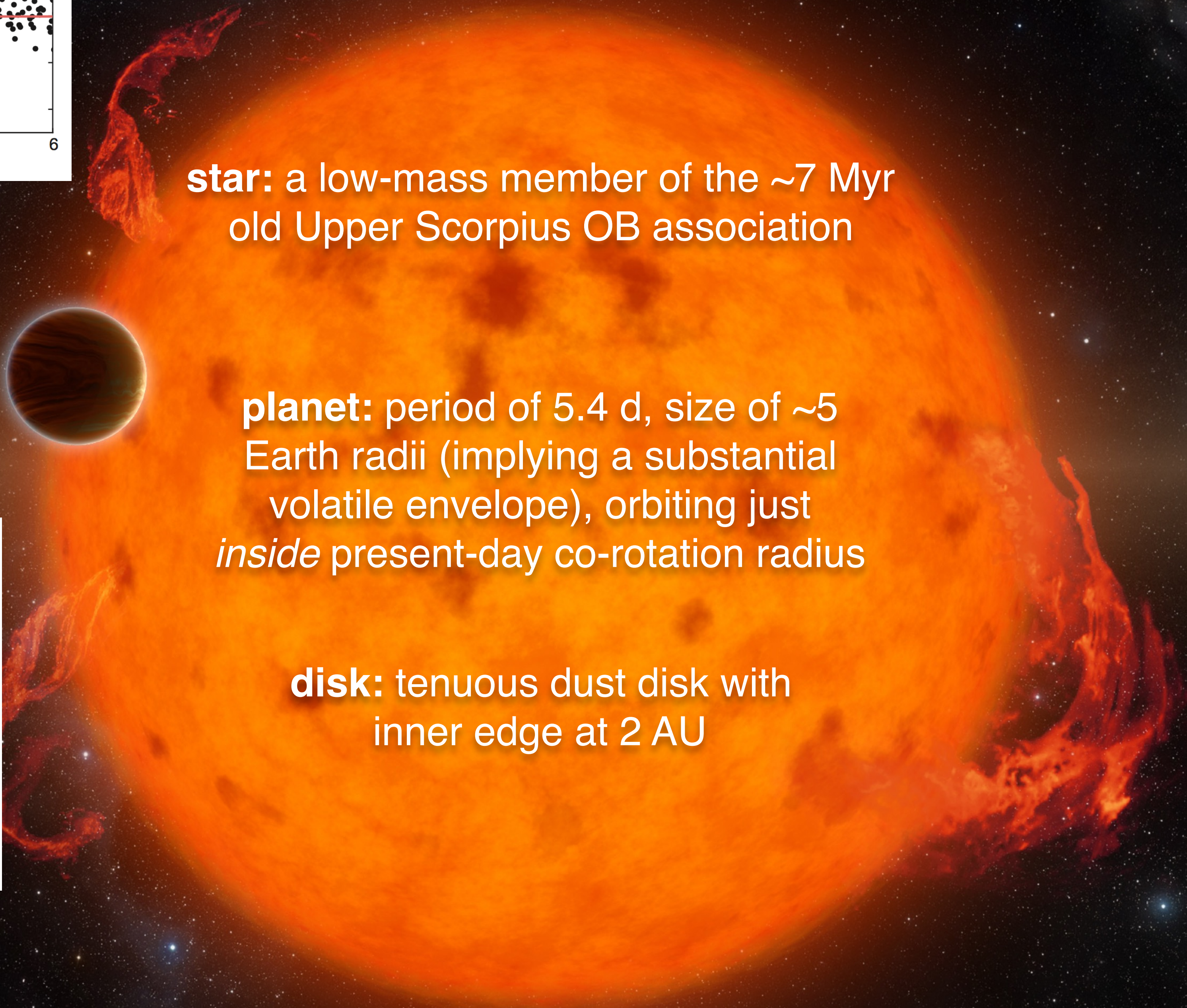
K2-33 b: extremely young and unusually large



K2
David, Hillenbrand, Petigura
et al. (2016)
(see also Mann et al. 2016)



Spitzer
Benneke, David, Petigura
et al. (*in prep.*)



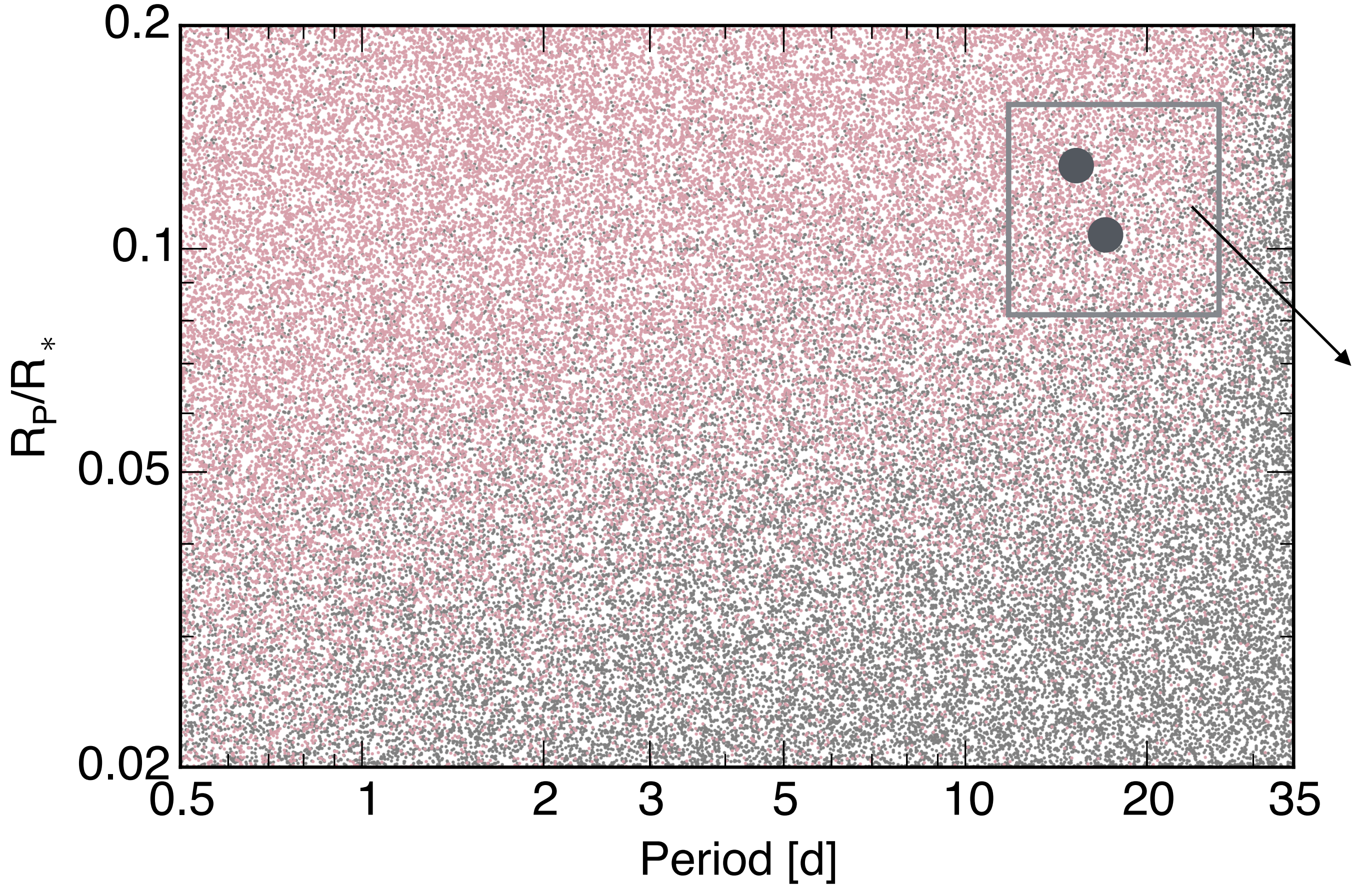
star: a low-mass member of the ~7 Myr old Upper Scorpius OB association

planet: period of 5.4 d, size of ~5 Earth radii (implying a substantial volatile envelope), orbiting just *inside* present-day co-rotation radius

disk: tenuous dust disk with inner edge at 2 AU

Image credit: Robert Hurt,
NASA/JPL-Caltech

Planet occurrence in a transit survey



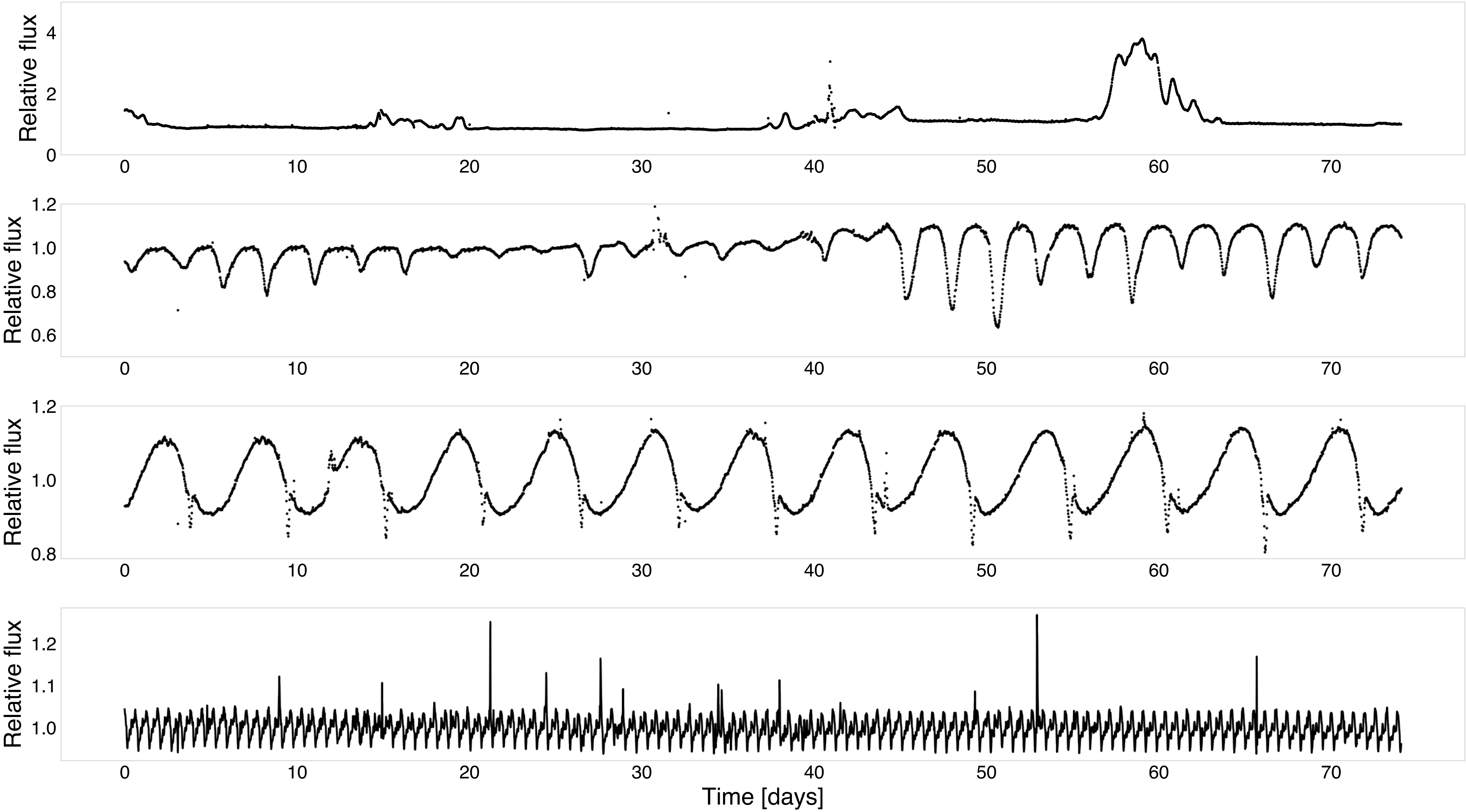
geometric correction

$$f_{\rm cell} = \sum_{j=1}^{n_{\rm pl,cell}} \frac{(a/R_*)_j}{n_{*,j} C_j}$$

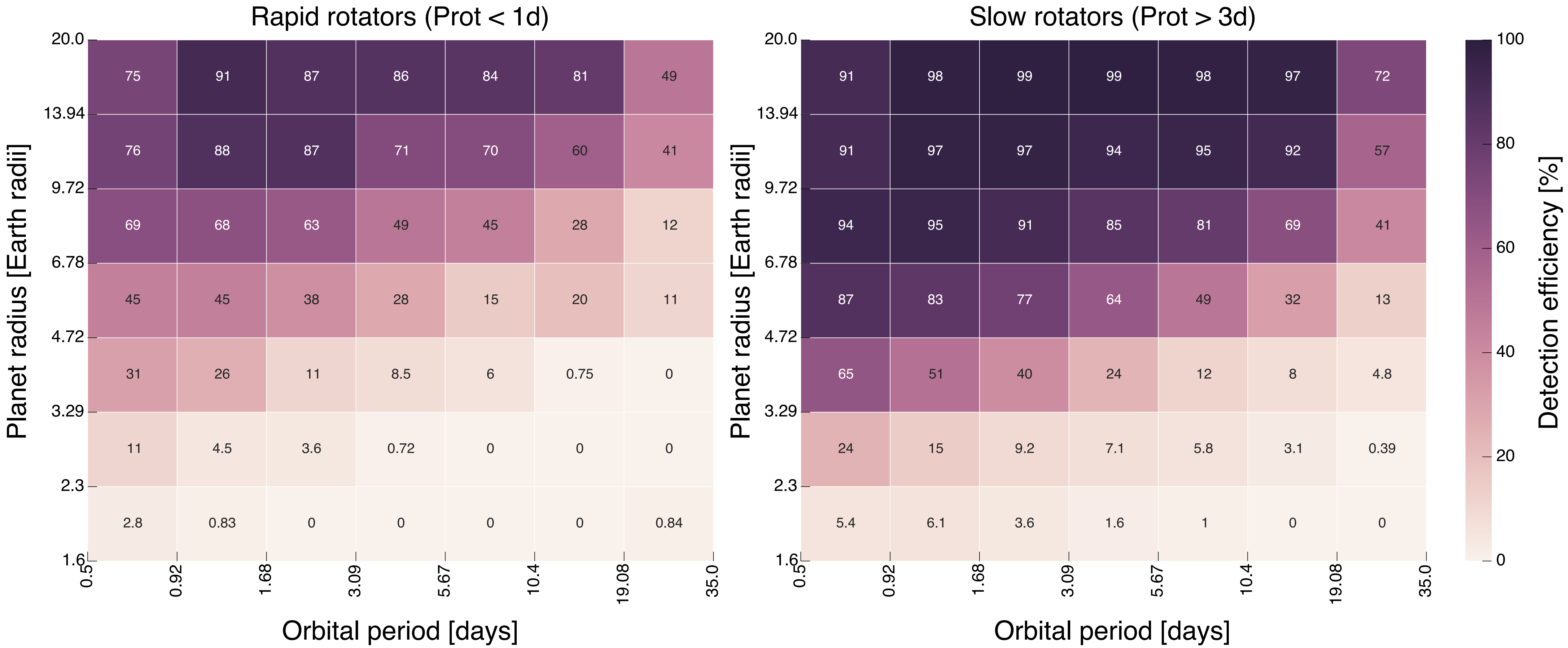
completeness correction

1) stellar radii for young stars are more uncertain
2) number of stars is limited by the cluster mass (and those of which show unocculted photospheres)
3) completeness maps can vary substantially from star-to-star

Variability of young stars



Effects of stellar activity on transit searches



Rapid rotators (Prot < 1d)

Planet radius [Earth radii] \ Orbital period [days]	0.5–0.92	0.92–1.68	1.68–3.09	3.09–5.67	5.67–10.4	10.4–19.08	19.08–35.0
13.94–20.0	75	91	87	86	84	81	49
9.72–13.94	76	88	87	71	70	60	41
6.78–9.72	69	68	63	49	45	28	12
4.72–6.78	45	45	38	28	15	20	11
3.29–4.72	31	26	11	8.5	6	0.75	0
2.3–3.29	11	4.5	3.6	0.72	0	0	0
1.6–2.3	2.8	0.83	0	0	0	0	0.84

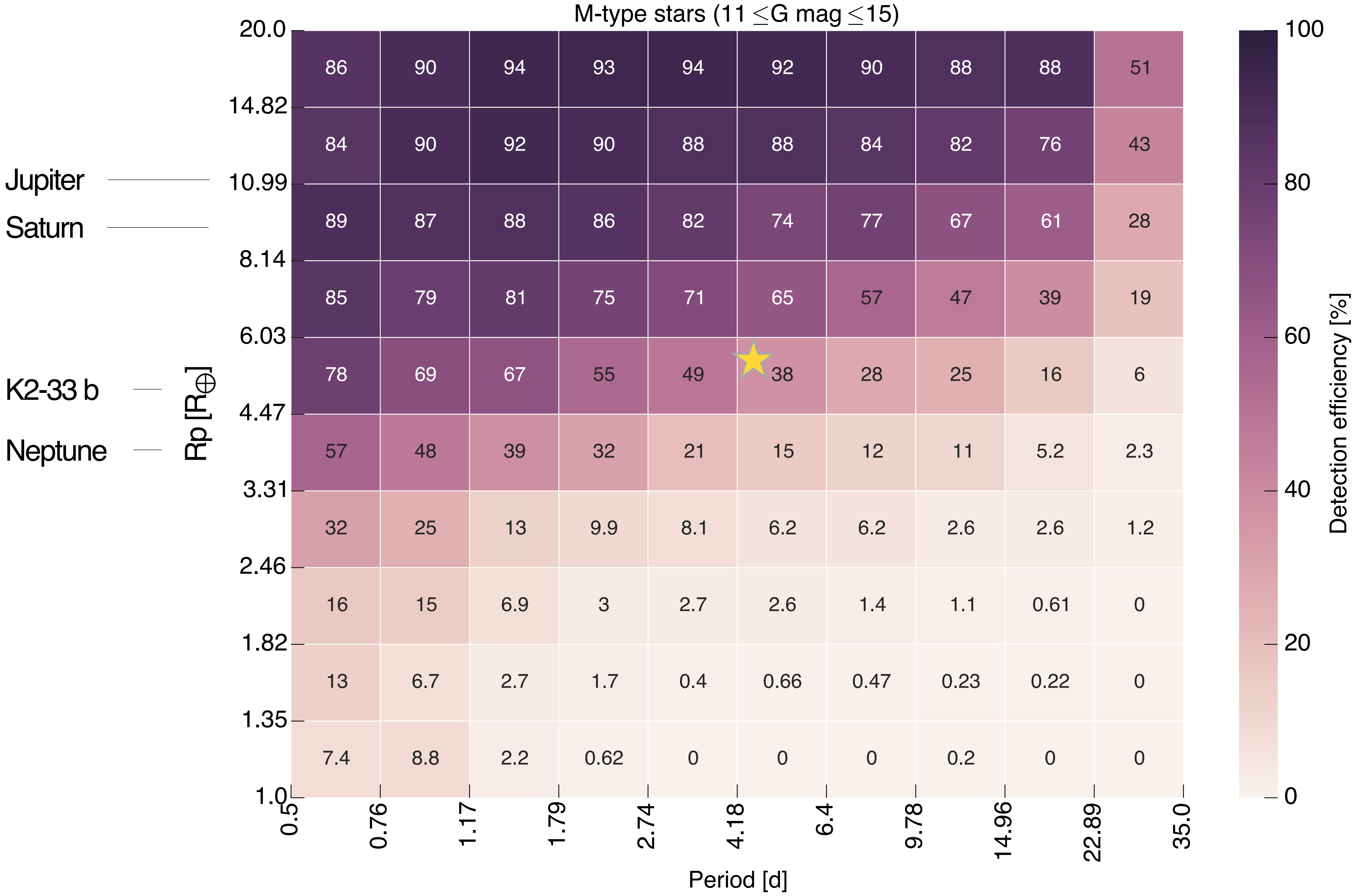
Slow rotators (Prot > 3d)

Planet radius [Earth radii] \ Orbital period [days]	0.5–0.92	0.92–1.68	1.68–3.09	3.09–5.67	5.67–10.4	10.4–19.08	19.08–35.0
13.94–20.0	91	98	99	99	98	97	72
9.72–13.94	91	97	97	94	95	92	57
6.78–9.72	94	95	91	85	81	69	41
4.72–6.78	87	83	77	64	49	32	13
3.29–4.72	65	51	40	24	12	8	4.8
2.3–3.29	24	15	9.2	7.1	5.8	3.1	0.39
1.6–2.3	5.4	6.1	3.6	1.6	1	0	0

survey completeness is a function of brightness, rotation period, activity amplitude
(all of which have some mass dependence)

*very preliminary

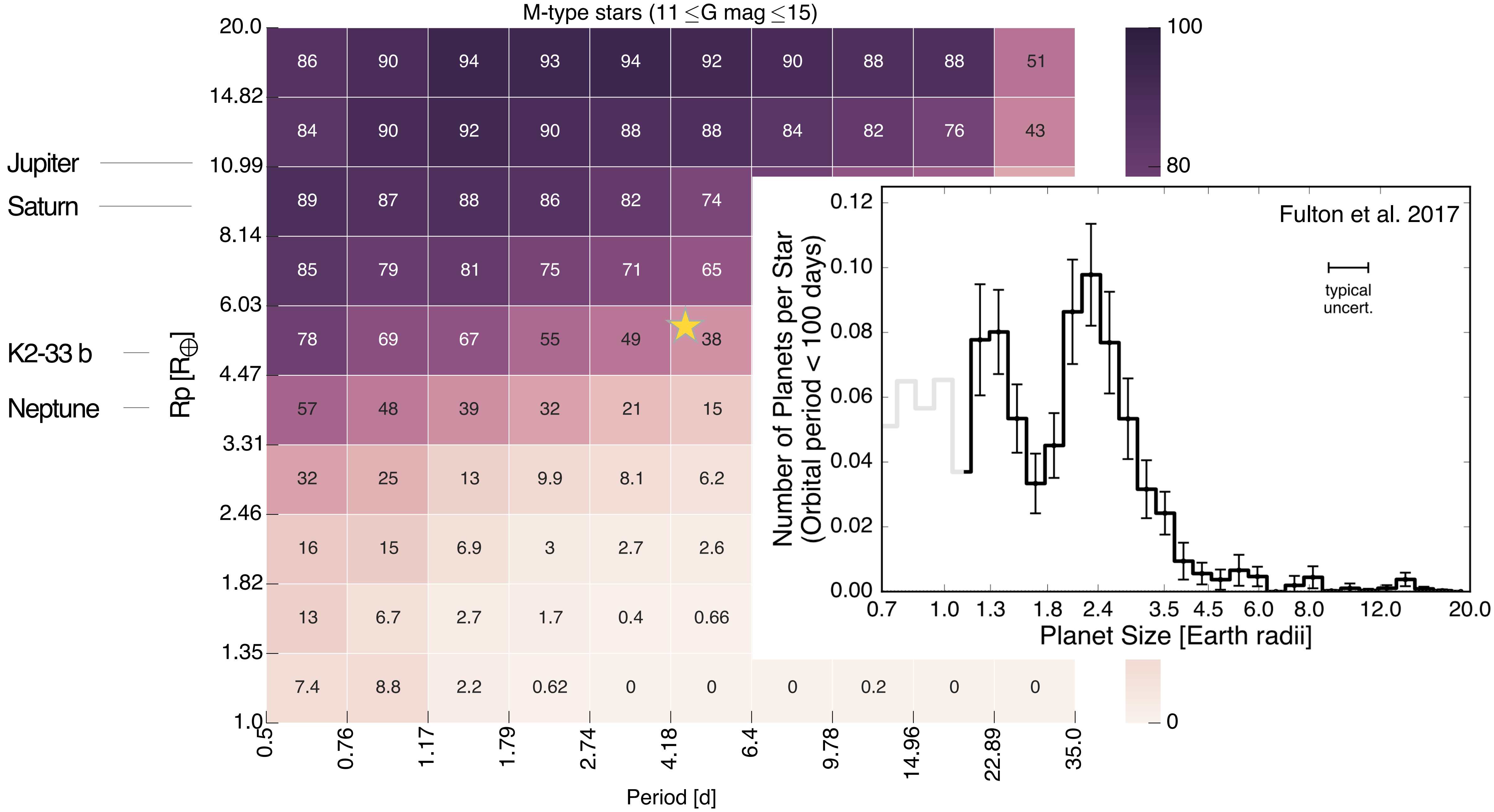
Completeness for young low-mass stars



Rp [R⊕] \ Period [d]	0.5–0.76	0.76–1.17	1.17–1.79	1.79–2.74	2.74–4.18	4.18–6.4	6.4–9.78	9.78–14.96	14.96–22.89	22.89–35.0
14.82–20.0	86	90	94	93	94	92	90	88	88	51
10.99–14.82	84	90	92	90	88	88	84	82	76	43
8.14–10.99	89	87	88	86	82	74	77	67	61	28
6.03–8.14	85	79	81	75	71	65	57	47	39	19
4.47–6.03	78	69	67	55	49	38	28	25	16	6
3.31–4.47	57	48	39	32	21	15	12	11	5.2	2.3
2.46–3.31	32	25	13	9.9	8.1	6.2	6.2	2.6	2.6	1.2
1.82–2.46	16	15	6.9	3	2.7	2.6	1.4	1.1	0.61	0
1.35–1.82	13	6.7	2.7	1.7	0.4	0.66	0.47	0.23	0.22	0
1.0–1.35	7.4	8.8	2.2	0.62	0	0	0	0.2	0	0

200 injections per star, 564 M-type stars, recovery = SNR > 7.5 (c.f. K2-33, SNR = 11.3)
*very preliminary

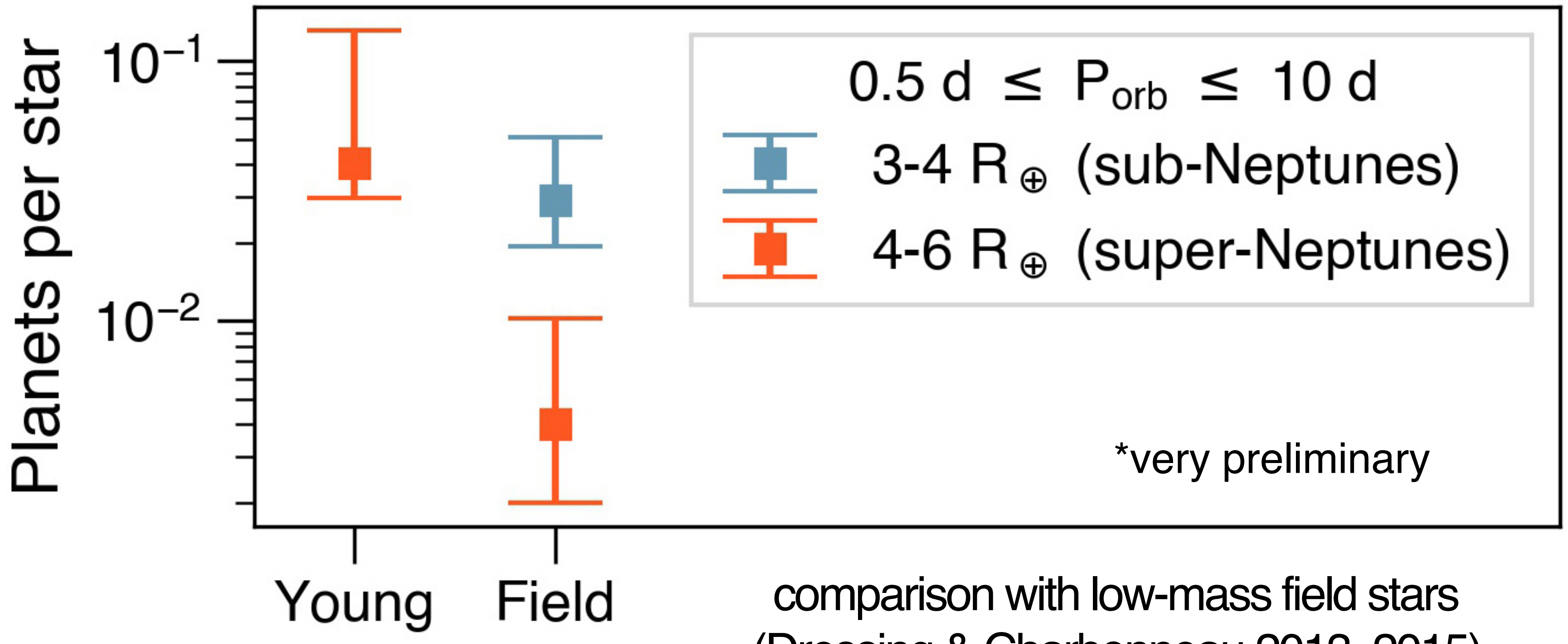
Completeness for young low-mass stars



Rp [R⊕] \ Period [d]	0.5–0.76	0.76–1.17	1.17–1.79	1.79–2.74	2.74–4.18	4.18–6.4	6.4–9.78	9.78–14.96	14.96–22.89	22.89–35.0
14.82–20.0	86	90	94	93	94	92	90	88	88	51
10.99–14.82	84	90	92	90	88	88	84	82	76	43
8.14–10.99	89	87	88	86	82	74				
6.03–8.14	85	79	81	75	71	65				
4.47–6.03	78	69	67	55	49	38				
3.31–4.47	57	48	39	32	21	15				
2.46–3.31	32	25	13	9.9	8.1	6.2				
1.82–2.46	16	15	6.9	3	2.7	2.6				
1.35–1.82	13	6.7	2.7	1.7	0.4	0.66				
1.0–1.35	7.4	8.8	2.2	0.62	0	0	0	0.2	0	0

200 injections per star, 564 M-type stars, recovery = SNR > 7.5 (c.f. K2-33, SNR = 11.3)
*very preliminary

What do occurrence rates tell you if radius and age are correlated?

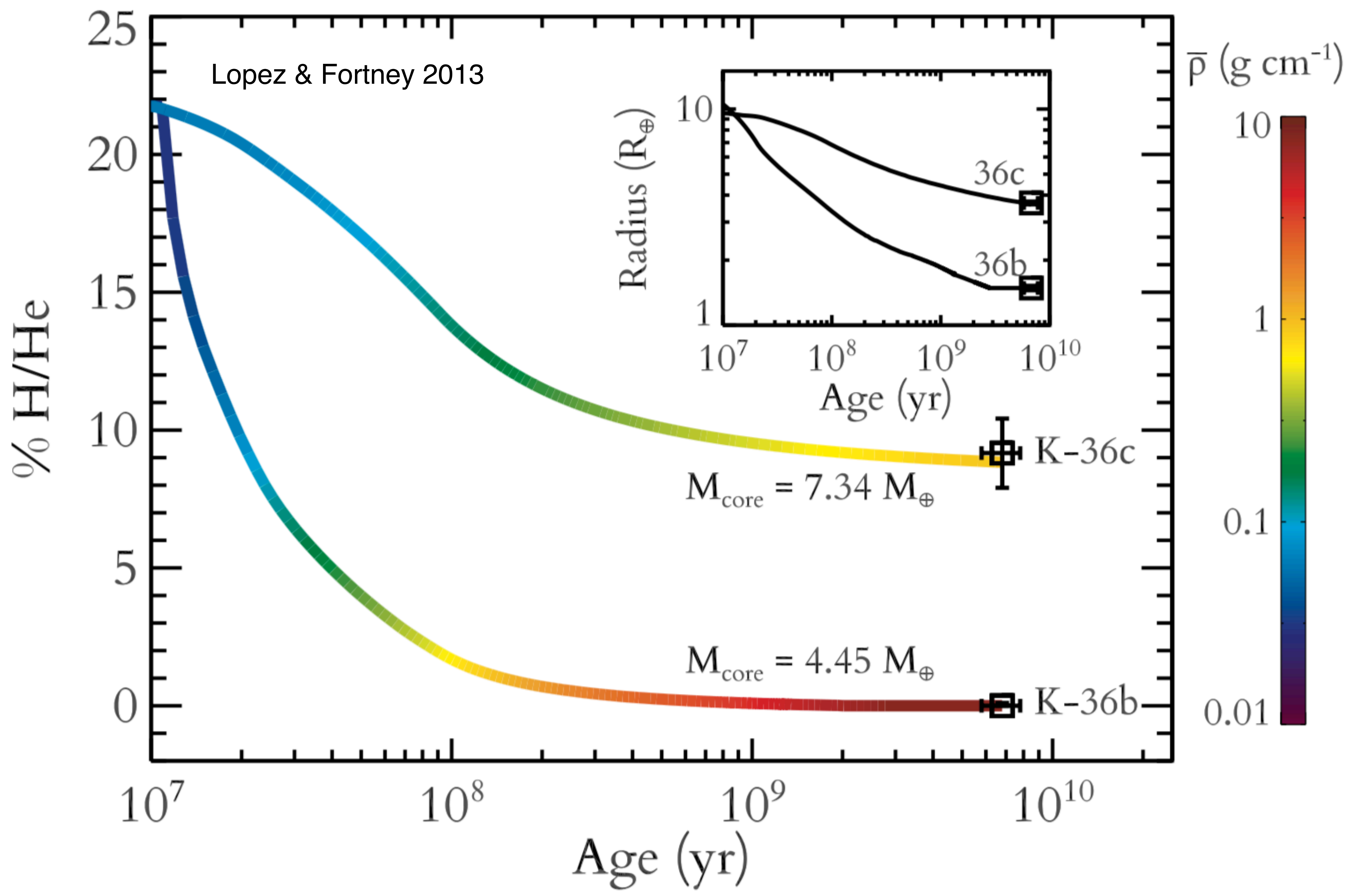


comparison with low-mass field stars
(Dressing & Charbonneau 2013, 2015)

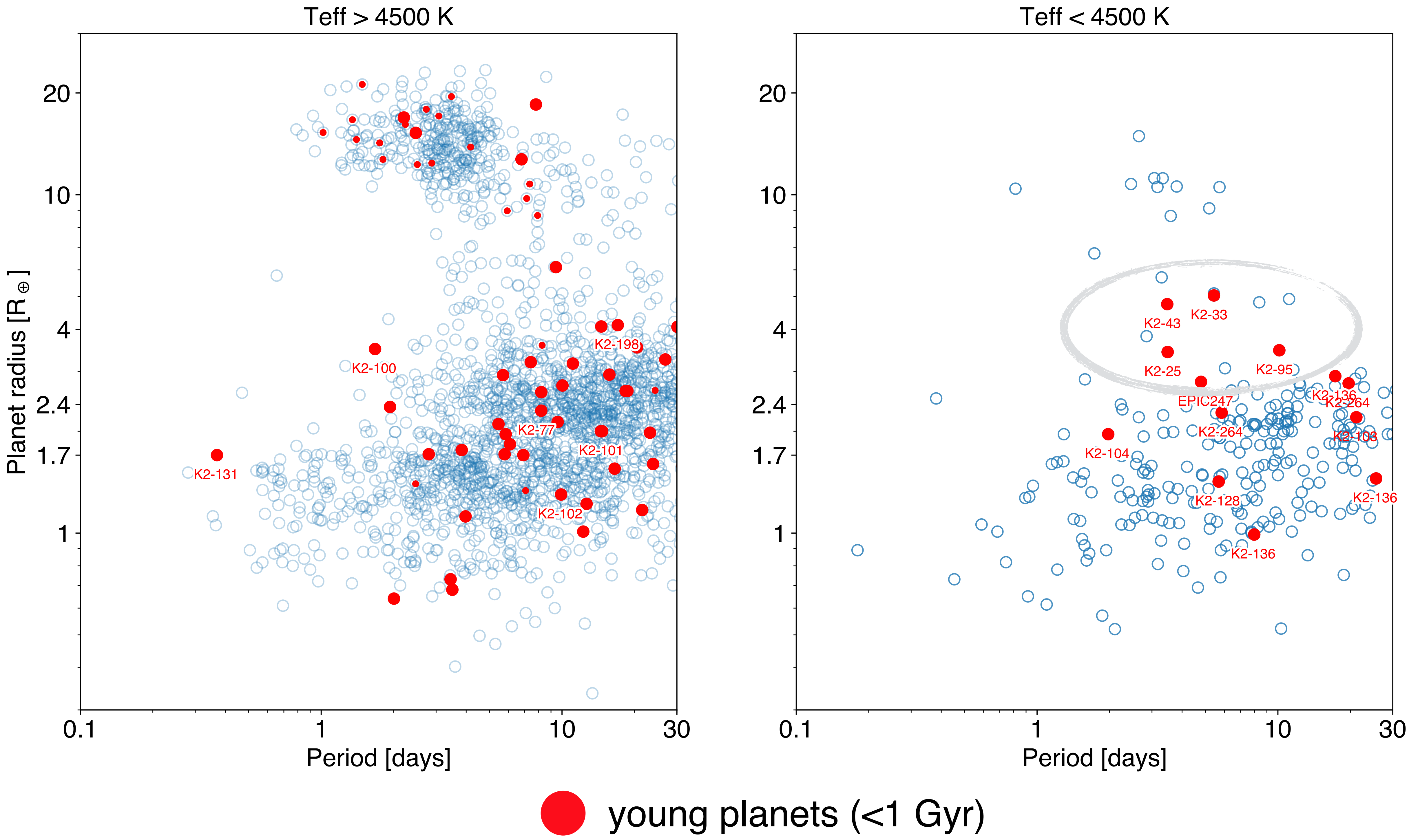
1) perhaps we were lucky and caught a sub-Saturn shortly after its formation (e.g. a GJ 436 progenitor)
2) perhaps K2-33 b will experience significant radial contraction, and is a sub-Neptune progenitor
3) in any event, there *does not* appear to be a large population of ~10 $R_\oplus$ planets

measuring the mass will require infrared PRVs, where stellar jitter is lower:
PARVI @ Palomar in 2019

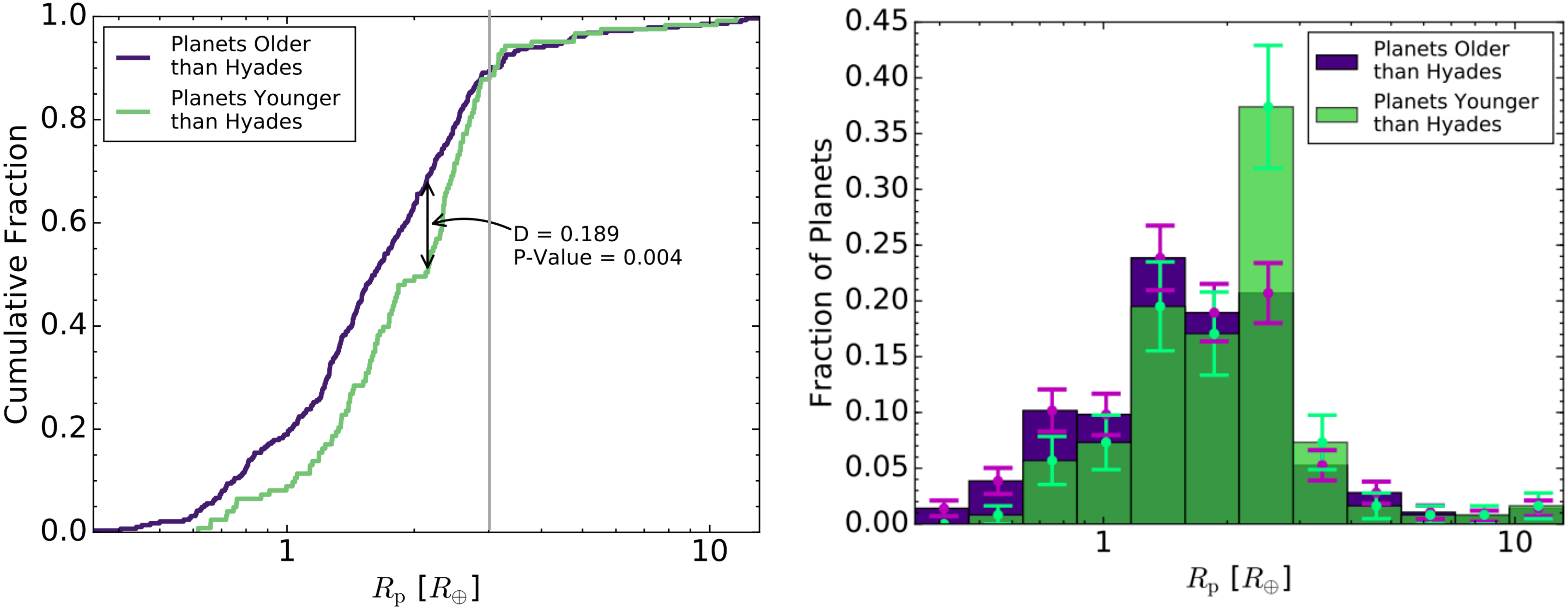
Photo-evaporation and the evolution of small planets



Evidence for radius inflation at young ages?



Evidence for radius inflation at young ages?



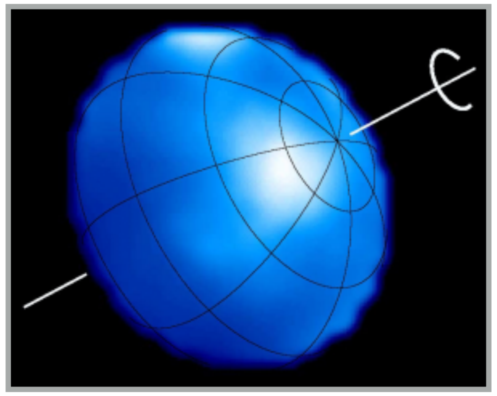
960 *Kepler* planet hosts, youth determined from lithium abundance
Berger, Howard, and Boesgaard (2018)

The radii of young stars

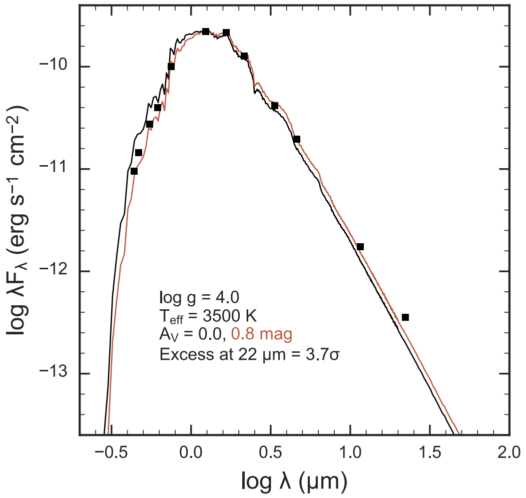
The mass-radius relation of young stars

a key ingredient in exoplanet occurrence rates are
stellar radii

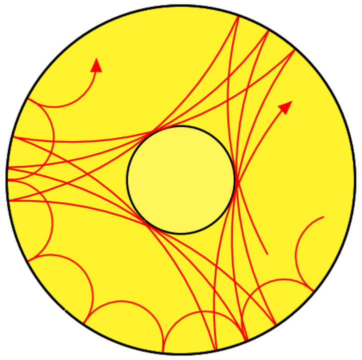
how are the radii of stars measured?



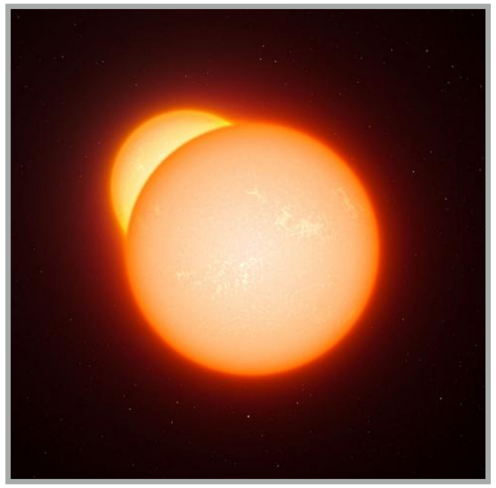
interferometry
only the nearest,
largest stars



SED fitting
model-dependent,
prone to reddening

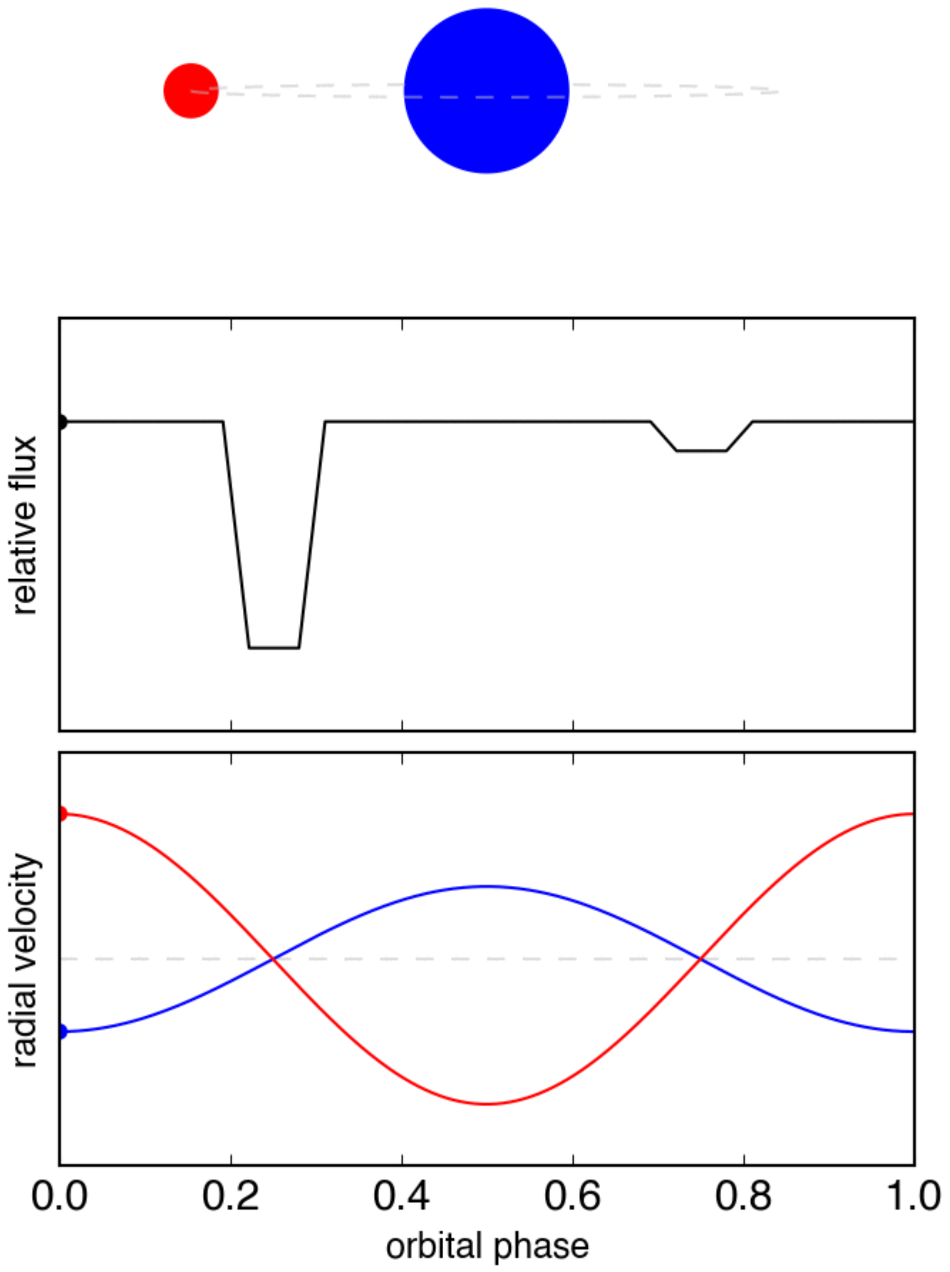


asteroseismology
model-dependent,
only certain regions of HR
diagram



**spectroscopically
double-lined eclipsing
binaries:** depends
essentially on geometry
and Kepler's 3rd law

Eclipsing spectroscopic binaries



mass ratio $$\frac{m_1}{m_2} = \frac{v_{r,2}}{v_{r,1}} = \frac{\Delta\lambda_2}{\Delta\lambda_1}$$

separation $$a = a_1 + a_2 = \frac{P}{2\pi}(v_1 + v_2)$$

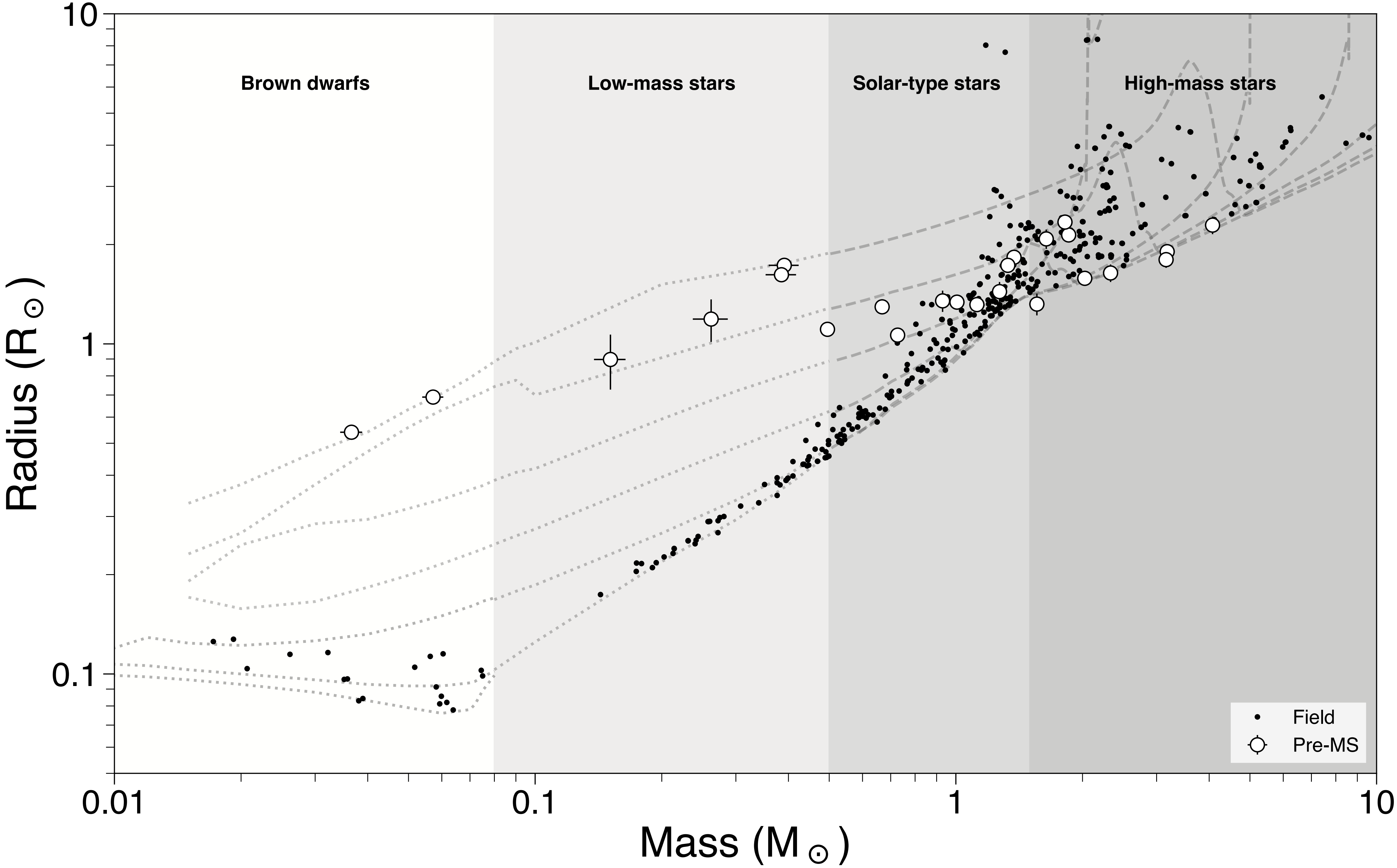
sum of masses $$m_1 + m_2 = \frac{P}{2\pi G}\frac{(v_{r,1} + v_{r,2})^3}{\sin^3 i}$$

radii $$r_1 = \frac{v_1 + v_2}{2}(t_c - t_a)$$

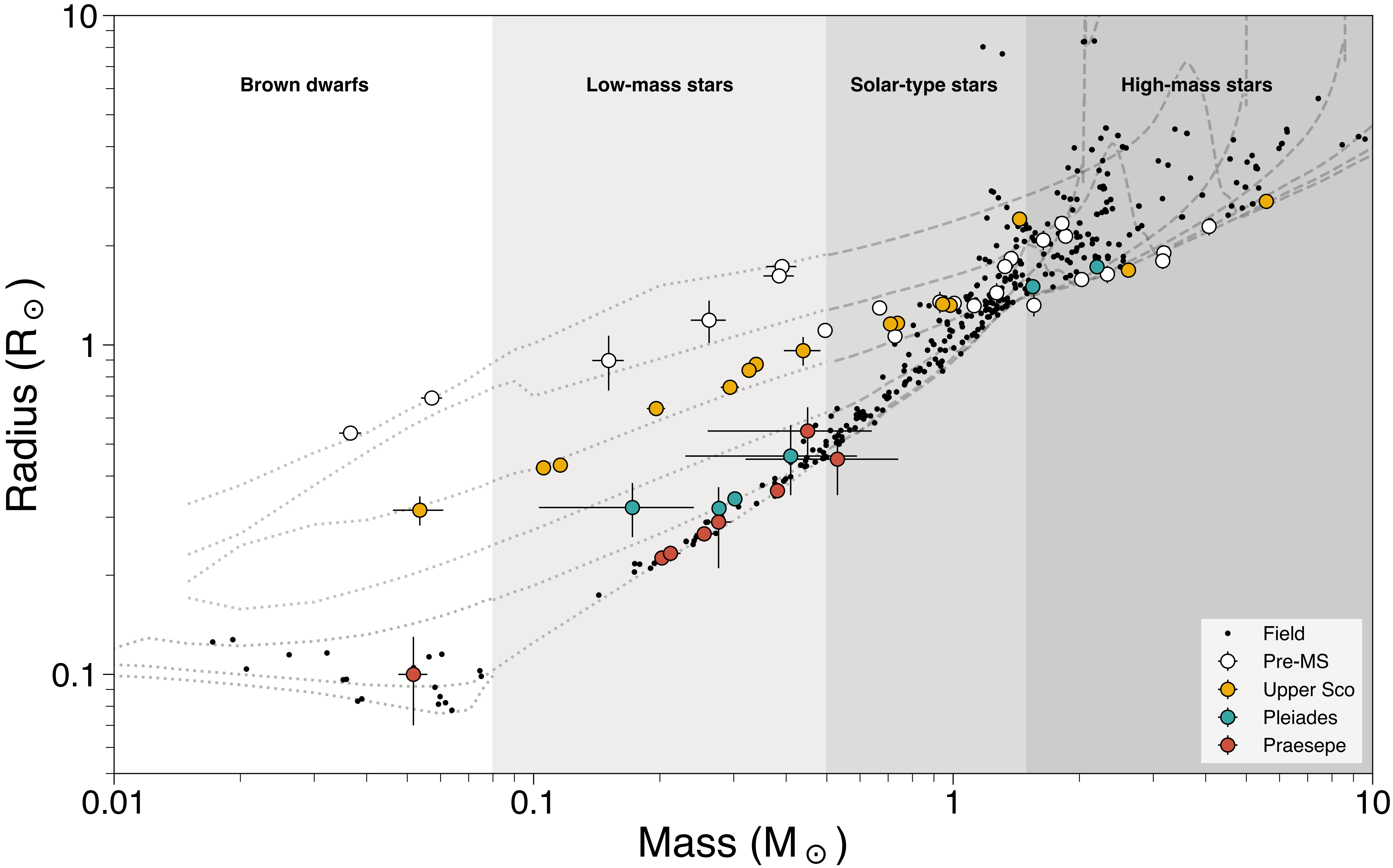
$$r_2 = \frac{v_1 + v_2}{2}(t_b - t_a)$$

fundamental masses & radii with precision of a few percent

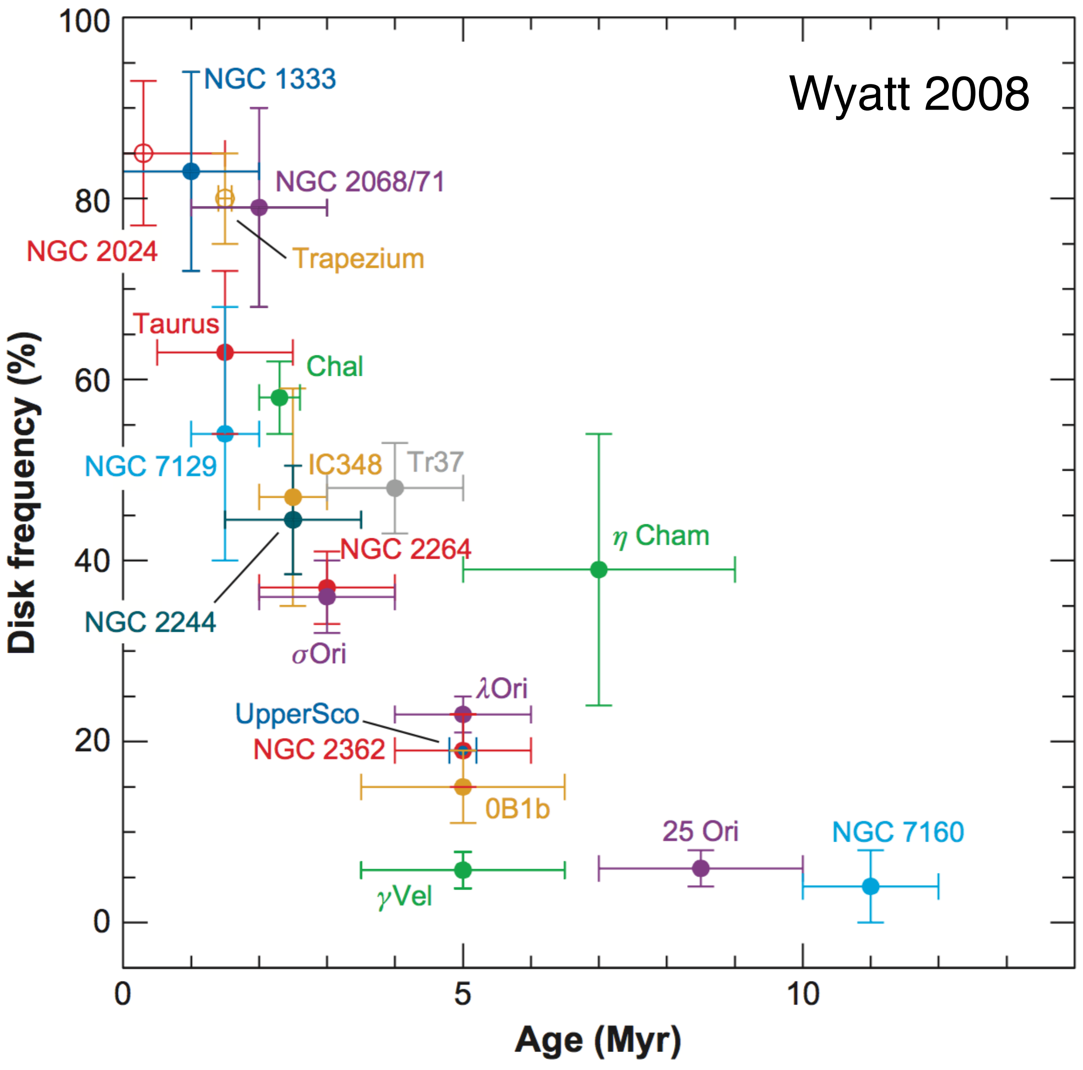
Very few pre-main-sequence stars have well-determined radii



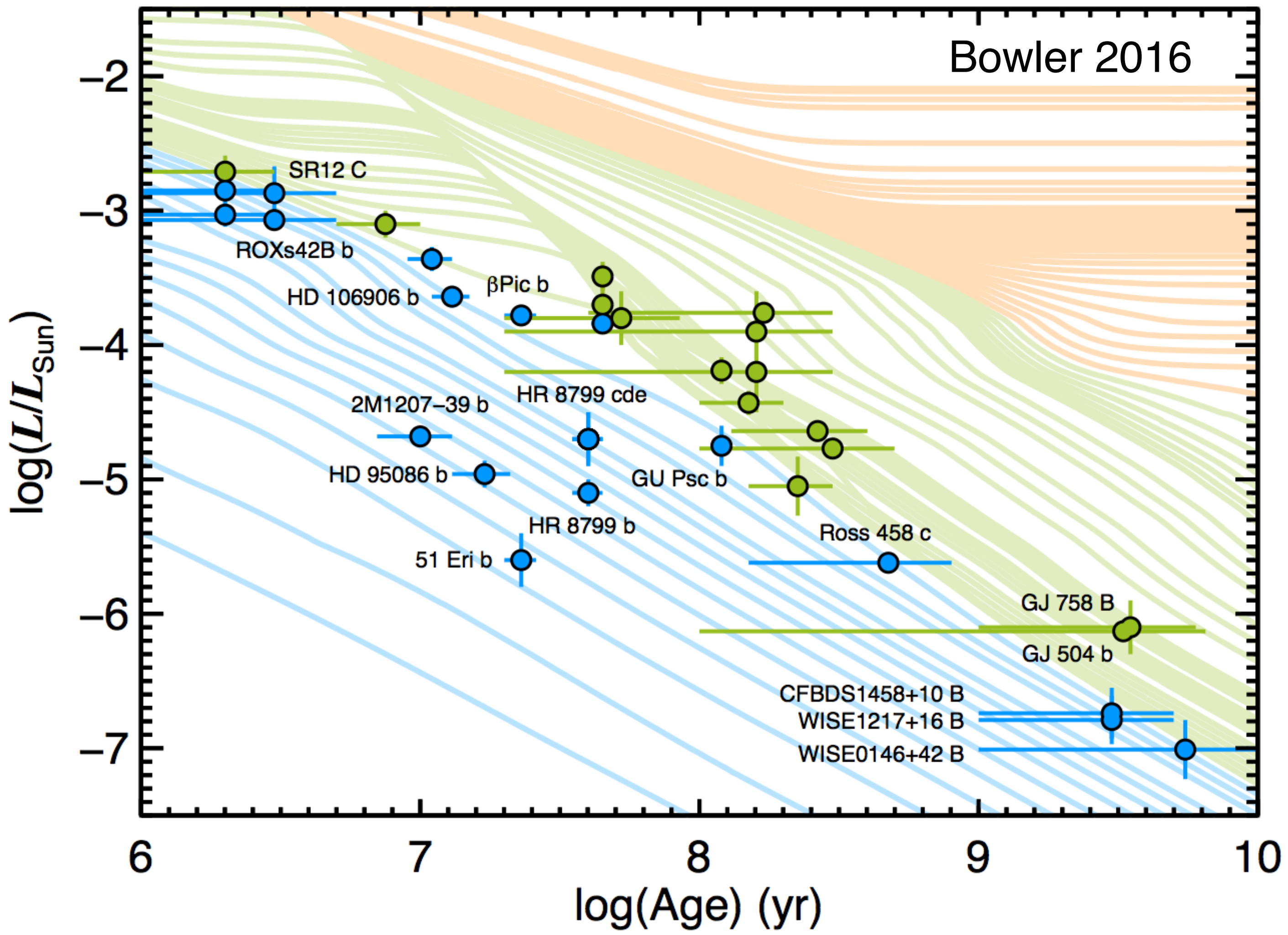
Very few pre-main-sequence stars have well-determined radii



Pre-main sequence evolutionary models



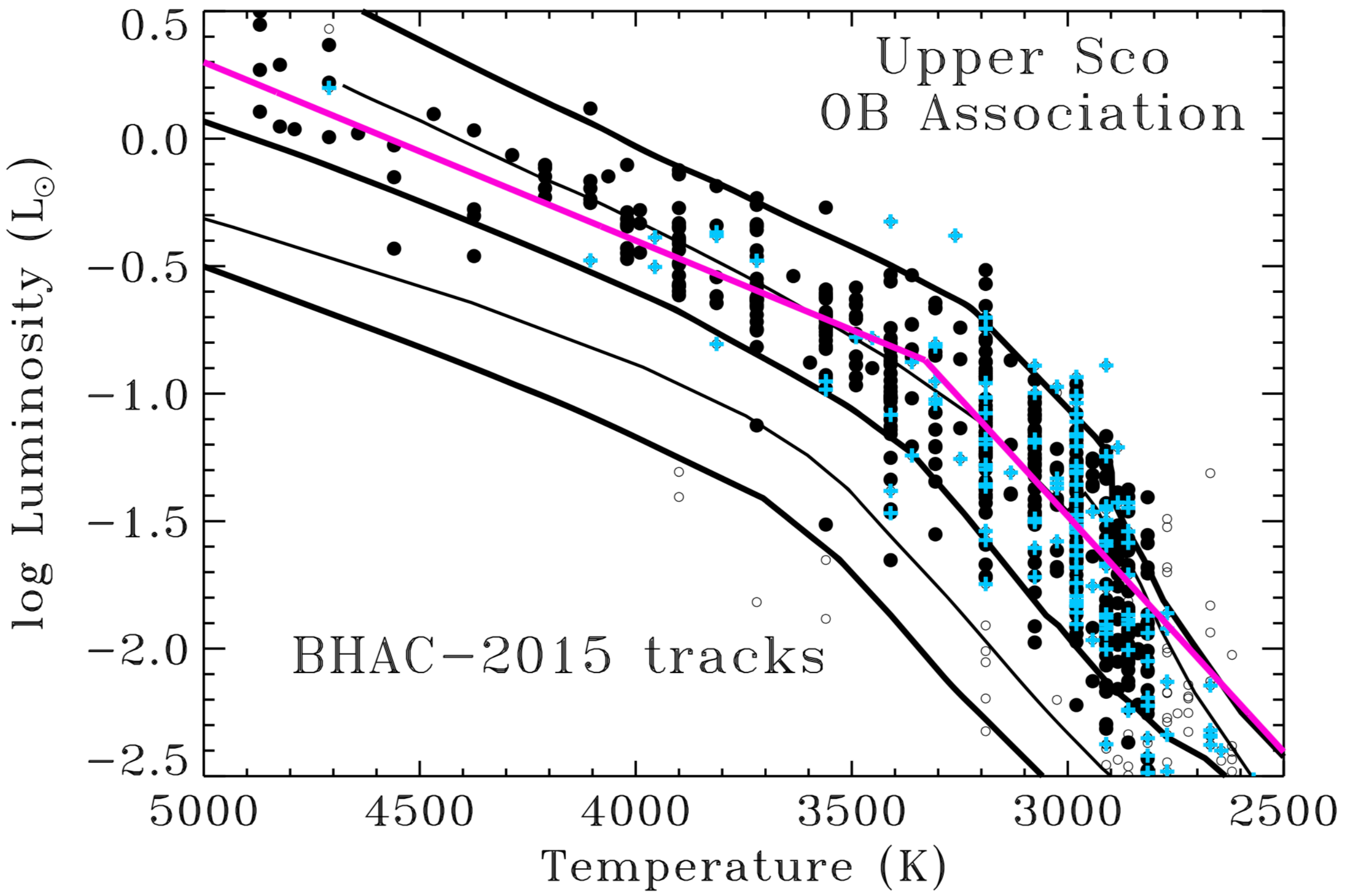
…set the timescale for
disk dispersal / giant planet formation



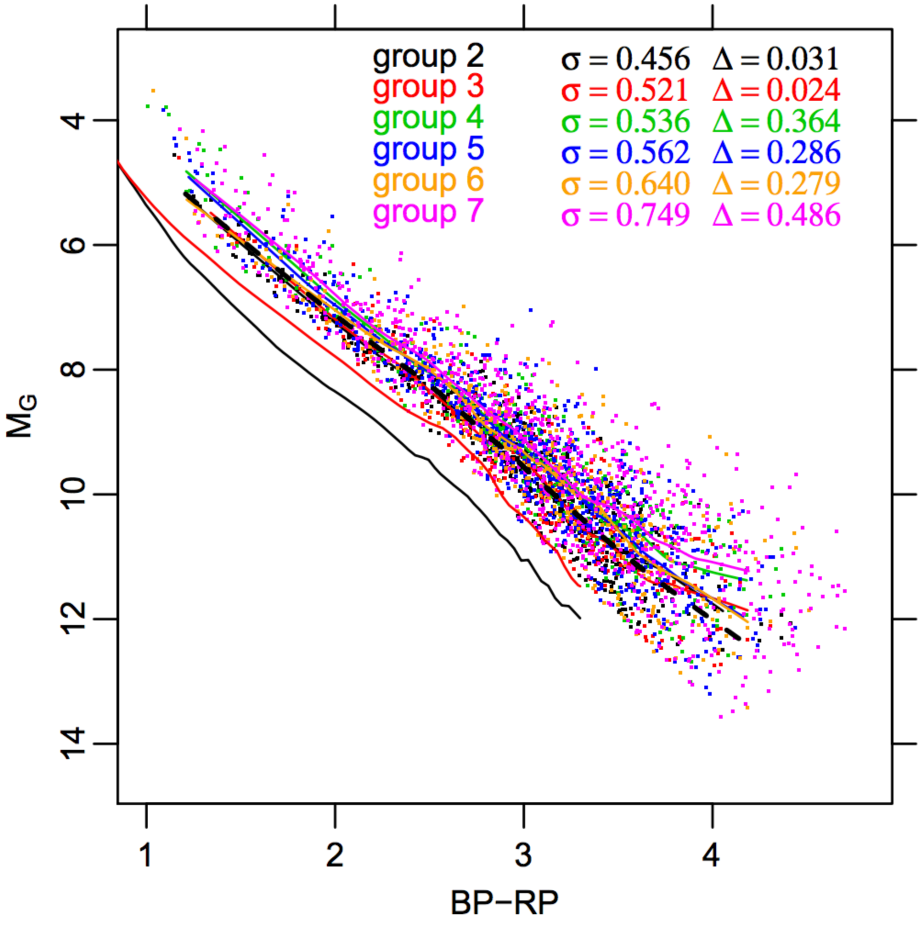
…determine the masses of directly imaged
brown dwarfs and giant planets

The Upper Sco HR diagram / CAMD

Herczeg & Hillenbrand (2015)



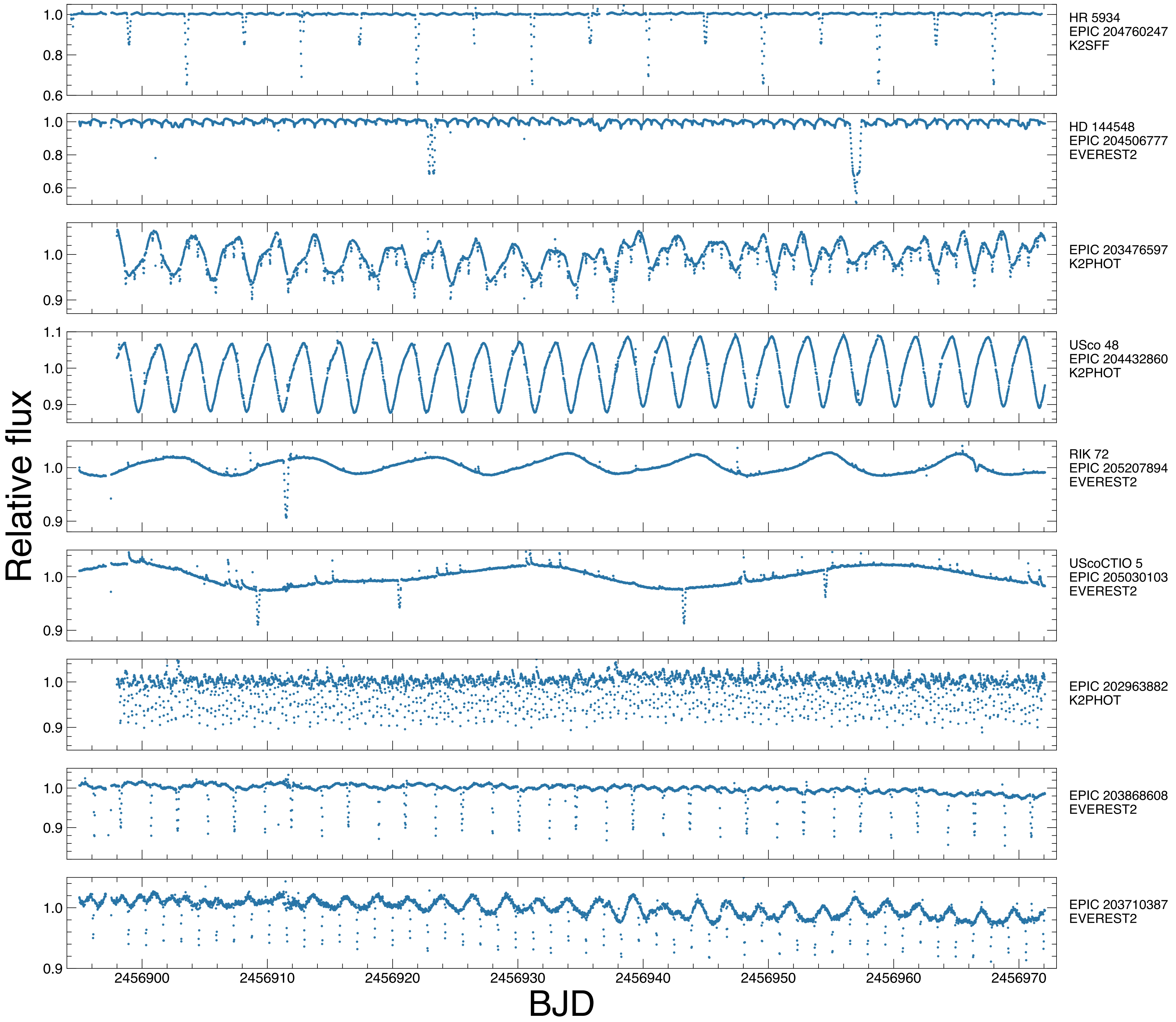
Damiani et al. 2018



individual stars exhibit ages between 1-10 Myr

distance spread, differential reddening, disk-related photometric variability, unresolved binaries, specific accretion histories, different spin/magnetic field strengths, genuine age spread…

Nine eclipsing binaries in Upper Sco



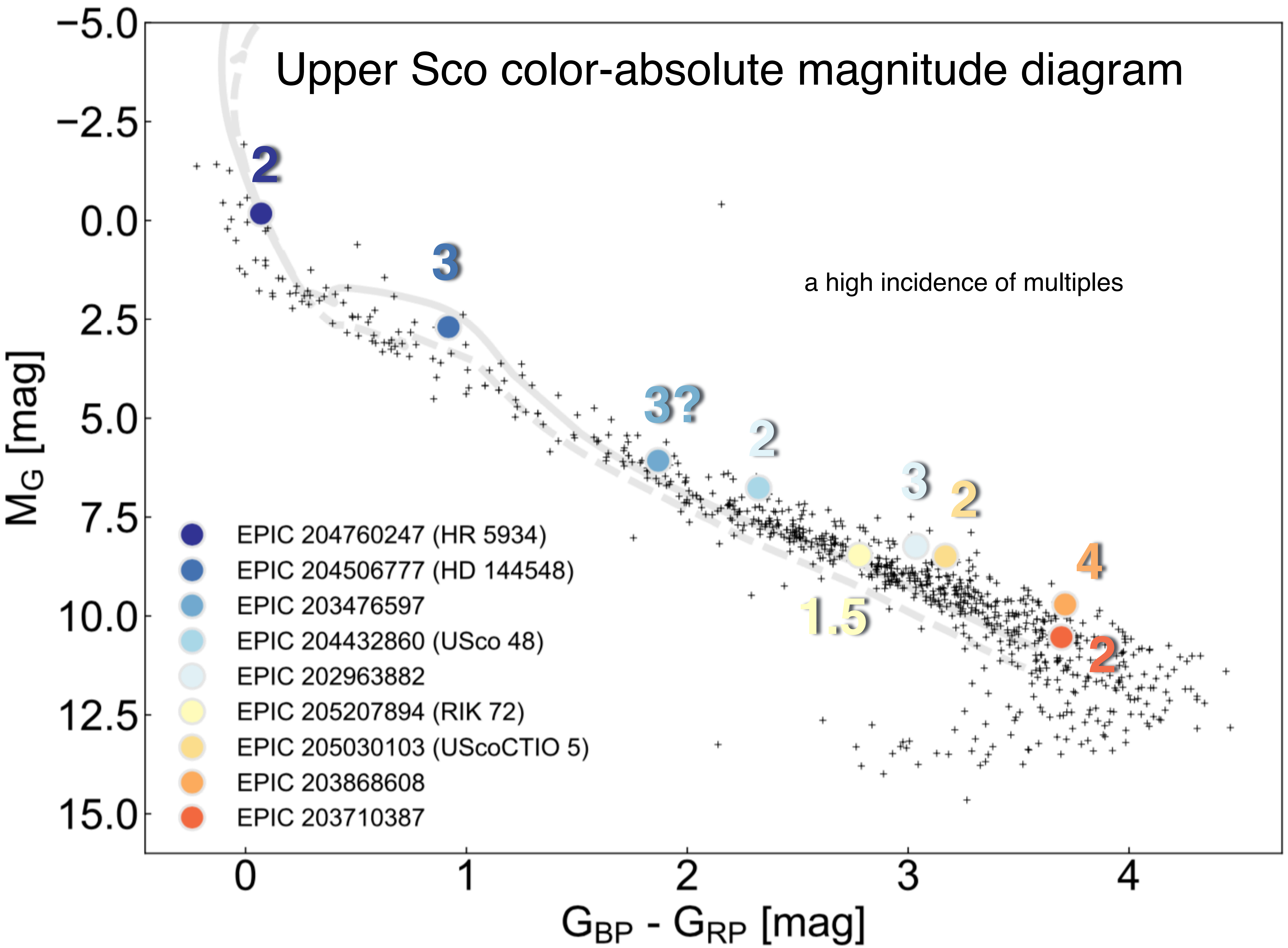
c.f. Maxted & Hutcheon 2018

Alonso et al. 2015

c.f. Kraus et al. 2015

see also Wang et al. 2018

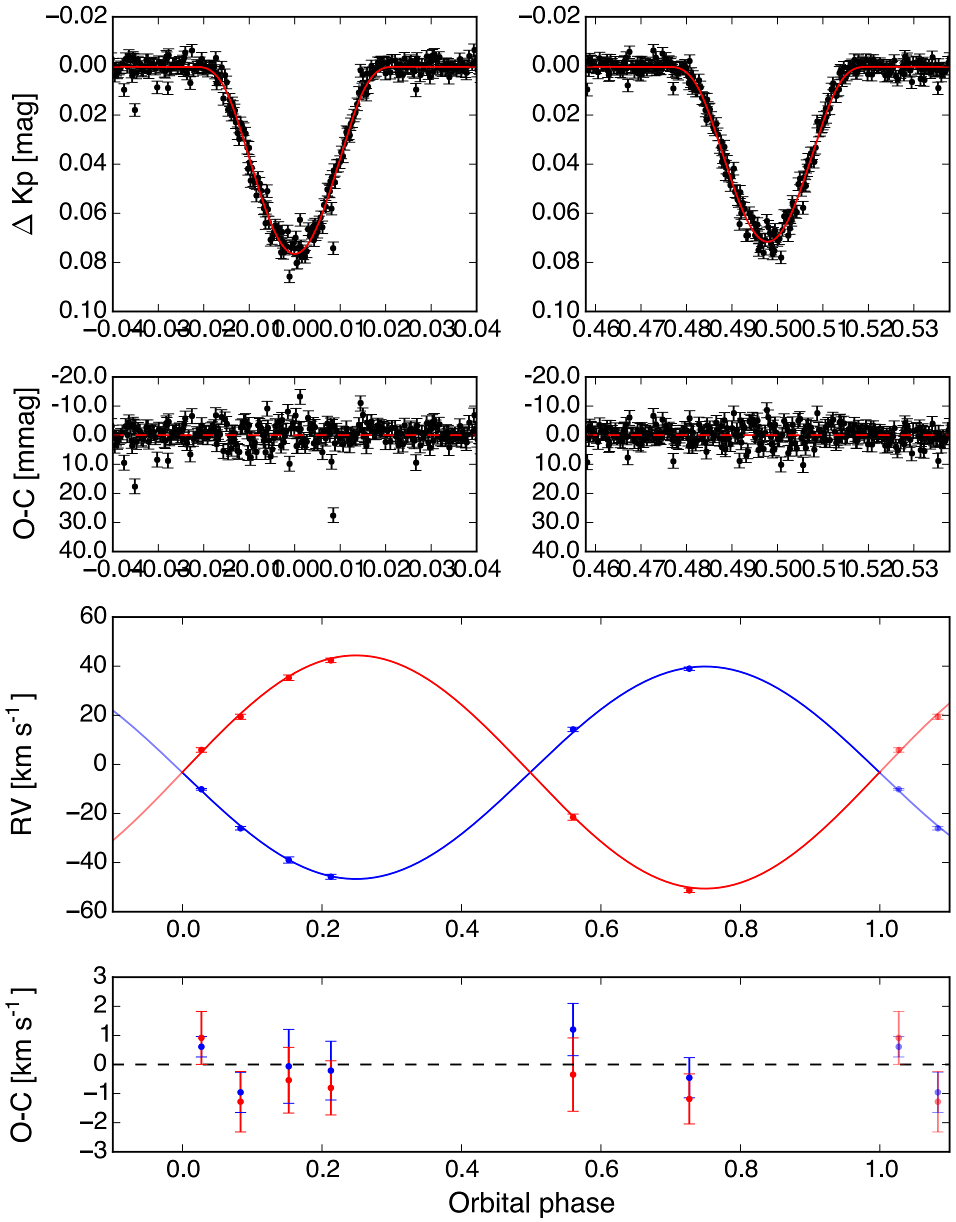
c.f. Lodieu et al. 2015



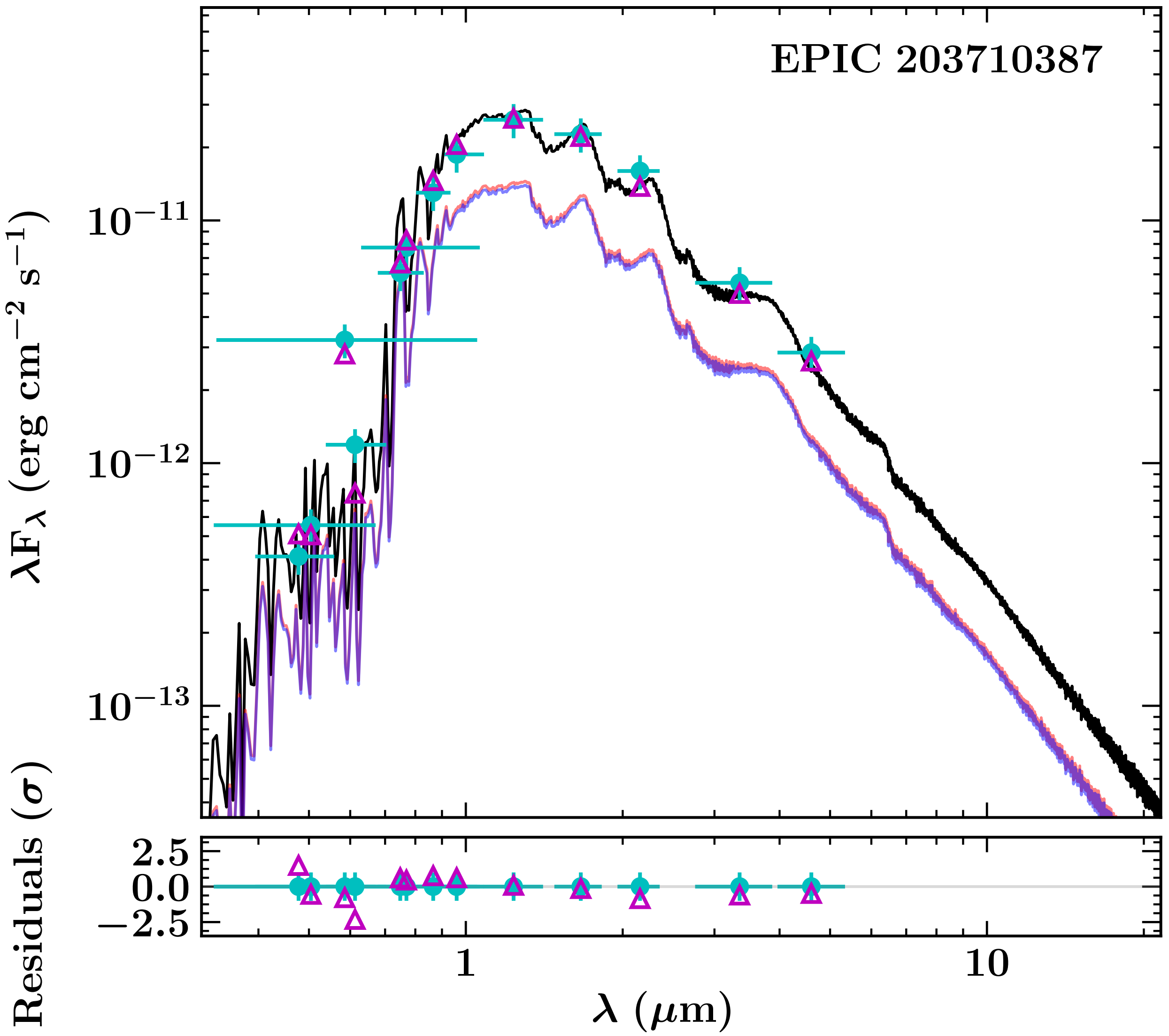
Upper Sco color-absolute magnitude diagram

a high incidence of multiples

From observables to fundamental parameters

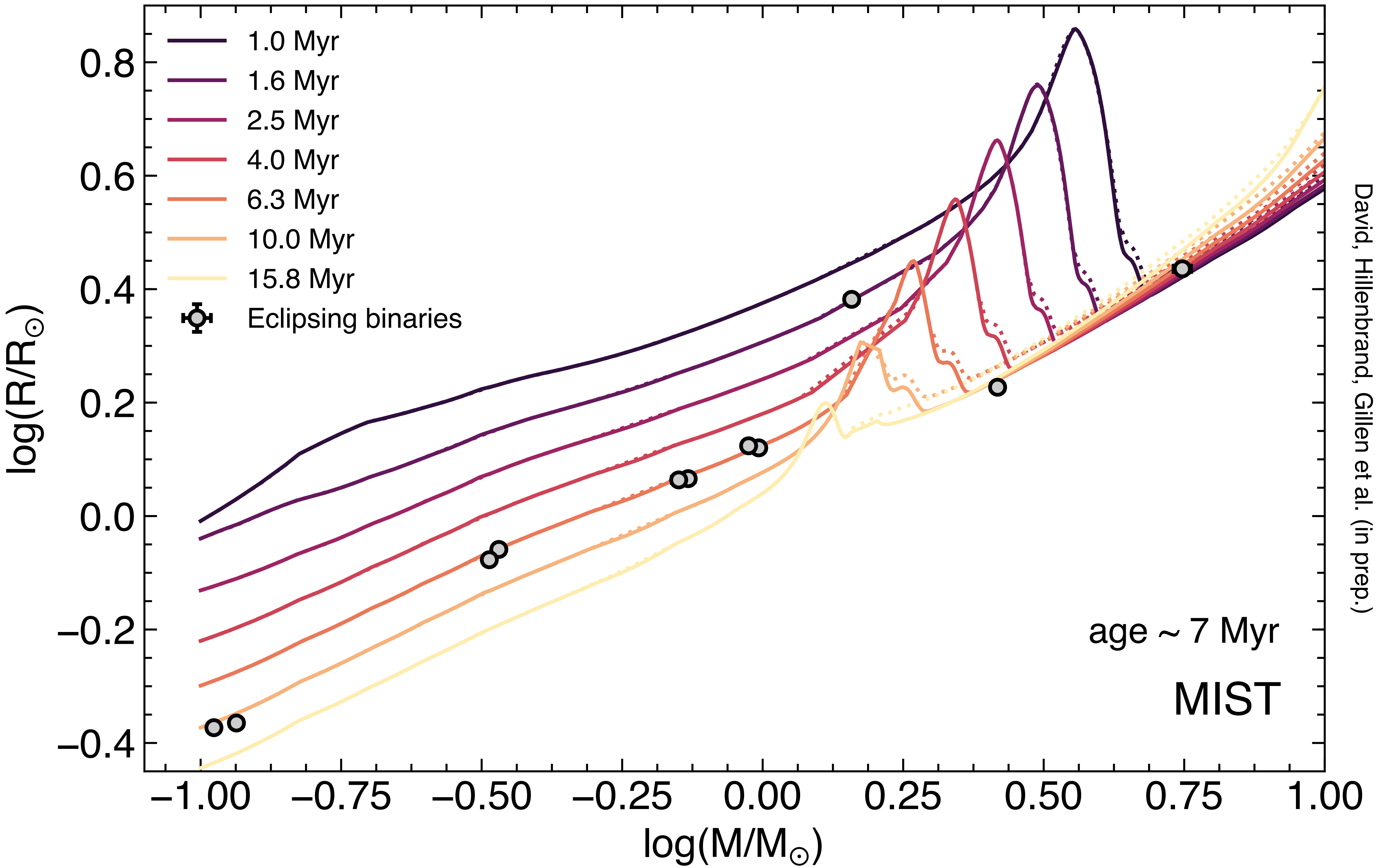


K2 photometry + Keck/HIRES RVs:
masses and radii to < 3 %



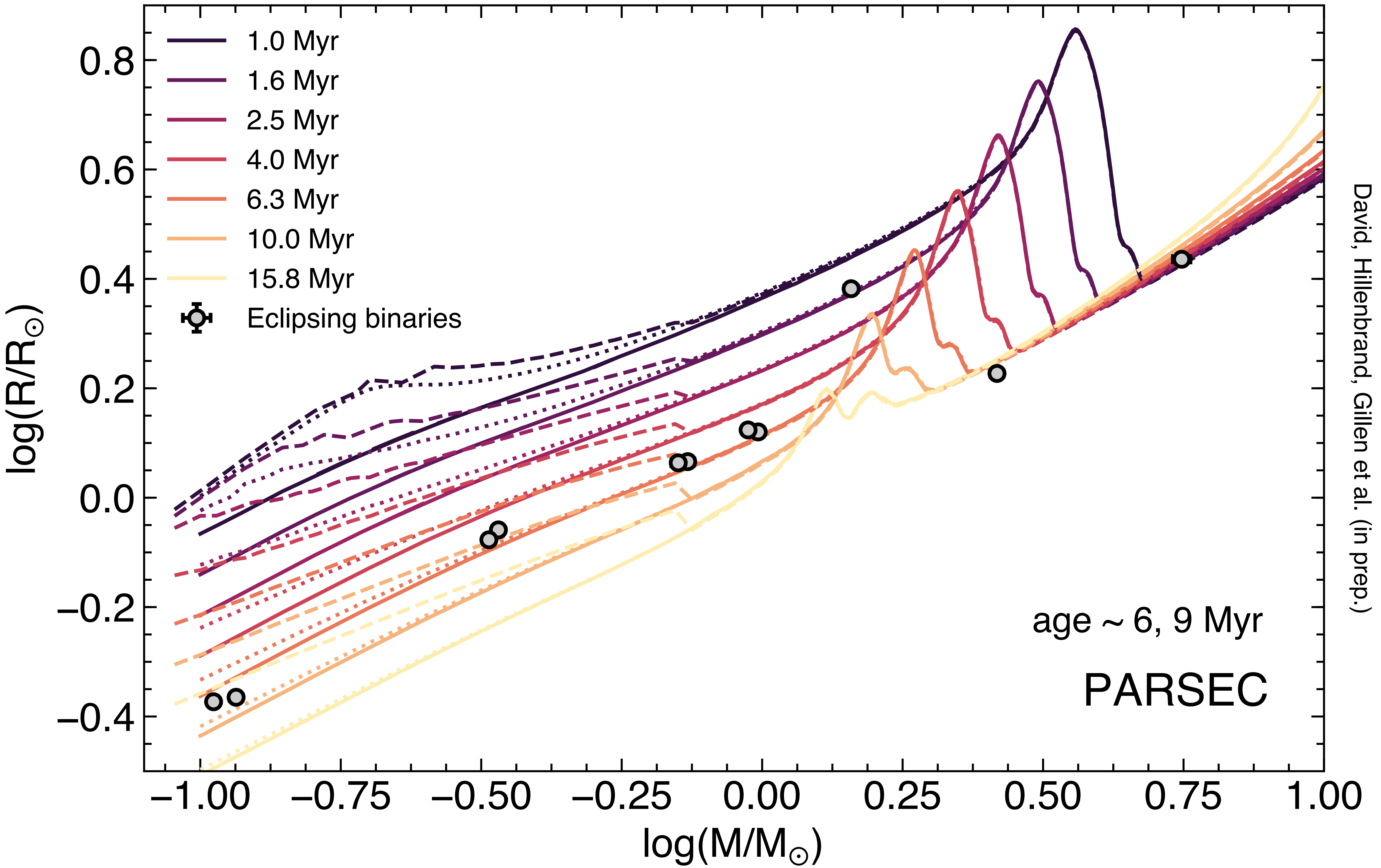
broadband photometry + *Gaia* parallaxes +
radii + log(g) + model atmospheres:
Teff to < 3%, logL to ~0.05 dex

The mass-radius relation in Upper Sco



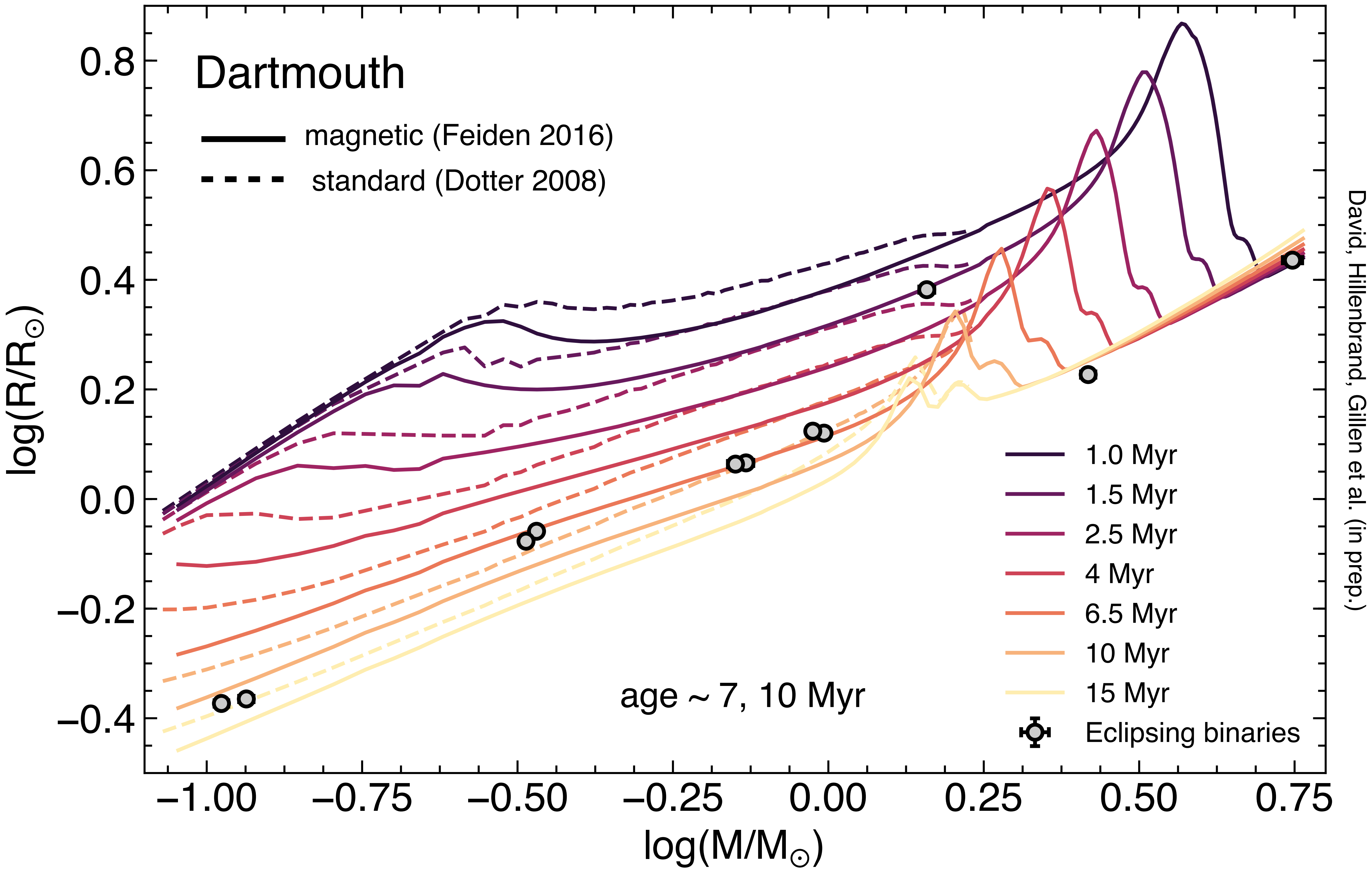
David, Hillenbrand, Gillen et al. (in prep.)

The mass-radius relation in Upper Sco



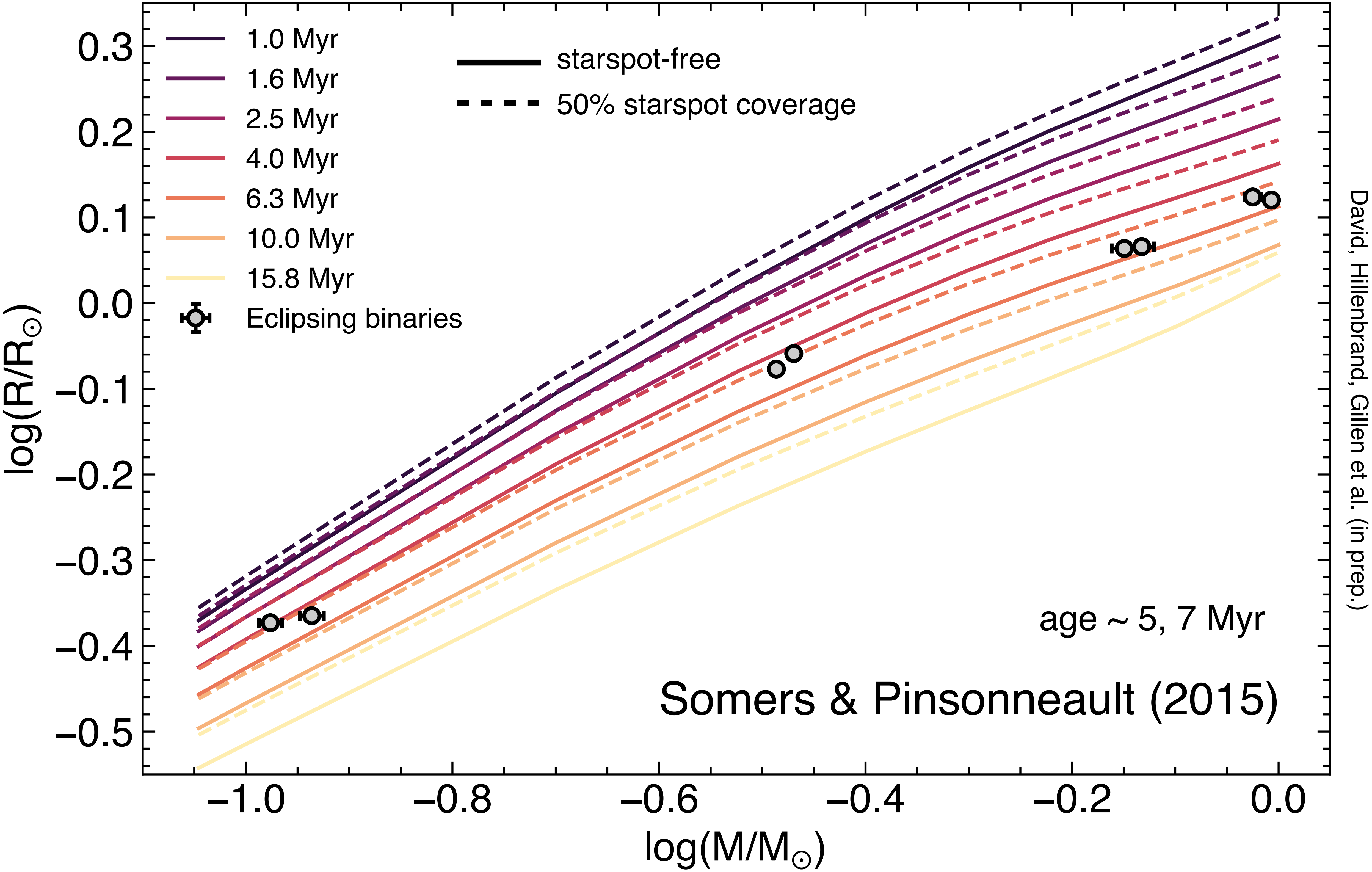
David, Hillenbrand, Gillen et al. (in prep.)

The mass-radius relation in Upper Sco



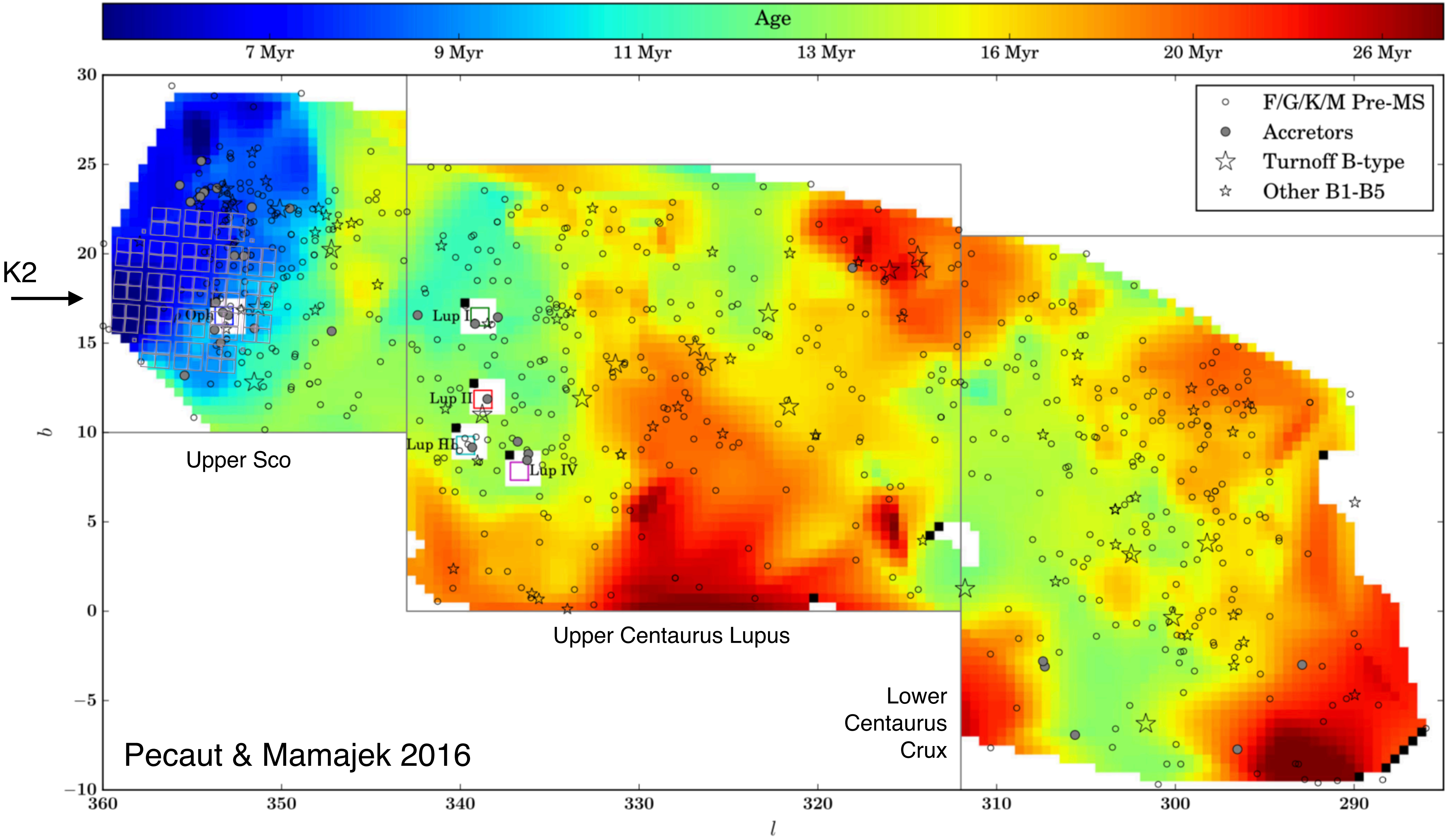
David, Hillenbrand, Gillen et al. (in prep.)

The mass-radius relation in Upper Sco



David, Hillenbrand, Gillen et al. (in prep.)

A ~7 Myr age in the context of Sco-Cen



K2

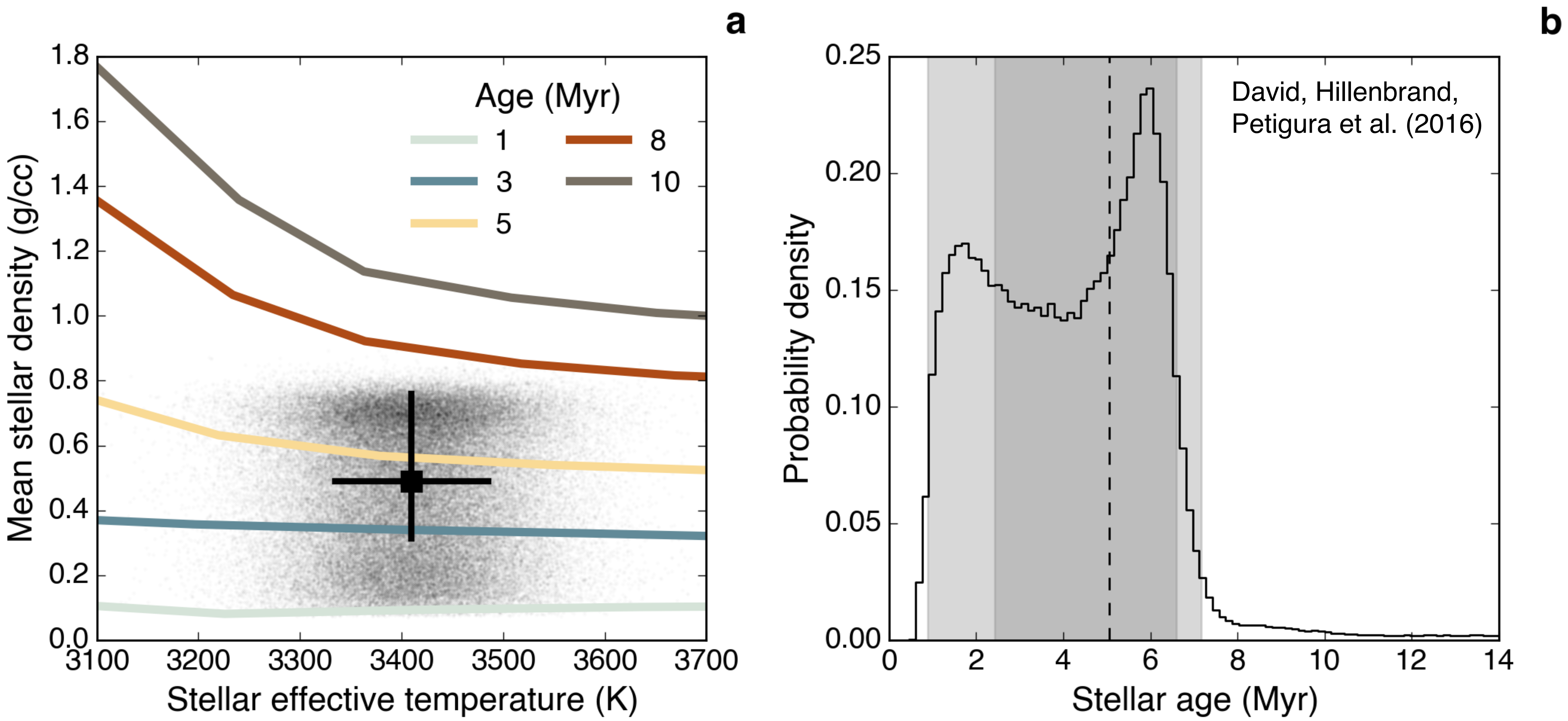
Upper Sco

Upper Centaurus Lupus

Lower
Centaurus
Crux

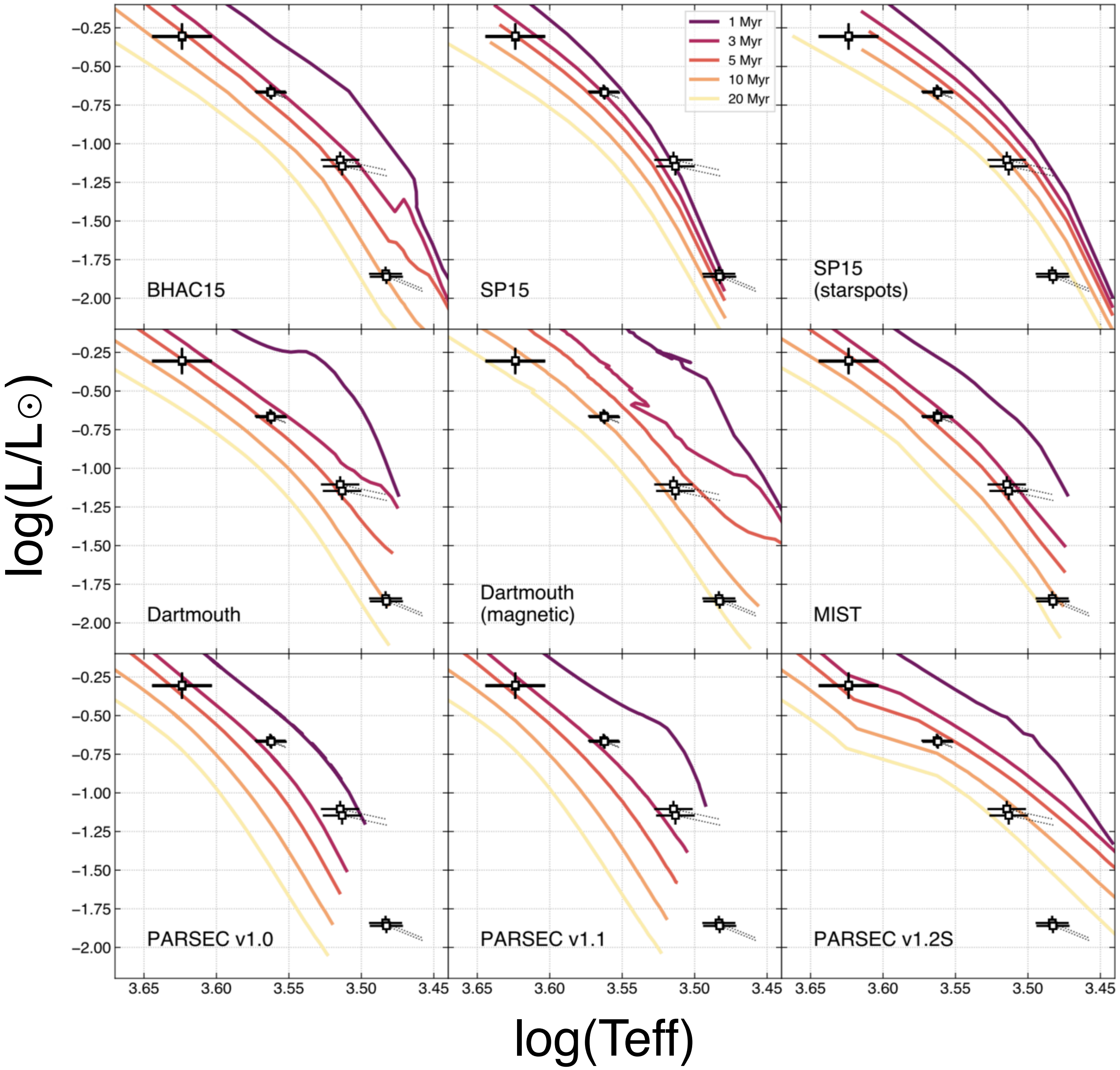
Pecaut & Mamajek 2016

Mean stellar density of K2-33

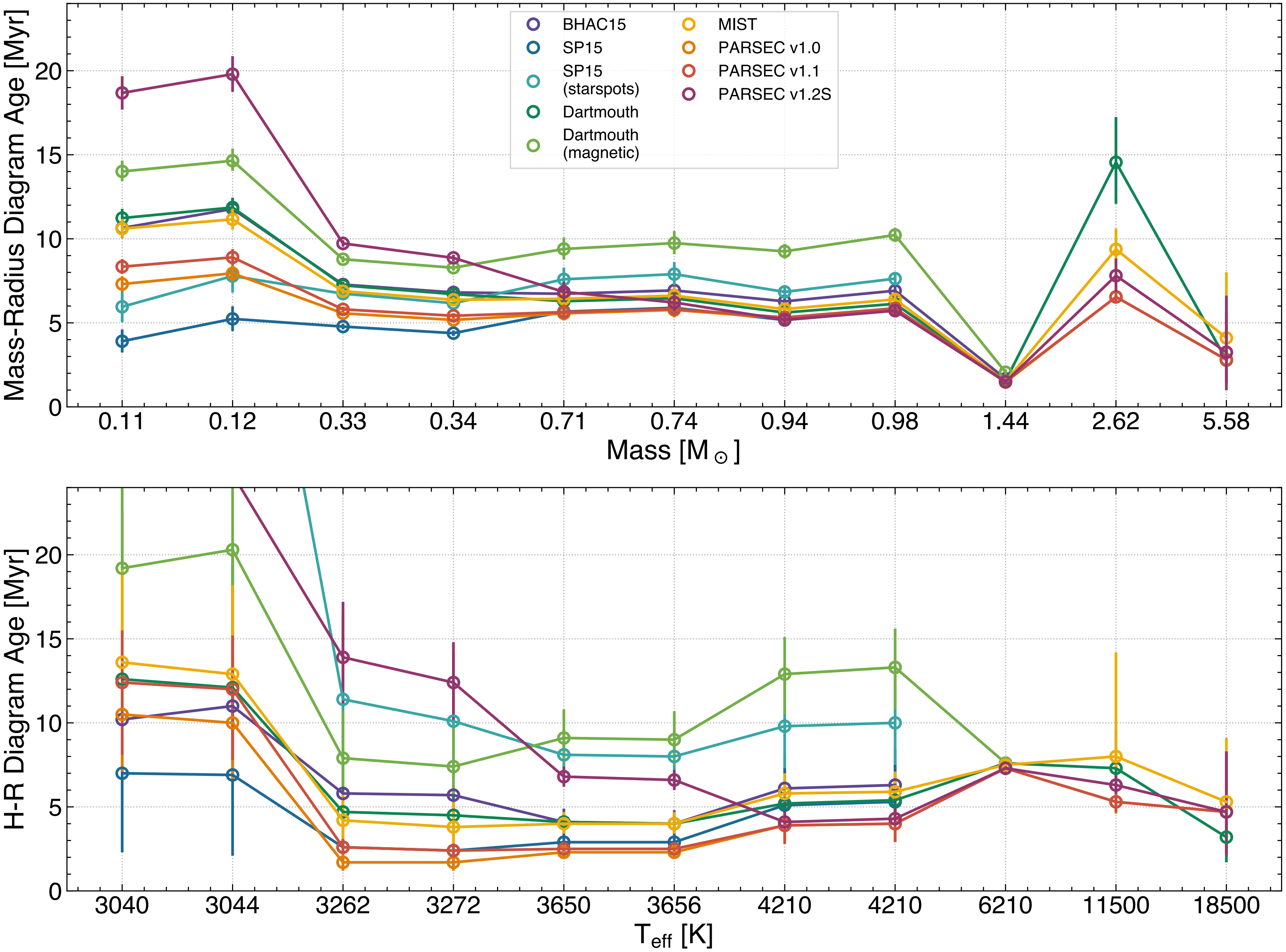


1) Transiting planets are astrophysical tools, useful for studying pre-MS stars
2) Mean stellar density is a viable way for identifying young hosts, investigating temporal trends in planet properties, particularly for very low-mass stars

H-R diagram ages



MRD vs. HRD, and trends with mass/Teff

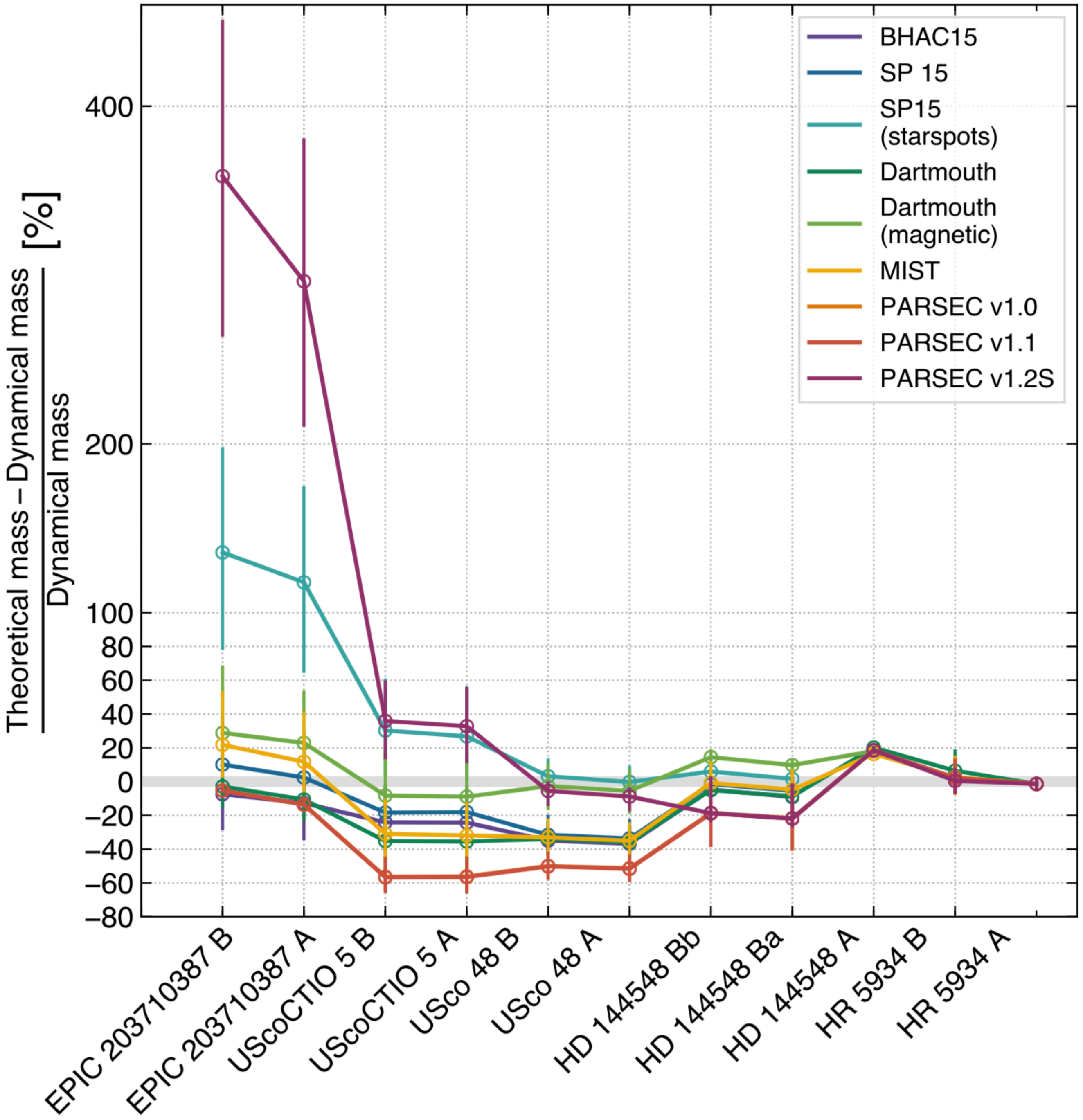


David, Hillenbrand, Gillen et al. (in prep.)

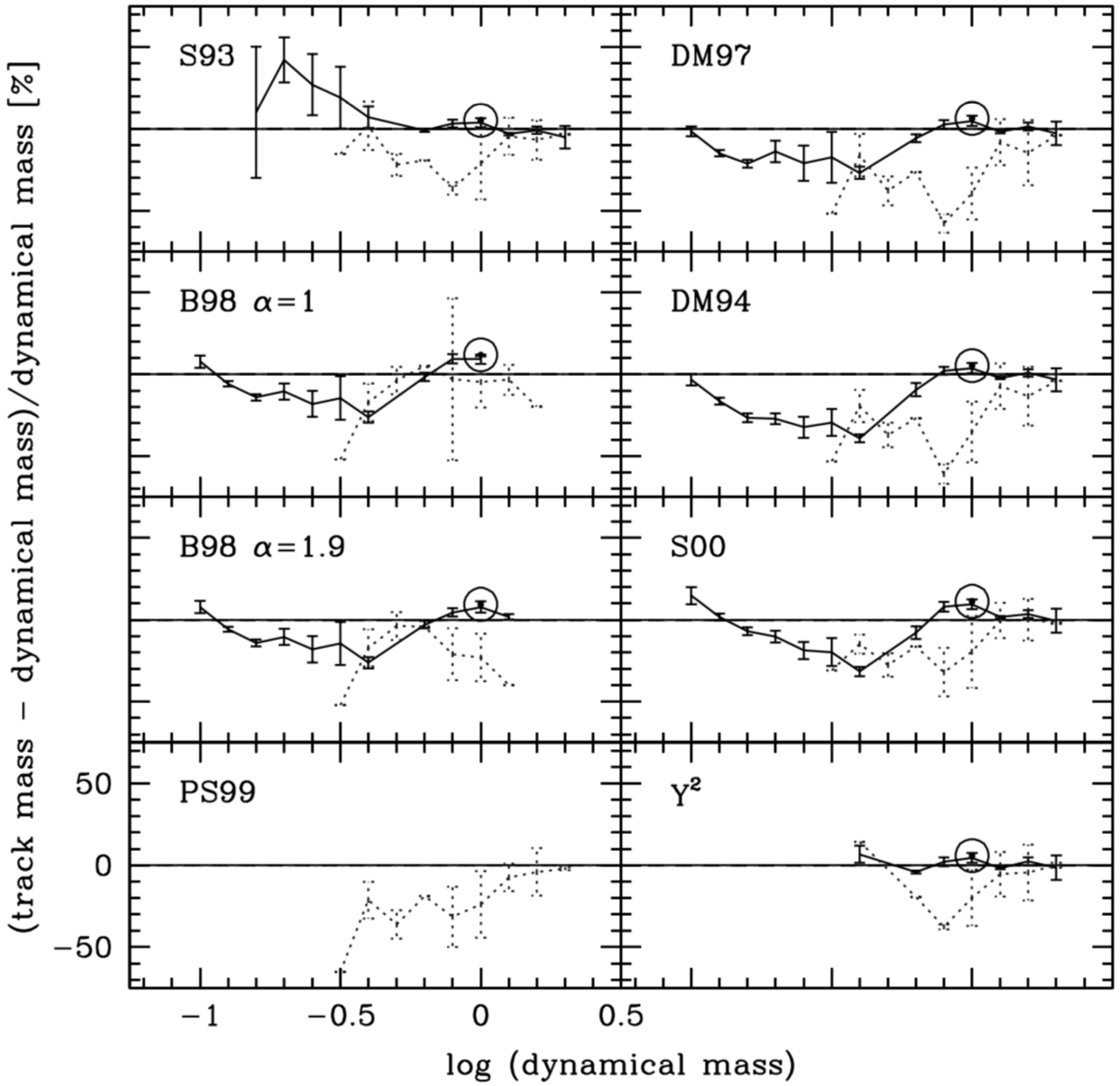
1) Many widely-used evolution models unable to reproduce M-R relation with a single-age
2) Nevertheless, the MRD exhibits less of a spread than the HRD
3) Most models indicate an age of 5-7 Myr, magnetic models suggest 9-10 Myr

Masses from pre-MS models

David, Hillenbrand, Gillen, et al. 2018 (in prep.)

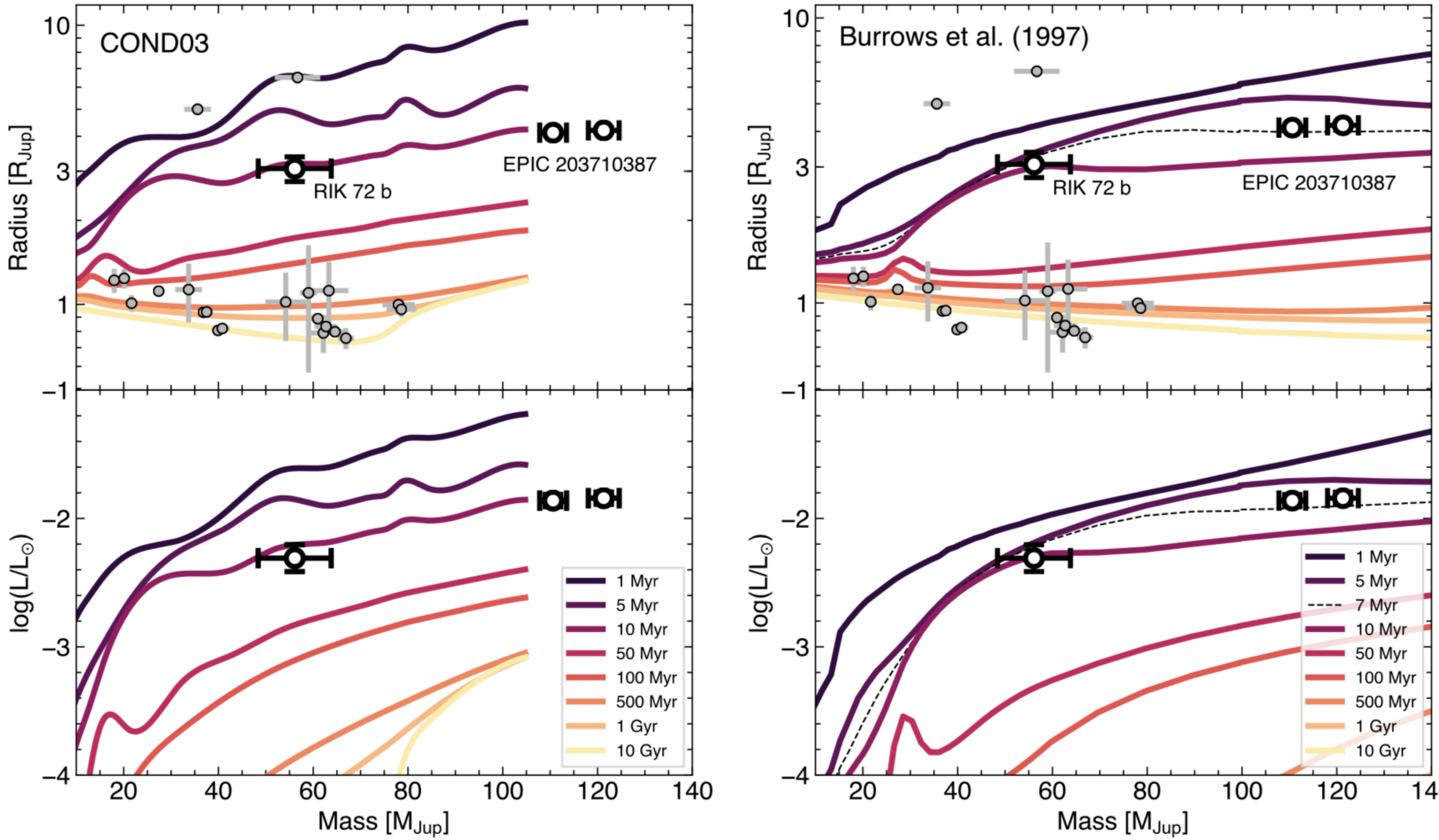


Hillenbrand & White 2004



most models under-predict the masses of low-mass stars by tens of percent
> this has implications for RV searches for planets around young stars

RIK 72 b: a likely transiting brown dwarf at ~7 Myr

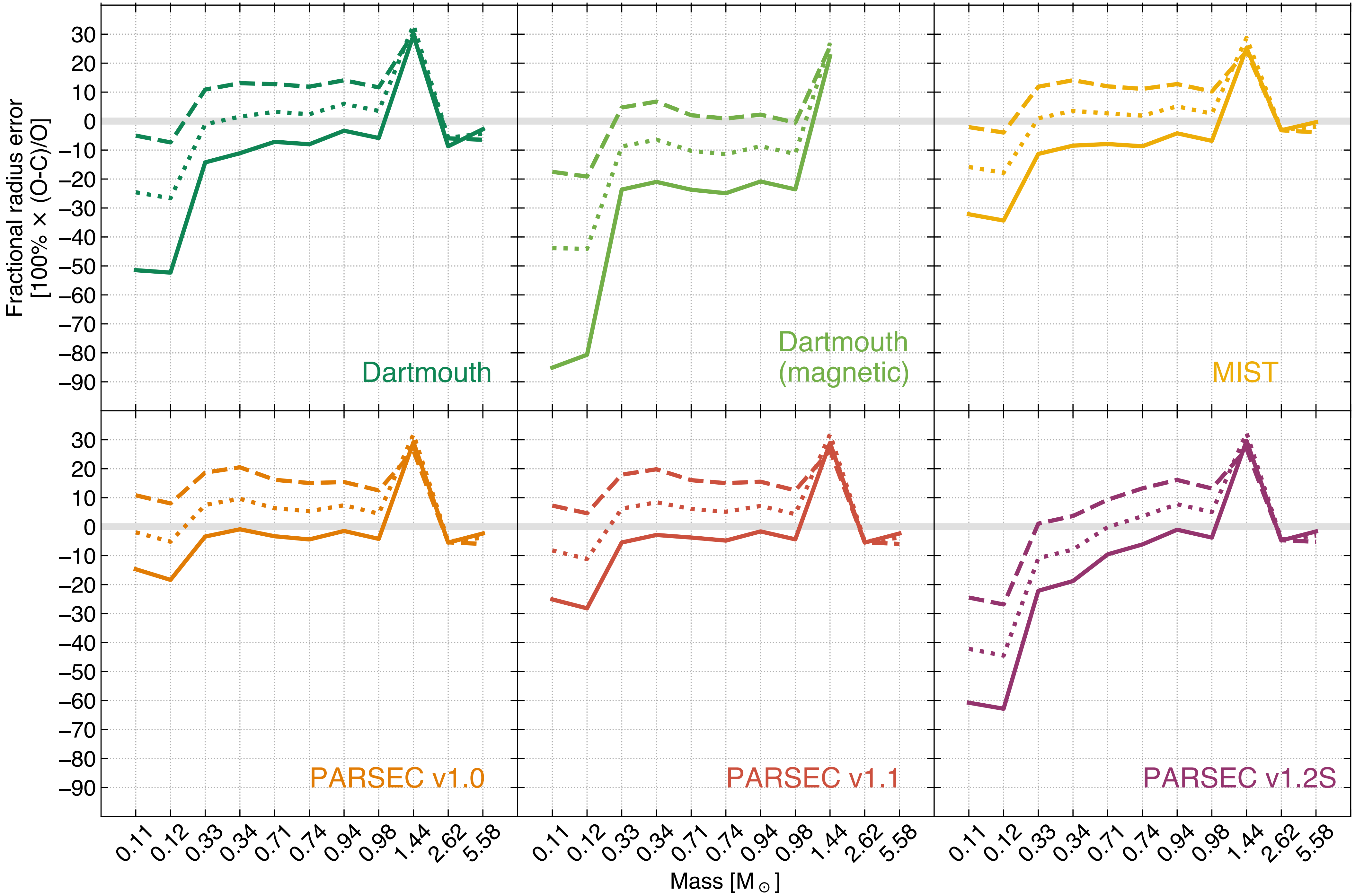


David, Hillenbrand, Gillen et al. (in prep.)

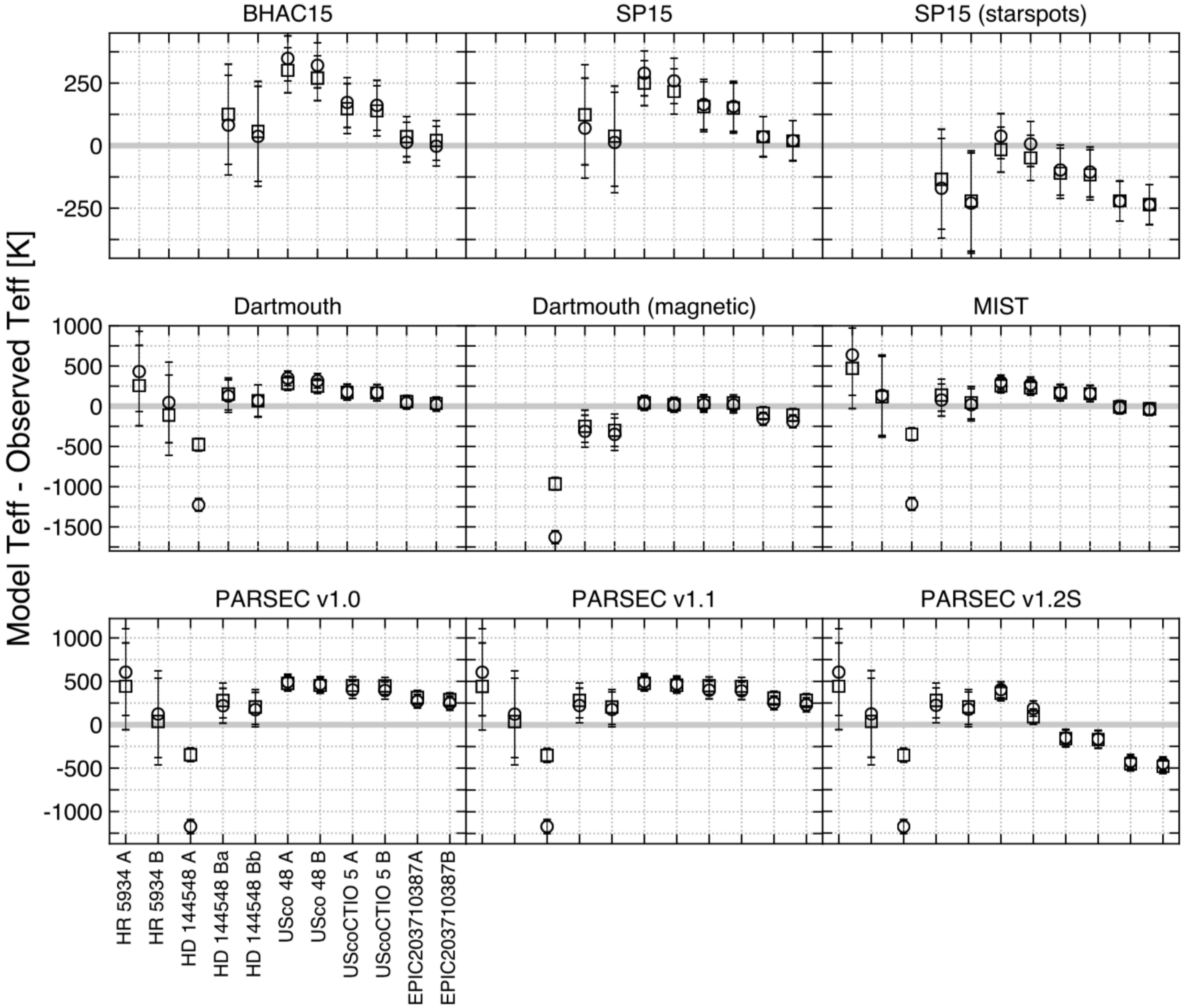
Looking forward

- **Planet occurrence across time**
  - Possible now with *K2*
  - *TESS* may offer better statistics, will fill in interesting age range with moving groups, but crowding may be a problem for some clusters
  - *Gaia* will provide a relatively unbiased view (activity affects astrometry negligibly)
- **Are young planets less dense?**
  - Precision infrared Doppler spectroscopy is needed to mitigate impact of activity
- **Is atmospheric escape more severe at early times? Can we directly constrain photo-evaporation timescales?**
  - *HST* or *JWST* survey of similarly-sized planets around stars of different ages
- **What are the temperatures and eccentricities of young transiting exoplanets?**
  - *JWST* secondary eclipse observations + RV
- **What are the primordial spin-orbit alignments of young transiting exoplanets?**
  - Doppler tomography with a ~10m-class telescope

How well do evolution models predict the radii of young stars?

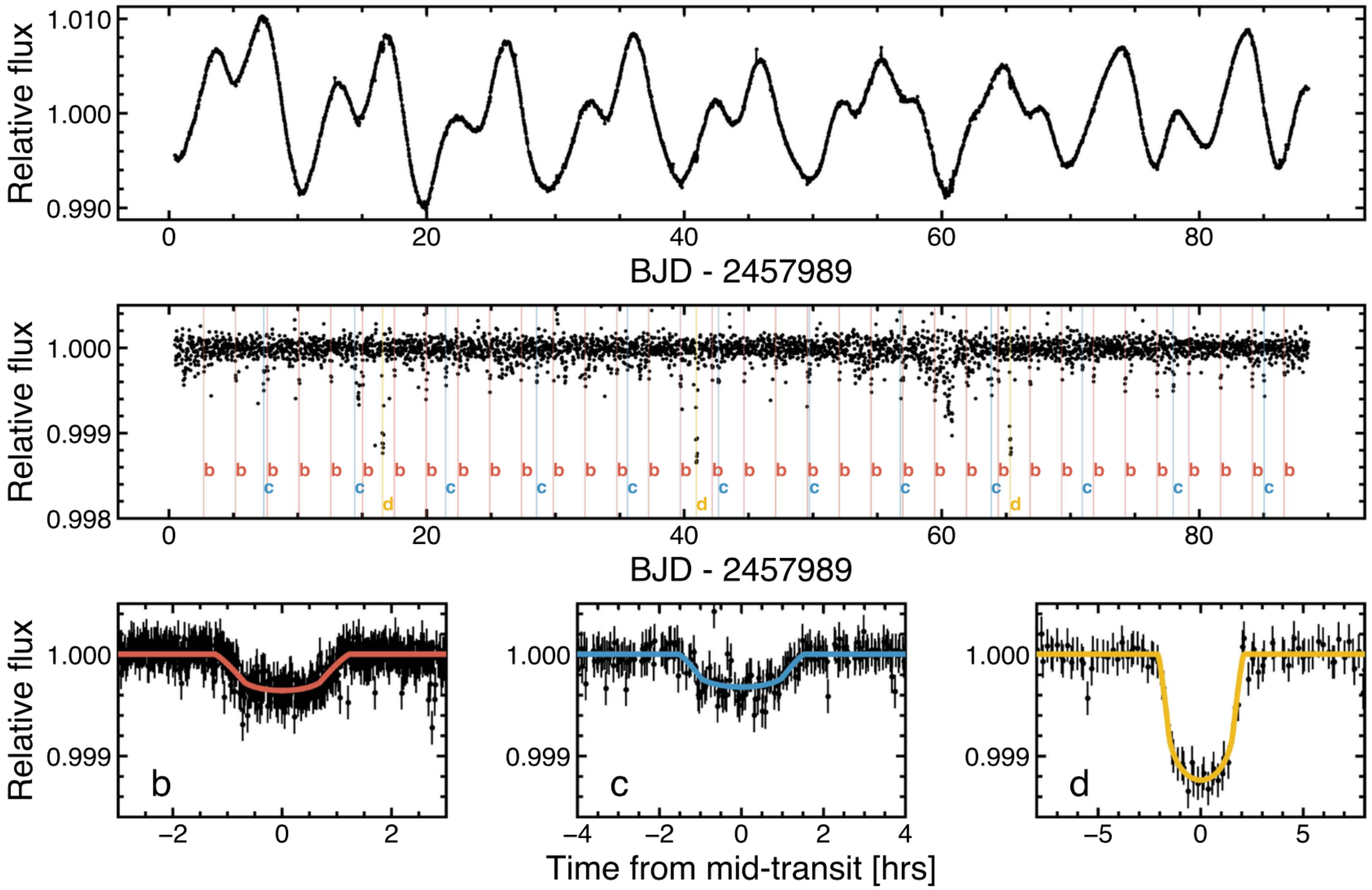


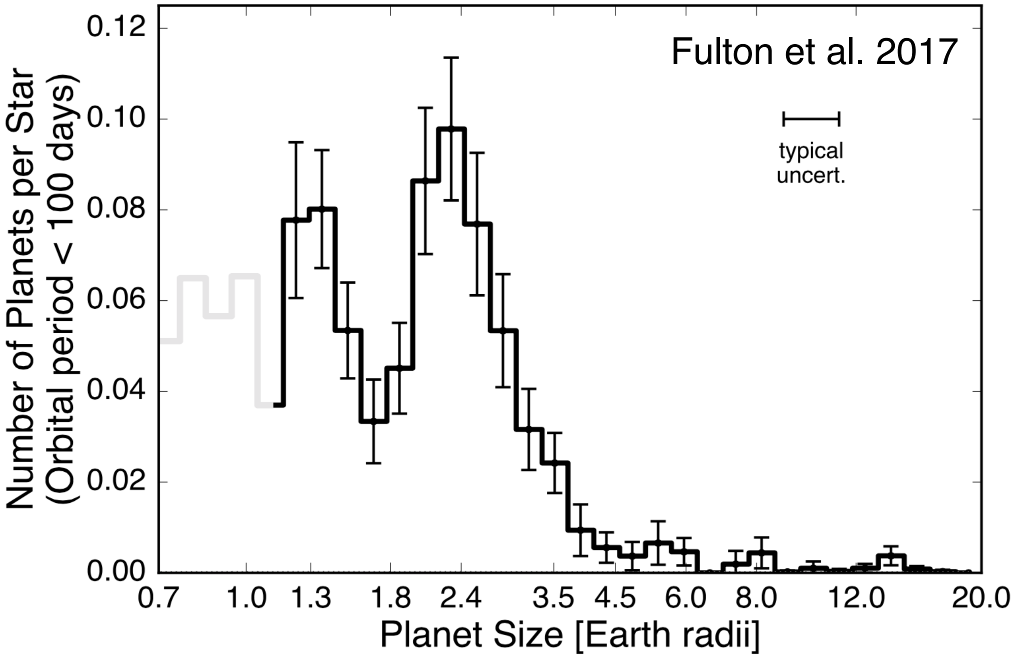
David & Hillenbrand (in prep.)


BHAC15
SP15
SP15 (starspots)
Dartmouth
Dartmouth (magnetic)
MIST
PARSEC v1.0
PARSEC v1.1
PARSEC v1.2S
Model Teff - Observed Teff [K]
250
0
-250
1000
500
0
-500
-1000
-1500
1000
500
0
-500
-1000
HR 5934 A
HR 5934 B
HD 144548 A
HD 144548 Ba
HD 144548 Bb
USco 48 A
USco 48 B
UScoCTIO 5 A
UScoCTIO 5 B
EPIC203710387A
EPIC203710387B

Young exoplanets from the K2 mission

Three small planets transiting a bright young field star

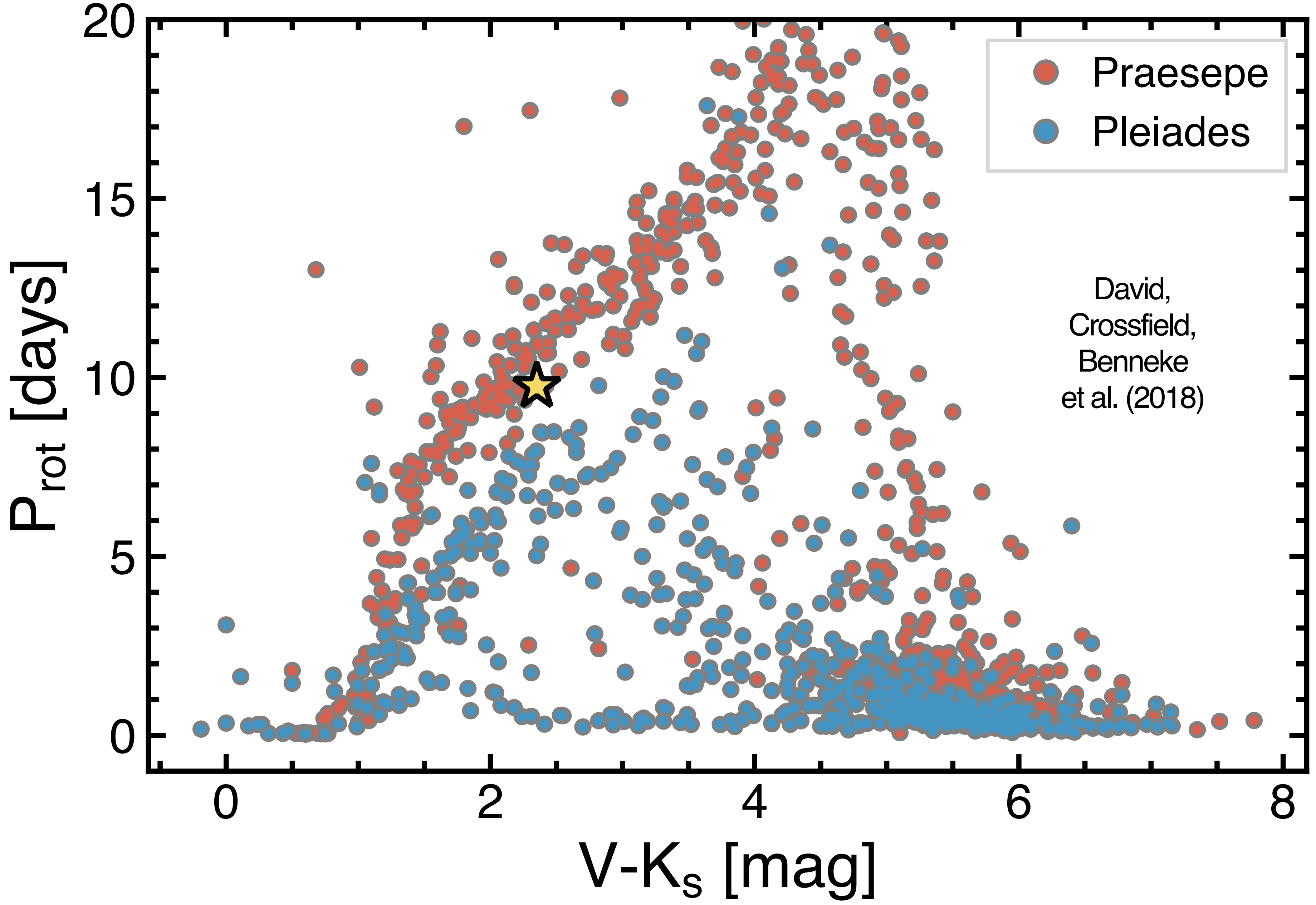




David,
Crossfield,
Benneke
et al. (2018)

K2-233 ($V = 10.7$ mag, $K_s = 8.4$ mag, age ~ 220—850 Myr)
also identified by citizen scientists
planets on both sides of the radius valley

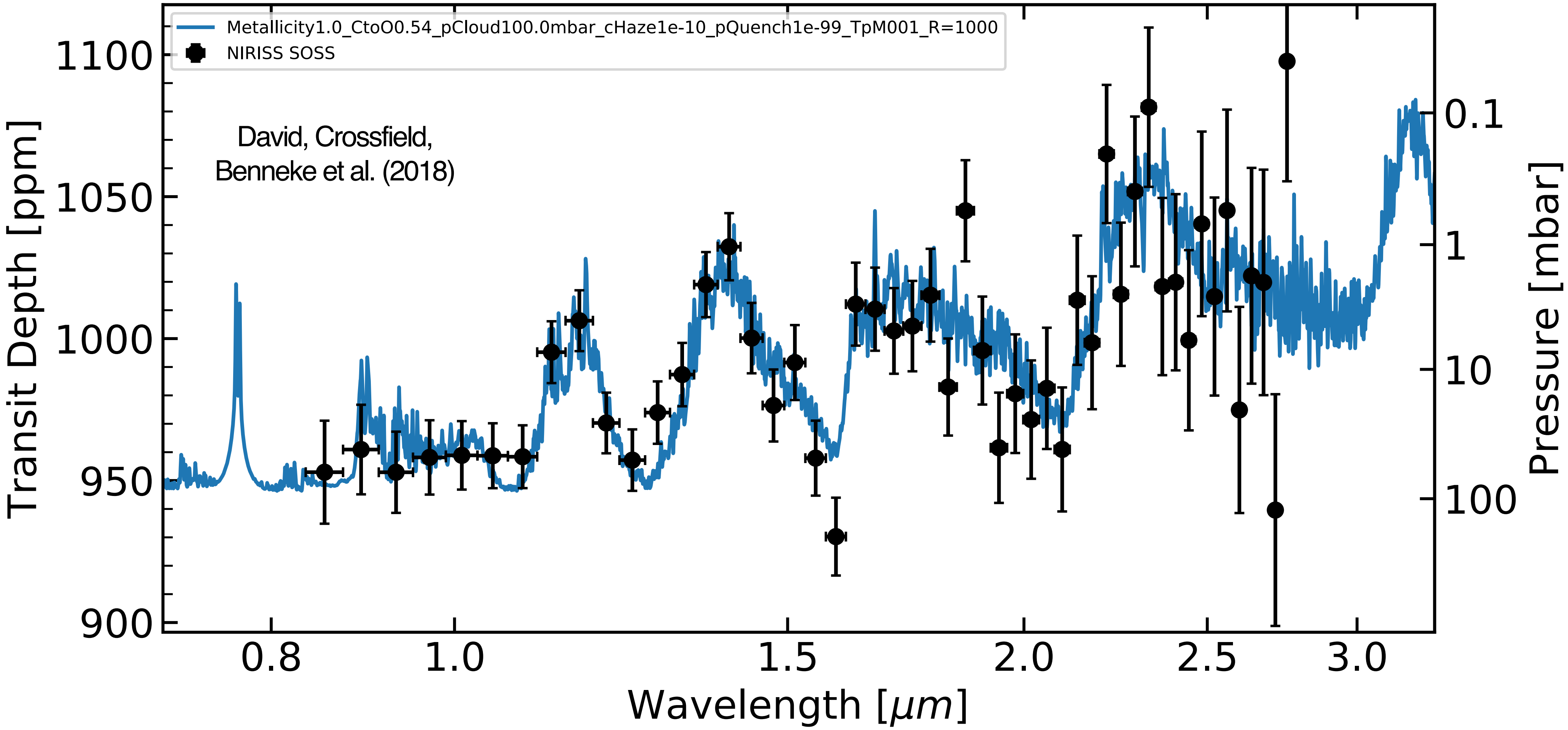
The power of gyrochronology



period-color-age relations

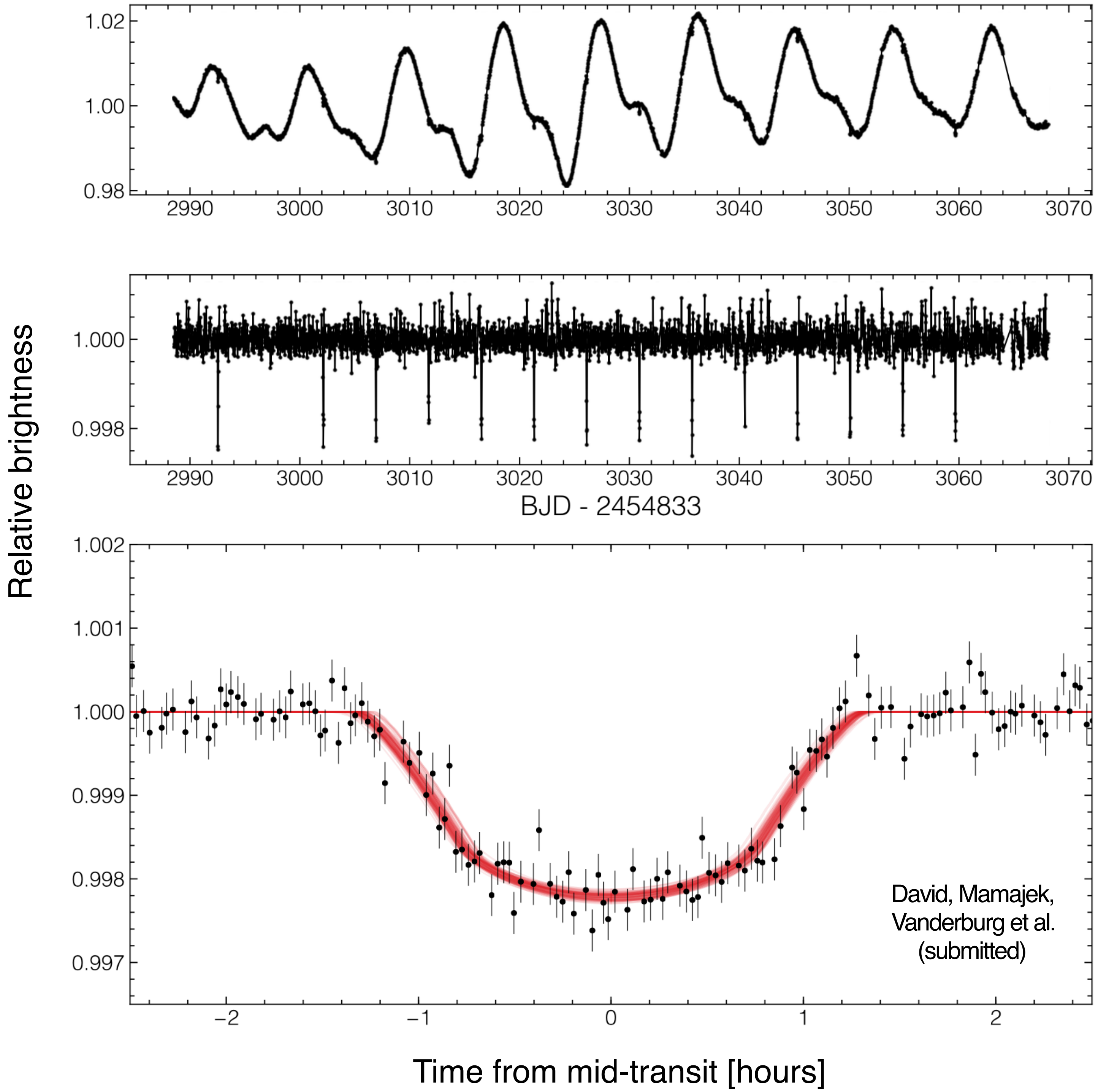
Barnes (2007),
Barnes et al. (2010),
Mamajek &
Hillenbrand (2008),
Angus et al. (2015)

K2-233 d: a tractable target for James Webb



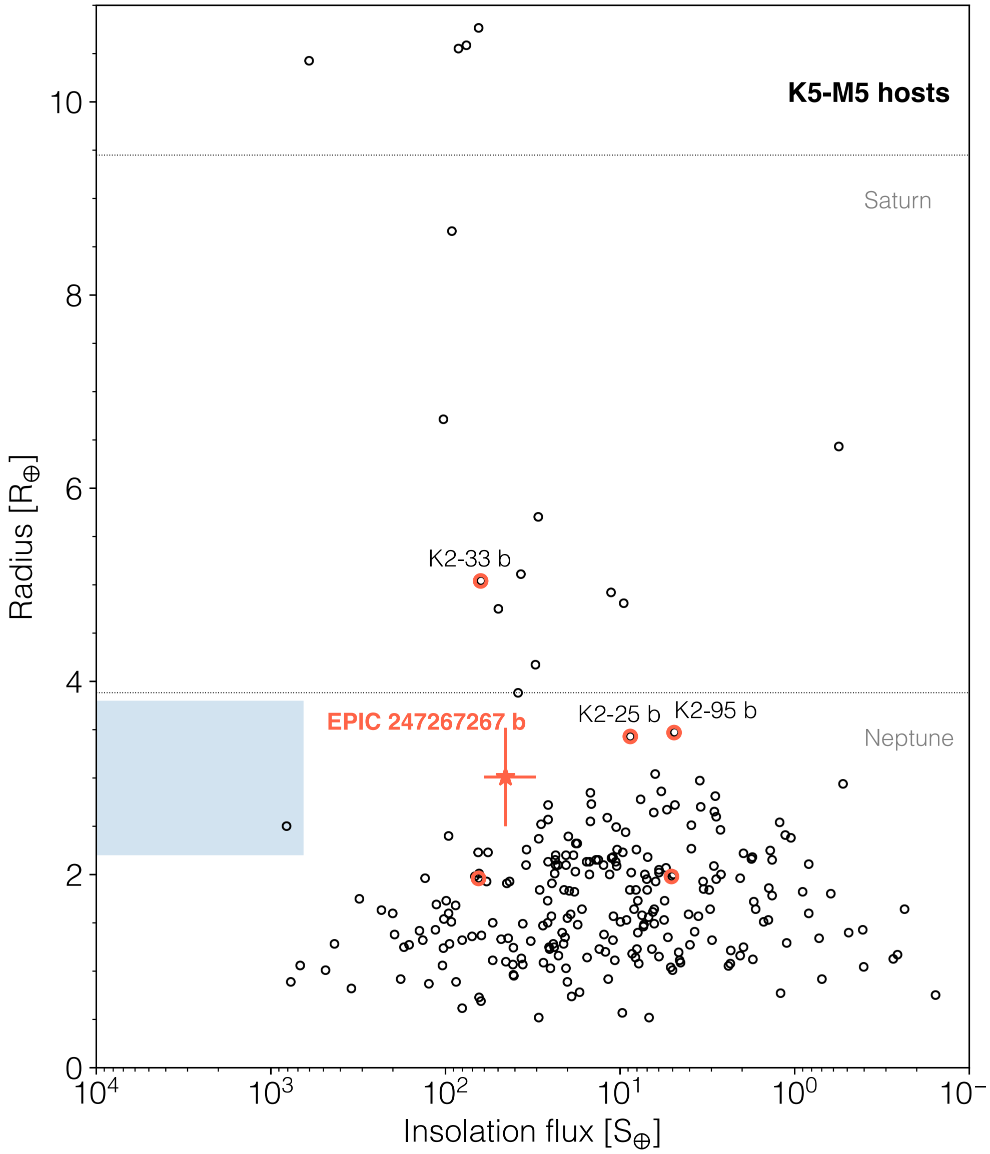
transit depth variations could be detected in K2-233 d
with a single *JWST* visit

An adolescent sub-Neptune in the Cas-Tau association

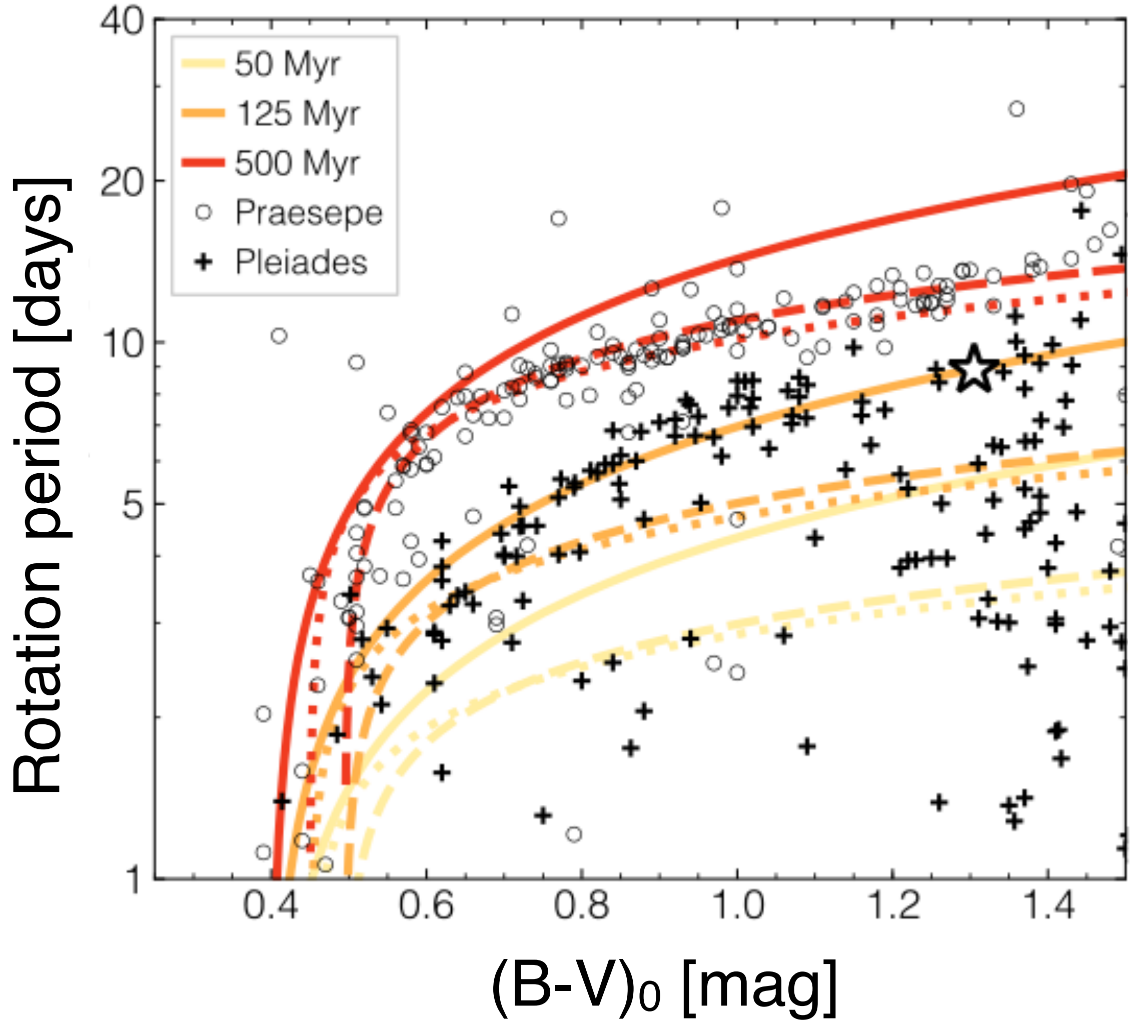


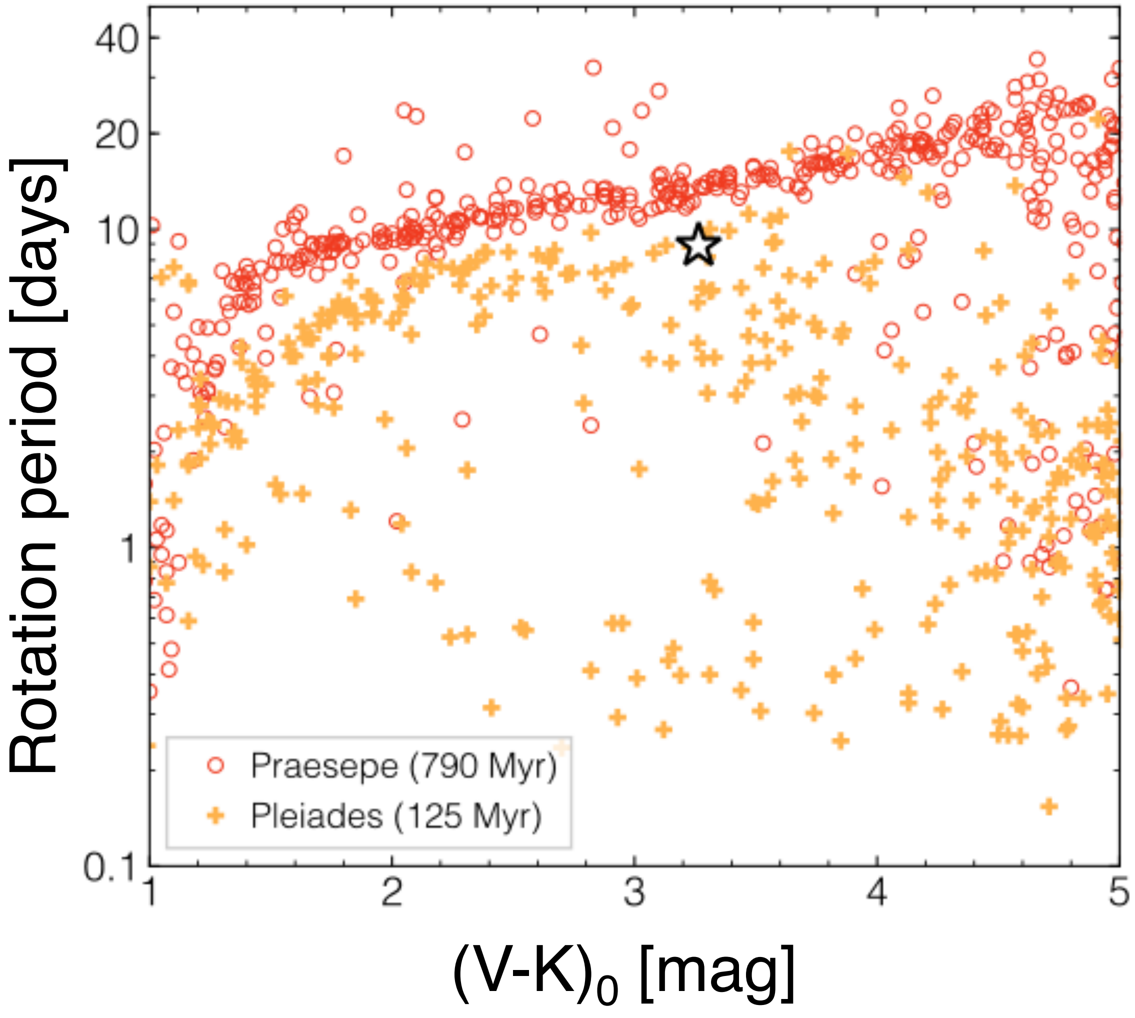
David, Mamajek, Vanderburg et al. (submitted)

EPIC 247267267 (Kp = 12.8)
Campaign 13
Prot = 8.88 d, 4% photometric variability
Kinematics point to
membership with Cas-Tau **(~50-90 Myr)**



Gyrochronology ages

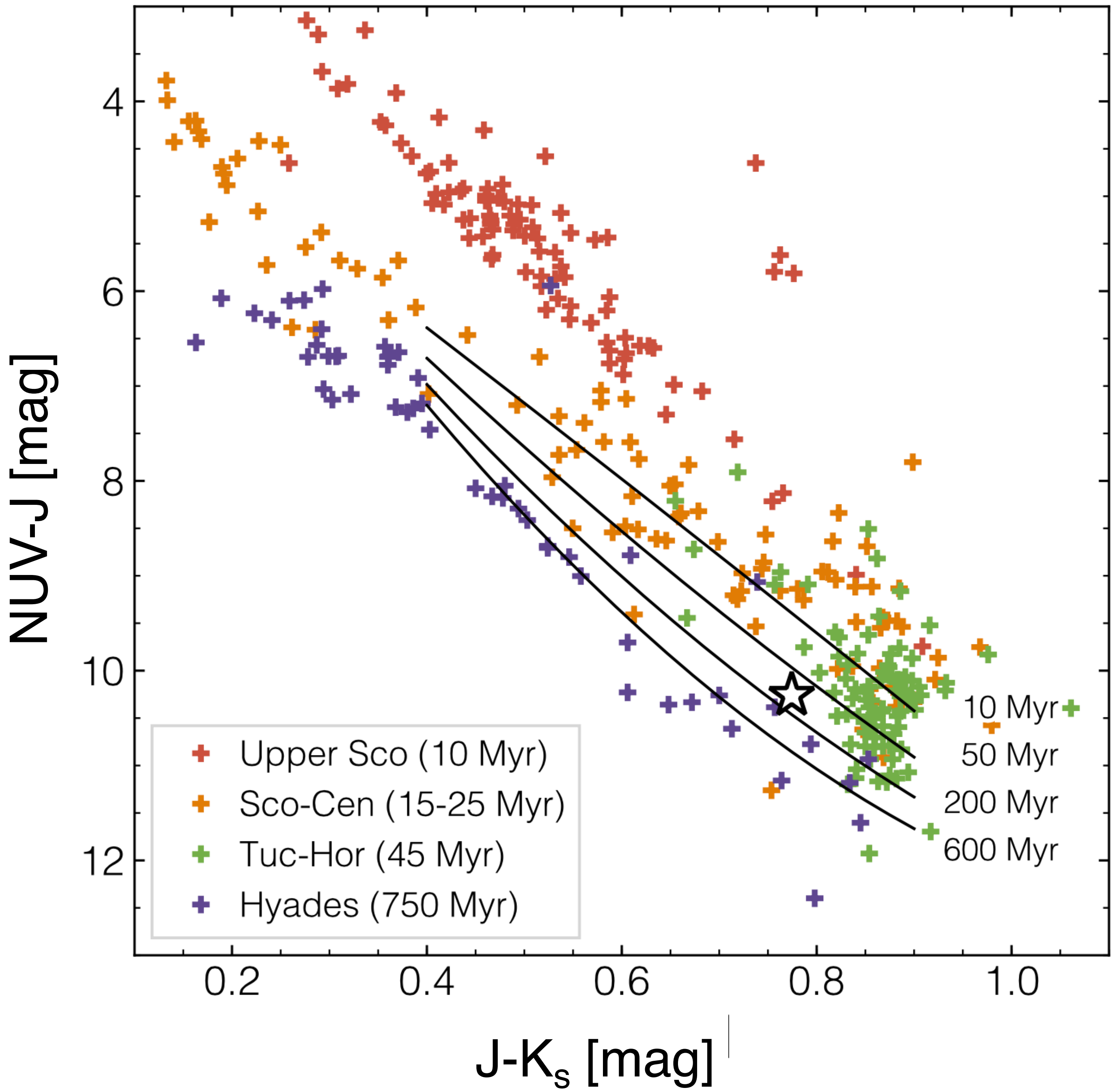




Periods from Rebull et al. (2016,2017)
Solid: Barnes (2007)
Dashed: Mamajek & Hillenbrand (2008)
Dot-dashed: Angus et al. (2015)

τ = 124 ± 15 Myr (Barnes 2007)
τ = 262 ± 40 Myr (Mamajek & Hillenbrand 2008)
*Note: gyrochronology not applicable on pre-MS

Stellar activity

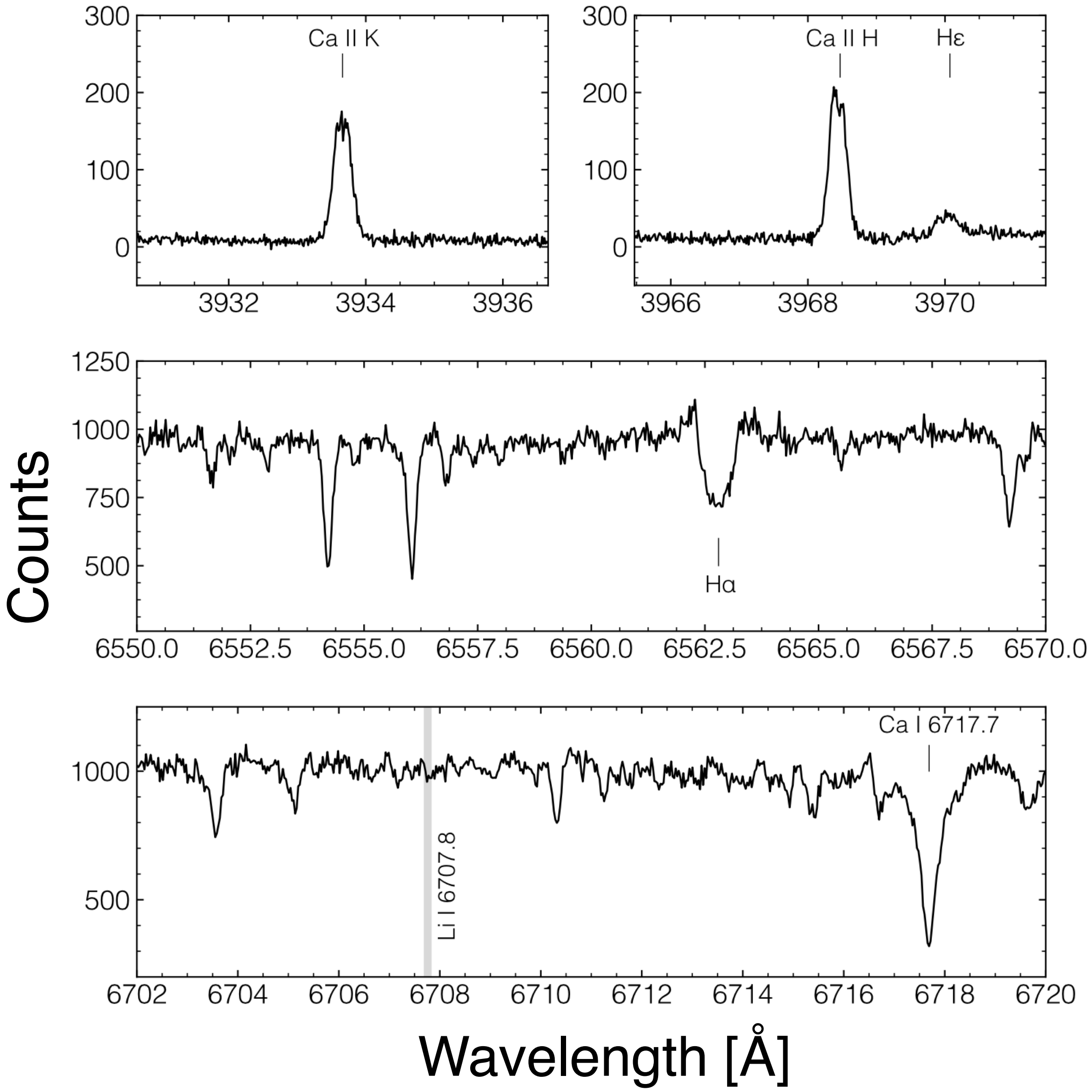


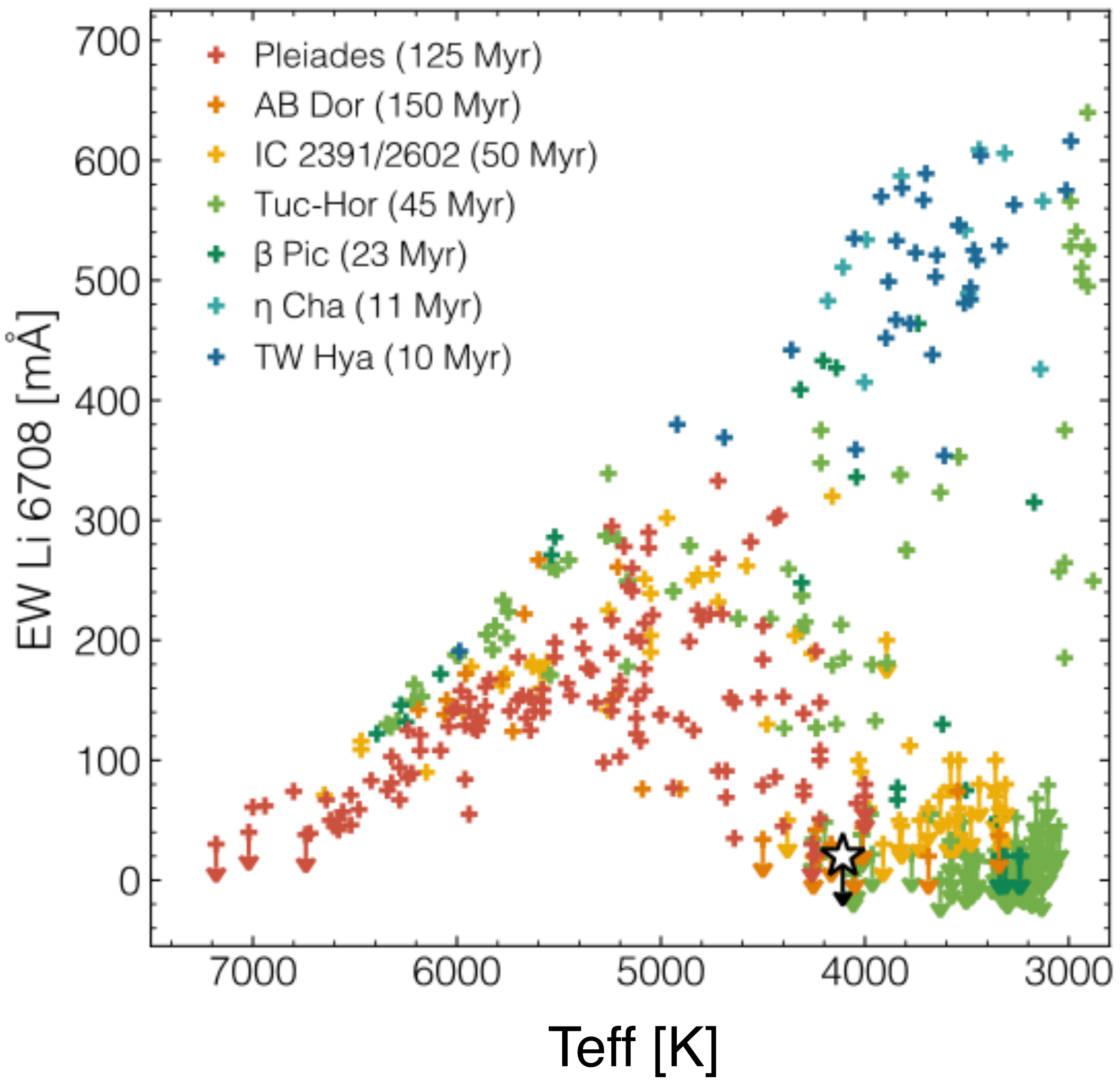
Chromospheric
emission in the UV
is correlated with age

Shkolnik et al. 2011
Rodriguez et al. 2011
Findeisen & Hillenbrand
2011

τ = 110 (+160, -65) Myr

Spectroscopic age indicators



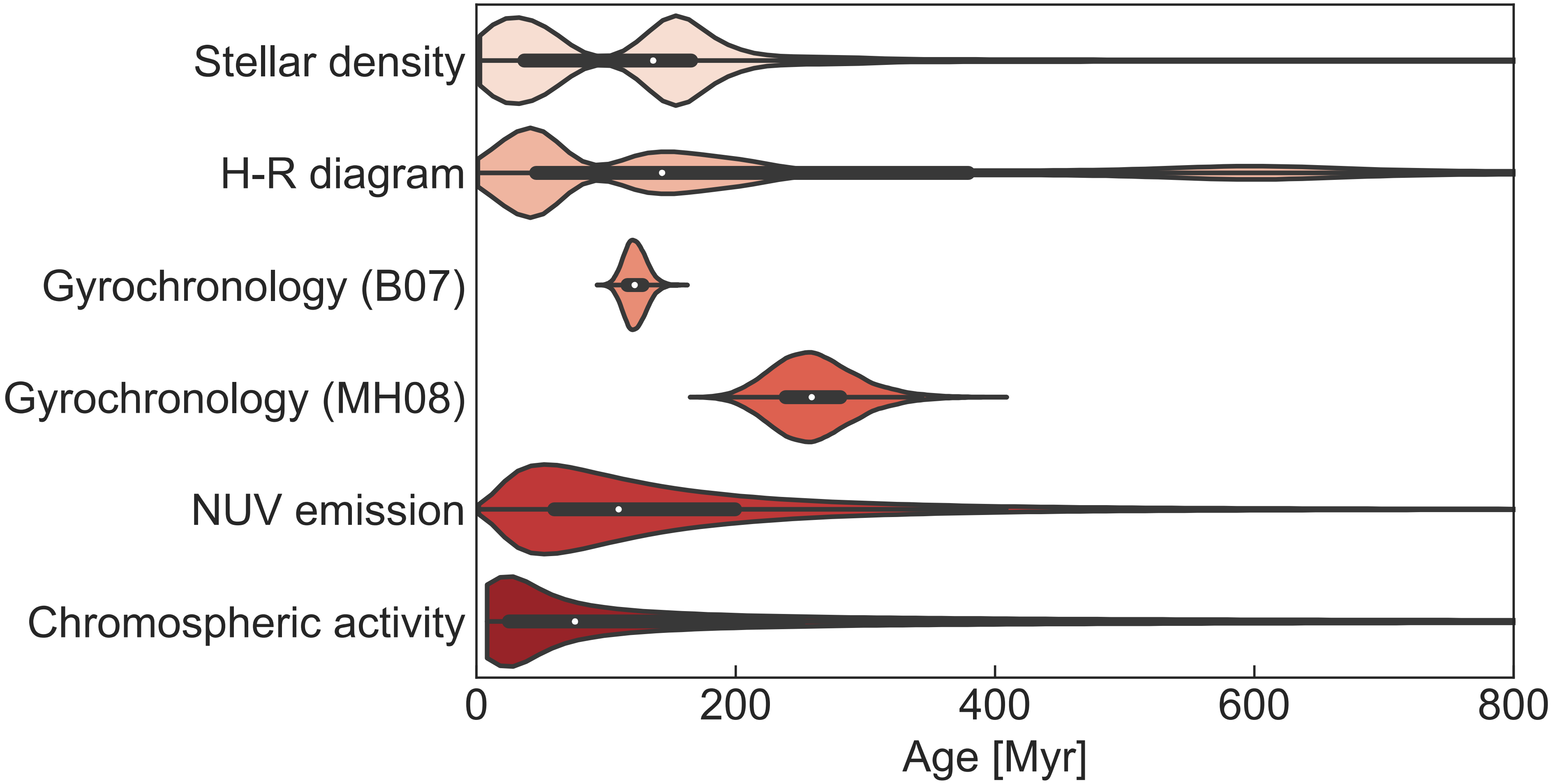


- Strong Ca II H&K emission
- Some Balmer line emission
- Hα in absorption, wings in emission
- No lithium

Spectroscopic characteristics are consistent with ~Pleiades age

Slower rotators show less lithium (Bouvier et al. 2017)

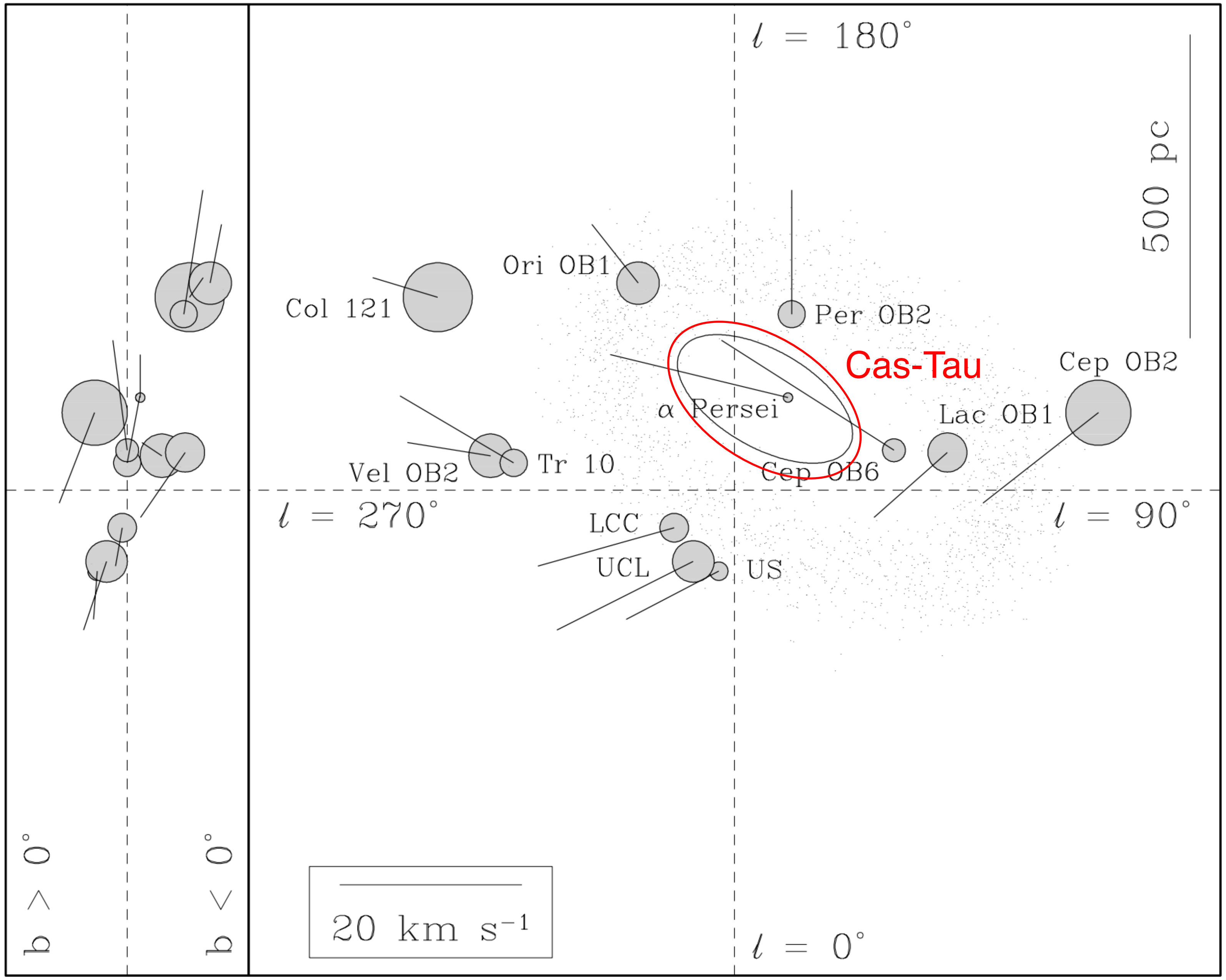
Age of EPIC 247267267



David, Mamajek,
Vanderburg et al.
2018 (in review)

- Independent methods agree on a range of 50-500 Myr at 68% confidence.
- Caveats: gyrochronology not applicable if star is pre-MS and, along with activity relations, these are statistical age indicators
- Kinematics point to younger end of this age range (50-90 Myr)

The Cas-Tau association



de Zeeuw et al. (1999)

1921 Rasmuson notes stream of BA stars co-moving with α Per, far from cluster core

1956 Blaauw suggests a new association, “Cas-Tau,” from kinematics of 49 B stars

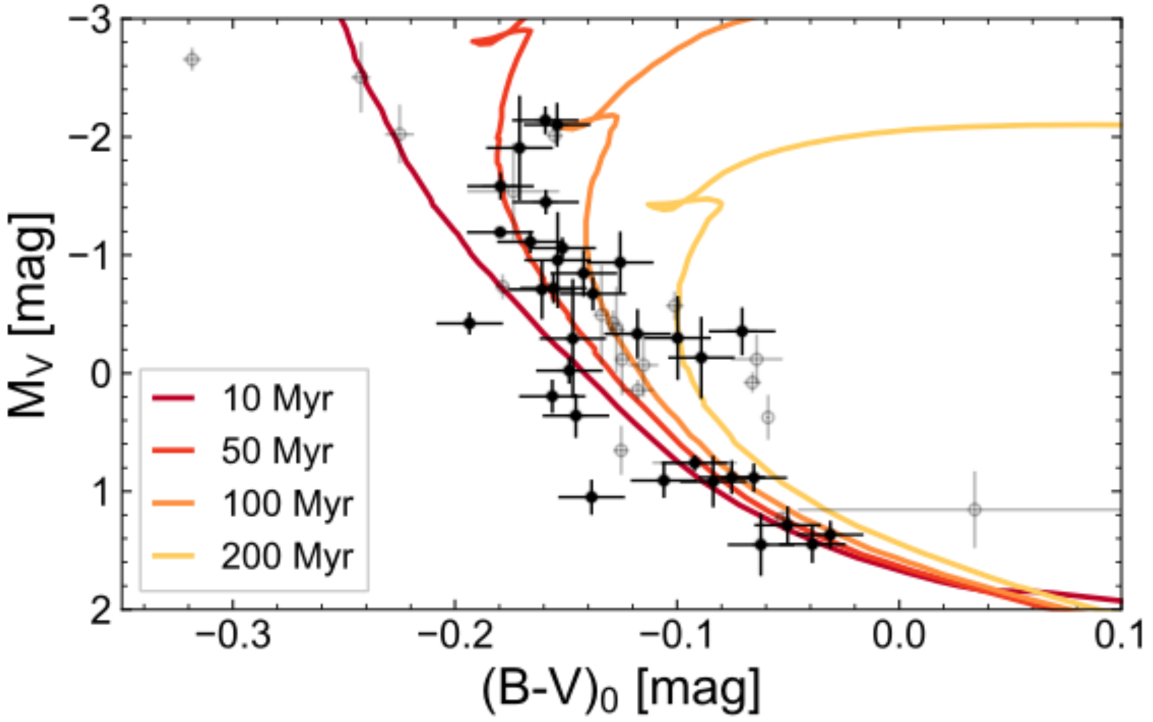
1958 Petrie challenges on basis of RV scatter

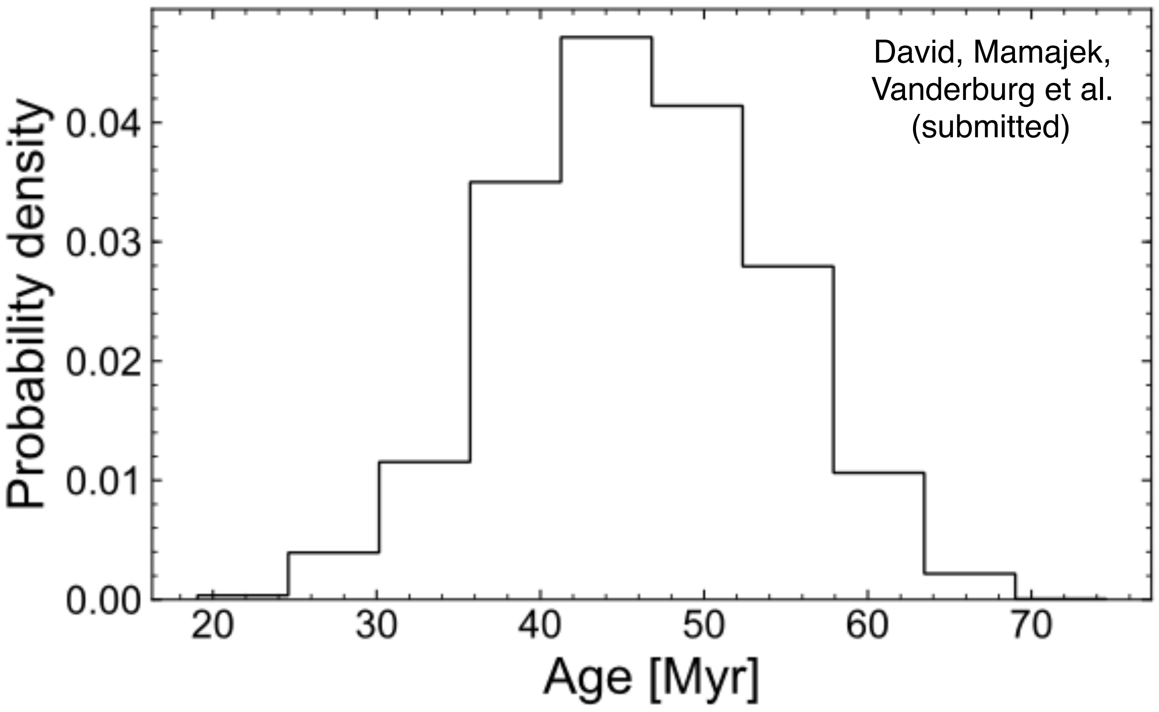
1963 Crawford challenges due to scatter in CMD

1999 de Zeeuw et al. conclude from *HIPPARCOS* data Cas-Tau is a *bona fide* association, though keeping only 1/3 of Blaauw’s original members

covers ~15% of the sky

A new turnoff age for Cas-Tau

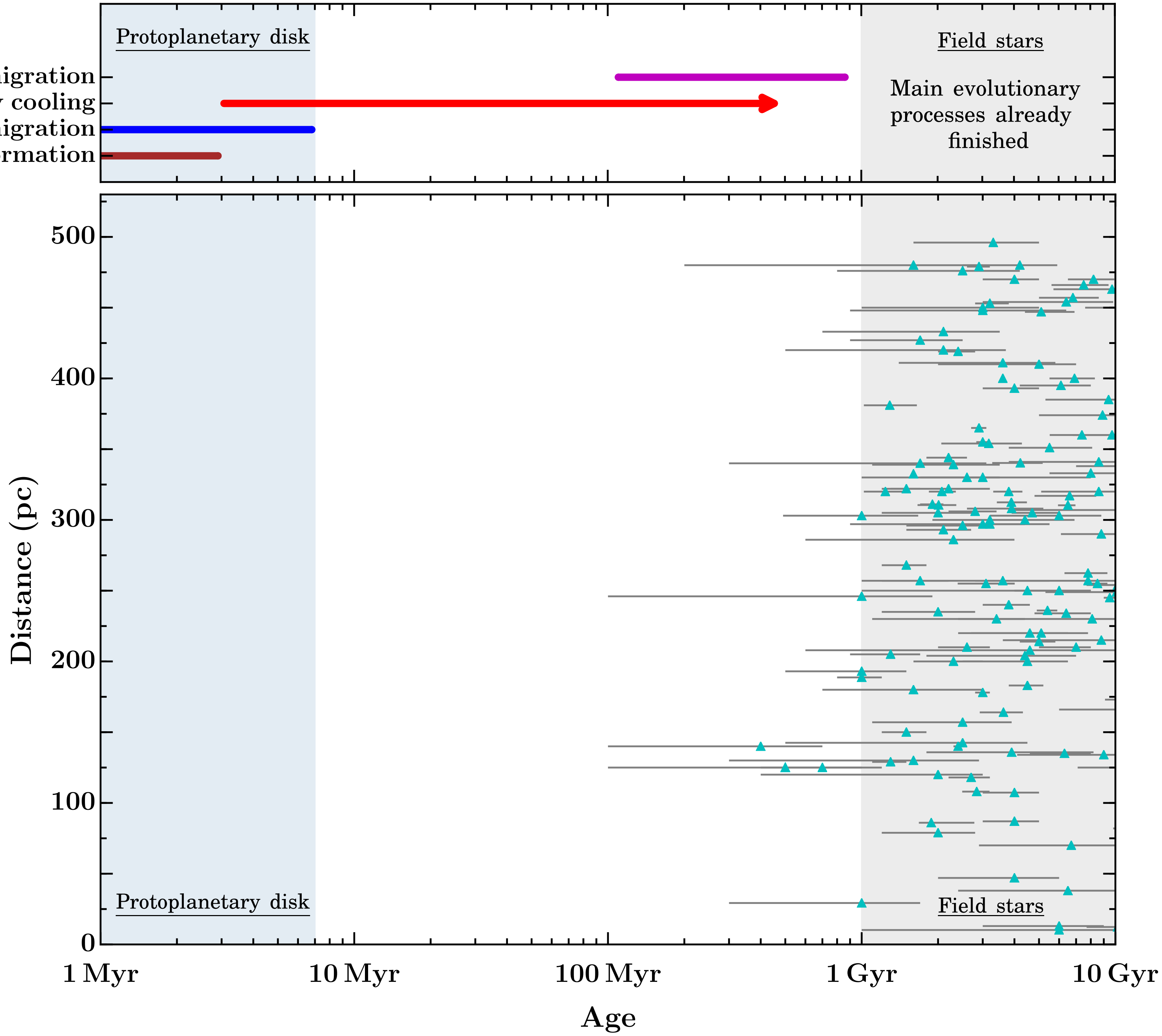




David, Mamajek,
Vanderburg et al.
(submitted)

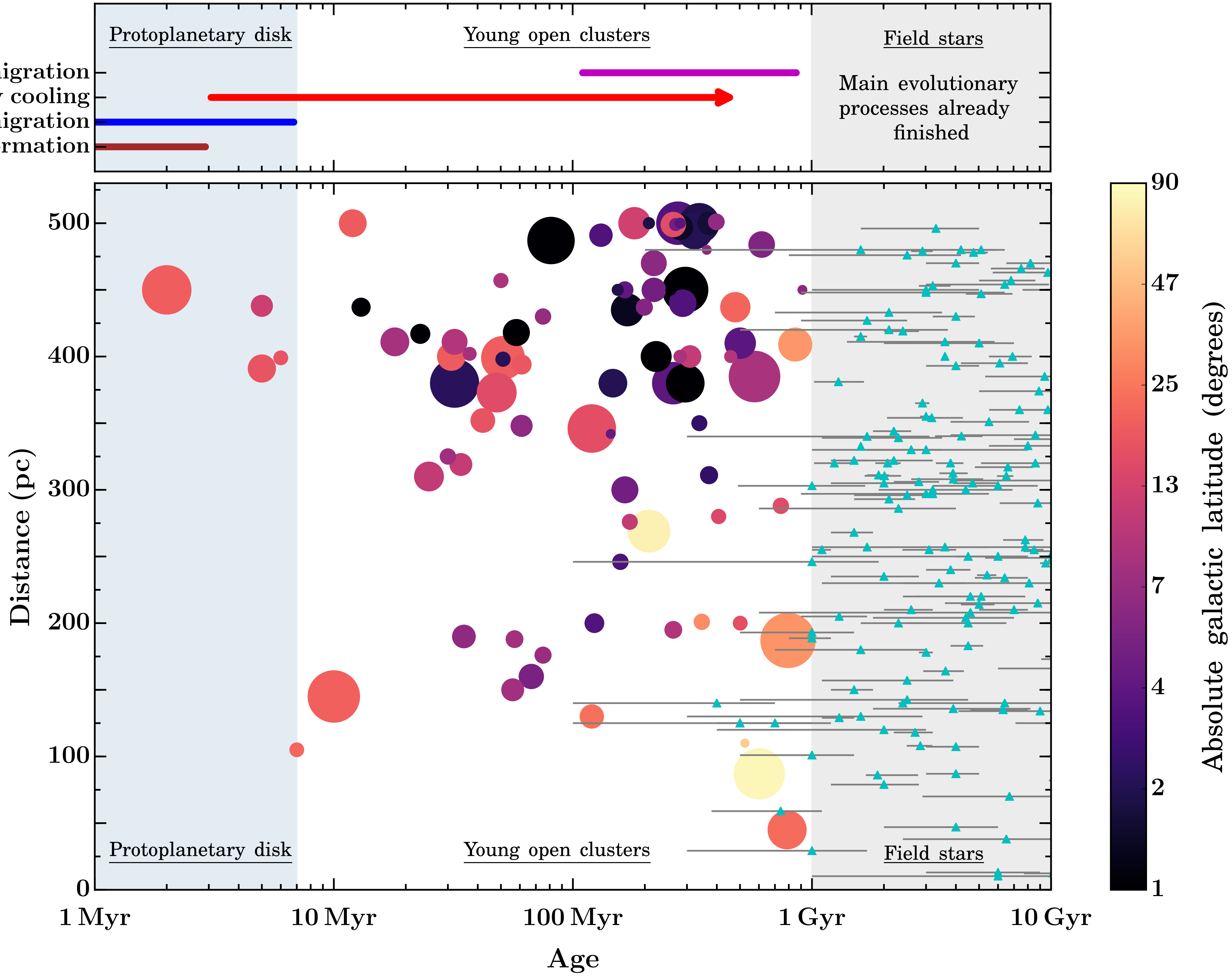
de Zeeuw et al. (1999) suggested 83 members
Color-magnitude diagram constructed from *UBV* photometry (Mermilliod 2006)
and *Hipparcos/Gaia DR1* parallaxes
Exclude low probability (<90%) members, EBs, emission line stars
Age = 46 ± 8 Myr
(c.f. Blaauw 1956 kinematic estimate of 50-70 Myr,
de Zeeuw & Brand 1985 turnoff age of 20-30 Myr)

Young clusters as a window into exoplanet evolution

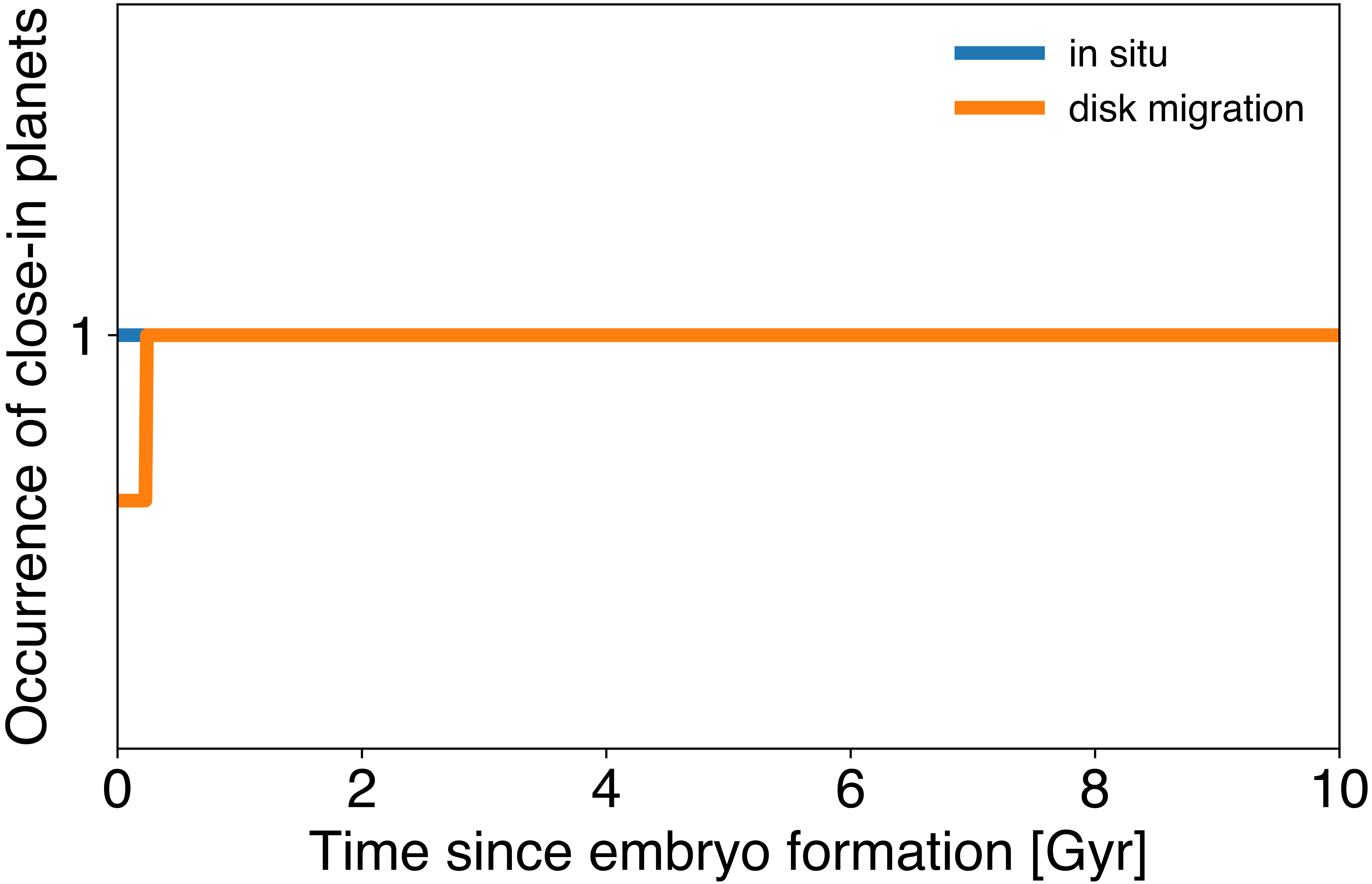


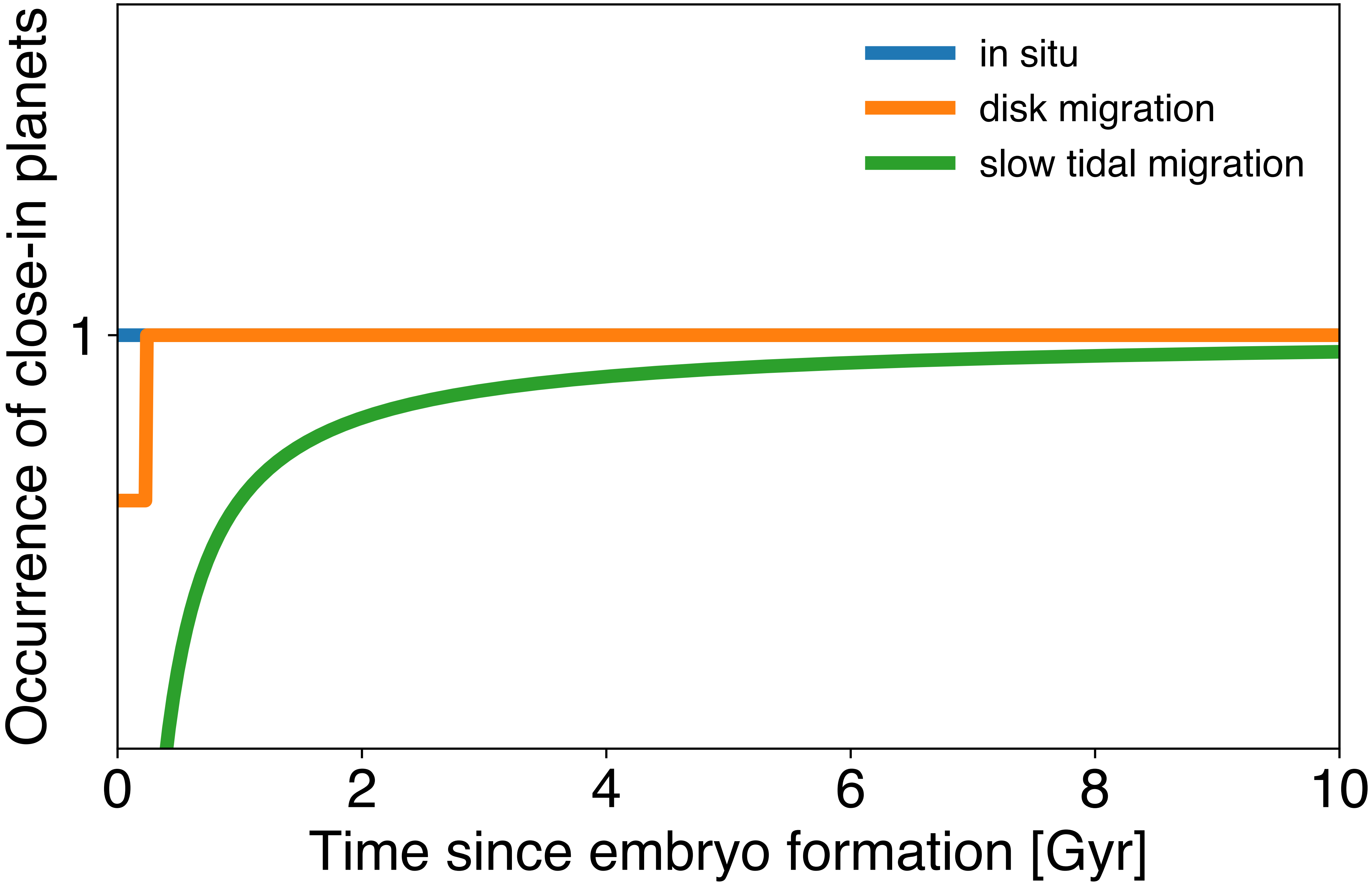
slide:
E. Gillen

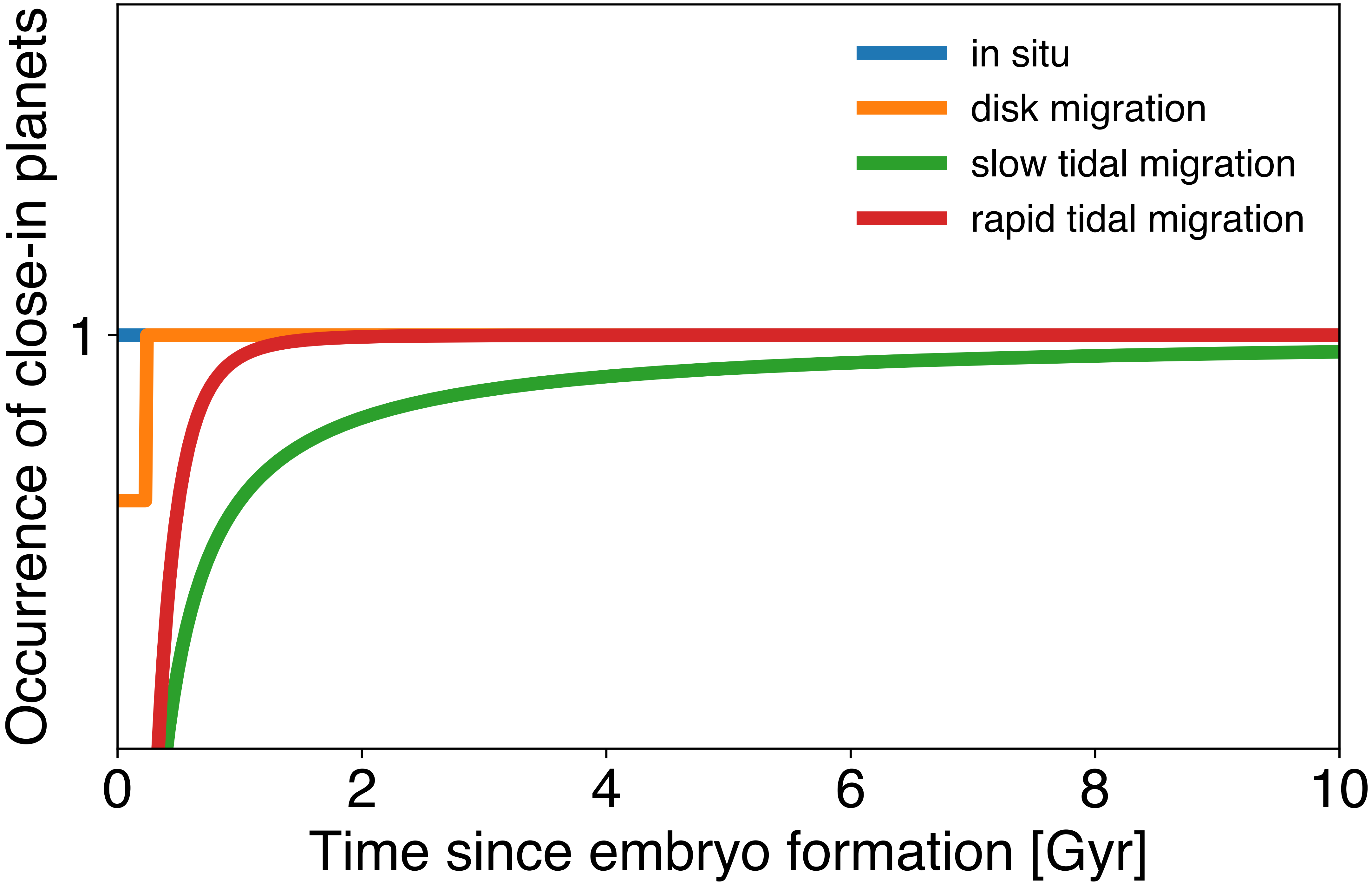
Young clusters as a window into exoplanet evolution

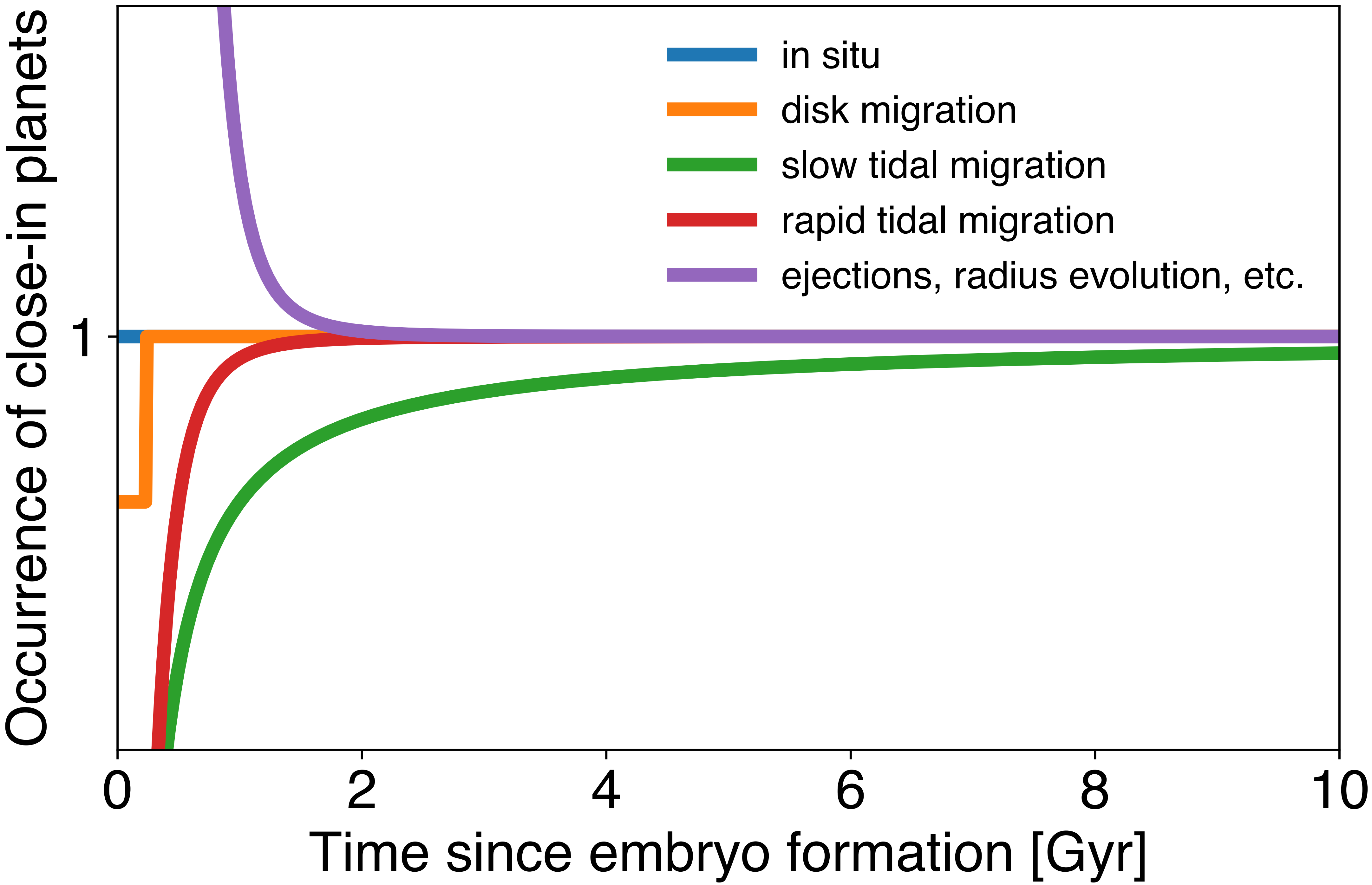


slide:
E. Gillen


in situ
disk migration
Occurrence of close-in planets
1
0
2
4
6
8
10
Time since embryo formation [Gyr]


in situ
disk migration
slow tidal migration
Occurrence of close-in planets
1
0
2
4
6
8
10
Time since embryo formation [Gyr]


in situ
disk migration
slow tidal migration
rapid tidal migration
1
Occurrence of close-in planets
0
2
4
6
8
10
Time since embryo formation [Gyr]


in situ
disk migration
slow tidal migration
rapid tidal migration
ejections, radius evolution, etc.
1
0
2
4
6
8
10
Occurrence of close-in planets
Time since embryo formation [Gyr]