Under supervision of V. Van Grootel, L. Siess and F. Pozuelos

Probing the consequences of planetary engulfment during the RGB using hot subdwarf stars

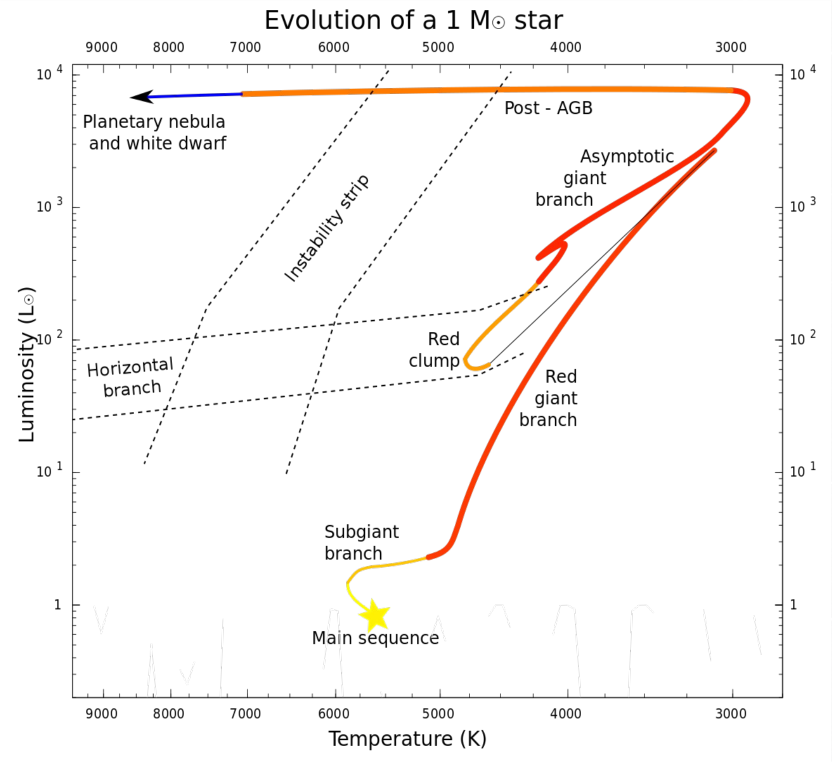
23 May 2024

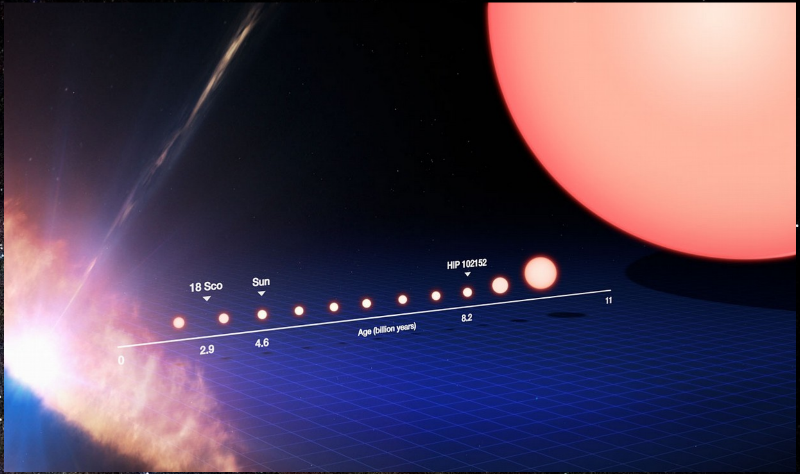
Antoine Thuillier

22nd Meeting of the FNRS Contact Group Astronomie & Astrophysique - ROB

Introduction

Brief recall on stellar evolution

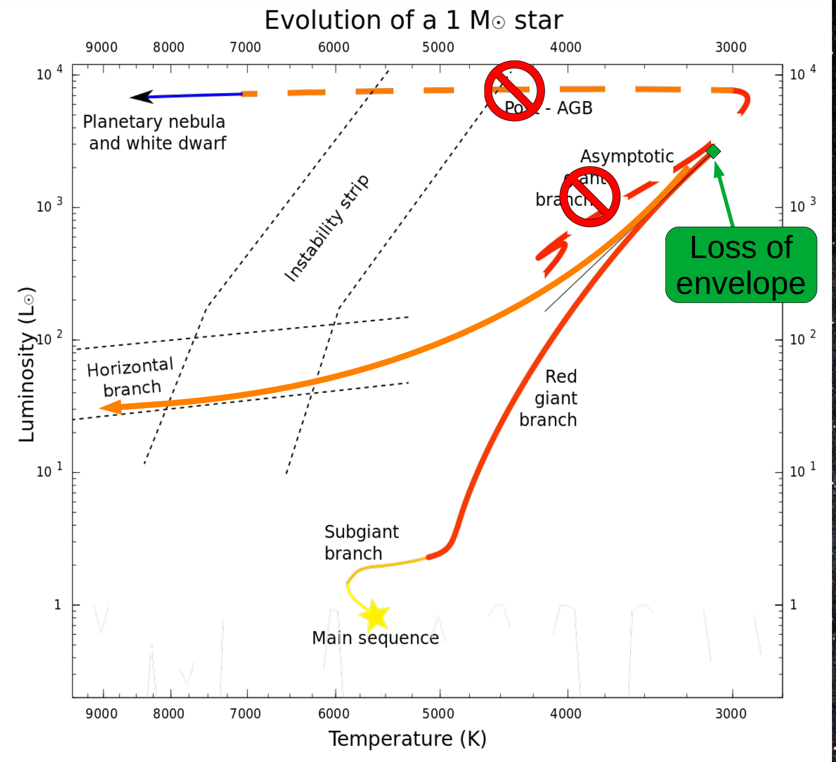


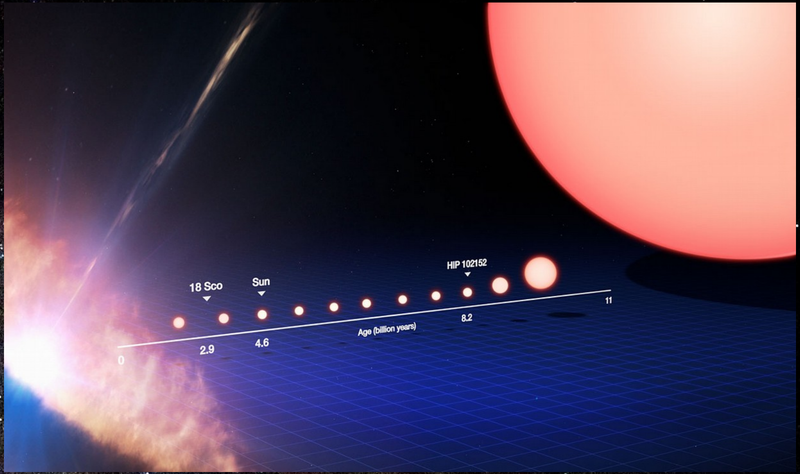


Usual stellar evolution :
MS => RGB => AGB => WD

Introduction

Hot subdwarfs (sdB)





Hot subdwarfs stars evolution :

MS => RGB => ~~AGB~~ => WD

EHB

Introduction

Goals

- Can some close-in planet survive the RGB ?

- Do hot subdwarfs have planets ?

- Can hot subdwarfs be formed through planet-star interactions ?

Introduction

Goals

- Can some close-in planet survive the RGB ?
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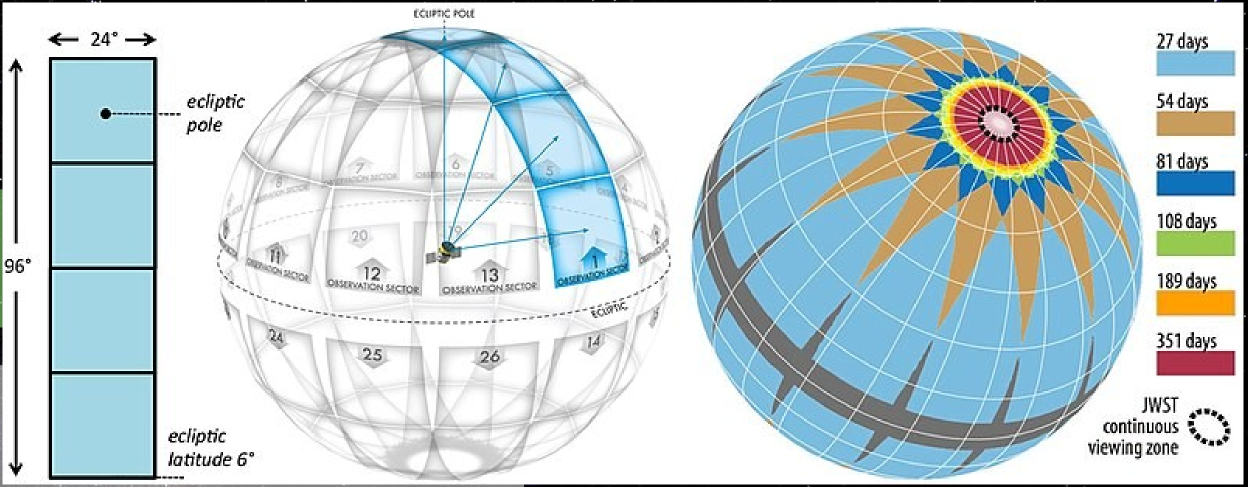
Look for planets around sdBs

Model the interactions

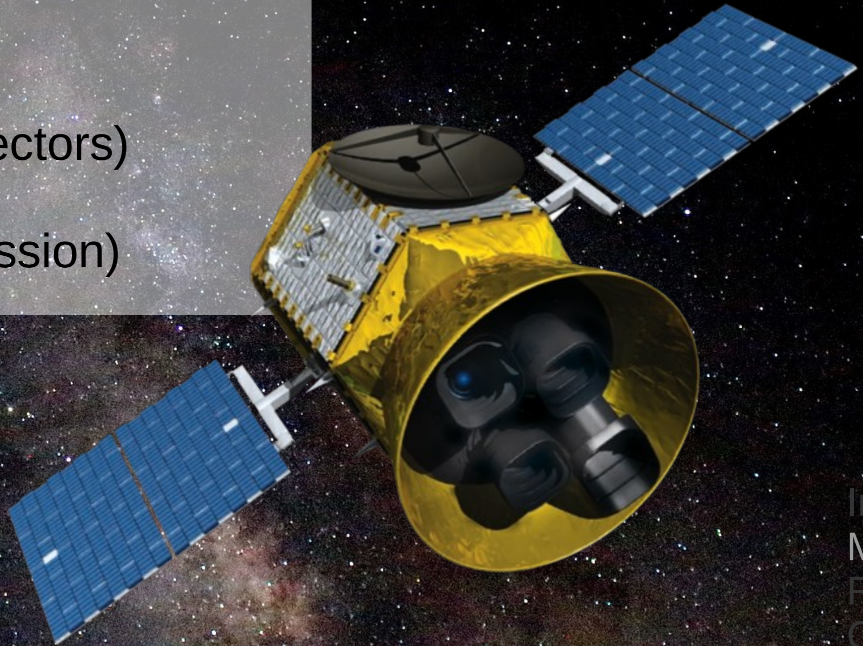
Method

Method

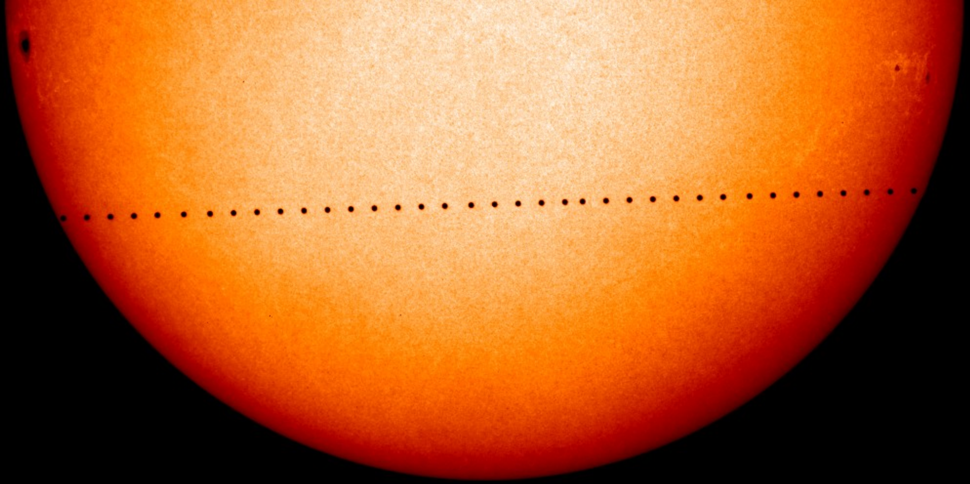
Data : The TESS mission



- Launched in 2018 by the NASA
- 4 * Ø 10 cm telescopes
- Large survey of 90% of the sky (cycles, sectors)
- 1302 hot subdwarfs observed (primary mission)



Method

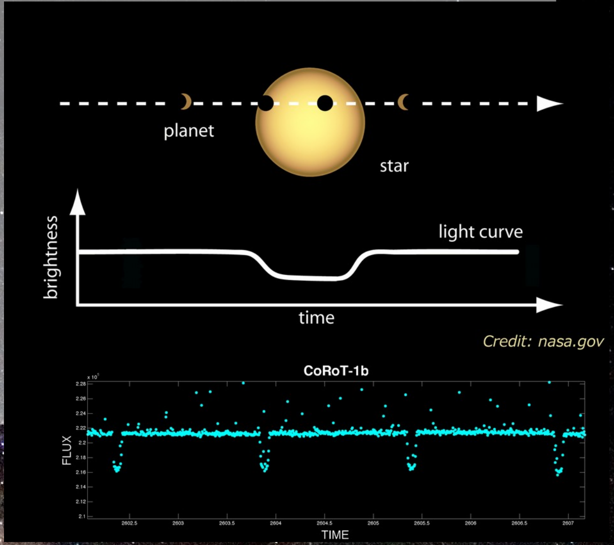


Quick recall : the transit method

Looking for flux drop in star's light curves

Efficiency depends on:

- $(R_{planet} / R_{star})^2$
- Planet's period



Method

The SHERLOCK PIPEline

Looking for shallow transits with the SHERLOCK PIPEline

(Searching for Hints of Exoplanets fRom Lightcurves Of spaCe-based seeKers)

We want to consider a maximum of potential signals

=> Low SNR threshold

=> Higher rates of false positives

=> Need to detect and discard them

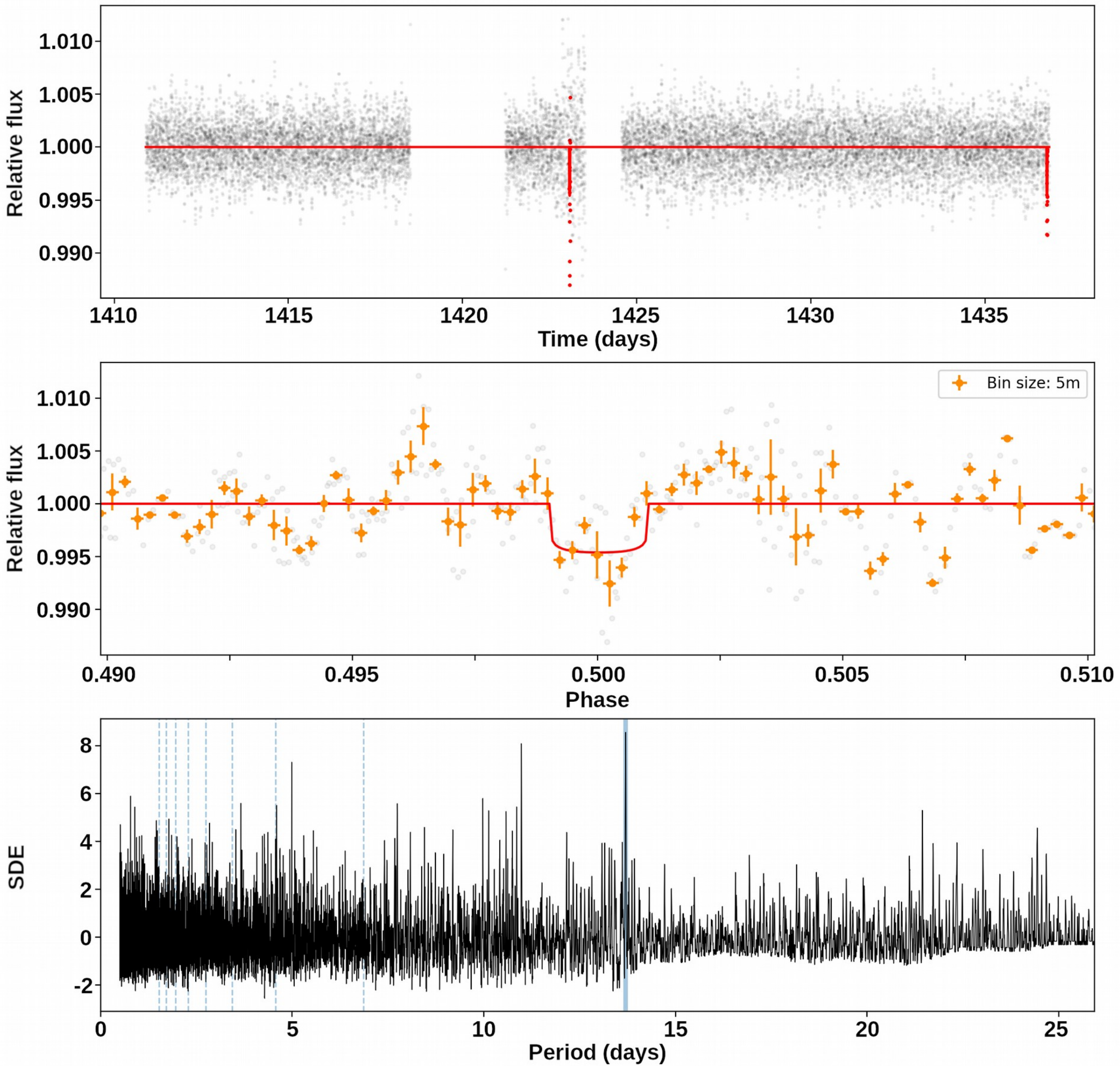
=> Vetting steps

Method

Vetting

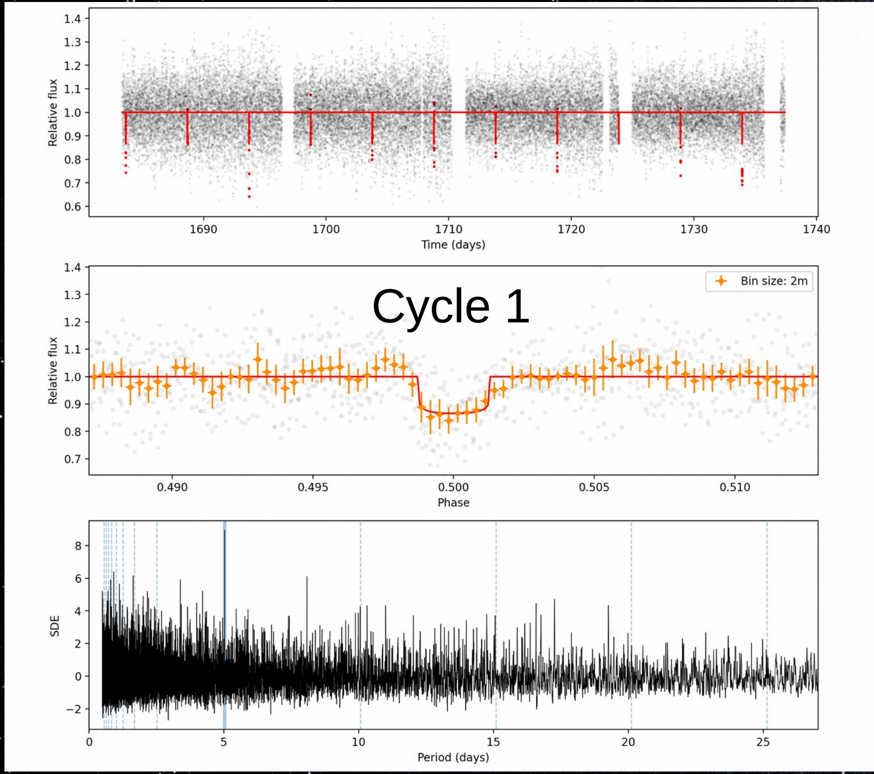
The numbers look good,
the shape… a bit less.

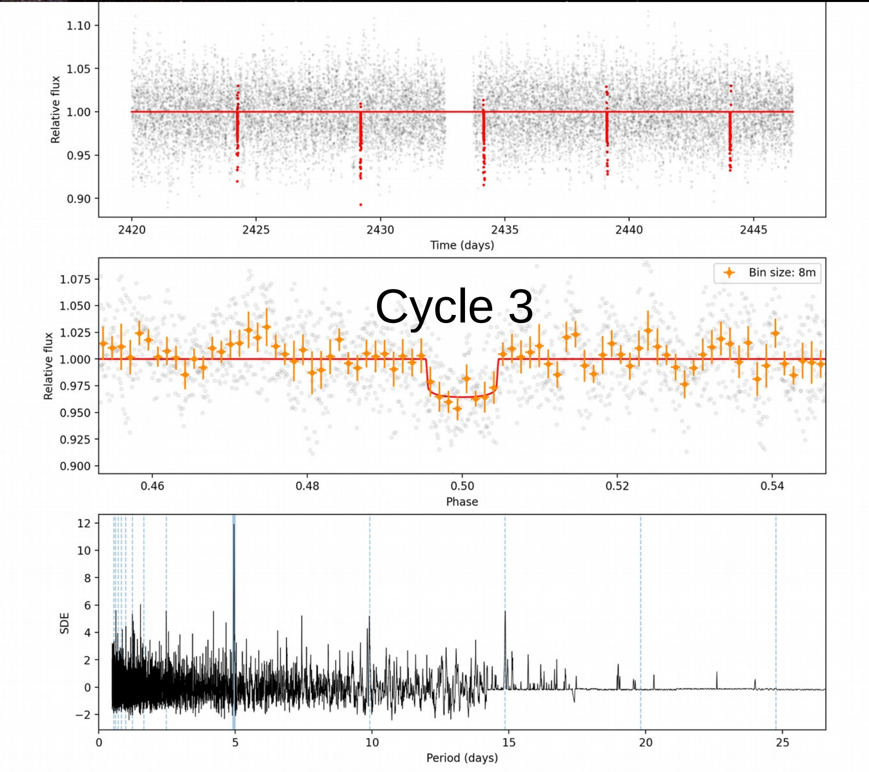
=> Visual check of all results
- global shape
- glitches
- undetected pulsation
- periodic variations



Method

Vetting



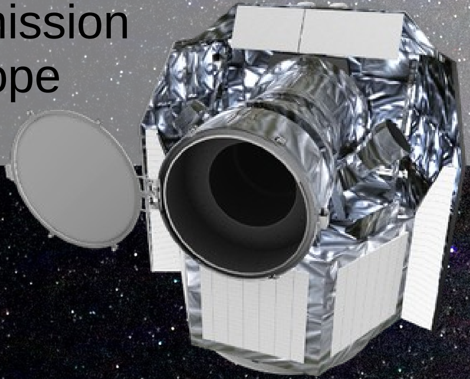


Method

Follow up

TRAPPIST
- Two Ø60 cm telescopes
  - La silla, Chile
  - Oukaïmeden, Moroco

CHEOPS (ESA)
- Space based mission
- Ø32 cm telescope



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Method

Occurrences

$$f_{max} = 1-\left(1-\boxed{C}\right)^{\frac{1}{\left(\boxed{N}*\boxed{P_{transit}}*\boxed{P_{detection}}\right)+1}}$$

Developed form of eq. 1 from Thuillier et al. 2022, adapted from eq. 7 of Van Sluijs & Van Eylen 2018

Confidence level

Number of star

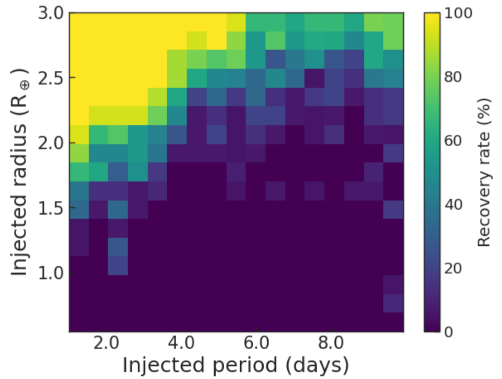
Transit probability

$$P_{transit} = \frac{R_*+R_p}{a}\cancel{\frac{1+e\sin(\omega)}{1-e^2}}$$

$$P_{transit} = \frac{R_*+R_p}{a}$$

Detection probability

Depends on a lot of parameters
=> Injection & recovery tests



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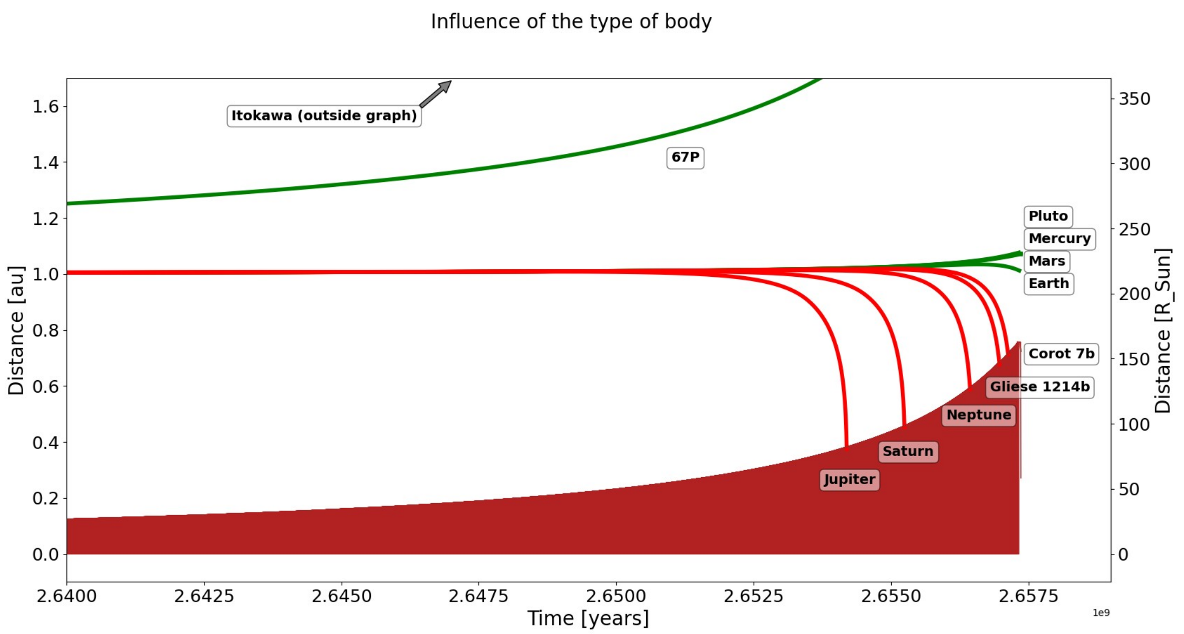
Models



Modeling the sdB progenitors
=> Starevol

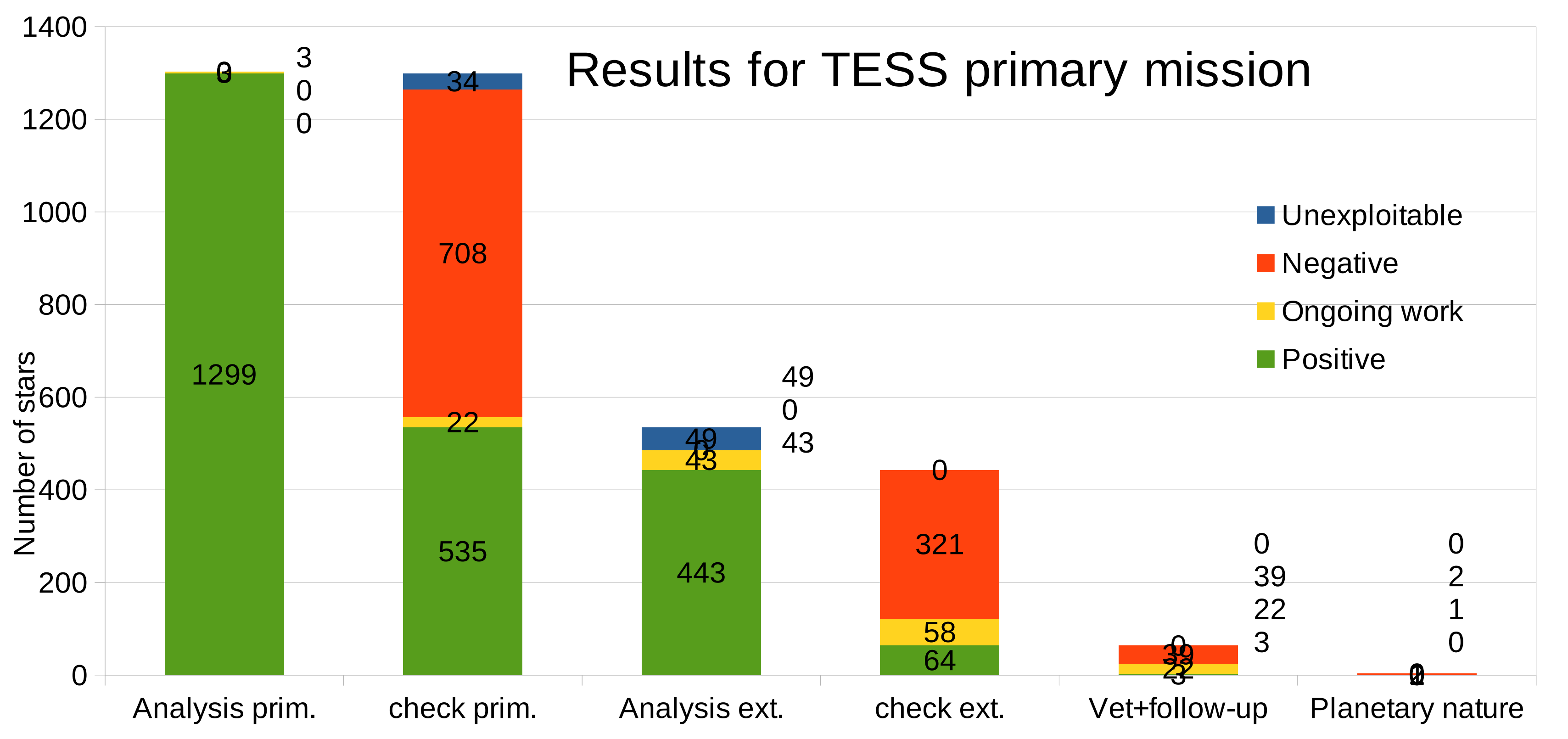
Modeling the evolution of planets parameters through the RGB
=> Sekhmet

Comparing star's envelope binding energy to the planet's energy.

Results

Results

Observations



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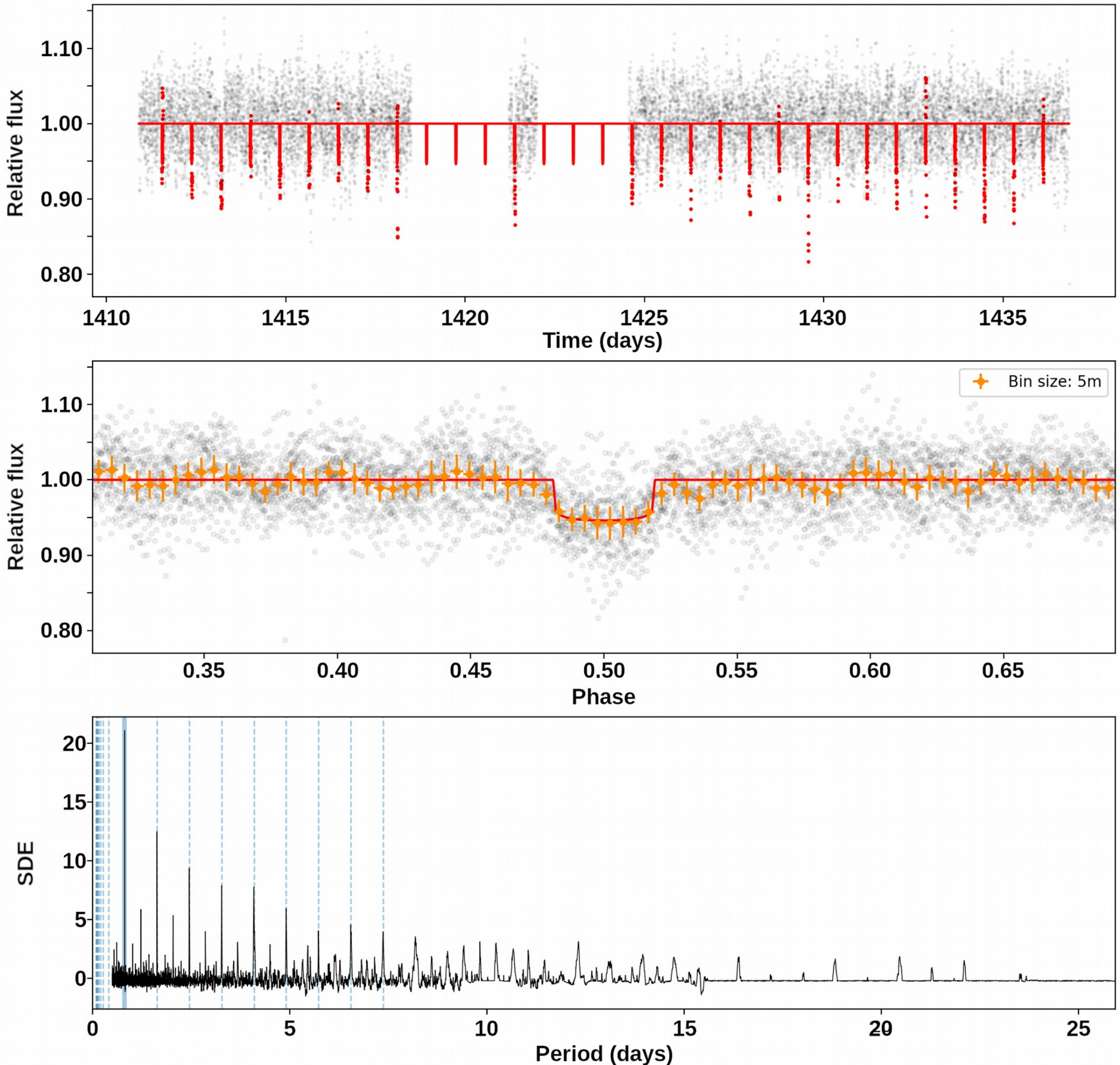
Results

False positives

Is this real?

or just fantasy?



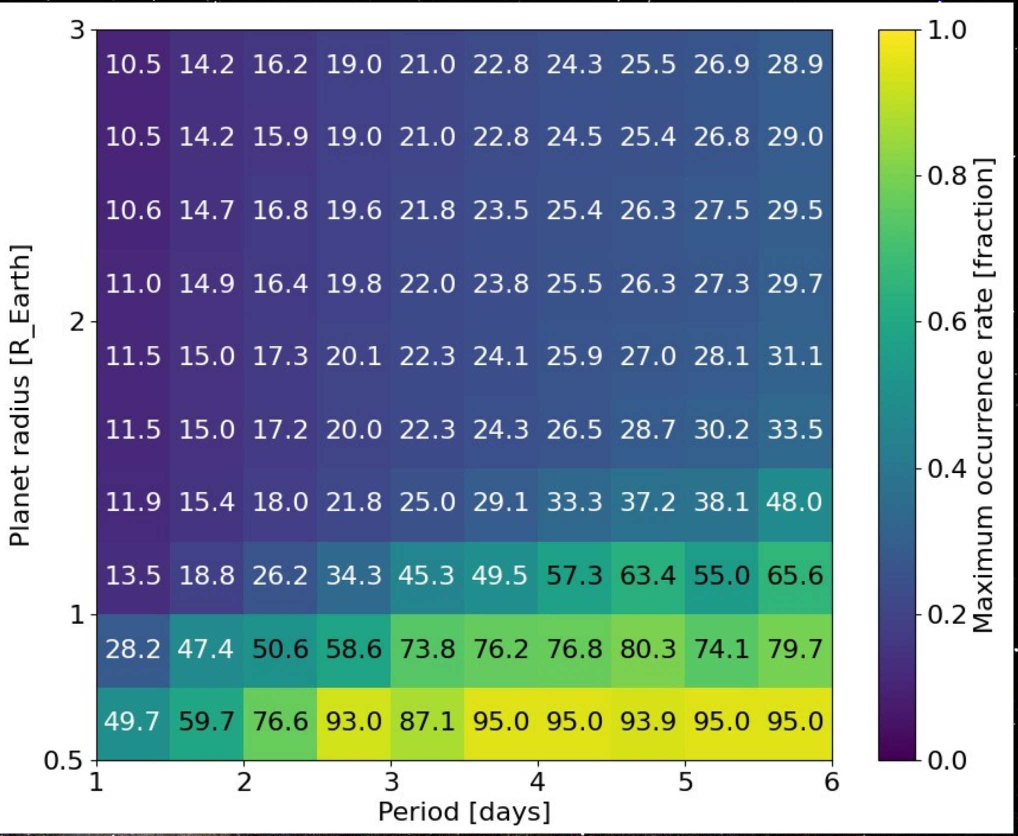
Results

Occurrences

Preliminary results from Cycle 1 (549 stars)

Better constraints for:
- bigger planets
- shorter periods

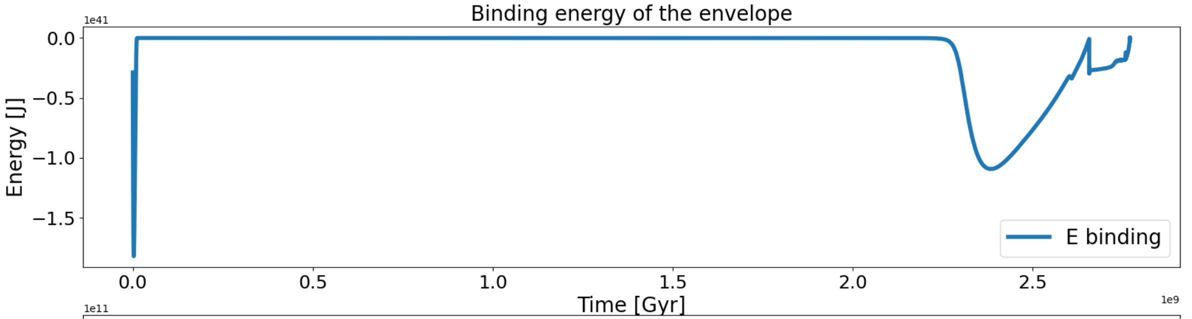
Ex: There is at most ~20% of sdB that have a 2 R_{Earth} planet with a period of 3 days (with 95% confidence).

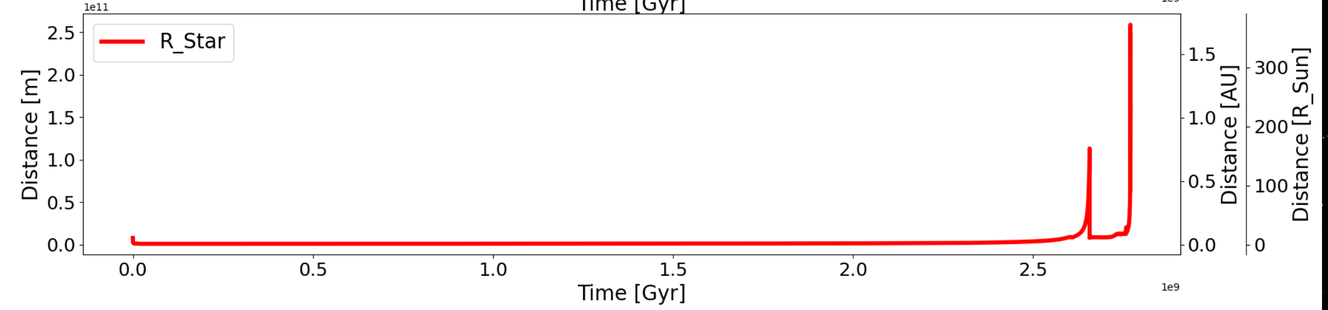


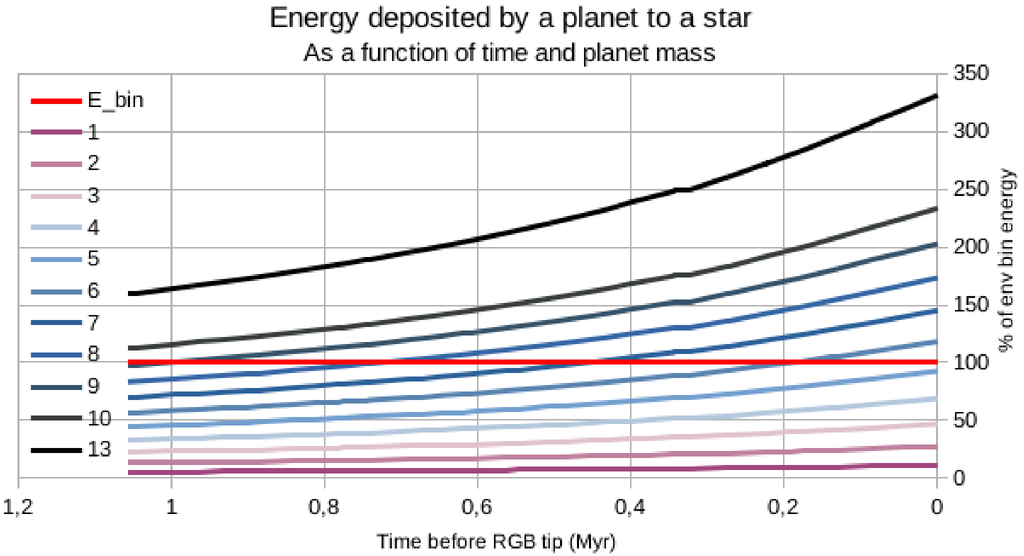
Results

Models

Energy is not a problem, planets have enough of it !







Conclusion

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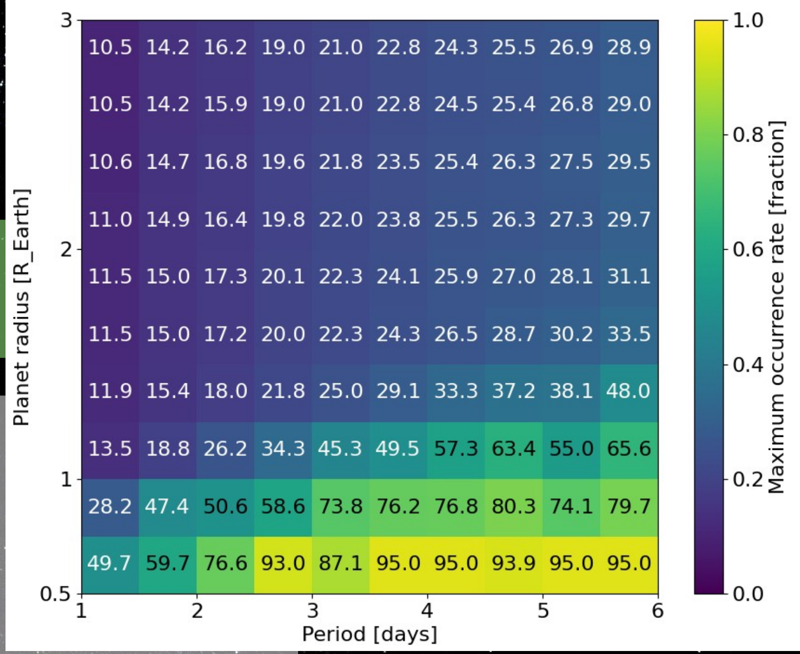

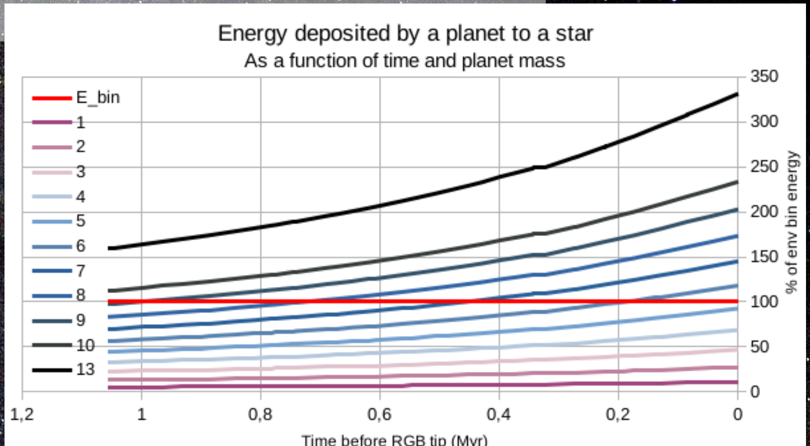

More info :
Thuillier A., Van Grootel V., Dévora-Pajares M. et al., 2022, A&A, 664, A113.
Van Grootel V., Pozuelos F.J., Thuillier A. et al. 2021, A&A, 650, 205.

All credits for the illustrations are in appendix

Take home message

- Goals:
  - Determine the fate of close-in planets during the RGB.
  - Determine whether sdBs have planets.
  - Determine whether sdBs can form from planets engulfment.

- Method:
  - Analyse all sdBs in TESS data to find transits
  - Model planet-star interactions

- Results :
  - No confirmed planets so far, if sdB have some, it's not much.
  - Planets have enough energy to expel envelope.

Thank you for your attention

Appendices

Introduction

RGB & substellar bodies

Close to the star :
=> Destruction and accretion

Far from the star :
=> Almost unperturbed survival

In-between :
=> Probably a bit of both

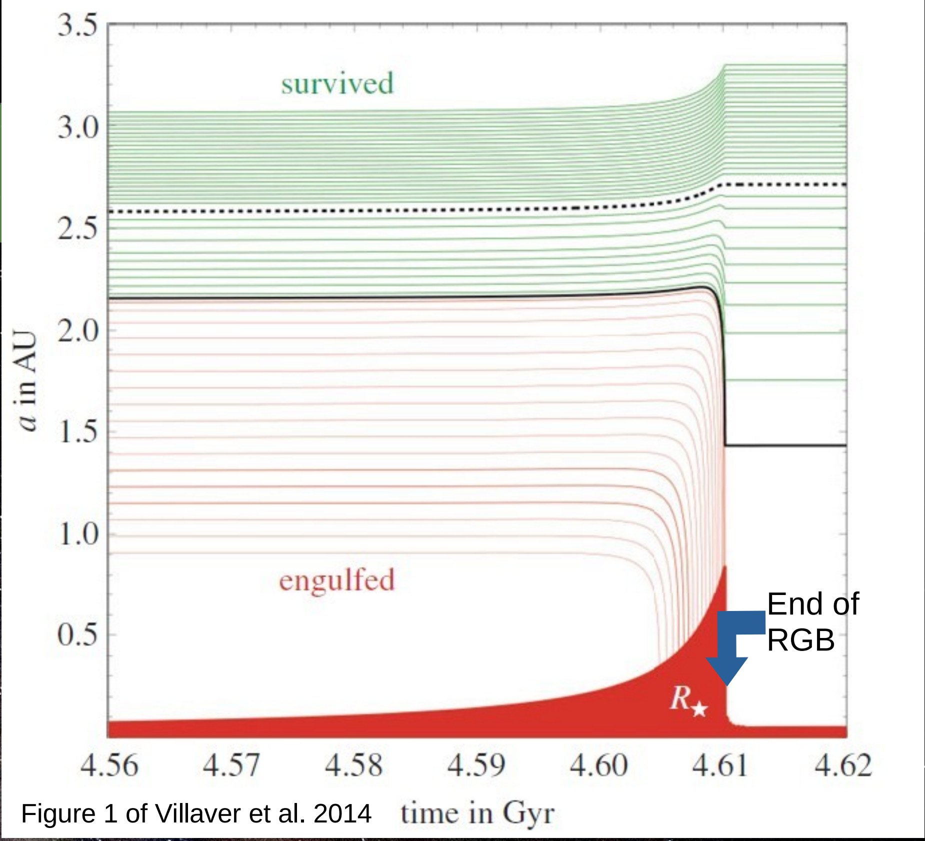

Figure 1 of Villaver et al. 2014

Introduction

RGB & substellar bodies

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Close orbiting planets after the RGB

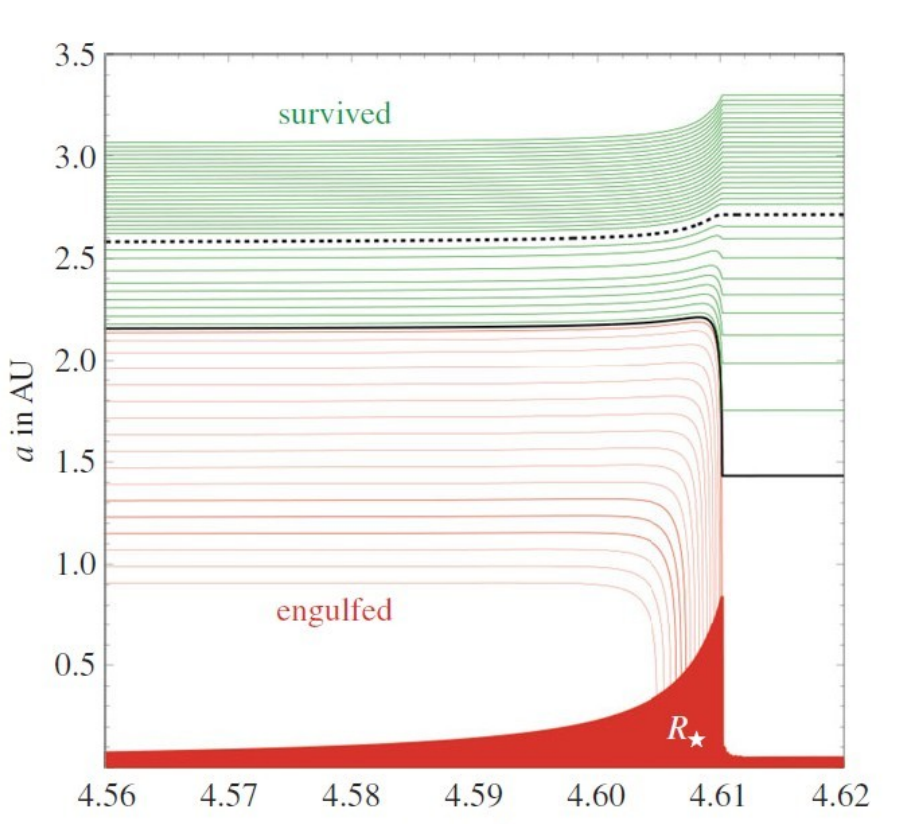

Figure 1 of Villaver et al. 2014

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Materials can form 2^nd gen. planets

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Can migrate in the system

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Materials can form 2nd gen. planets

Can migrate in the system

SdB's lifetime : ~100 Myr

Possible but very unlikely for sdB given their short lifetime

Transit method

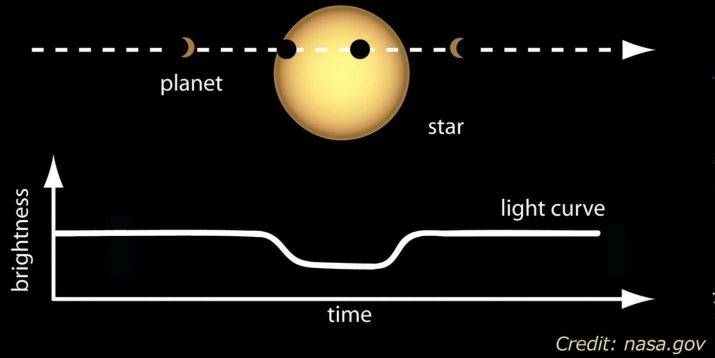
The depth of a transit depends on the ratio between the star's radius and the transiting body radius

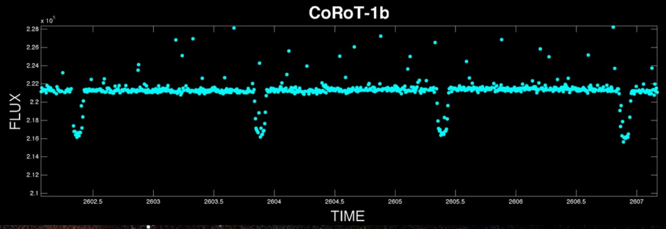
$$Depth = \frac{R^2_{Planet}}{R^2_{Star}}$$

Probability of transit is fully determined by geometry

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

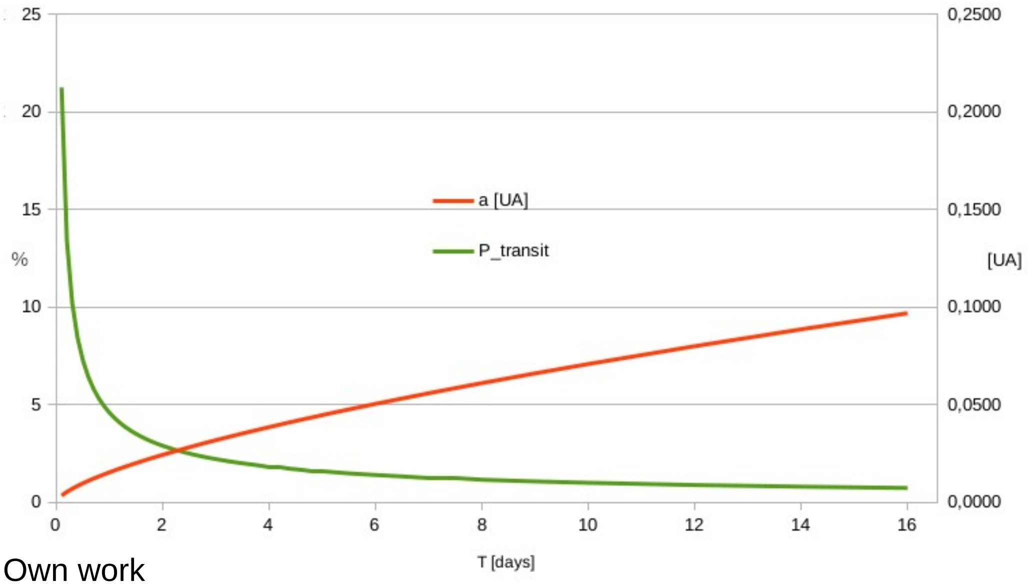
Transit : NASA, https://svs.gsfc.nasa.gov/30558





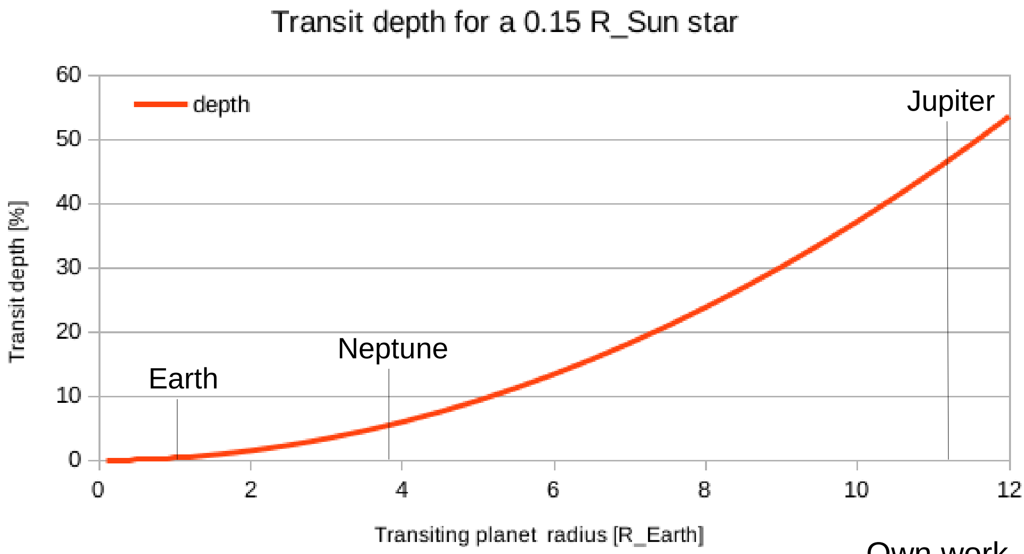
Transit method

Geometric transit probability



Own work

Transit depth



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	3.9	7	11.2
Depth [%]	0.1	0.4	1.5	5.7	18.2	46.7
Equivalent		Earth		Neptune		Jupiter

Thresholds

Signal to noise ratio (SNR) > 6

$$SNR = \frac{\text{Signal depth}}{\text{White noise}}$$

Signal Detection Efficiency (SDE) > 8

$$SDE = \frac{1 - \langle SR \rangle}{\sigma(SR)}$$

SR: *Signal residue for a tested period*
σ: *standard deviation*

SHERLOCK positive

Quantifiers:

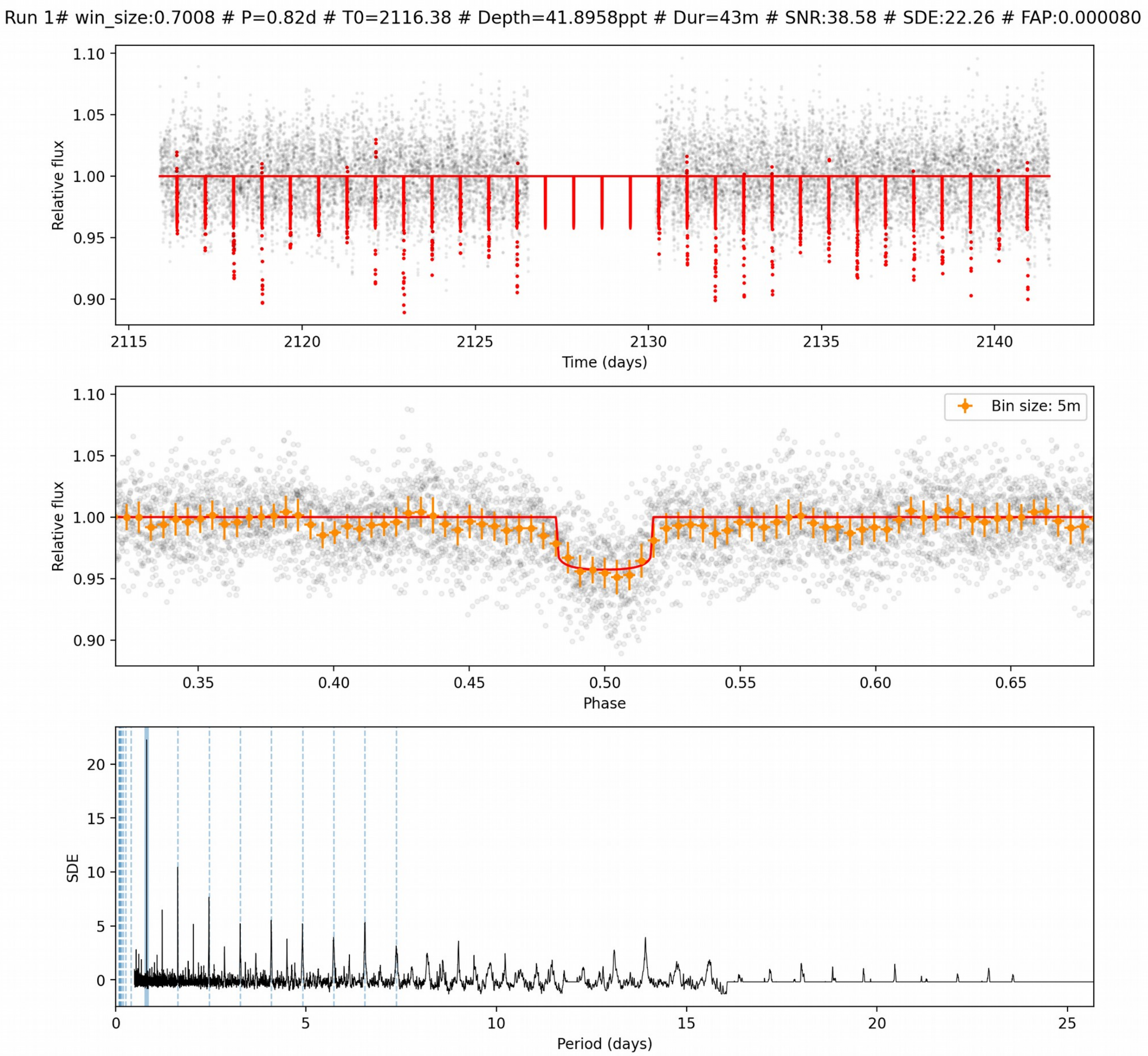
SNR, SDE

Main parameters:

Period, depth, duration

visual aspect, harmonics

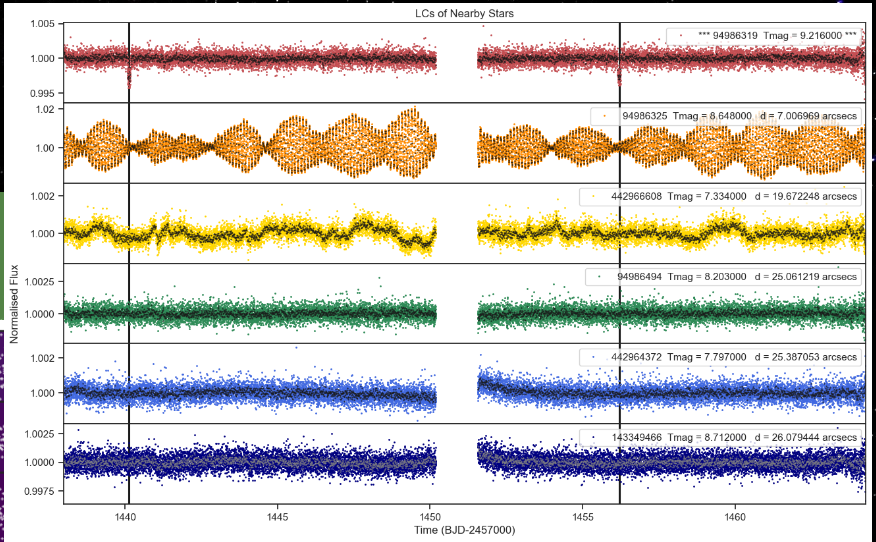
0.82 days signal on TIC 397833009. Main star is likely a sdF and the transiting body a BHB star

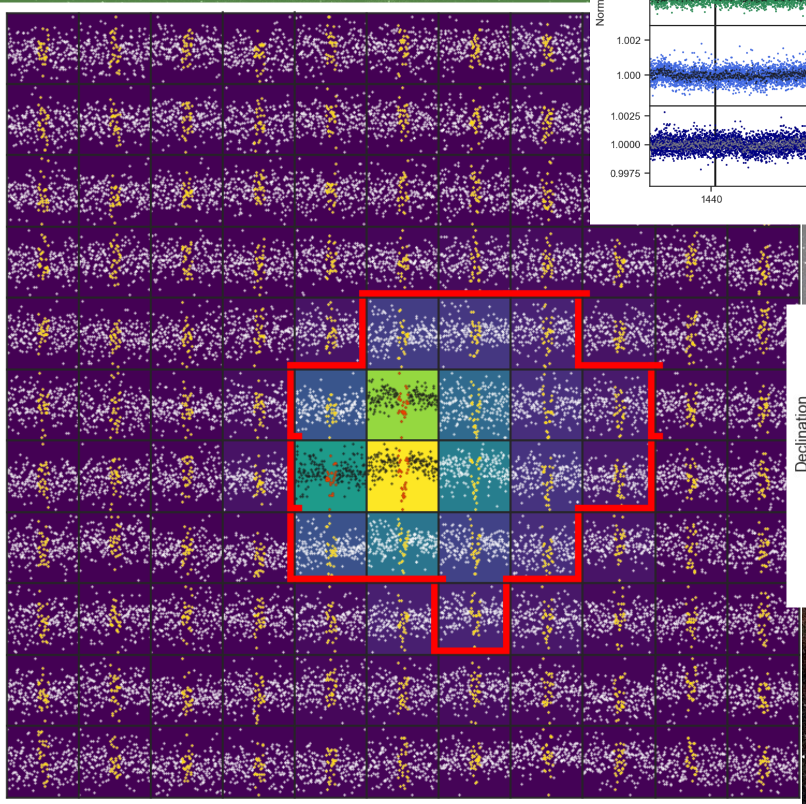


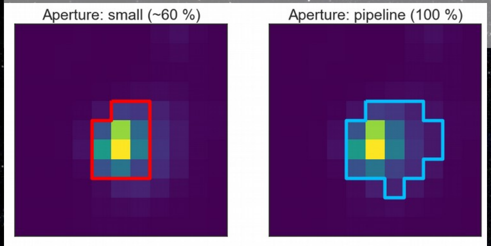
Method

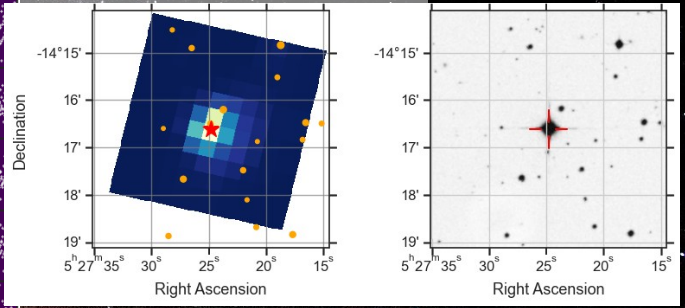
Vetting

- Backgroung check
- Close bright stars
- Close star variability
- Aperture check
- Pixel comparation









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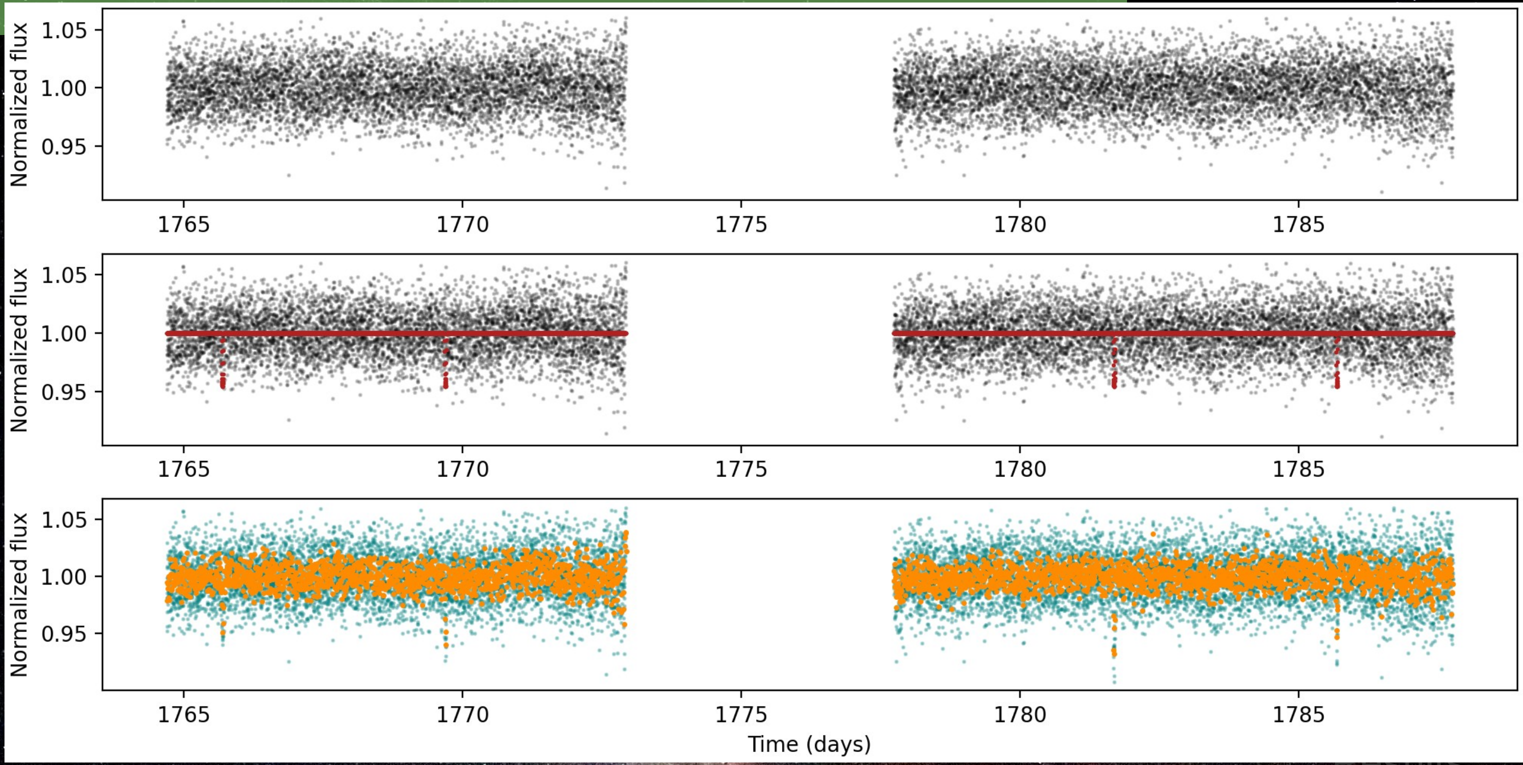
Injection & recovery tests

- Real lightcurve

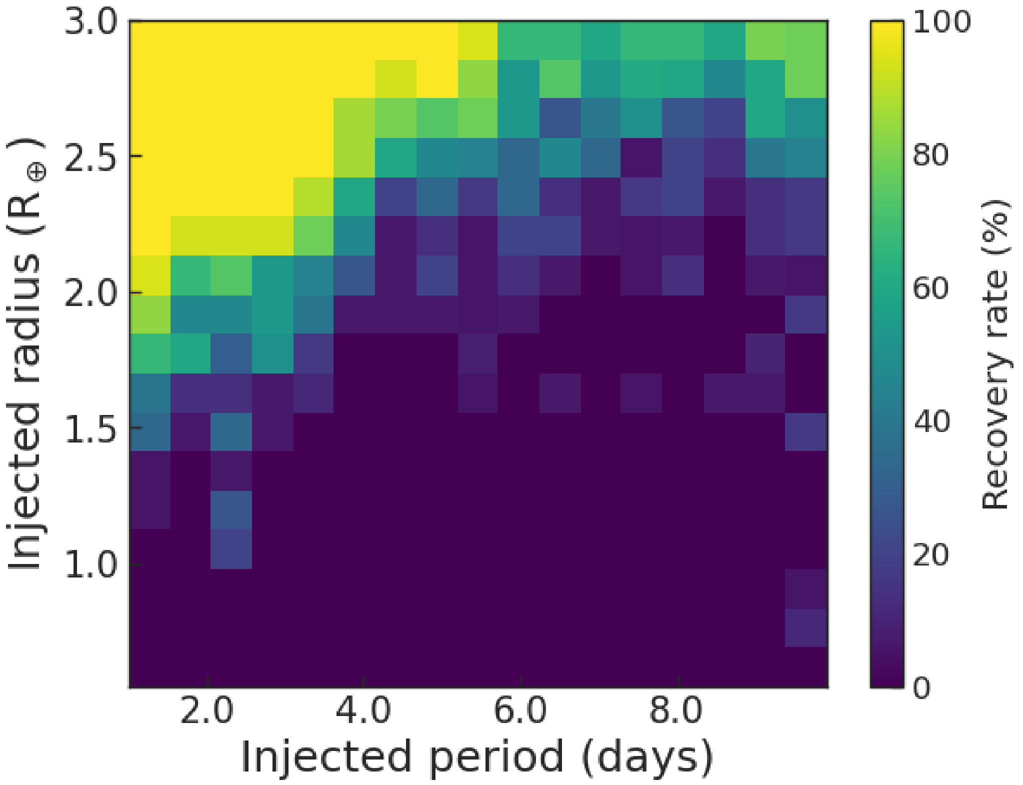
- Synthetic planet
  (e = 0 ; i = 90°)



Method

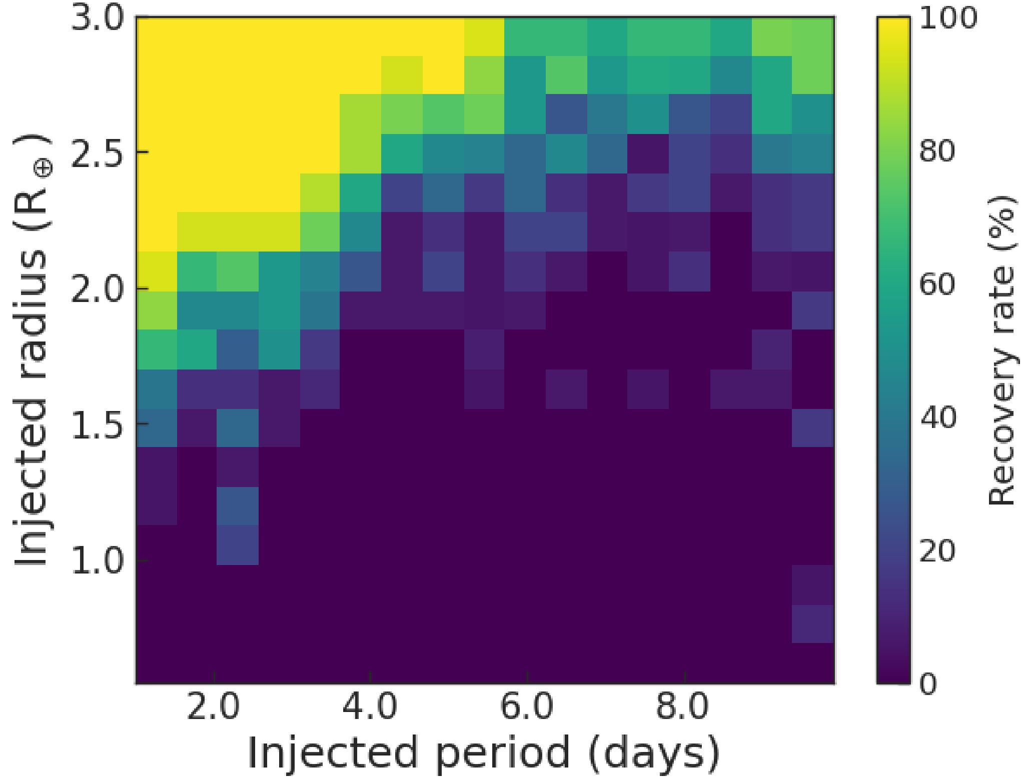
Injection & recovery tests

- Inject a synthetic planet
- Detrend the lightcurve
- Try to recover the signal
- Repeat varying radius and period
- Compute the recovery rate



Injection-recovery output for TIC 85400493. (Own work)

Injection & recovery tests longer periods



Injection-recovery output for TIC 85400493. (Own work)

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 $0.47 \pm 0.03\ M_\odot$.

F

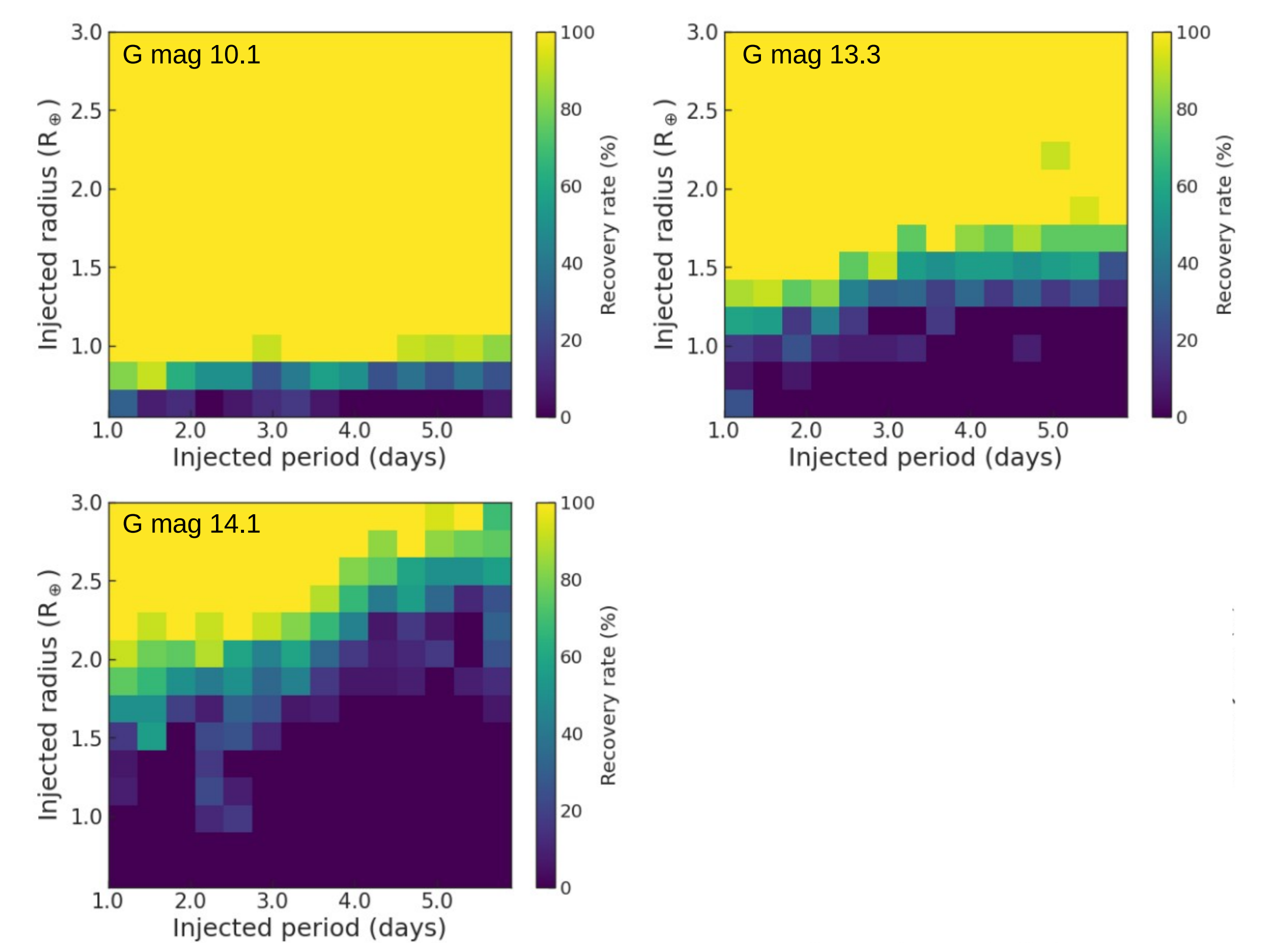
Method

Injection & recovery tests

- Detection capability
    1 R_Earth: exceptional

- Magnitudes (G mag)
    G mag in 12-15=90% targets

- Other parameters



Injection-recovery test for four different hot subdwarfs. From my master thesis.

Method

Injection & recovery tests

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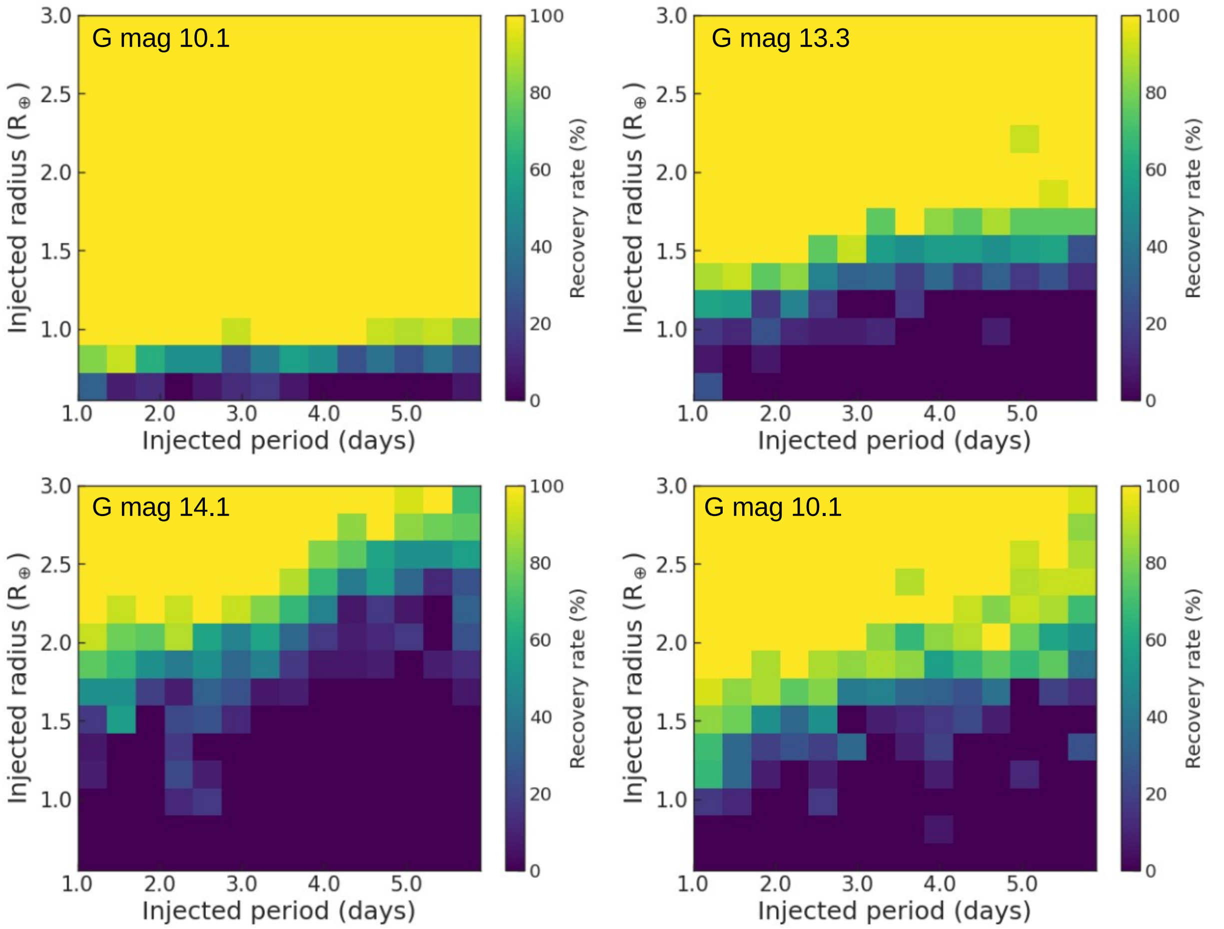


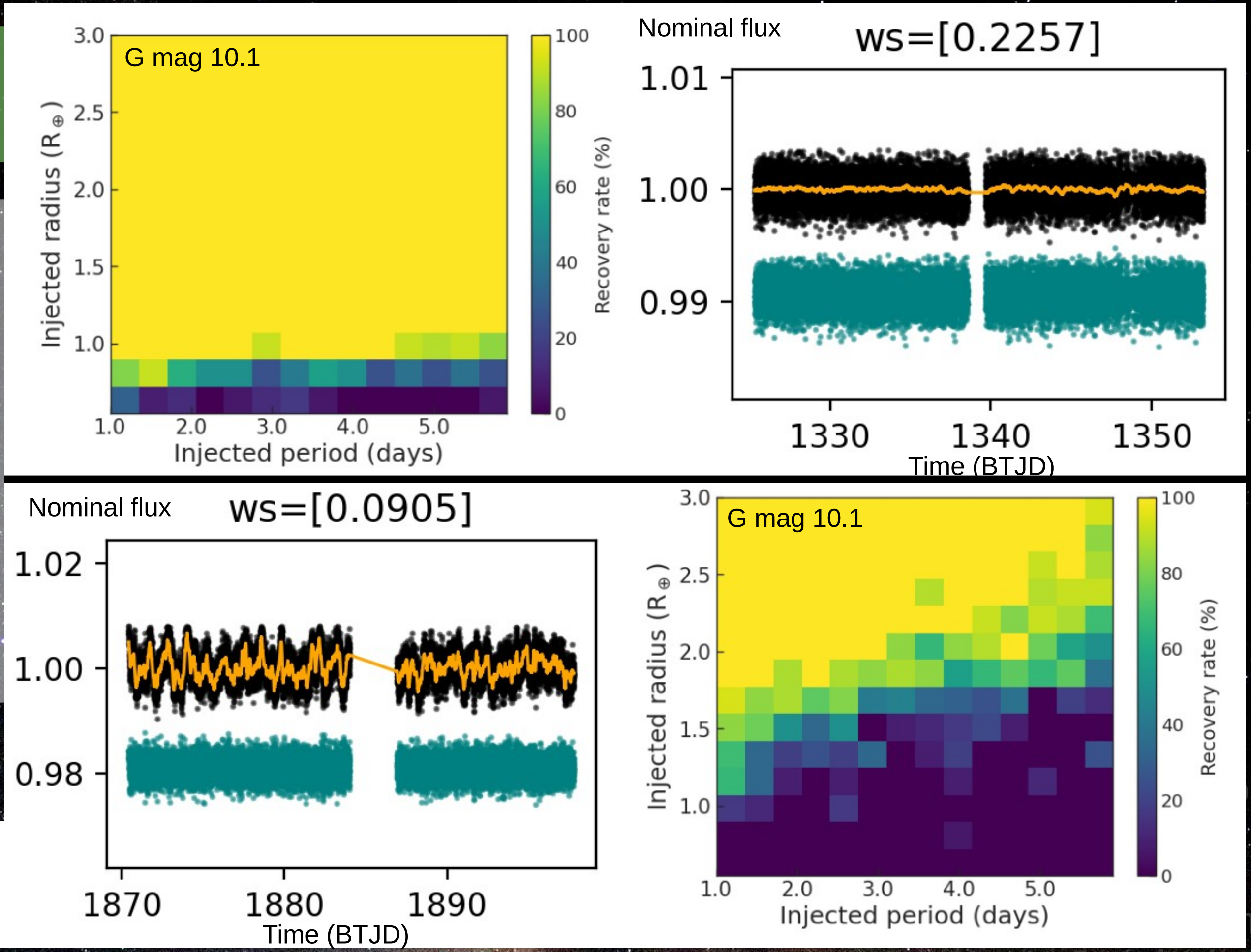
Injection-recovery test for four different hot subdwarfs. From my master thesis.

Method

Injection & recovery tests

Ligth curve aspects

- Calm and 'stormy' aspects
- Improvements for known pulsative stars

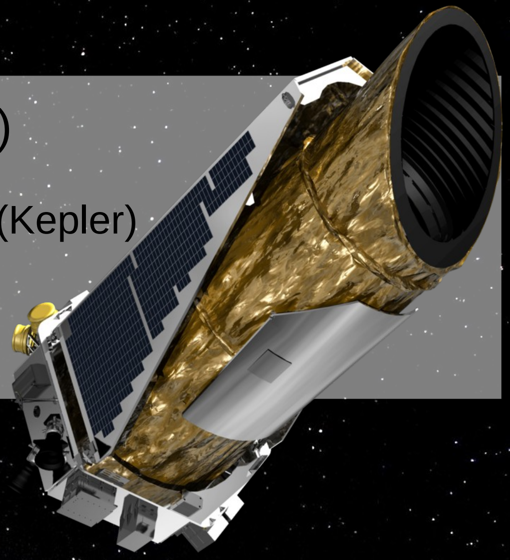


Lightcurves and injection-recovery test for TIC 147283842 and TIC 372681399. From my master thesis.

Mission description

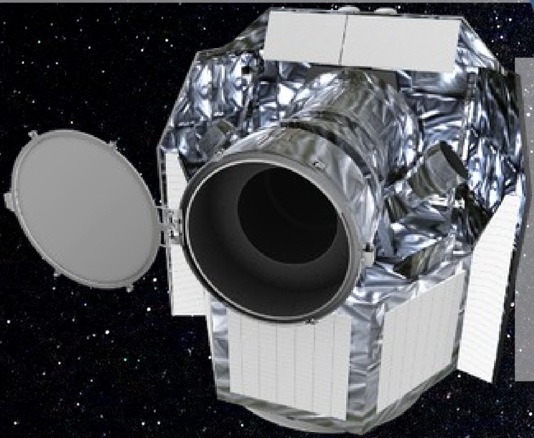
Kepler/K2 (2009-2013 / 2014-2018)

- 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

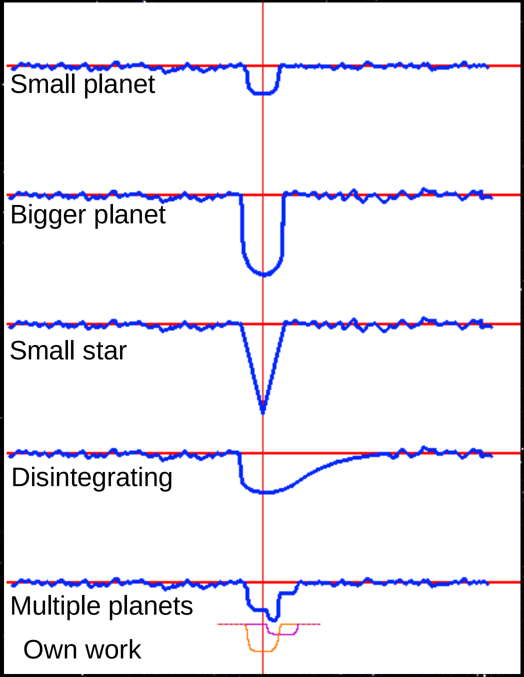


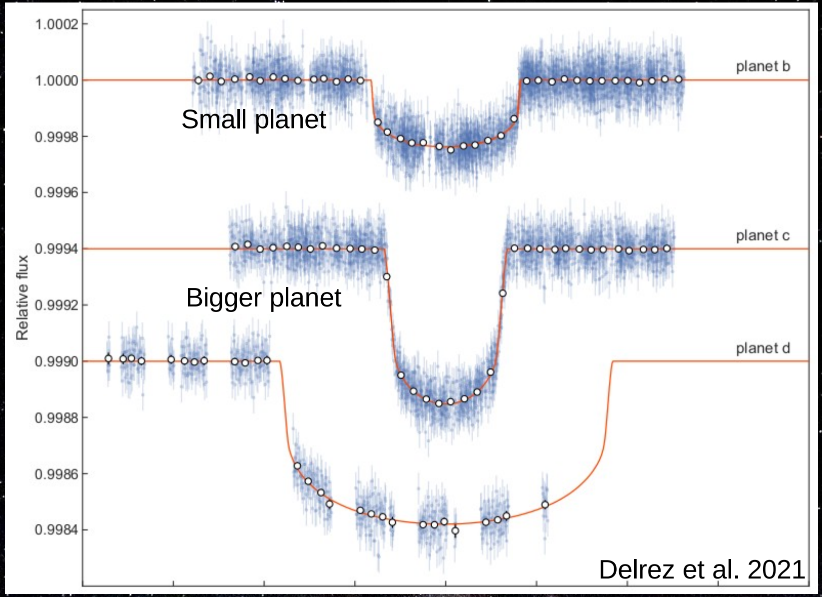
CHEOPS (2019-?)

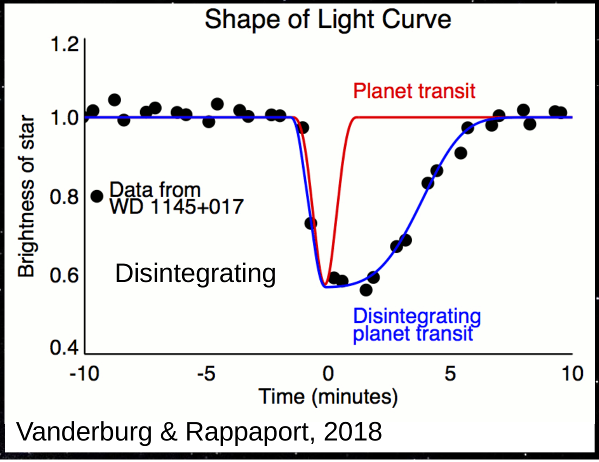
- ESA
- Characterization of already discovered exoplanets
- Ø : 32cm
- Launch mass : 273kg

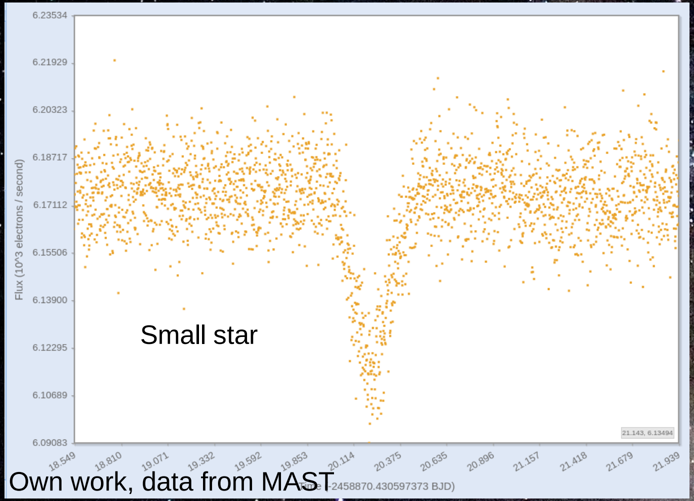
G

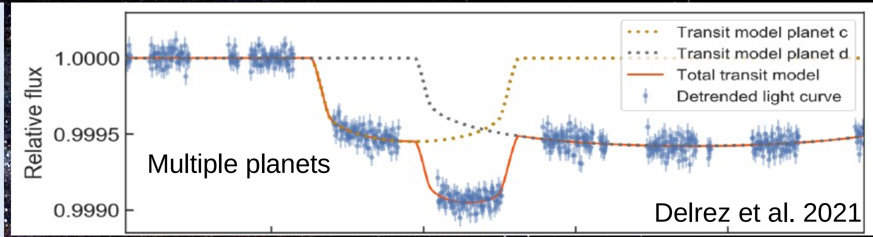
Transit shapes











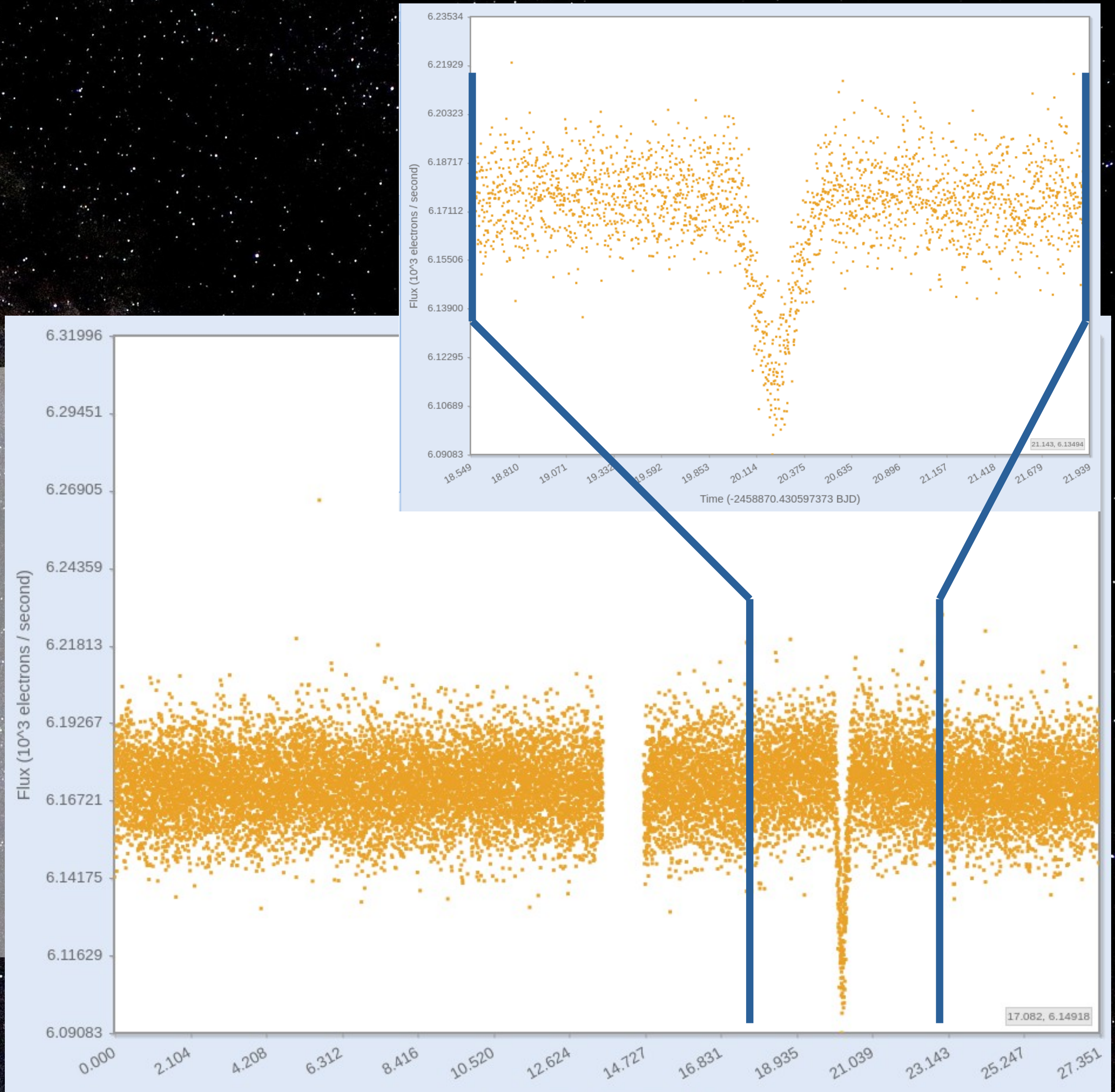
J

Single events

>= 2 transits needed to get the period

but some single transit are in the data.

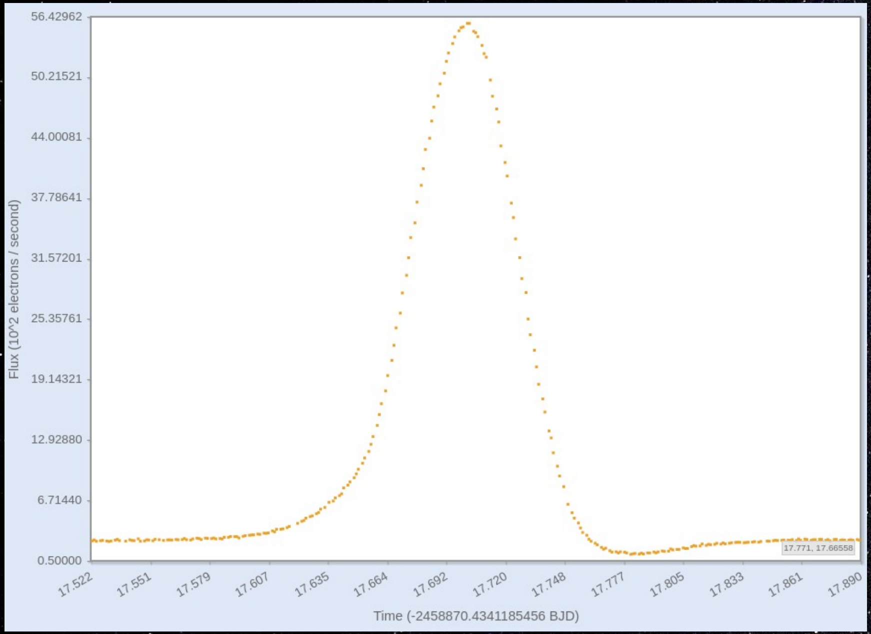
Exemple : TIC 156458527
Cycle 2, 5 sectors, 1 event.

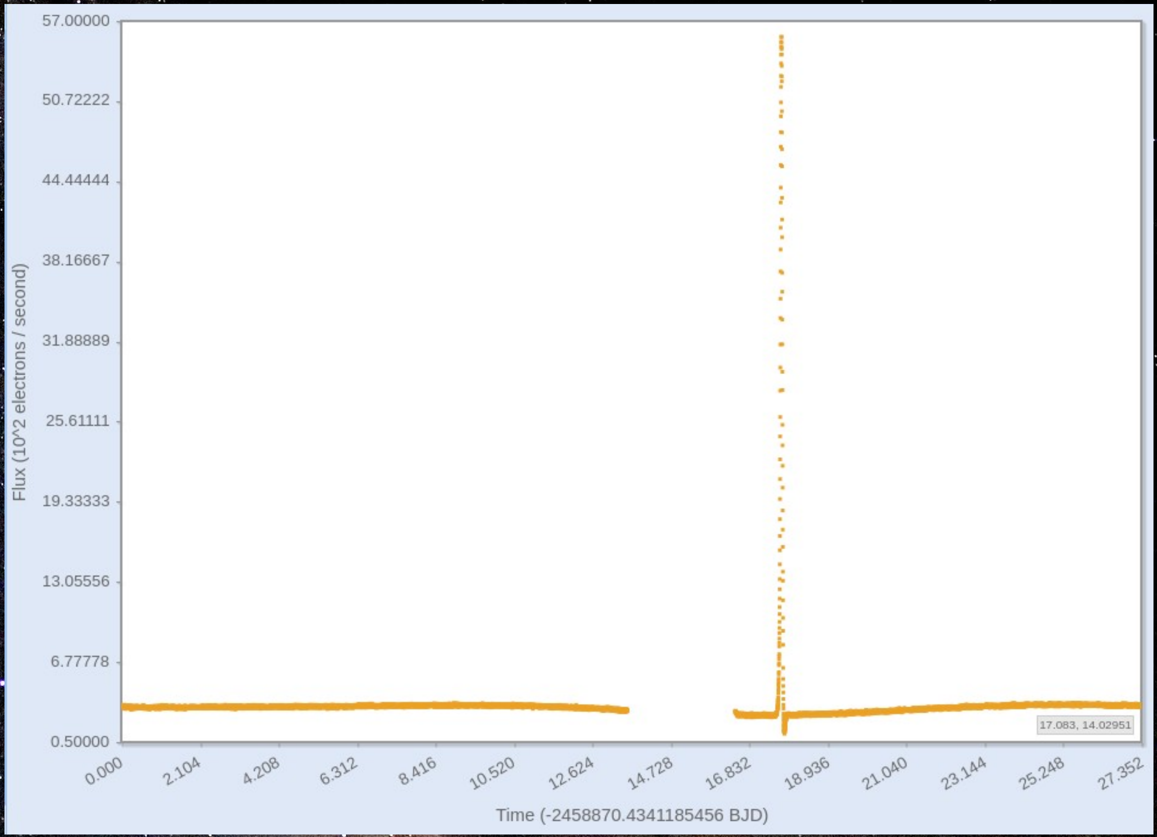


Own work, data from MAST

Perturbating events

Solar system object
Exemple : TIC 88021496





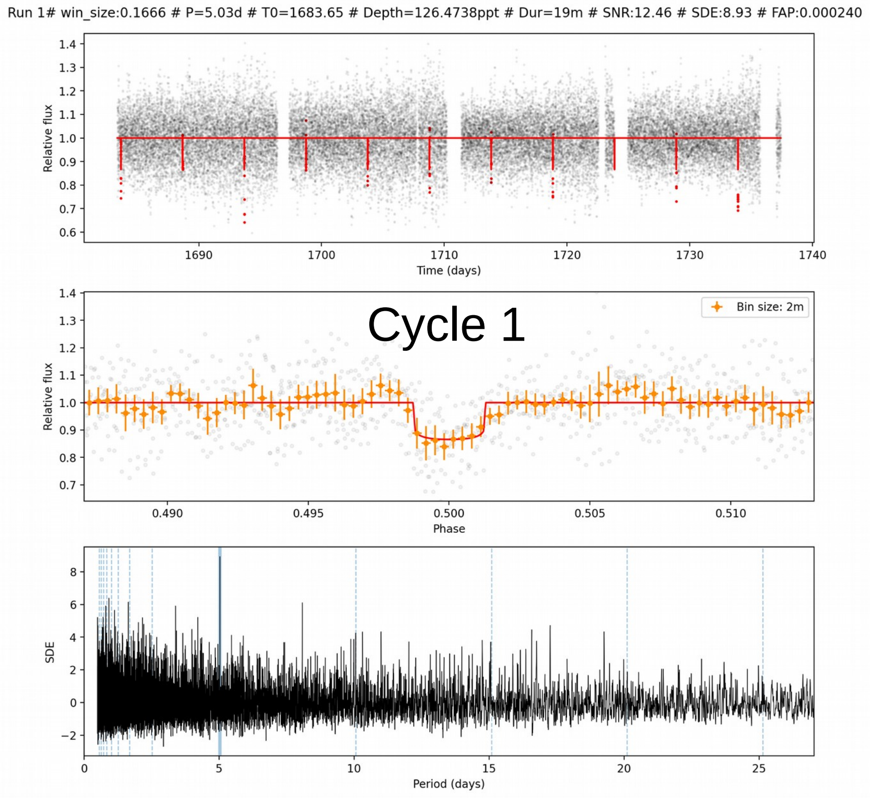
M

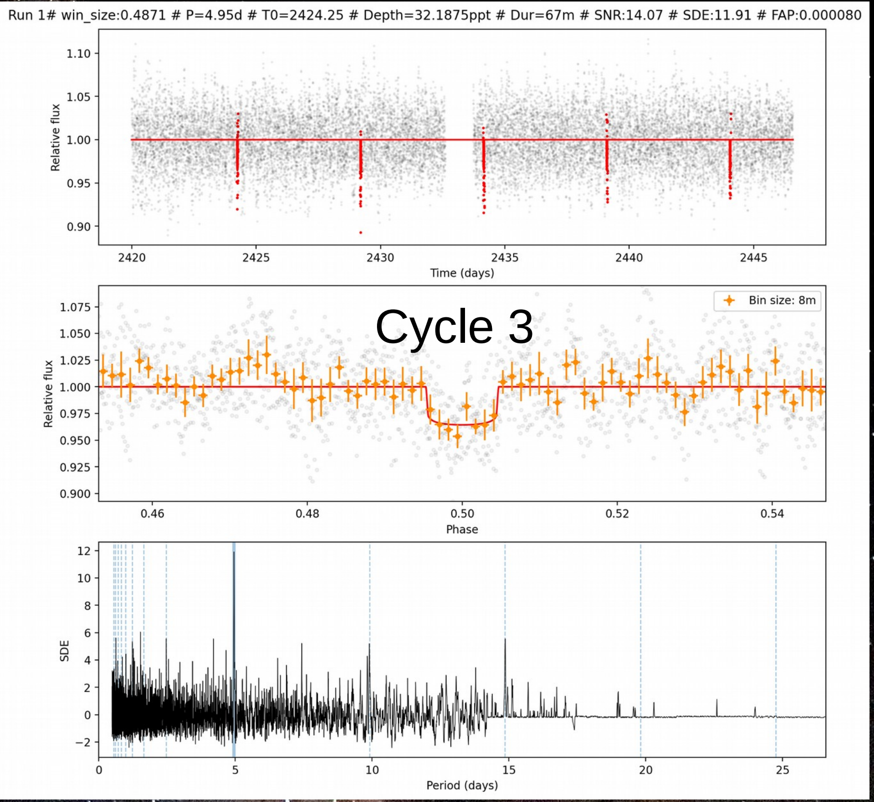
Method

Vetting

Run 1# win_size:0.1666 # P=5.03d # T0=1683.65 # Depth=126.4738ppt # Dur=19m # SNR:12.46 # SDE:8.93 # FAP:0.000240

Run 1# win_size:0.4871 # P=4.95d # T0=2424.25 # Depth=32.1875ppt # Dur=67m # SNR:14.07 # SDE:11.91 # FAP:0.000080





Credits

Background : Milky Way and Sagittarius : User Alpsdake on wikimedia
https://commons.wikimedia.org/wiki/File:Milky_Way_and_Sagittarius.JPG

Slide 2 : Stellar evolution (HR diagram) : User Lithopsian on wikimedia
https://upload.wikimedia.org/wikipedia/commons/thumb/a/a1/Evolutionary_track_1m.svg/1166px-Evolutionary_track_1m.svg.png

Slide 2 : Artist view of Sun expansion : ESO
https://www.eso.org/public/images/eso1337a/

Slide 3 : Fate of planets during the RGB : Figure 1 of Villaver et al. 2014

Slide 5 : Same as Slide 2

Slide 6 : Stellar evolution of sdOB stars (HR diagram) : own work, adapted from user Lithopsian on wikimedia (see Slide 2)

Slide 8 : Same as Slide 3

Slide 9 : Artist view of TESS : NASA
https://en.wikipedia.org/wiki/File:Transiting_Exoplanet_Survey_Satellite_artist_concept_(transparent_background).png

Slide 9 : TESS field of view, sectors and cycles : NASA
https://commons.wikimedia.org/wiki/File:TESS_science_sector_suddivision-fr.png?uselang=fr

Slide 11 : Transit of Mercury : Solar and Heliospheric Observatory/NASA/ESA
https://mars.nasa.gov/allaboutmars/nightsky/rover-astronomy/mercury-transit-mars/

Slide 11 : Transit of Corot-1b : NASA :
https://svs.gsfc.nasa.gov/30558

Slide 12 : Sherlock logo
https://github.com/franpoz/SHERLOCK

Slide 13a : Detrending : Own work from Sherlock output

Slide 13b : Time mask : Own work

Slide 13c : RMS mask : Own wrok from Sherlock output

Slide 13d : Pre-whitening : Own work using the FELIX code (S.Charpinet)

Slide 13e : SG filter : Own work, adapted from user Cdang on wikimedia
https://commons.wikimedia.org/wiki/File:Lissage_sg3_anim.gif?uselang=fr

Slide 15 : Visual vetting : Own work, from Sherlock output

Slide 16 : Comparison cycle 1 - cycle 3 : Own work, from Sherlock output

Slide 17 : Vetting LATTE : Nora Eisner
https://github.com/noraeisner/LATTE

Slide 18a : Watson logo
https://github.com/PlanetHunters/watson

Slide 18b, 18c, 18d : Vetting Watson : Own work from Watson output

Slide 19 : Corner plot : Own work from Sherlock output

Credits

Slide 20 : TESS field of view (pixel maps) : Own work from Sherlock output

Slide 20 : TRAPPIST field of view : good question

Slide 21 : Schedulling : Own work from Sherlock output

Slide 22 : CHEOPS : ESA
https://sci.esa.int/web/cheops/-/54127-artist-s-impression-of-the-characterising-exoplanet-satellite-cheops--front-view

Slide 22 : TRAPPIST north (top) and south (bottom) : good question again

Slide 23 : Injection & recovery tests : Own work, with an adaptation of a code provided by Francisco Pozuelos

Slide 24 : Model of injection : Provided by F. Pozuelos

Slide 25, 26 : Same as Slide 23

Slide 27 : Light curve aspects : Own work from injection and recovery tests and Sherlock output

Slide 28 : Position of targets from TESS cycle 1 : Own work, with an adaptation of a code provided by Francisco Pozuelos

Slide 29a : Transit : Own work from Sherlock output

Slide 29b : White dwarf :

Slide 29b : Brown dwarf : R. Hurt/NASA
https://commons.wikimedia.org/wiki/File:L-dwarf-nasa-hurt.png?uselang=fr

Slide 20 : TESS field of view (pixel maps) : Own work from Sherlock output

Slide 20 : TRAPPIST field of view : good question

Slide 21 : Schedulling : Own work from Sherlock output

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https://commons.wikimedia.org/wiki/File:L-dwarf-nasa-hurt.png?uselang=fr

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