The Extreme Horizontal Branch Stars in ω Cen: a population apart?

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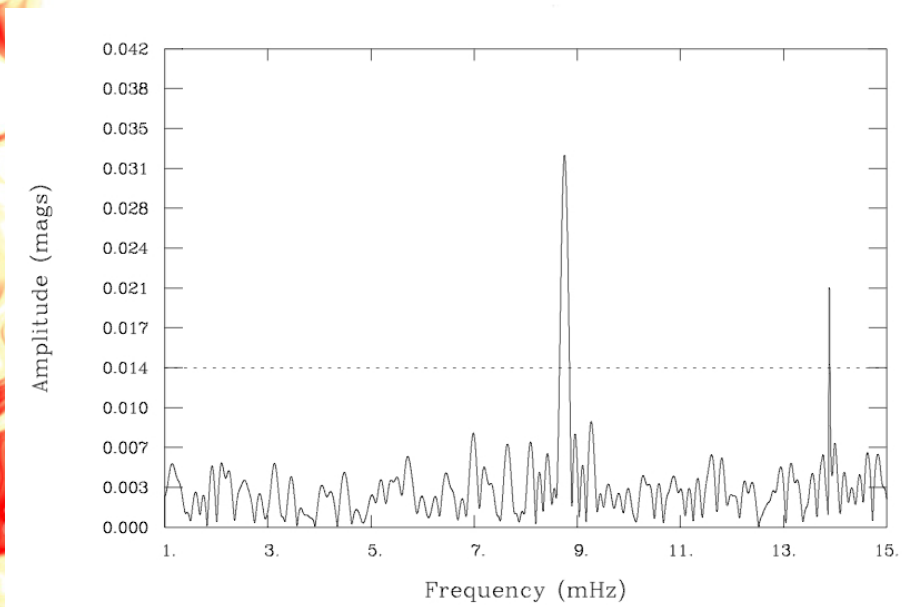
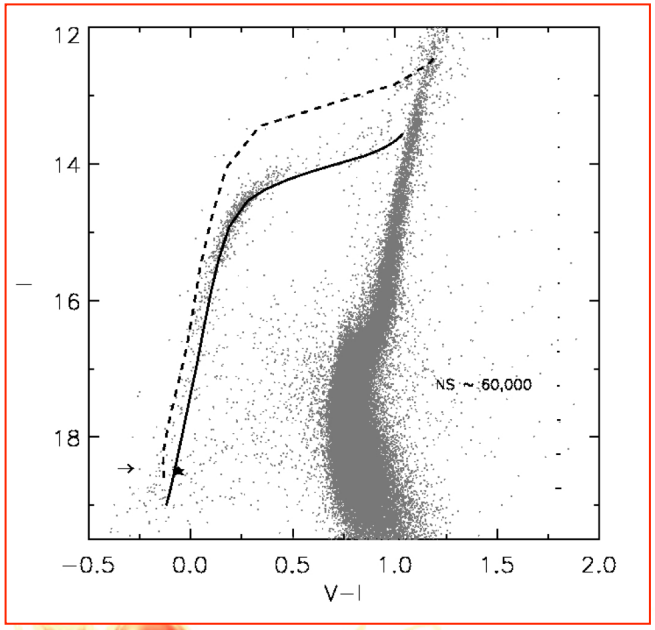
Our ω Cen survey

Motivated by the serendipitous discovery of a candidate rapid EHB pulsator based on 2 hours of SUSI2@NTT data in 2008





Why ω Cen?

- Has a known spread of metal abundances, likely the remnant of a dwarf galaxy

- One of the closest GCs, with low reddening
- $(m-M)_V$=13.97, the EHB is found around V~17.5-19.5
- Most massive GC with a huge sample of ~900 EHB stars
- WFI/ACS catalogue available – can use this to select EHB stars (Castellani+ 2007)
- FLAMES-GIRAFFE spectroscopy available for a sub-sample of EHB stars (Moehler+ 2011)

Our ω Cen survey

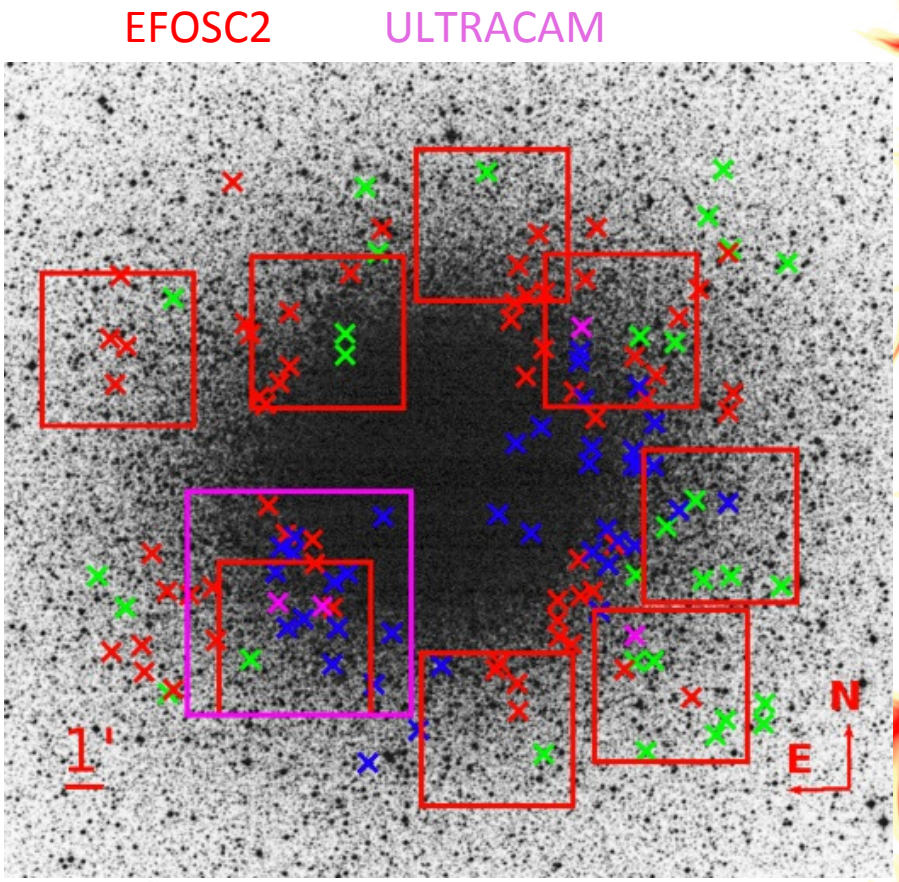
1) Fast time-series photometry observations with EFOSC2 (2009, 2013) and ULTRACAM (2011) @NTT

2) Medium-resolution spectroscopy from FORS (2008, 2011, 2013) & FLAMES (2005, 2006) @ VLT

3) Radial velocity survey with VIMOS (2014,2015) @VLT

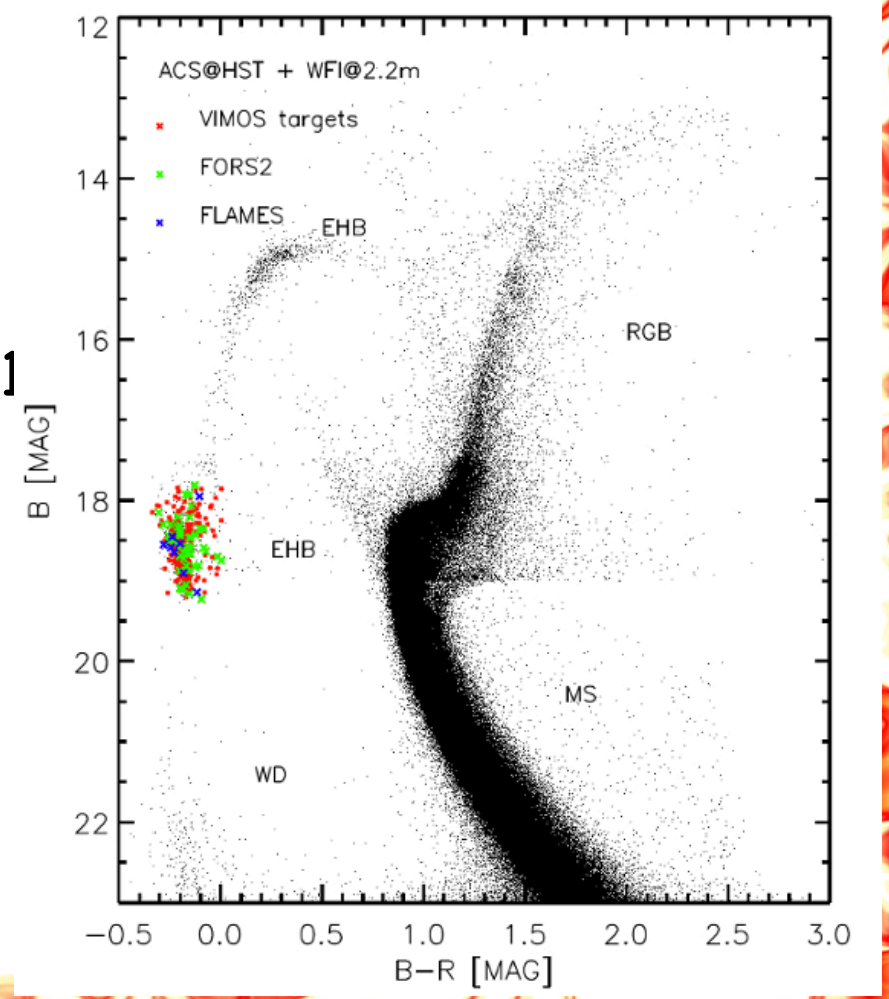
Time-series photometry: observations

- EFOSC2:
  - Bessel *B*
  - cycle time 40 s
  - 45 h total: 2.5–11 h per field
- ULTRACAM:
  - u′g′r′
  - cycle time 6 s
  - 50 h total



Time-series photometry: EHB statistics

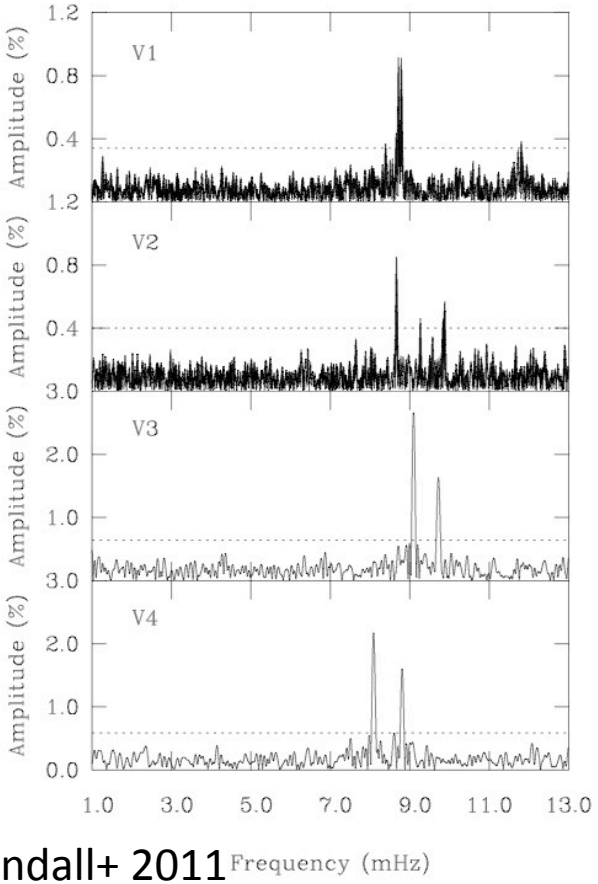
- Selection of EHB stars based on colour-magnitude cut in combined ACS/WFI catalogue
- Detected total of 293/441 EHB candidates
- Useful light curves for 142 EHB stars
- Can exclude pulsations down to 0.5% for 57 targets
- 5 short-period pulsators



Pulsators

Longer time-series -> more fine structure in FT

EFOSC2 sample



Randall+ 2011

	Period (s)	Frequency (mHz)	Amplitude (%)	S/N
V1				
f_1	114.705±0.005	8.7180±0.0004	0.88±0.07	10.4
f_{1+}	113.727±0.005	8.7930±0.0004	0.91±0.07	10.7
f_{1-}	115.300±0.011	8.6730±0.0004	0.43±0.07	5.1
f_2	119.111±0.012	8.3955±0.0009	0.41±0.07	4.8
f_5	84.652±0.006		0.40±0.07	4.7
V2				
f_1	115.413±0.006		0.86±0.08	8.6
f_2	101.168±0.007	9.8845±0.0007	0.54±0.08	5.4
f_3	107.898±0.010	9.2602±0.0009	0.45±0.08	4.5
V3				
f_1	109.908±0.021	9.0985±0.0002	2.69±0.13	16.8
f_2	102.865±0.030		1.68±0.13	10.5
V4				
f_1	123.602±0.035		2.20±0.12	14.9
f_2	113.488±0.040	8.8115±0.0031	1.65±0.12	11.1

30 h time-series

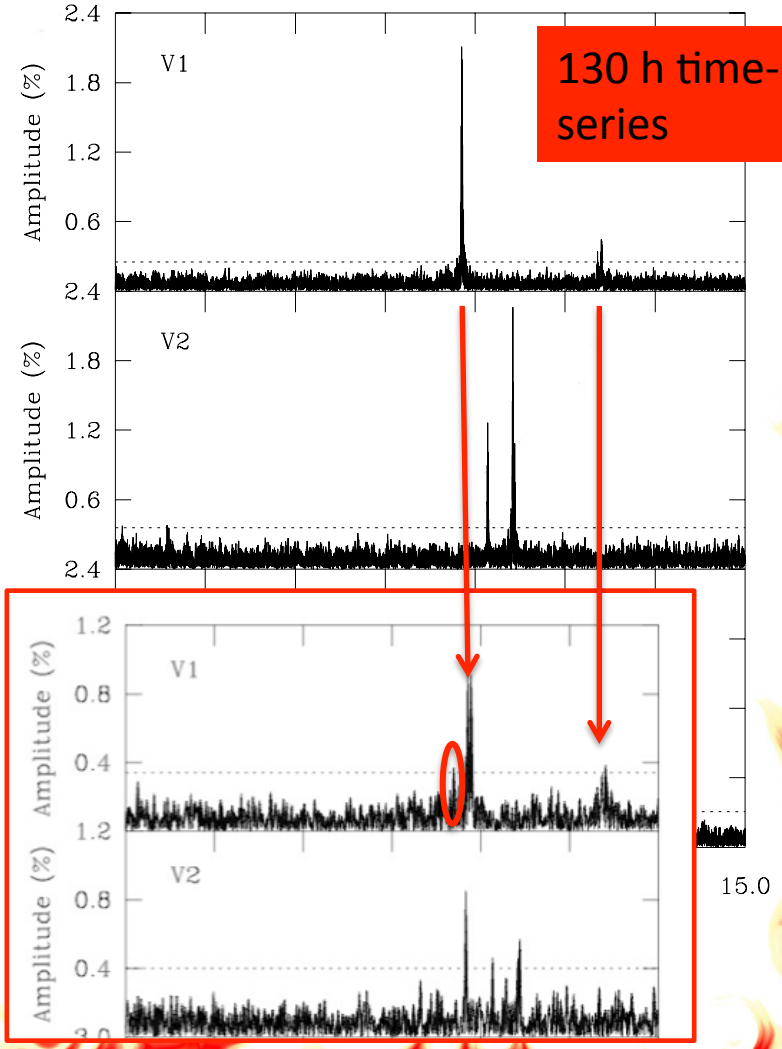
3-4 h time-series

Pulsators

Strong amplitude variations!!!

	Period (s)	Frequency (mHz)	Amplitude (%)
V1			
1	115.0	8.70	2.4
2	114.7	8.72	2.2
3	84.7	11.81	0.60
4	114.4	8.74	0.47
5	84.3	11.86	0.36
V2			
1	101.7	9.83	2.5
2	107.8	9.28	1.2
3	101.2	9.88	1.4

V1			
f_1	114.705±0.005	8.7180±0.0004	0.88±0.07
f_{1+}	113.727±0.005	8.7930±0.0004	0.91±0.07
f_{1-}	115.300±0.011	8.6730±0.0004	0.43±0.07
f_2	119.11[illegible]±0.012	8.3955±0.0009	0.41±0.07
f_5	84.652±0.006	11.8131±0.0009	0.40±0.07
V2			
f_1	115.413±0.006	8.6645±0.0005	0.86±0.08
f_2	101.168±0.007	9.8845±0.0007	0.54±0.08
f_3	107.898±0.010	9.2602±0.0009	0.45±0.08



Pulsators

Strong amplitude variations!!!

	Period (s)	Frequency (mHz)	Amplitude (%)
V1			
1	115.0	114.98 and 114.92 s peaks	
2	114.7	114.69, 114.64 and 114.57 s peaks	
3	84.7	84.73, 84.59 s peaks	
4	114.4		
5	84.3		
V2			
1	101.7	101.68 and 101.63 s peaks	
2	107.8	107.78 and 107.77 s peaks	
3	101.2	101.27 and 101.22 s peaks	

Main peaks show fine frequency splitting in the FT – caused by amplitude variations?

V1			
f_1	114.705±0.005	8.7180±0.0004	0.88±0.07
f_{1+}	113.727±0.005	8.7930±0.0004	0.91±0.07
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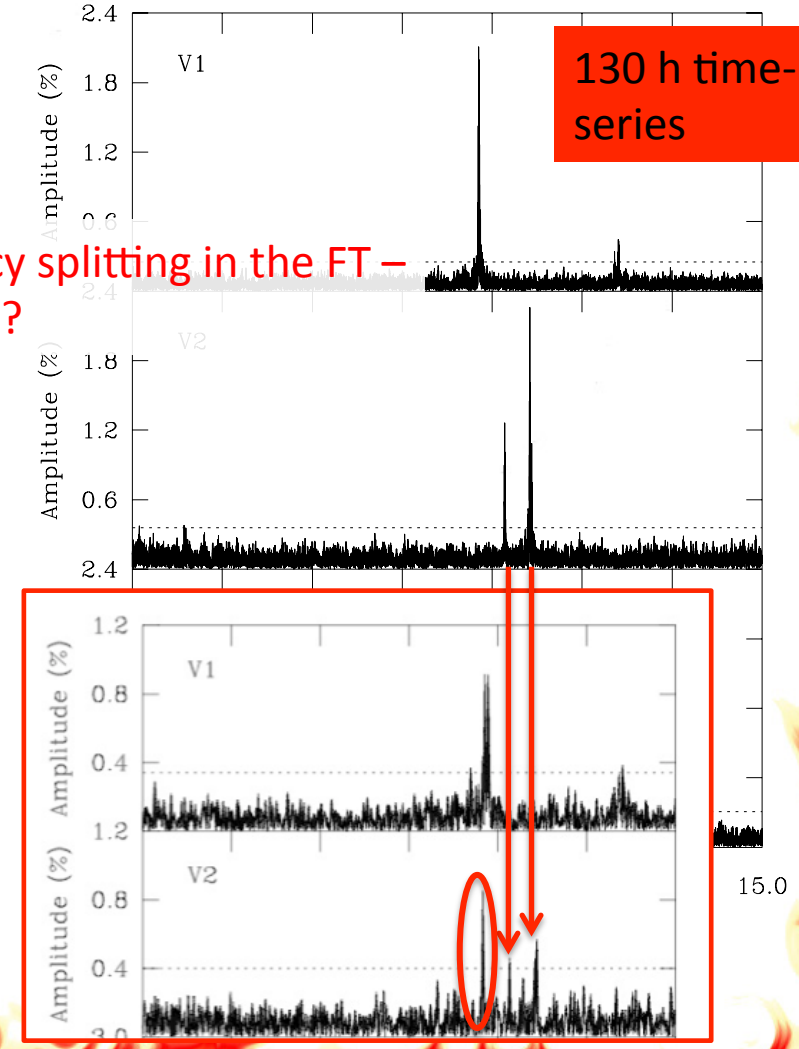
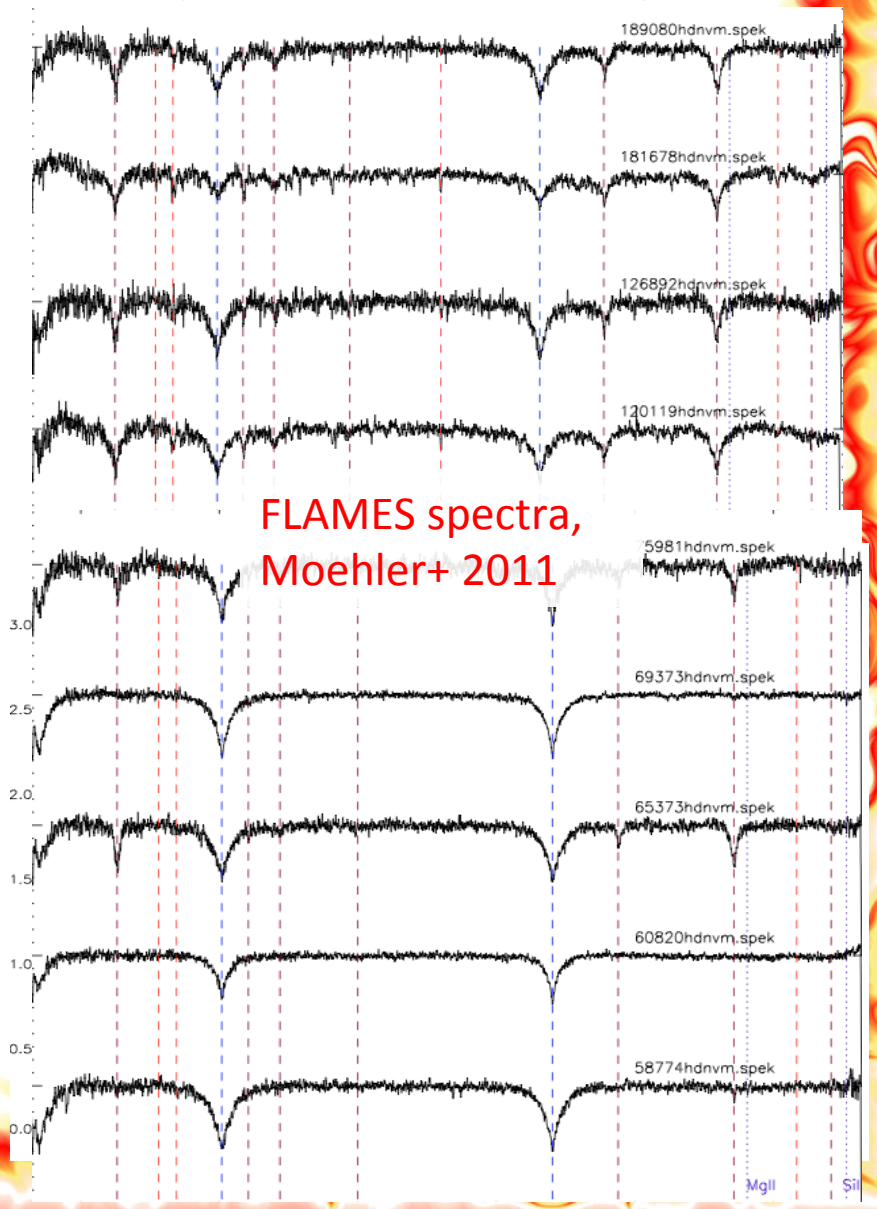
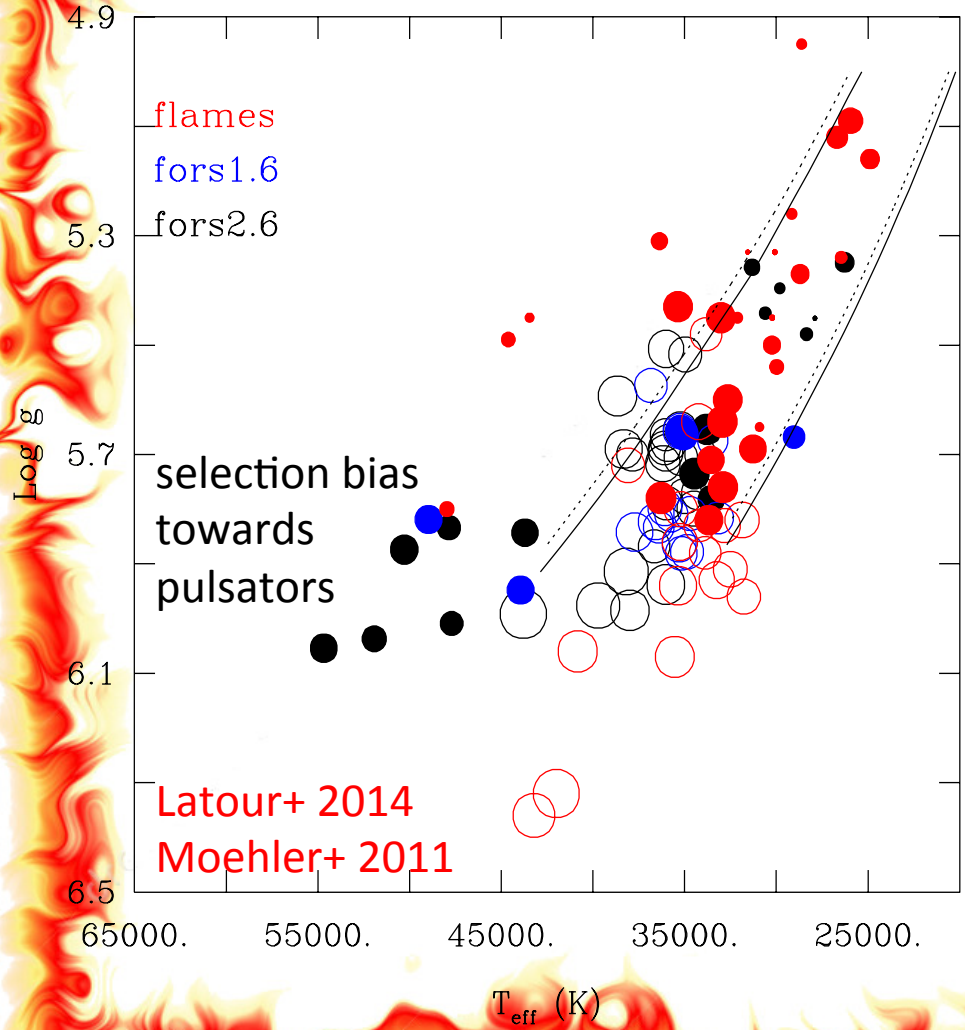


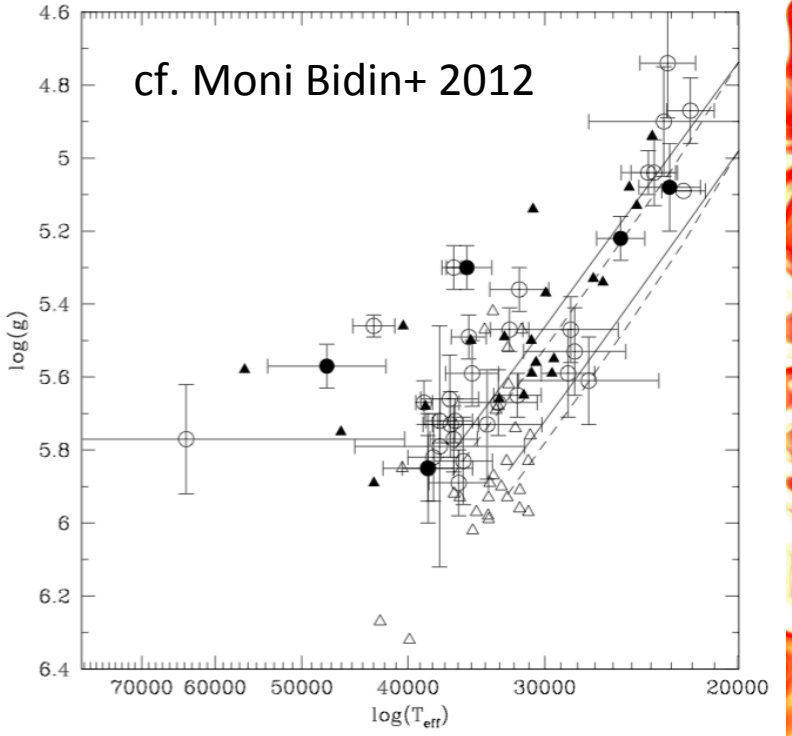
Medium-resolution spectroscopy

- Spectra for 97 EHB star candidates analysed in a homogeneous way (solar CNO in models)
- FORS2.6: 38 targets
- FORS1.6: 17 targets
- FLAMES: 48 targets (0.7 A resolution)
- Only "clean" non-contaminated spectra retained, small overlap between samples

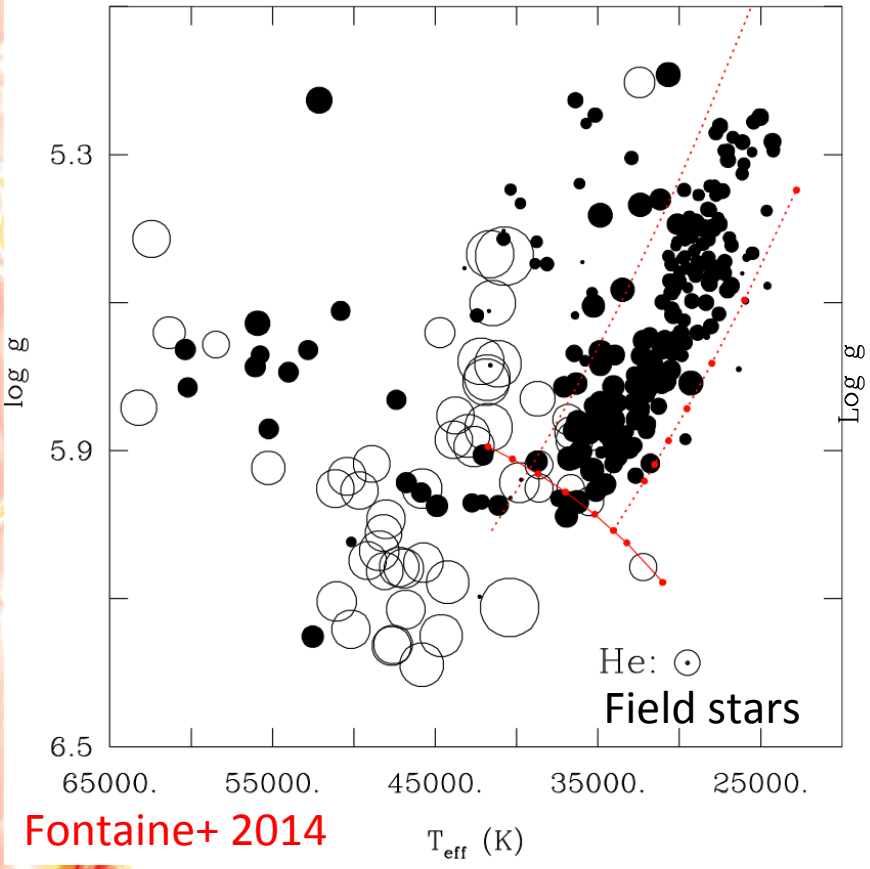


Atmospheric parameters



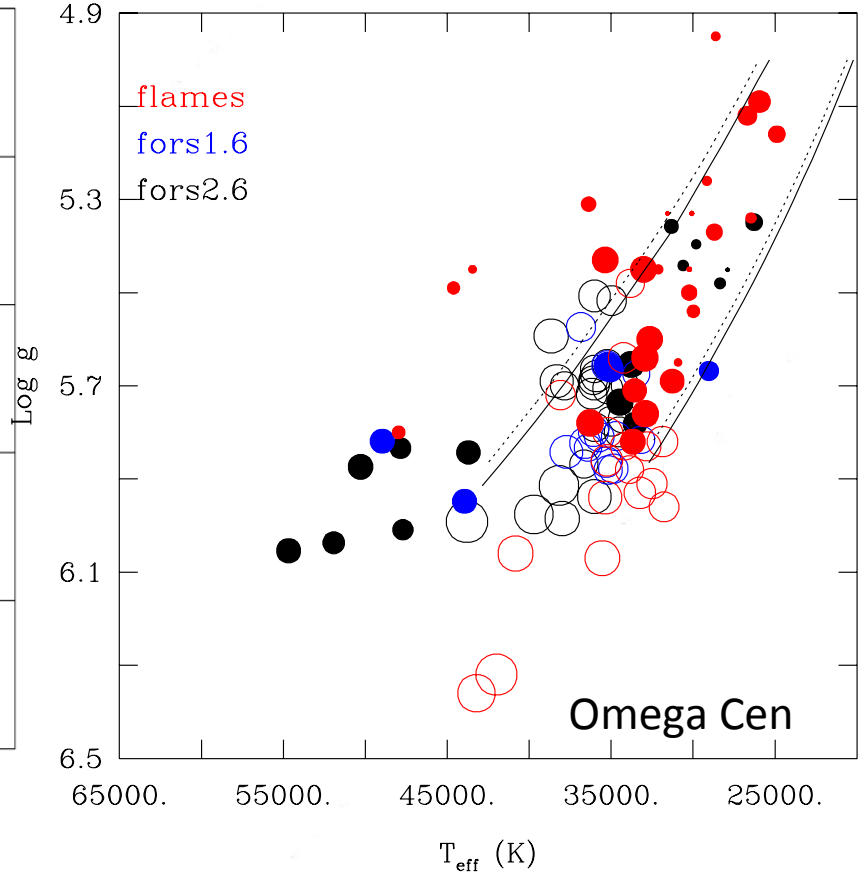


Field Vs. omega Cen



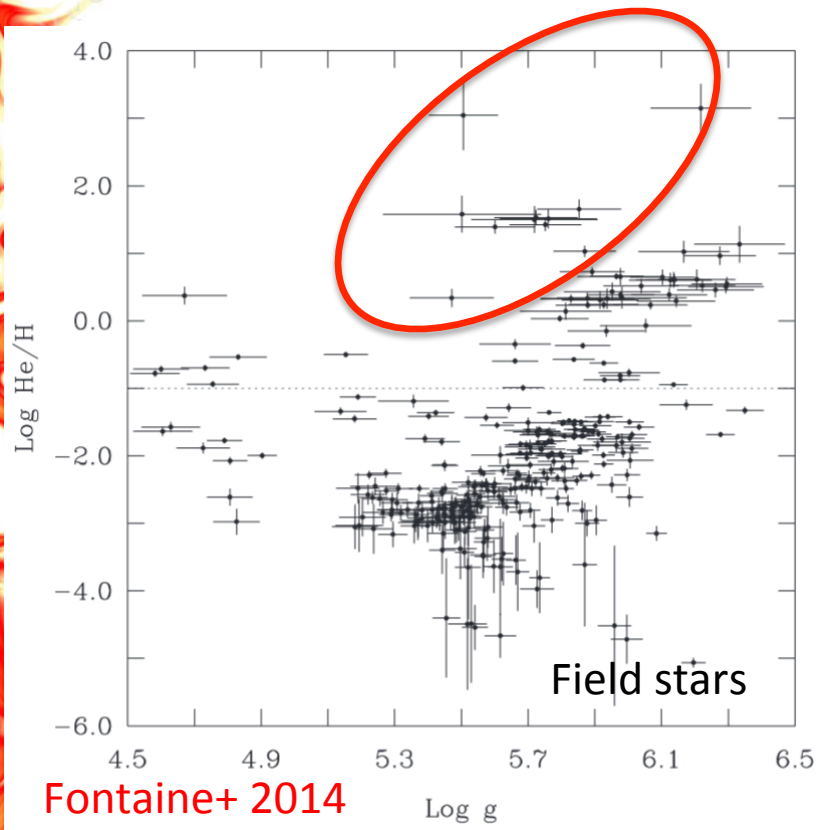
Fontaine+ 2014

- Dominated by H-sdBs ~25,000-35,000 K
- Clustering of He-rich stars ~40,000-50,000 K
- Hot H-sdOs at log g ~ 5.7



- Dominated by He-rich sdOBs
- Clustering of He-rich stars ~30,000-40,000 K
- Absence of VERY He-rich stars
- Hot H-sdOs at log g ~ 5.9

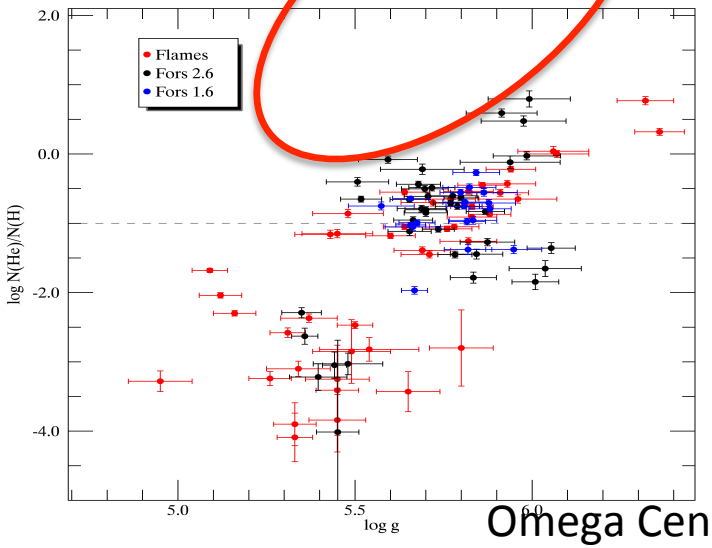
Field Vs. omega Cen



Fontaine+ 2014

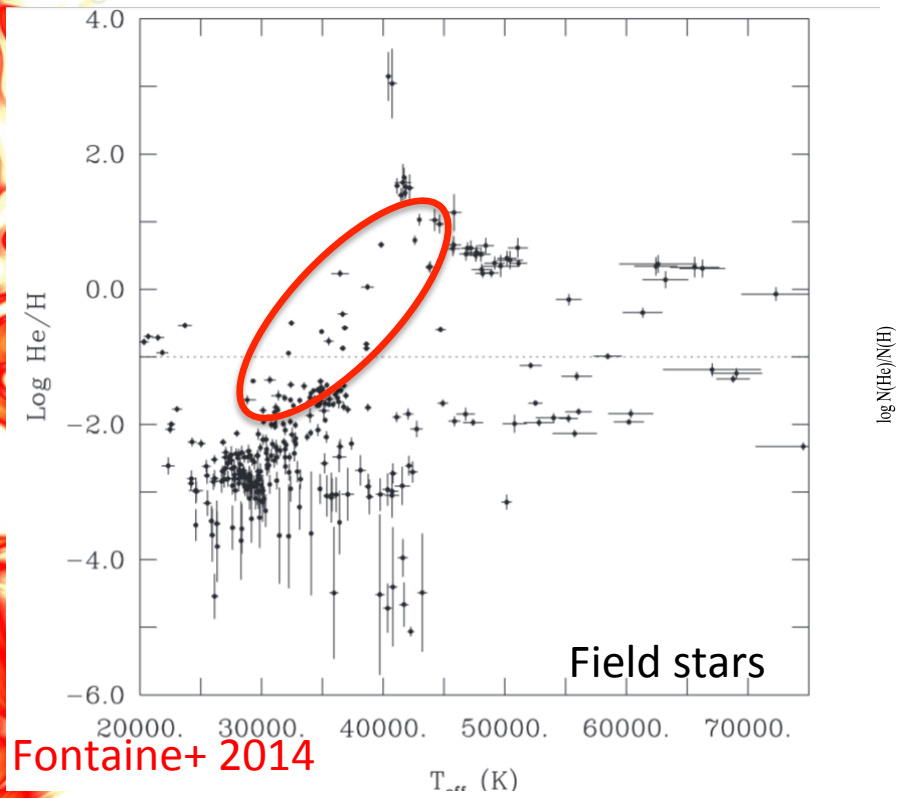
Distribution more complex in the field

No very He-rich stars!



Appear to have a ~linear relationship between He-abundance and log g

Field Vs. omega Cen



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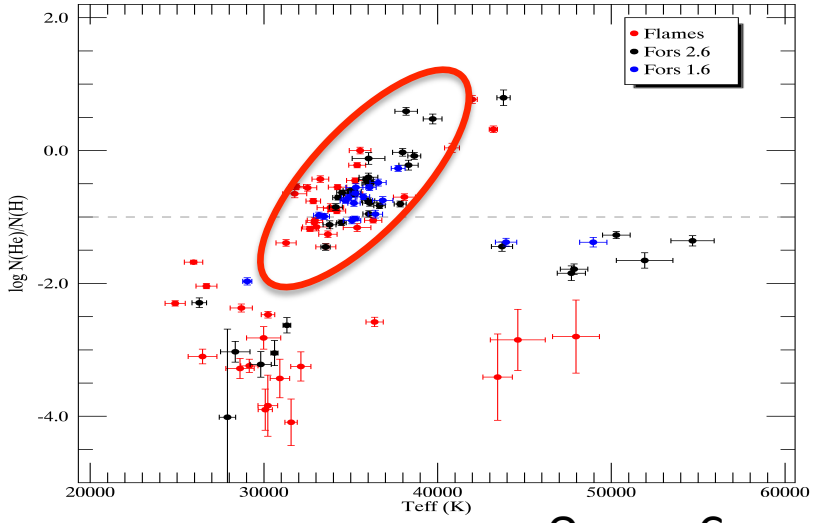
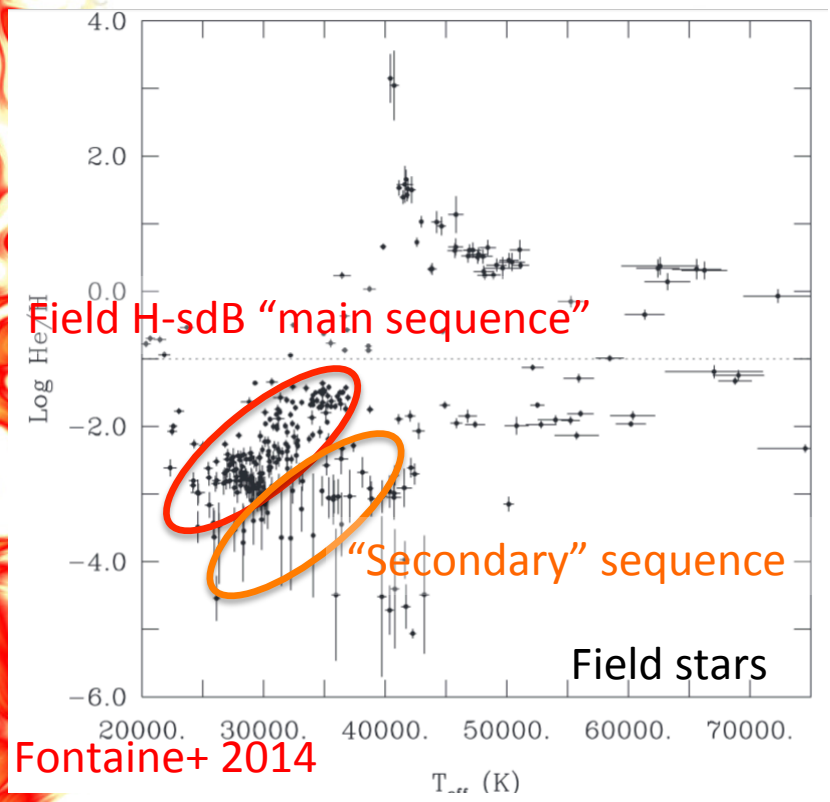


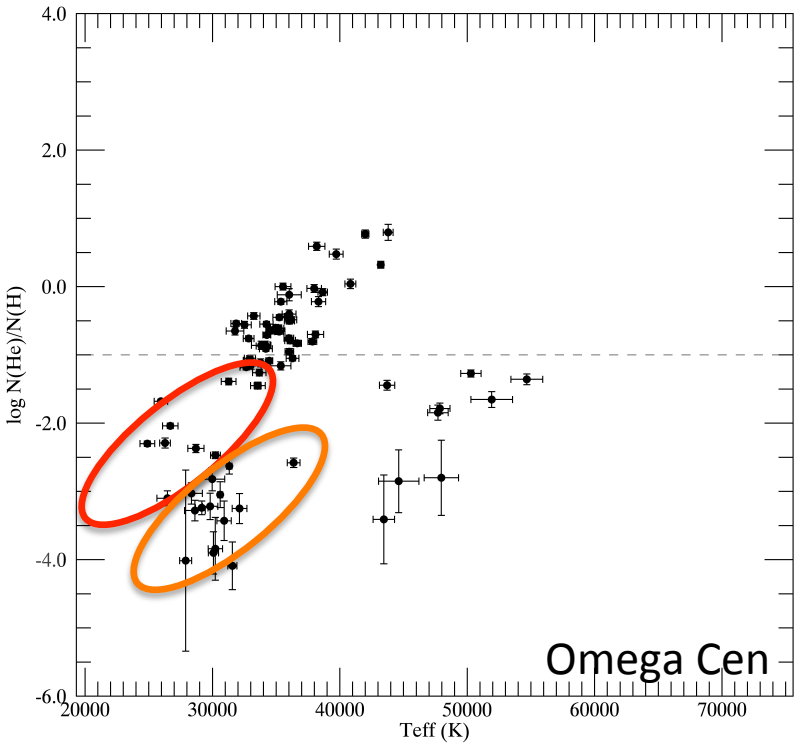
Some counterparts to the omega Cen He-rich sdOBs also found in the field – could these be the halo stars?

Similar population of He-rich stars found for NGC 2808 (Moehler+ 2004)

Field Vs. omega Cen



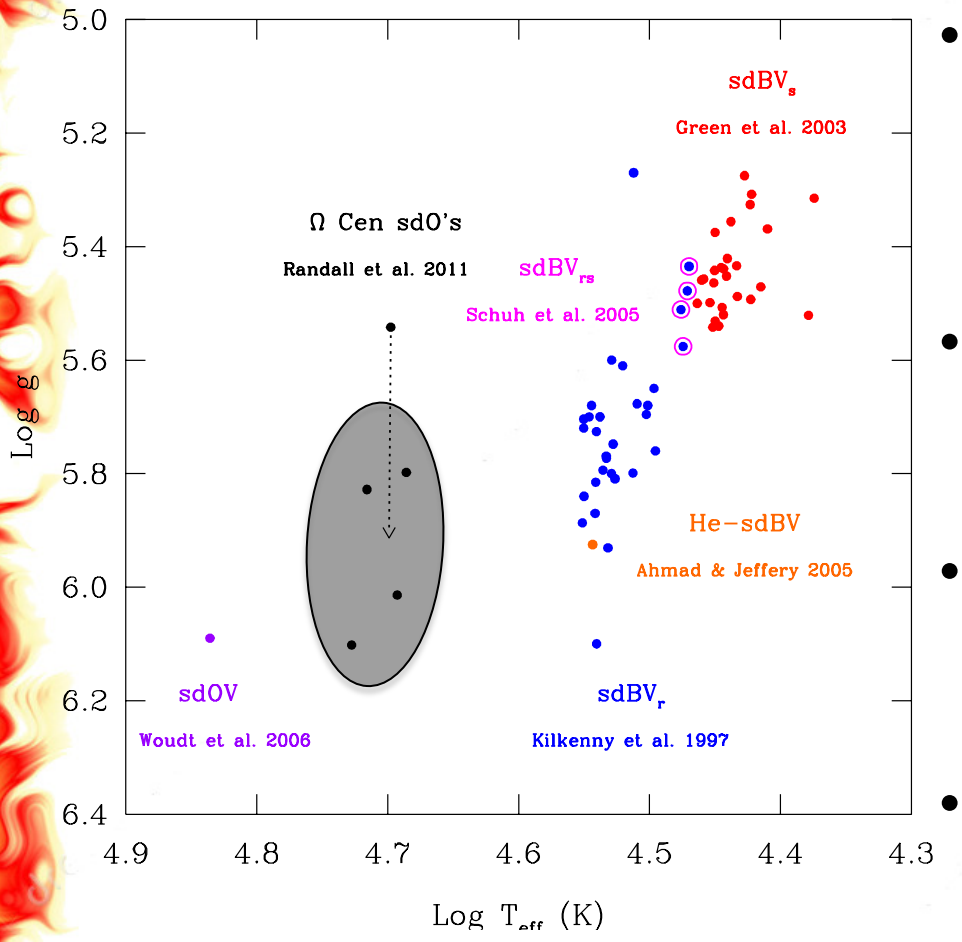
Fontaine+ 2014



~75% of H-sdBs are found along a well-defined sequence in He-abundance/T_{eff} space, ~25 % are found on a "secondary" sequence (e.g. Geier+ 2012)

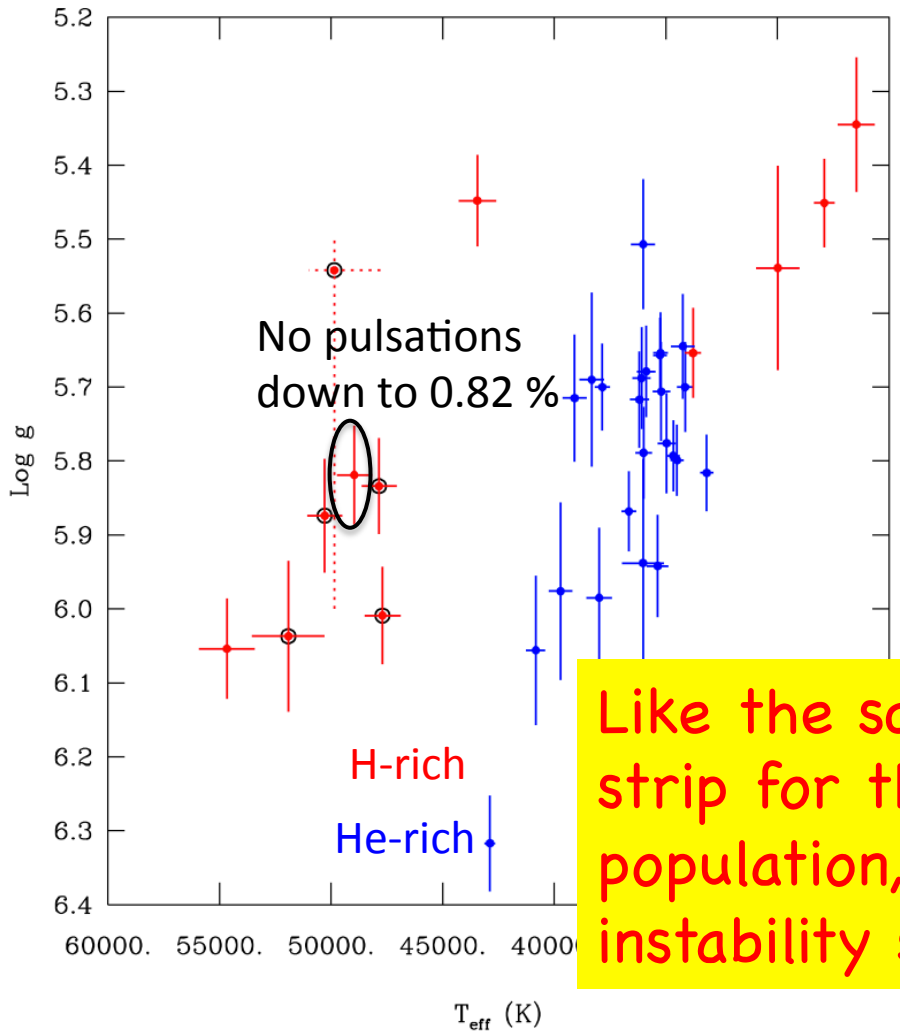
In omega Cen, it is the "secondary" He-poorer sequence that is more populated

A distinct class of pulsator



- Pulsators in omega Cen are a homogeneous group of H-rich sdOs at ~50,000 K with periods ~80-120 s
- No counterparts found among the field population (Johnson+ 2014)
- No counterparts to field pulsators found in omega Cen
- No counterparts among NGC2808 variables (Brown+ 2014)

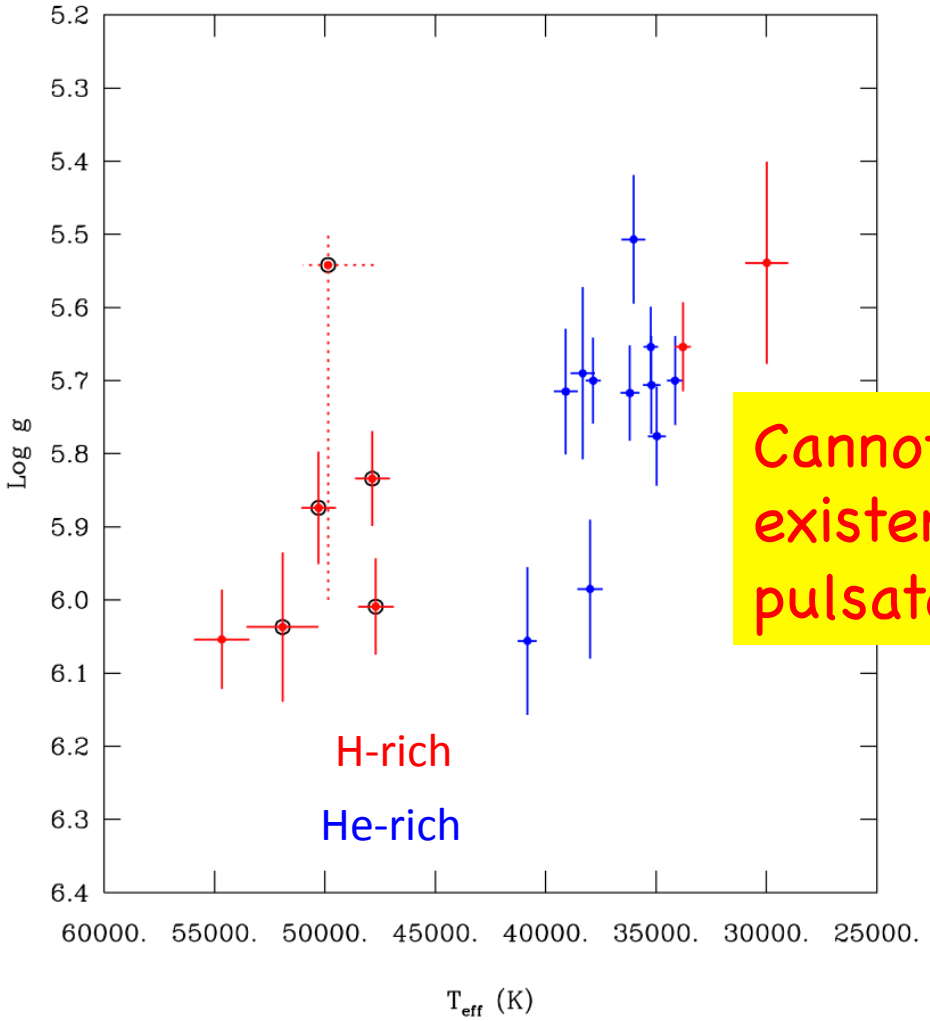
The ω Cen instability strip



3.7 σ < 1 %

Like the sdBVr instability strip for the field population, the ω Cen instability strip is not pure!!!

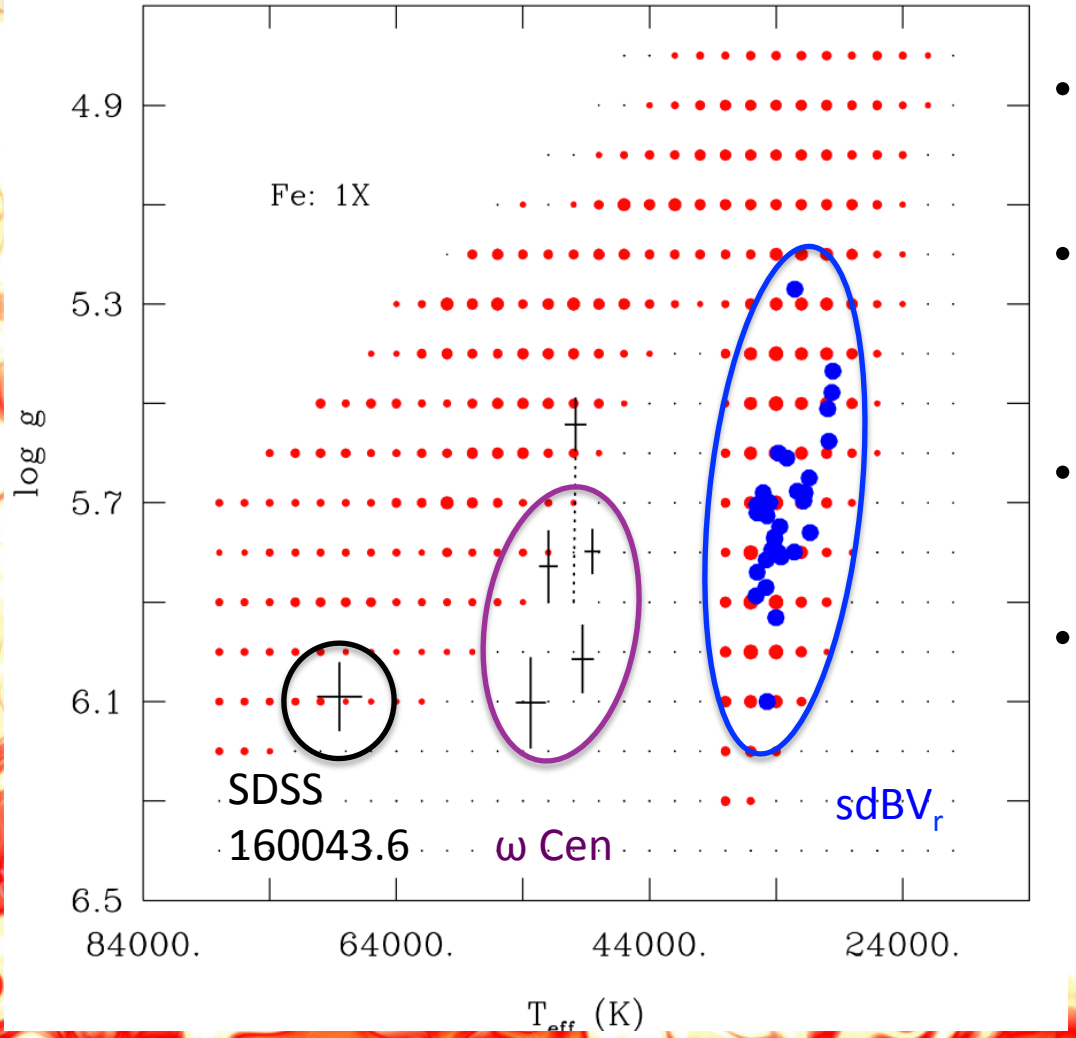
The ω Cen instability strip



3.7 σ < 0.5 %

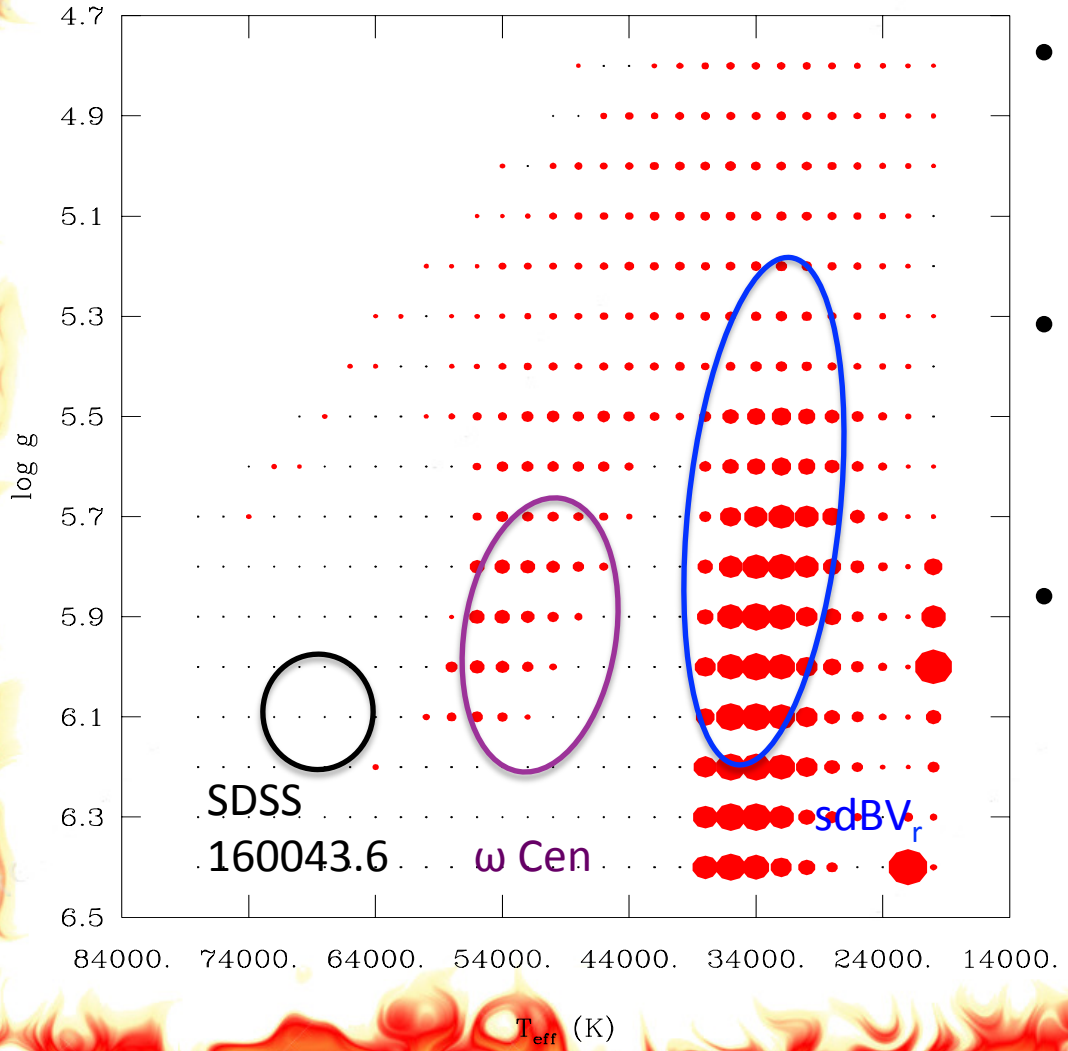
Cannot exclude existence of sdBV$_r$ pulsators in ω Cen!

Comparison with theory



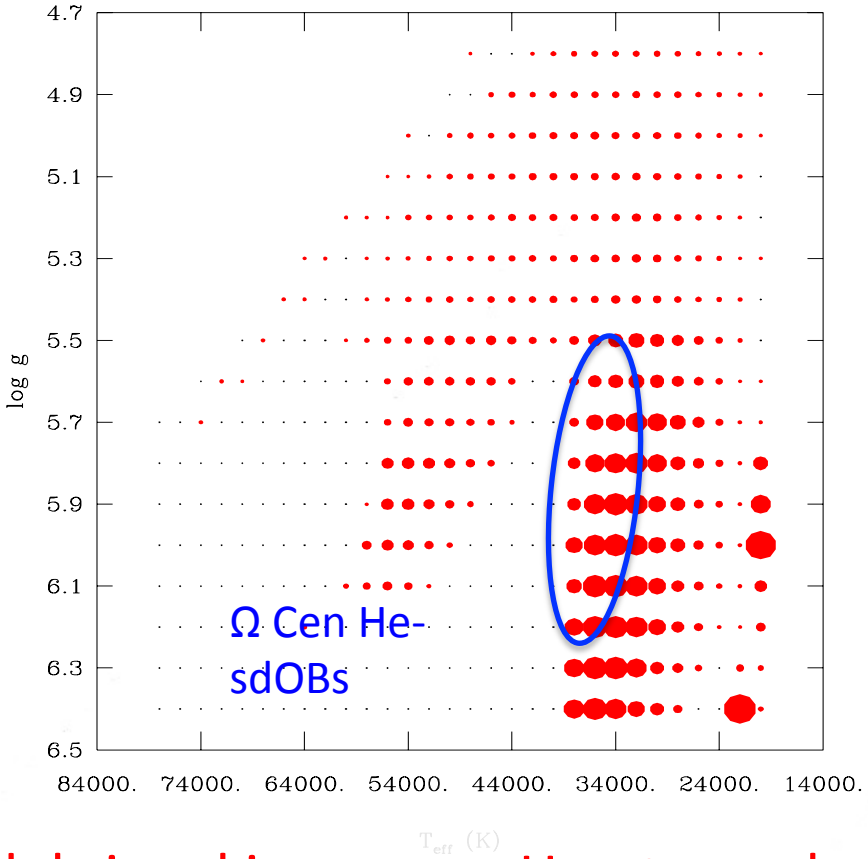
- Montreal 2nd generation models: Fe levitating in a pure H-background
- *p*- mode instability strip shows a jaw-like shape, extending to higher temperatures
- ω Cen pulsations likely also driven by Fe-related κ–mechanism
- Problems at the quantitative level – likely due to other heavy elements like Ni not being included in models

Comparison with theory

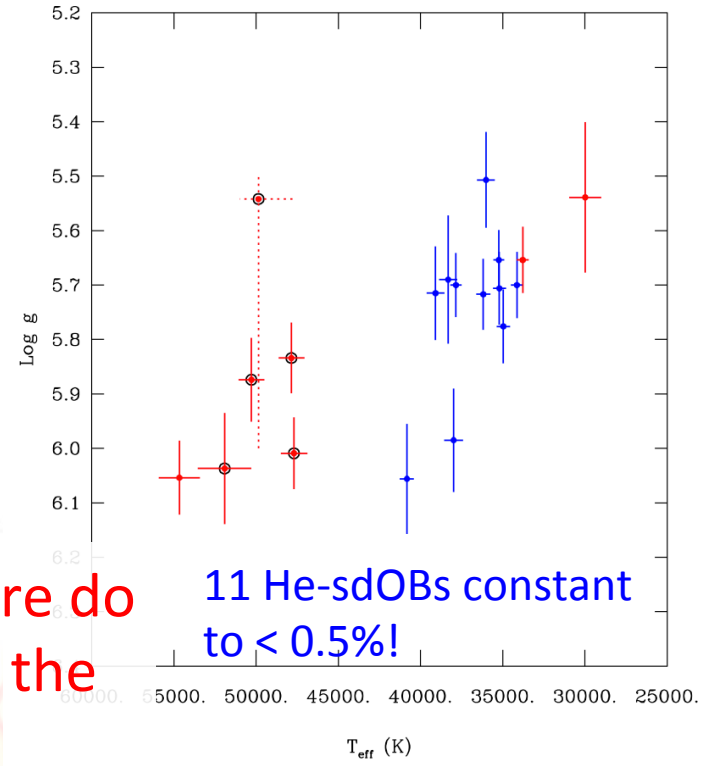


- New models with Fe levitating in a pure He-background
- sdO instability strip slightly closer to to that observed in ω Cen
- But what about SDSS – a He-rich star – pulsations can no longer be excited!?

Comparison with theory

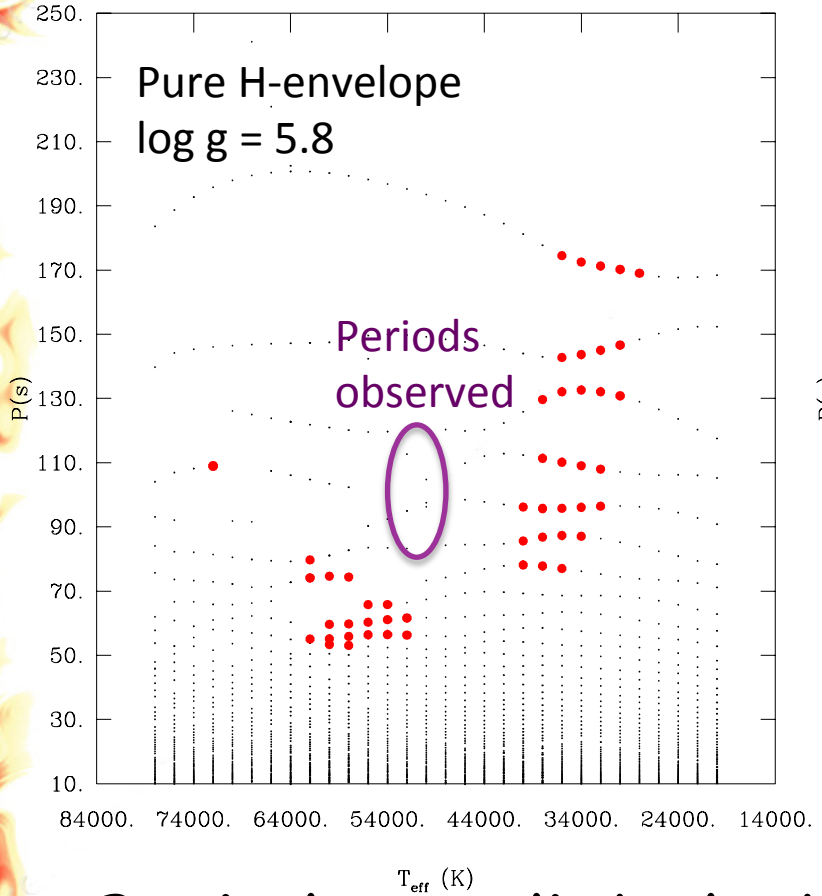


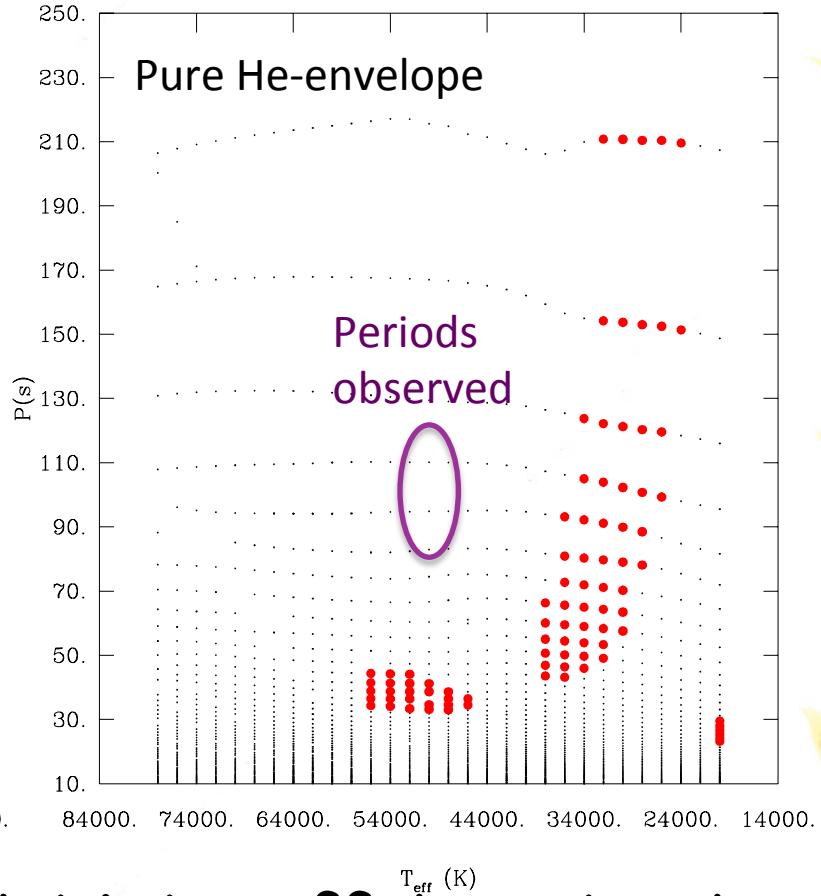
If we believe these models: where are the He-rich pulsators then?



Models invoking a pure He-atmosphere do not solve the instability problem – on the contrary!

Comparison with theory





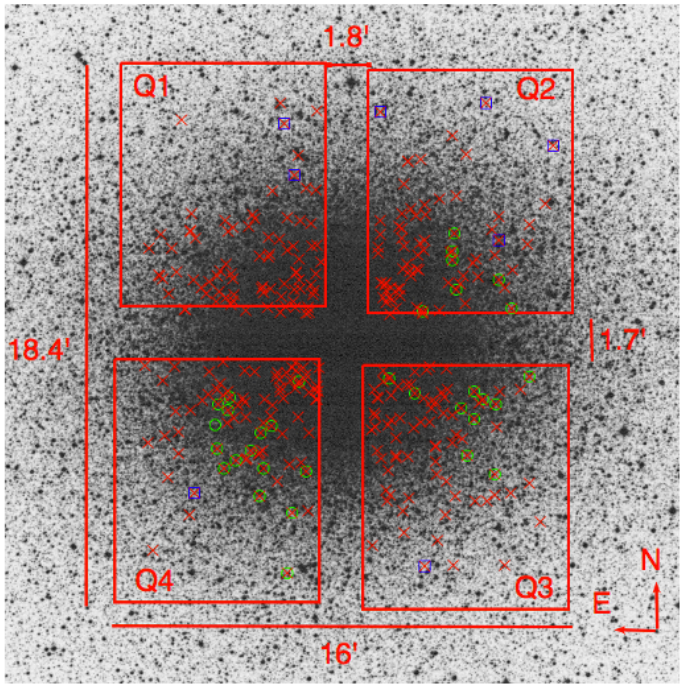
- Periods predicted at high Teff too short compared to those observed in omega Cen!

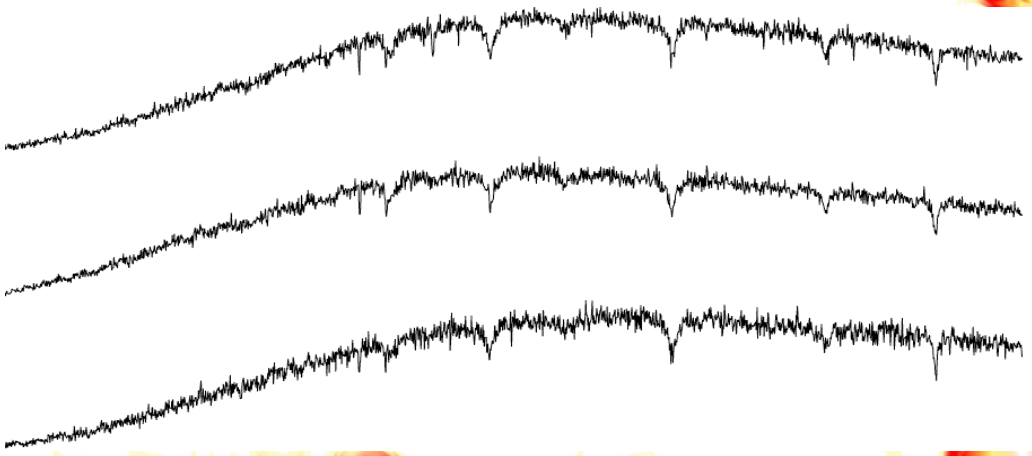
Radial velocity survey: motivation

- From radial velocity surveys of the field population 40-70% of sdBs are in close binaries (P~0.05-30 d) (e.g. Maxted+ 2001)
- These are post-common envelope systems with mostly white dwarfs, some late-type MS companions and sub-stellar companions
- A smaller fraction (30-40%) of sdOBs are thought to be in wide binaries (P~100+ days) with F-K type MS companions
- Searches for EHB binarity in Globular Clusters NGC 6752, M 80, NGC 5986 (Moni Bidin+ 2008, 2009) reveal a "low" binary fraction (just two binary candidates)

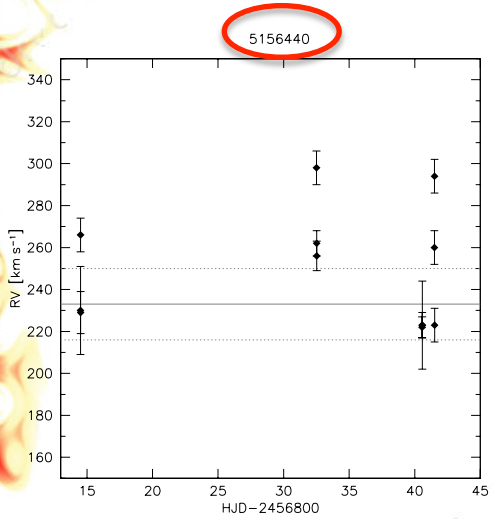
Radial velocity survey

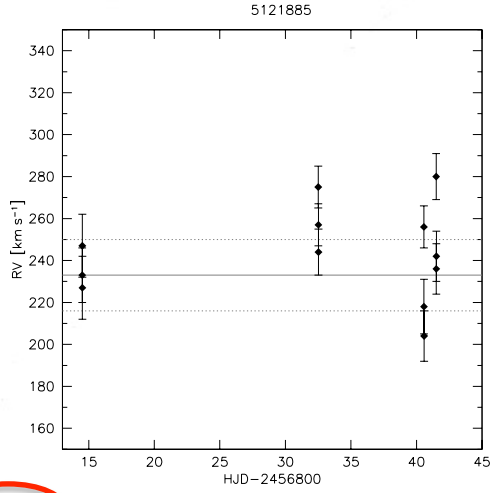
- VIMOS HR blue spectra gathered at several epochs (<4 in 2014 & <6 in 2015)
- Each epoch: 3x10 mins on-source
- 102 EHB candidates (33 FLAMES/FORS overlap)

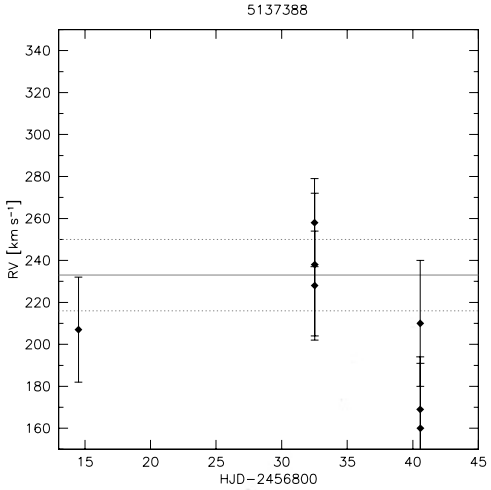


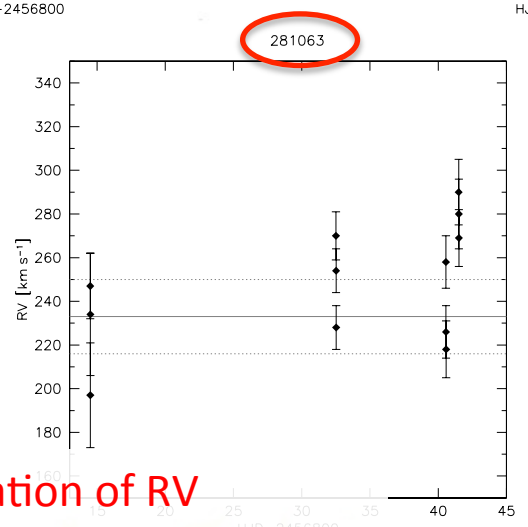


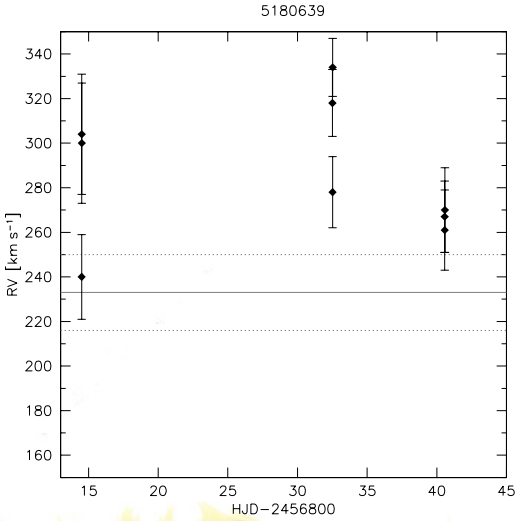
Radial velocities











Some indication of RV variability from the 2014 data – need full analysis to be sure!

2014 data

Conclusion

- ω Cen pulsators present new challenge for both theorists and observers ☺
- ω Cen EHB stars show a different T_{eff} / log g / He distribution to field sample – need to disentangle populations using kinematic analysis
- ω Cen binary fraction may not turn out to be as low as expected... identified at least one candidate for a close binary