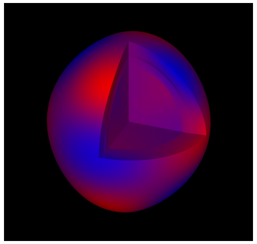
The Eighth Meeting on Hot Subdwarf stars
and Related Objects



New observations and asteroseismic analysis of the sdB pulsator PG 1219+534

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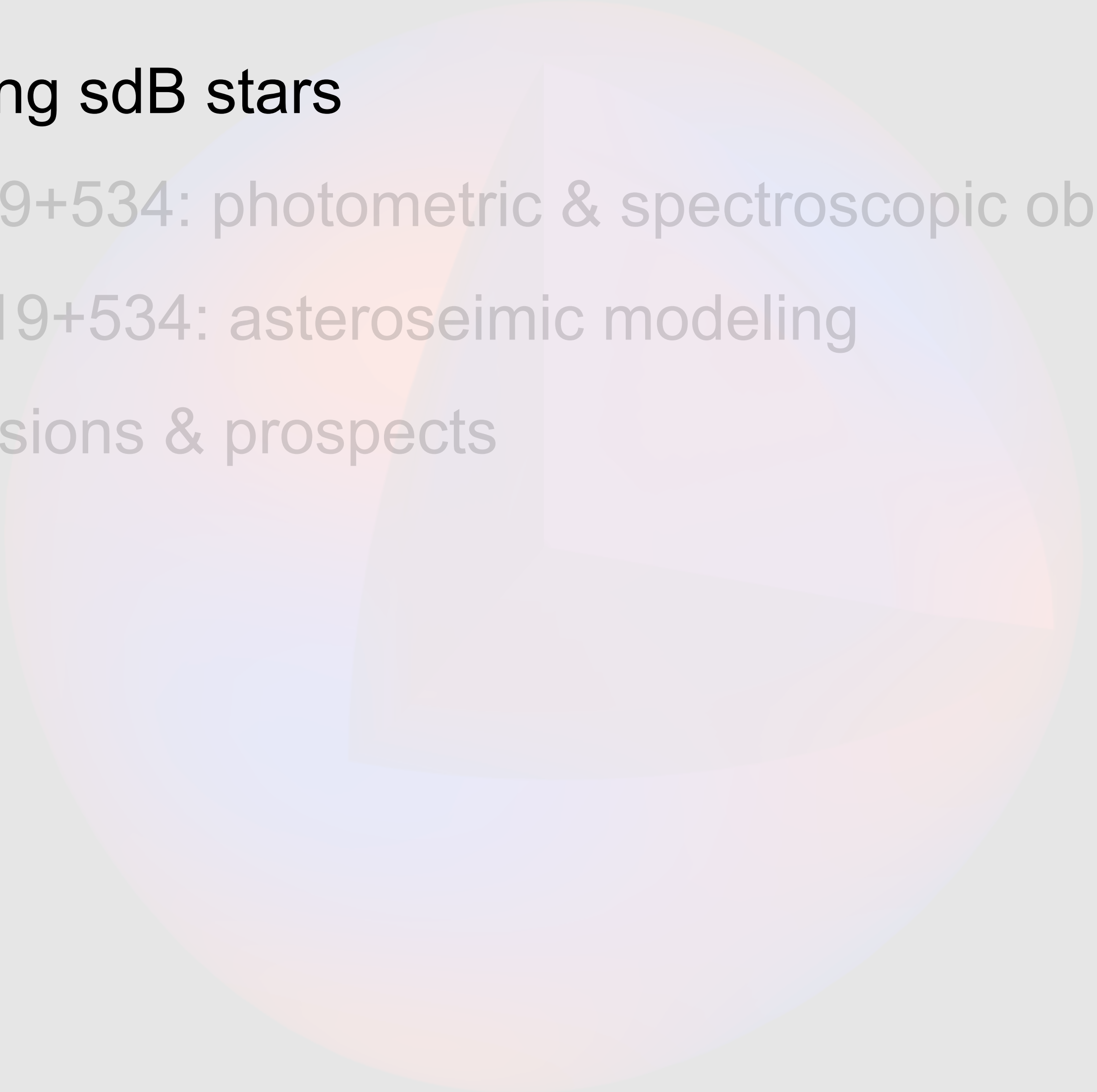
Outline



I. Pulsating sdB stars

II. PG1219+534: photometric & spectroscopic observations

III. PG 1219+534: asteroseimic modeling

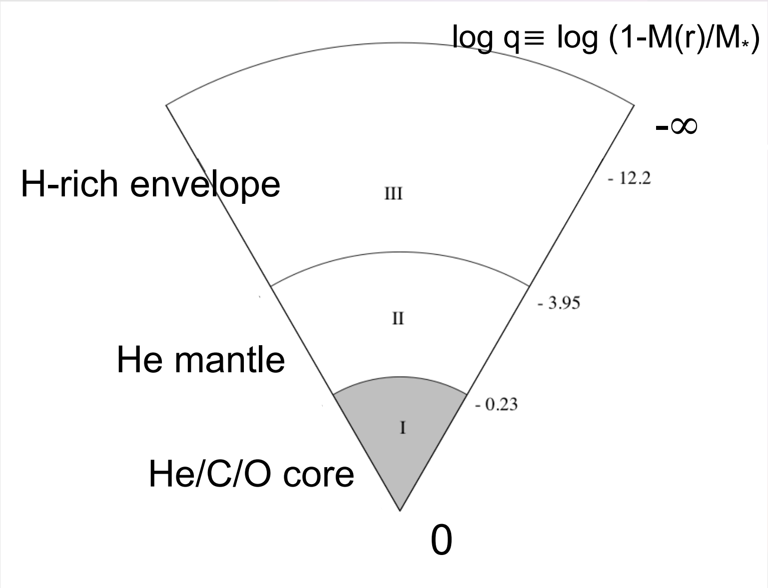
IV. Conclusions & prospects

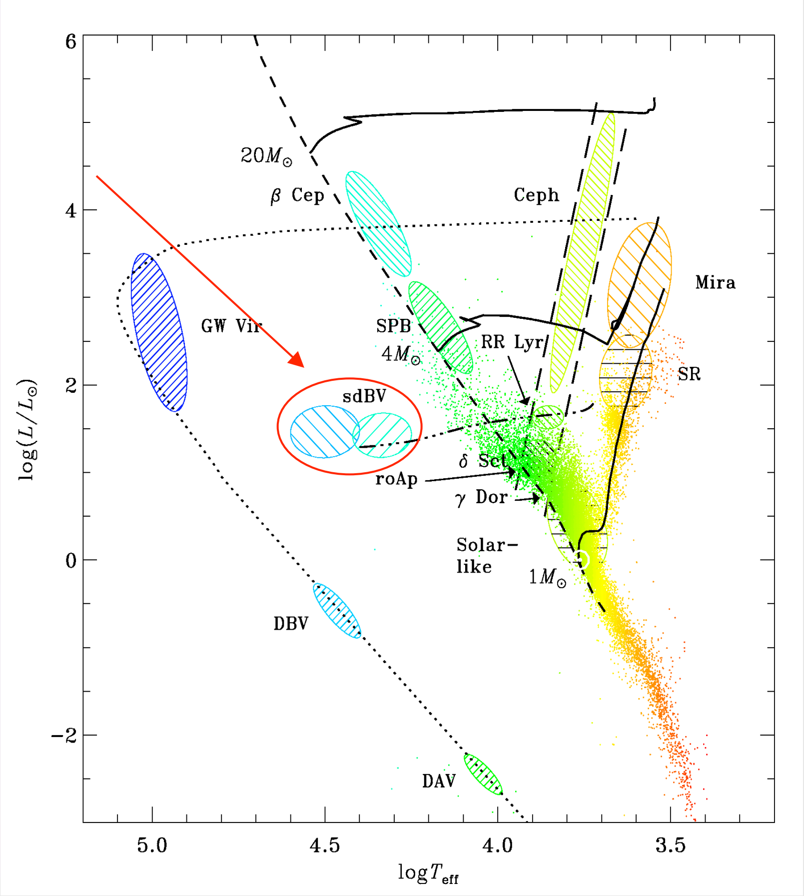
The Extreme Horizontal Branch (EHB) stars

Hot (T_{eff} ~ 30 000 K) and compact stars (log g ~ 5.5) belonging to Extreme Horizontal Branch (EHB), an intermediate stage of evolution

Internal structure:

I. He → C+O fusion (convective core)
II. radiative He mantle
III. radiative H-rich envelope
(M_{env} ~ 10^{-5} - 2.10^{-2} Msun pour M_* ~ 0.5 Msun)





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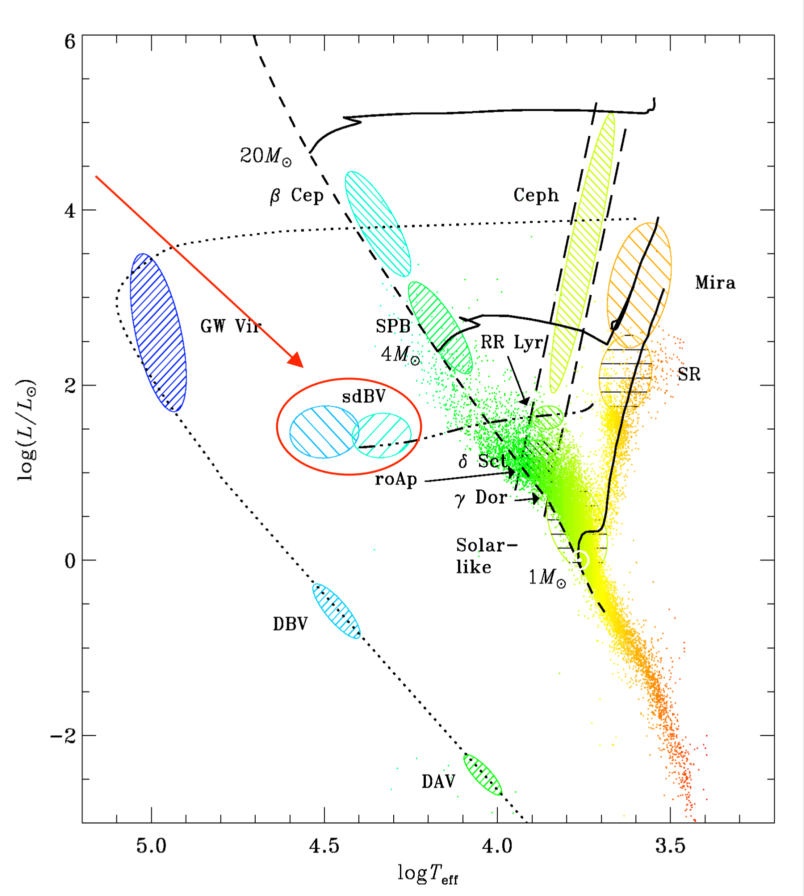


Two classes of multi-periodic EHB pulsators:

\> short-periods (P ~ 80 - 600 s), A ≤ 1%, p-modes (EC14026, V361Hya, sdBV_r,…)

\> long-periods (P ~ 30 min - 3 h), A ≤ 0.1%, g-modes (PG1716, V1093 Her, Betsy stars, sdBV_s,…)

\+ **hybrids** (many of them)

Excitation mechanism in sdBs

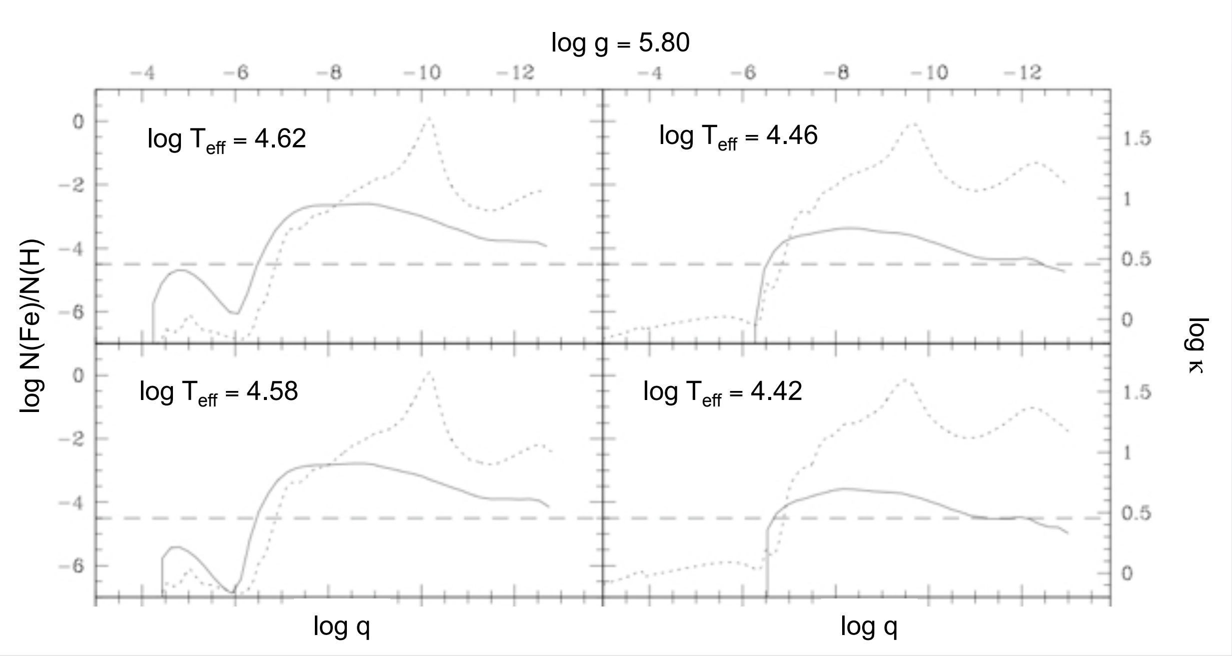
κ mechanism, by partial ionization of heavy elements (e.g. Iron) in the envelope of the star

- the Z-bump region is a driving region for pulsations
- but, inefficient at solar metallicity

considering microscopic diffusion
(gravitational settling - radiative levitation) :
local iron surabundances in the envelope

- Prediction of short period sdB pulsators, *p-modes*
(l≤4; k≤7-8)
(Charpinet et al., 1996, 1997)

- Same mechanism for long periods sdB pulsators, *g-modes*
(l≤4; k~10-50)
(Fontaine et al., 2003)



+ importance of nickel
(Jeffery & Saio, 2006, 2007; Hu +2011, Bloemen+2014)

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III. PG 1219+534: asteroseimic modeling

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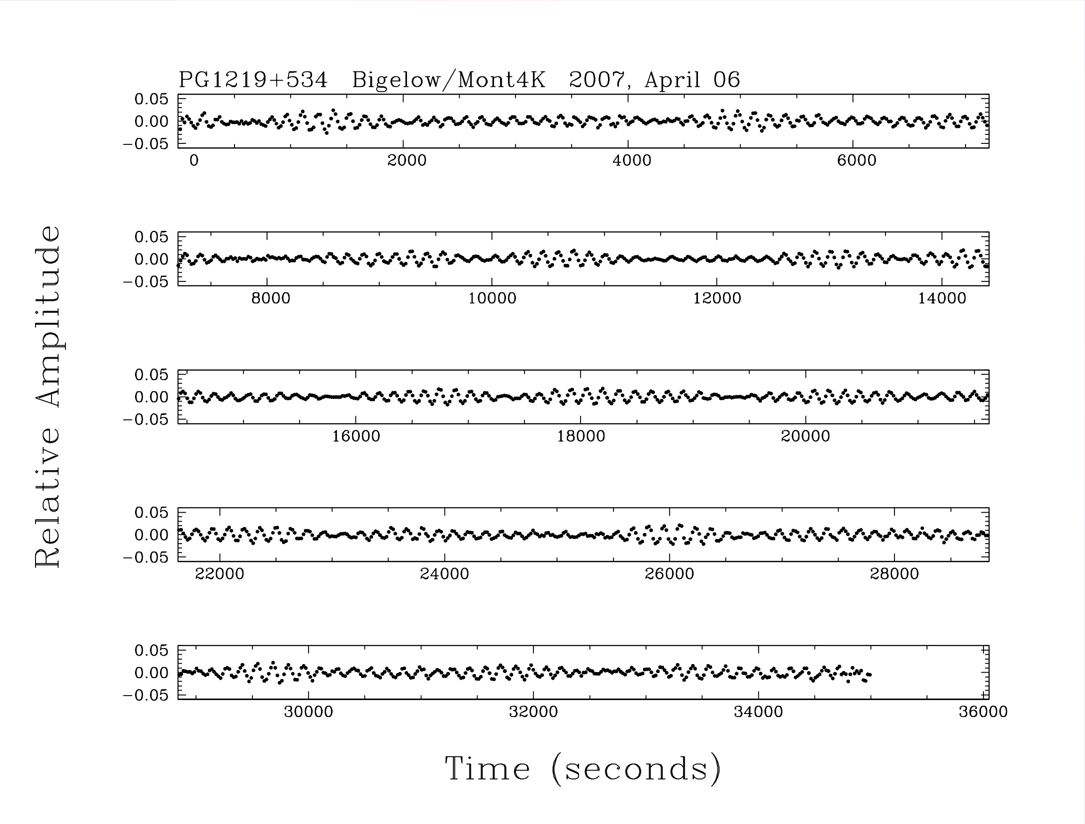
PG 1219+534: photometric observations

PG 1219+534 = single sdB pulsator (no companion)

- Koen et al. (1999) : discovery of a rapidly pulsating sdB star, with 4 pulsations in the range 129-148 s
- Charpinet et al. (2005), 4 nights @CFHT, 9 independent pulsations 122-172 s
- This work: 198.7h @61"(1.6m) Mont Bigelow telescope (3/2/2007-3/5/2007), Arizona (USA)



Formal resolution:

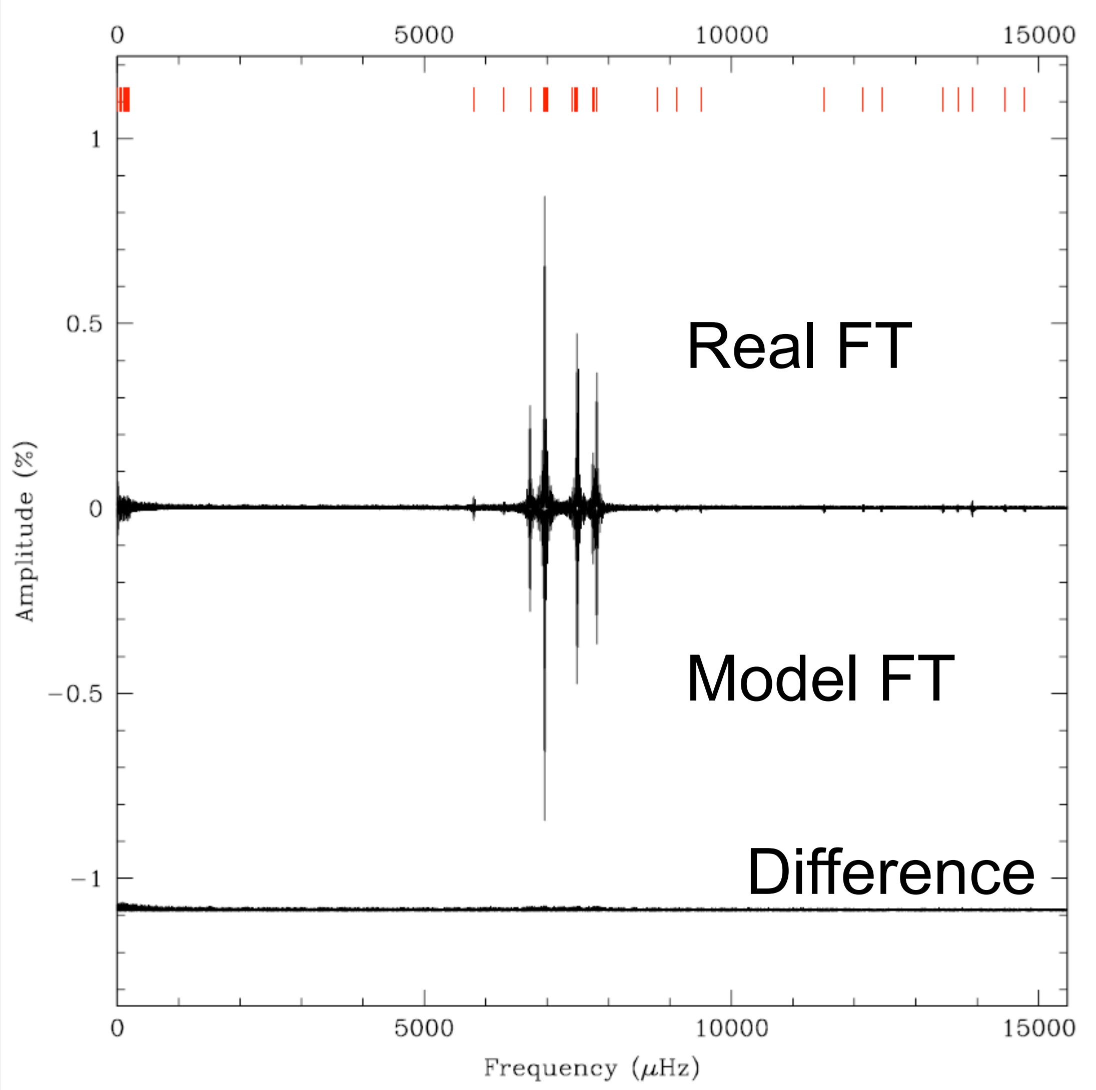
0.13μHz

Noise level:

43 ppm

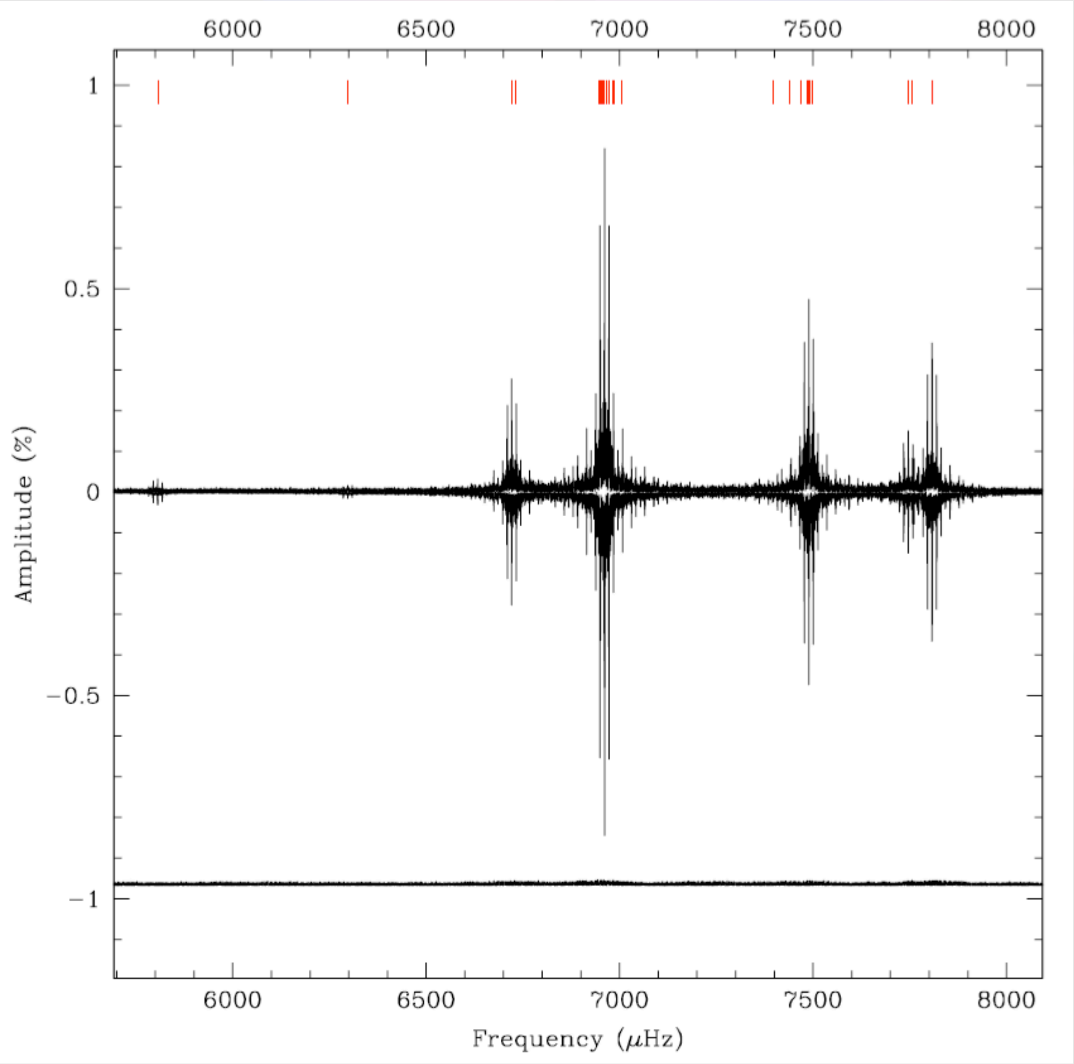
PG 1219+534: Fourier analysis

Fourier transform + prewithening techniques to extract pulsation properties



PG 1219+534: Fourier analysis

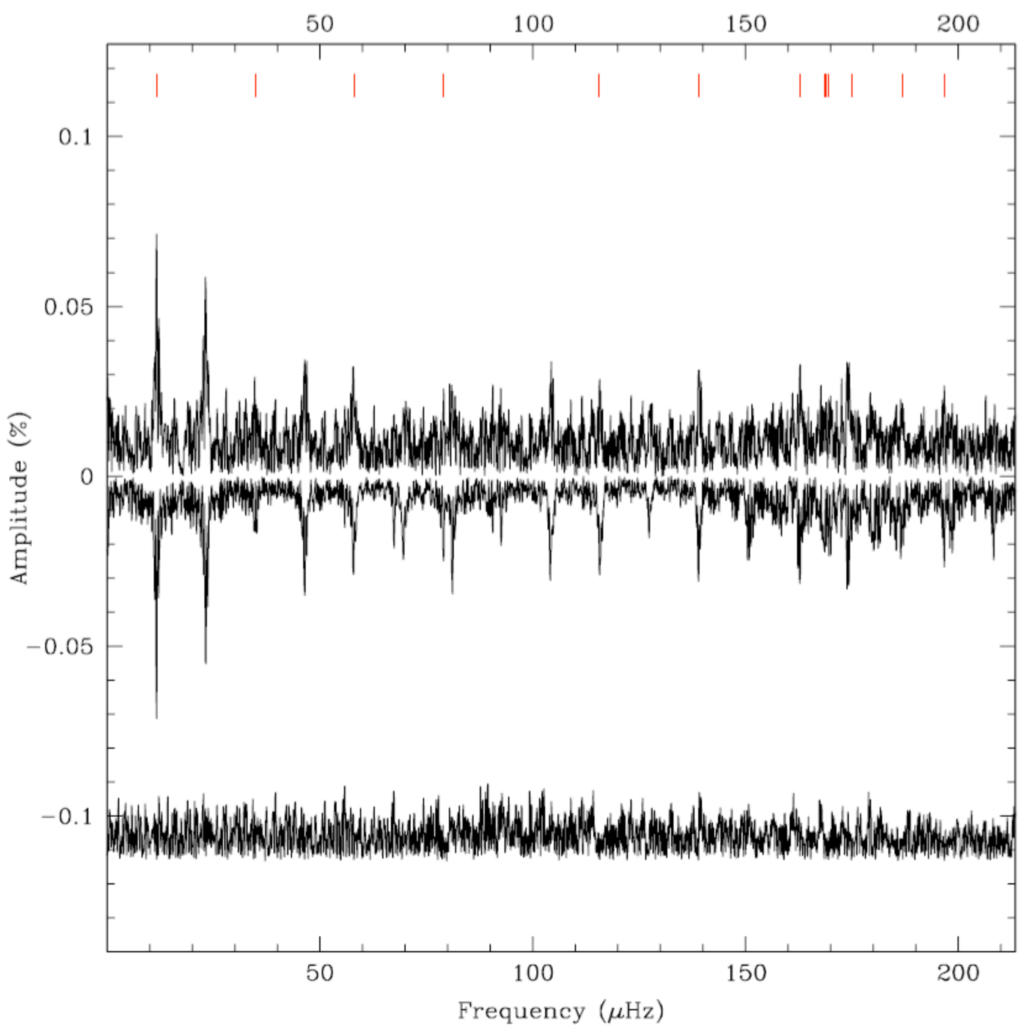
Fourier transform + prewithening techniques to extract pulsation properties



Zoom in p-modes region

PG 1219+534: Fourier analysis

Fourier transform + prewithening techniques to extract pulsation properties



Zoom in g-modes region

PG 1219+534: Fourier analysis

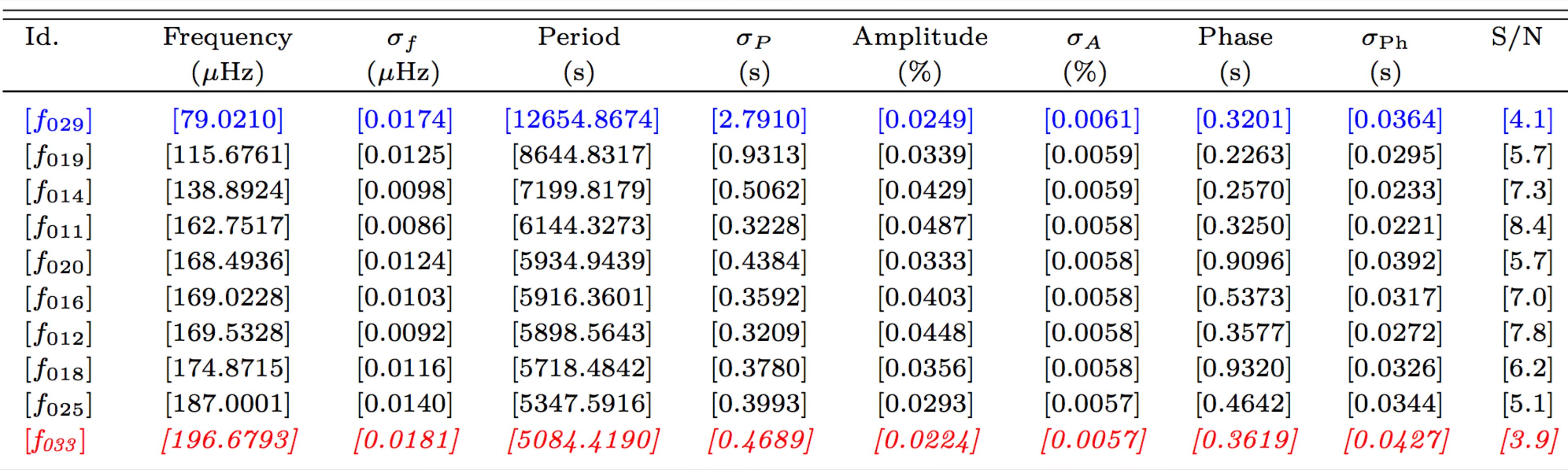
p-modes

Id.	Frequency (μHz)	Period (s)	Amplitude (%)	P_{CFHT04} (s)	A_{CFHT04} (%)	Comments
$\boldsymbol{f}_{\mathbf{022}}$	5806.54	172.220	0.0312	172.214	0.0456	
f_{042}	6297.88	158.784	0.0160	...		
$\boldsymbol{f}_{\mathbf{041}}$	6297.60	158.791	0.0163	158.789	0.0334	
$\boldsymbol{f}_{\mathbf{004}}$	6721.49	148.777	0.3035	148.775	0.4053	Also in Koen et al. (1999)
$\boldsymbol{f}_{\mathbf{001}}$	6961.38	143.650	0.8373	143.649	0.7228	Also in Koen et al. (1999)
f_{noise}	*[7398.16]*	*[135.169]*	*[0.0147]*	[135.160]	[0.0429]	below detection threshold; not used for seismology
f_{005}	7490.09	133.510	0.2913	...		
$\boldsymbol{f}_{\mathbf{002}}$	7489.45	133.521	0.3915	133.516	0.6874	Also in Koen et al. (1999)
f_{006}	7488.83	133.532	0.2655	...		
$\boldsymbol{f}_{\mathbf{007}}$	7746.37	129.093	0.1567	...		
f_{037}	7808.06	128.073	0.0198	...		
$\boldsymbol{f}_{\mathbf{003}}$	7807.75	128.078	0.3745	128.077	0.7972	Also in Koen et al. (1999)
f_{030}	7807.42	128.083	0.0237	...		
f_{CFHT}	...	...	...	122.408	0.0963	not present in the Mt Bigelow data
$\boldsymbol{f}_{\mathbf{053}}$	11 511.59	86.869	0.0097	...		
$\boldsymbol{f}_{\mathbf{056}}$	12 145.32	82.336	0.0091	[82.261]	0.0190	not used by Charpinet et al. (2005)

Stable pulsation spectrum over the years!

PG 1219+534: Fourier analysis

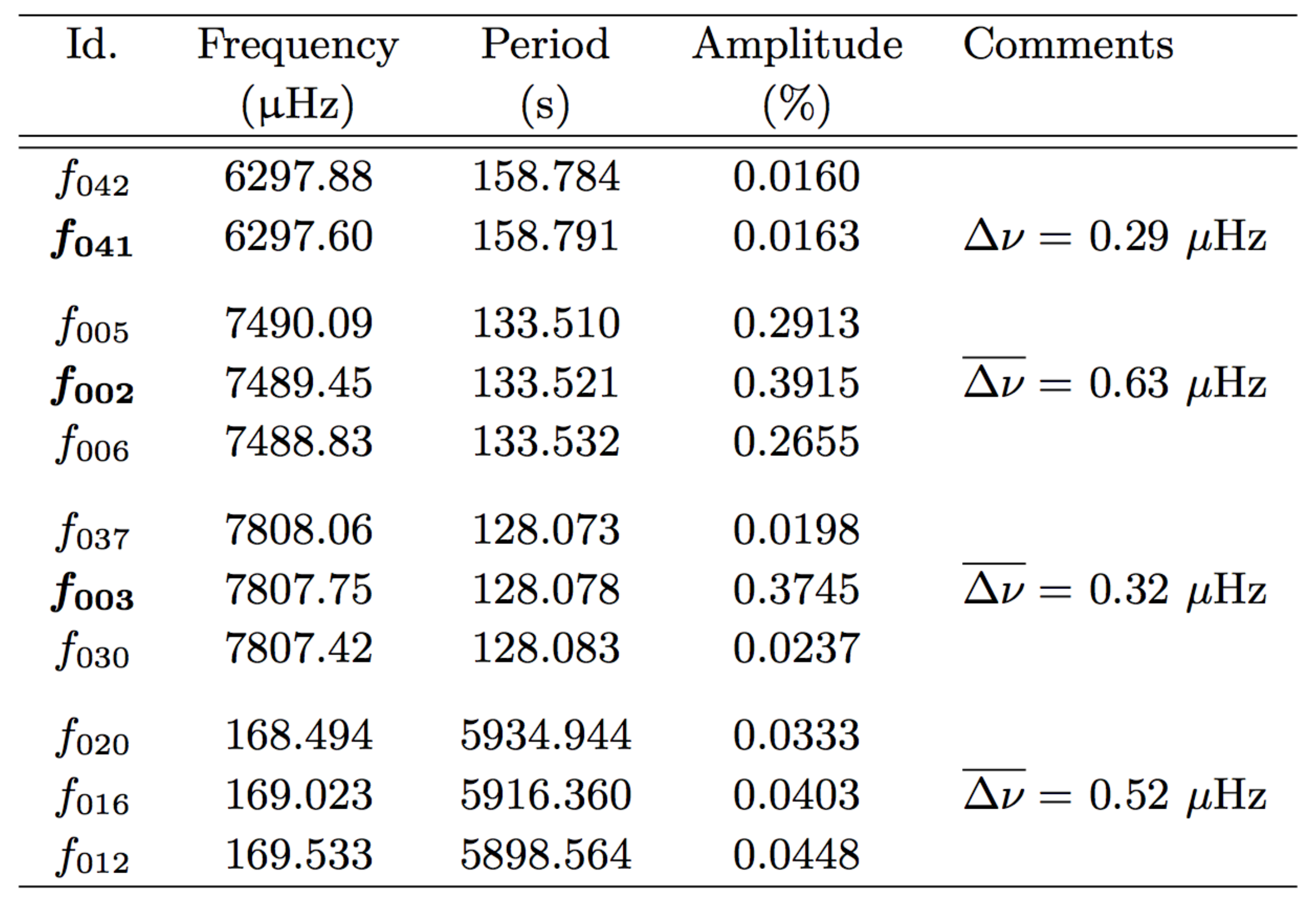
g-modes



Id.	Frequency (μHz)	σ_f (μHz)	Period (s)	σ_P (s)	Amplitude (%)	σ_A (%)	Phase (s)	$\sigma_{\rm Ph}$ (s)	S/N
[f_{029}]	[79.0210]	[0.0174]	[12654.8674]	[2.7910]	[0.0249]	[0.0061]	[0.3201]	[0.0364]	[4.1]
[f_{019}]	[115.6761]	[0.0125]	[8644.8317]	[0.9313]	[0.0339]	[0.0059]	[0.2263]	[0.0295]	[5.7]
[f_{014}]	[138.8924]	[0.0098]	[7199.8179]	[0.5062]	[0.0429]	[0.0059]	[0.2570]	[0.0233]	[7.3]
[f_{011}]	[162.7517]	[0.0086]	[6144.3273]	[0.3228]	[0.0487]	[0.0058]	[0.3250]	[0.0221]	[8.4]
[f_{020}]	[168.4936]	[0.0124]	[5934.9439]	[0.4384]	[0.0333]	[0.0058]	[0.9096]	[0.0392]	[5.7]
[f_{016}]	[169.0228]	[0.0103]	[5916.3601]	[0.3592]	[0.0403]	[0.0058]	[0.5373]	[0.0317]	[7.0]
[f_{012}]	[169.5328]	[0.0092]	[5898.5643]	[0.3209]	[0.0448]	[0.0058]	[0.3577]	[0.0272]	[7.8]
[f_{018}]	[174.8715]	[0.0116]	[5718.4842]	[0.3780]	[0.0356]	[0.0058]	[0.9320]	[0.0326]	[6.2]
[f_{025}]	[187.0001]	[0.0140]	[5347.5916]	[0.3993]	[0.0293]	[0.0057]	[0.4642]	[0.0344]	[5.1]
[f_{033}]	*[196.6793]*	*[0.0181]*	*[5084.4190]*	*[0.4689]*	*[0.0224]*	*[0.0057]*	*[0.3619]*	*[0.0427]*	*[3.9]*

PG 1219+534: Fourier analysis

Multiplets structure is present



Id.	Frequency (μHz)	Period (s)	Amplitude (%)	Comments
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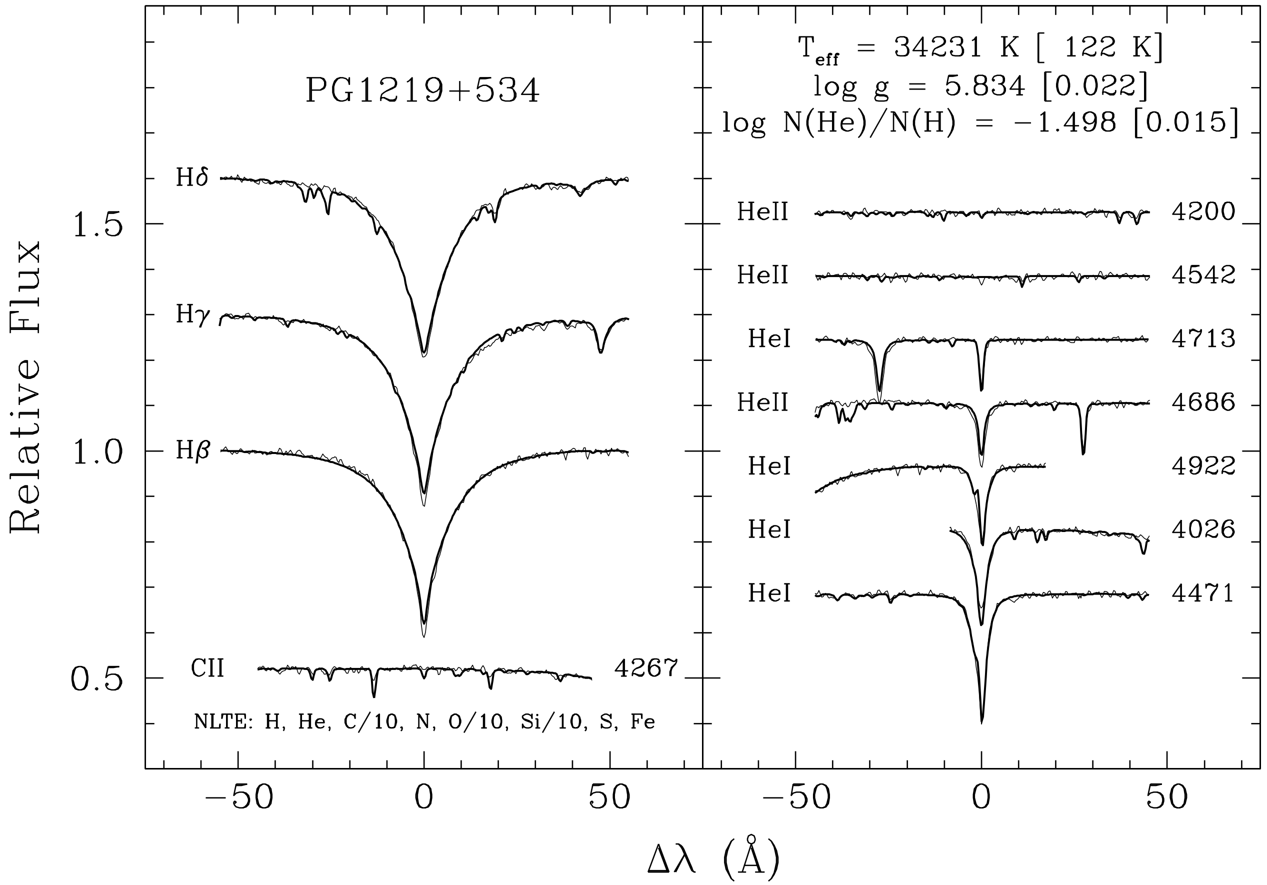
$\mathbf{f_{041}}$	6297.60	158.791	0.0163	$\Delta\nu = 0.29\ \mu\mathrm{Hz}$
f_{005}	7490.09	133.510	0.2913	
$\mathbf{f_{002}}$	7489.45	133.521	0.3915	$\overline{\Delta\nu} = 0.63\ \mu\mathrm{Hz}$
f_{006}	7488.83	133.532	0.2655	
f_{037}	7808.06	128.073	0.0198	
$\mathbf{f_{003}}$	7807.75	128.078	0.3745	$\overline{\Delta\nu} = 0.32\ \mu\mathrm{Hz}$
f_{030}	7807.42	128.083	0.0237	
f_{020}	168.494	5934.944	0.0333	
f_{016}	169.023	5916.360	0.0403	$\overline{\Delta\nu} = 0.52\ \mu\mathrm{Hz}$
f_{012}	169.533	5898.564	0.0448	

Most probable explanation: rotational multiplets (see later)

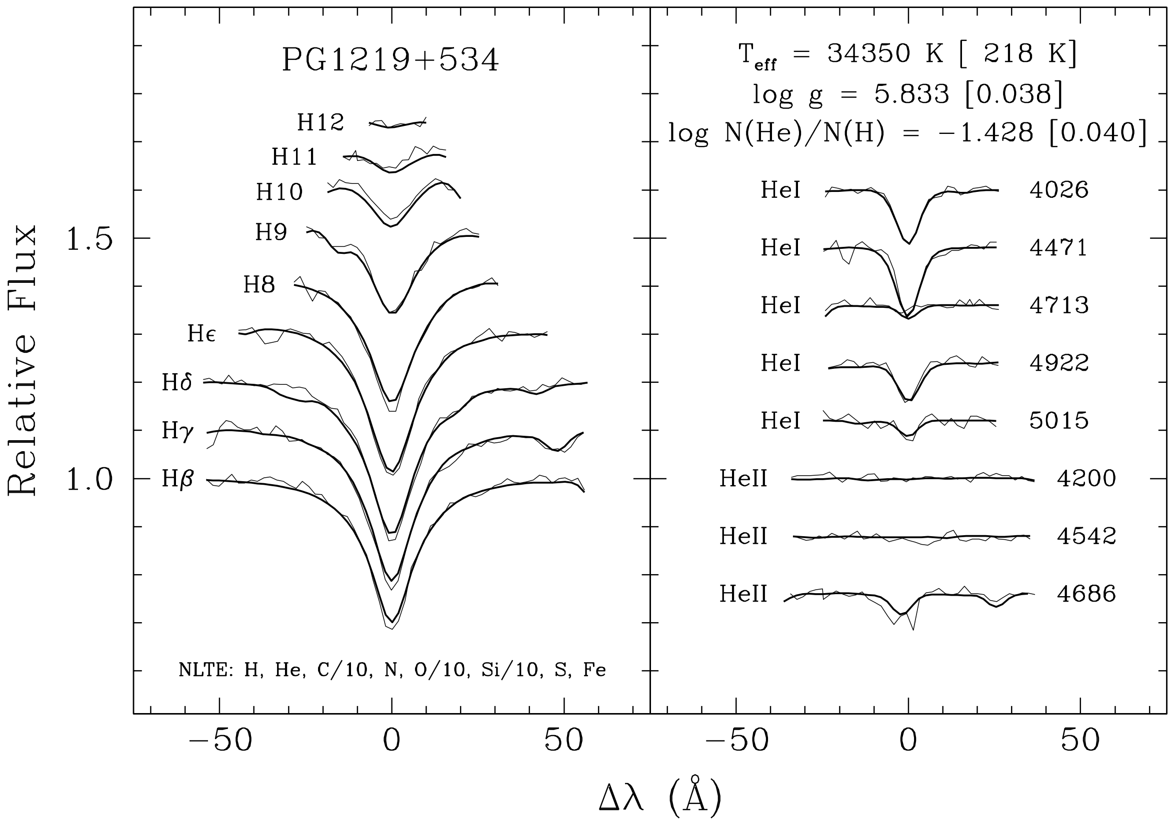
PG1219+534: spectroscopy

MMT spectra, 1Å resolution, (moderately) high S/N



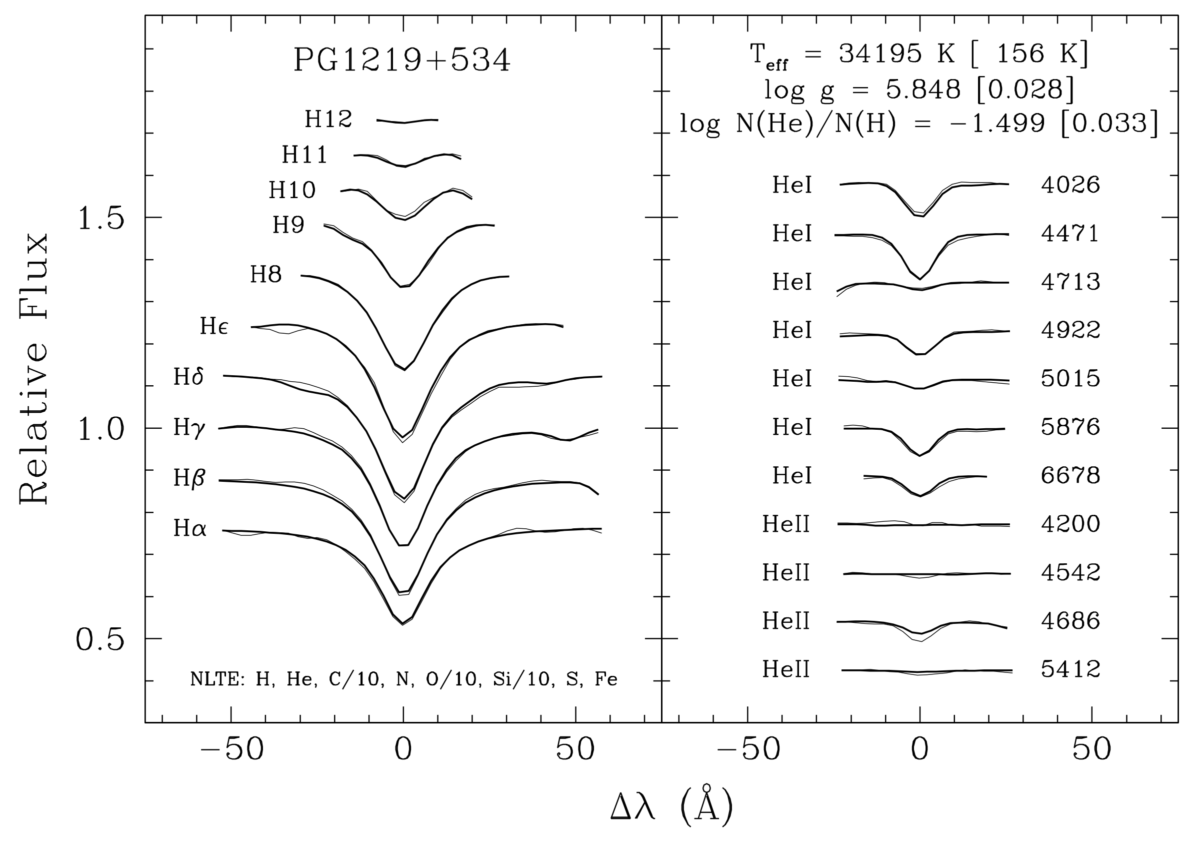
PG1219+534: spectroscopy

90'' 2.3m Bok telescope spectra, 6Å resolution, high S/N



PG1219+534: spectroscopy

90'' 2.3m Bok telescope spectra, 9Å resolution, high S/N



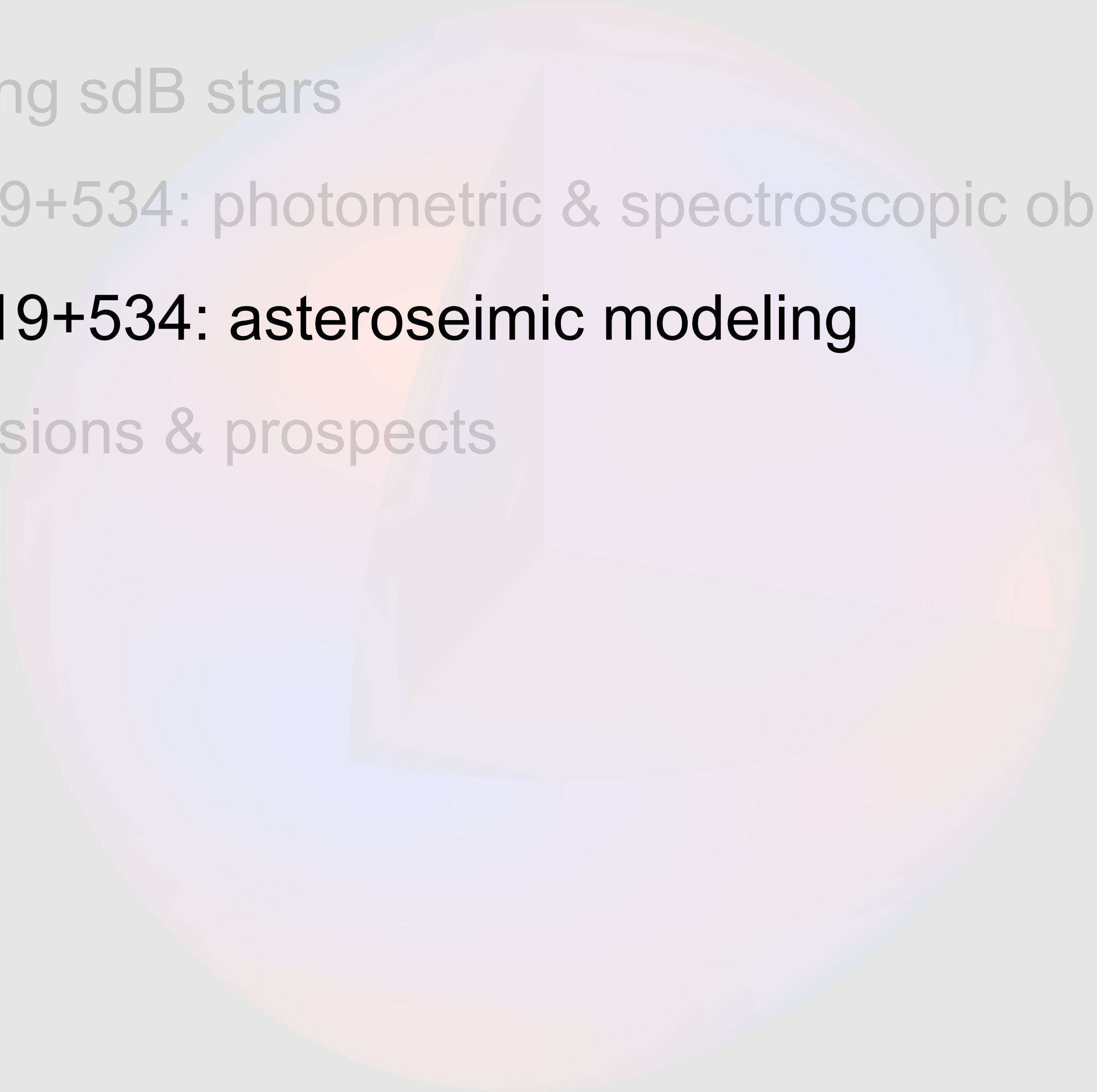
PG1219+534: spectroscopy

H/He NLTE + metals « à la Blanchette al. (2008) »
(1/10 Solar: C, O, Si; solar: N, S, Fe)

T_{eff}= 34,258 ± 170 K
log g= 5.838 ± 0.030
log N(He)/N(H)=-1.475±0.030

NB: Same, without metals: T_{eff}= 33,824 ± 137 K
log g= 5.824 ± 0.028
log N(He)/N(H)=-1.479±0.028

Outline



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Models for sdB stars seismology

Static models = Parametrized models (*<u>independent</u> of stellar evolution)*

> 2^{nd} generation (2G) models:

- static **envelope** structures; central regions (e.g. convective core) ≡ hard ball
- include detailed envelope microscopic diffusion (nonuniform envelope Fe abundance in an otherwise pure H envelope),
- 4 input parameters : T_{eff}, log g, M_*, envelope thickness log (M_{env}/M_*)

> 3^{rd} generation (3G) models:

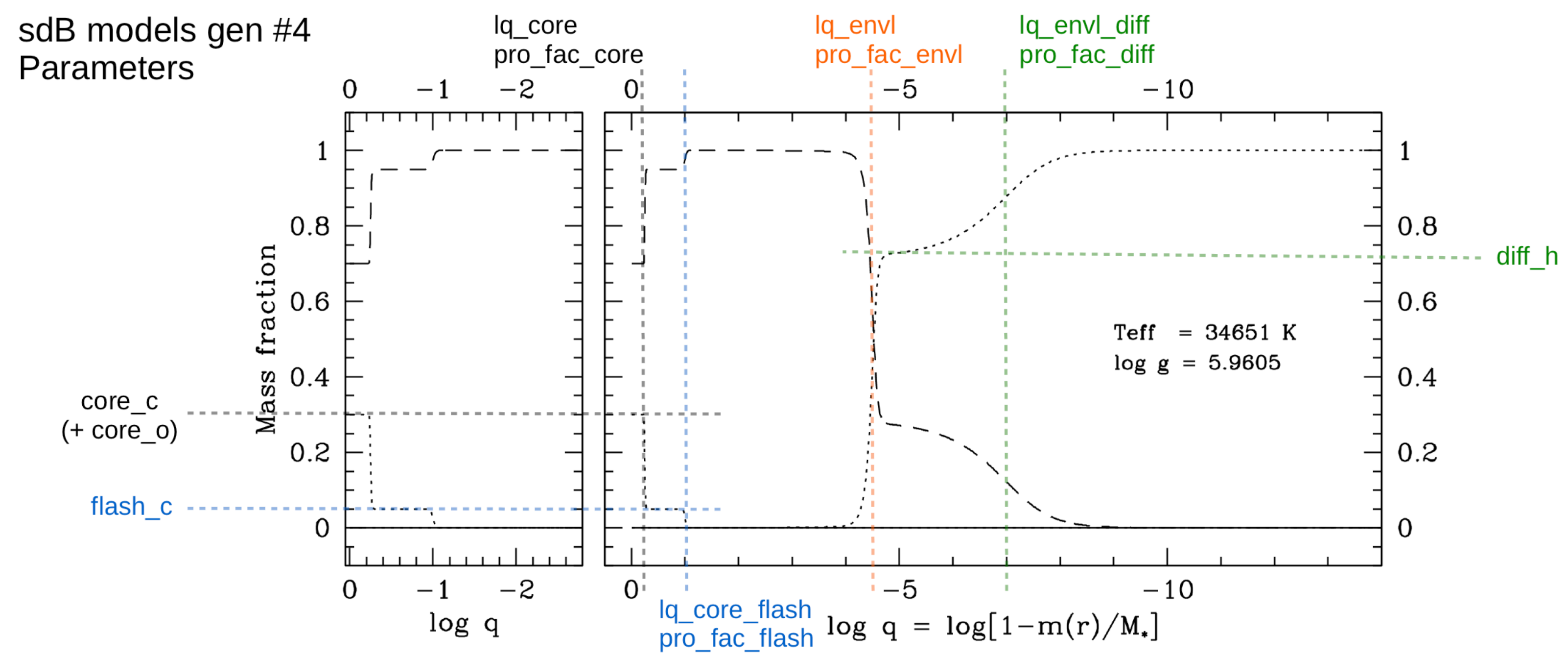
- **complete** static structures; including detailed central regions description
- only for sdB on EHB (He-burning)
- include detailed envelope microscopic diffusion (nonuniform envelope Fe abundance)
- input parameters : M_*, log (M_{env}/M_*), log (M_{core}/M_*), $X_{core}(C+O)$ (with C+O+He = 1)

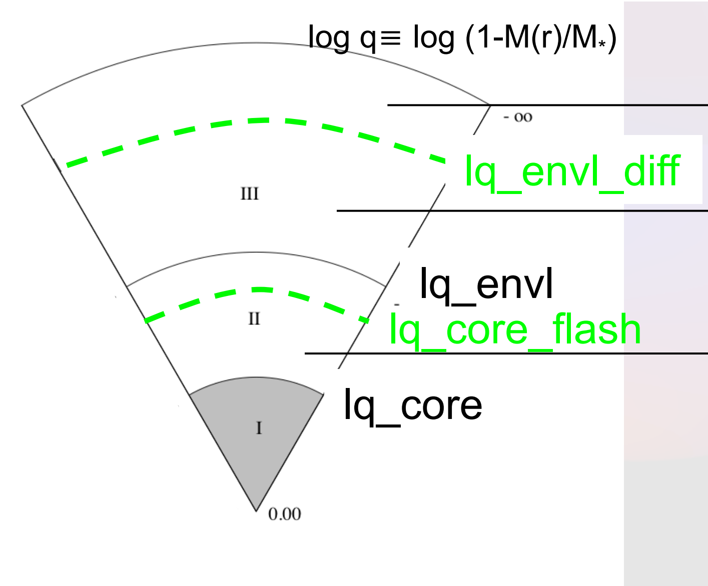
> 4^{th} generation (4G) models: idem 3G models+

- double transition H/He envelope (2 parameters)
- C-contamination of the He mantle (during He-flash) possible (2 parameters)
- "smoothness" of the chemical transition profiles (4 parameters)

=> Up to 12 input parameters

Models for sdB stars seismology





Pure H

H/He envelope (+Fe)

Up to 7 % of C in the He mantle on ~ 90% of the mantle

Method for sdB stars seismology

Search the stellar model(s) whose theoretical periods best fit all the observed ones, in order to minimize

$$S^2(a_1, a_2, ..., a_N) = \sum_{i=1}^{N_{\rm obs}} (P_{\rm obs}^{(i)} - P_{\rm th}^{(i)})^2$$

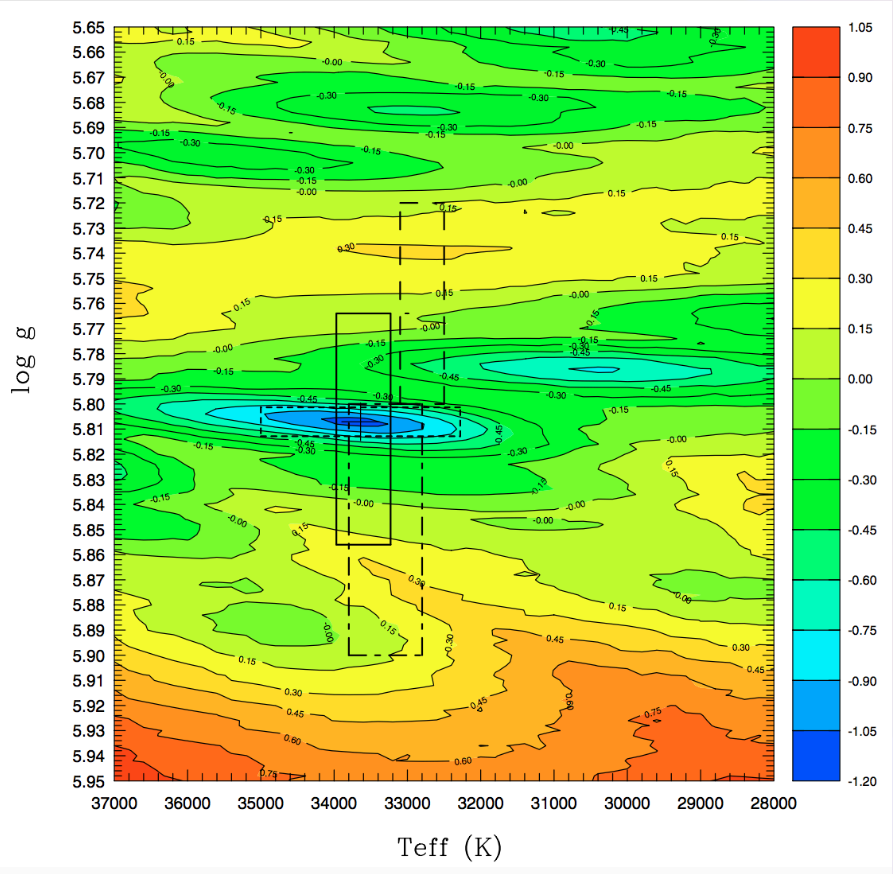
> **Optimization procedure**: Efficient optimization codes (based on *Genetic Algorithms*) to thoroughly explore the parameter space and find the minima of S^2

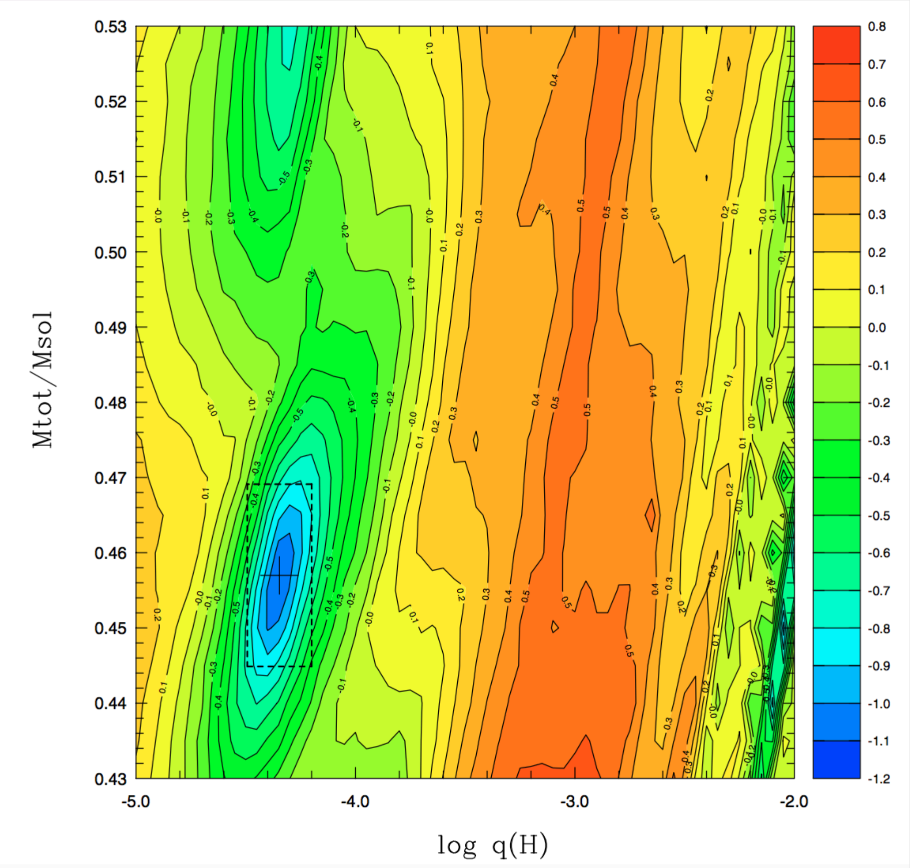
Under *external* constraints from spectroscopy + mode identification (if available, ex. from observed multiplets)

✓ Search parameter space
- $0.3 \leq M_*/M_s \leq 0.7$ (Han et al. 2002, 2003)
- $-6.0 \leq \log (M_{env}/M_*) \leq -3.5$
- Teff, log g @ 3σ spectroscopy
- $-0.40 \leq \log (M_{core}/M_*) \leq -0.10$ (3G, 4G)
- $0 \leq X(C+O) \leq 1$ (3G, 4G)
- H(envelope): 60-100% + location of the transition (4G)
- C(mantle): 0-7% + location of the transition (4G)
- Steep to smooth profiles (4G)

> **Results**: structural and core parameters of the star (M_*, M_{env}, M_{core}, etc.), internal chemical stratification

Seismic modeling with 2G models (Charpinet et al. 2005)



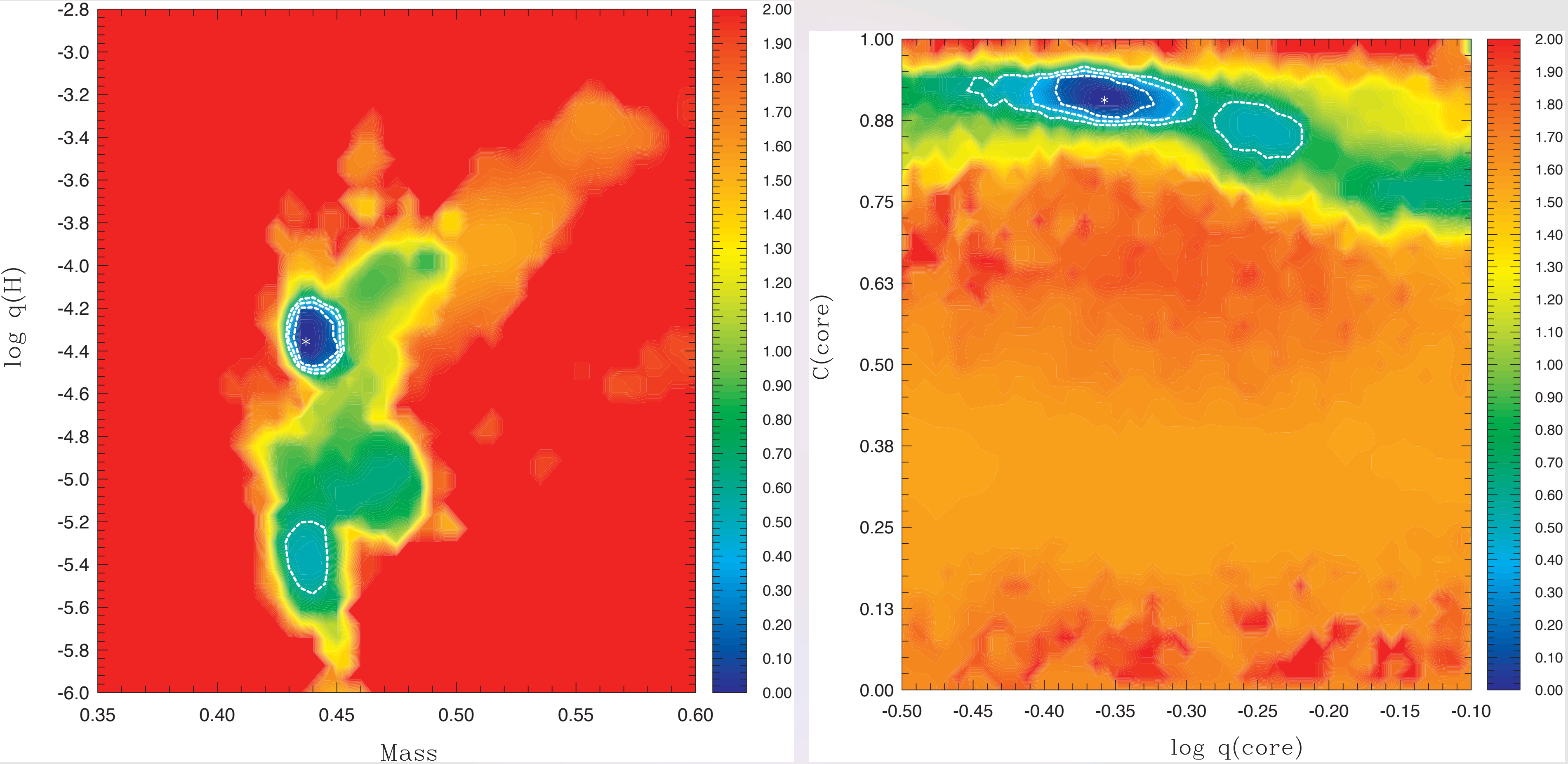


T_{eff}=33,640 ± 1360 K
log g= 5.8071 ± 0.0057

log (M_{env}/M_*)=-4.254±0.147
M_*/M_{sun}=0.457±0.012

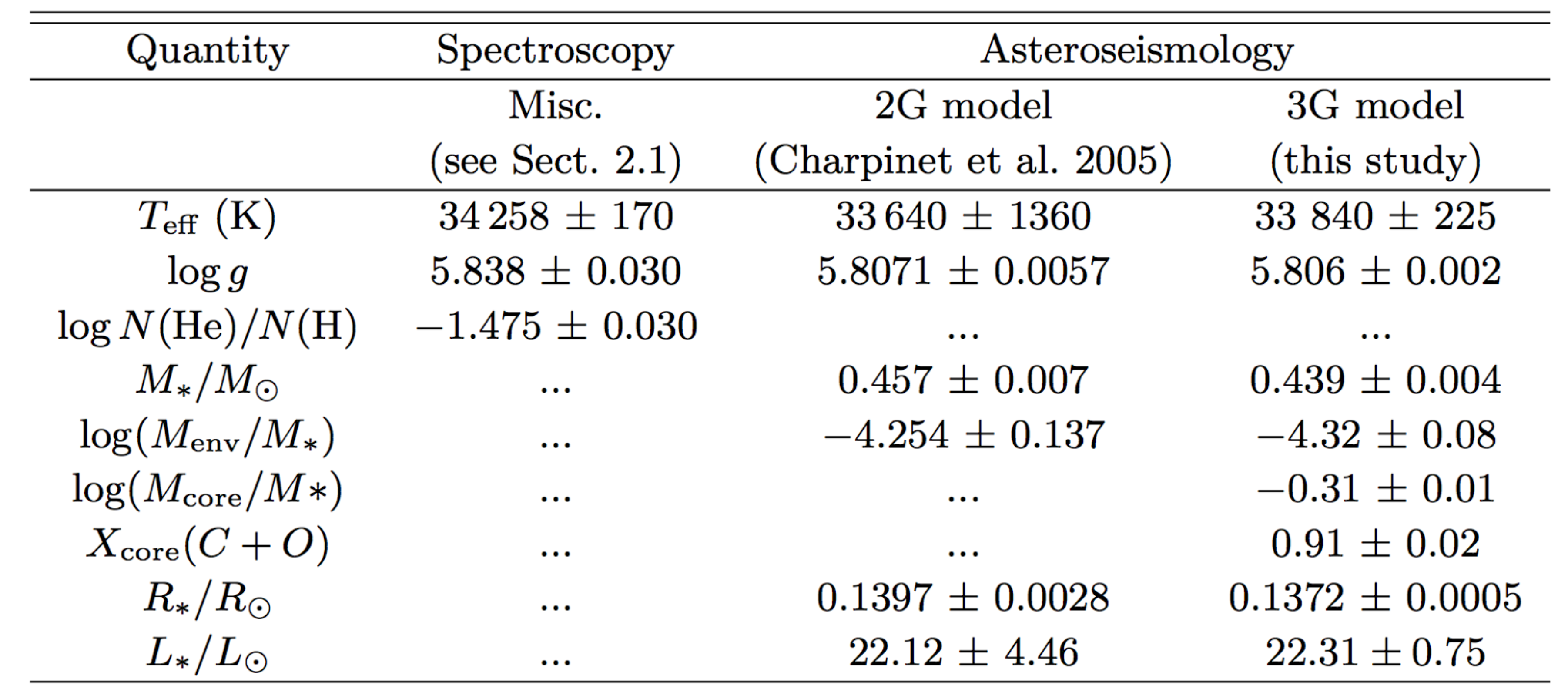
Fit to 9 modes (p-modes): <dX/X>~0.6%, <dP>=0.8s

Seismic modeling with 3G models (M.J. Péters)



Fit to 9 periods (p-modes): <dX/X>~0.35%, <dP>=0.37s

Comparison 2G/3G results



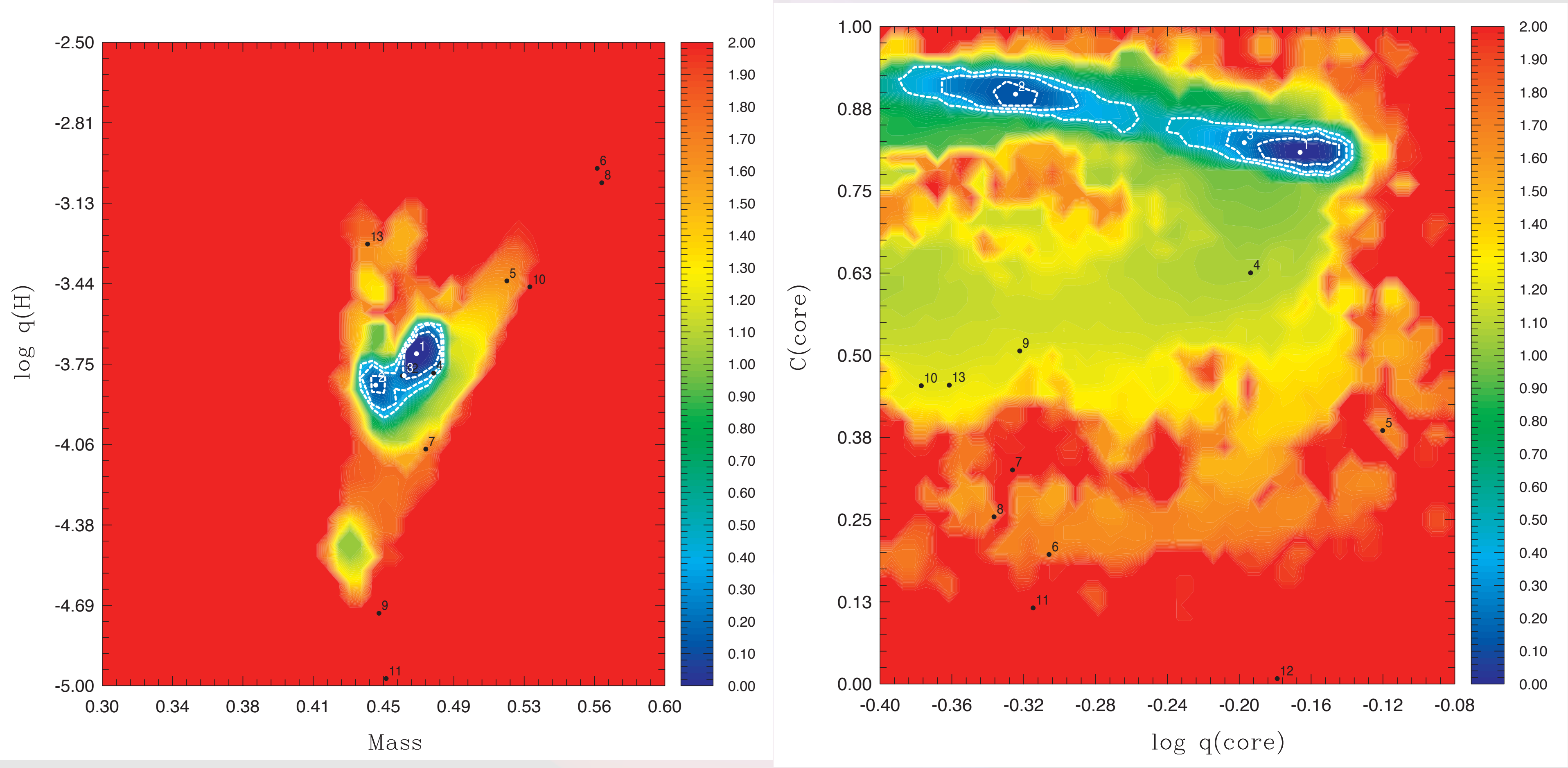
Quantity	Spectroscopy	Asteroseismology	
	Misc. (see Sect. 2.1)	2G model (Charpinet et al. 2005)	3G model (this study)
T_{eff} (K)	$34\,258 \pm 170$	$33\,640 \pm 1360$	$33\,840 \pm 225$
$\log g$	5.838 ± 0.030	5.8071 ± 0.0057	5.806 ± 0.002
$\log N(\mathrm{He})/N(\mathrm{H})$	-1.475 ± 0.030	...	...
$M_*/M_\odot$	...	0.457 ± 0.007	0.439 ± 0.004
$\log(M_{\mathrm{env}}/M_*)$	...	-4.254 ± 0.137	-4.32 ± 0.08
$\log(M_{\mathrm{core}}/M*)$	...	...	-0.31 ± 0.01
$X_{\mathrm{core}}(C+O)$	...	...	0.91 ± 0.02
$R_*/R_\odot$	...	0.1397 ± 0.0028	0.1372 ± 0.0005
$L_*/L_\odot$	...	22.12 ± 4.46	22.31 ± 0.75

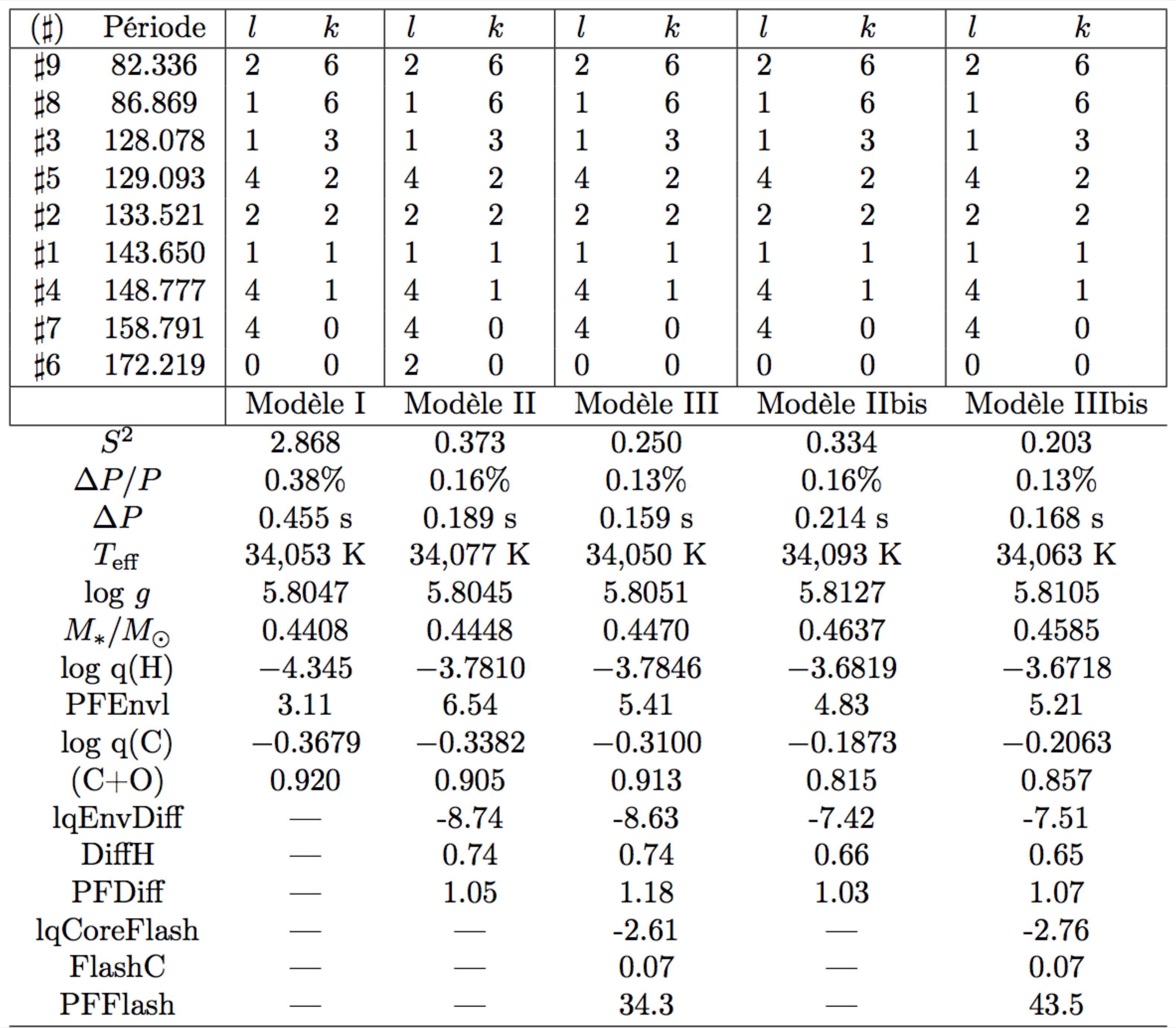
2G/3G very similar + PG 1219+534 is at the end of He burning

Fit to 9 periods (p-modes): <dX/X>~0.35%, <dP>=0.37s

Seismic modeling with 4G models (only p-modes)

2 models emerged (more exhaustive search ?)





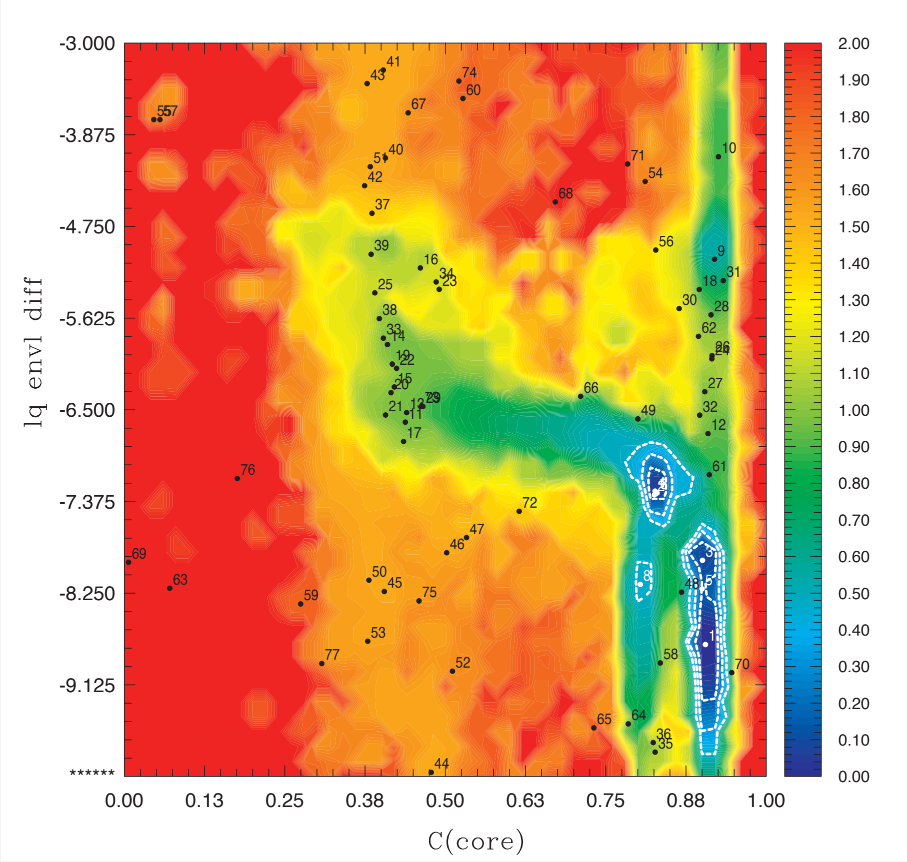
(♯)	Période	l	k	l	k	l	k	l	k	l	k
♯9	82.336	2	6	2	6	2	6	2	6	2	6
♯8	86.869	1	6	1	6	1	6	1	6	1	6
♯3	128.078	1	3	1	3	1	3	1	3	1	3
♯5	129.093	4	2	4	2	4	2	4	2	4	2
♯2	133.521	2	2	2	2	2	2	2	2	2	2
♯1	143.650	1	1	1	1	1	1	1	1	1	1
♯4	148.777	4	1	4	1	4	1	4	1	4	1
♯7	158.791	4	0	4	0	4	0	4	0	4	0
♯6	172.219	0	0	2	0	0	0	0	0	0	0

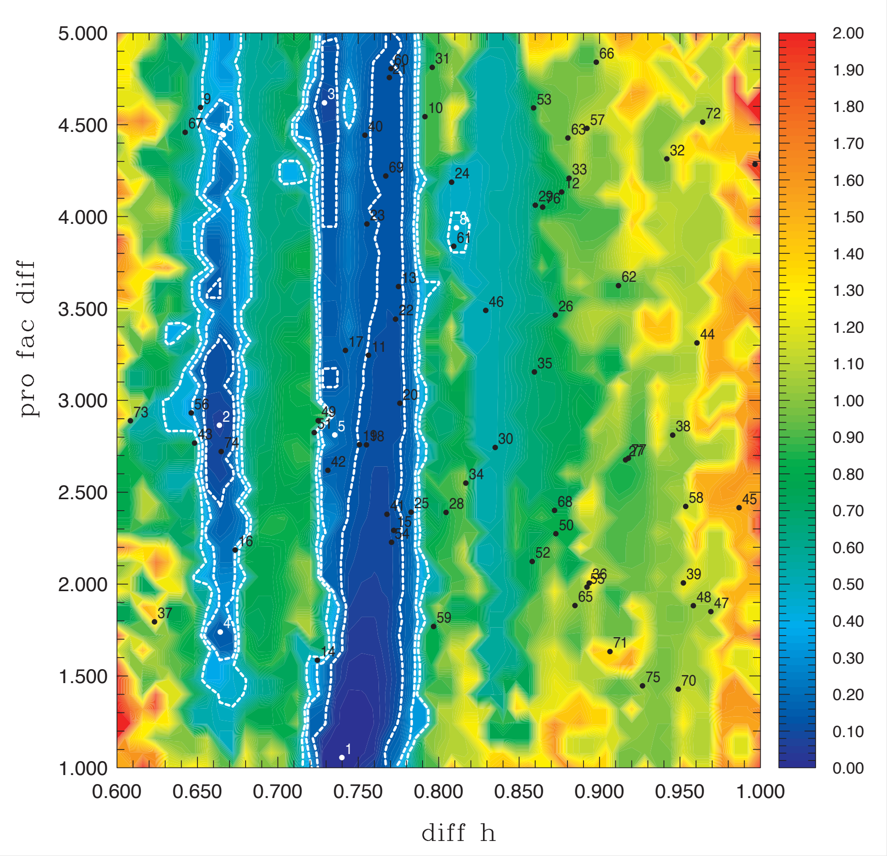
	Modèle I	Modèle II	Modèle III	Modèle IIbis	Modèle IIIbis
S^2	2.868	0.373	0.250	0.334	0.203
$\Delta P/P$	0.38%	0.16%	0.13%	0.16%	0.13%
ΔP	0.455 s	0.189 s	0.159 s	0.214 s	0.168 s
$T_{\rm eff}$	34,053 K	34,077 K	34,050 K	34,093 K	34,063 K
log g	5.8047	5.8045	5.8051	5.8127	5.8105
$M_*/M_\odot$	0.4408	0.4448	0.4470	0.4637	0.4585
log q(H)	−4.345	−3.7810	−3.7846	−3.6819	−3.6718
PFEnvl	3.11	6.54	5.41	4.83	5.21
log q(C)	−0.3679	−0.3382	−0.3100	−0.1873	−0.2063
(C+O)	0.920	0.905	0.913	0.815	0.857
lqEnvDiff	—	-8.74	-8.63	-7.42	-7.51
DiffH	—	0.74	0.74	0.66	0.65
PFDiff	—	1.05	1.18	1.03	1.07
lqCoreFlash	—	—	-2.61	—	-2.76
FlashC	—	—	0.07	—	0.07
PFFlash	—	—	34.3	—	43.5

Seismic modeling with 4G models (only p-modes)

Not constrained by p-modes:
- C pollution of the He mantle
- « Slopes » of chemical transitions

Little constraints on double-transition in the envelope: 65-75% H abundance, transition up to pure H very « high » the star





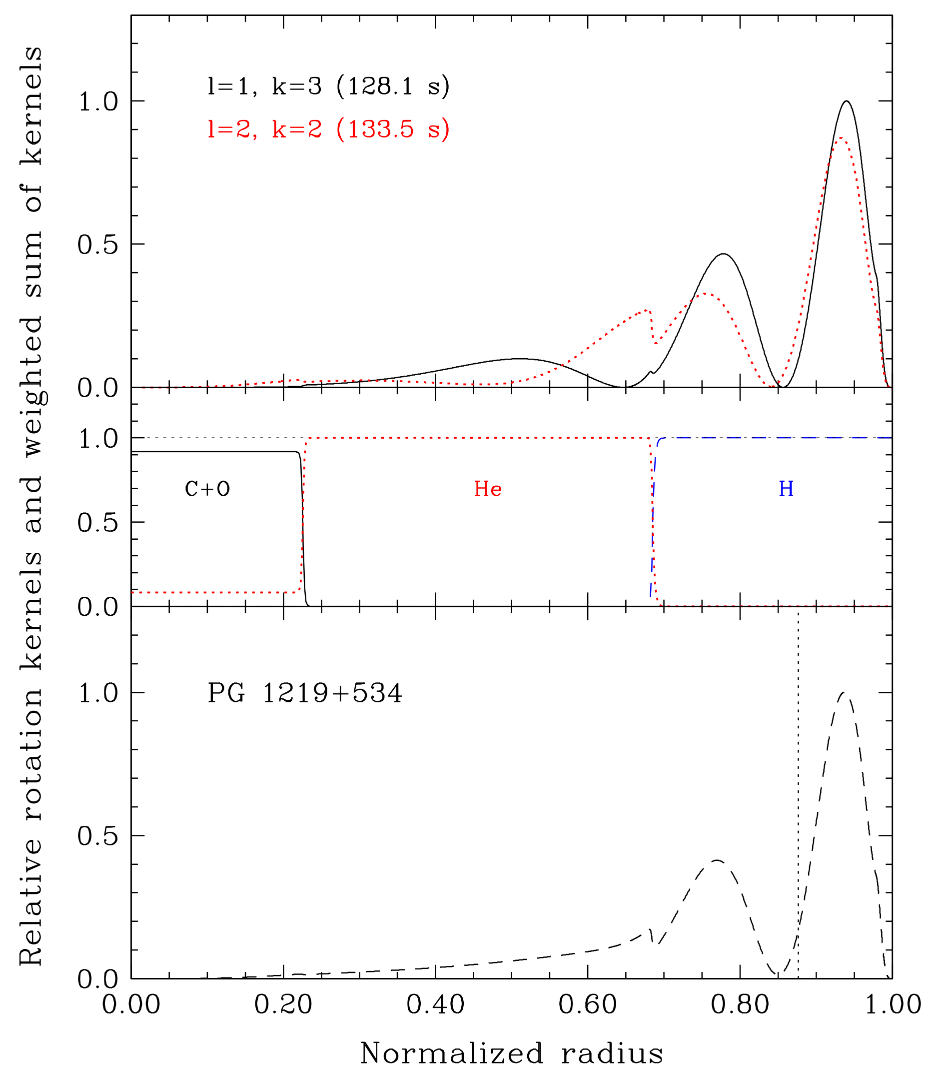
Seismic modeling with 4G models

- Including the 6 g-modes: similar models and fits (dX/X~0.16%); do not help to further constrain core/mantle properties (high-order g-modes)

- **Preliminary conclusions**, 4G models for PG 1219+534:
  - including a double-transition envelope improves the fit
  - The structure of the envelope can be (little) constrained
  - p-modes (and high-order g-modes) do not constrain mantle and core detailed properties
  - Models too far in terms of fit quality ? (see example of white dwarfs, work and poster of N. Giammichele)

Rotation of PG 1219+534

Based on two firm multiplets: 128.1s & 133.5s



Rotation of PG 1219+534

Slow rotation: 1st-order perturbative approach

$$\nu_{klm} = \nu_{kl} - m \int_0^R \Omega(r) K_{kl}(r) dr \quad ; \quad K_{kl}(r) = \frac{\xi_r^2 - [l(l+1) - 1]\xi_h^2 - 2\xi_r \xi_h}{\int_0^R [\xi_r^2 + l(l+1)\xi_h^2] \rho r^2 dr} \rho r^2$$

Solid-body rotation

$$\Delta\nu = \nu_{klm} - \nu_{kl} = m \frac{1 - C_{kl}}{P_{\mathrm{rot}}} \quad ; \quad C_{kl} = \frac{\int_0^R \{\xi_h^2 + 2\xi_r \xi_h\} \rho r^2 dr}{\int_0^R \{\xi_r^2 + l(l+1)\xi_h^2\} \rho r^2 dr} \, .$$

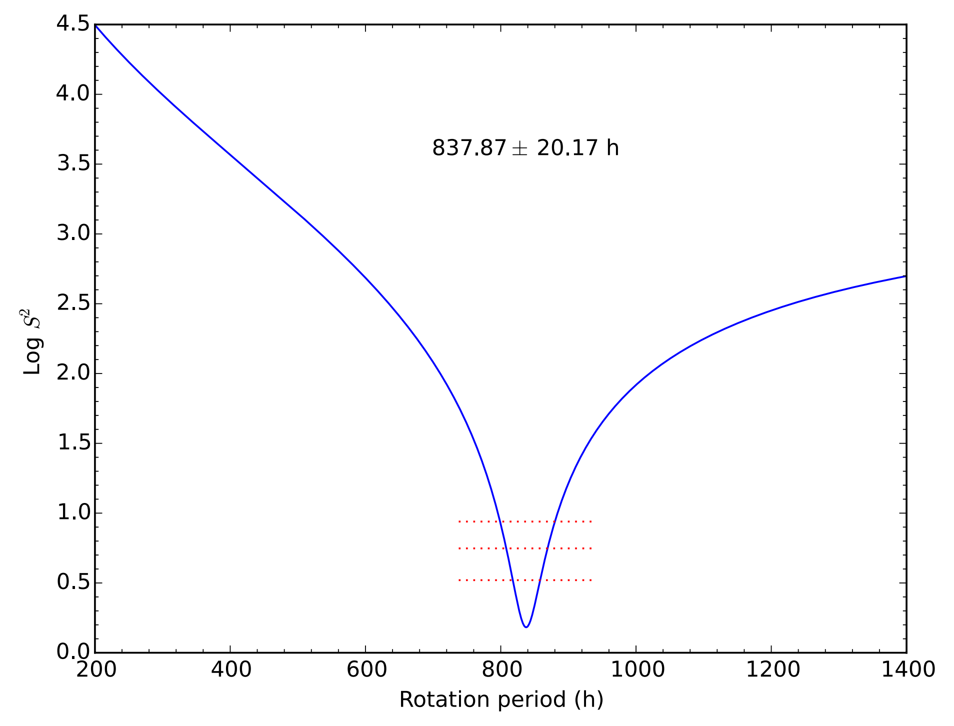
C_{kl} <0.02 for p-modes

C_{kl}~0.5 for ell=1 g-modes

C_{kl}~0.2 for ell=2 g-modes

Rotation of PG 1219+534

Assuming solid-body rotation:

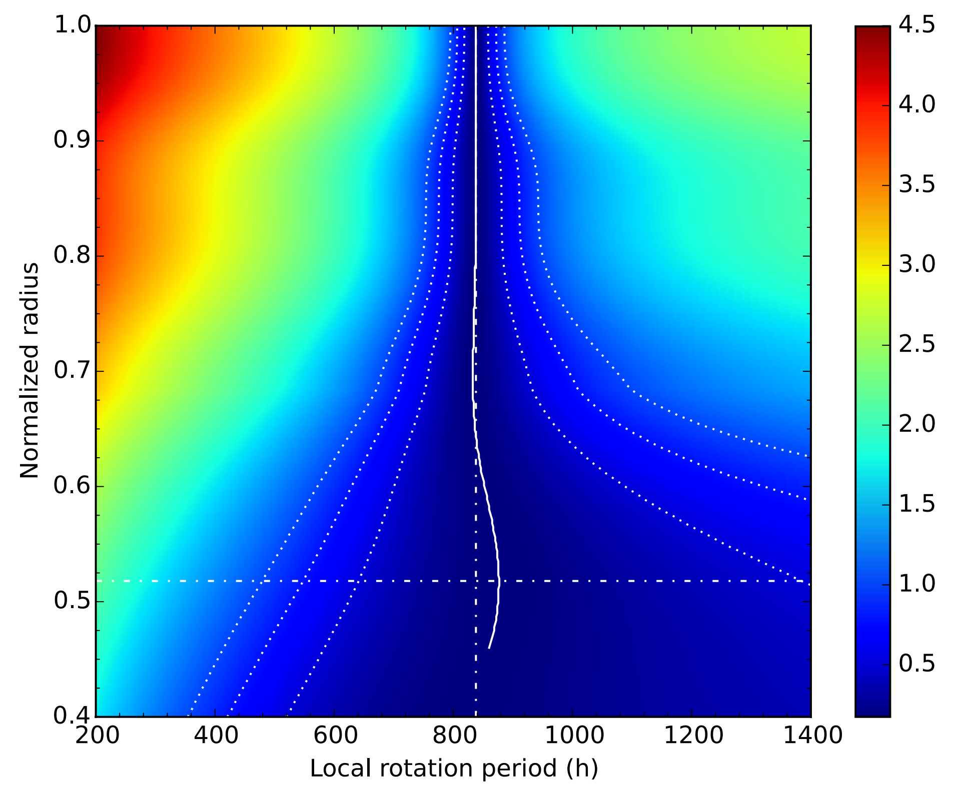


P_{rot} = 34.91±0.91 d

g-mode triplet: if ell=2 (Ckl~0.16), Δv=0.54 μHz (observed: 0.52μHz)

Rotation of PG 1219+534

Internal rotation profile



The star rotates as a solid-body at least down to ~0.5R$_*$

(TO DO: include g-mode triplet)

Outline

I. Pulsating sdB stars

II. PG1219+534: photometric & spectroscopic observations

III. PG 1219+534: asteroseimic modeling

IV. Conclusions & prospects

Conclusions

- PG 1219+534:
  - “Canonical” mass sdB star: 0.46 ± 0.02 Msun
  - Star at the end of He-burning: 85±6% of He burnt
  - Slow rotator (35 d), solid body at least down to 0.5 R*
  - p-modes neither (the 6) high-order g-modes can constrain
    - extension of the convective core
    - possible contamination by C in He mantle
    - “slopes” of chemical transition

Prospects:

✓All data from Mt Bigelow campaign (PG 1336-018, Feige 48, PG1605+072, PB5450,…) and Kepler/K2 to analyze – not a trivial task !