Exoplanets in star clusters

(associations & moving groups)

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PLATO Science in Italy Workshop: ready to PLATO data exploitation?
INAF Catania - September 27th, 2023

Galactic Field stars …

HD 108236: 5 planets but …

Young **or** **old?**

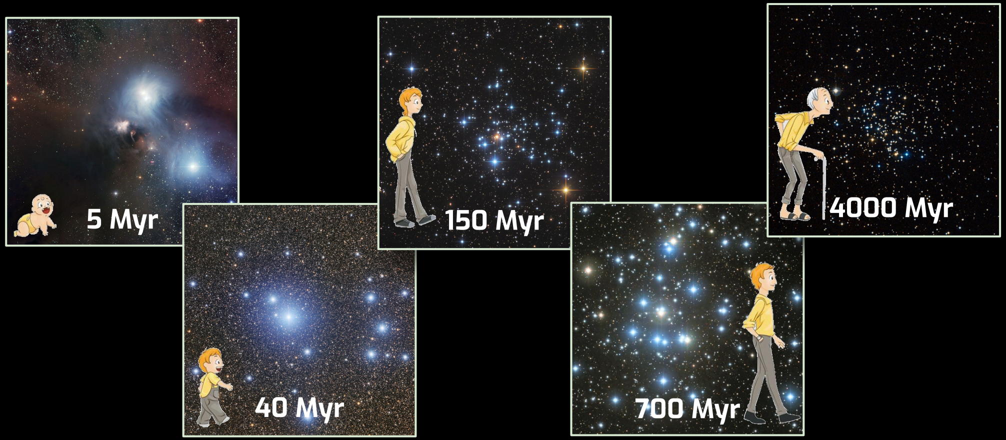
…vs. Star Clusters' members

- Coeval stars at same **distance** and sharing the same **chemical properties**
- Many (accurate) methods to measure the **age**:
  - theoretical models (e.g. isochrones)
  - empirical approaches (e.g. gyrochronology)
- **Small uncertainties** on the age estimate, but also on stellar parameters (R_*, M_*, T_{eff}, etc.)

Why should we look for exoplanets in stellar clusters and associations?

★ Accurate stellar parameters (radii, masses, temperatures, chemical properties, etc.) result in **precise planetary characteristics**

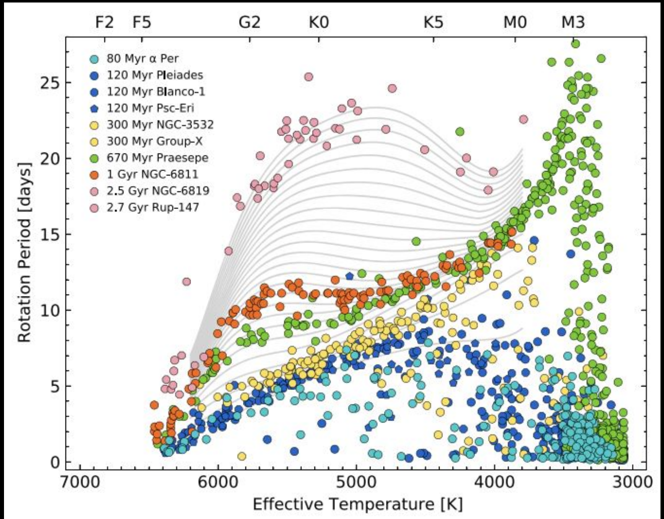
★ Star clusters allow us to follow the **temporal evolution** of exoplanets, from the earliest stages of their formation until they become elderly



Credits: (1) R Corona Australis (ESO); (2) IC 2602 (Casey Good) ; (3) NGC 2516 (Buenos Aires Skies) ; (4) M44 (G. Donatiello); (5) M67 (Palomar Obs./STScI); (6) HD108236 (DSS2)

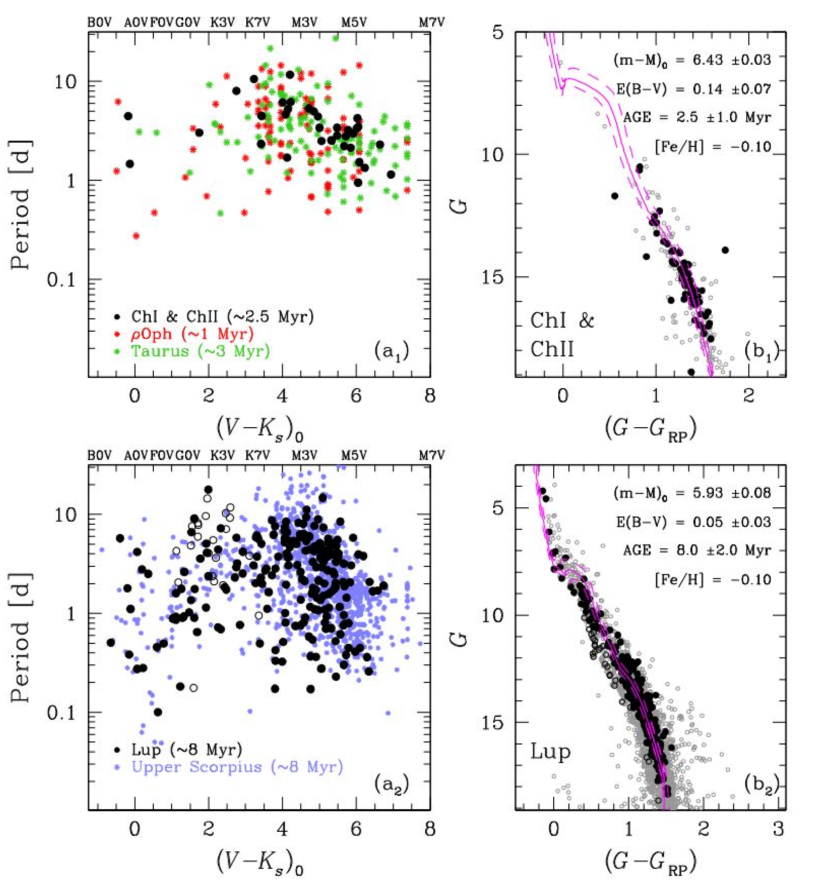
The age of the stars in clusters from light curves

Curtis et al. (2019)



Gyrochronology:
not dependent on the distance
No an universal calibration for now, only relative comparisons.

Isochrone fitting + Gyrochronology:
e.g., useful in the case of very young association for which single methods are inadequate to constrain the age

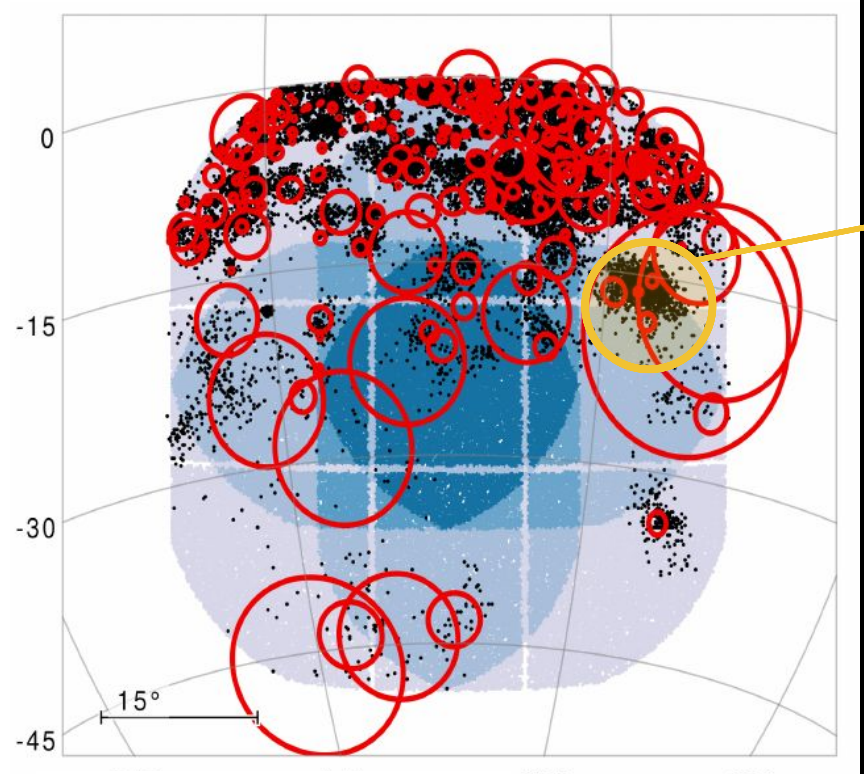


Nardiello (2020)

See Monday talks!

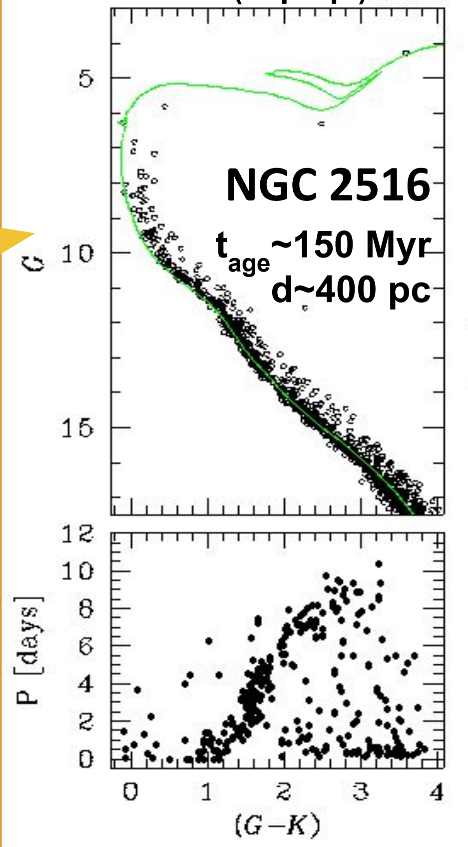
The age of the stars in clusters from light curves: the example of NGC 2516

Stellar clusters and associations in **LOPS2** field
(see Valerio's talk!)



Nascimbeni et al. (in prep.)

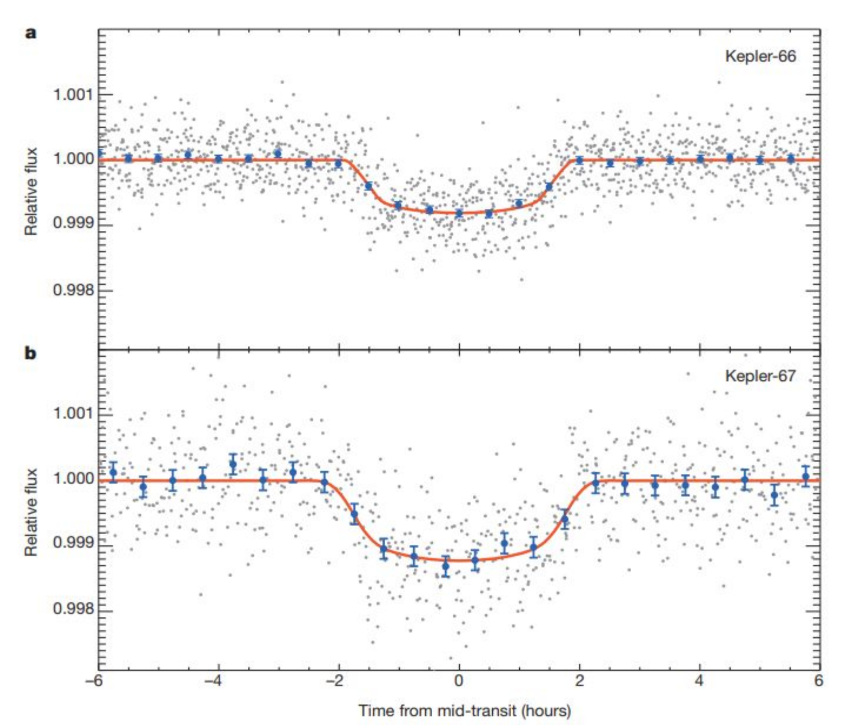
Nardiello et al. (in prep.)



Many cluster have already been observed by TESS in several sectors, the difficulties to "stack" the light curves of different sectors limited the P-color analysis to short periods (≲ 10 d).

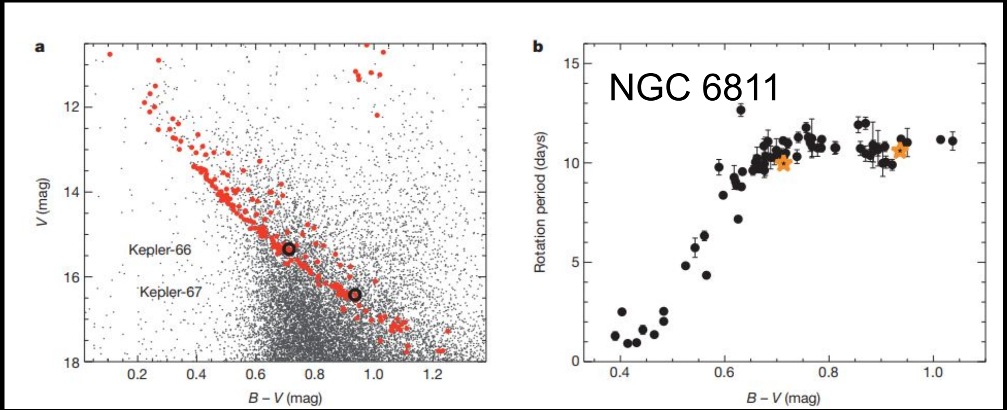
PLATO's (≳)2yr uninterrupted observations of star clusters will allow longer rotation periods to be measured (especially for old star clusters).

The first discovered transiting exoplanets in an **open cluster**



Stellar properties	Kepler-66	Kepler-67
Right ascension	19 h 35 min 55.573 s	19 h 36 min 36.799 s
Declination	46° 41′ 15.906″	46° 09′ 59.181″
Spectral type	G0V	G9V
Effective temperature, T_{eff} (K)	5,962 ± 79	5,331 ± 63
log[Surface gravity (cm s^{-2})]	4.484 ± 0.023	4.594 ± 0.022
Rotation period (days)	9.97 ± 0.16	10.61 ± 0.04
Mass (solar masses)	1.038 ± 0.044	0.865 ± 0.034
Radius (solar radii)	0.966 ± 0.042	0.778 ± 0.031
Density (solar)	1.15 ± 0.15	1.89 ± 0.17
Visual magnitude, V	15.3	16.4
Age (billion years)	1.00 ± 0.17	
Distance (parsec)	1,107 ± 90	
Metallicity, Z	0.012 ± 0.003	

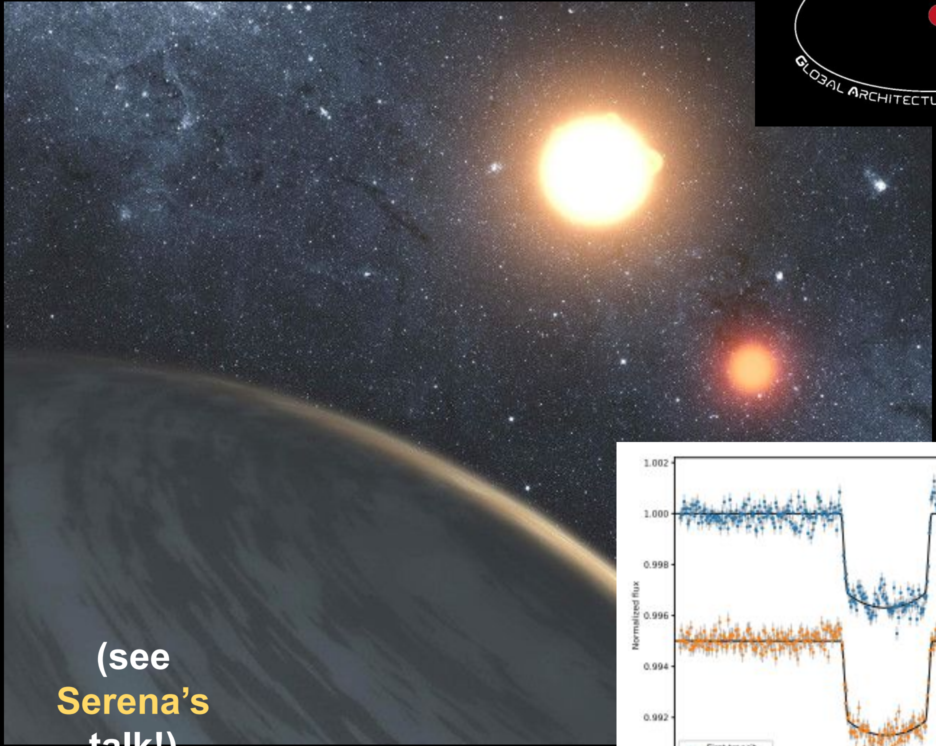
Planetary parameters	Kepler-66b	Kepler-67b
Orbital period (days)	17.815815 ± 0.000075	15.72590 ± 0.00011
Impact parameter	0.56 ± 0.26	0.37 ± 0.21
Time of mid-transit (BJD)	2454967.4854 ± 0.0025	2454966.9855 ± 0.0048
Planet-to-star radius ratio	0.02646 ± 0.00097	0.03451 ± 0.0013
Scaled semi-major axis (a/R_{star})	30.3 ± 1.0	32.4 ± 1.1
Semi-major axis (AU)	0.1352 ± 0.0017	0.1171 ± 0.0015
Radius ($R_{\oplus}$)	2.80 ± 0.16	2.94 ± 0.16



Discovered by Kepler

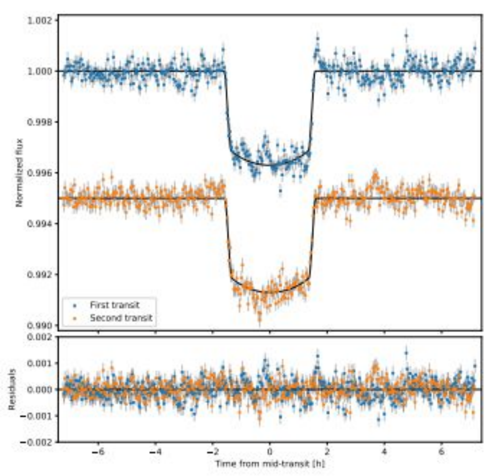
Meibom et al. (2013)

DS Tuc A + DS Tuc B + DS Tuc A b

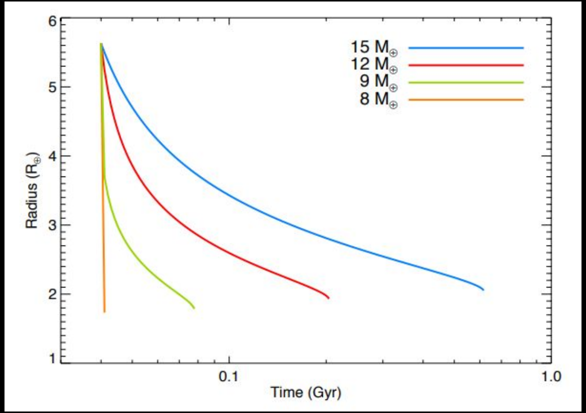


(see Serena's talk!)

Discovered by TESS

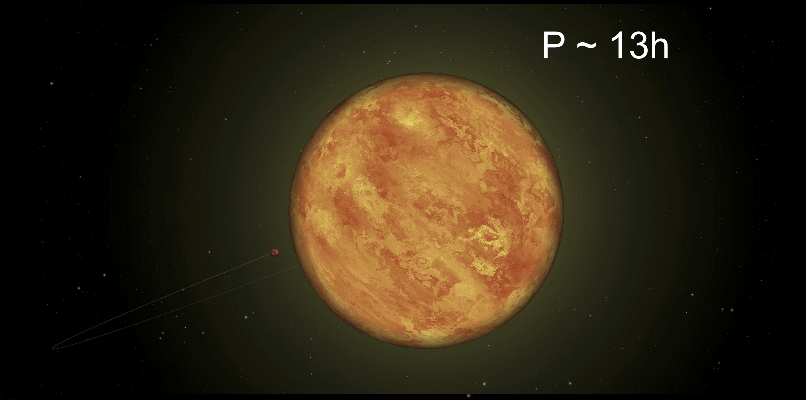


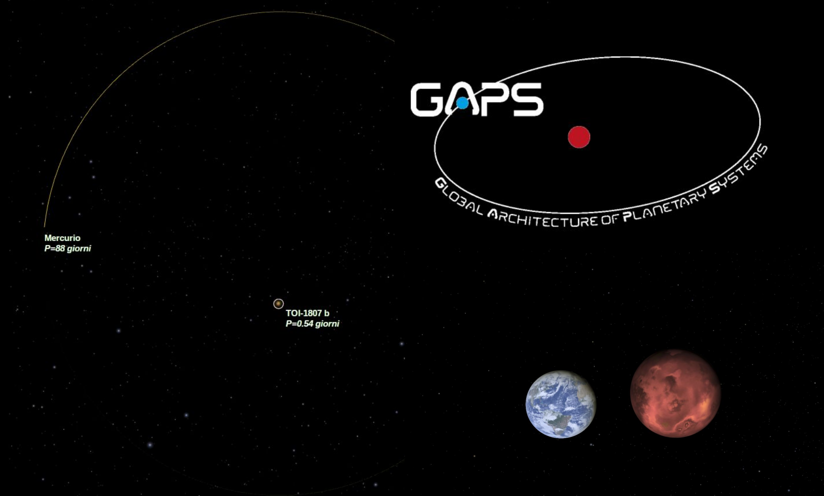
- Binary system formed by G6 + K3 star
- Members of Tuc-Hor **association**
- Age = 40 +/- 5 Myr
- Planet orbits DS Tuc A
- Radius = 5.6 R_{Earth}
- Mass < 15 M_{Earth}
- Possible inflated planet
- Expected final radius ~ 2 R_{Earth}



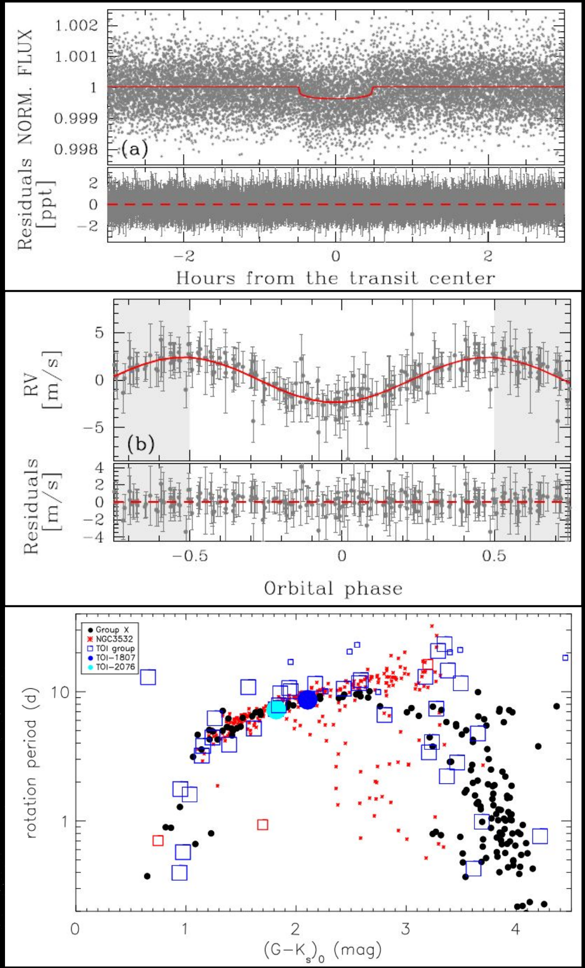
Benatti et al. (2019, 2021)

TOI-1807b





Nardiello et al. (2022)



- Member of 300+/80 Myr **moving group**
- The **youngest** ultra-short period planet (P~13h)
- To date, TOI-1807b is the **only** young super-Earth with a precise mass determination
- Radius = 1.37+/-0.09 $R_\oplus$
- Mass = 2.57 +/- 0.50 $M_\oplus$
- density= 1.04 +/- 0.28 $\rho_\oplus$

Transiting exoplanets with a well constrained age

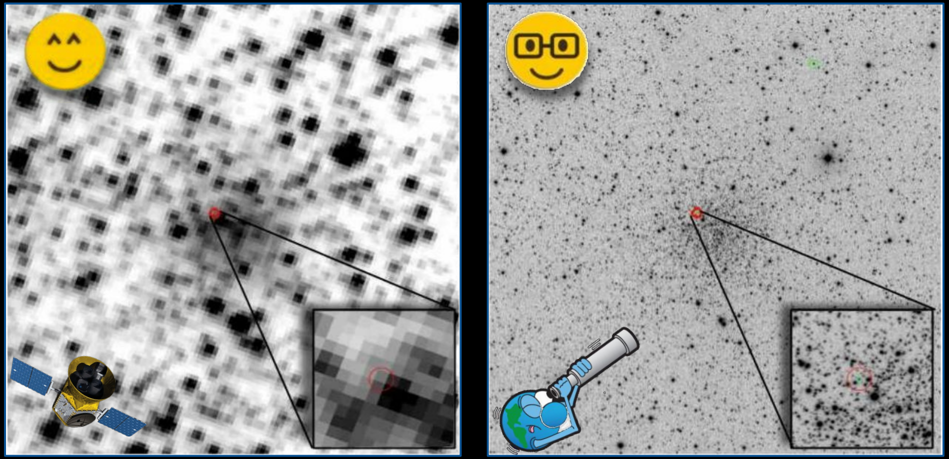
Object	Cluster/Association	Age (Myr)	R_P ($R_\oplus$)	Reference	Object	Cluster/Association	Age (Myr)	R_P ($R_\oplus$)	Reference
K2-33 b	Upp-Sco	$9.3^{+1.1}_{-1.1}$	$5.04^{+0.34}_{-0.37}$	Mann et al. (2016b)	TOI-2076 c	TOI-1807 MG	300^{+80}_{-80}	$3.50^{+0.04}_{-0.04}$	Osborn et al. (2022)
TOI-1227 b	Low Cen Crux OB	11^{+2}_{-2}	$9.6^{+0.8}_{-0.6}$	Mann et al. (2022)	TOI-2076 d	TOI-1807 MG	300^{+80}_{-80}	$3.23^{+0.06}_{-0.06}$	Osborn et al. (2022)
HIP 67522 b	Sco-Cen	17^{+2}_{-2}	$10.07^{+0.47}_{-0.47}$	Rizzuto et al. (2020)	HD 63433 b	UMa	414^{+23}_{-23}	$2.15^{+0.10}_{-0.10}$	Mann et al. (2020)
AU Mic b	AU Mic	22^{+3}_{-3}	$4.07^{+0.17}_{-0.17}$	Martioli et al. (2021)	HD 63433 c	UMa	414^{+23}_{-23}	$2.67^{+0.12}_{-0.12}$	Mann et al. (2020)
AU Mic c	AU Mic	22^{+3}_{-3}	$3.24^{+0.16}_{-0.16}$	Martioli et al. (2021)	K2-95 b	Praesepe	670^{+100}_{-100}	$3.7^{+0.2}_{-0.2}$	Mann et al. (2017)
V 1298 Tau b	Tau	23^{+4}_{-4}	$9.53^{+0.32}_{-0.32}$	Feinstein et al. (2022)	K2-100 b	Praesepe	670^{+100}_{-100}	$3.8^{+0.2}_{-0.2}$	Barragán et al. (2019)
V 1298 Tau c	Tau	23^{+4}_{-4}	$5.05^{+0.14}_{-0.14}$	Feinstein et al. (2022)	K2-101 b	Praesepe	670^{+100}_{-100}	$3.0^{+0.1}_{-0.1}$	Mann et al. (2017)
V 1298 Tau d	Tau	23^{+4}_{-4}	$6.13^{+0.28}_{-0.28}$	Feinstein et al. (2022)	K2-102 b	Praesepe	670^{+100}_{-100}	$1.3^{+0.1}_{-0.1}$	Mann et al. (2017)
V 1298 Tau e	Tau	23^{+4}_{-4}	$9.94^{+0.39}_{-0.39}$	Feinstein et al. (2022)	K2-103 b	Praesepe	670^{+100}_{-100}	$2.2^{+0.2}_{-0.1}$	Mann et al. (2017)
KOI-7368 b	Cep-Her	36^{+10}_{-8}	$2.22^{+0.12}_{-0.12}$	Bouma et al. (2022b)	K2-104 b	Praesepe	670^{+100}_{-100}	$1.9^{+0.2}_{-0.1}$	Mann et al. (2017)
KOI-7913 b	Cep-Her	36^{+10}_{-8}	$2.34^{+0.12}_{-0.18}$	Bouma et al. (2022b)	K2-264 b	Praesepe	670^{+100}_{-100}	$2.27^{+0.20}_{-0.16}$	Rizzuto et al. (2018)
Kepler-1627 b	δ Lyr	38^{+6}_{-5}	$3.78^{+0.16}_{-0.16}$	Bouma et al. (2022a)	K2-264 c	Praesepe	670^{+100}_{-100}	$2.77^{+0.20}_{-0.18}$	Rizzuto et al. (2018)
DS TUcA b	Tuc-Hor	40^{+5}_{-5}	$5.63^{+0.22}_{-0.21}$	Benatti et al. (2019)	HD 283869 b	Hyades	730^{+100}_{-100}	$1.96^{+0.13}_{-0.16}$	Vanderburg et al. (2018)
Kepler-1643 b	Cep-Her	46^{+9}_{-7}	$2.32^{+0.14}_{-0.14}$	Bouma et al. (2022b)	K2-25 b	Hyades	730^{+100}_{-100}	$3.43^{+0.95}_{-0.31}$	Mann et al. (2016a)
K2-284 b	Cas-Tau	120^{+640}_{-20}	$2.78^{+0.14}_{-0.12}$	David et al. (2018)	K2-136A b	Hyades	730^{+100}_{-100}	$0.99^{+0.06}_{-0.04}$	Mann et al. (2018)
TOI-451 b	Psc-Eri	$134^{+6.5}_{-6.5}$	$1.91^{+0.12}_{-0.12}$	Newton et al. (2021)	K2-136A c	Hyades	730^{+100}_{-100}	$2.91^{+0.11}_{-0.10}$	Mann et al. (2018)
TOI-451 c	Psc-Eri	$134^{+6.5}_{-6.5}$	$3.10^{+0.13}_{-0.13}$	Newton et al. (2021)	K2-136A d	Hyades	730^{+100}_{-100}	$1.45^{+0.11}_{-0.08}$	Mann et al. (2018)
TOI-451 d	Psc-Eri	$134^{+6.5}_{-6.5}$	$4.07^{+0.15}_{-0.15}$	Newton et al. (2021)	K-66 b	NGC 6811	863^{+30}_{-30}	$2.80^{+0.16}_{-0.16}$	Meibom et al. (2013)
TOI-1098 b	Melange-1	250^{+50}_{-70}	$3.2^{+0.1}_{-0.1}$	Tofflemire et al. (2021)	K-67 b	NGC 6811	863^{+30}_{-30}	$2.94^{+0.16}_{-0.16}$	Meibom et al. (2013)
TOI-2076 b	TOI-1807 MG	300^{+80}_{-80}	$2.52^{+0.04}_{-0.04}$	Osborn et al. (2022)	K2-231 b	Ruprecht 147	3000^{+250}_{-250}	$2.5^{+0.2}_{-0.2}$	Curtis et al. (2018)

\+ Candidate exoplanets from:

- **PATHOS** project (Nardiello et al. 2019, 2020, 2021, Nardiello 2020)
- **CDIPS** project (Bouma et al. 2019)
- …

Updated to June 2022

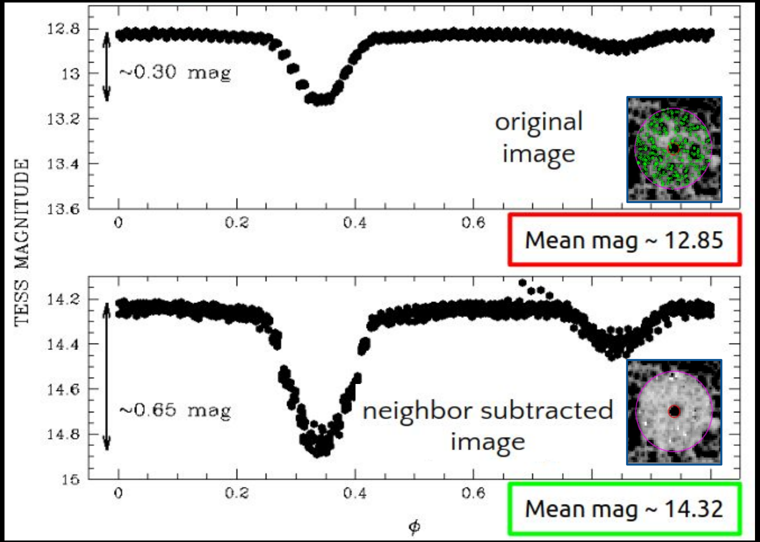
…anyway the number of exoplanets in stellar clusters, associations and moving groups << number of exoplanets around field stars



A big obstacle: the crowding

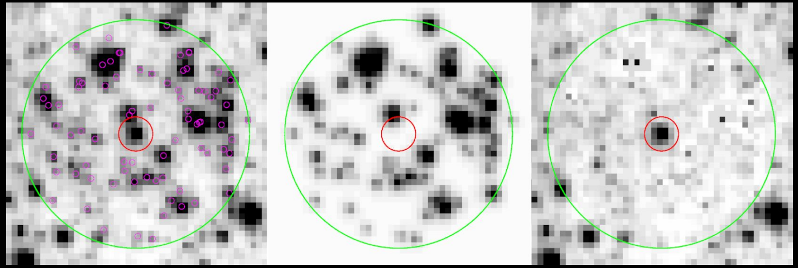
Low resolution of **wide field** cameras:

- even sparse star clusters and associations appear as dense stellar systems
- **contamination** and **dilution** effects due to the neighbors can mimic or falsify signals of planetary transits
- The need for a special data reduction pipeline (DIA, PSF-based approach, etc.)



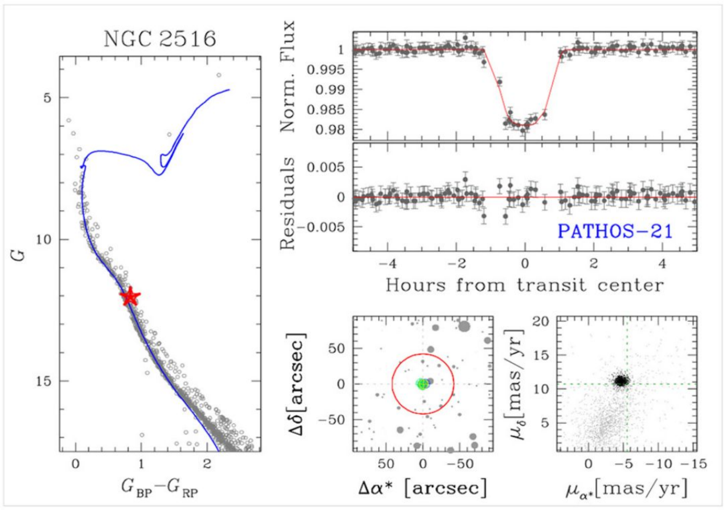
An example: the PATHOS pipeline for TESS (but also Kepler and GB)

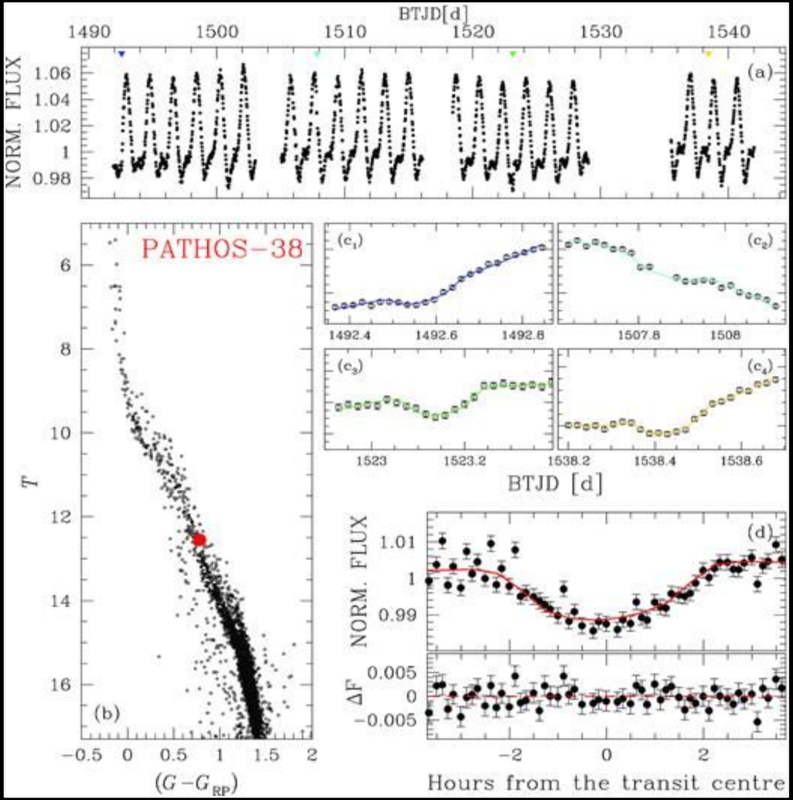
- Light curve extraction recipe: **PSF** & **neighbor subtraction**
  - Minimization of dilution effects
  - High-precision light curves even for faint stars (T>15)
- Finding, vetting, and modelling of transiting objects



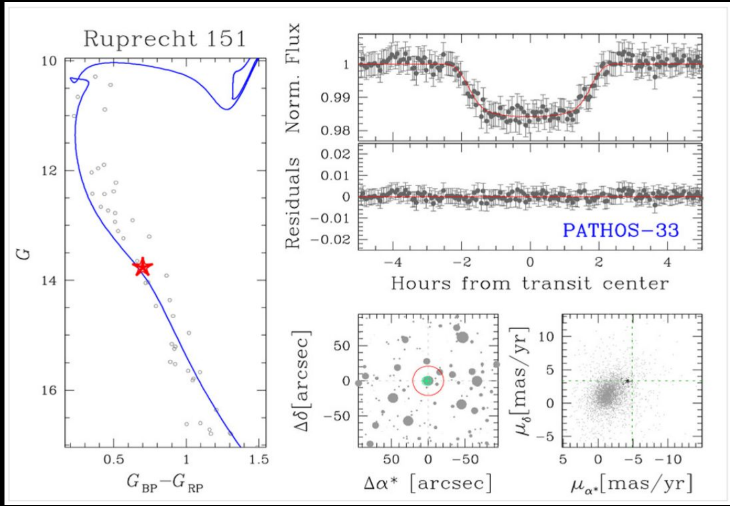
Nardiello et al. (2019)

Some **candidate exoplanets** in stellar clusters and young associations from the PATHOS project





The position on the CMD can help us to exclude likely binary stars



Frequency of candidate exoplanets in open clusters

$$f_\star(R_\mathrm{P}, P) = \frac{\sum_{i=1}^{N_\mathrm{cand}} [1 - \mathrm{FPP}_c^i(\mathrm{R_P}, P)]}{\sum_{j=1}^{N_\mathrm{stars}} [\mathrm{de}^j(R_\mathrm{P}, P) \times \mathrm{Pr}_\mathrm{transit}^j(P)]}$$

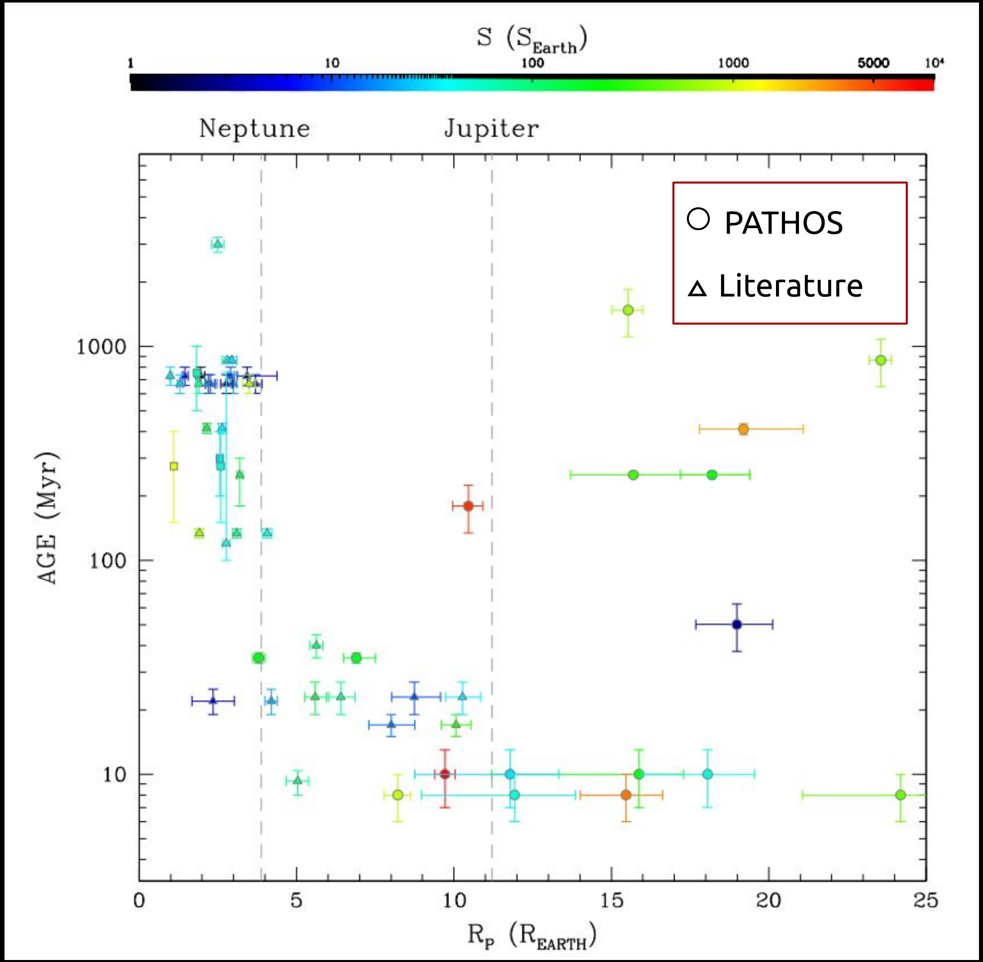
- ➔ **FPP** = False Positive Probability (computed with VESPA)
- ➔ **de** = detection efficiency of planets with radius R_P and orbital period P
- ➔ **$Pr_{transit}$** = transit probability of a planet with period P

On average, the measured and upper limit frequencies are **lower** than the values reported in literature for field stars.

	$0.85 < R_P \leq 3.9 R_{Earth}$			$3.9 < R_P \leq 11.2 R_{Earth}$			$1.0 < R_P \leq 2.5 R_J$		
Period	$f_\star^{min}$	$f_\star^{mid}$	$f_\star^{max}$	$f_\star^{min}$	$f_\star^{mid}$	$f_\star^{max}$	$f_\star^{min}$	$f_\star^{mid}$	$f_\star^{max}$
(d)	(per cent)	(per cent)	(per cent)	(per cent)	(per cent)	(per cent)	(per cent)	(per cent)	(per cent)
0.5–2.0	<0.034	<0.063	<0.086	<0.004	<0.007	<0.009	<0.002	<0.004	<0.006
2.0–10.0	<0.092	<0.191	<0.269	0.034 ± 0.025	0.070 ± 0.052	0.098 ± 0.073	0.023 ± 0.013	0.047 ± 0.027	0.066 ± 0.038
10.0–85.0	<0.533	<1.505	<2.218	<0.327	<0.925	<1.364	0.555 ± 0.336	1.568 ± 0.955	2.312 ± 1.413
85.0–365.0	<2.716	<5.200	<7.174	<2.197	<4.205	<5.806	<2.102	<4.022	<5.553

Kepler - TESS - PLATO **synergy** will help to improve these frequencies.

Nardiello et al. (2021)

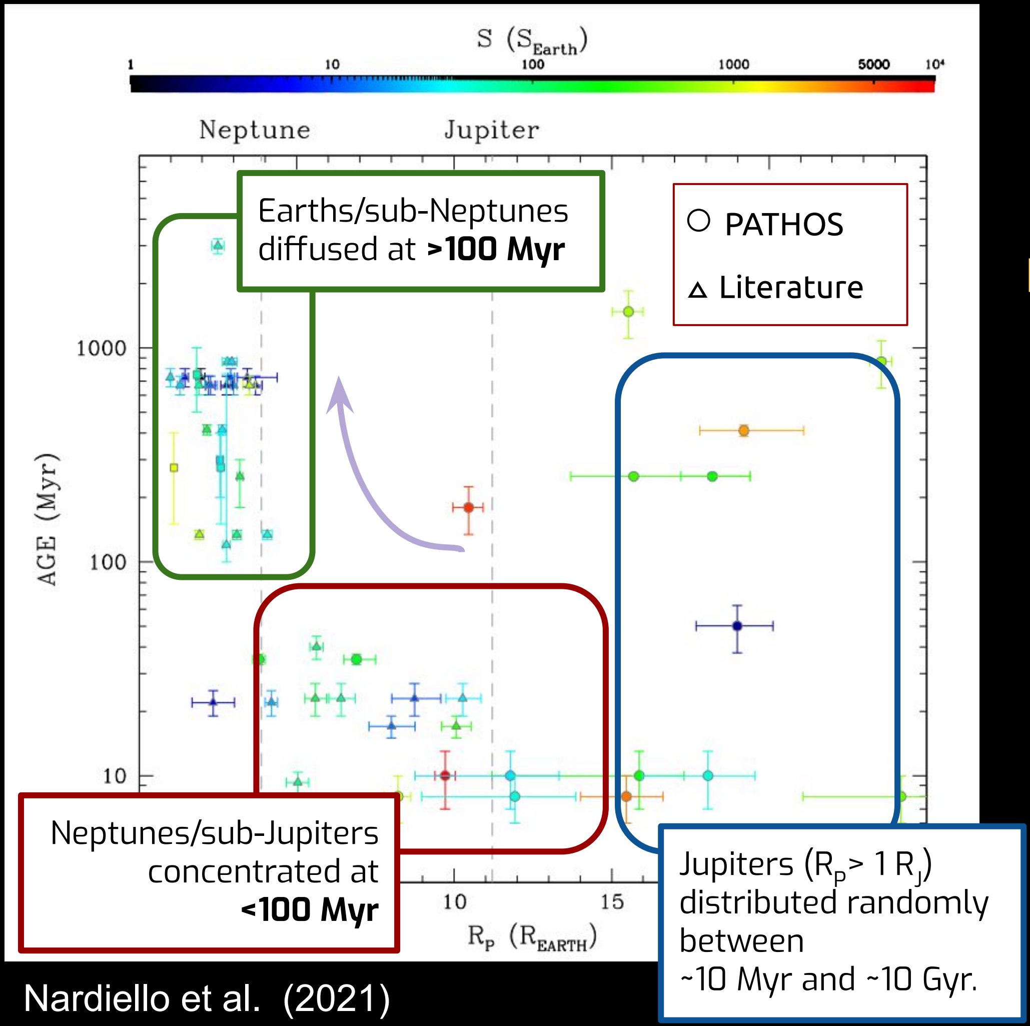


Nardiello et al. (2021)

Close-in candidate and confirmed exoplanets

P_{orb} < 100 days & well constrained ages

How does the **Age vs. Rp** distribution help us to understand the **evolution** of close-in exoplanets?



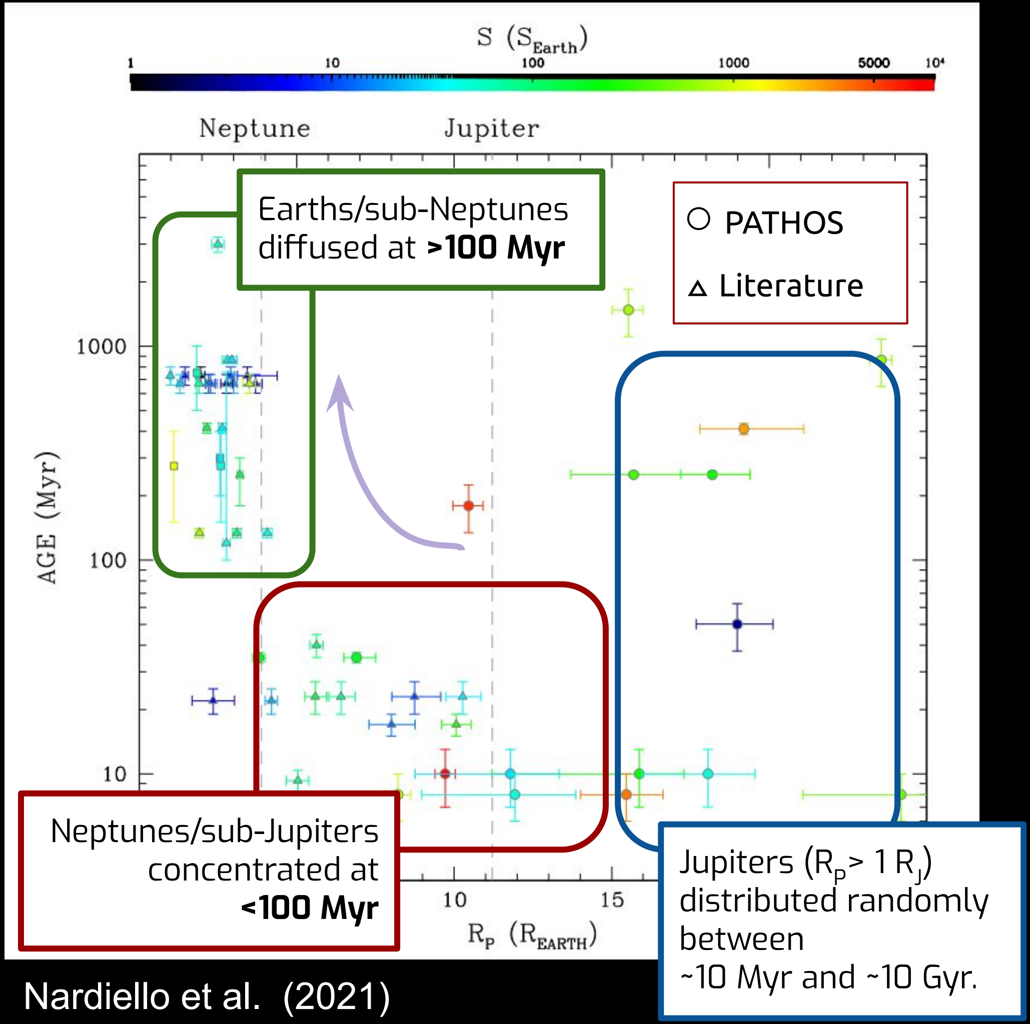
Nardiello et al. (2021)

Close-in candidate and confirmed exoplanets

P_{orb} < 100 days & well constrained ages

- **Lack of small size** (<4 R_{Earth}) **young exoplanets** (<100 Myr): probable observing bias due to the difficult detection of shallow transits in highly variable light curves
- **No planets** at ages >100 Myr in the range 4-10 R_{Earth} : unlikely observing bias
- Hint of planetary evolution? (photoevaporation, core-powered mass loss, migration, …)

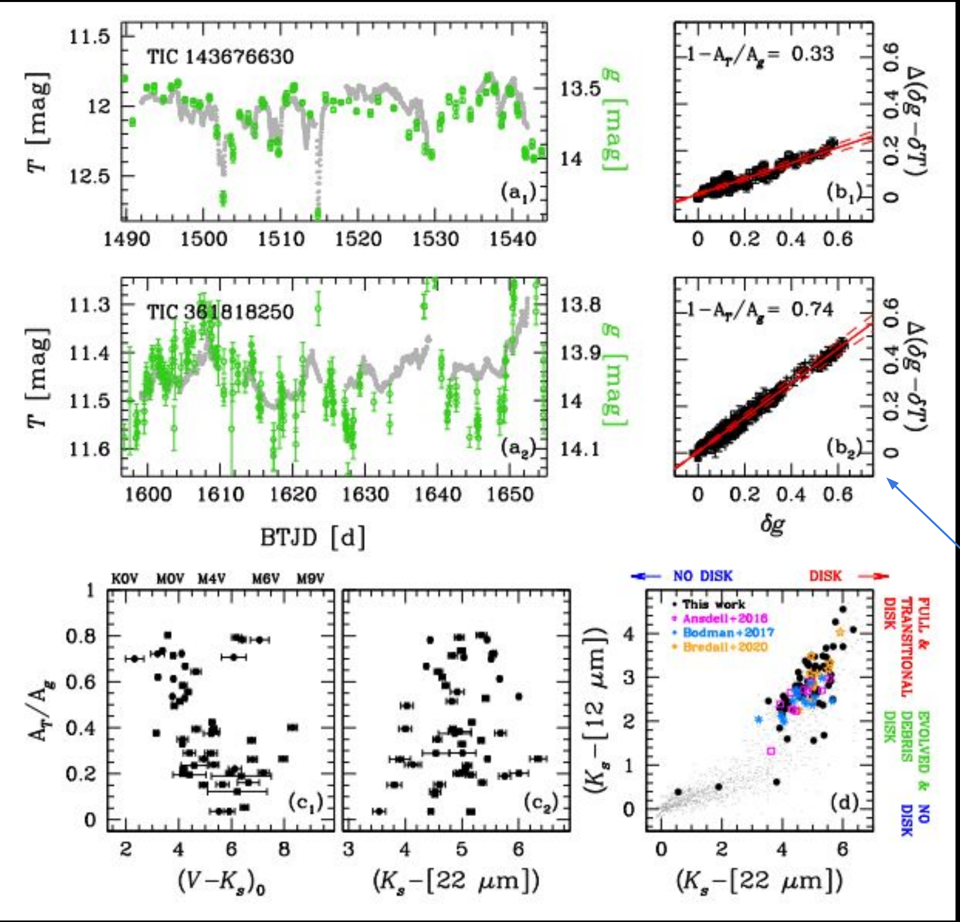
(see Serena's talk!)



Nardiello et al. (2021)

Observations of members of young open clusters, stellar associations and moving groups with PLATO, will be useful for filling the region of young, small planets.

Moreover, PLATO will detect planets with P>100 days, allowing us to study the same relationship for long period planets.



(Nardiello 2020)

Not only exoplanets

Dippers in young associations (<10 Myr)

Simultaneous (ground-based) observations in another band(s) provide information on the extinction due to the dust in circumstellar disks.

If the dust is dominated by small grains, the quantity A_T/A_g will be smaller than the case in which the grains have large size; if the size of the grains are larger than the wavelengths in which the TESS observations were performed (λcentral ~ 800 nm), the ratio $A_T/A_g \rightarrow 1$, and the reddening **$E(g-T) = A_g - A_T \rightarrow 0$.**

Dippers are important for understanding the early stages of planetary formation and evolution (first <1-10 Myr).

THANK
YOU