Are there planets around hot subdwarf stars ?

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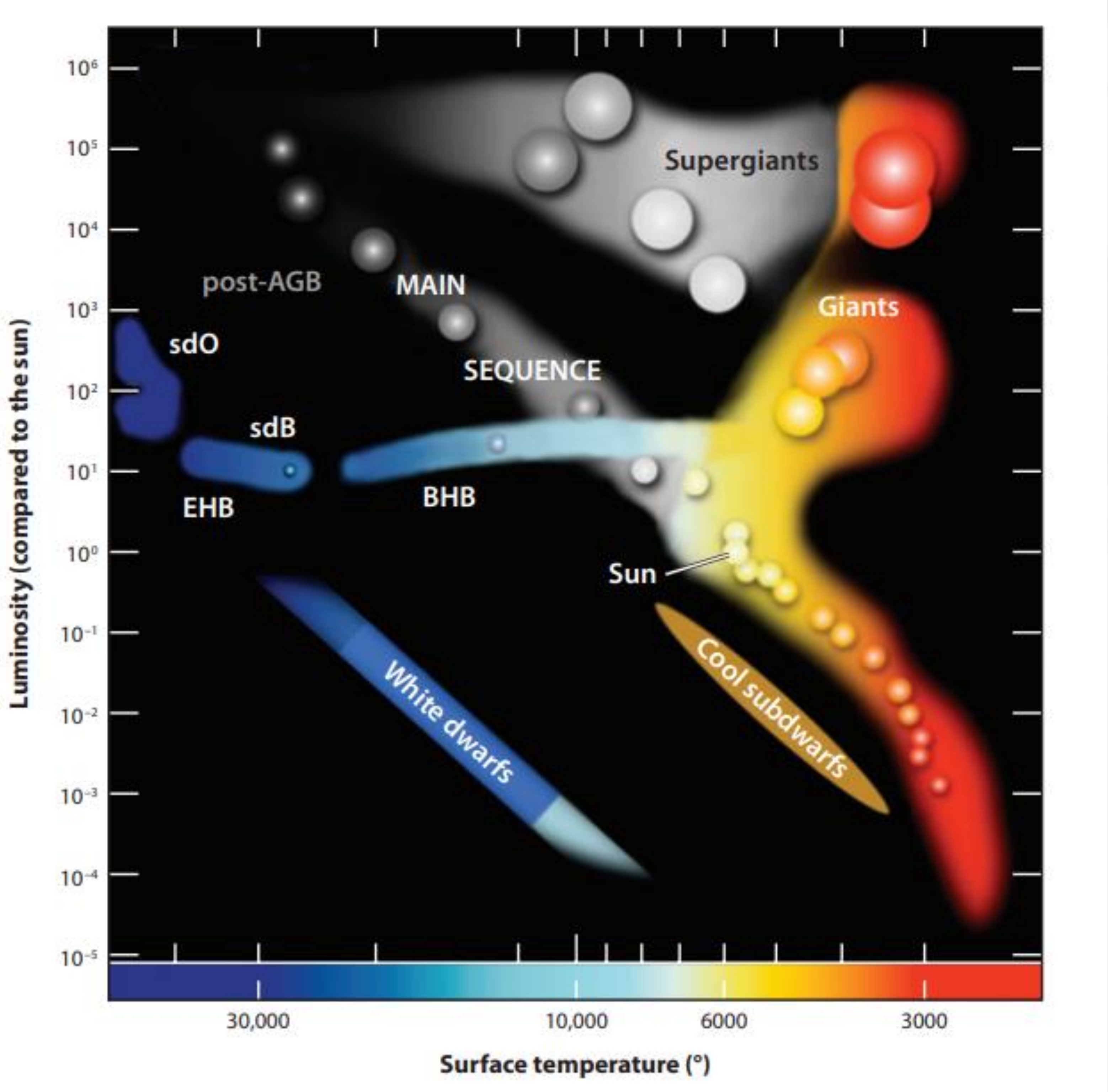
- What are hot subdwarf stars ?
- Why searching for planets around them ?
- Search for planets around hot subdwarfs:
  - Current status
  - A search for transiting planets in space-based light curves

Hot subdwarf stars

Subdwarf B (sdB) stars
Subdwarf O (sdO) stars

- sdB stars: 20,000 – 40,000 K, compact stars (log g= 5.2 – 6.2)
- sdO stars: 40,000 – 80,000 K; some post-sdB stars (log g=5.2-6.2), some direct post-RGB, some post-AGB (log g < 5.2)



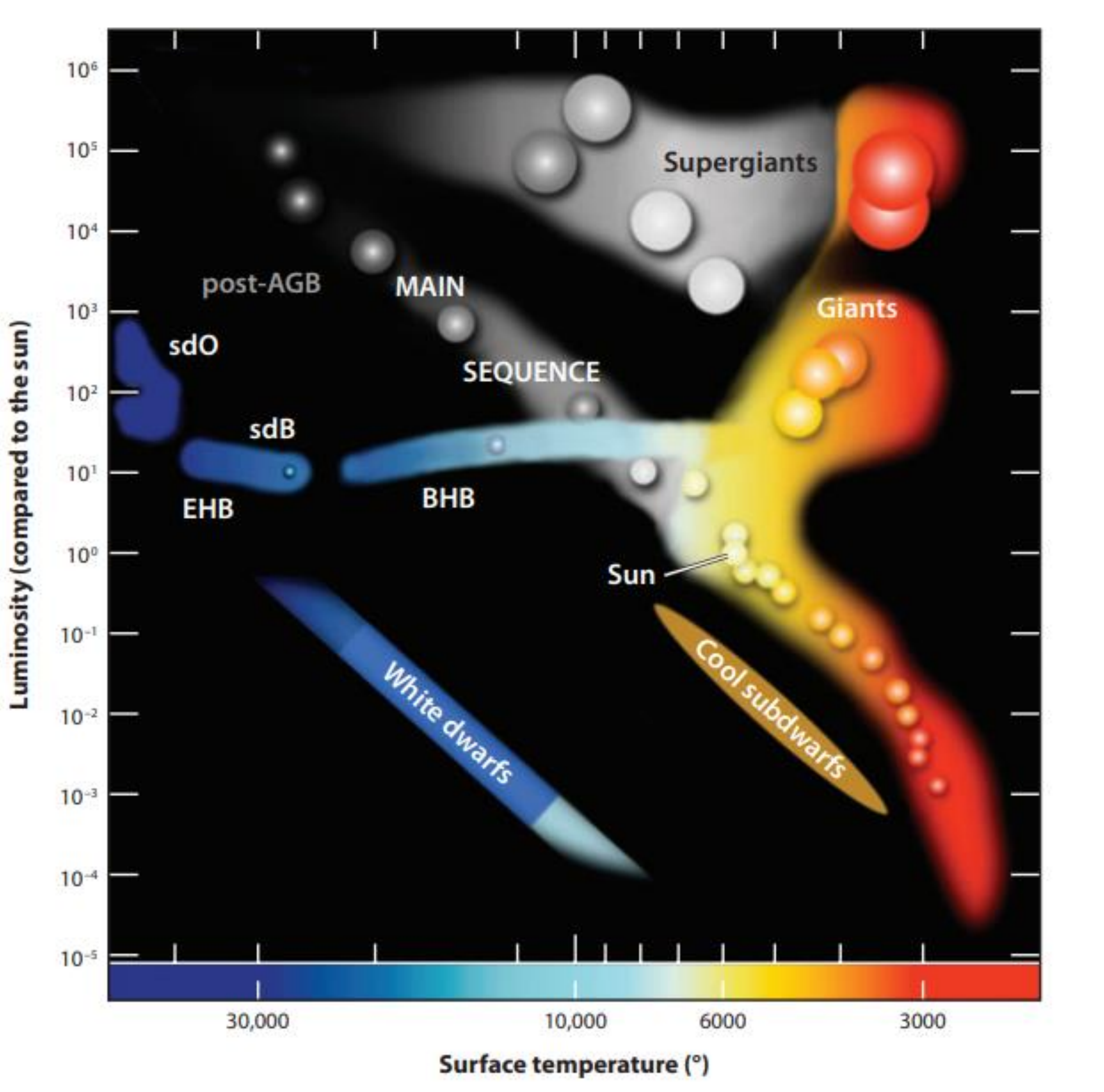
Heber 2009

Hot subdwarf stars

Subdwarf B (sdB) stars

- Core-He burning objects, belonging to the Extreme Horizontal Branch (EHB)
- Extremely thin H-rich envelope, unlike « normal » core-He burning giants (aka Red Clump stars = Red Horizontal Branch stars)
- 0.1 – 0.3 R_{sun} for ~0.5 M_{sun}

Where do these stars come from ?



Heber 2009

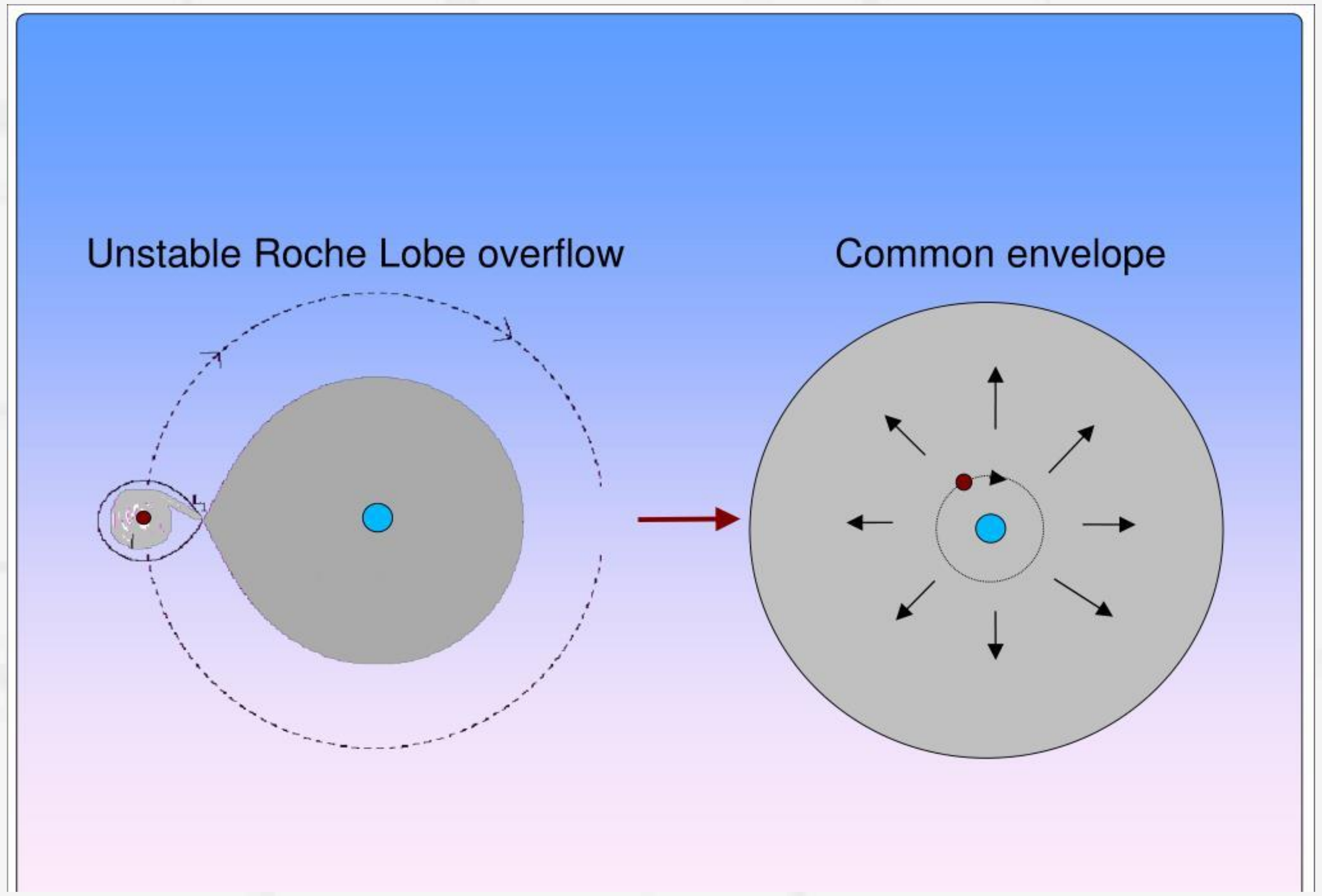
Hot subdwarf stars

1/3 in short-period binaries, 1/3 in long-period binaries, 1/3 single

Hot subdwarf stars

1/3 in short-period binaries, 1/3 in long-period binaries, 1/3 single

Common-envelope evolution with a white dwarf, or a late-type main-sequence star, or a brown dwarf (common!)



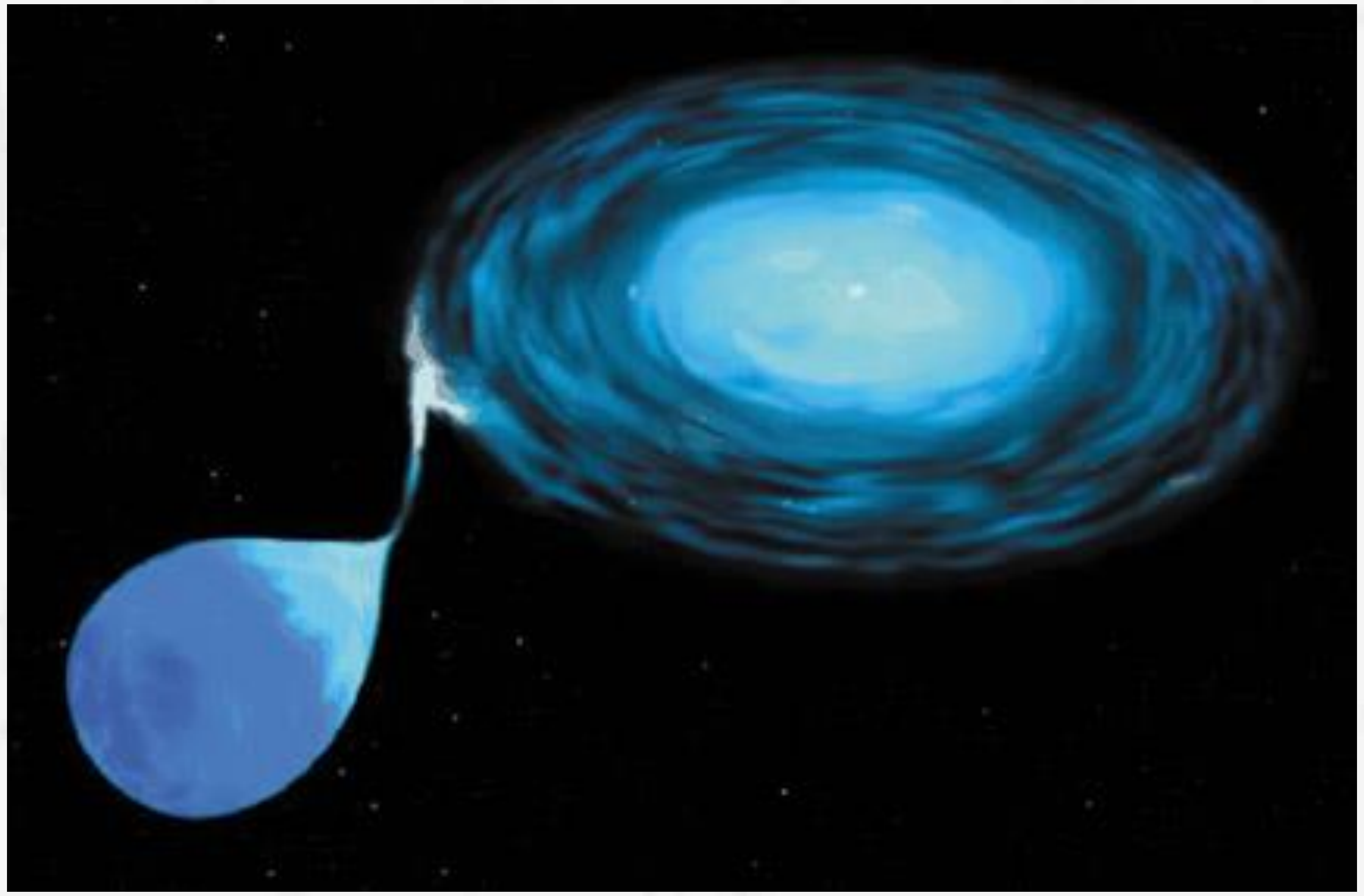
O. De Marco 2005

=> Such sdB stars are post-Red Giant Branch (RGB) stars

Hot subdwarf stars

1/3 in short-period binaries, 1/3 in long-period binaries, 1/3 single

Stable Roche Lobe Overflow with a main-sequence star (F-G types)

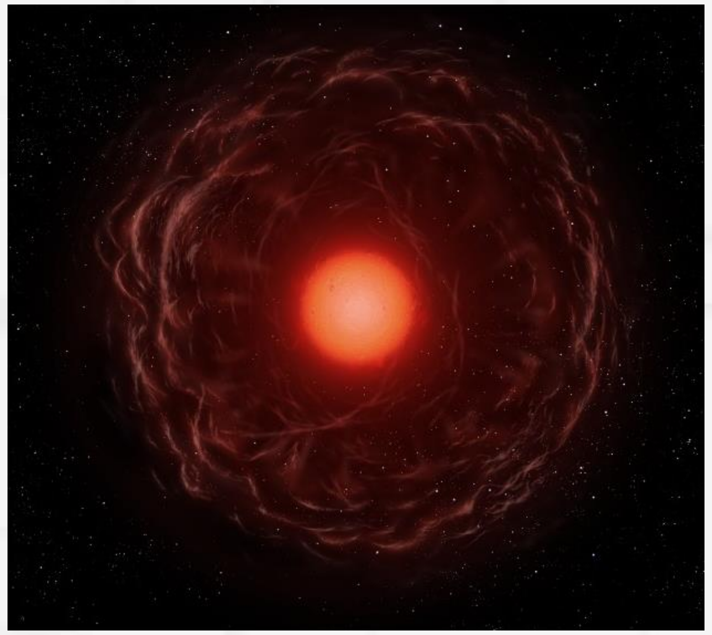


=> Such sdB stars are post-RGB stars

Hot subdwarf stars

1/3 in short-period binaries, 1/3 in long-period binaries, 1/3 single

Single-star evolution (ejection of the envelope at the tip of RGB) or from merger events ?



or

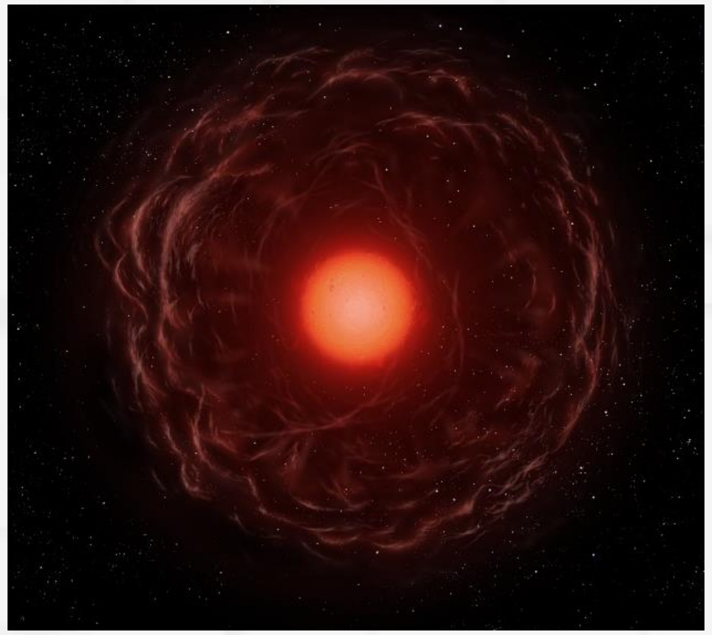
Long-story short (eg Fontaine et al. 2012, Geier & Heber 2012, Schaffenroth et al. 2022): **single sdB stars are also (mostly) post-RGB stars**

= Hot subdwarfs are (mostly) post-RGB stars

Hot subdwarf stars

1/3 in short-period binaries, 1/3 in long-period binaries, 1/3 single

Single-star evolution (ejection of the envelope at the tip of RGB) or from merger events ?



or

Long-story short (eg Fontaine et al. 2012, Geier & Heber 2012, Schaffenroth et al. 2022): **single sdB stars are also (mostly) post-RGB stars**

PS: the cause of the envelope ejection of a single RGB star is unknown…it *may* have to deal with engulfed massive planets (Soker 1998)

Why searching for planets around hot subdwarfs?

1. Post-RGB stars (and they do not ascend the AGB)
2. Small stars: 0.1 – 0.3 R_{sun} => well suited for the transit method in particular => close-in, ex-engulfed bodies
3. Short lives: 100-200 Myr (core-He burning phase, sdB), 10-20 Myr (He-shell burning phase, sdO) => migration scenarios and/or formation of second-generation planets less likely.

Hot subdwarfs are ideal candidates to address the question of the evolution of planetary systems directly after the RGB phase of stellar evolution and of the survival of engulfed planets (possibly as small remnants)

Why searching for planets around hot subdwarfs?

- Red Clump stars (core-He burning stars, post-RGB): from ~5 to 1000 R_{sun} and masses often >1.5 M_{sun} => no access to small potential survivors/remnants
- White dwarfs: RGB+AGB+Planetary Nebula phases, + ample time for migration or formation of second-generation planets
- A word of caution: hot subdwarfs do have expelled their envelopes:
  - Maybe this has swept-up the planets
  - Maybe this allowed planet survival, by stopping the spiral-in inside the envelope of the giant

Hot subdwarfs are ideal candidates to address the question of the evolution of planetary systems directly after the RGB phase of stellar evolution <u>and</u> of the survival of engulfed planets (possibly as small remnants)

Search for planets around hot subdwarfs: **Current status**

Search for planets around hot subdwarfs: Current status

Long story short: to date, no confirmed planet around hot subdwarfs

Search for planets around hot subdwarfs: Current status

Vol 449 | 13 September 2007 | doi:10.1038/nature06143 nature

LETTERS

A giant planet orbiting the 'extreme horizontal branch' star V 391 Pegasi

R. Silvotti[1], S. Schuh[2], R. Janulis[3], J.-E. Solheim[4], S. Bernabei[5], R. Østensen[6], T. D. Oswalt[7], I. Bruni[5], R. Gualandi[5], A. Bonanno[8], G. Vauclair[9], M. Reed[10], C.-W. Chen[11], E. Leibowitz[12], M. Paparo[13], A. Baran[14], S. Charpinet[9], N. Dolez[9], S. Kawaler[15], D. Kurtz[16], P. Moskalik[17], R. Riddle[18] & S. Zola[14,19]

The first announcement: Silvotti et al. (2007)

- By pulsation timing analysis (O-C of main pulsations of the sdB star)
- A (min) 3.2 Jupiter-mass planet at ~1.7 AU
- Likely 'close to engulfment' during RGB phase
- Disputed (not discarded) by Silvotti et al. (2018)

By RVs (difficult, broad lines):

- Close-in (P_{orb}=2.4 d) planet of a few Jupiter mass around HD149382 (Geier et al. 2008) => discarded by better measurements of Norris et al. (2011)
- Silvotti et al. (2020): mini-survey with HARPS-N on 8 apparently single sdBs: no close-in massive planets have been found

Search for planets around hot subdwarfs: Current status

By eclipse-timing variations in several sdB+dM eclipsing (aka HW Vir) systems: several claims. Actually, in all but one of these well-studied systems (9 among 10). Typical claim: one or two circumbinary planet(s) of a few Jupiter masses

A&A 577, A146 (2015)
DOI: 10.1051/0004-6361/201425392

Astronomy & Astrophysics

Detection of a planet in the sdB + M dwarf binary system 2M 1938+4603

A. S. Baran[1], S. Zola[1,2], A. Blokesz[1], R. H. Østensen[3], and R. Silvotti[4]

The Astrophysical Journal Letters, 745:L23 (5pp), 2012 February 1 doi:10.1088/2041-8205/745/2/L23

CIRCUMBINARY PLANETS ORBITING THE RAPIDLY PULSATING SUBDWARF B-TYPE BINARY NY Vir

S.-B. Qian[1,2,3], L.-Y. Zhu[1,2], Z.-B. Dai[1,2], E. Fernández-Lajús[4,5], F.-Y. Xiang[6], and J.-J. He[1,2]
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Astronómicas y Geofísicas, Universidad Nacional de La Plata, 1900 La Plata, Buenos Aires, Argentina
Instituto d...
...hysics De...
Received ...

The Astronomical Journal, 137:3181–3190, 2009 February doi:10.1088/0004-6256/137/2/3181

THE sdB+M ECLIPSING SYSTEM HW VIRGINIS AND ITS CIRCUMBINARY PLANETS

Jae Woo Lee[1], Seung-Lee Kim[1], Chun-Hwey Kim[2], Robert H. Koch[3], Chung-Uk Lee[1], Ho-Il Kim[1], and Jang-Ho Park[1,2]
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[2] Department of Astronomy and Space Science, College of Natural Science and Institute for Basic Science Research, Chungbuk National University, Cheongju 361-763, Korea; kimch@chungbuk.ac.kr
[3] Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, USA; rhkoch@earthlink.net
Received 2008 August 7; accepted 2008 November 5; published 2009 January 28

RAA 2019 Vol. 19 No. 9, 134(8pp) doi: 10.1088/1674–4527/19/9/134

http://www.raa-journal.org http://iopscience.iop.org/raa
Research in Astronomy and Astrophysics

A close-in substellar object orbiting the sdOB-type eclipsing-binary system NSVS 14256825

Li-Ying Zhu[1,2,3,4], Sheng-Bang Qian[1,2,3,4], Eduardo Fernández Lajús[5,6], Zhi-Hua Wang[1,2,3,4] and Lin-Jia Li[1,2,3]

Search for planets around hot subdwarfs: Current status

By eclipse-timing variations in several sdB+dM eclipsing (aka HW Vir) systems: several claims. Actually, in all but one of these well-studied systems (9 among 10). Typical claim: one or two circumbinary planet(s) of a few Jupiter masses

But:

- Only 1% of the progenitors of such systems have circumbinary planets (Welsh et al. 2012)
- The properties (and numbers) of claimed planets often change with additional measurements
- Most of these systems are predicted dynamically unstable (eg, Wittenmyer et al. 2013)
- None of these circumbinary planets have been confirmed by another technique

This *may* call for another explanation than planets for these observed eclipse-timing variations (see eg Bours et al. 2016)

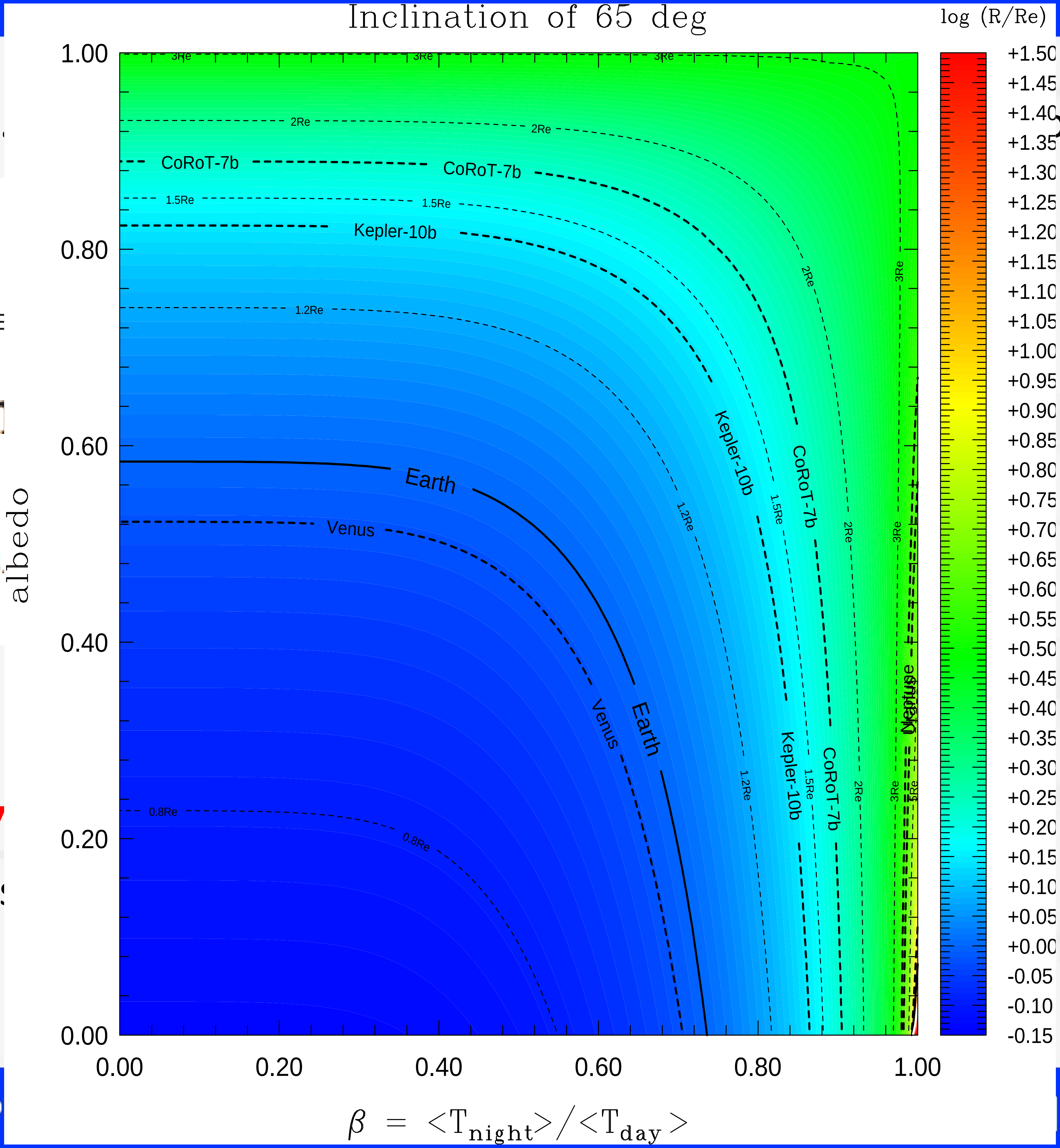
Search for planets around hot subdwarfs: Current status

By phase curve: Kepler-70, Charpinet et al. … onths over 21)

LETTER

A compact system of small plan… red-giant star

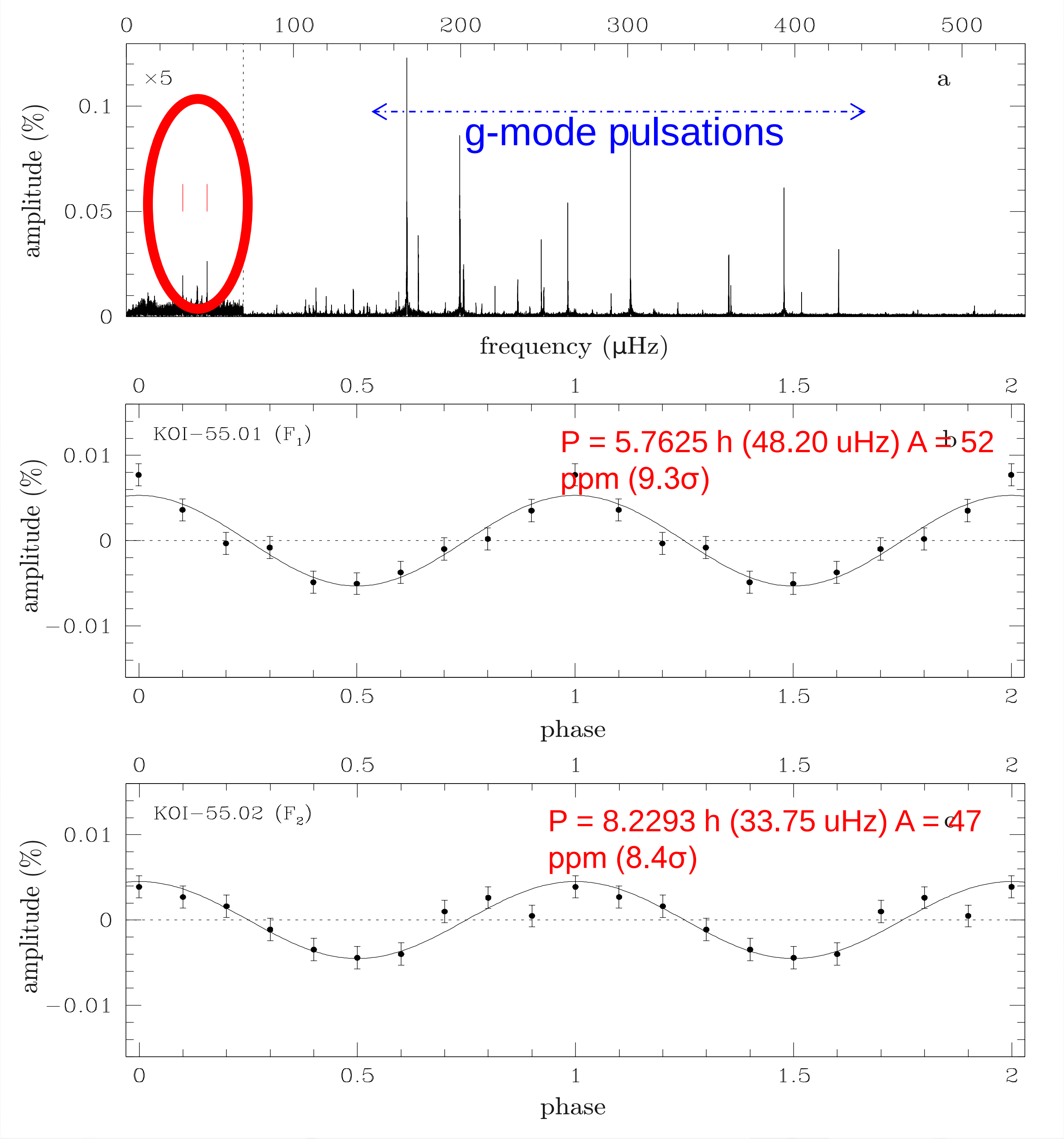
S. Charpinet[1,2], G. Fontaine[3], P. Brassard[3], E. M. Green[4], V. Van Grootel[5,6], S.…
R. H. Østensen[11], S. D. Kawaler[10] & J. H. Telting[12]



Two Earth-sized planets orbiting at 5.7…
from a simple light reflection and thermal re-emis…

Search for planets around hot subdwarfs: Current status

By phase curve: Kepler-70, Charpinet et al. 2011 (based on Kepler quarters Q2.3+Q5-Q8)



Two periodic and coherent brightness variations found at low frequencies, with tiny amplitudes

Charpinet et al., Nature, 480, 491

Search for planets around hot subdwarfs: Current status

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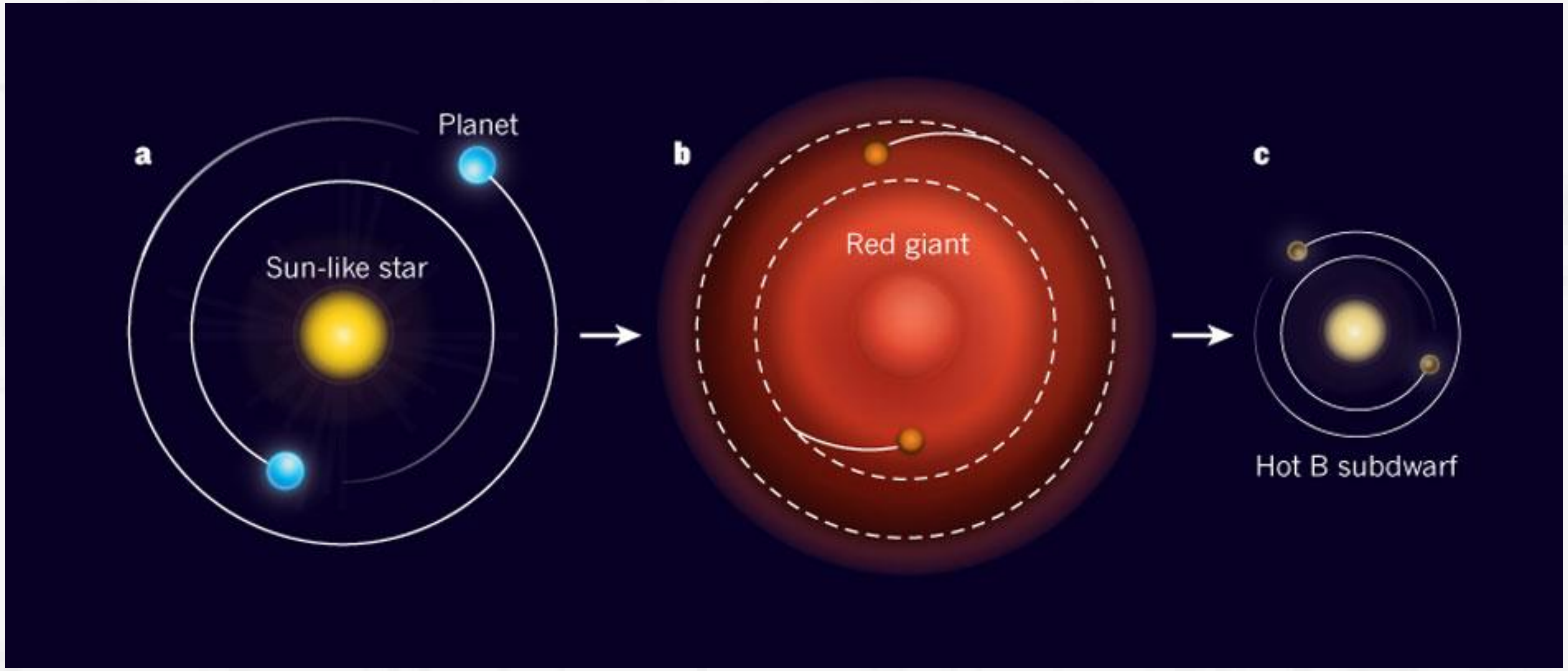
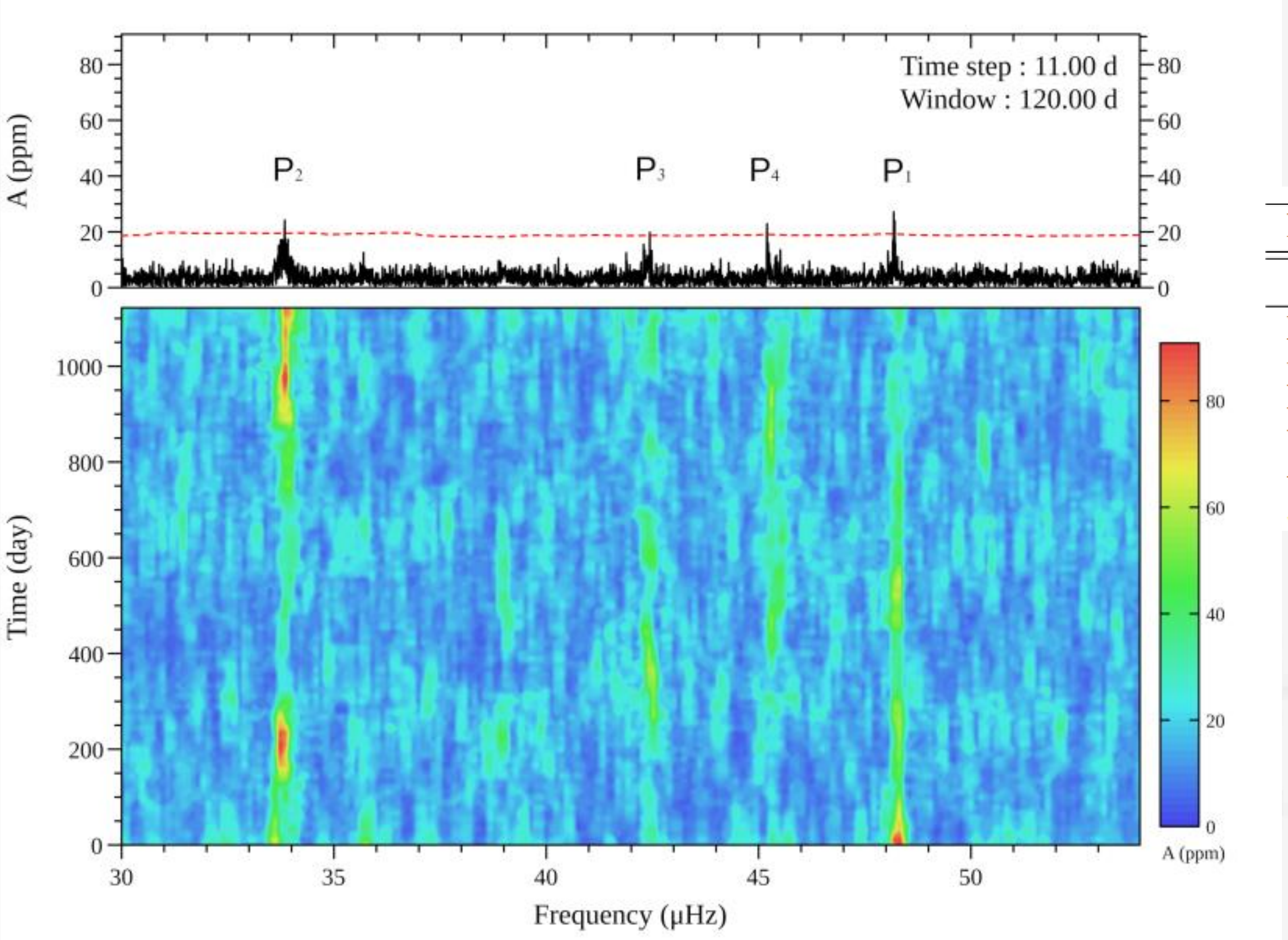


Kempton et al. 2011

Search for planets around hot subdwarfs: Current status

By phase curve: Kepler-70, Charpinet et al. 2011 (based on Kepler quarters Q2.3+Q5-Q8)
From the full (Q2.3, Q5-Q17.2) light curve: **now 4 low-amplitude frequencies in 33-47 muHz range**



Planet id.	P_1	P_2	P_3	P_4
Orbital parameters (see text)				
Frequency (μHz)	48.1824 ± 0.0007	33.8423 ± 0.0008	42.4375 ± 0.0010	45.1987 ± 0.0008
Period (s)	20754.5 ± 0.3	29548.9 ± 0.7	23564.0 ± 0.5	22124.5 ± 0.4
Resonance P_2/P_n	7:5	1	5:4	4:3
Amplitude (ppm)	27 ± 3	24 ± 3	20 ± 3	23 ± 3
S/N	8.2σ	7.3σ	6.0σ	6.9σ

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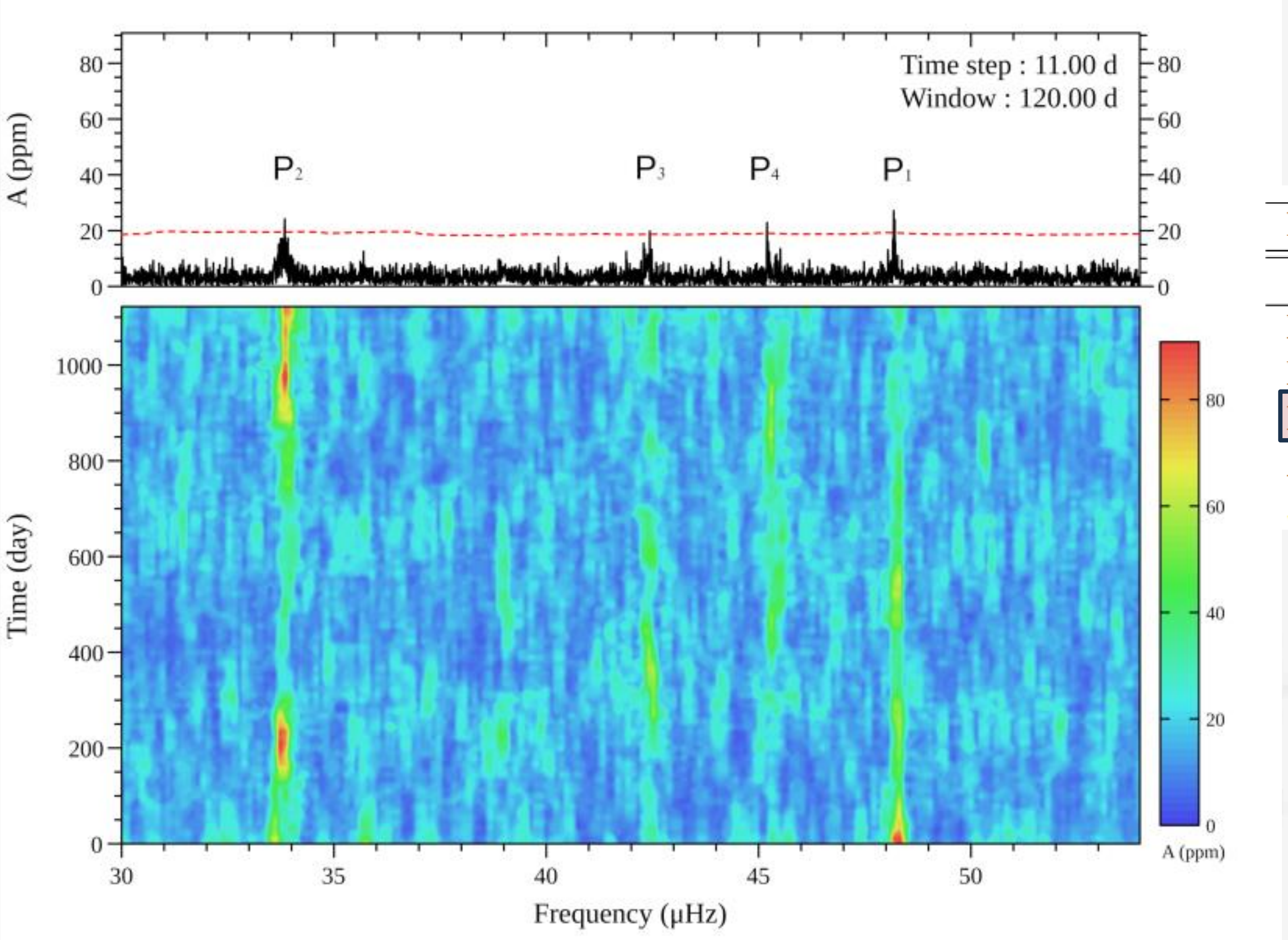

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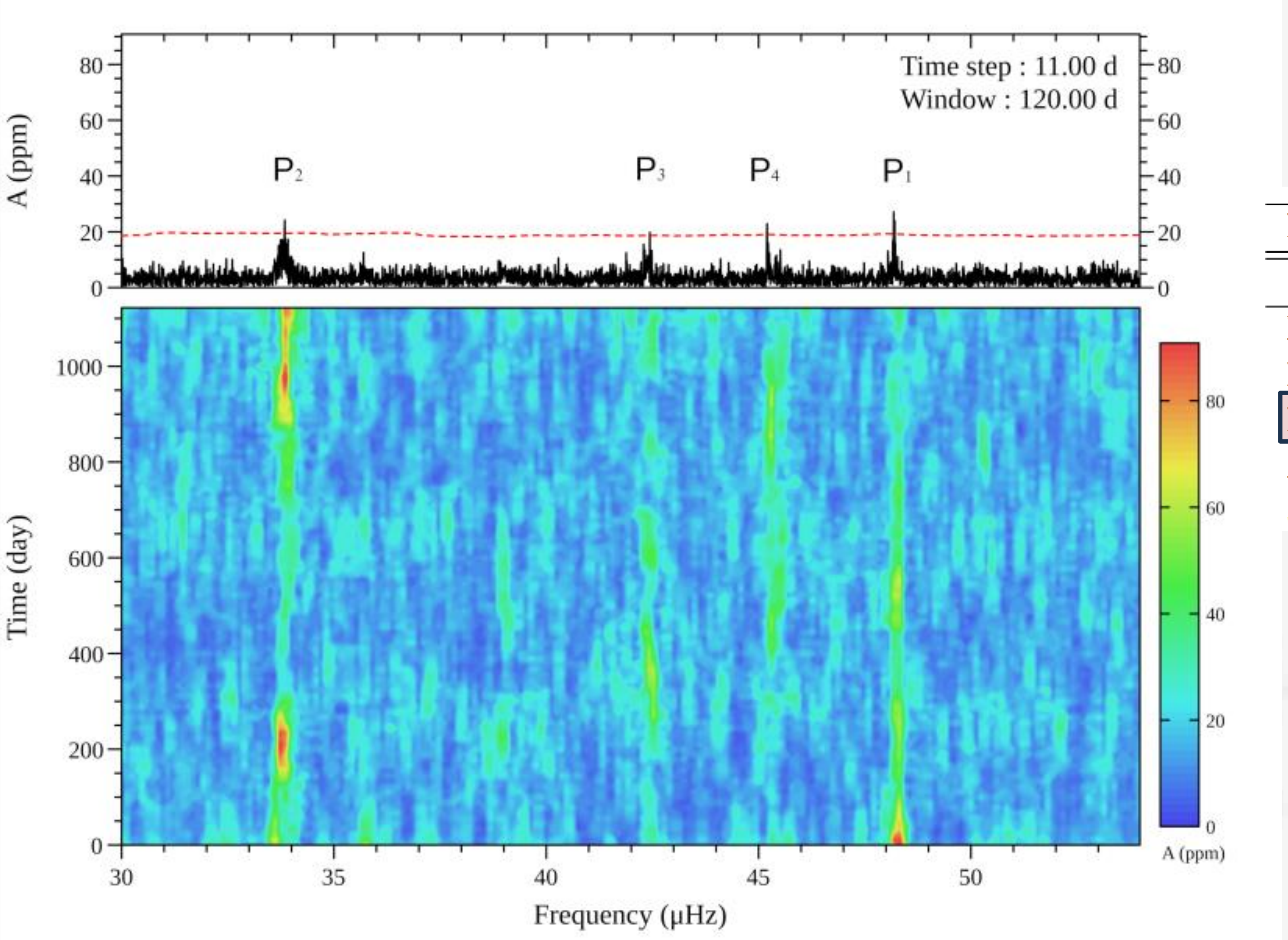

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But…hard to make such compact 4-planet system dynamically stable with reasonable masses…(unless planet/satellite or so)…work ongoing !

Search for planets around hot subdwarfs: Current status

By phase curve: Kepler-70, Charpinet et al. 2011.
Also, this interpretation of such signals as phase curves of orbiting bodies has been disputed by Krzesinski (2015) and Blokesz et al. (2019):

1. These frequencies could be linear combinations of some of the pulsation g-mode frequencies
2. frequency and amplitude variations are seen throughout the full ~ 3 years of Kepler observations, arguing this is in contradiction with orbital signatures expected to be stable.

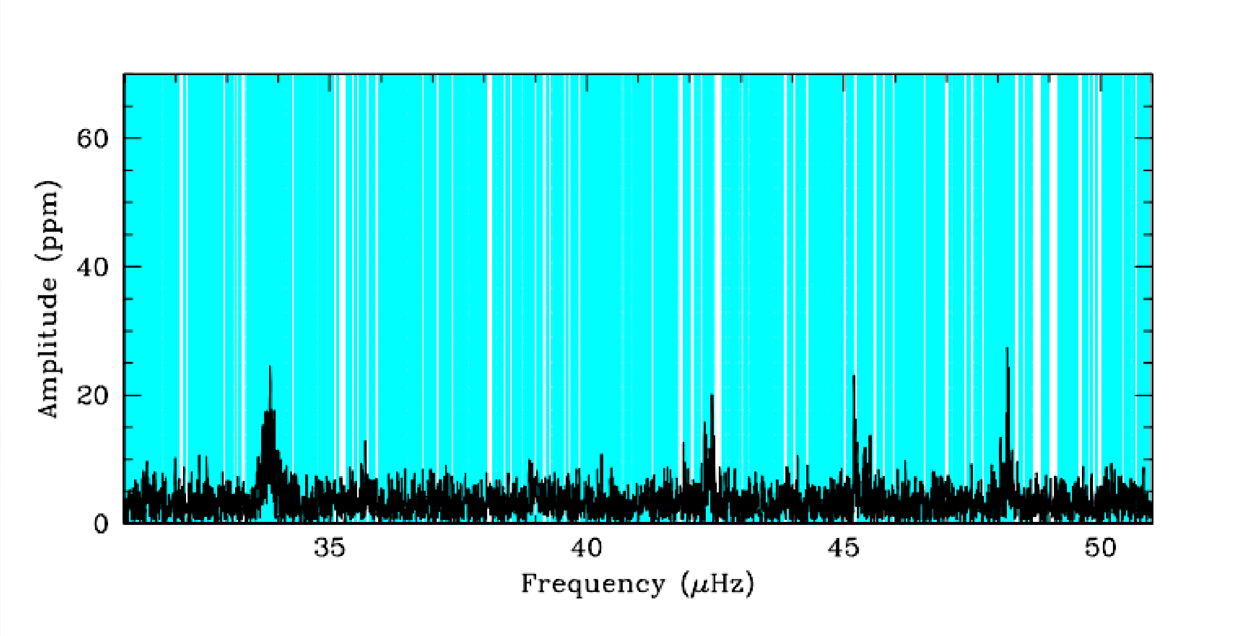
Search for planets around hot subdwarfs: Current status

By phase curve: Kepler-70, Charpinet et al. 2011. The interpretation of these signals as phases curves of 2 exoplanets has been disputed by Krzesinski (2015) and Blokesz et al. (2019):

1. These two frequencies could be linear combinations of some of the pulsation g-mode frequencies

NO: the amplitudes of g-modes (0.1% at most) are too low to produce observable linear combinations or harmonics

+ given the very dense pulsation spectrum, any f_n-f_k combination cover >90% of the frequency domain



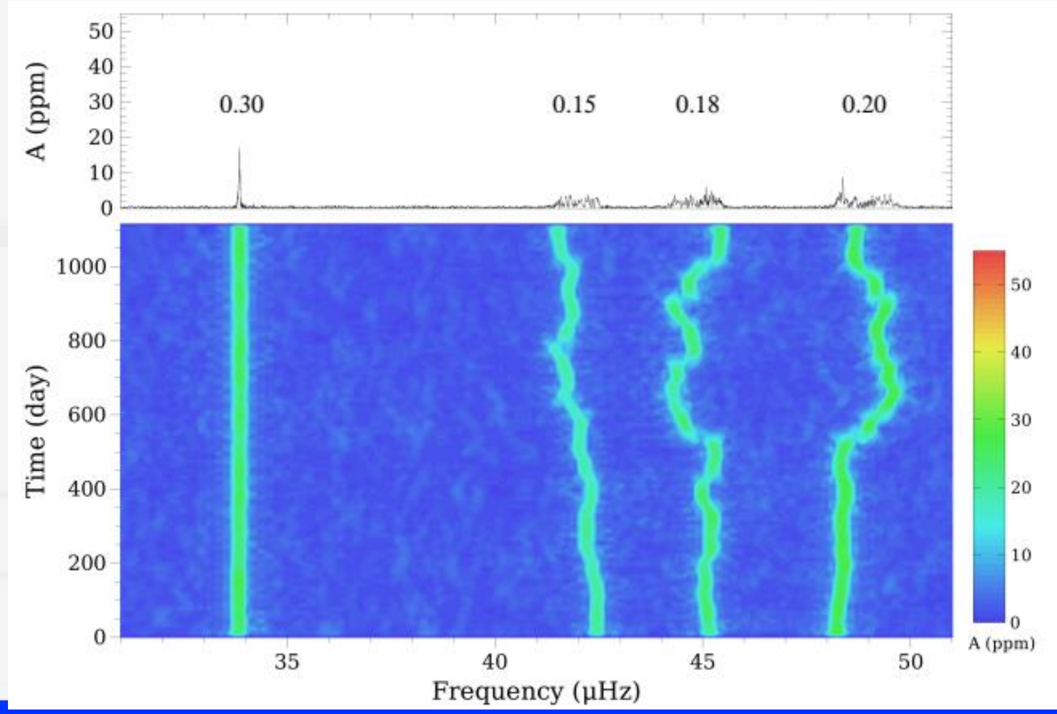
Charpinet, Van Grootel & Silvotti, in prep.

Search for planets around hot subdwarfs: Current status

By phase curve: Kepler-70, Charpinet et al. 2011. The interpretation of these signals as phases curves of 2 exoplanets has been disputed by Krzesinski (2015) and Blokesz et al. (2019):

2. frequency and amplitude variations are seen throughout the full ∼ 3 years of Kepler observations, arguing this is in contradiction with orbital signatures expected to be stable.

NO: On the contrary, changes in orbital periods ('TTVs') are expected (so much that it is hard to make such 4-body system dynamically stable)



Search for planets around hot subdwarfs: A search of transits in space-based data

A project initiated in 2020:

- Presentation, feasibility and performance tests: Van Grootel et al. (2021)
- Null results on TESS Cycle 1: Thuillier et al. (2022)
- Latest news: Poster from A. Thuillier, this conference

A&A 650, A205 (2021)
https://doi.org/10.1051/0004-6361/202140381

Astronomy & Astrophysics

A search for transiting planets around hot subdwarfs

I. Methods and performance tests on light curves from *Kepler*, K2, TESS, and CHEOPS★

V. Van Grootel[1], F. J. Pozuelos[1,2], A. Thuillier[1], S. Charpinet[3], L. Delrez[1,2,4], M. Beck[4], A. Fortier[5,6], S. Hoyer[7], S. G. Sousa[8], B. N. Barlow[9], N. Billot[4], M. Dévora-Pajares[10,11], R. H. Østensen[12], Y. Alibert[5], R. Alonso[13,14],

A&A 664, A113 (2022)
https://doi.org/10.1051/0004-6361/202243554

Astronomy & Astrophysics

A search for transiting planets around hot subdwarfs

II. Supplementary methods and results from TESS Cycle 1

A. Thuillier[1,2], V. Van Grootel[1], M. Dévora-Pajares[3], F. J. Pozuelos[1,4], S. Charpinet[5], and L. Siess[2]

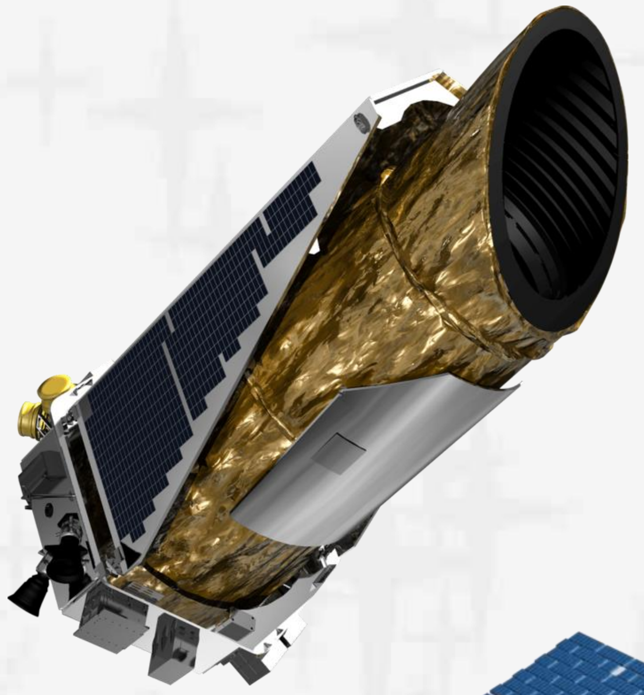
Search for planets around hot subdwarfs: A search of transits in space-based data

Light curves available:

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

- TESS: ~4000 targets at 2-min and 20s cadence at Sector 64

- CHEOPS: 61 targets, not observed by TESS (for most of them) neither by Kepler, 1-min cadence



"*CHaracterizing ExOPlanet Satellite*"
ESA class S mission
Heliosynchronous orbit of Earth at 700km altitude

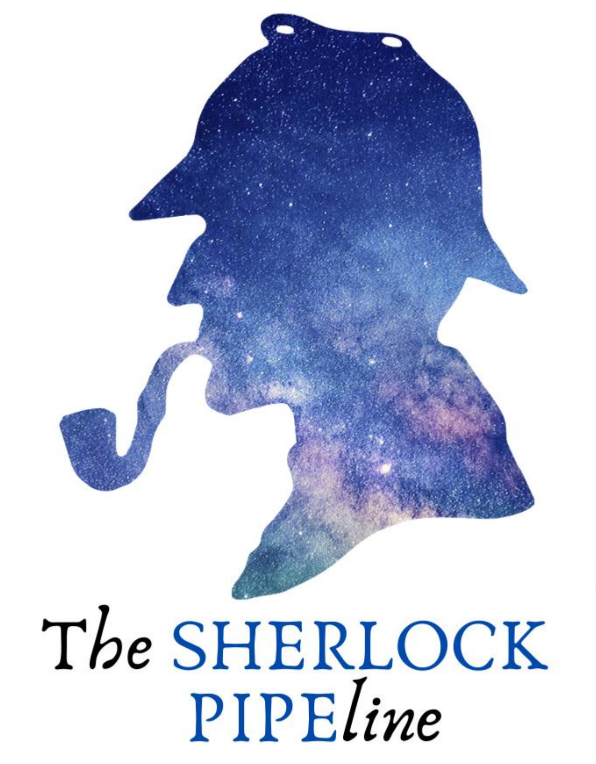
Search for planets around hot subdwarfs: A search of transits in space-based data

Method:

1. Searching for transits with the SHERLOCK PIPEline (Pozuelos et al. 2020), incl. vetting process. https://github.com/franpoz/SHERLOCK

2. Confirming the transits by follow-up observations: CHEOPS, TRAPPIST telescopes (La Silla, Oukaïmeden)

3. Characterising the transiting body, eg RV data to constrain the transiting body's mass (LAMOST, ESO archives, network/community,…)

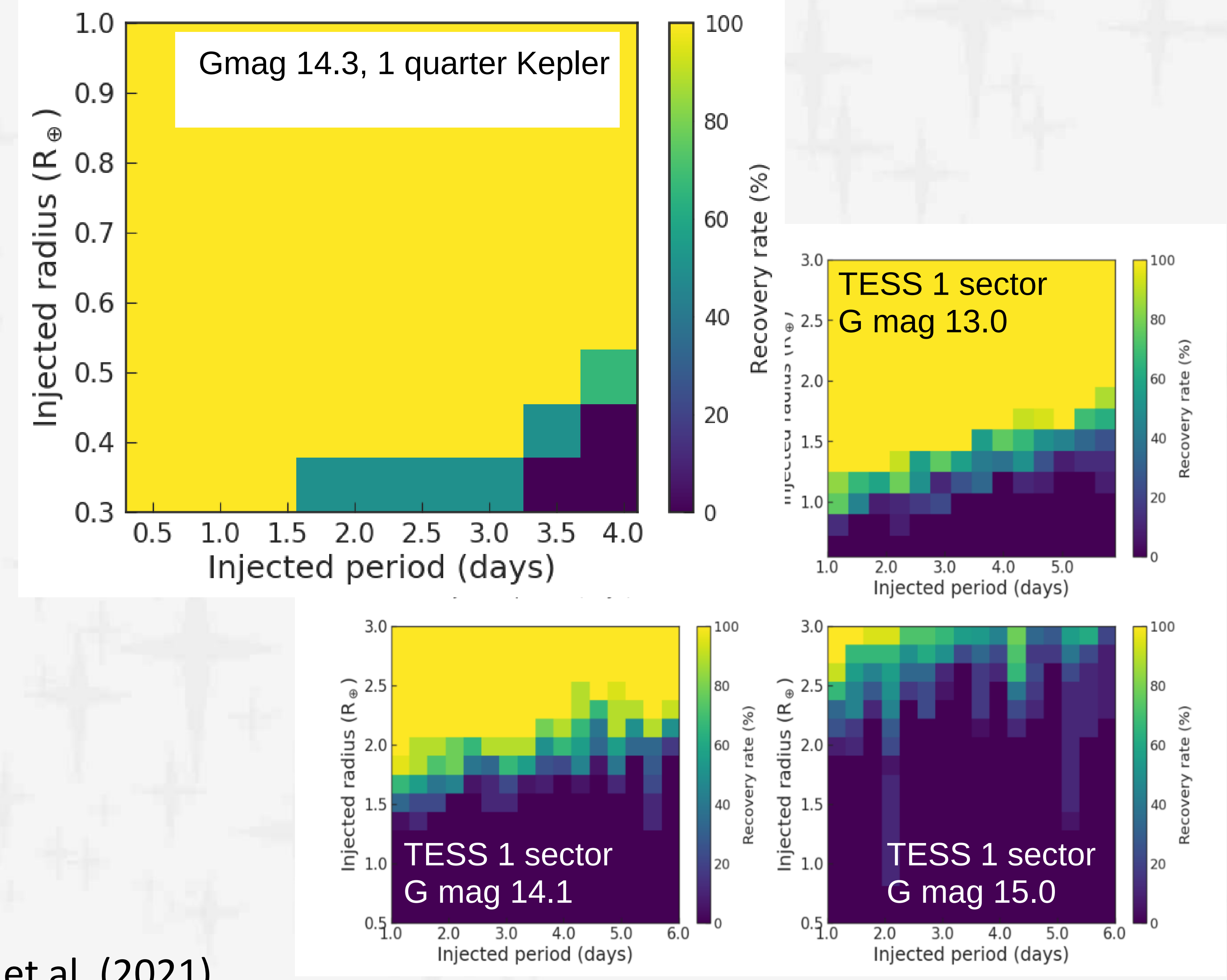


Search for planets around hot subdwarfs: A search of transits in space-based data

Injection-&-recovery tests:

- Kepler targets: can reach **0.3 R_E transiting bodies**
- K2 targets, best TESS targets and CHEOPS targets: detection of ≲ 1 R_E planets
- Bulk of TESS targets: 1.5-2.5 R_E planets

TESS data will allow us to measure the planet occurence rate around hot subwarfs (statistic), Kepler/K2/CHEOPS will allow us to test the survival of engulfed planets as small remnants



Full results in Van Grootel et al. (2021)

Search for planets around hot subdwarfs: A search of transits in space-based data

Results from TESS Cycle 1 (Thuillier et al. 2022), 792 stars:

- 46 signals spotted in Cycle 1 also seen in Cycle 3
- Some of these stars with signals are now followed-up (2 signals retrieved thus far); 0 planetary body confirmed
- 549 stars display no signal (list in Thuillier et al.). Based on this non-detection, the upper limit f_{max} of the **occurrence rate of planets around hot subdwarfs** is (Faedi et al. 2011):

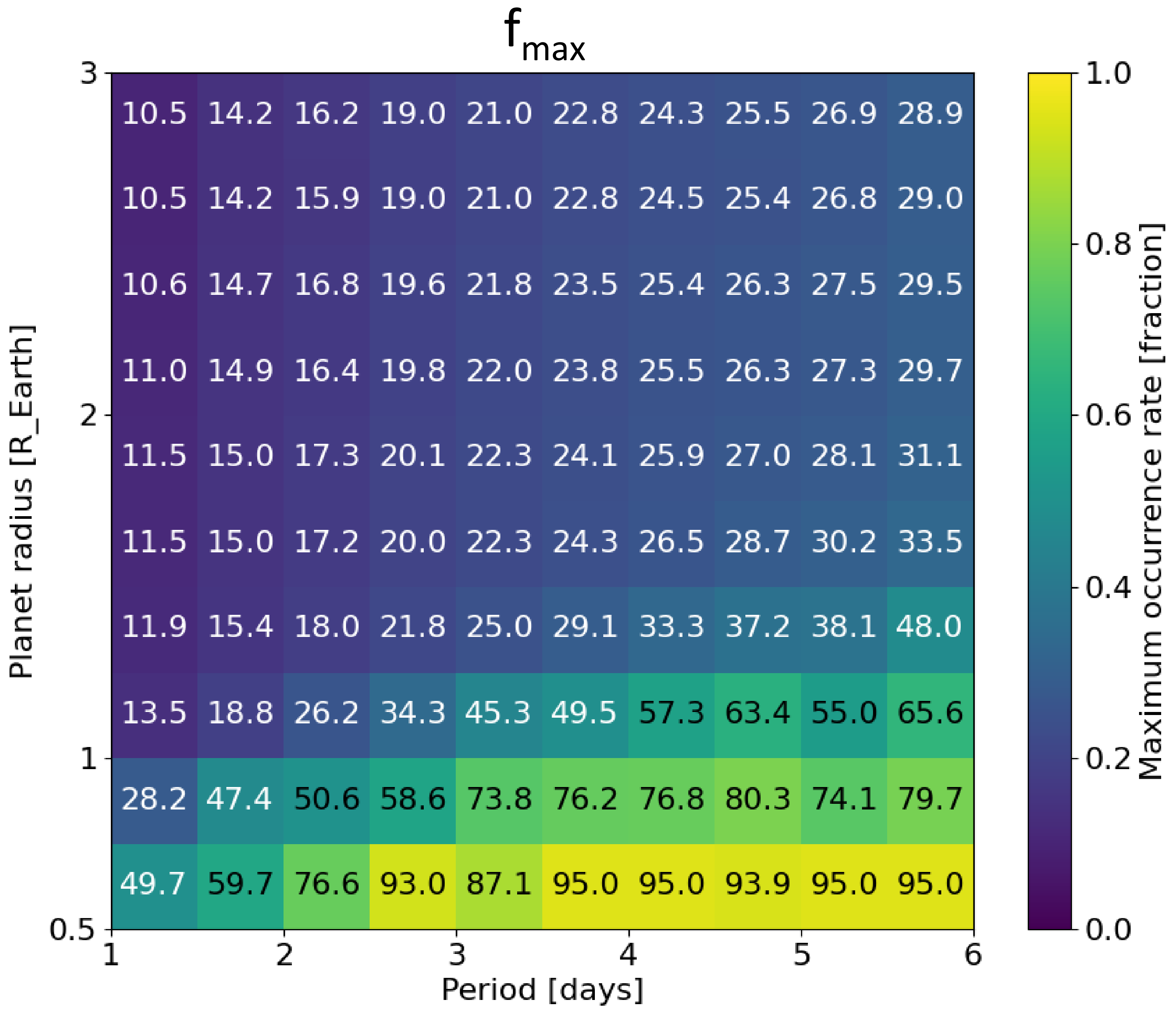
$$f_{max} = 1 - (1 - C)^{\frac{1}{N'+1}}$$

$$N' = N \times P_{\mathrm{transit}} \times P_{\mathrm{detection}}$$

C: confidence level (=0.95)
$P_{transit}$: (geometrical) probability of transit
$P_{detection}$: probability of detection (i&r tests)

Search for planets around hot subdwarfs: A search of transits in space-based data

Occurrence rate of planets around hot subdwarfs



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

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

Conclusions

Because they are:

1. Post-RGB stars (and they do not ascend the AGB)
2. Small stars (0.1 – 0.3 R_{sun})
3. Short-lived (100-200 Myr)

Hot subdwarfs are ideal candidates to address the question of the evolution of planetary systems directly after the RGB phase of stellar evolution and of the survival of engulfed planets (possibly as small remnants)

No planets have been confirmed yet around them…work ongoing (in particular for the transit survey)…a null result is still valuable !

“ Thanks for your attention ☺ ”

[redacted]