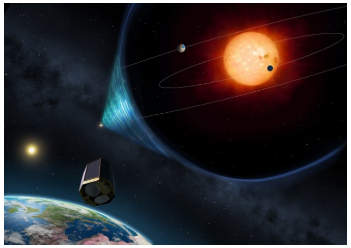
PLATO 2.0 Science Workshop



Reaching the 1% accuracy level on stellar mass and radius determinations from asteroseismology

The case of hot subdwarf B stars

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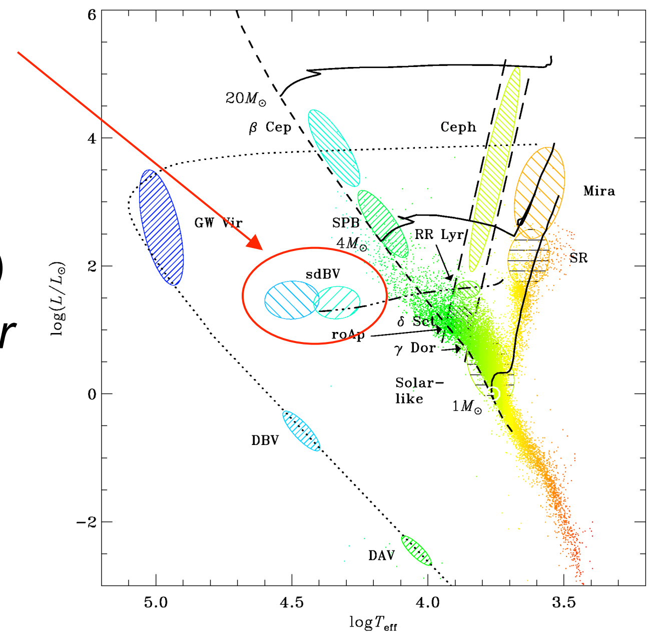
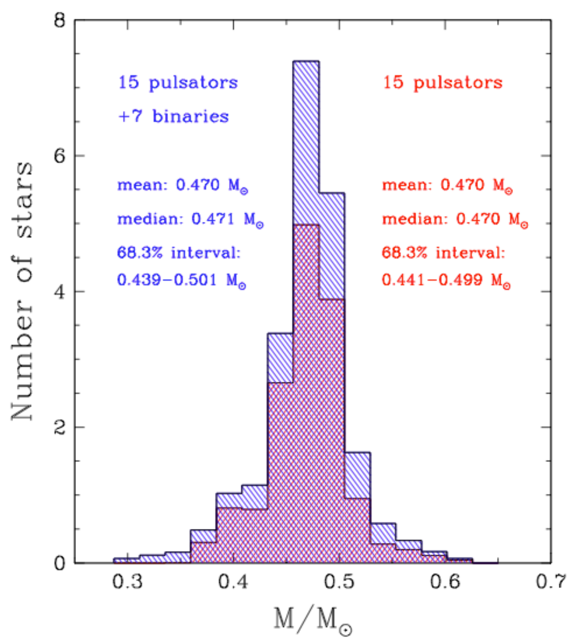
1. Introduction to hot subdwarf B (sdB) stars

Hot (T_{eff} = 20 000 - 40 000 K) and compact (log g = 5.2 - 6.2) stars

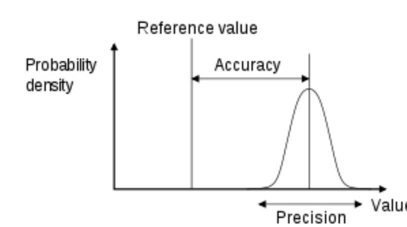
- Core He-burning, extremely thin H envelope
- sdBs are thought to be post-red giants having lost most of their H-envelope through binary interaction (stellar, sub-stellar and planets →see R. Silvotti's talk)
- p-mode and g-mode pulsators (15 observed by *Kepler* and 1 by Corot)



Mass distribution of sdB stars



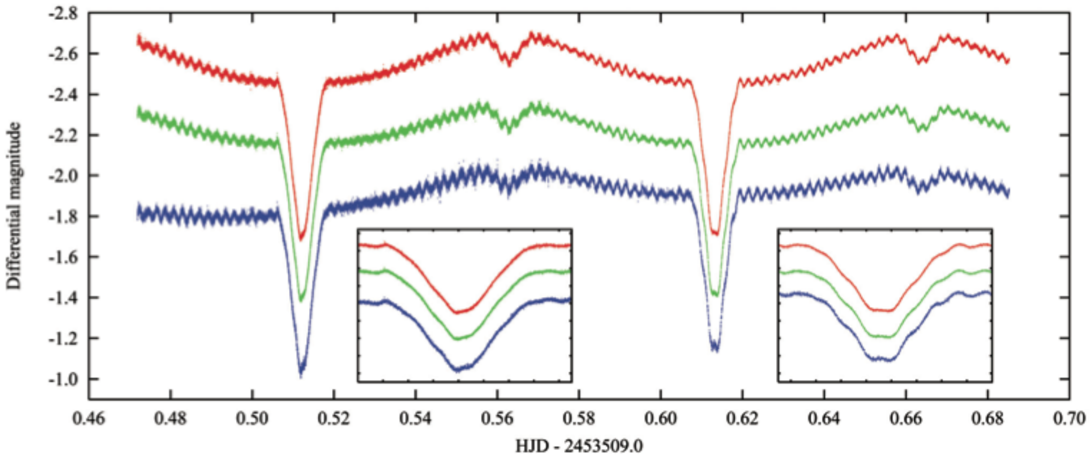
- To date: 15 sdB pulsators modeled by seismology
  - Mass: ~1% precision
  - log g: ~0.1% precision
  - Radius: ~0.6% precision



Is this reliable ? Is this accurate ? Is this precise ?

2. GW Virginis, the Rosetta stone of sdB seismology

pulsating sdB+dM eclipsing binary (P_{orb}=2.4244h)

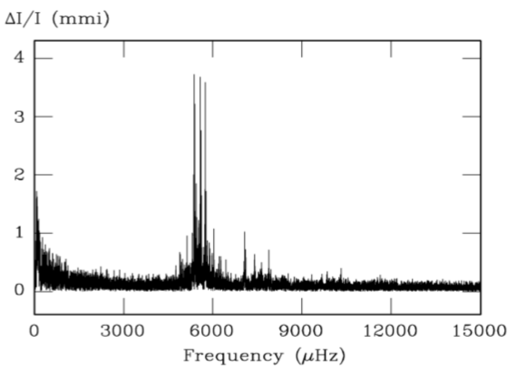


Eclipses and light curve modeling (multicolor photometry ULTRACAM@VLT)
+accurate spectroscopy (RV curve UVES@VLT):

orbital solutions for mass, radius (and log g) of the sdB component

(Vuckovic et al. 2007, A&A, 471, 605)

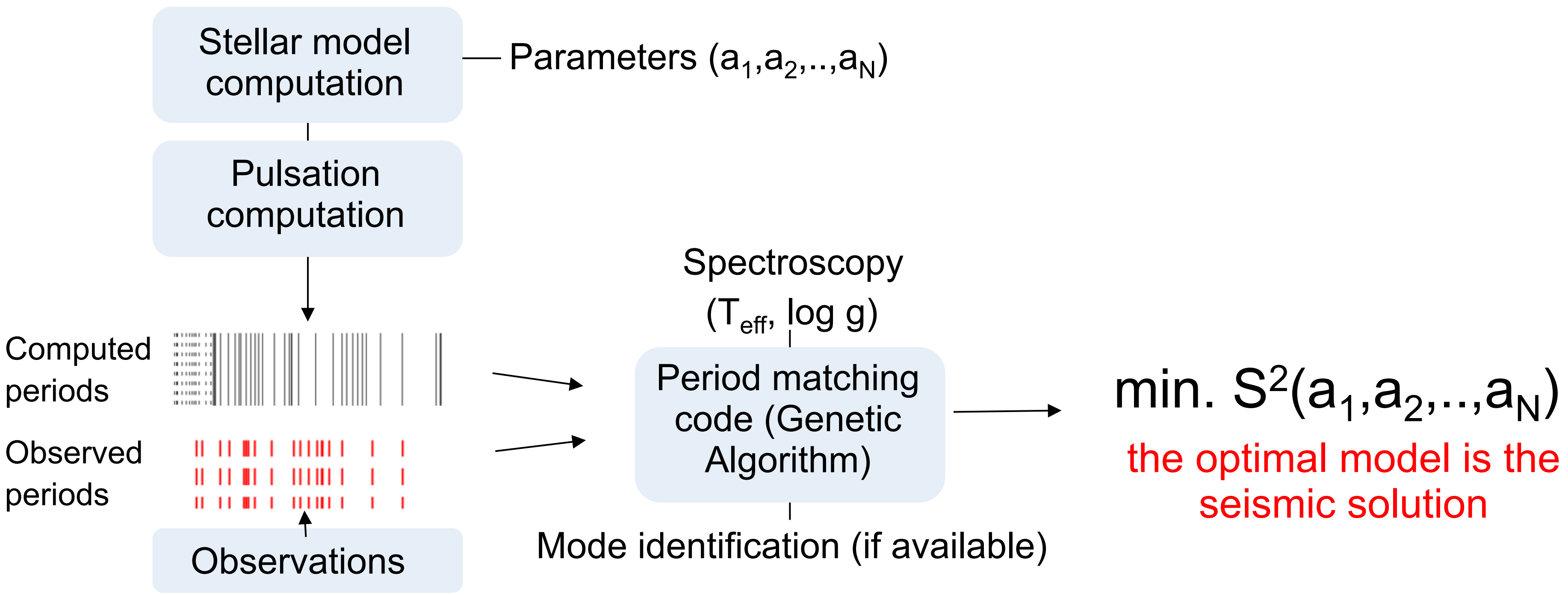
- Whole Earth Telescope campaign: 25 pulsation periods for the sdB component in the range 96-205s (p-modes), Kilkenny et al. 2003 (MNRAS, 345, 843)



3. The forward modeling approach for asteroseismology

The method consists of finding the best possible match between the observed frequencies and those computed from models → optimization procedure

$$S^2 = \sum_{i=1}^{N_{\rm obs}} \left(\frac{P^i_{\rm obs} - P^i_{\rm th}}{\sigma_i} \right)^2$$



3. The forward modeling approach for asteroseismology

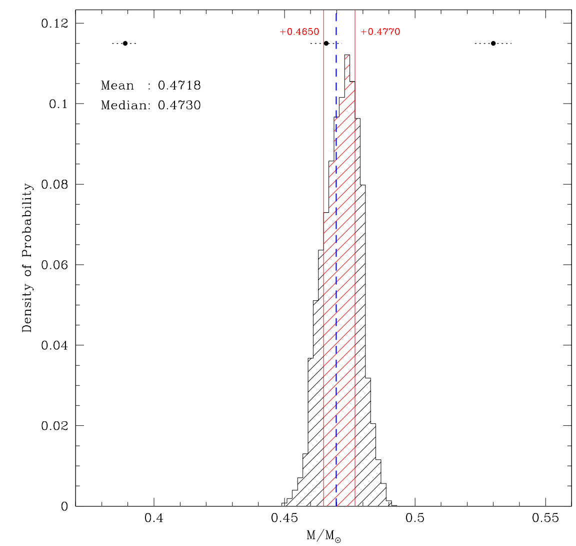
Error estimates: using probability distributions (Van Grootel et al. 2013,A&A, 553, 97)

Likelihood function $\mathcal{L}(a_1, a_2, a_3, a_4) \propto e^{-\frac{1}{2}S^2}$

Probability density function for parameter a_1 (ex. mass):

$$\mathcal{P}(a_1)\mathrm{d}a_1 \propto \mathrm{d}a_1 \iiint \mathcal{L}(a_1, a_2, a_3, a_4)\mathrm{d}a_2\mathrm{d}a_3\mathrm{d}a_4$$

(with $\int \mathcal{P}(a_1)\mathrm{d}a_1 = 1$)



Questions/limitations:

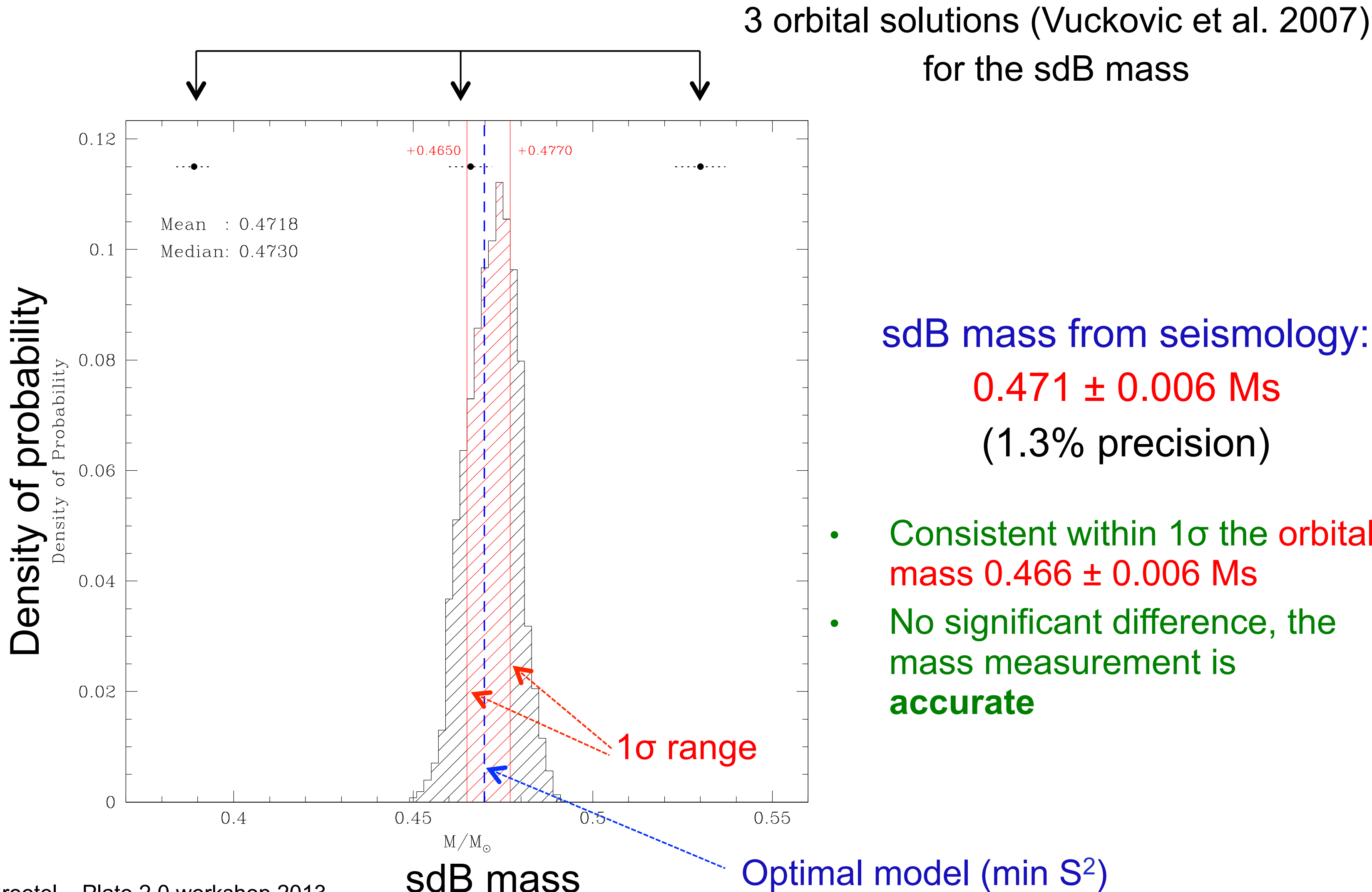
Seismic best-fit method is model-dependent:

- are seismic estimates accurate? Do model uncertainties introduce systematics on parameters determined form seismology?
- are seismic estimates precise (error estimates reliable)?

→ Seismic analysis of GW Vir and comparison with orbital solution

4. Seismic analysis of the pulsating sdB GW Virginis

- Optimization procedure is launched in a vast parameter space where sdB stars are found (details in Van Grootel et al. 2013, A&A, 553, 97)
- Best-fit solution to the 25 observed periods:



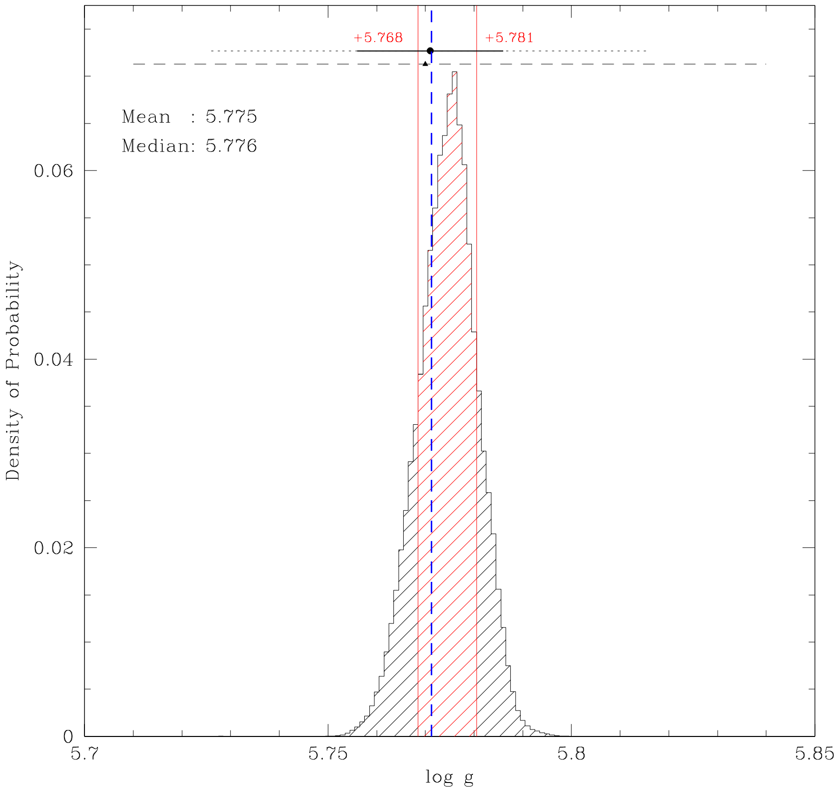
sdB mass from seismology:
0.471 ± 0.006 Ms
(1.3% precision)

- Consistent within 1σ the orbital mass 0.466 ± 0.006 Ms
- No significant difference, the mass measurement is **accurate**

4. Seismic analysis of the pulsating sdB PG 1336-018

Surface gravity log g

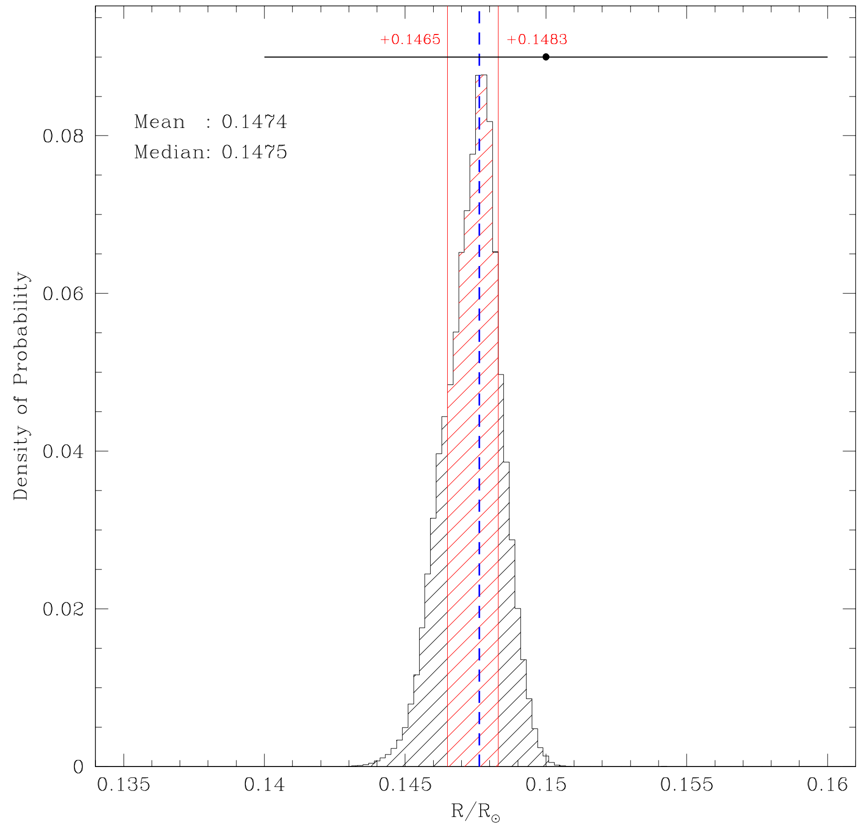
- Seismic solution: 5.775 ± 0.007 (0.1% precision)
- Orbital solution: 5.77 ± 0.06
- Spectroscopy: 5.771 ± 0.015



sdB log g

Stellar radius

- Seismic solution: 0.147 ± 0.001 Rs (0.6% precision)
- Orbital solution: 0.15 ± 0.01 Rs



sdB radius

No significant difference, R and log g are accurately derived

5. Precision and accuracy of seismology

In summary:

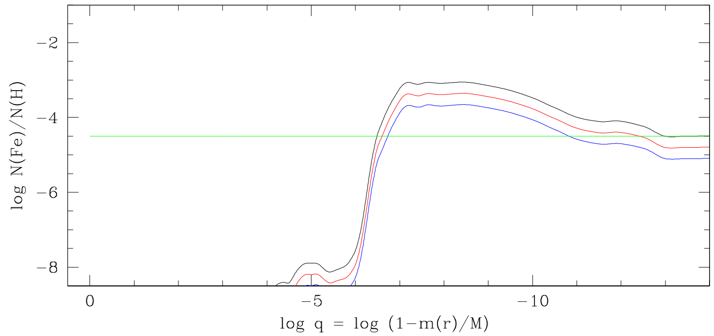
Stellar models for asteroseismology of sdB stars allow for both **precise** *and* **accurate** determinations of the stellar parameters, in particular mass and radius.

But how do the model uncertainties impact this result ?

3 main sources of uncertainties in sdB models:

- Envelope Iron profile (standard: radiative levitation=gravitational settling)
- Core/envelope transition profile (standard: not smoothed by diffusion)
- He-burning nuclear reaction rates (standard: Caughlan & Fowler 1988)

5. Precision and accuracy of seismology: envelope iron profile



Green: uniform solar profile

Black: standard profile (radiative levitation = gravitational settling)

Red: standard/2

Blue: standard/4

We redo 3 seismic analyses of GW Vir with the modified models. Results:

Table 4. Parameters derived for PG 1336–018 using various iron abundance profiles.

Parameter	Uniform/Solar	$\frac{1}{4} \cdot \frac{N(Fe)}{N(H)}$	$\frac{1}{2} \cdot \frac{N(Fe)}{N(H)}$	$1 \cdot \frac{N(Fe)}{N(H)}$	Largest drift	Likely drift
$M/M_\odot$	0.471 ± 0.009	0.474 ± 0.009	0.474 ± 0.009	0.471 ± 0.006	$+0.003 \pm 0.011$	$+0.003 \pm 0.011$
$\log g$	5.814 ± 0.007	5.795 ± 0.008	5.786 ± 0.009	5.775 ± 0.007	$+0.039 \pm 0.010$	$+0.020 \pm 0.011$
$R/R_\odot$	0.1406 ± 0.0011	0.1443 ± 0.0012	0.1459 ± 0.0012	0.1474 ± 0.0009	-0.0068 ± 0.0014	-0.0031 ± 0.0015
$\log q(H)$	-4.11 ± 0.08	-3.70 ± 0.09	-3.74 ± 0.09	-3.83 ± 0.06	-0.28 ± 0.10	$+0.07 \pm 0.11$
$X(C+O)$	0.46 ± 0.10	0.48 ± 0.10	0.51 ± 0.09	0.58 ± 0.06	-0.12 ± 0.12	-0.10 ± 0.12
$L/L_\odot$	20.6 ± 0.7	21.8 ± 0.7	22.3 ± 0.8	22.9 ± 0.6	-2.3 ± 0.9	-1.1 ± 0.9
S^2 (opt.)	5.95	5.93	5.46	4.81		
$\overline{\Delta X/X}$ (%)	0.24	0.21	0.19	0.18		
$\overline{\Delta\nu}$ (μHz)	14.07	12.75	11.43	11.37		

No drift on stellar mass

2σ drift on log g and radius

Despite significant changes in the iron abundance profiles, the derived parameters are mostly unaffected (e.g. the mass) or only subject to very small systematic drifts

5. Precision and accuracy of seismology

Core/Envelope transition profile

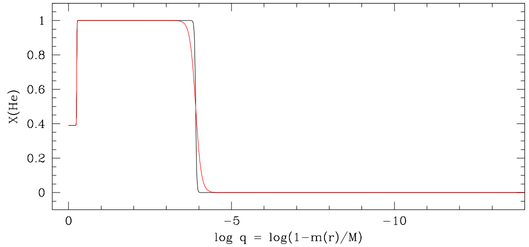


Table 5. Parameters derived for PG 1336−018 using a sharp or a smooth He/H transition profile.

Parameter	Sharp transition	Smooth transition	Drift
$M/M_\odot$	0.471 ± 0.006	0.476 ± 0.009	$+0.005 \pm 0.011$
$\log g$	5.775 ± 0.007	5.777 ± 0.007	$+0.002 \pm 0.010$
$R/R_\odot$	0.1474 ± 0.0009	0.1476 ± 0.0011	$+0.0002 \pm 0.0014$
$\log q(\mathrm{H})$	-3.83 ± 0.06	-3.79 ± 0.08	$+0.04 \pm 0.10$
$X(\mathrm{C+O})$	0.58 ± 0.06	0.53 ± 0.09	-0.05 ± 0.11
$L/L_\odot$	22.9 ± 0.6	22.8 ± 0.7	-0.1 ± 0.9
S^2 (opt.)	4.81	4.91	
$\overline{\Delta X/X}$ (%)	0.18	0.18	
$\overline{\Delta \nu}$ (μHz)	11.37	11.48	

He-burning rate: $^{12}C(\alpha,\gamma)^{16}O$ x2

Table 6. Parameters derived for PG 1336−018 using models with modified reaction rates for the triple-α and $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction rates.

Parameter	CF88	2 × CF88	Drift
$M/M_\odot$	0.471 ± 0.006	0.474 ± 0.010	$+0.003 \pm 0.012$
$\log g$	5.775 ± 0.007	5.775 ± 0.008	0.00 ± 0.011
$R/R_\odot$	0.1474 ± 0.0009	0.1479 ± 0.0010	$+0.0005 \pm 0.0013$
$\log q(\mathrm{H})$	-3.83 ± 0.06	-3.84 ± 0.09	-0.01 ± 0.11
$X(\mathrm{C+O})$	0.58 ± 0.06	0.54 ± 0.10	-0.04 ± 0.12
$L/L_\odot$	22.9 ± 0.6	23.0 ± 0.7	$+0.1 \pm 0.9$
S^2 (opt.)	4.81	5.12	
$\overline{\Delta X/X}$ (%)	0.18	0.19	
$\overline{\Delta \nu}$ (μHz)	11.37	11.52	

No significant drift on stellar mass, radius and log g

The seismic solution is robust against uncertainties in the constitutive physics of the models

6. Conclusion

Conclusion

We can indeed achieve ~1% for mass and radius determinations from asteroseismology

Seismic parameters determined from asteroseismology for sdB stars are both precise, accurate, and robust again model uncertainties

Remarks:

✓Here for sdB stars, a favorable case (no convective envelope)

✓ We are still (very) far from reproducing the precision of the observations (1 nHz for Kepler, 0.1μHz for ground-based observations; vs 10μHz for seismic model) => **asteroseismology has still not delivered its full potential**