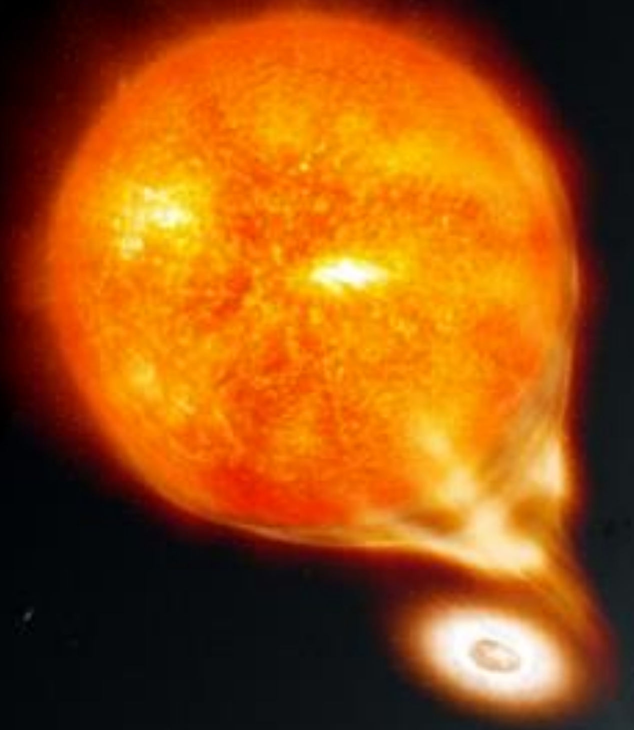
Hot Subdwarfs

as Progenitors, Hosts or Descendants of Compact Objects

The sdBV+dM binary TIC 137608661: an example of potential CV progenitor on the way to synchronization



(Image from SdOB10 meeting booklet)

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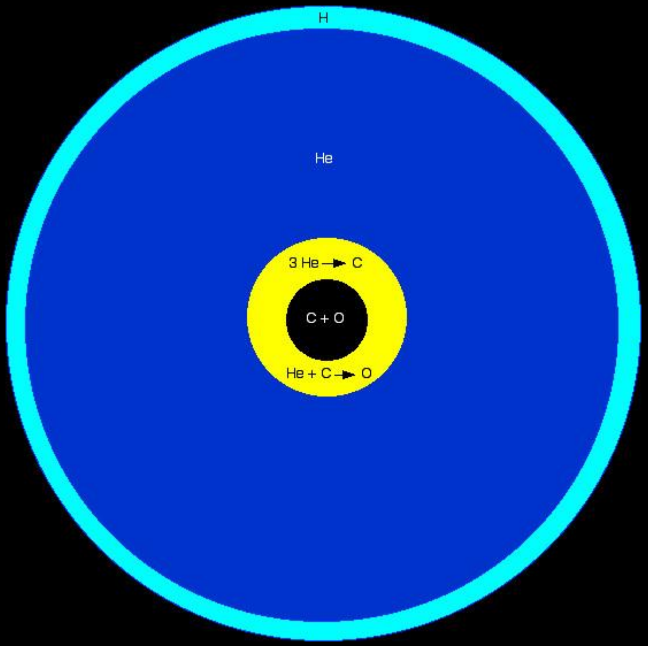
INAF-Osservatorio Astrofisico di Torino

CNOC XII, Cefalù, 27-30 Settembre 2022

1. Hot Subdwarfs

as Progenitors, Hosts or Descendants of Compact Objects

With typical radii of ~0.2 R_{SUN}
hot subdwarfs are not such compact objects



However, there are strong links with much more compact objects.
Indeed sdO/B subdwarfs stars are:

1) Precursors of low-mass CO WDs, CVs, AM CVn, GW emitters, SNe Ia

2) Primary components of sdOB+WD/NS/BH binaries

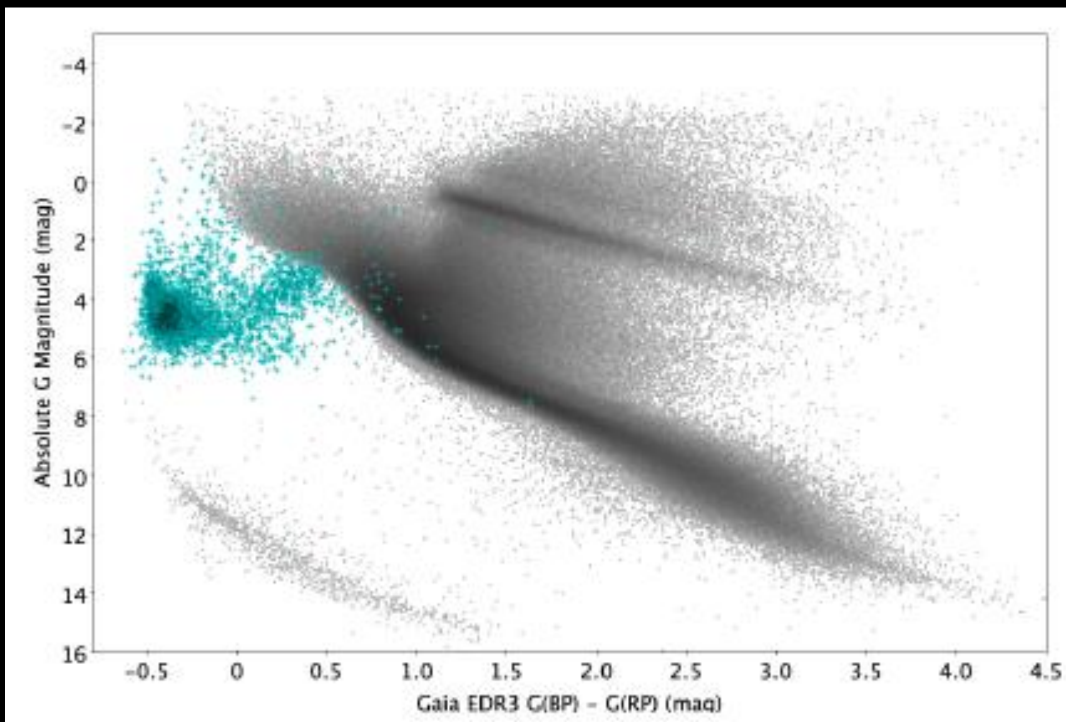
3) Potential descendants of double-WD mergers, and potential remnants of SNe Ia (hyper-velocity He-sdOs)

Hot subdwarfs and evolution

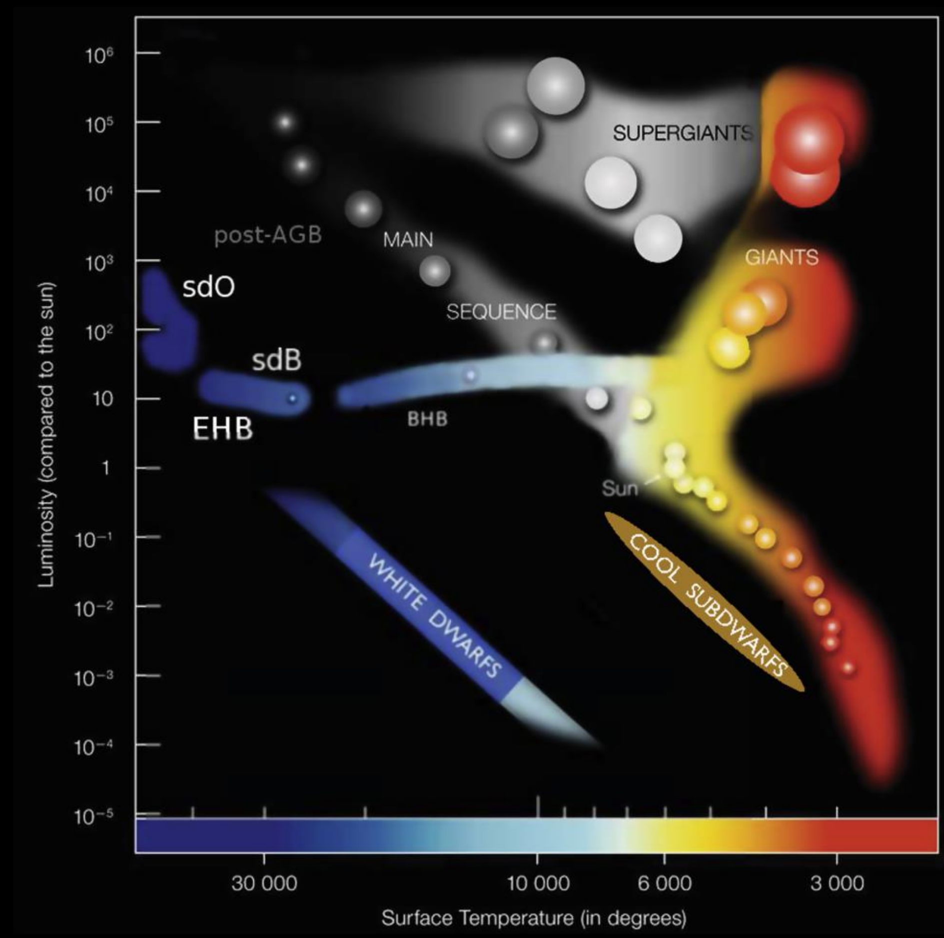
B and O-type subdwarfs represent different stages in the late evolution of low-mass stars:

sdBs are a quite homogeneous group of EHB core-He burning stars

sdOs are much less homogeneous including both post-EHB and post-AGB objects



3373 most reliable hot subdwarfs from Gaia EDR3 (Culpan+2022)

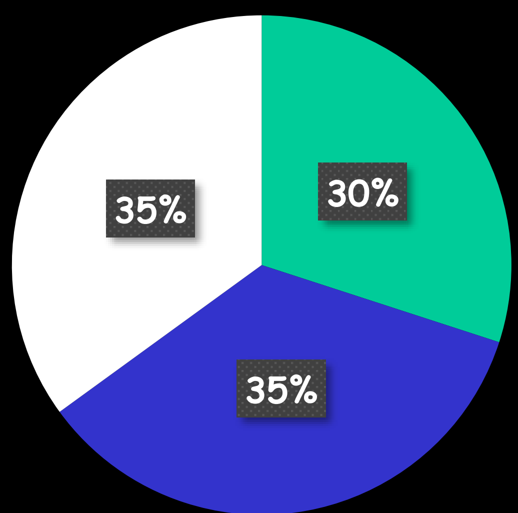


Hot subdwarfs and binarity

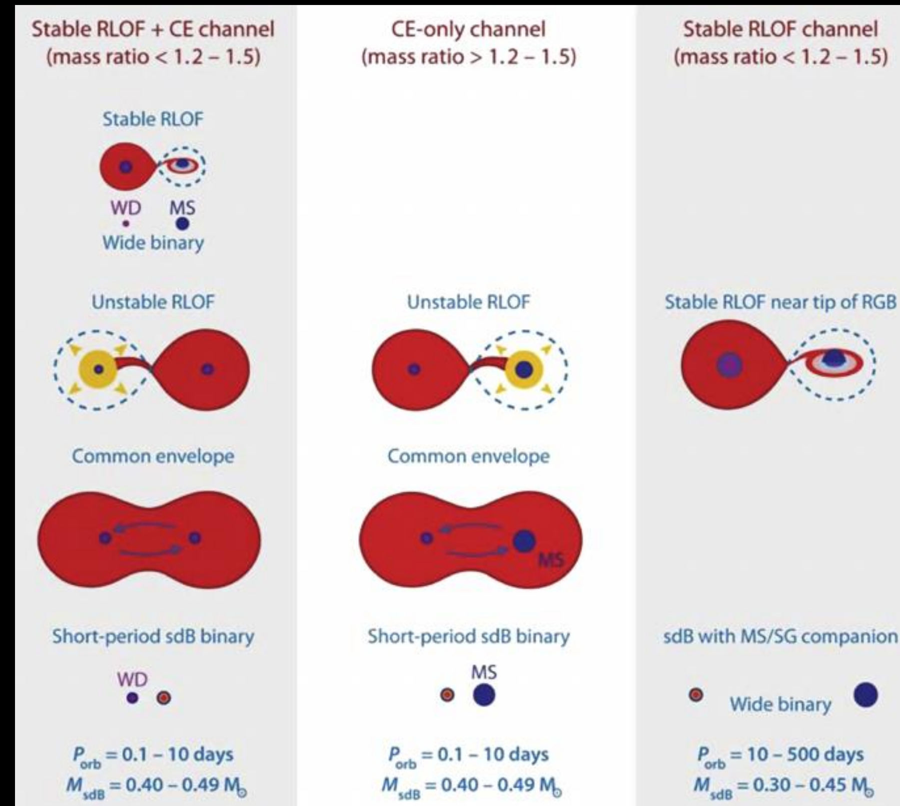
At least 2/3 of hot subdwarfs (HSDs) are in binary systems, 1/3 in short-period binaries ($P_{ORB}\approx$1 d) with a WD or dM/BD companion.

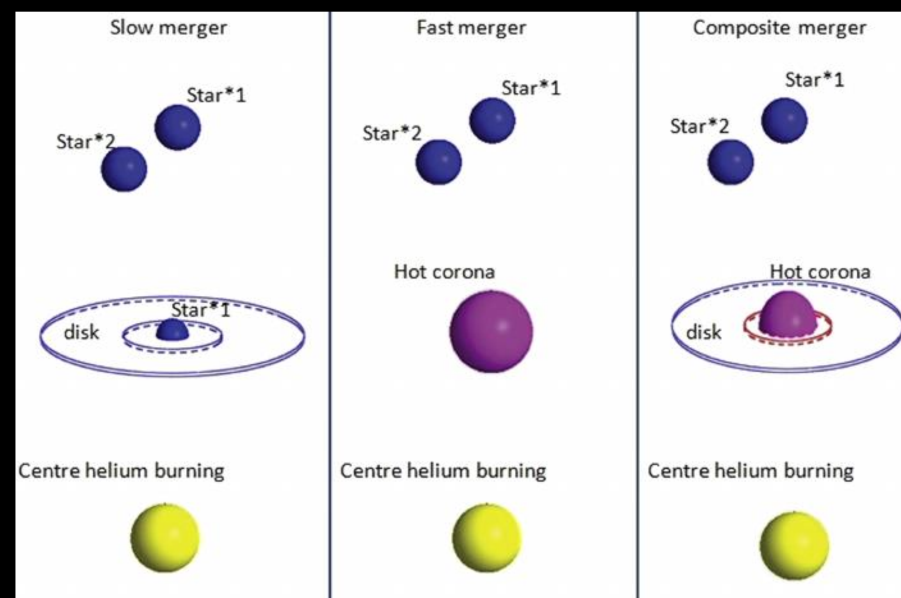
*And there is some evidence that binary interaction is **always** required to form HSDs (Pelisoli+2020).*

Thus HSDs are excellent laboratories to study binary evolution, CE/PCEBs physics and evol., merger physics, tidal interactions, differential rotation, tidal synchronization in close binaries.



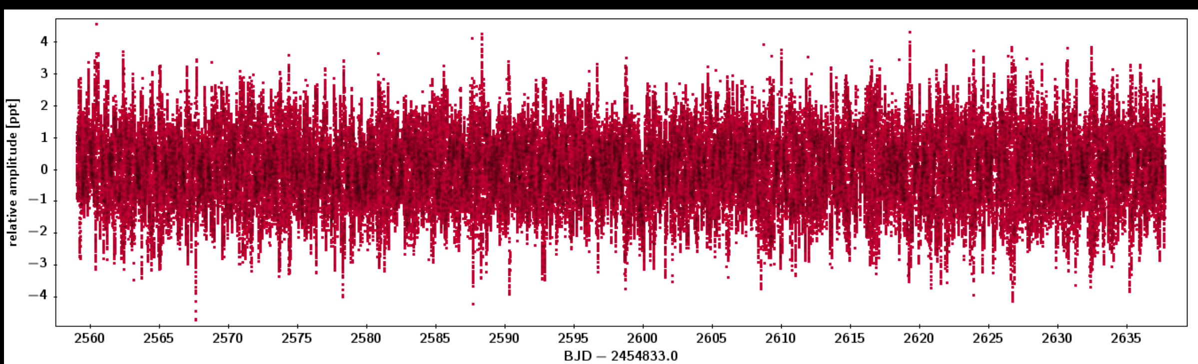
- wide binaries with F/G/K companions
- short-period binaries with dM/WD companion
- apparently single sdO/Bs

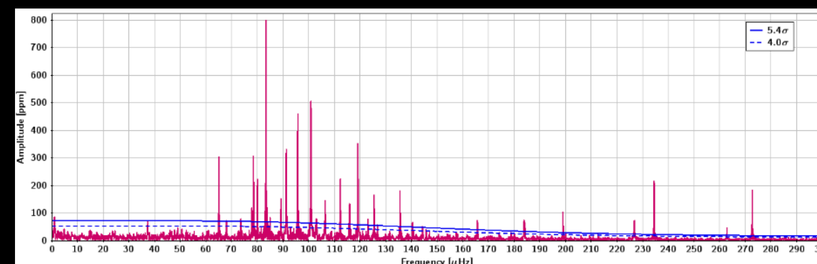


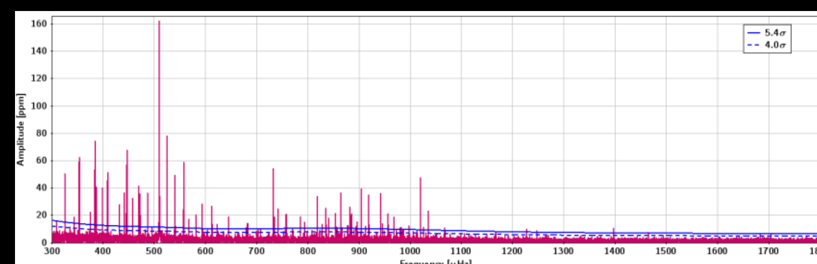


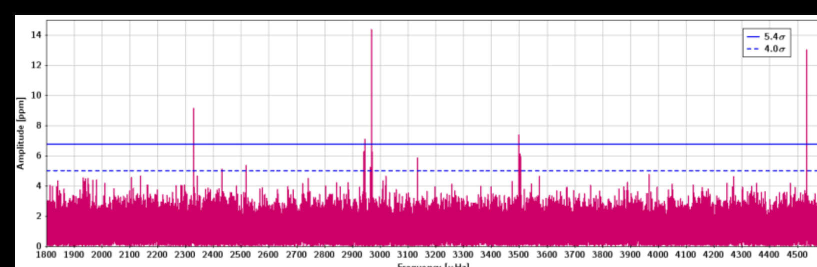
Hot subdwarfs and pulsations

HSDs are also excellent labs for asteroseismic studies: showing both p- and g-mode oscillations, they are among the richest pulsators accross the HR diagram, and allow detailed studies on: core He burning phase [e.g. $C^{12}(\alpha,\gamma)\ O^{16}$ reaction rate, mixing at the convective core boundary (overshoot, semi-convection)], atomic diffusion (radiative lev., gravitational settling, sdO/B’s pulsations are driven by Fe-group elements pushed up by radiative levitation), weak pulsational effects like amplitude/frequency variations, nonlinear interactions, tidally perturbed pulsators, etc. ...







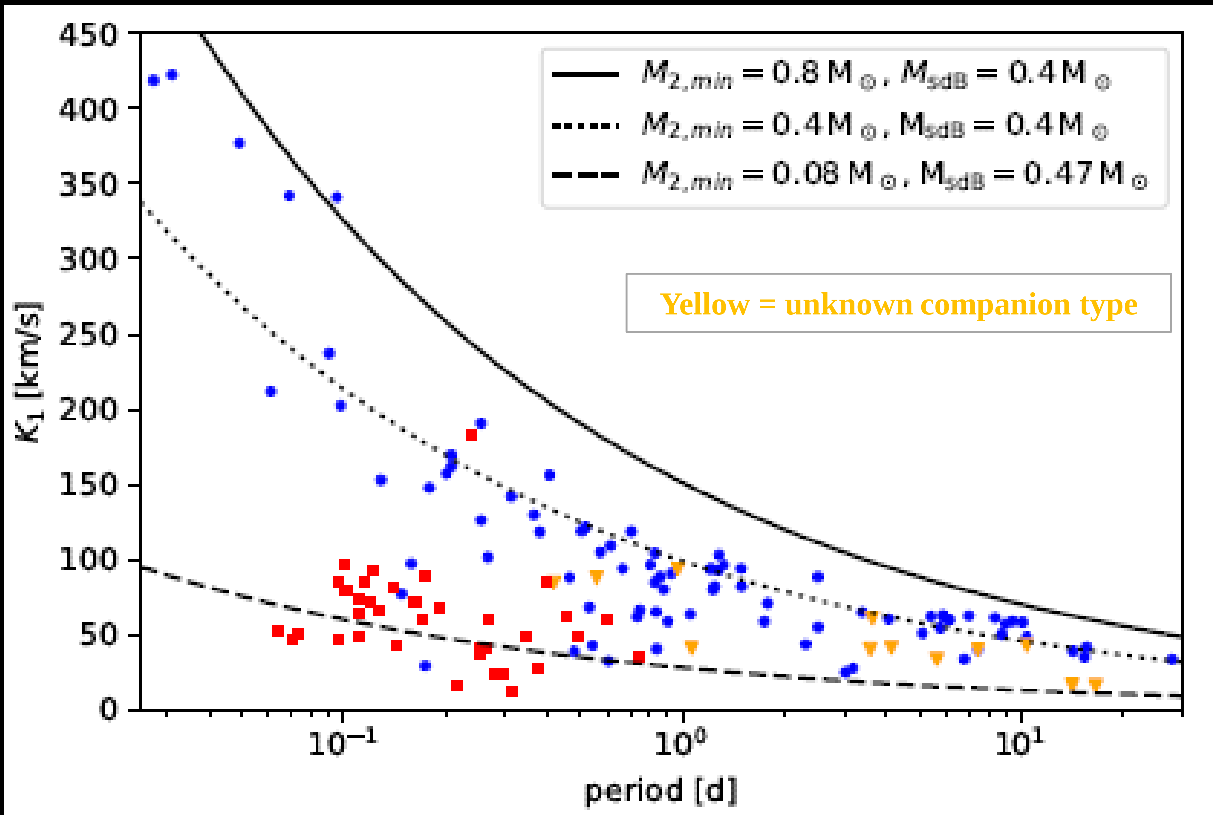


An example of sdB pulsators: K2 light curve (78.7 days) and amplitude spectrum of HD 4539 showing >124 p- and g-mode pulsation frequencies with $l \leq 12$ (Silvotti+2019)

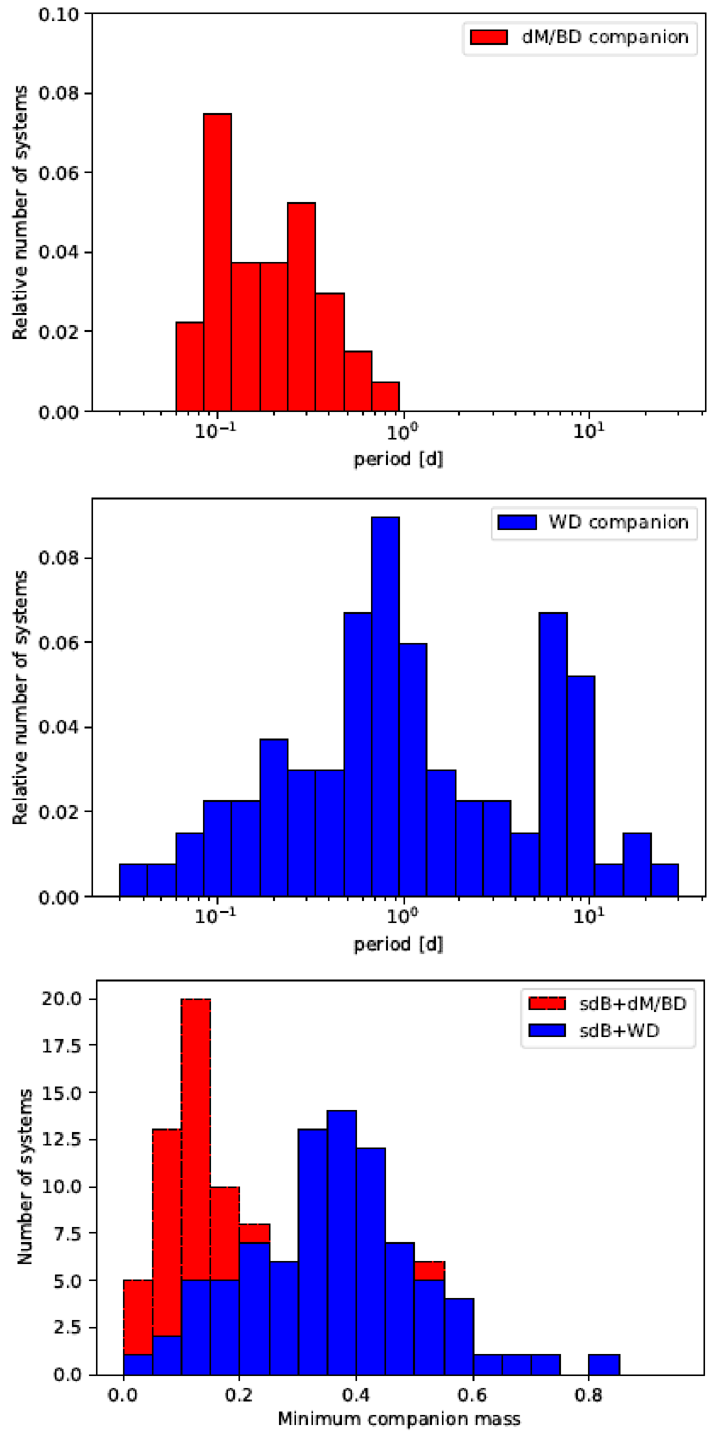
Hot subdwarfs in short-period binaries

~1/3 with M-dwarf/BD companions and P_{ORB}<1 d are potential progenitors of CVs

~2/3 with WD companions and periods up to ~10 d may be progenitors of AM CVn systems



Schaffenroth+2022: Orbital periods and companion mass for all the known short-period sdB binaries with spectroscopic solutions and with TESS or Kepler lightcurves (~130 systems).

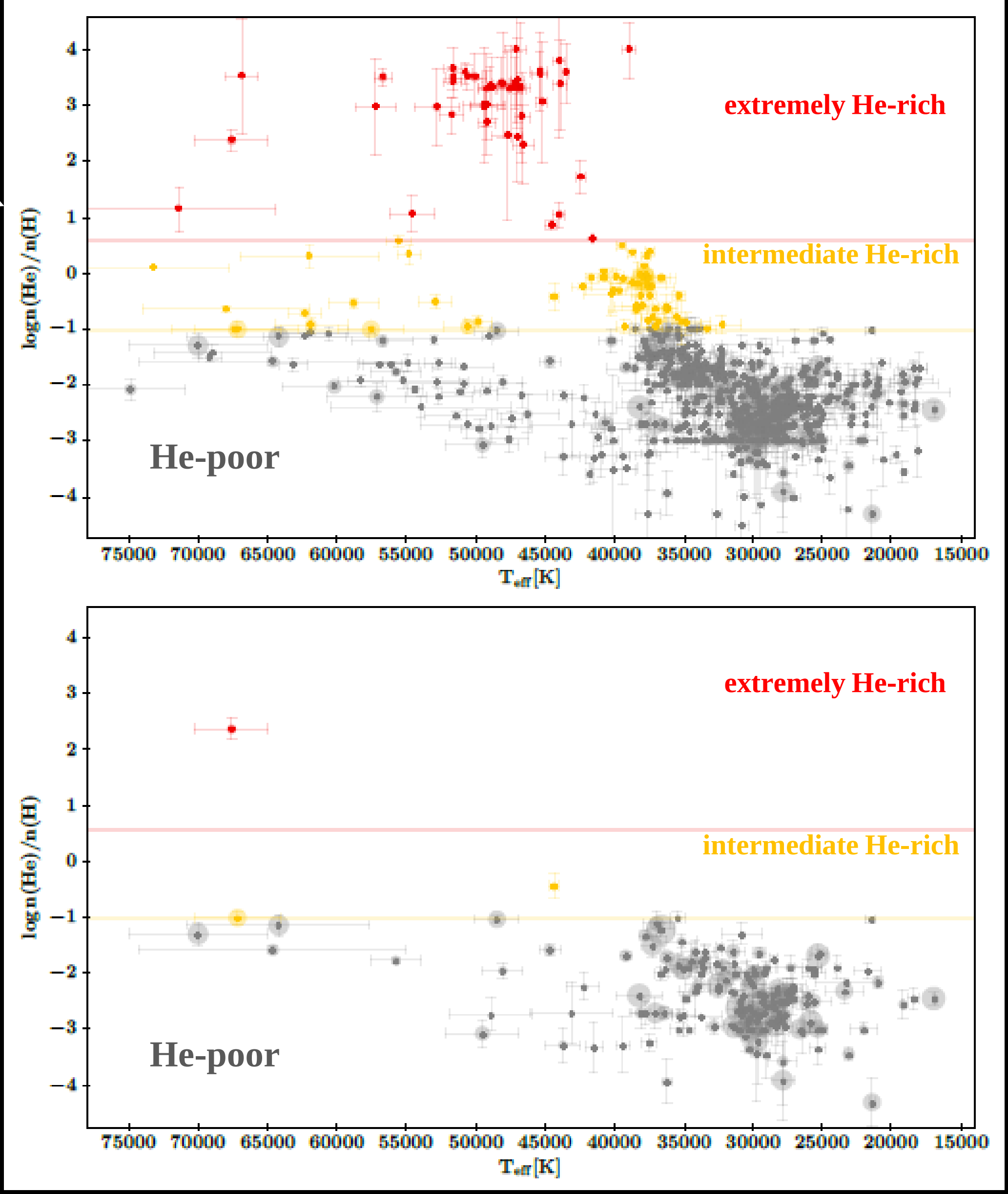


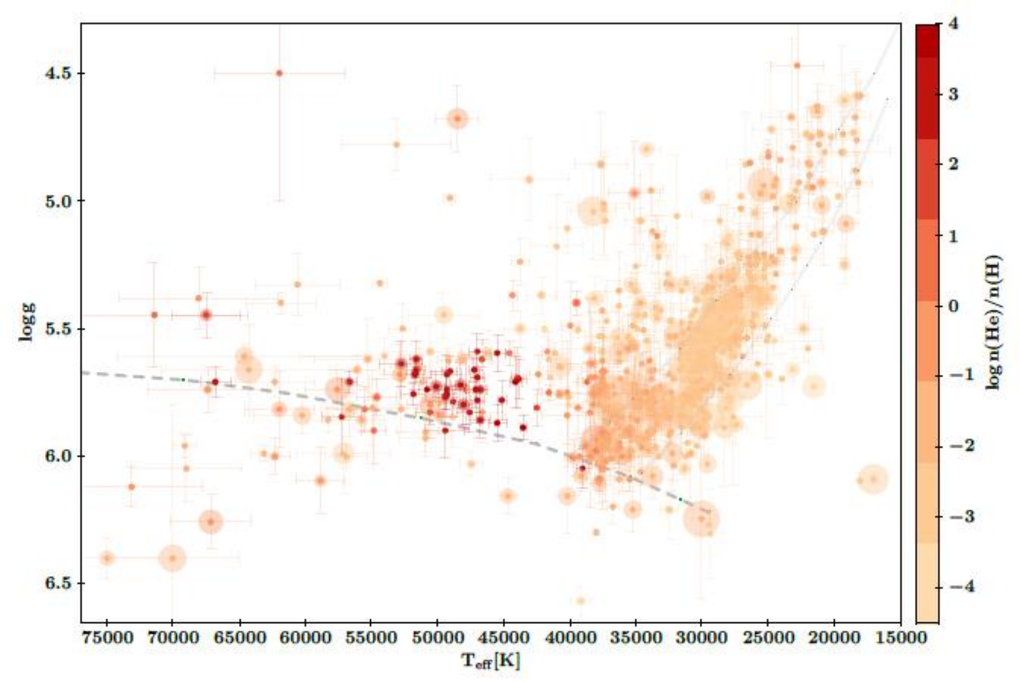
But short-period binaries are not found in He-rich subdwarfs !

Those He-rich do not show significant RV variations, at least down to ≈10 km/s (Geier+2022).

And, for a dozen of bright sdO/Bs we have much stronger upper limits of ≈100 m/s (Silvotti+2020, ongoing program)

RV variability vs He abundance: the size of the symbols scales with ΔRV_{max}. In the lower panel only sdOB/O stars with significant RV variability are shown.



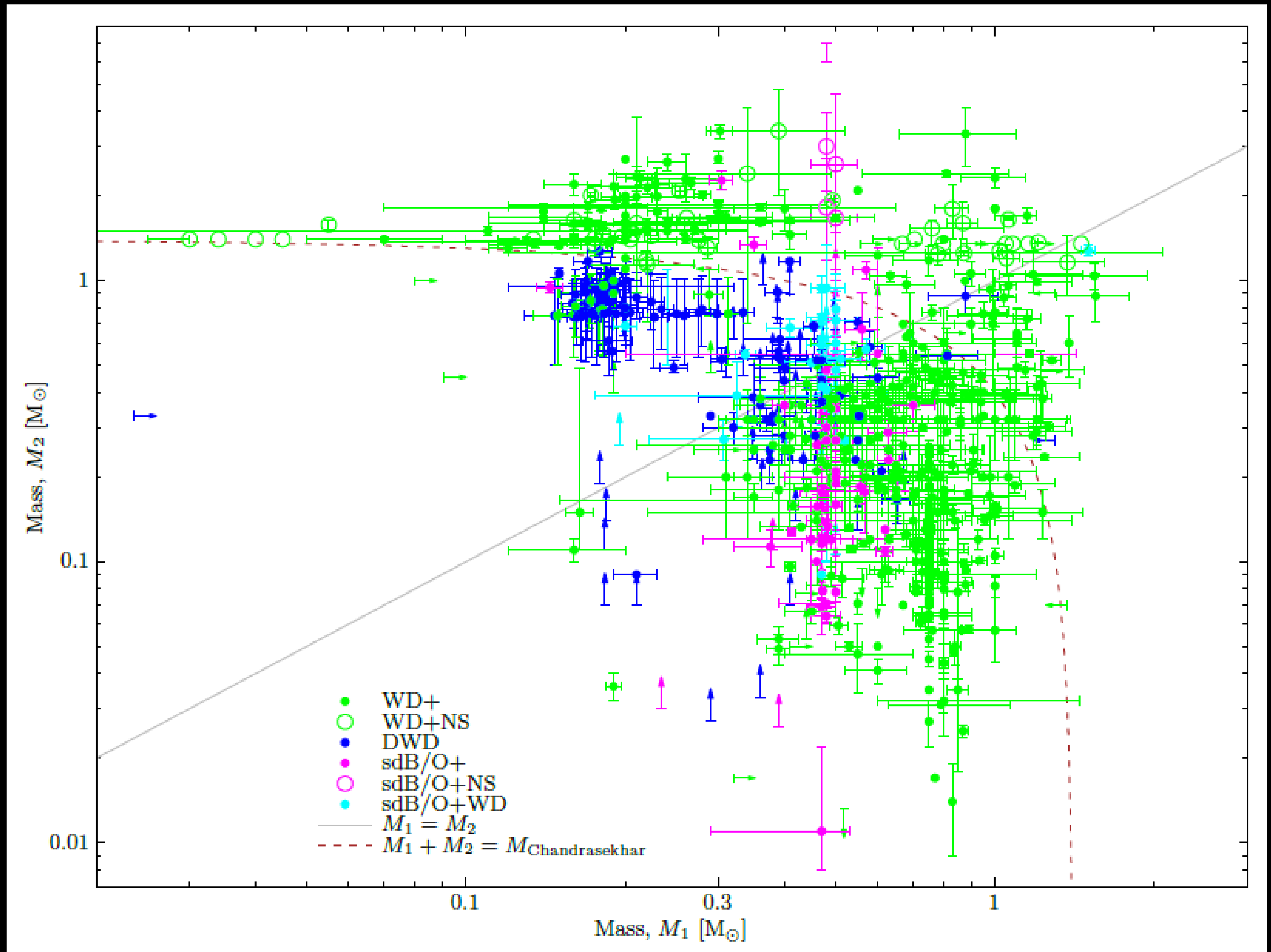


Teff-log*g* diagram of the full sample of hot luminous stars with RV measurements. Solid lines are evolutionary tracks from Dorman+1993, dashed line is HE MS from Paczynski 1971.

SdO/B stars in short-period binaries are the product of a previous CE phase

criteria	sdB/O+	DWD	WD+
all	185	123	531
mass, M_1	$184^{\downarrow 49}_{\uparrow 51}$	$122^{\downarrow 96}_{\uparrow 96}$	$506^{\downarrow 389}_{\uparrow 411}$
mass, M_2	$71^{\downarrow 72}_{\uparrow 181}$	$94^{\downarrow 75}_{\uparrow 117}$	$505^{\downarrow 449}_{\uparrow 450}$
masses, M_1 and M_2	71	93	492
WD companion	126	123	0
sdB companion	1	0	0
MS companion	56	0	15
NS companion	6	0	45
BH companion	7	0	0
BD companion	6	0	24
M type companion	35	0	164
K type companion	2	0	34
G type companion	1	0	11
F type companion	0	0	42
A type companion	0	0	26
unknown companion (-)	2	0	170
no flag (-)	39	64	244
mass transfer (MT)	2	1	22
cataclysmic variable (CV)	0	0	223
statistically (S)	0	56	20
assumed WD mass (SWD)	0	0	82
assumed sdB mass (SsdB)	140	0	0
assumed mass ratio (Sq)	5	0	2
assumed companion mass (SM2)	0	1	19
triple (TRI)	1	1	7

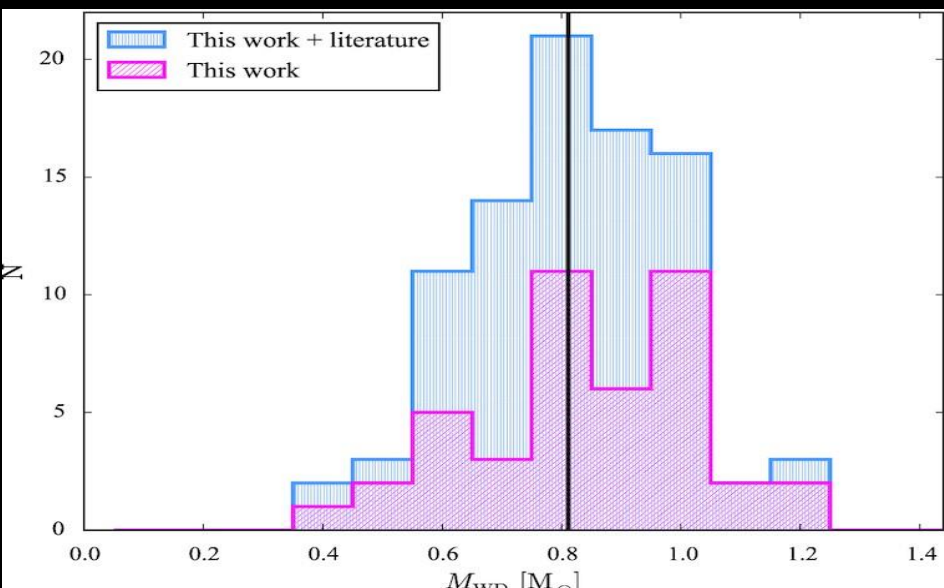
Kruckow+2021: A Catalogue of Potential Post-CE Binaries (from literature)



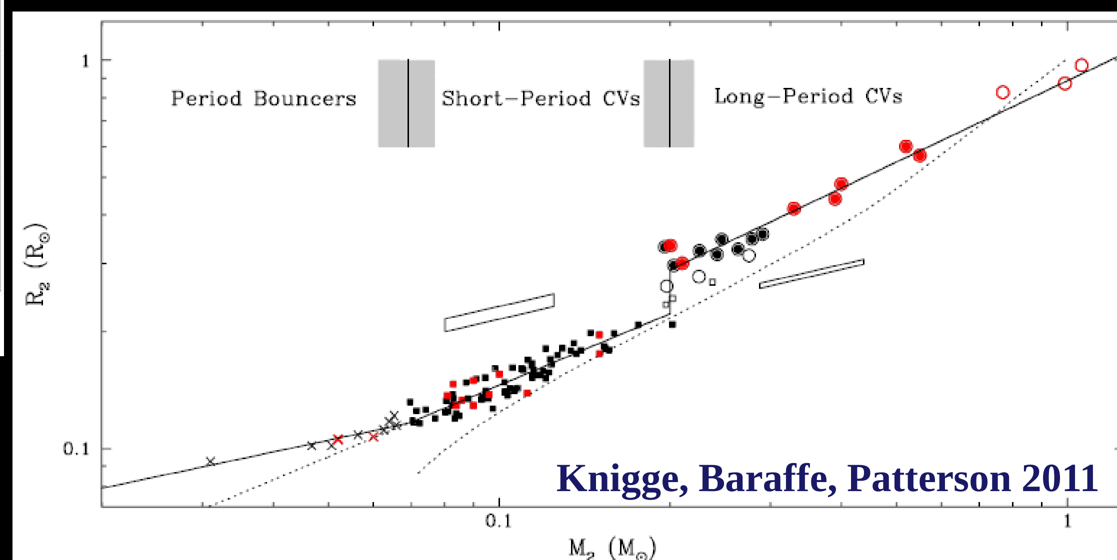
CO WD precursors: sdB stars have an extremely thin H-rich envelope (M_{env}<0.01 M_{sun}), too thin to sustain H-shell burning and ascend the AGB. Thus they will evolve directly to the WD cooling sequence, forming lower-than-average CO WDs.

CV precursors: short-period sdO/B+dM/BD binaries (P$\lesssim$1 day) are good candidates to become CVs

BUT



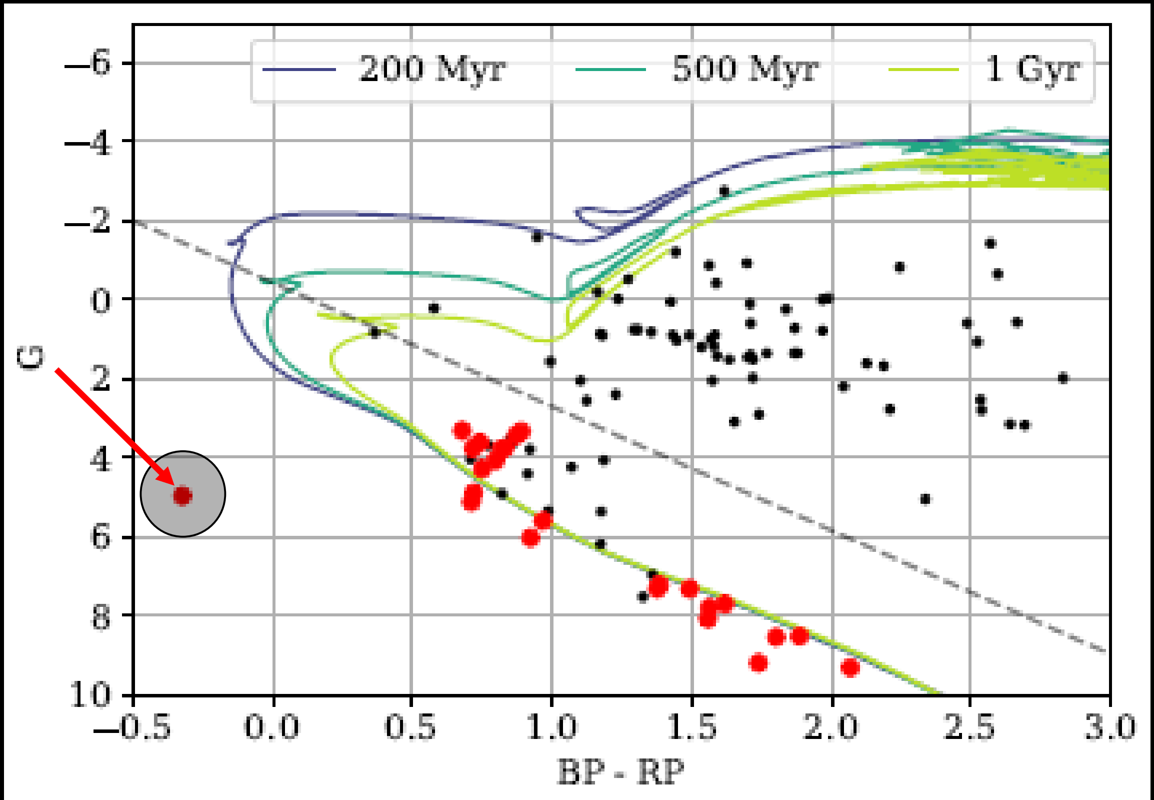
While the masses of the secondaries are more or less compatible, the mass distribution of the CV WDs peaks at 0.8 M_{SUN} ! (Pala+2022, Yu+2022). Thus sdO/B+dM binaries can contribute to the low-mass tail of the CV WD mass distribution.



SdB+NS/BH binaries

A sdB+NS wide binary candidate detected through Gaia DR3 astrometry (Andrew+2022):

GAIA DR3 ID	ϖ (mas)	G_{mag}	P_{orb} (d)	e	m_f	M_1	M_2
3649963989549165440	1.37±0.10	14.30	893±120	0.36±0.28	$0.79^{+0.50}_{-0.23}$	0.47±0.2	$1.41^{+0.62}_{-0.34}$

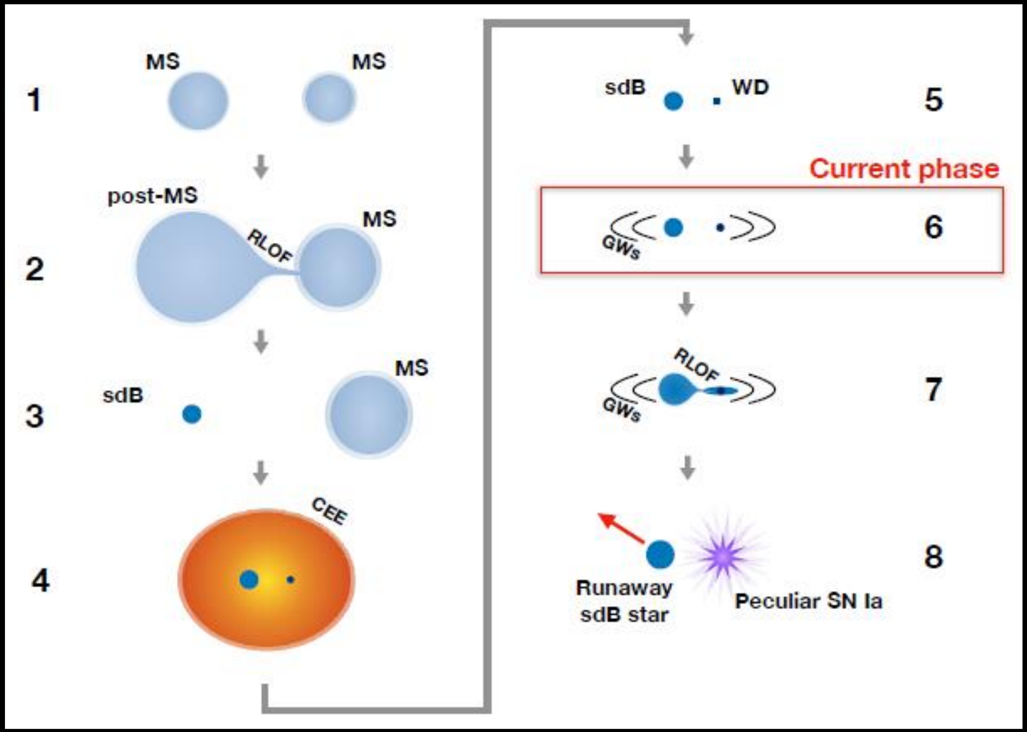


The long orbital period of ~900 days is compatible with theoretical formation models from MS+NS binaries through stable RLOF, with an initial MS star mass of ~2 M_{SUN} (Wu+2018).

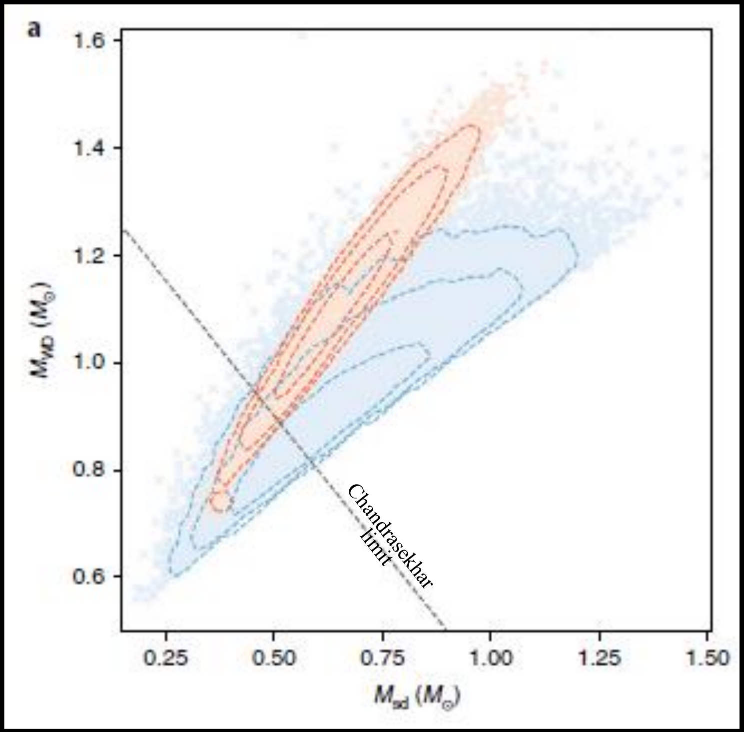
SdO/B+WD binaries as SN Ia progenitors

We know at least 4 SN Ia progenitor candidates with a sdOB/B primary + massive WD secondary in very tight orbits ($1 \lesssim P_{ORB} \lesssim 2$ h): KPD 1930+2752 (Maxted+2000), CD 3011223 (Vennes+2012, Geier+2013), PTF1 J2238+7430 (Kupfer+2021), HD 265435 (Pelisoli+2021).

For 2 of them the total mass should exceed the Chandrasekhar limit, leading to a single-degenerate or double-degenerate SN Ia, depending on how long it takes for the sdB star to become a WD.
For the other two a sub-Chandrasekhar double-detonation scenario is possible.

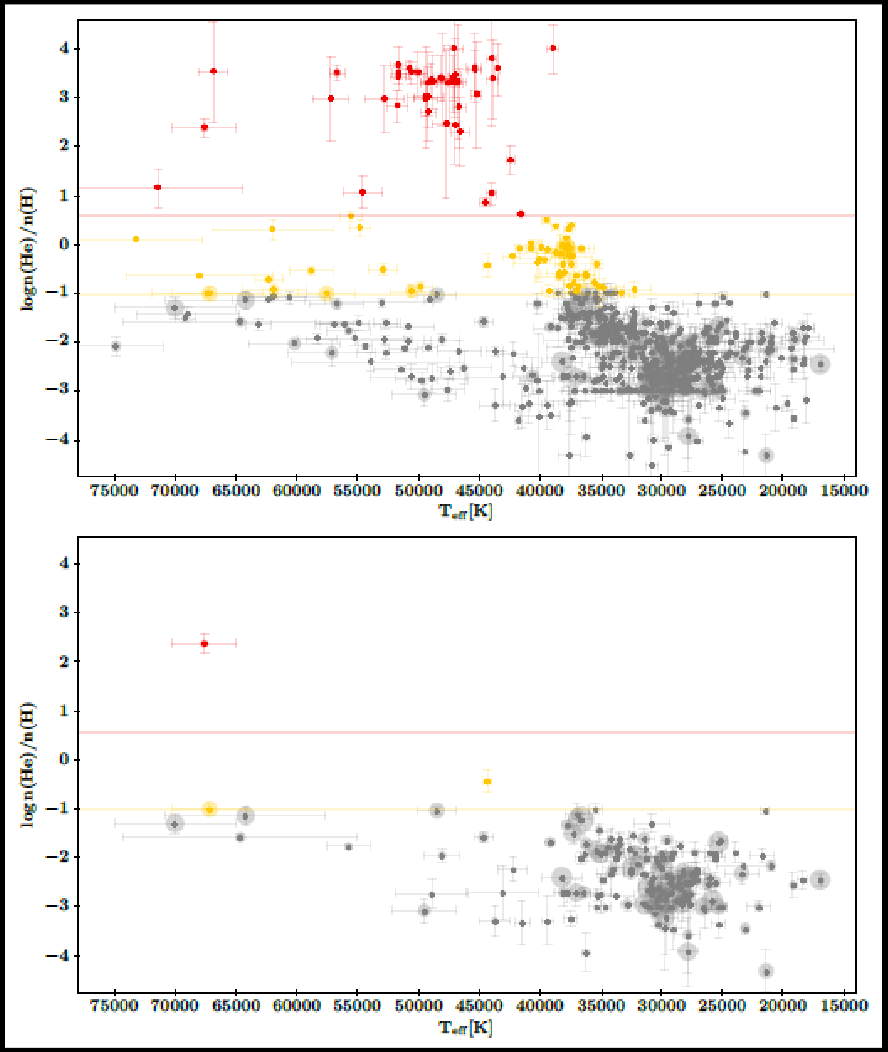


The sub-Chandrasekhar SN Ia candidate PTF1 J2238+7430 (Kupfer+2021).



The super-Chandrasekhar SN Ia candidate HD 265435 (Pelisoli+2021). The dashed contours correspond to confidence levels of 68%, 95% and 99%.

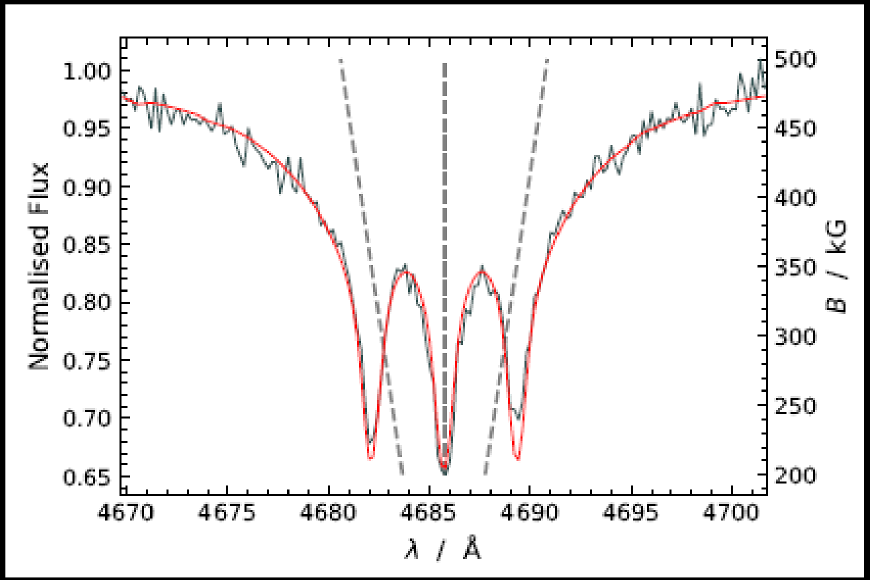
He-sdOs as probable descendants of double-WD mergers



One out of three evolutionary channels to form an sdO/B star is the merging of two He-core WDs (Han et al. 2002, 2003). Recently this theoretical prediction seems corroborated by the observations since He-rich sdOs do not have close companions (see left figure from Geier+2022).

This scenario is further supported by the recent discovery of a massive He-sdO star (M=0.9 M_{SUN}) that shows strong Zeeman splitting corresponding to a ~350 kG magnetic field (see figure below from Dorsch+2022).

However, it's not clear why no other sdOs show a measurable magnetic field. One possibility is that the surface magnetic field observed for J0809-2627 is not stable and weakens quickly after the merging.



He-sdOs as probable descendants of double-WD mergers

Comparison between binary population synthesis and observations (Yu+2021)

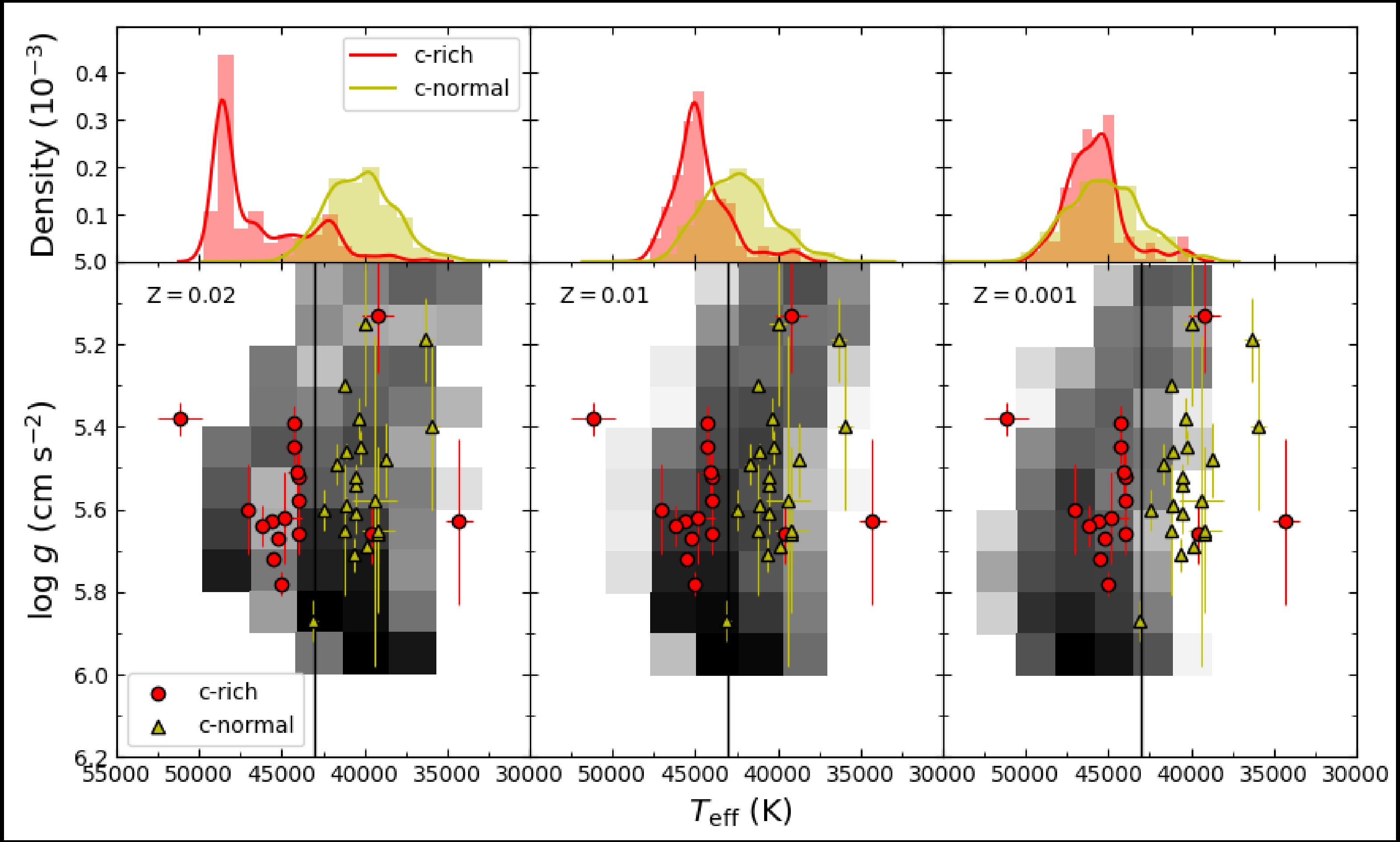


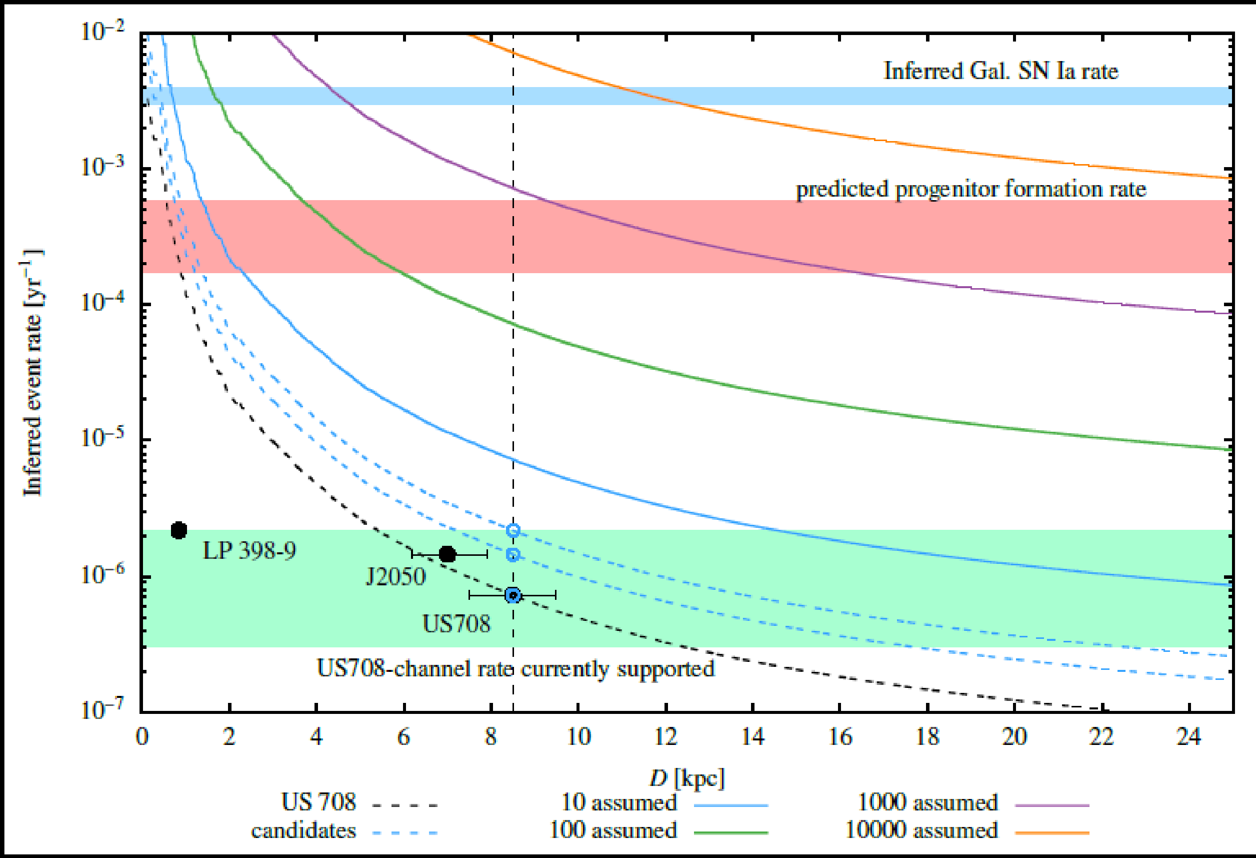
Figure 3. Distribution of the He-rich hot subdwarfs formed via the double HeWDs merger channel. The red dots and yellow triangles represent the C-rich and C-normal hot subdwarfs, respectively. The observed samples are from Hirsch (2009) and Naslim et al. (2010). In the top three panels, red and yellow lines represent the C-rich and C-normal normalized number density in the effective temperature range, respectively. The background grayscale distribution represents the relative number distribution of merged white dwarfs for He-rich hot subdwarfs.

Hyper-velocity He-sdOs as potential remnants of SNe Ia

In the single degenerate channel (SN Ia thermonuclear explosion from a WD+MS or a WD+He-rich donor) the donor star is generally expected to survive and is flung away with a velocity that can be high enough to make the donor unbound from the Galactic potential, creating a hypervelocity star (HVS) like e.g. US708 moving at ~750 km/s (Hirsch+2005, Geier+2013). Two recent articles by Meng & Luo 2021 and Neunteufel+2022 present, respectively, binary population synthesis and ejection trajectories of WD+MS and WD+evolved He donor.

Neunteufel+2022: calculated event rates. The number of currently observed population members suggests that the He-donor scenario, as suspected before, is not a dominant contributor to the number of observed SNe Ia. However, even at the low event rate suggested, we find that the majority of possibly detectable population members is still undetected.

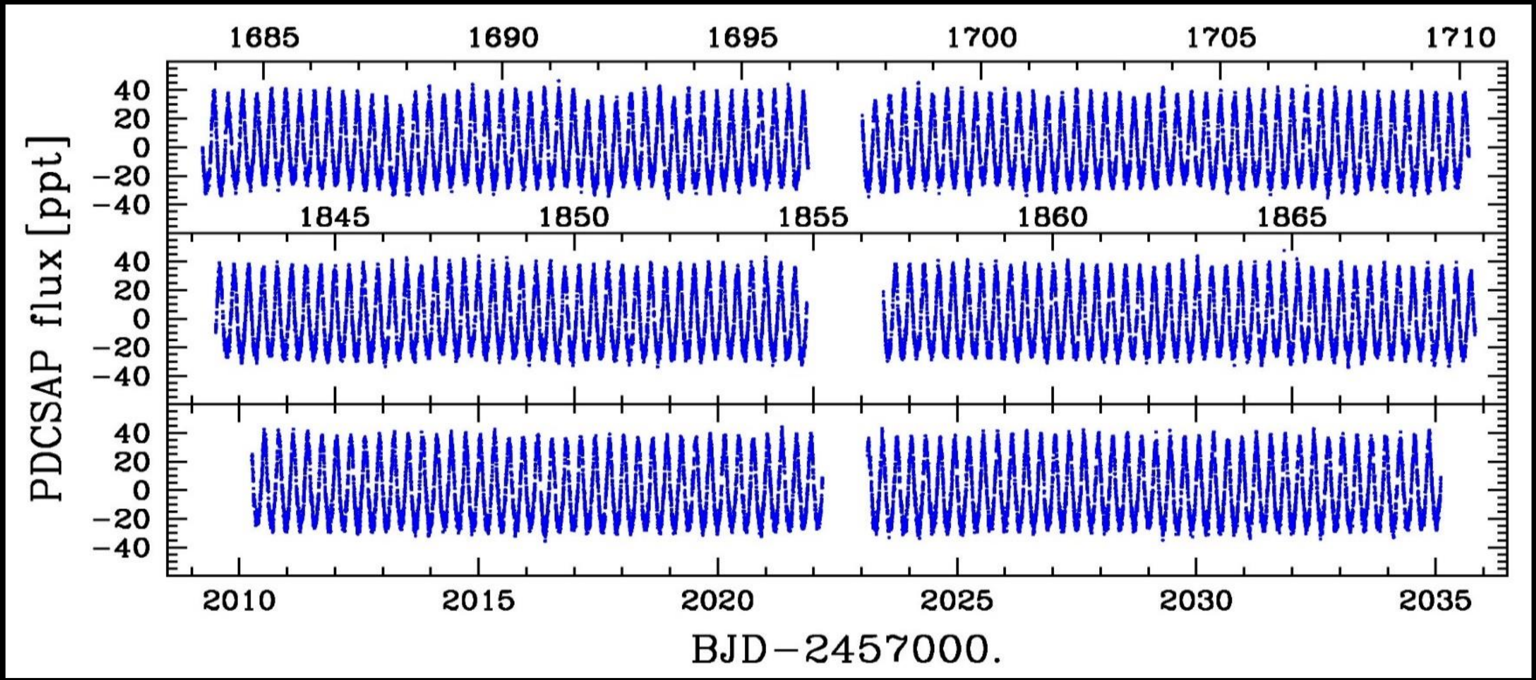
[Dashed lines indicate the distance-dependent event rate based on the 3 observed candidates. Solid lines indicate event rates under the assumption of the indicated number of detections. Distances to the observed objects (with error bars) and associated event rates are indicated by filled and hollow circles. The error bars for LP 398-9 are smaller than the radius of the circles.]

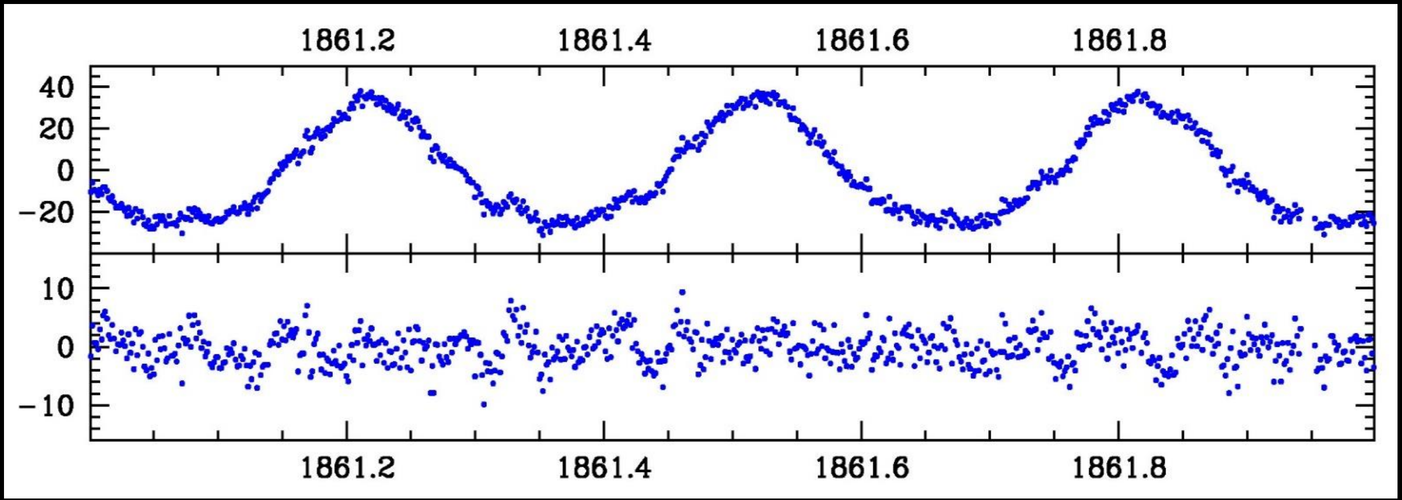


2. The sdBV+dM binary TIC 137608661: an example of potential CV progenitor on the way to synchronization

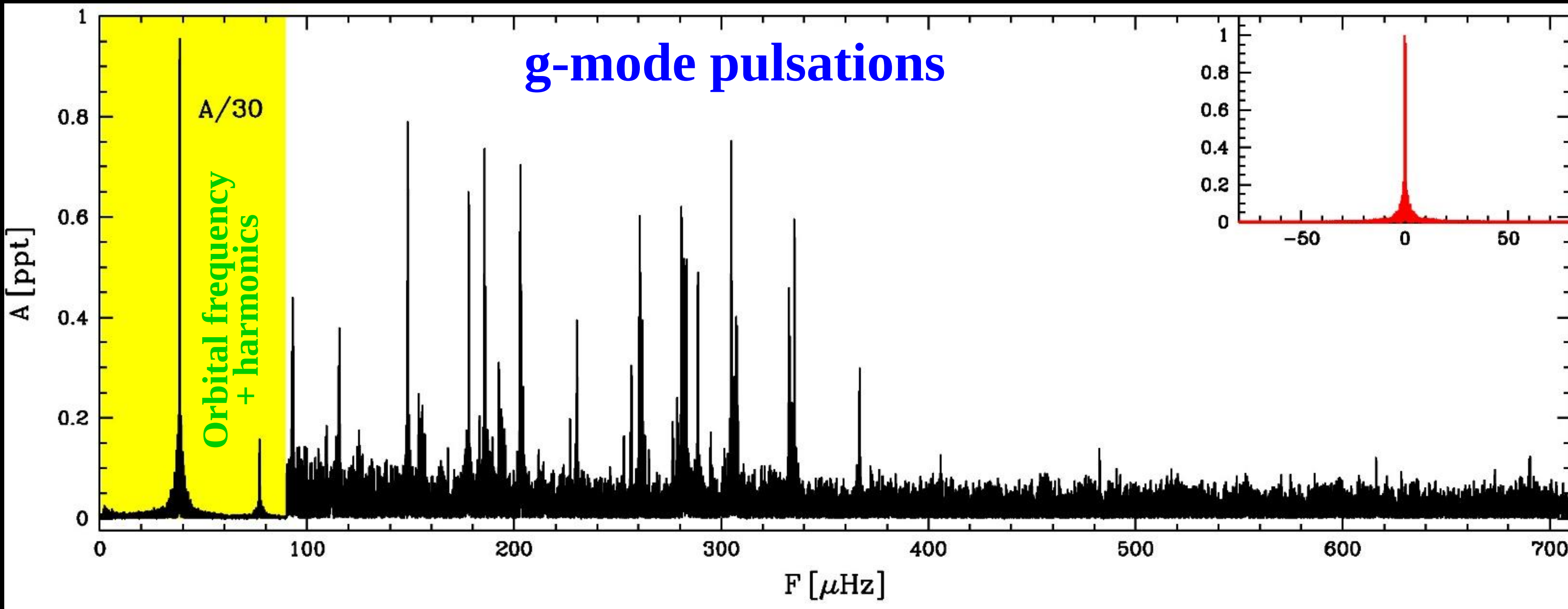
(Silvotti, Németh, Telting et al. 2022, MNRAS 511, 2201)

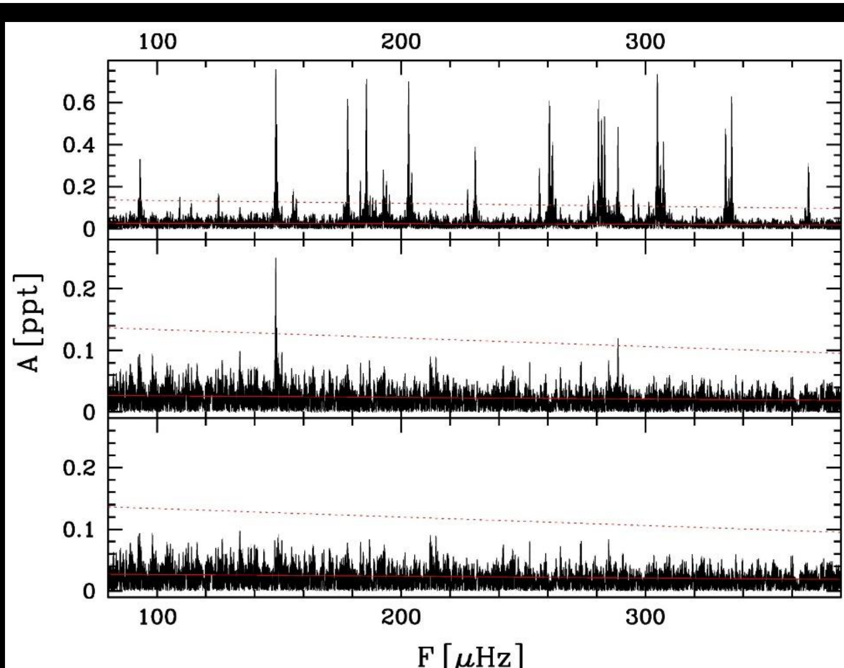
TIC 137608661/TYC 4544-2658-1/FBS 0938+788 is a relatively bright sdB star (G=11.11 mag) observed by TESS in sectors 14, 20 and 26

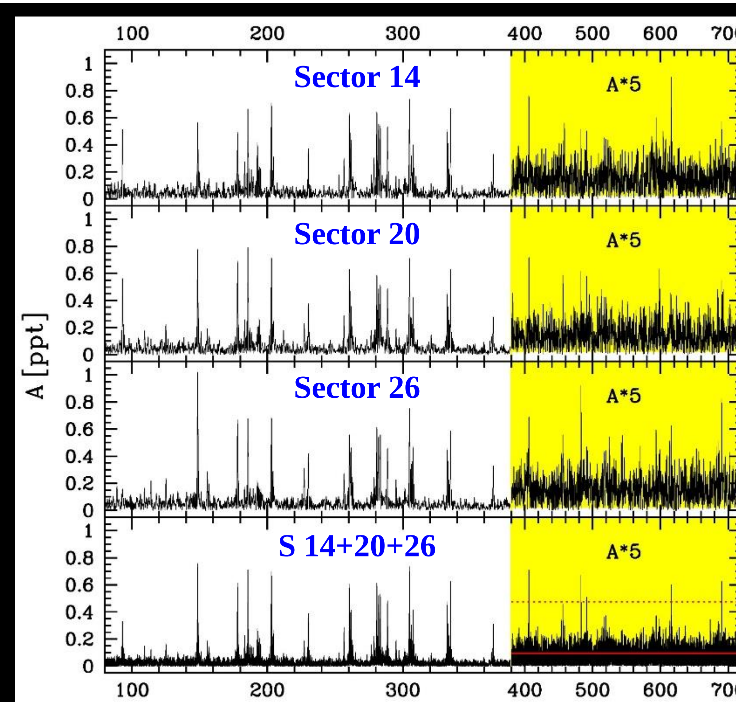




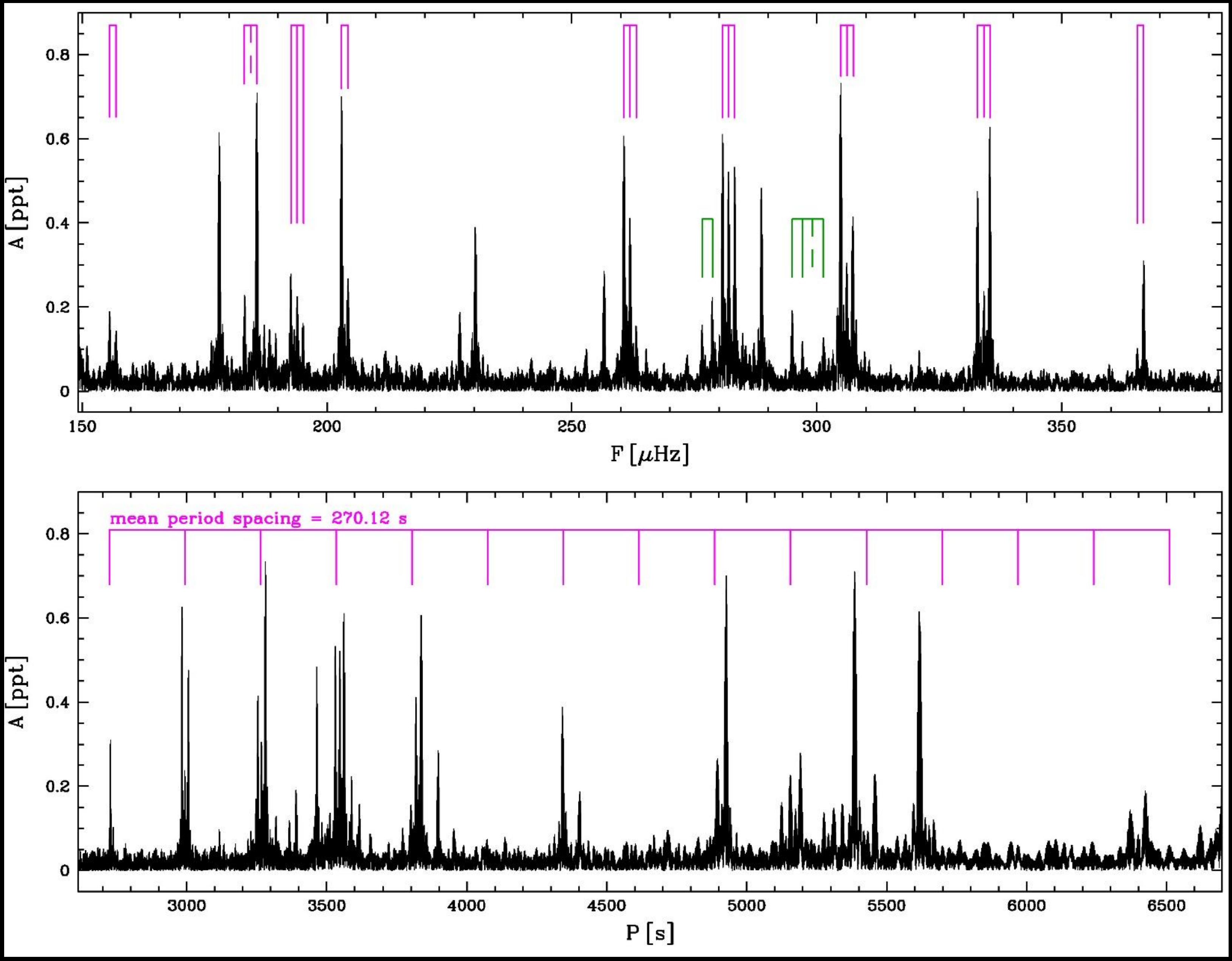
The light curve shows an orbital modulation with P_{orb} = 7.21 h (reflection effect from a dM secondary) + g-mode pulsations from the sdB primary

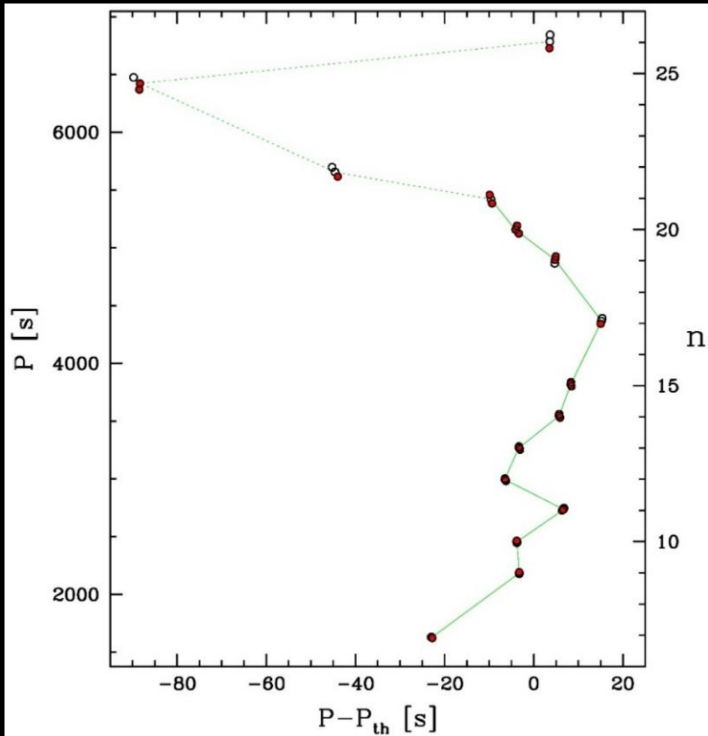

g-mode pulsations
A/30
Orbital frequency
+ harmonics
A [ppt]
F [μHz]


A [ppt]
F [μHz]


Sector 14
Sector 20
Sector 26
S 14+20+26
A*5
A [ppt]

TIC137608661 was selected because of its very clean amplitude spectrum with many consecutive *l*=1 rotational triplets



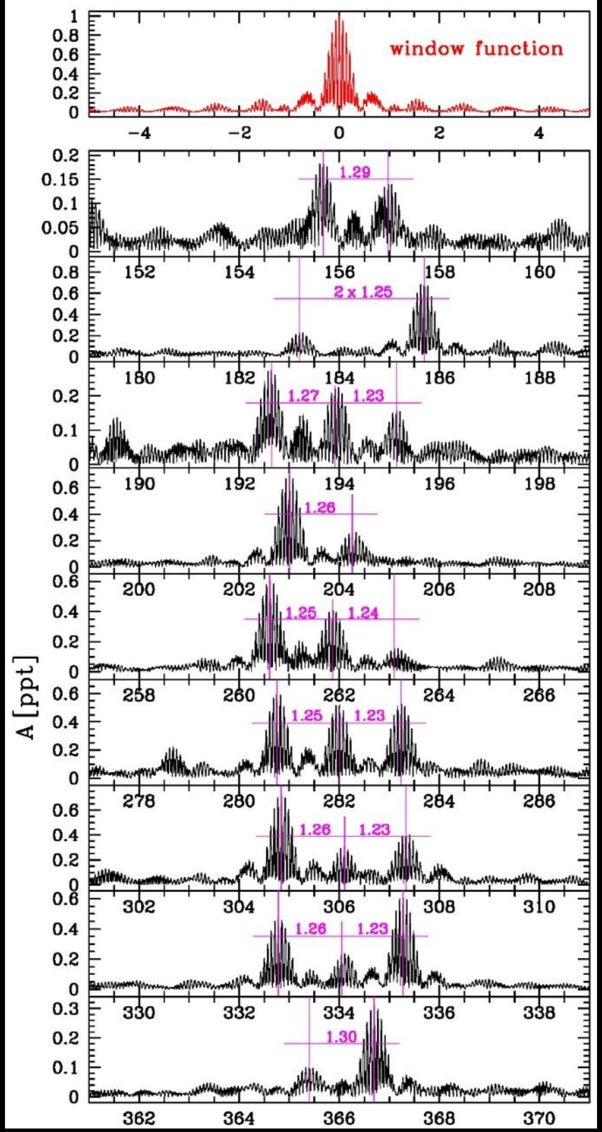


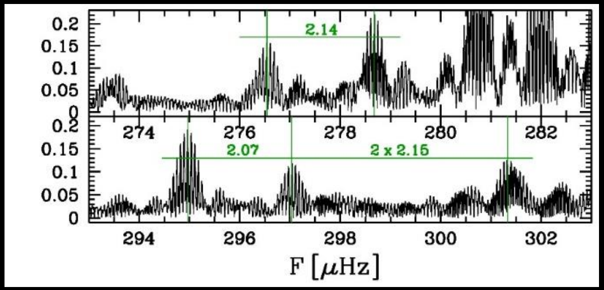
From pulsation analysis we obtain:

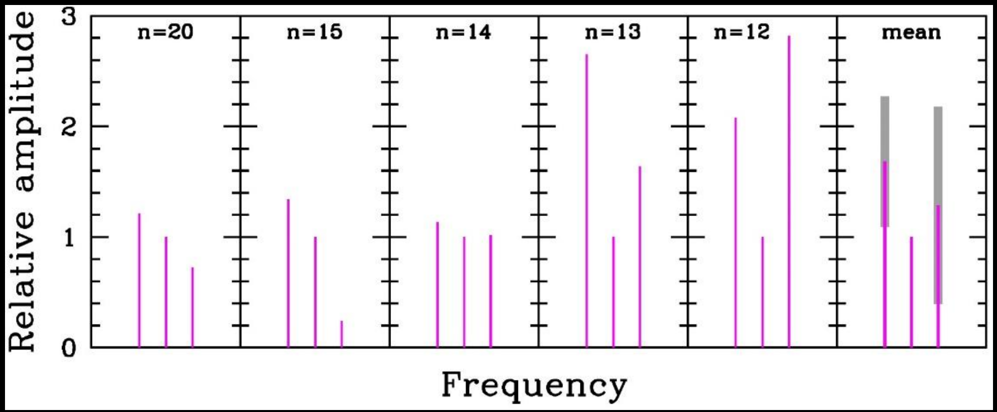
- **Prot = 4.6 ± 0.1 days**
  in the deep layers of the sdB star

- mode identification and
  ***l*=1 $\langle P_{spacing} \rangle$ = 270.12 ± 1.19 s**

- inclination between rotation
  axis and line of sight $\boldsymbol{i = (65^{+10}_{-20})°}$
  (assuming rotation axis parallel to pulsation axis)
  [Pesnell 1985, Charpinet et al. 2011]

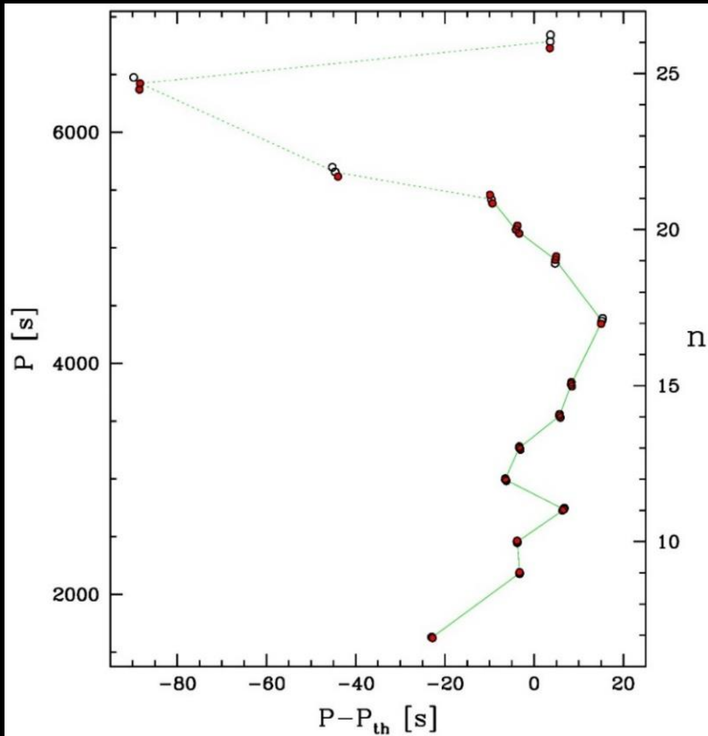






l=1 triplets

l=2 quintuplets



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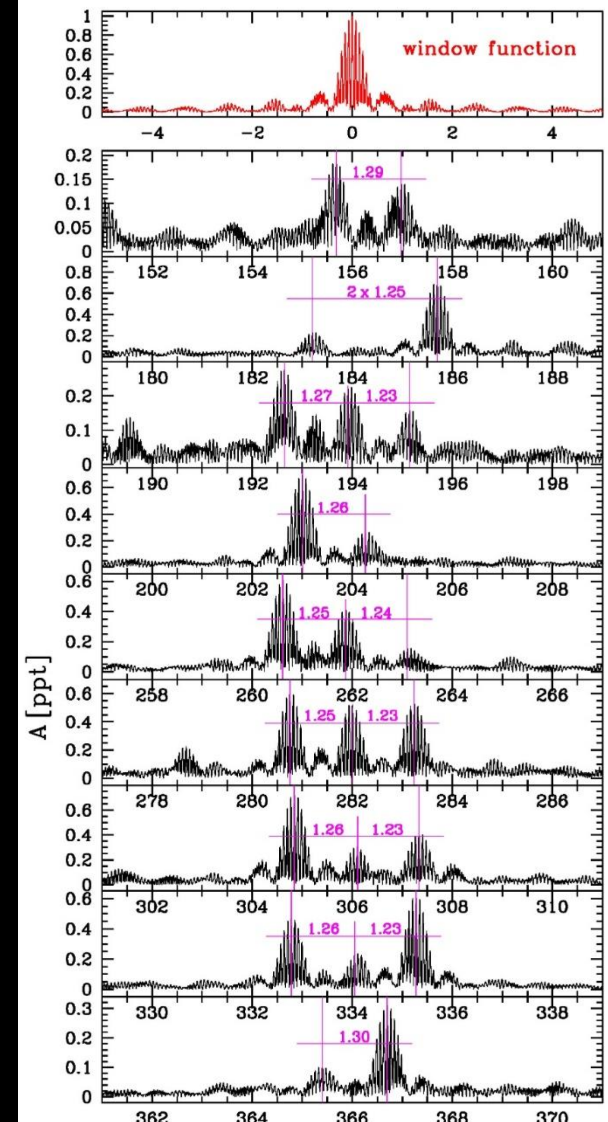
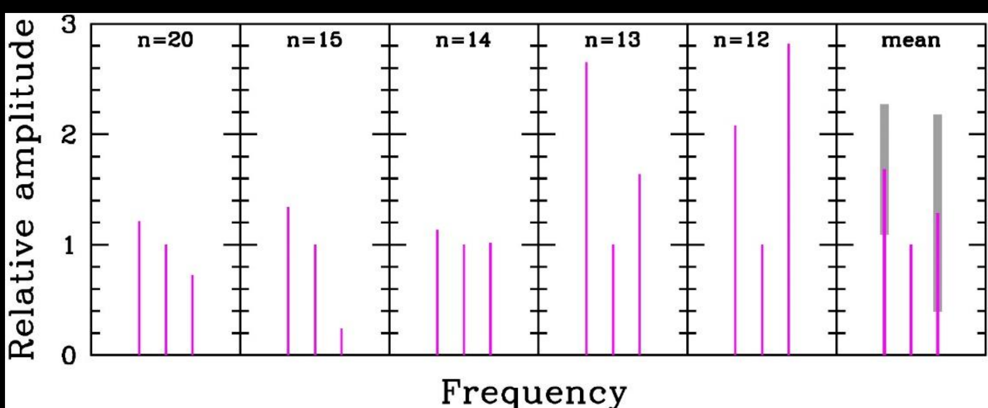
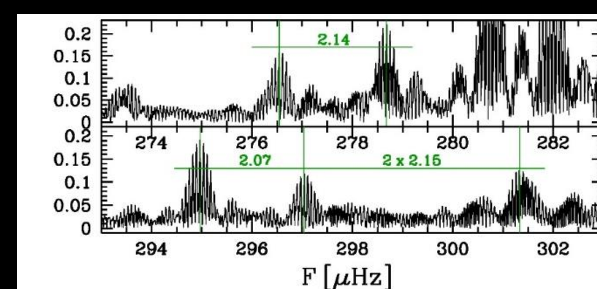




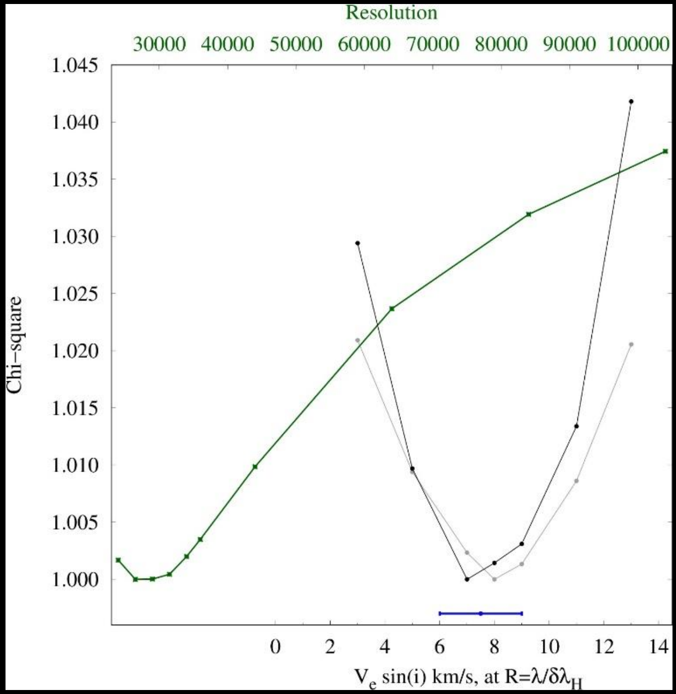
l=1 triplets

l=2 quintuplets



Surface rotation rate

(from HR spectroscopy with HERMES@Mercator)



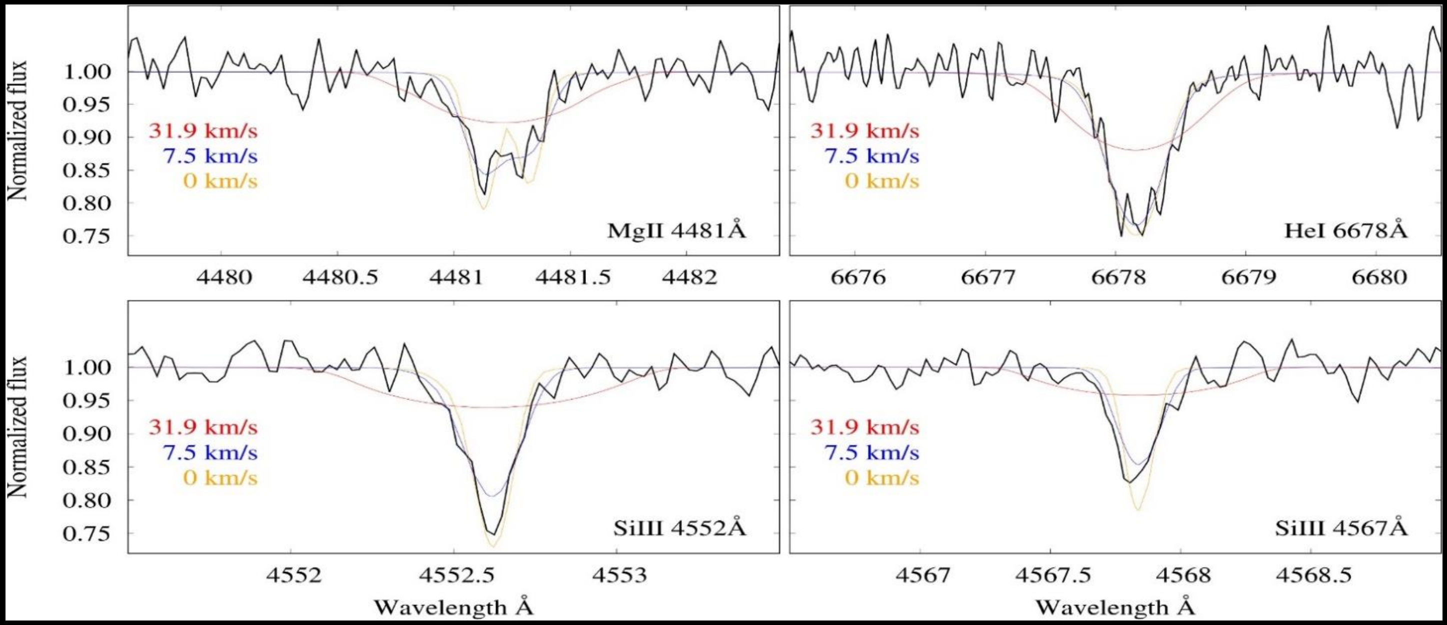
33 from 64 HR spectra near orbital phase 0.25 or 0.75 were selected (to minimize orbital broadening) and used to analyze rotational profiles.

From single line fits we can rule out synchronous rotation with the binary orbit at 31.9 km/s, but we can not exclude rigid body rotation at 2.1 km/s.

However, using several metal lines we reach a χ^2 minimum at **v sin *i* = 7.5 ± 1.5 km/s** that would correspond to **$P_{rot} \cong$ 1.3 days** at the stellar surface (assuming i=65°).

metal abundances from HERMES

Element	$\log nX/nH$	$\log \epsilon/\epsilon_\odot$
C	-4.44 ± 0.16	-0.74
N	-4.49 ± 0.03	-0.29
O	-4.44 ± 0.08	-1.20
Ne	-4.29 ± 0.25	-0.28
Mg	-5.23 ± 0.11	-0.72
Si	-5.54 ± 0.12	-1.16
Fe	-4.30 ± 0.20	0.39



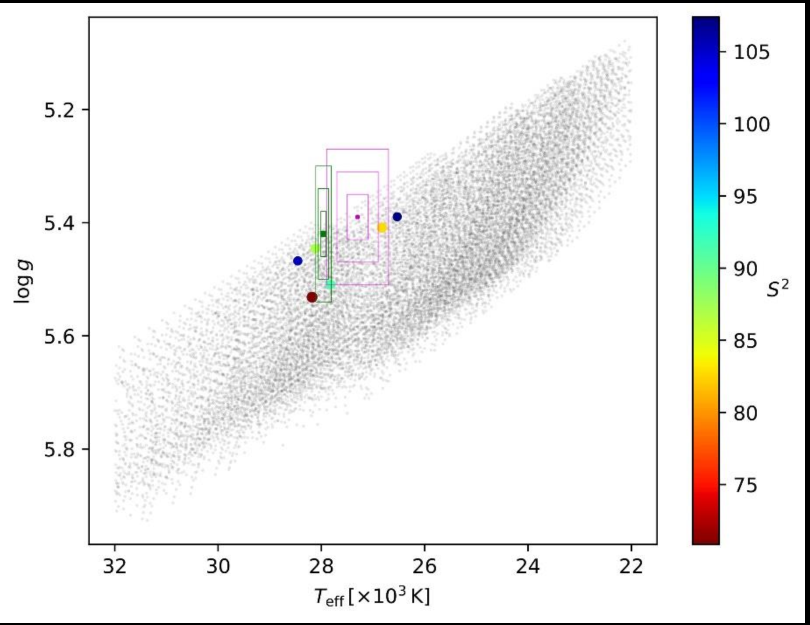
SED + asteroseismic analysis

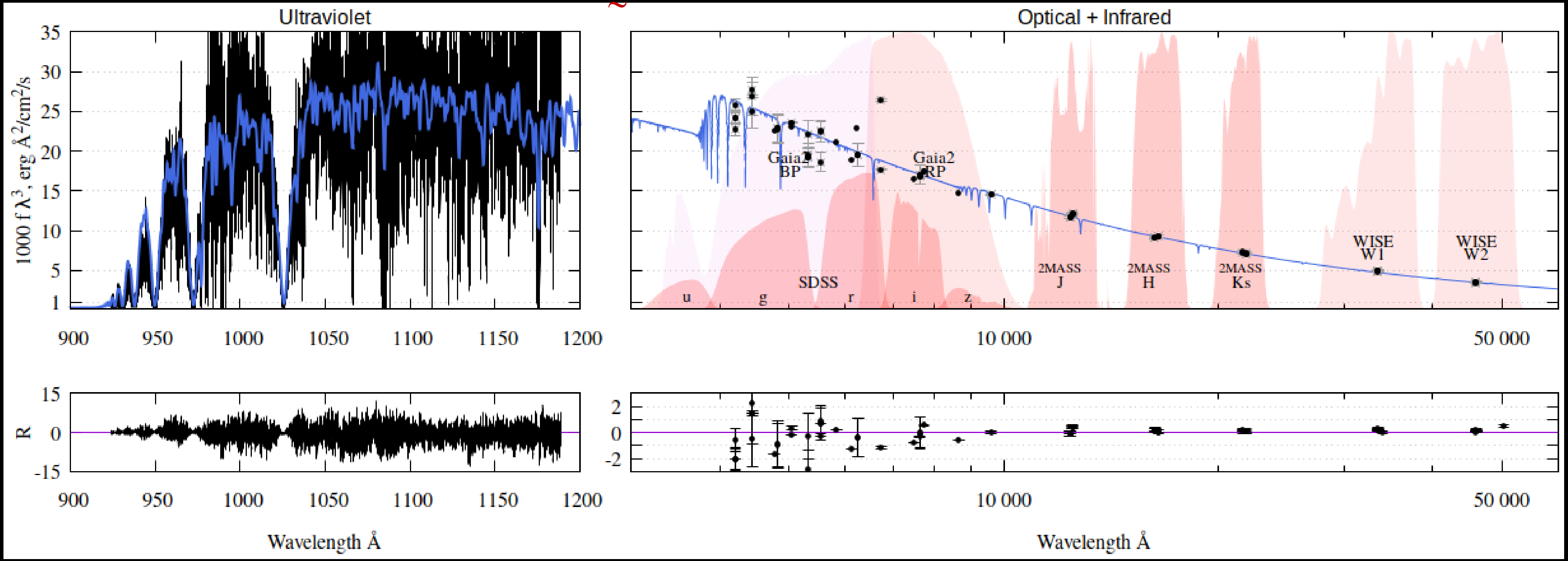
- From SED+Gaia EDR3: d=256.5±2.6 pc, $R=0.209\pm0.005\ R_{sun}$, $L=24.0\pm1.1\ L_{sun}$, $M=0.42\pm0.04\ M_{sun}$

  Moreover, SED compatible with single sdB

  ► secondary must be a dM with Teff $\lesssim$ 4000 K

- from asteroseismic analysis (MESA+GYRE):
  M_{env}=0.0006-0.0009 M_{sun}, Y_c=0.3-0.1
  M_i=1.1-1.2 M_{sun}, Z_i=0.010-0.015 , Age=5.4-7.3 Gyr

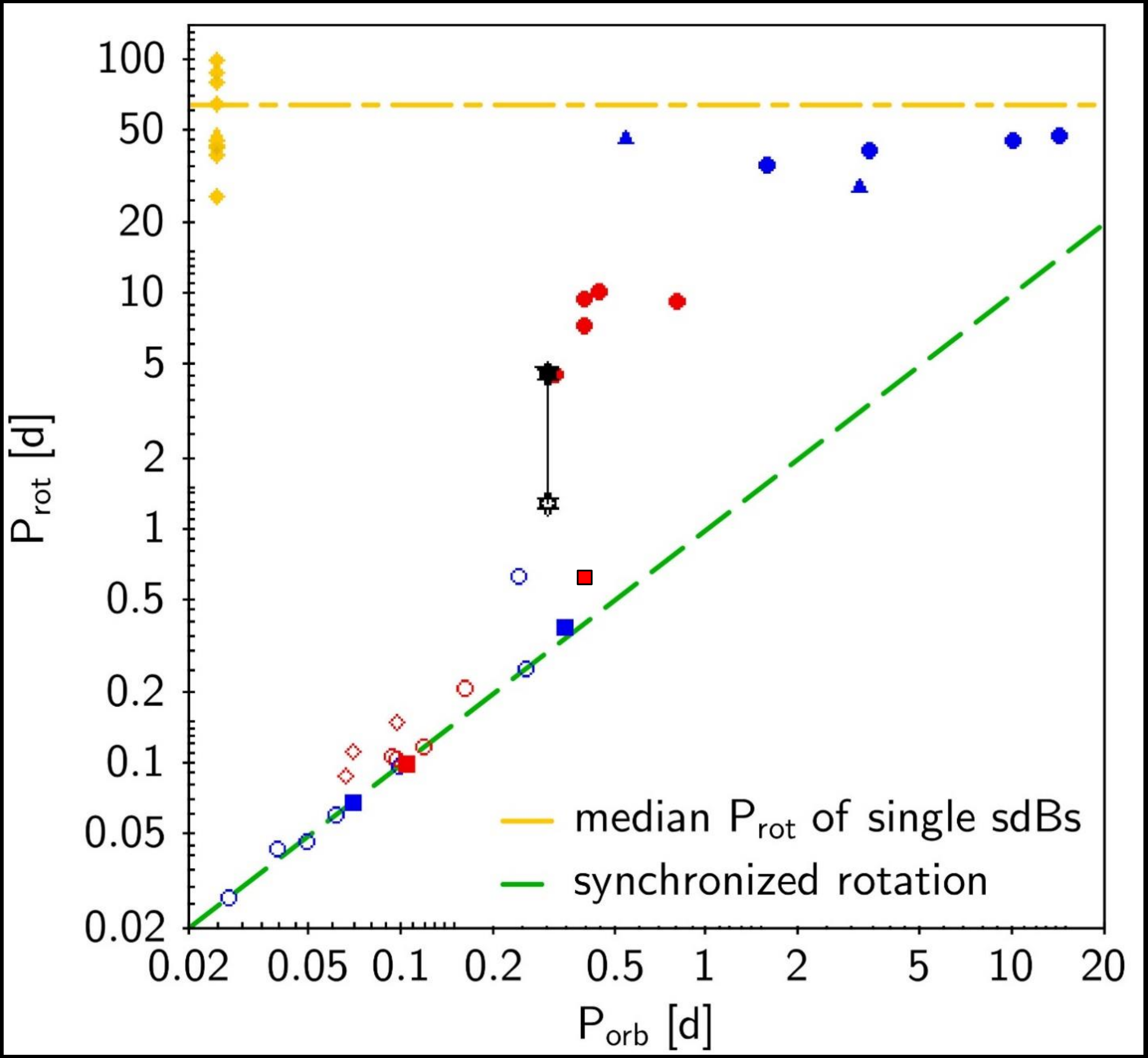




TIC 137608661's characterization: summary

	sdB	dM	binary
d (pc)			256.5±2.6 (EDR3)
P_{orb} (d)			0.300
i (°)			65^{+10}_{-20} (asteroseis.)
$P_{rot\text{-}core}$ (d)	4.6±0.1 (asteroseismology)		
$P_{rot\text{-}surf.}$ (d)	~1.3 (spectr.)		
Teff (K)	27300±200 (spectr.)	~2750 (Baraffe models)	
log g	5.39±0.04 (spectr.)		
log nHe/nH	-2.95±0.05 (spectr.)		
R (Rsun)	0.209±0.005 (d+SED)	~0.12 (Baraffe models)	
M	0.419±0.041 Msun (logg+R)	93-105 Mjup (mass ratio + i)	
L (Lsun)	23.98±1.09 (d+SED)	~0.00076 (Baraffe models)	
M_{env} (Msun)	0.0006–0.0009 (asteroseis.)		
Y_c	0.3 – 0.1 (asteroseis.)		
$M_{initial}$ (Msun)	1.1–1.2 (asteroseismology)		
$Z_{initial}$	0.010–0.015 (asteroseis.)		
Age (Gy)			5.4–7.3 (asteroseis.)

TIC 137608661 in context:
synchronized vs non-synchronized sdB+dM / sdB+WD



Red symbols: sdB+dM

filled circles: P_{rot} from *g*-modes
filled squares: P_{rot} from *p*-modes
empty circles: P_{rot} from spectral line broadening (SLB)
empty diamonds: P_{rot} from SLB and BD companion

Black: TIC 137608661

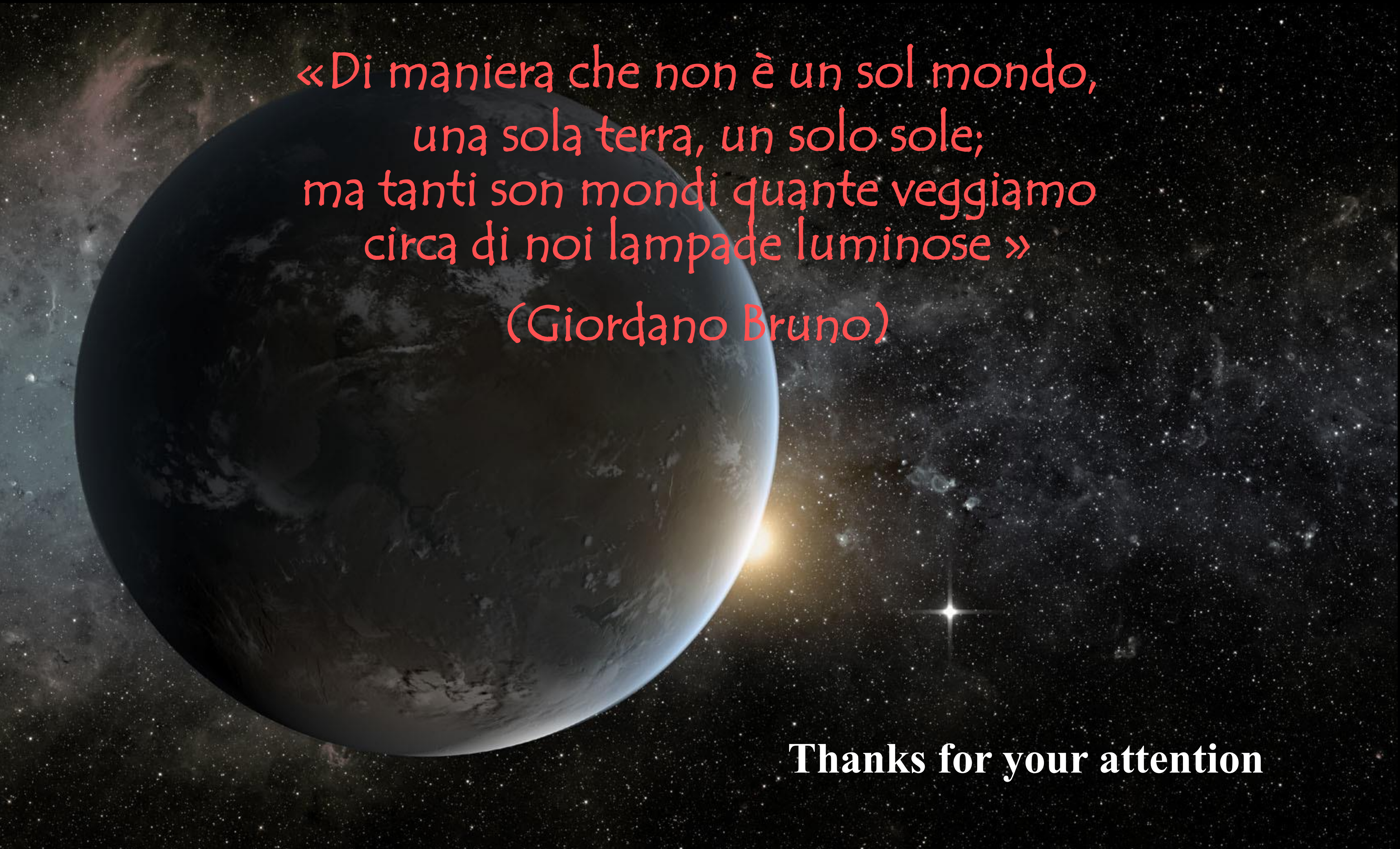
filled star: P_{rot} in deep layers from *g*-modes
Empty star: P_{rot} in surface layers from SLB

Blue symbols: sdB+WD

filled circles: P_{rot} from *g*-modes (triangles=lower limit)
filled squares: P_{rot} from *p*-modes
empty circles: P_{rot} from spectral line broadening

Yellow symbols: single sdB stars

P_{rot} from *g*-modes (triangles=lower limit)


«Di maniera che non è un sol mondo,
una sola terra, un solo sole;
ma tanti son mondi quante veggiamo
circa di noi lampade luminose »
(Giordano Bruno)
Thanks for your attention