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A search for transiting planets around hot subdwarfs

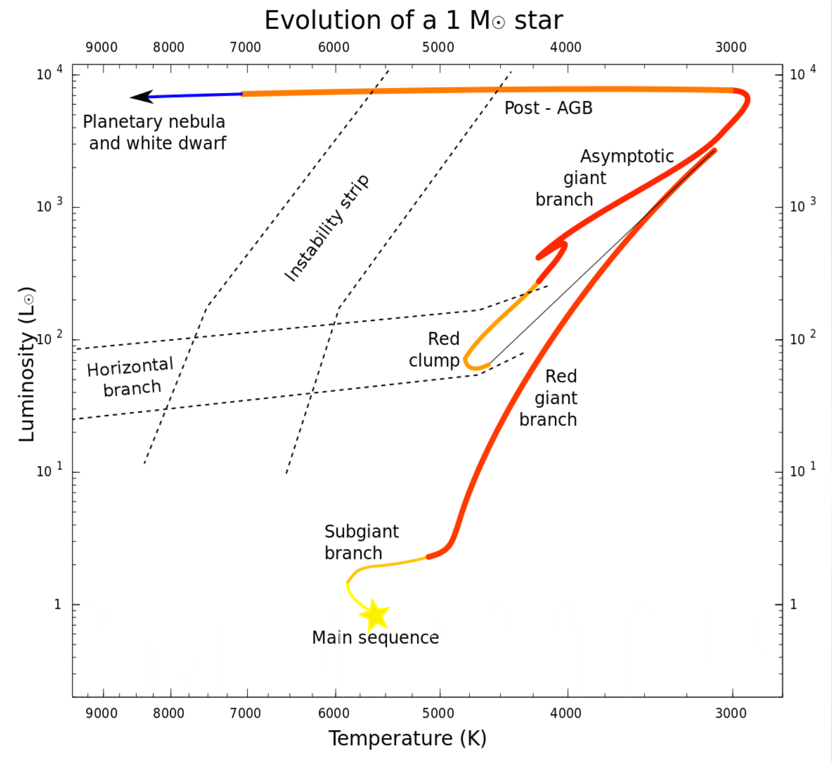
Valérie Van Grootel

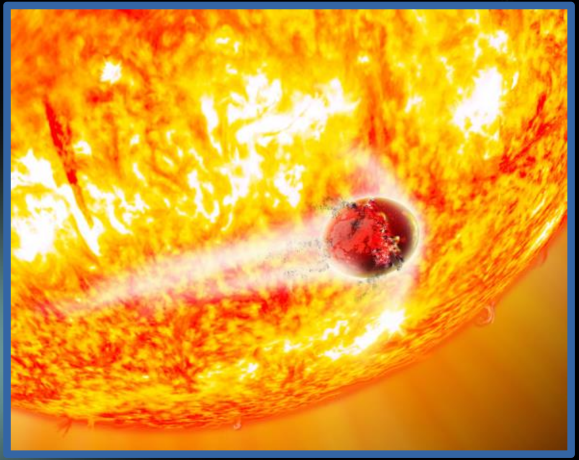
10 March 2022

F.J. Pozuelos, A. Thuillier, M. Dévora-Pajares

Introduction

Planetary systems during stellar evolution



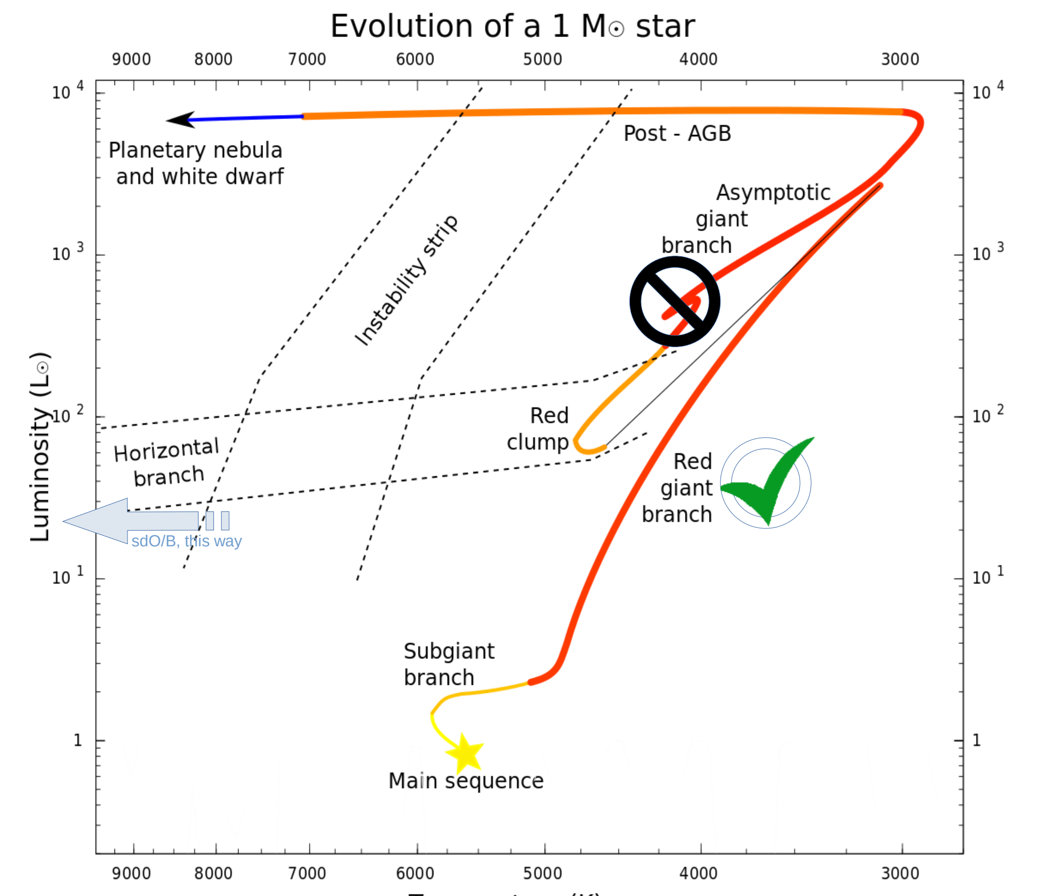


Why hot subdwarfs?

- Subdwarf B (sdB, 20,000-40,000 K): post-RGB stars, now on Extreme Horizontal Branch (He-core burning)

- Subdwarf O (sdO, 40,000-80,000 K): some post-sdB, some post-RGB, some mergers, some post-AGB

- Small stars (0.1-0.3 R_{sun})
=> well-suited for the **transit** method: small stars brings small planets !



Stellar evolution, Public domain

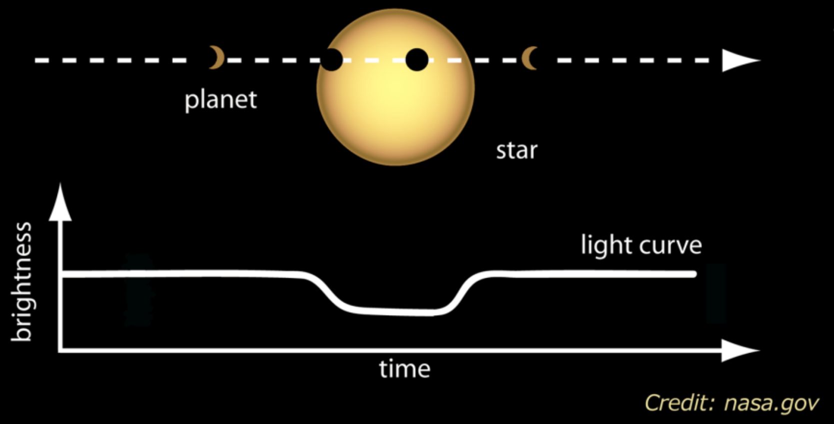
The transit method

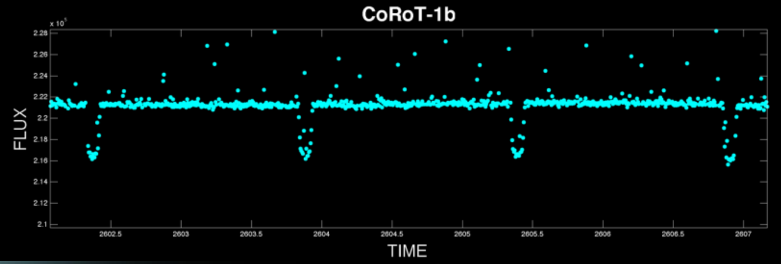
- Depth of the transit (if planet reflected light negligible):

$$F = \sqrt{\frac{R_{planet}}{R*}}$$

- Probability of transit is fully determined by geometry:

$$p_{transit} = \left(\frac{R_* + R_{Planet}}{a}\right)\frac{1 + e\sin(\omega)}{1 - e^2}$$





Motivation

I. Do hot subdwarfs have planets?

- No occurrence rates for planets around hot subdwarf stars
  => Do they have planets? If yes, which type and in which proportions?

II. Can planets survive an engulfment?

- No observational constraints for engulfed planets or remnants
  => Can planet survive this process?
  => If yes, what are the remnants?

Planets around evolved stars: census

1) Around 'classical' red-giant stars

They are ~5-10 to ~1000 R_{sun} (for ~1-3 M_{sun} stars)

=> Only large and massive planets are detected (Jones et al. 2021)
+ difficulty to distinguish RGB, normal Horizontal Branch, and AGB stars

2) Around white dwarfs

25-40% white dwarfs show metal pollution in their atmospheres
+ Evidences for:
- Transiting disintegrating planetesimals (Vanderburg et al. 2015)
- Accretion of a giant planet (Gänsicke et al. 2019)
- Transit of a giant planet (Vanderburg et al. 2020)

Planets around evolved stars: census

3) Around hot subdwarf stars

No confirmed planets around hot subdwarfs

But:
- No systematic survey to find them (transit, RV,…)
- M dwarfs and brown dwarf companions are frequent (>15% of all sdB in binaries; Schaffenroth et al. 2018)
- The ejection of the envelope for hot subdwarfs not only enables the detection of small objects as remnants, but it may be the reason for the existence of these remnants, by stopping the spiraling-in in the host star.

Plan

- Introduction & Motivation
- **Methods & Data**
- Results:
  - Injection-and-recovery tests
  - Results from TESS Cycle 1
  - First occurrence rates
- Conclusions and coming work

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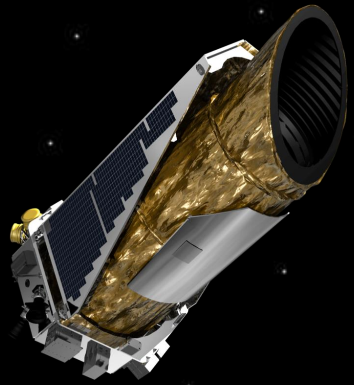
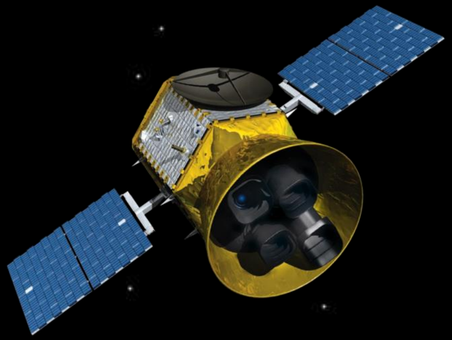
Data



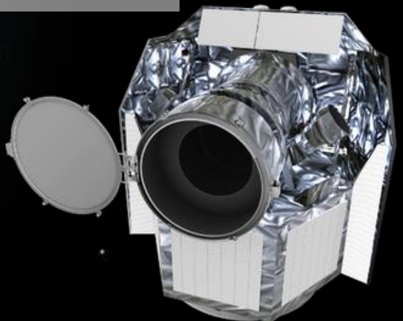
Light curves available

- Kepler+K2: 72 + 174 targets at 1-min cadence

- TESS: ~2300 targets at 2-min cadence, >5500 at long cadence (30-min, 10-min, soon 3.5-min)



- CHEOPS: 46 targets, not observed by TESS neither by Kepler, 1-min cadence



Data

Kepler/K2 (2009-2013 / 2014-2018)

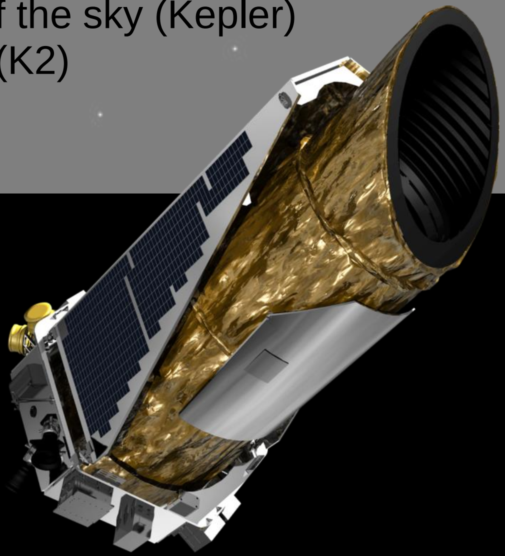
NASA

Survey focused on a part of the sky (Kepler)

Survey on the ecliptic plan (K2)

Ø : 95cm

Launch mass : 1039kg



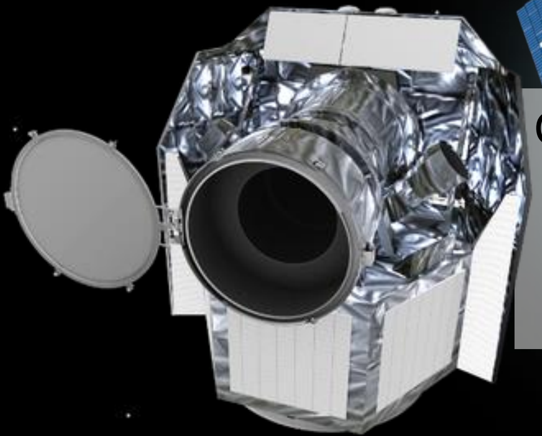
TESS (2018-)

NASA

Large survey of 90% of the sky

Ø : 10cm * 4

Launch mass : 350kg



CHEOPS (2019-)

ESA

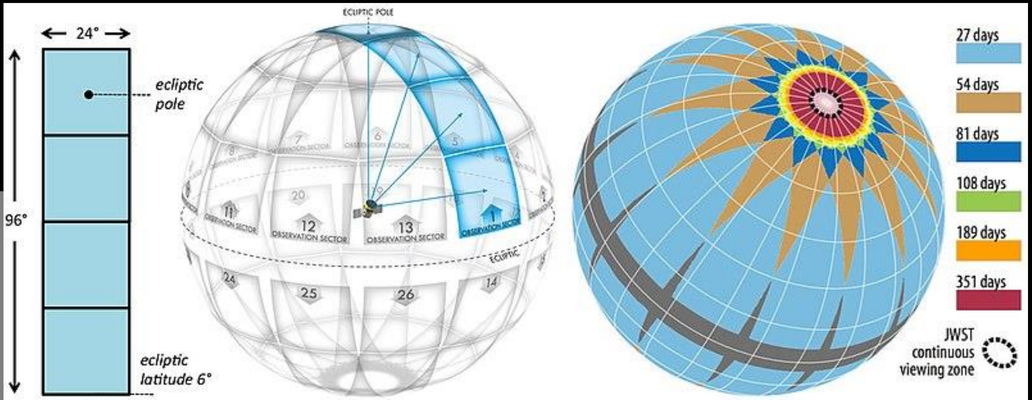
Characterization of already discovered exoplanets

Ø : 32cm

Launch mass : 273kg

Data

TESS



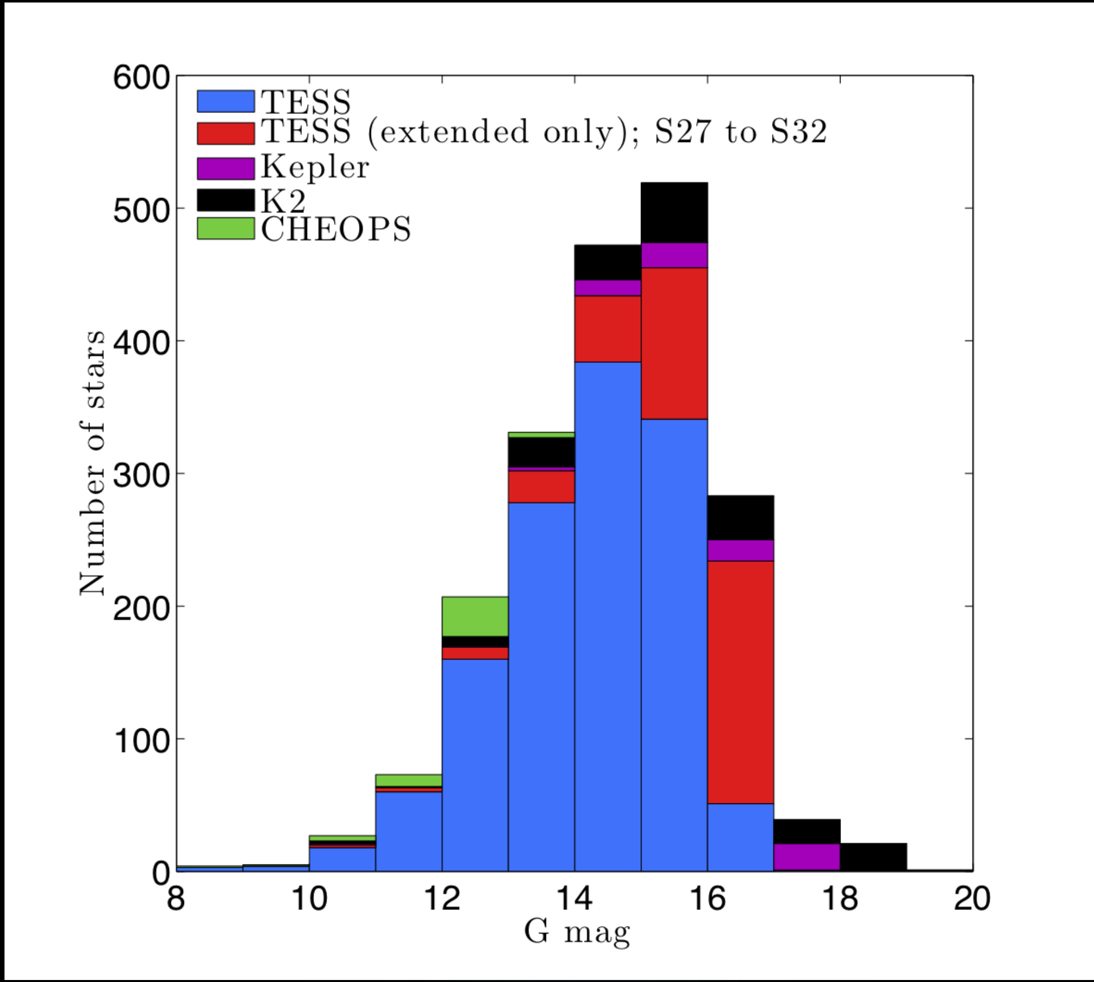
Primary mission (2018 - 2019)
Cycles 1 (south) and 2 (north)

Extended mission (2020 - 2022)
Cycles 3 (south) and 4 (north)

1 cycle = 13 sectors of ~27 days each (= 2 TESS orbits)

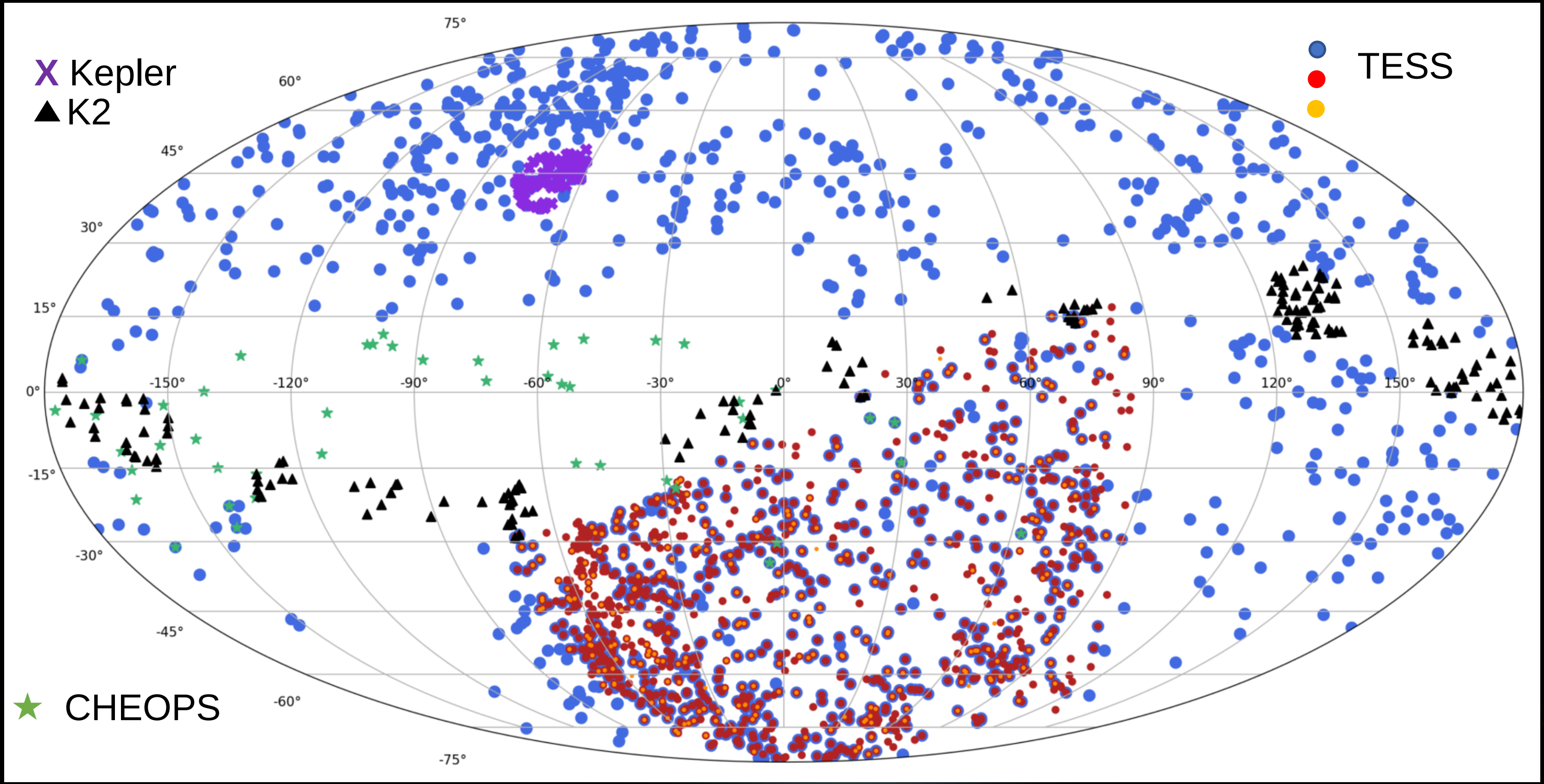
Currently in cycle 4

Data



Van Grootel et al. 2021

Data



X Kepler
▲ K2
★ CHEOPS
TESS
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°

Method

1) Looking for transits with the SHERLOCK PIPEline

Searching for **H**ints of **E**xoplanets f**R**om **L**ightcurves **O**f spa**C**e-based see**K**ers

Pozuelos et al., A&A 641, A23, 2020

Available on open access on Github:
https://github.com/franpoz/SHERLOCK

The SHERLOCK PIPEline

Method

1) Looking for transits with the SHERLOCK PIPEline

1. Gathering data:
We download from the MAST (NASA Mikulski Archive for Space Telescopes) the PDC-SAP (pre-search data conditioning simple aperture) Kepler/K2 & TESS data

2. Cleaning data:

- PDC-SAP light curve detrended in 12 different ways (bi-weight filter or Gaussian process with various window/kernel sizes)
- Pulsations removed by pre-withening technique

3. Search for transits:
with Transit Least Squares (TLS; Hippke & Heller 2019) in the 12 detrended + original lc

4. Vetting process:
Checking the background variation, location and brightness of nearby stars, lc from each pixel in the target pixels etc.

The SHERLOCK PIPEline

Method

1) Looking

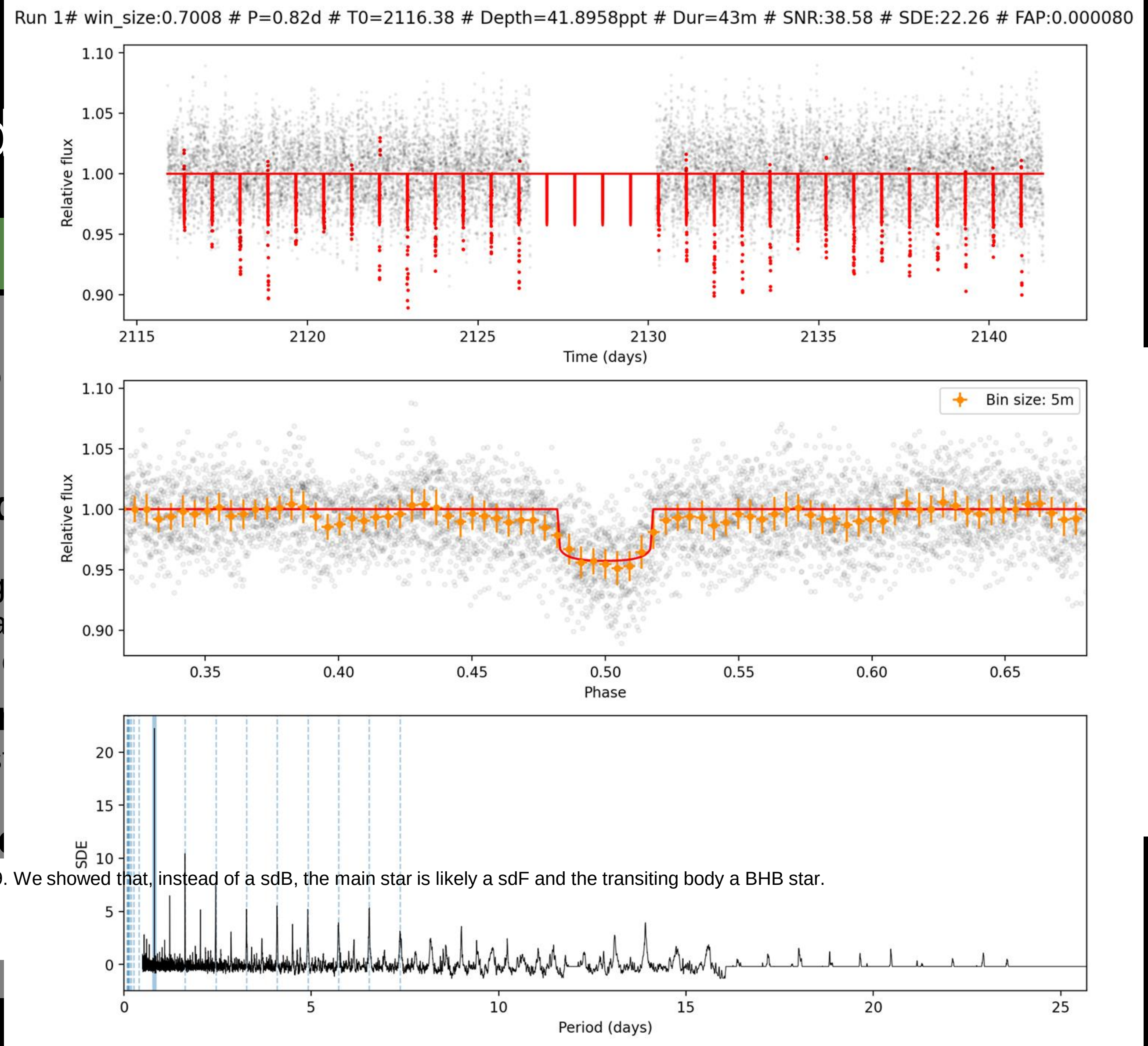
1. Gathering
We download fro
SAP (pre-search

2. Cleaning c

- PDC-SAP lig
  filters with va
- Pulsations/P

3. Search fo
with Transit Leas

4. Vetting pr



0.82 days signal on TIC 397833009. We showed that, instead of a sdB, the main star is likely a sdF and the transiting body a BHB star.

The SHERLOCK PIPEline

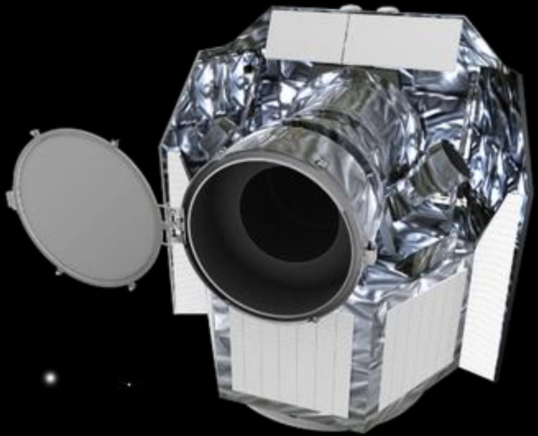
Method

2) Confirming the transit by follow-up observations

TRAPPIST

"*TRAnsiting Planets and PlanetesImals Small Telescope*"
Two ground based telescopes:
- Northern hemisphere: Oukaimeden observatory (Morocco).
- Southern hemisphere: La silla observatory (Chile).

Ø : 60cm
Sensitivity: ~2.5 ppth.



CHEOPS

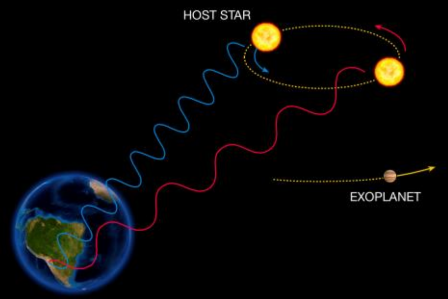
"*CHaracterizing ExOPlanet Satellite*"
ESA class S mission
Heliosynchronous orbit of Earth at 700km altitude
Ø : 32cm
Sensitivity: ~0.05 ppth

Method

3) Characterizing the transiting body

By Radial Velocity data to obtain the transiting body's mass:

- ESO archives
- Hot subdwarf community
- (soon) CARMENES@3.5m Calar Alto
- Write proposals…



Plan

- Introduction & Motivation
- Methods & Data
- **Results:**
  - **Injection-and-recovery tests**
  - Results from TESS Cycle 1
  - First occurrence rates

- Conclusions and coming work

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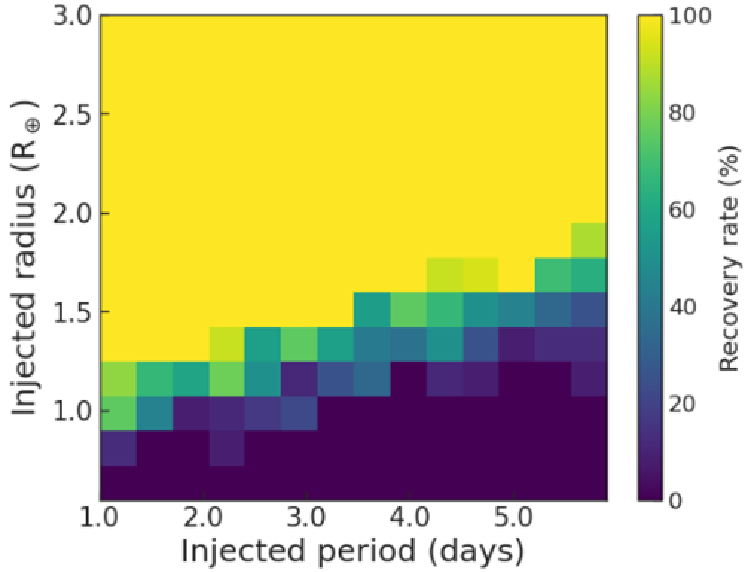
Results

1. Injection-and-recovery tests

Aim: determine the kind of bodies we are able to detect with our tools:

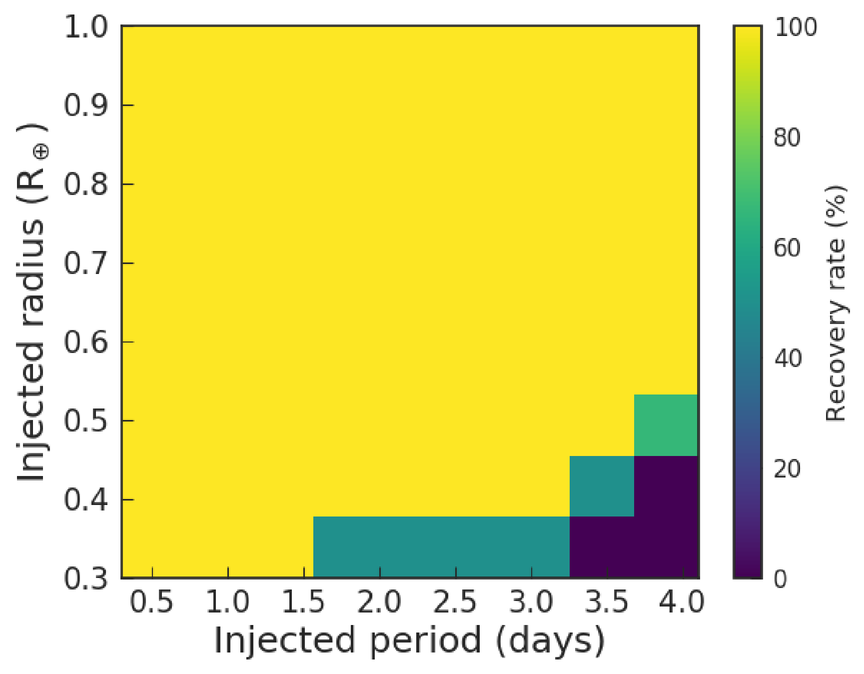
1. Take a real light curve
2. Inject a synthetic planet
3. Detrend the light curve
4. Try to recover the signal
5. Repeat by varying R_p, T, T_0
6. Compute the recovery rate



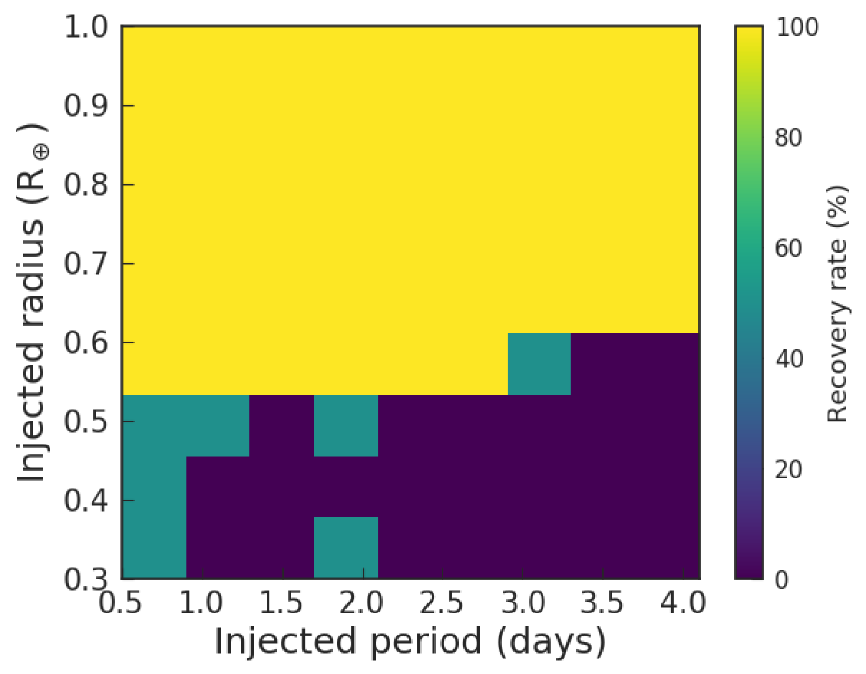
Injection-recovery test of TIC 96949372 (Gmag 13.0).

Results

1. Injection-and-recovery tests: Kepler/K2 data



KIC 8054179 (Gmag 14.3), 90 days of data (Q6 Kepler).

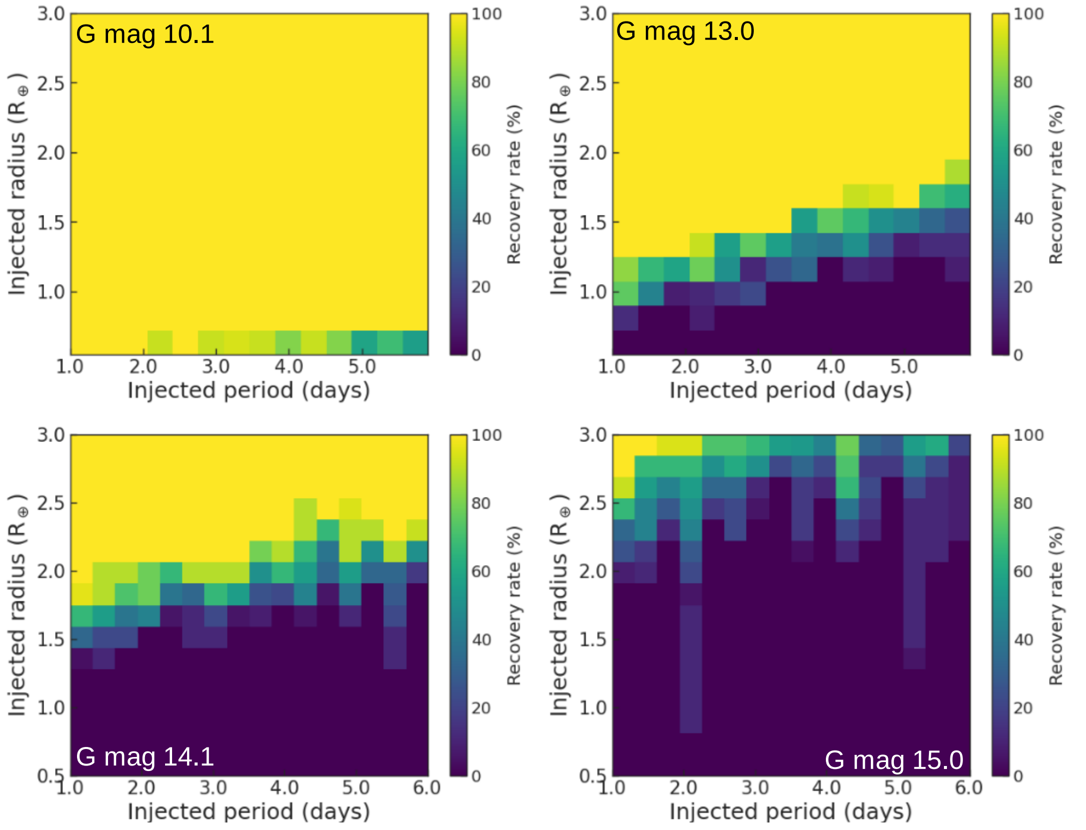


EPIC 206535752 (Gmag=14.0), 81 days of data (C3 K2)

Results

1. Injection-and-recovery tests: TESS data

1-sector data, increasing magnitudes (Gmag in 12-15=90% targets)

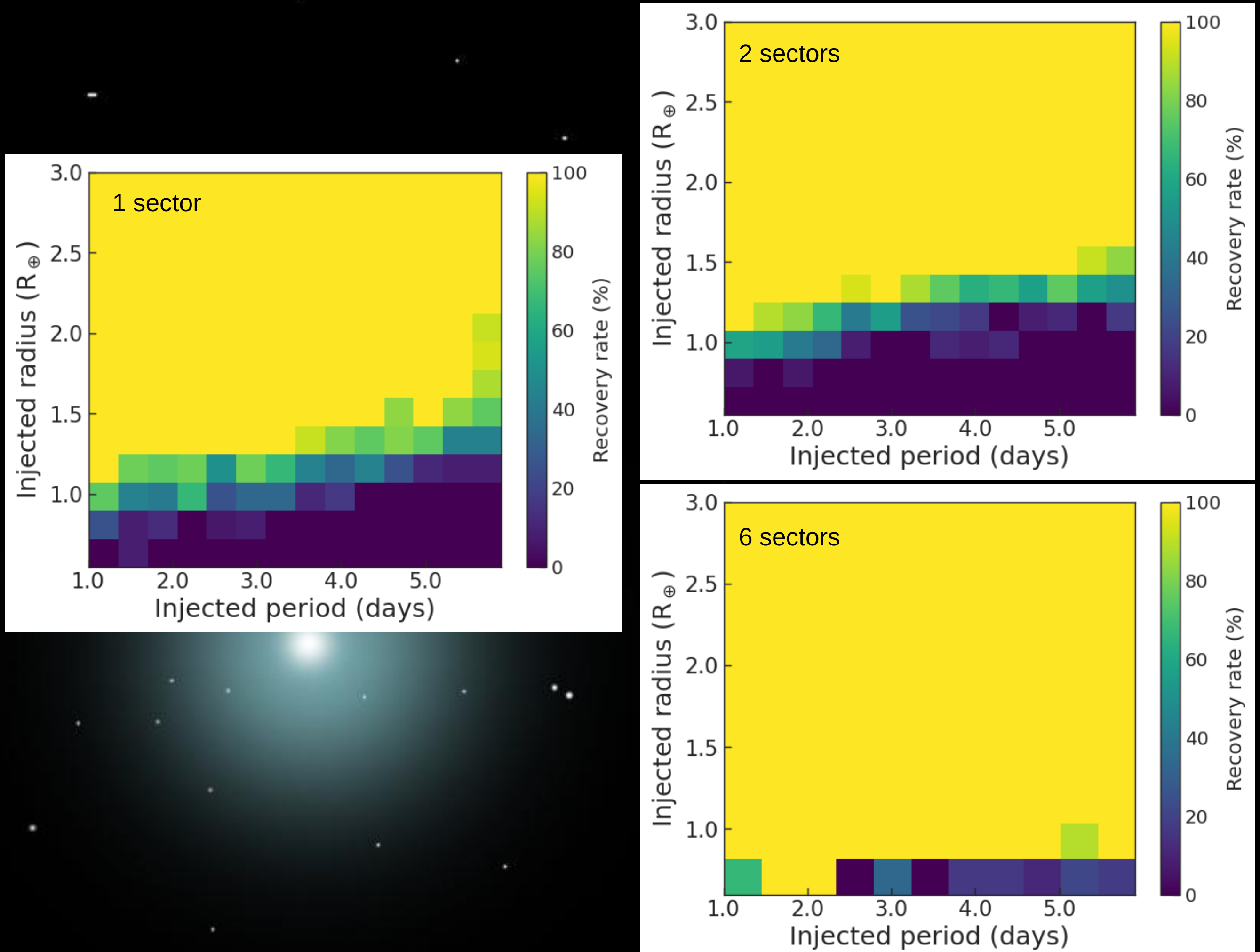


Injection-recovery test of four different hot subdwarfs having various magnitude.
Top left : TIC 147283842 (Gmag 10.1), top right TIC 96949372 (Gmag 13.0),
bottom left : TIC 85400193 (Gmag 14.1), bottom right : TIC 372681399 (Gmag 15.0).
From Van Grootel et al. 2021 (A&A, 650, 205).

Results

1. Injection-and-recovery tests: TESS data

Increasing observation duration:
(TIC362103375, Gmag=13.0)
1 -> 2 -> 6 sectors



Results

1. Injection-and-recovery tests

Wrapping-up:

Full results on Van Grootel et al. 2021 (A&A, 650, 205)

Main conclusions:

- TESS data will allow us to measure the planet occurence rate around hot subwarfs
- Best TESS targets and Kepler/K2 targets will allow us to detect small, possibly disintegrating objects

Table 3. Minimum size of planets in units of $R_\oplus$ that can be detected in typical light curves with a $\gtrsim 90\%$ recovery rate.

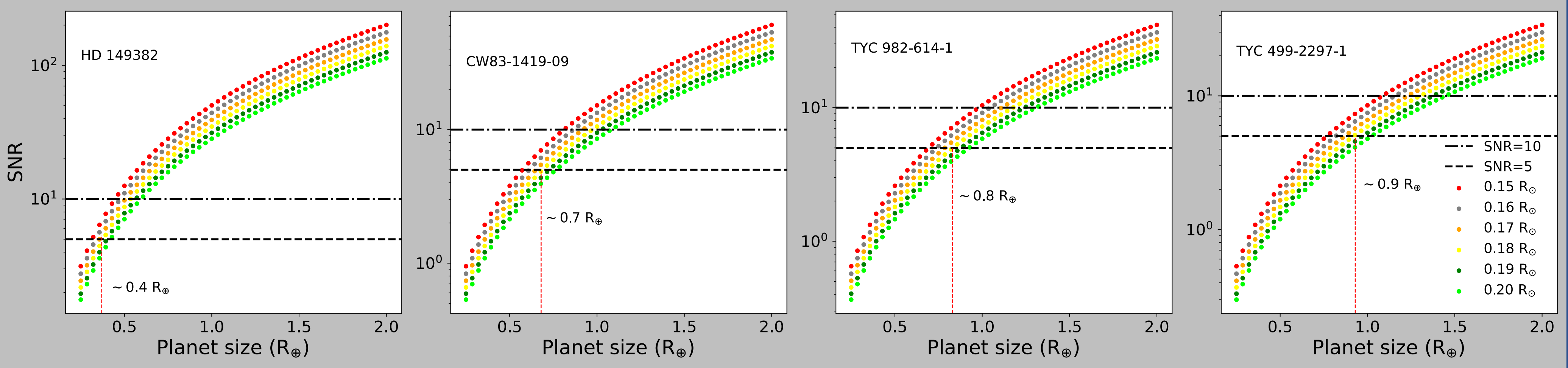
Object ID	G Mag	Data length (d)	1 d	5 d	15 d	25 d	35 d
Kepler							
8054179	14.3	90	0.3	0.5	0.8	1.0	1.2
		30	0.5	0.6	1.0	–	–
3353239	15.2	30	0.6	0.8	1.1	–	–
5938349	16.1	30	0.7	1.1	2.0	–	–
8889318	17.2	30	0.9	1.2	2.4	–	–
5342213	17.7	30	1.2	1.7	3.2	–	–
K2							
206535752	14.1	80	0.6	0.8	1.0	1.5	2.1
		30	0.6	0.9	1.6	–	–
211421561	14.9	30	0.7	1.4	1.9	–	–
228682488	16.0	30	1.0	1.4	2.5	–	–
251457058	17.1	30	1.4	2.3	3.4	–	–
248840987	18.1	30	2.1	3.3	5.4	–	–
TESS							
147283842	10.1	27	0.5	0.7	1.5	–	–
362103375	13.0	27	1.0	1.7	2.0	–	–
		162	0.7	0.8	0.9	1.0	1.3
096949372	13.0	27	1.1	1.8	2.0	–	–
441713413	13.1	27	1.3	1.7	2.0	–	–
		54	1.3	1.7	1.9	>10	>10
085400193	14.1	27	1.8	2.3	2.8	–	–
220513363	14.1	27	1.6	1.8	2.7	–	–
		81	1.3	1.6	2.5	3.0	3.0
000008842	15.0	27	2.7	3.2	4.7	–	–

Notes. All stars have $0.175 \pm 0.025\ R_\odot$ and $0.47 \pm 0.03\ M_\odot$.

Results

CHEOPS data

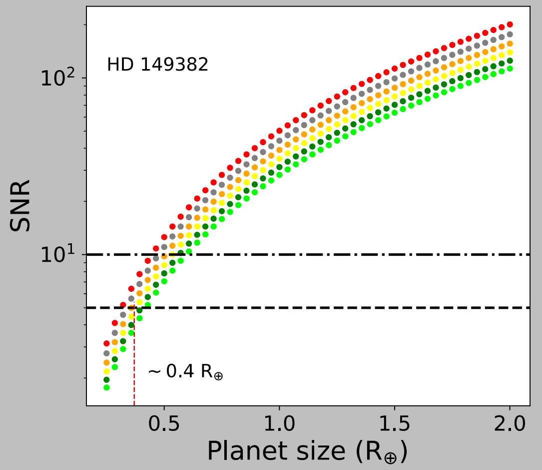
<1 R_Earth planets can be detected in the 46 targets

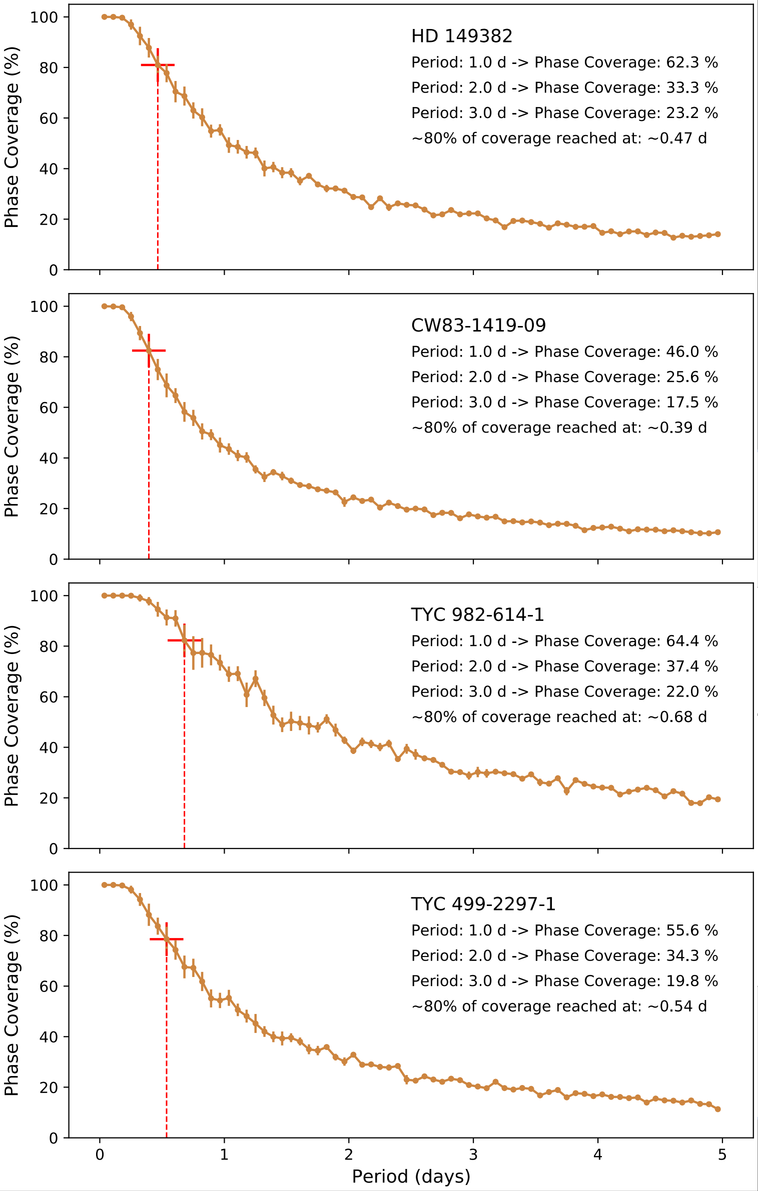


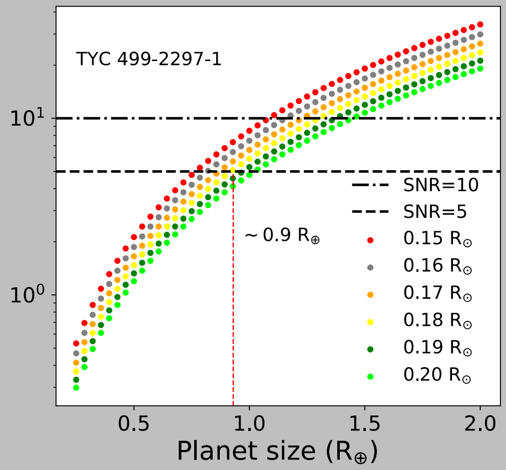
Results

CHEOPS da

<1 R_Earth planets can be







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2. Results from TESS Cycle 1

Number of sectors	Primary mission	Cycle 1	Cycle 2
1	877	627	250
2	205	95	110
3	72	25	47
4	23	7	16
5	21	3	18
6	24	10	14
7	7	2	5
8	10	5	5
9	6	3	3
10	6	1	5
11	13	3	10
12	23	7	16
13	15	4	11
Total	1302	792	510
Mean sect./star	2.1	1.6	2.8

2. Results from TESS Cycle 1

TESS cycle 1 fully analysed (792 stars):

- 352 signals (belonging to 243 stars)
but only 46 retrieved Cycle 3 (12 stars not re-observed)

- 7 stars with signals are now followed-up (2 signals retrieved thus far); 23 signals will be followed-up in coming weeks/months

- 0 planetary body confirmed

Thuillier et al., submitted to A&A

All targets (792 stars)

↓ Detection of a signal above thresholds and visually credible.

Stage 0 — 352 signals

↓ Signal recovered in TESS cycle 3.

Stage 1 — 46 signals

↓ Positive to our vetting process.

Stage 2 — 30 signals

↓ Recovered in follow-up observations

Stage 3 — 2 signals

↓ Planetary nature confirmed

Stage 4 — 0 signal

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First statistics on planet occurrence around hot subdwarfs

Based on 549 stars displaying no signal (list in Thuillier et al.). The higher limit f_{max} of the occurrence rate based on this non-detection is:

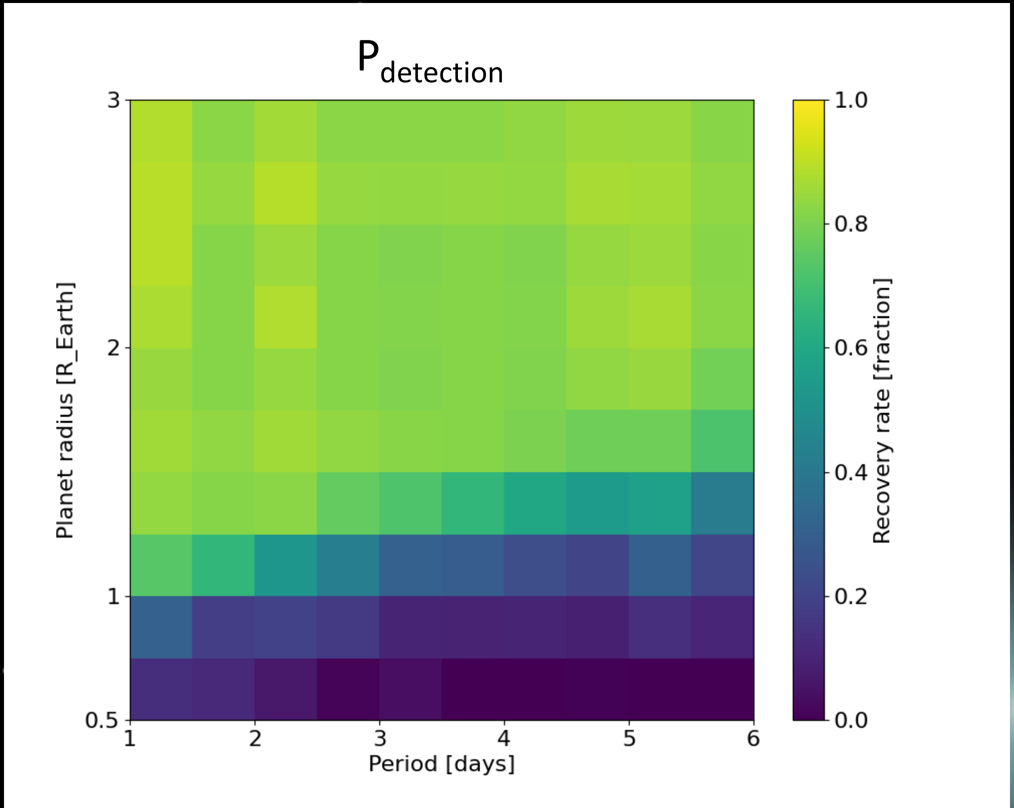
(Faedi et al. 2011)

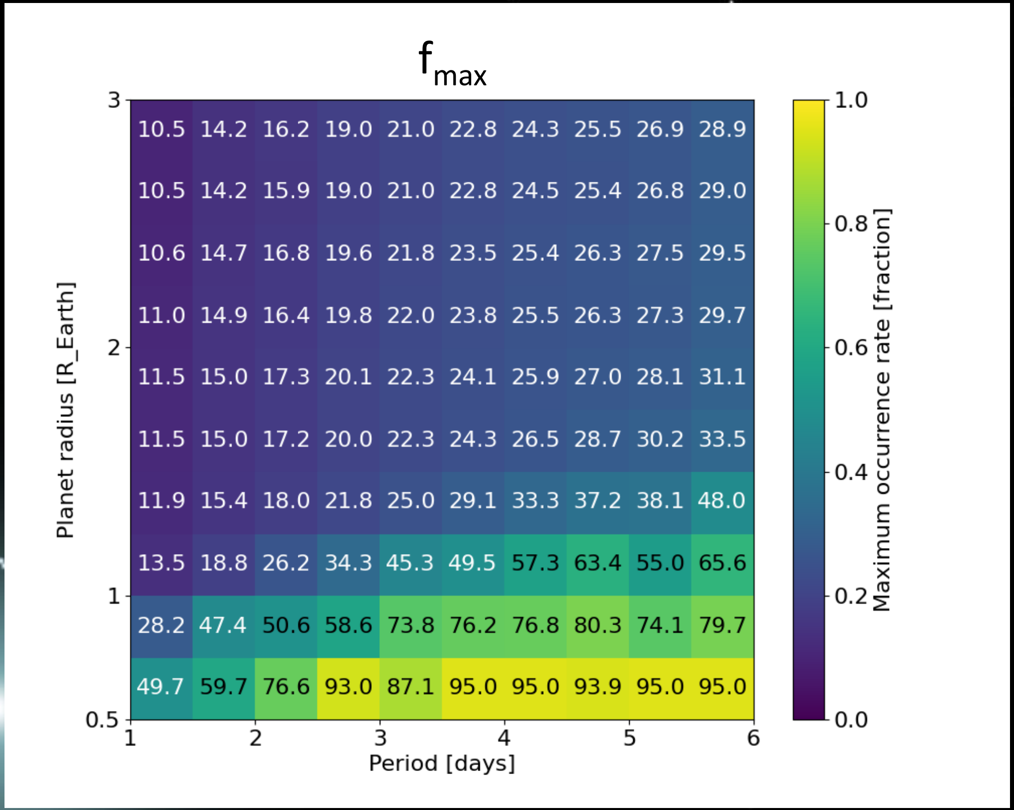
$$f_{max} = 1 - (1 - C)^{\frac{1}{N'+1}}$$

with:

- f_{max} : the higher limit for the occurrence rate of planets.
- C : the confidence level (between 0 and 1).
- $N' = N \times P_{\text{transit}} \times P_{\text{detection}}$, where N is the number of targets in the sample (549), P_{transit} is the geometrical transit probability, and $P_{\text{detection}}$ is the probability to detect a body that is transiting.

First statistics on planet occurrence around hot subdwarfs





With C=0.95, assuming the 549 targets are Gmag=13-13.5 and R_*=0.175Rsun

Ex: At 1d orbital period, we can exclude the presence of a 3 R_E (resp. 0.5 R_E) planets in 89.5% (resp. 50.3%) of hot subdwarfs

Plan

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- **Conclusions and coming work**

Conclusion

- Do hot subdwarf stars have planets?
- What happens when a planet is engulfed by its star when it evolves?

- TESS cycle 1 analysed / several interesting signals under follow-up

=> no detection : strong observational constraints for the survival of planets !

=> detection : 1st planet around a hot subdwarf + potential survivor of an engulfment !

Conclusion

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=> no detection : strong observational constraints for the survival of planets !

=> detection : 1st planet around a hot subdwarf + potential survivor of an engulfment !

- We have all the tools and data to settle this issue

=> Data from Kepler/K2, TESS, CHEOPS missions (~2500 sdO/B)

=> Tools to perform the analysis (Sherlock Pipeline)

=> Access to follow up observations (TRAPPIST, CHEOPS)

Conclusion

- Do hot subdwarf stars have planets?
- What happens when a planet is engulfed by its star when it evolves?

=> TESS cycle 1 analysed / several interesting signals under follow-up
=> If no detection : strong observational constraints for the survival of planets !
=> If detection : 1st planet around a hot subdwarf + potential survivor of an engulfment !

- We have all the tools and data to settle this issue

=> Data from Kepler/K2, TESS, CHEOPS missions (~2500 sdO/B)
=> Powerful tools to perform the analysis (Sherlock)
=> Easy access to follow up observations (TRAPPIST, CHEOPS)

- **Coming:**
  - search for disintegrating planets (non-symmetric transits)
  - Machine Learning techniques for the vetting process
  - By comparing occurrence rates to results for white dwarfs, and occurrences for ~0.8-3 M_{sun} stars, and subgiants/RGB stars: effect of the RGB alone on the evolution of planetary systems

Credits

Credits:

Background: sd catalog logo, Potsdam university
https://a15.astro.physik.uni-potsdam.de/w/projects/

Stellar evolution: https://upload.wikimedia.org/wikipedia/commons/thumb/a/a1/Evolutionary_track_1m.svg/1166px-Evolutionary_track_1m.svg.png

Sun expansion: ESO
https://www.eso.org/public/images/eso1337a/

TESS: https://en.wikipedia.org/wiki/File:Transiting_Exoplanet_Survey_Satellite_artist_concept_(transparent_background).png

CHEOPS: https://sci.esa.int/web/cheops/-/54127-artist-s-impression-of-the-characterising-exoplanet-satellite-cheops--front-view

Transit by Corot : NASA
https://svs.gsfc.nasa.gov/30558

TRAPPIST: https://www.eso.org/public/images/jehin_trappist_5269/

Roche limit : Shoemaker-Levy 9 comet disrupted by Jupiter
https://hubblesite.org/contents/news-releases/1994/news-1994-26.html

Radial velocity : ESO
https://www.eso.org/public/images/eso0722e/

Z

Appendices

Hot subdwarfs

Mass: ~0.5 M_Sun
Radius: ~0.1 - 0.3 R_Sun

Life span: ~100 million years

Spectral types:
O (sdO) and B (sdB)

Temperature:
sdB: ~20 000 - 40 000K
sdO: ~40 000 - 80 000K

Luminosity:
sdB: ~20 - 30 L_Sun
sdO: ~100 L_Sun

- Almost all envelope expelled during RGB
- Lie on the Extreme Horizontal Branch (EHB)
- Burn Helium in the core
- ¾ sdB and ¼ sdO
- Some sdO are post-AGB, (indicator : log(g))

Hot subdwarfs' life span implications

Formation times of planet:

~50 to 100 Myr in protostellar disc conditions

Way more in post-RGB conditions.

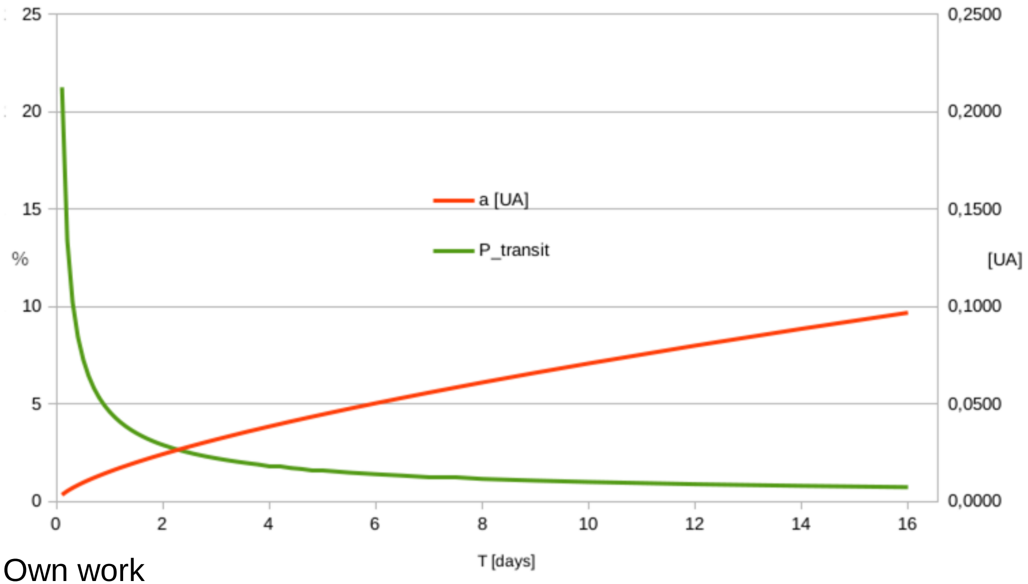
Planetary migration time:

Larger than 100 Myr

Collaborations established (Warwick University) to precisely compute these times with various initial conditions.

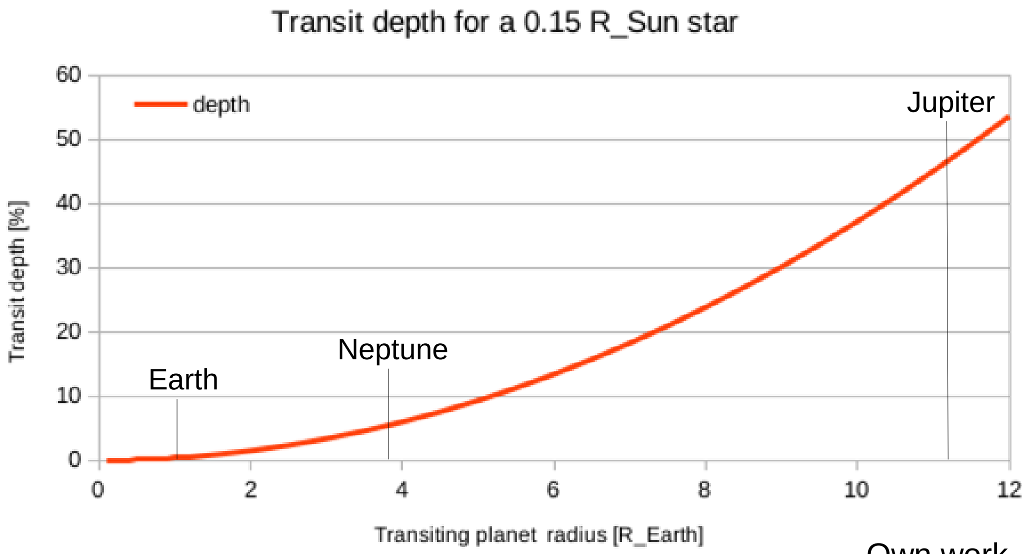
Transits method

Geometric transit probability



Own work

Transit



Own work

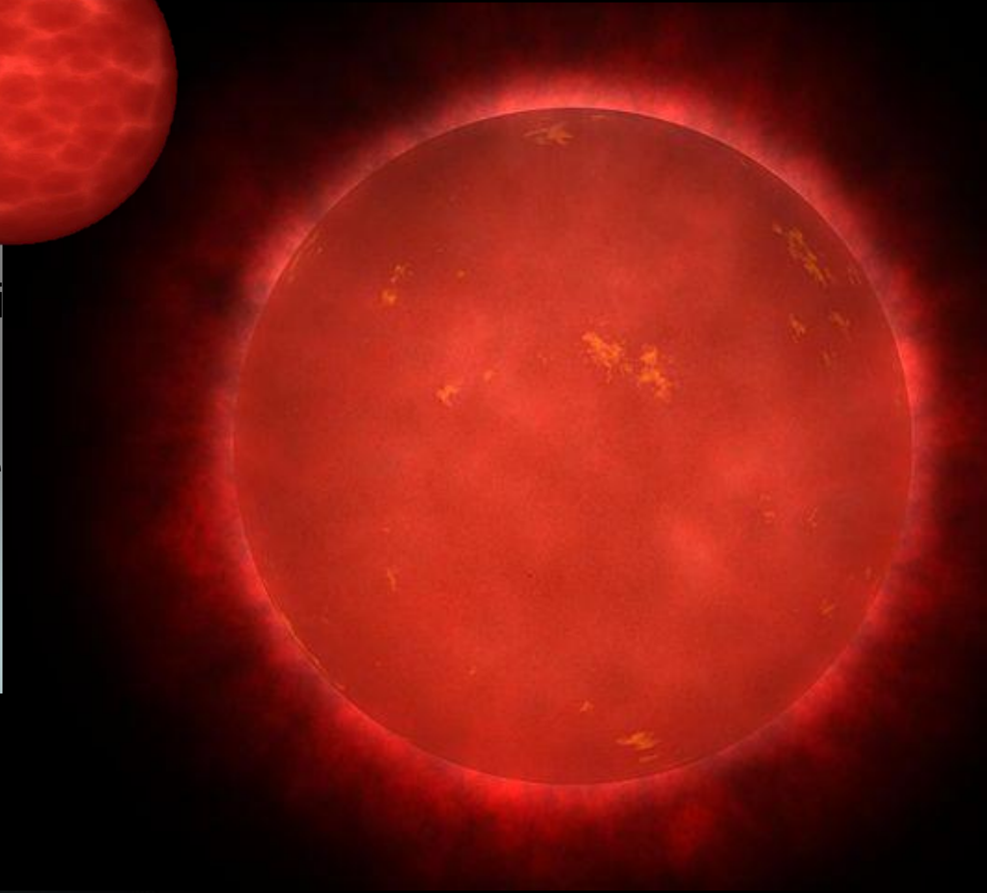
For 0.15 R_Sun, 0.5 M_Sun star:

T [days]	0.1	2	10	50	200	518 (1.4 yr)	1600 (4.3 yr)
a [AU]	0.0035	0.025	0.072	0.21	0.53	1	2.1
P_geo [%]	~21	~3	~1	0.36	0.14	0.075	0.036

For 0.15 R_Sun, 0.5 M_Sun star:

R planet [R_Earth]		0.5		1		2
Depth [%]		0.1		0.4		1.5
Equivalent			Earth		Neptune	

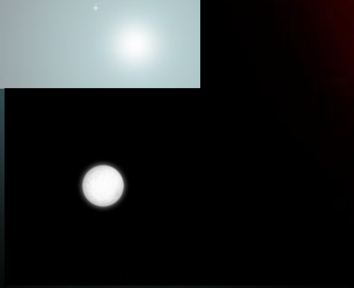
Different kind of transiting bodies



- Brown dwarfs: Very cool, Jupiter-sized
  => Reflection effect, IR excess and si

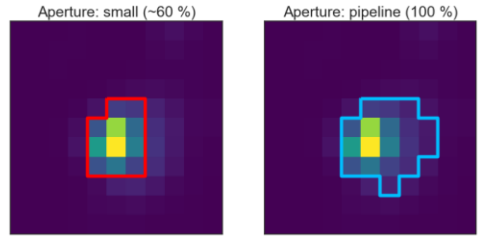
- M dwarfs: Cool, 1-5 Jupiter-sized
  => IR excess, radial velocity and size

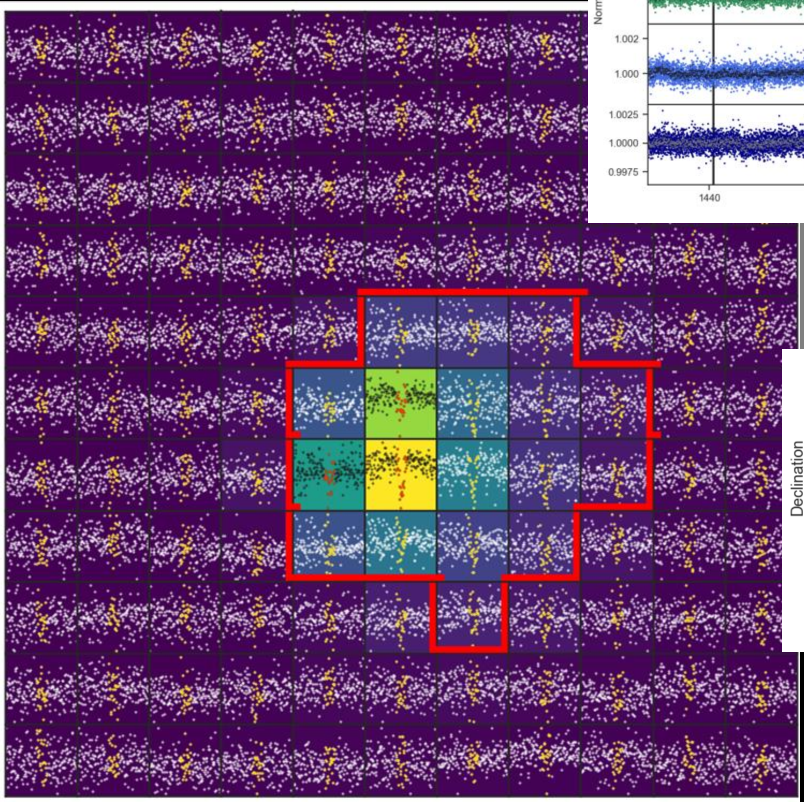
- White dwarfs: Dense, Earth-sized
  => Radial velocity

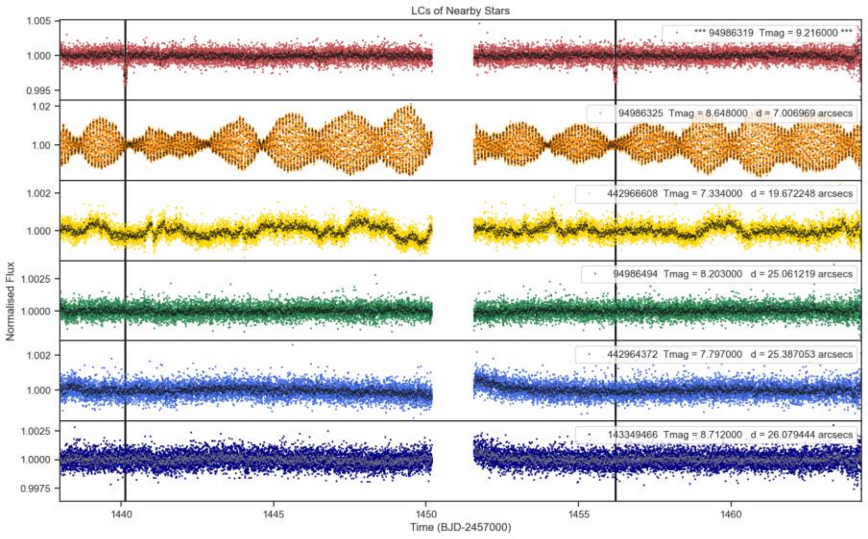


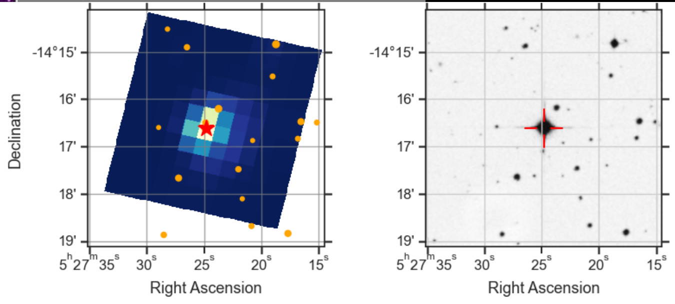
Vetting process

- Aperture
- Close stars
- Background
- pixels









D

Computation of the occurrences

Fraction of star with a planet consistent with having no detection in 530 observed targets.

P_detec(R_Planet, T_Planet, Magnitude_Star)

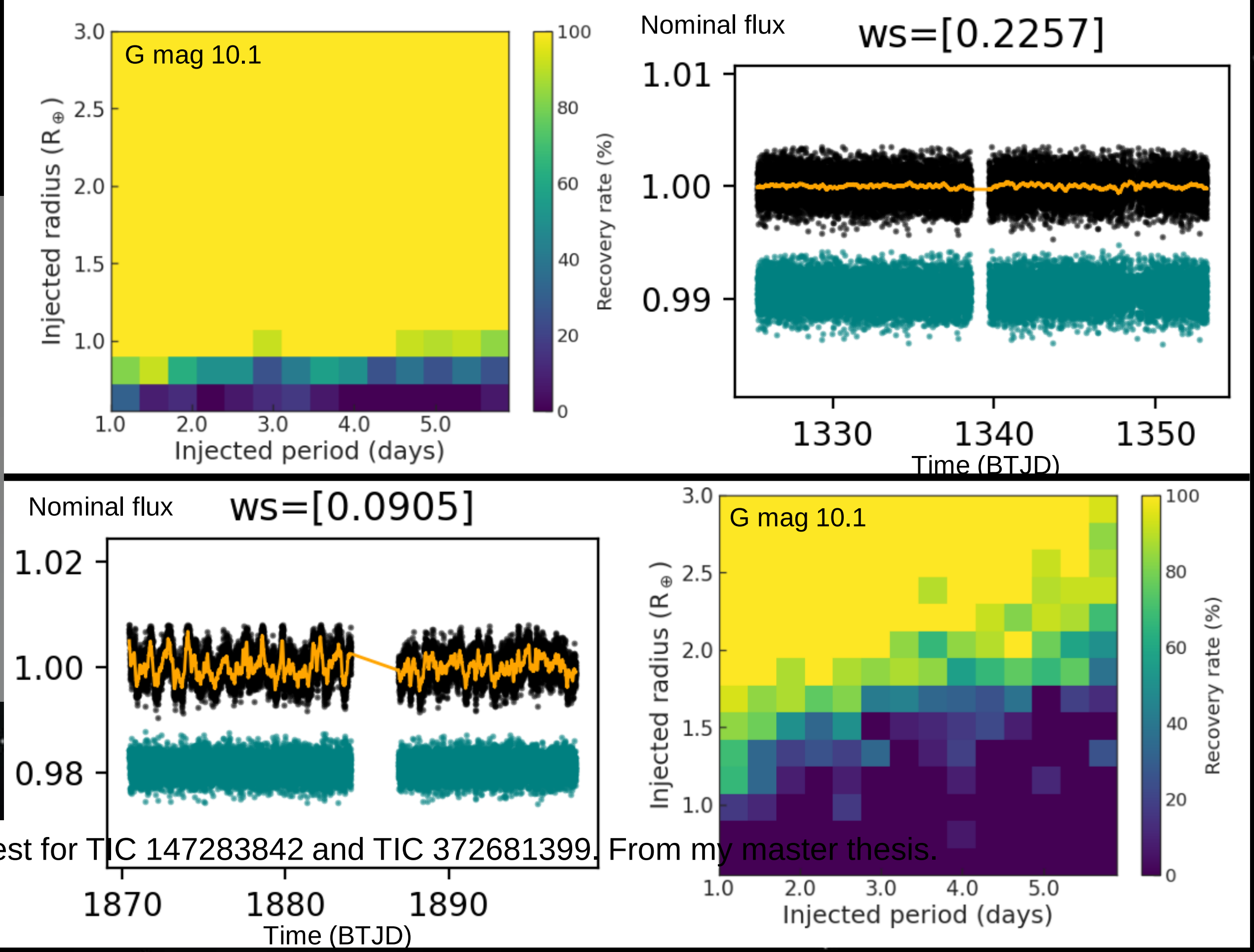
R*	0,17	R_Sun	118378140	m			
M*	0,47	M_Sun	9,4E+029	m			
n	530	nb_stars_with_no_signal					
P_transit	1	%	0,01	frac	geometric transit probability	10d ~ 1%	
P_detec	80	%	0,8	frac	detection probability		
confidence	99	%	0,99	frac			
	there is, at most one over		422	sdO/B with a planet with		99	% confidence

$$\eta = \frac{(1-conf^{1/n})}{P_{transit} * P_{detection}}$$

Lightcurves aspects

- Calm and 'stormy' aspects

- Improvements for known pulsative stars

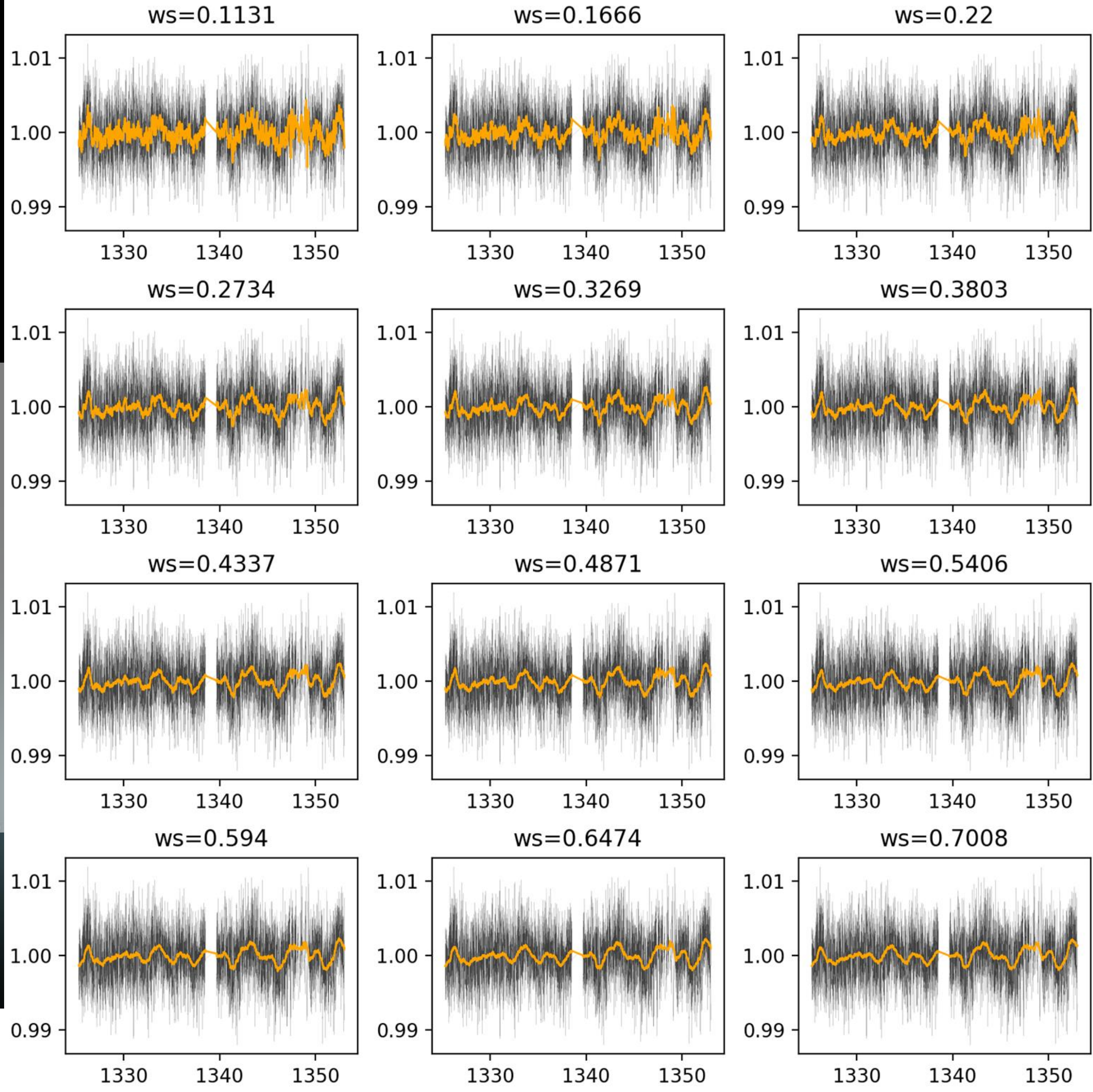


Lightcurves and injection-recovery test for TIC 147283842 and TIC 372681399. From my master thesis.

Detrending

- Example of detrendings

- Window size influence



The 12 detrendings with different window sizes

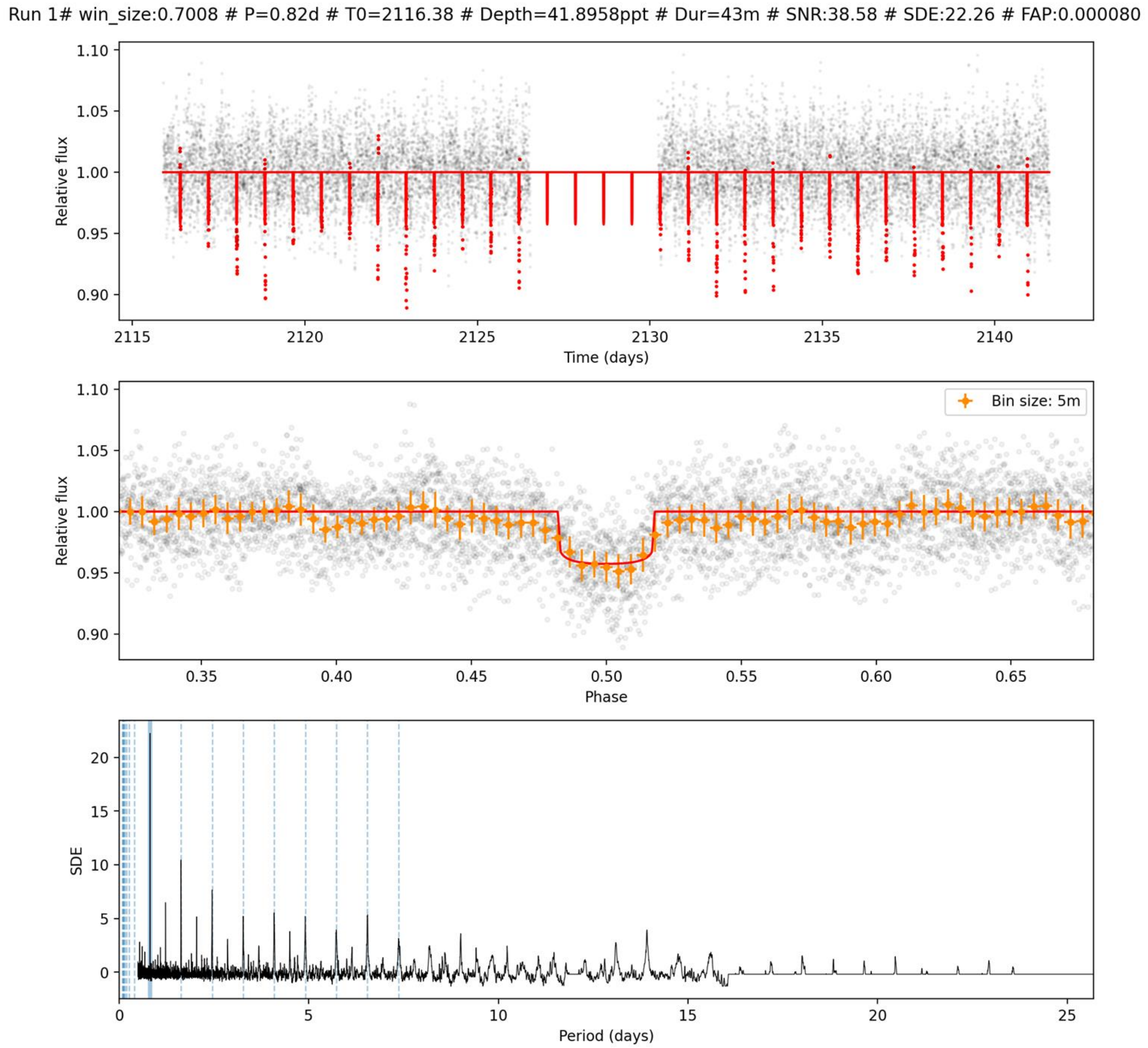
SHERLOCK positive

Quantifiers:

SNR, SDE

Main parameters:

Period, depth, duration
visual aspect, harmonics



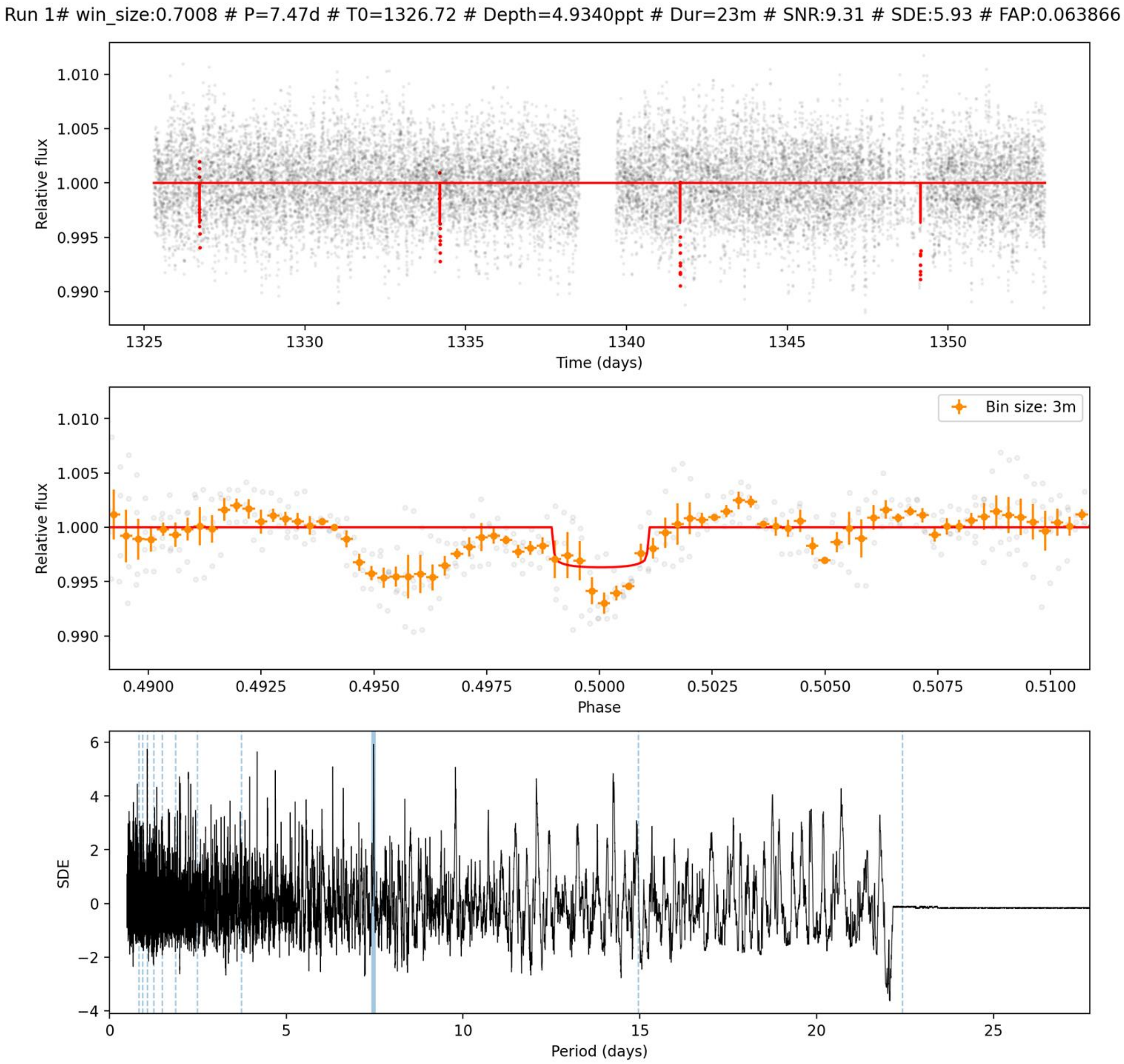
0.82 days signal on TIC 397833009. Main star is lil

J1

SHERLOCK negative

Hints for a negative:
- low SNR and/or SDE
- systematics
- visually inconclusive
- no harmonics

Other possibilities:
- pulsations, SSO, etc.



Outputs of TIC 2290515228.

TIC 396720998 - TOI 709.01

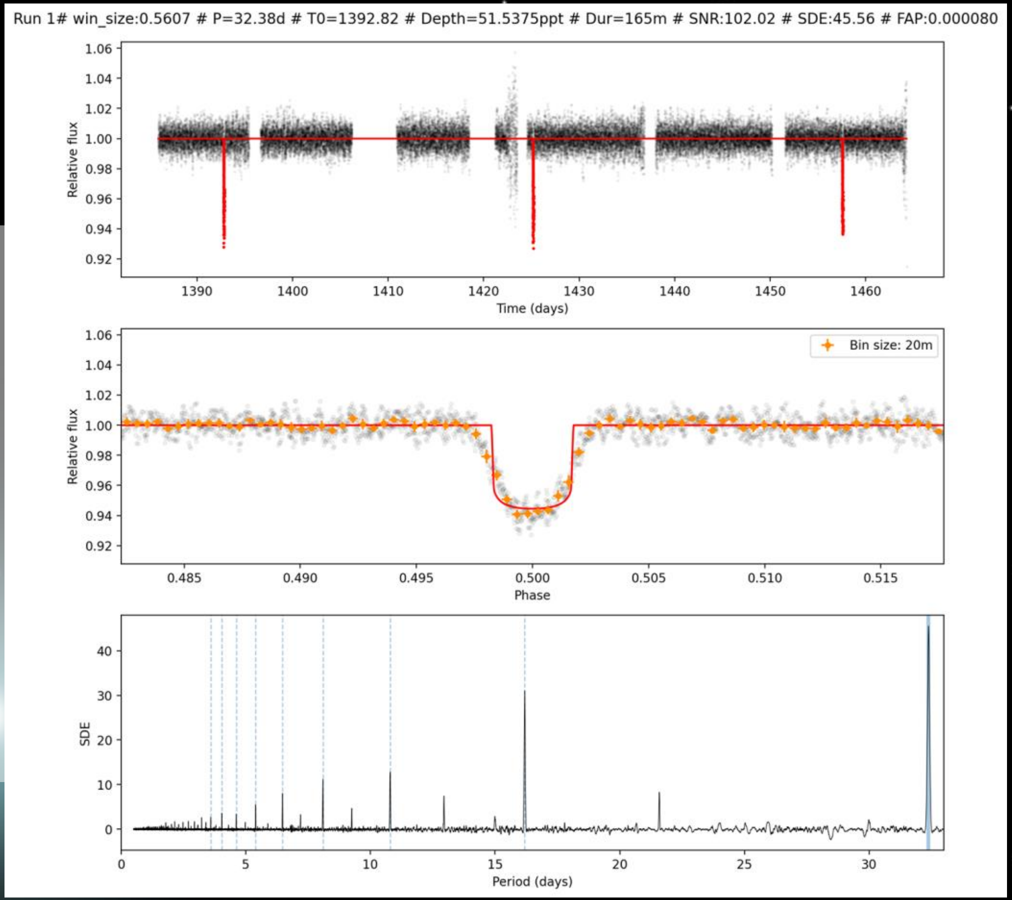
Period: 32 days.

Potentially from stellar origin (V shape).

Follow-up ongoing
=> already observed once with TRAPPIST

Not bright, planet?, brown darwf?, cool star?

A complex system: Solar-like star + sdO



K

Radial velocity

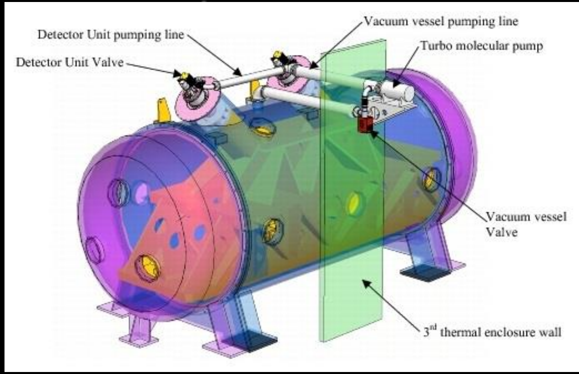
Instruments:
HARPS
On ESO's 3.6m telescope in La Silla, Chile

Espresso
On the VLT (4*8.2m), Cerro Paranal, Chile

CARMENES
On a 3.5m telescope, Calar Alto, Spain

Use in the study:
Distinguish between planets and stellar companions.
RV of planets: few m/s
RV of stellar-mass companion: dozens of km/s
=> difficult to detect planets, easy to rule out stars



Roche limit and disintegrating bodies

The comet Shoemaker-Levy 9 after its disruption by Jupiter (NASA)

At their Roche limit, bodies are destroyed due to tidal forces.

SHERLOCK includes an option to look for disintegrating bodies (dust tail).

Roche limit [AU]						
Planet radius	Planet mass [M_Earth] 0,5	1	2	5	10	50
0,5	0,053	0,042	0,033	0,025	0,020	0,011
1	0,106	0,084	0,067	0,049	0,039	0,023
2	0,212	0,168	0,134	0,099	0,078	0,046
4	0,424	0,337	0,267	0,197	0,156	0,091
6	0,637	0,505	0,401	0,296	0,235	0,137
8	0,849	0,674	0,535	0,394	0,313	0,183
10	1,061	0,842	0,668	0,493	0,391	0,229
12	1,273	1,011	0,802	0,591	0,469	0,274

Roche radius estimation as a function of planet's mass and radius (in Earth units). Own work.

M

Toward engulfment

Planets are driven inward from far away

Minimum Orbital Radius to Avoid Tidal Capture

M_*	$R_*^{\max}$ (AU)	$a_{\min}$ (AU)		
		$M_p = M_J$	$M_p = 3\,M_J$	$M_p = 5\,M_J$
$1\,M_\odot$	1.10	3.00	3.40	3.70
$2\,M_\odot$	0.84	2.10	2.40	2.50
$3\,M_\odot$	0.14	0.18	0.23	0.25
$5\,M_\odot$	0.31	0.45	0.55	0.60

Table 1 of Villaver et al. 2009

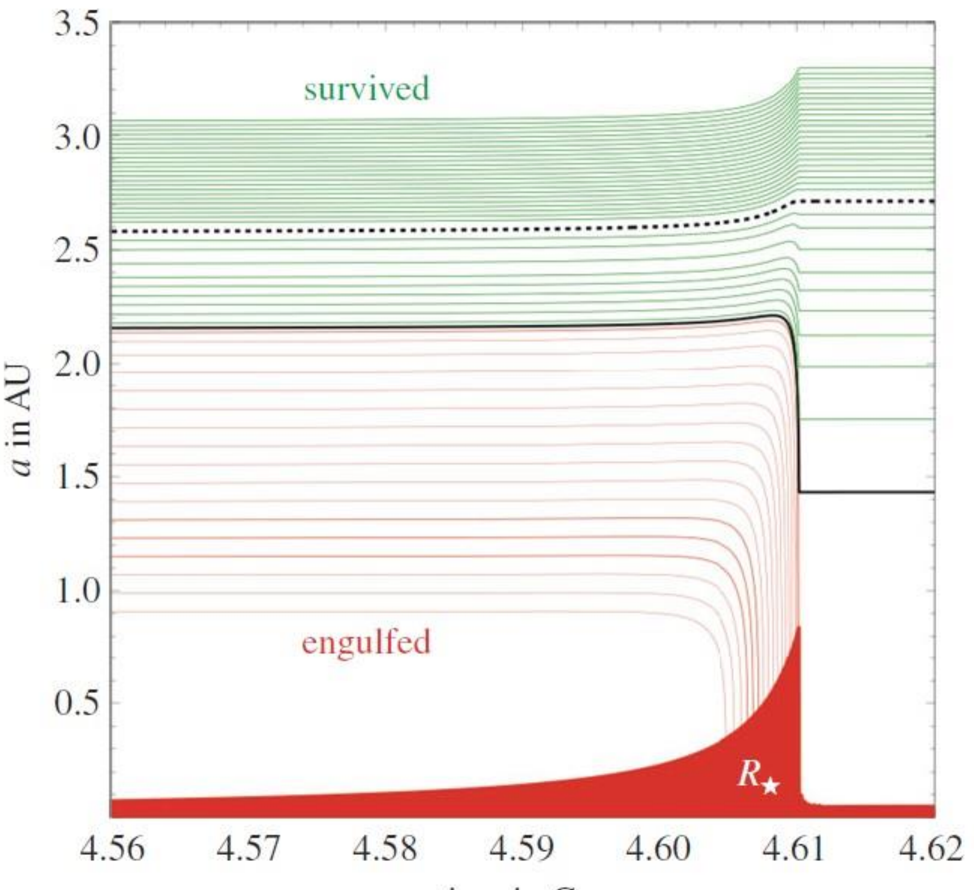


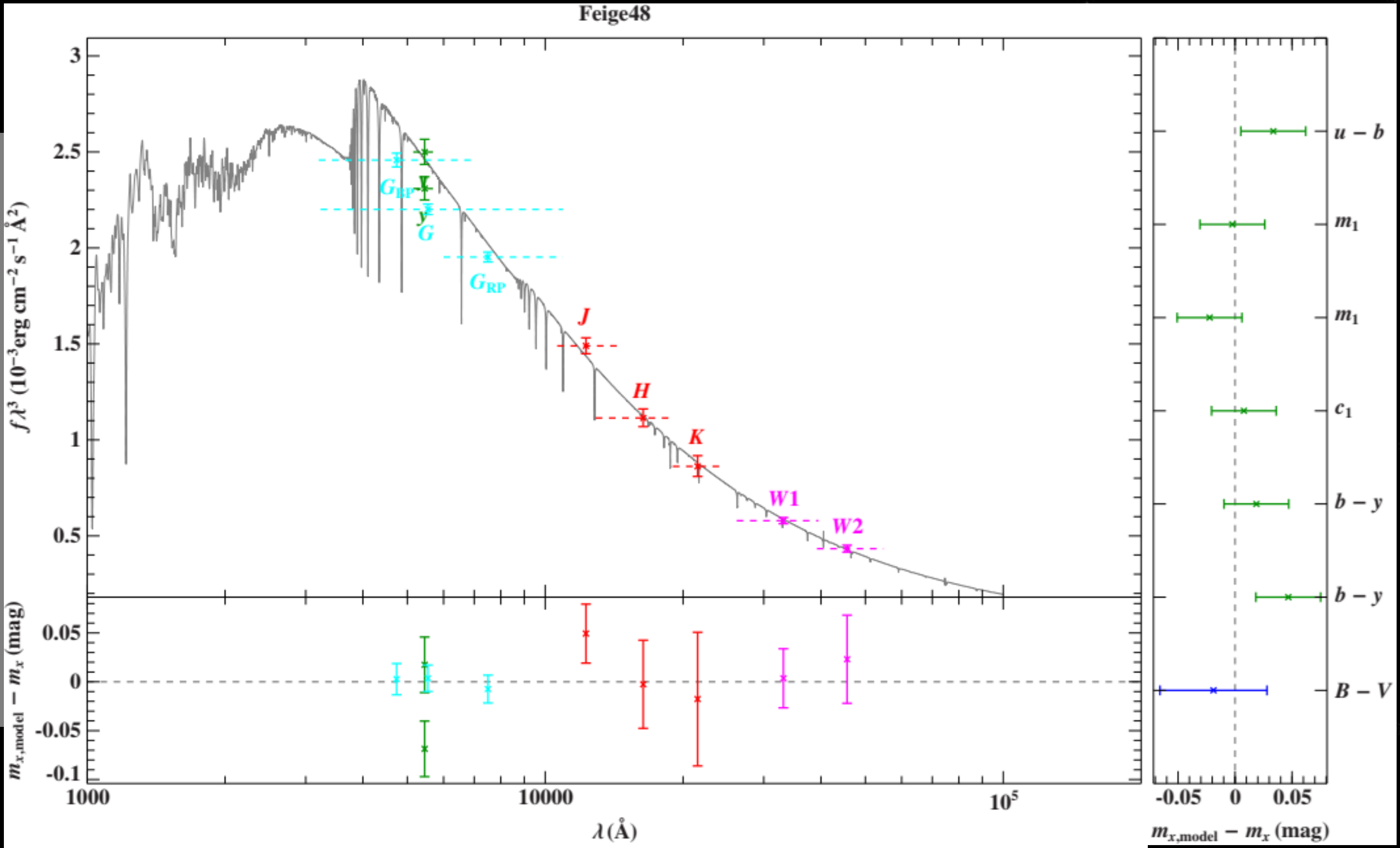
Figure 1 of Villaver et al. 2014

Spectral Energy Distribution

Target flux as a function of wavelength

Allow for detection of cool bodies (IR excess)

Determination of stellar parameters (including radius)



SED of Feige 48. Figure from Uli Heber (Bamberg Observatory, private communication)