

High-degree gravity modes in the single sdB star HD 4539

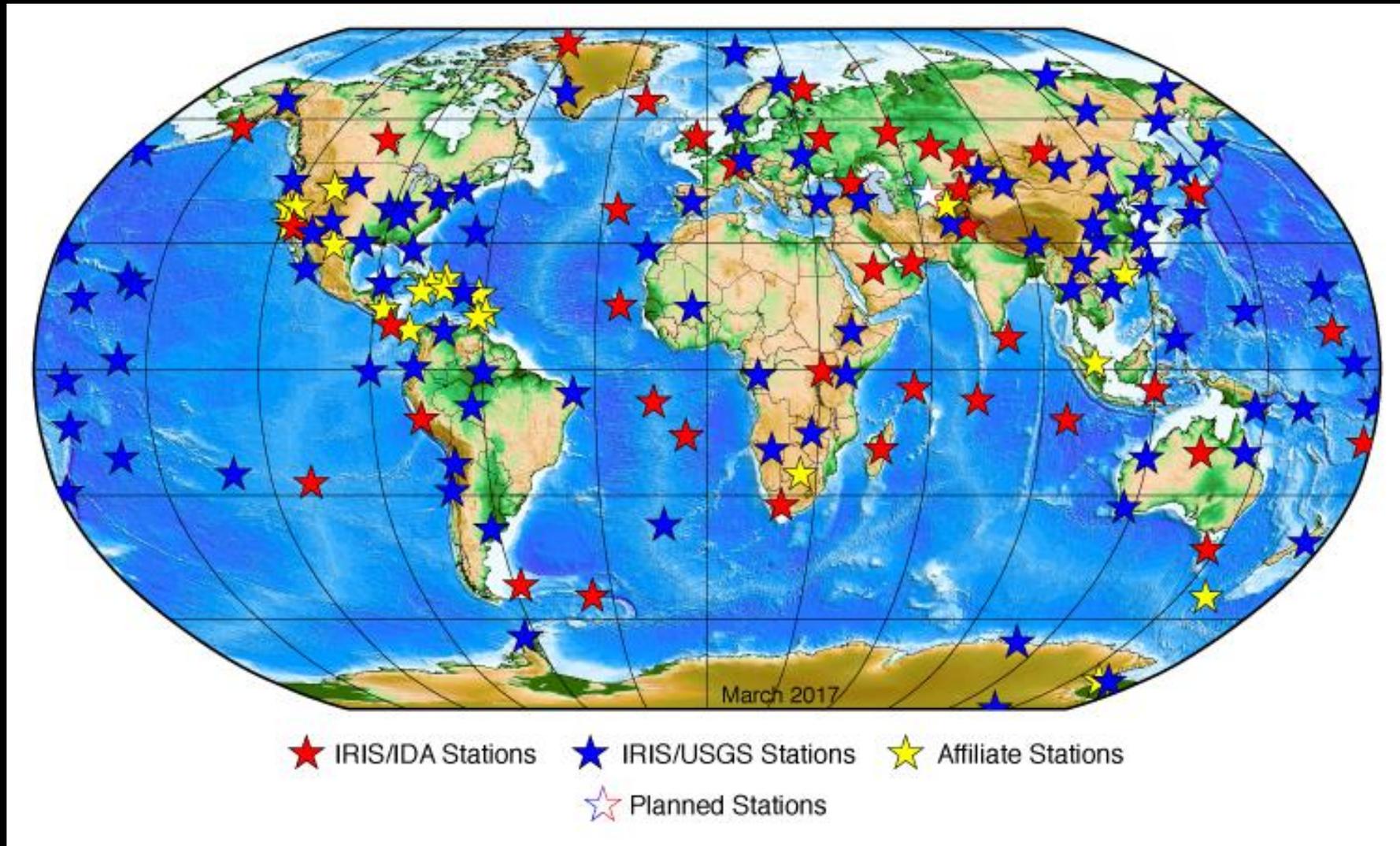
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U. Heber,⁶ M. D. Reed⁴ and M. Vücković²

HD 4539: la grande sinfonia di una piccola stella antica

INAF-OATo *Astrocoffee*
23 Ottobre 2019

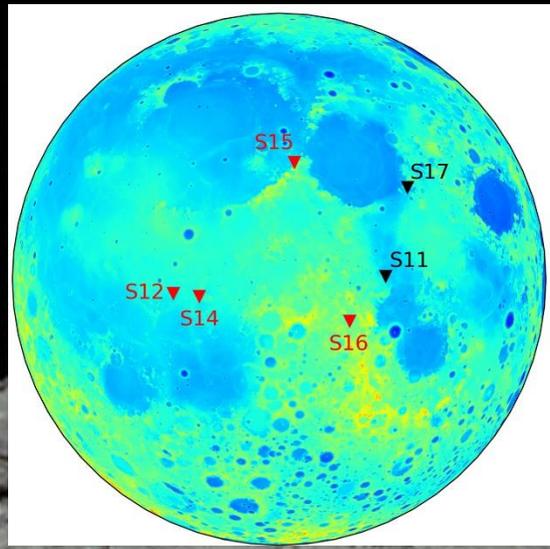
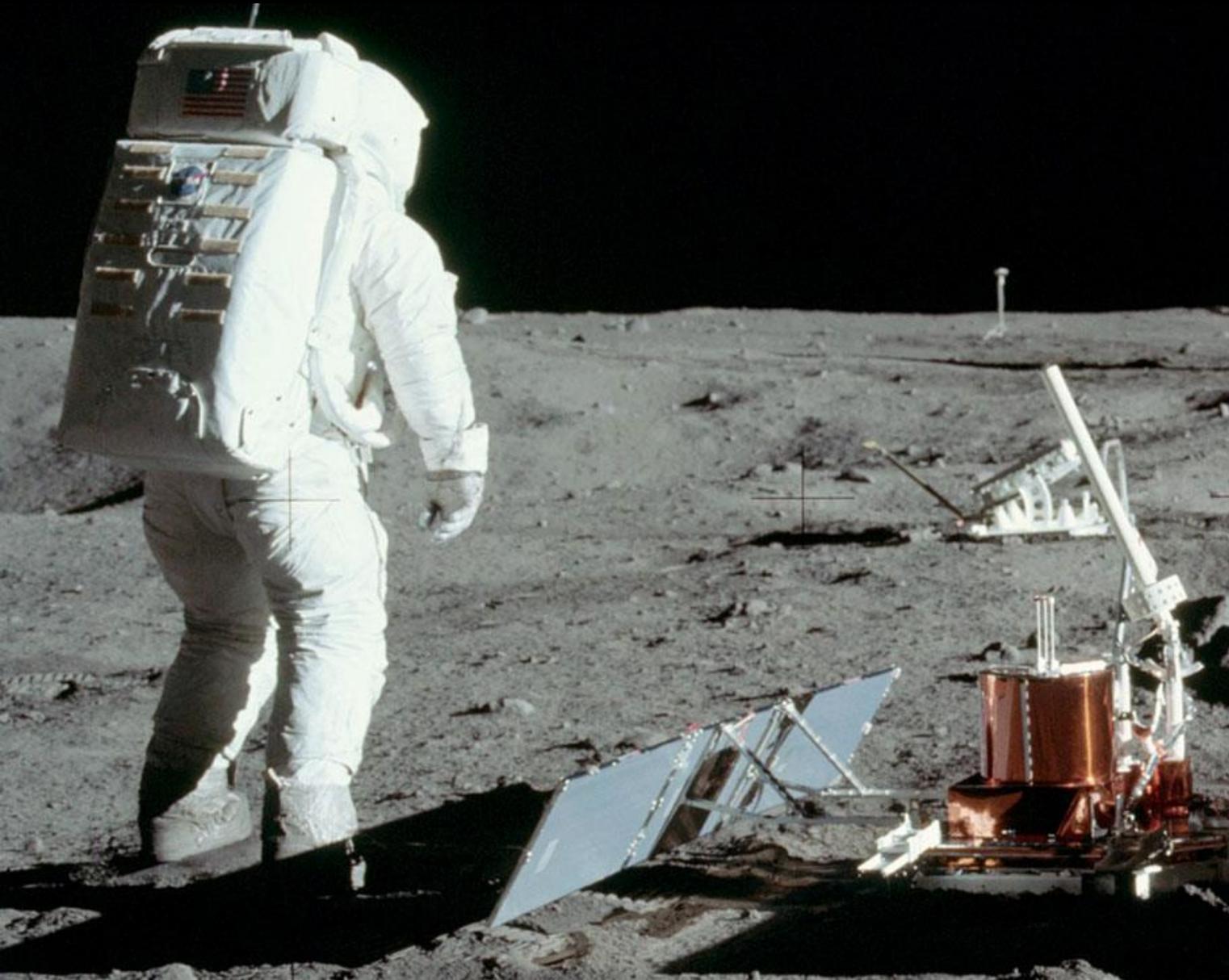


Come nel caso della Terra, dove lo studio della propagazione delle onde sismiche permette di studiare la struttura interna del nostro pianeta, qualcosa di simile si fa anche per altri corpi celesti.

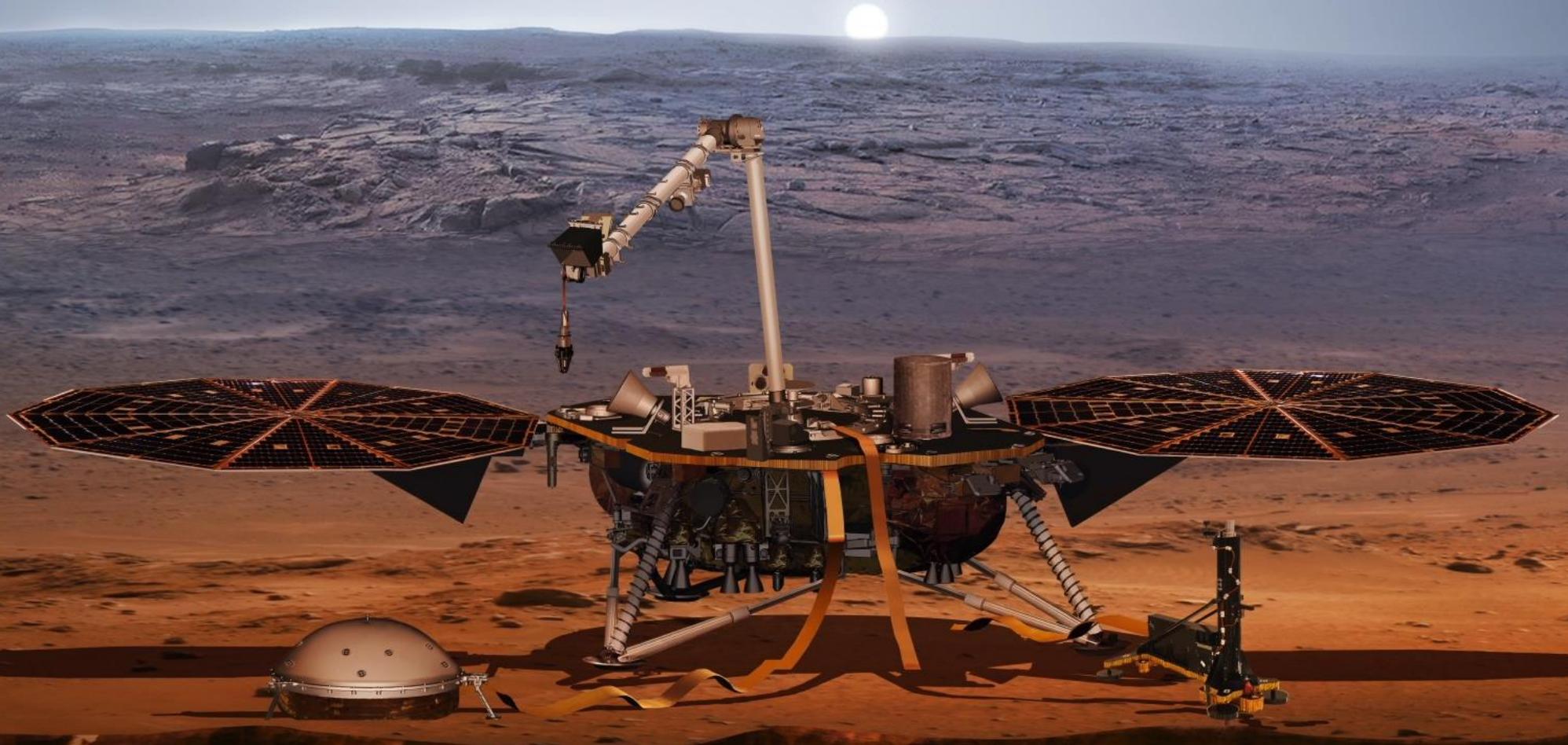


GSN (Global Seismographic Network)

Di recente, nuove analisi dei dati registrati dai 6 sismografi portati sulla Luna dalle missioni Apollo indicano che la Luna potrebbe essere piu` attiva di quanto si pensasse.



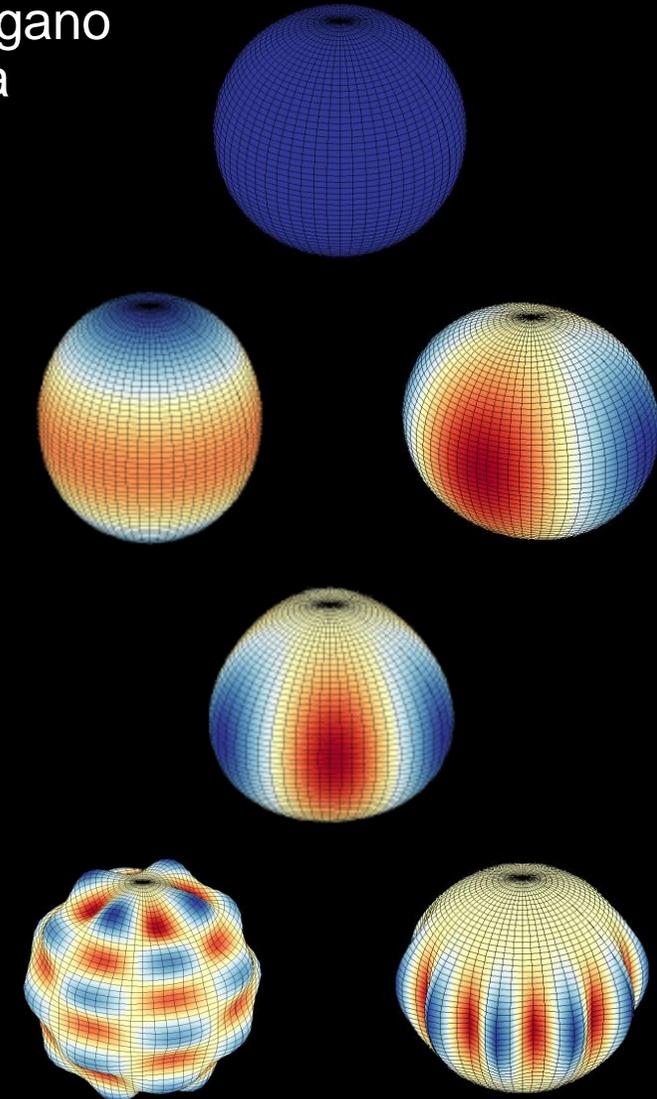
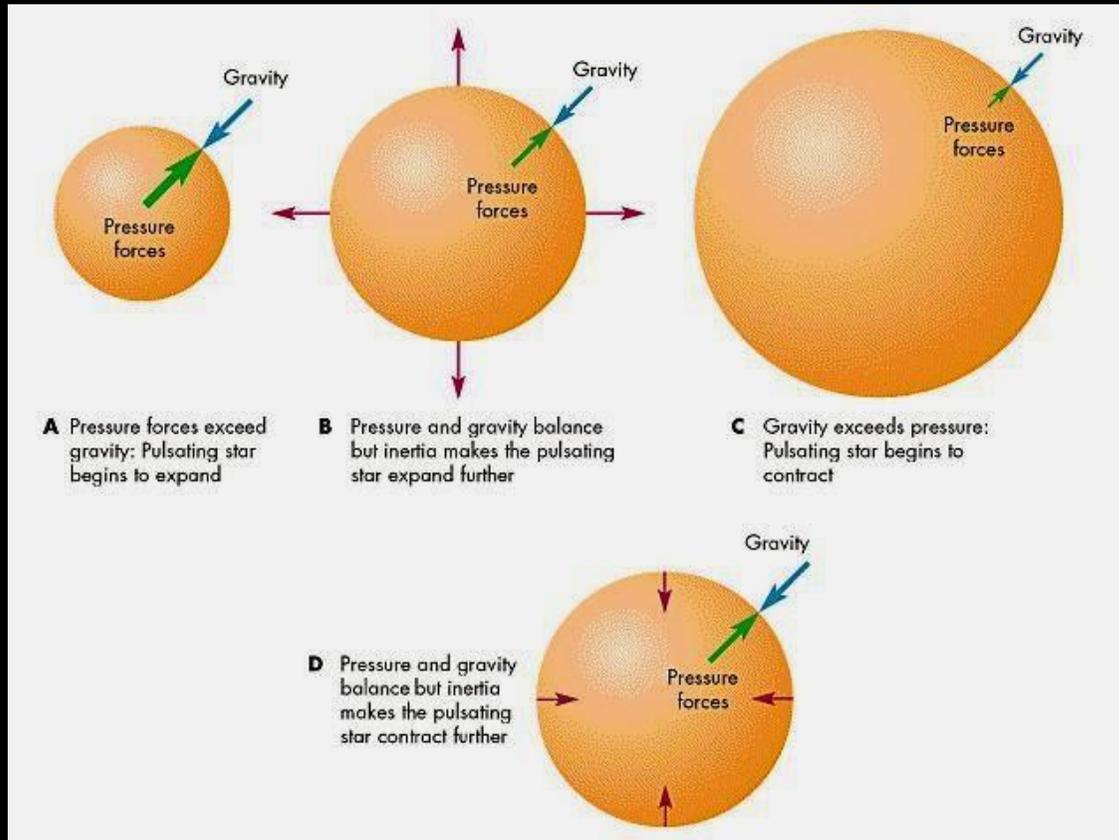
E da meno di un anno per la prima volta il sismografo della missione Insight sta fornendo i primi dati sismici dal suolo di Marte.



Ma qui ci occupiamo di stelle.

Studi simili si fanno da decenni anche per il Sole (eliosismologia) e per varie classi di stelle (asterosismologia).

L'idea di base è la stessa: dallo studio di come si propagano le onde sismiche all'interno della stella si può dedurre la densità dei vari strati interni e quindi la struttura stessa della stella.

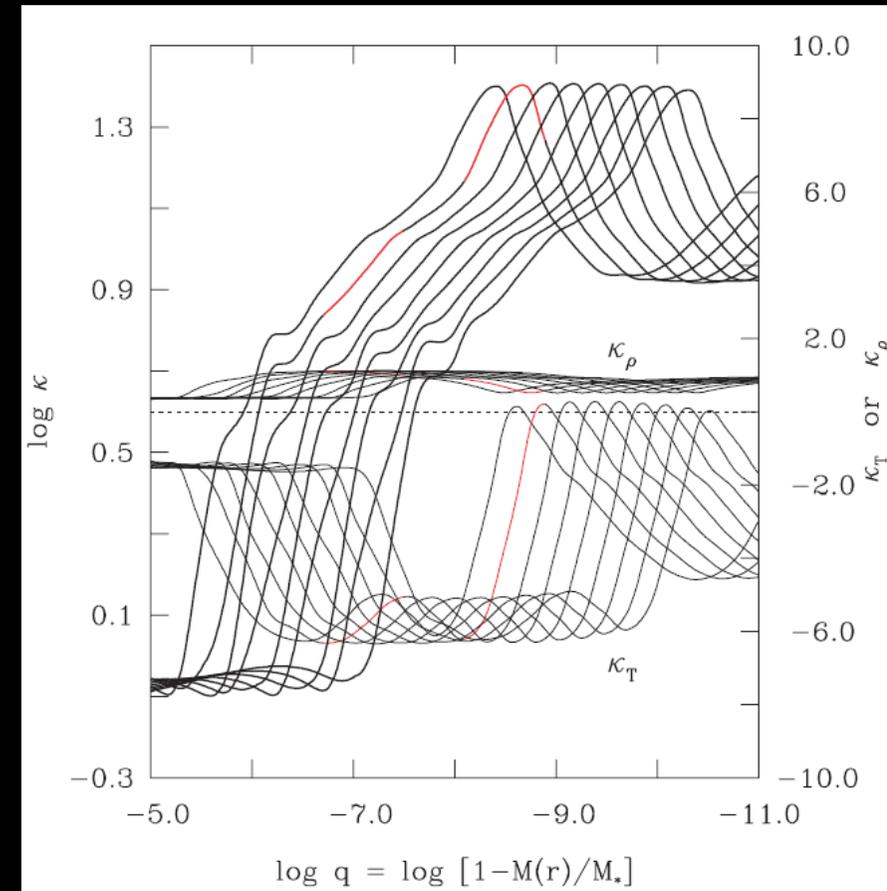


Ma qual è il meccanismo che rende le pulsazioni stabili ?

Per le maggior parte delle stelle pulsanti è il cosiddetto **meccanismo k** (dove k sta per opacità).

Normalmente se il gas stellare viene compresso aumentano temperatura e pressione e con l'aumento della temperatura diminuisce l'opacità (leggi di Kramer) e quindi il maggior rilascio di energia riporta il sistema in equilibrio: la stella è stabile.

Ma se la regione di compressione del gas corrisponde a una zona di ionizzazione parziale di un elemento, in genere H o He, l'eccesso di energia della compressione serve ad aumentare la percentuale di materiale ionizzato. **In questo caso l'opacità aumenta con la temperatura !** L'energia immagazzinata da questo processo viene rilasciata solo dopo un certo tempo, quando il gas viene spinto verso l'esterno dalla pressione, fino a che la decompressione porta alla ricombinazione.



Fontaine et al. 2003

[T_{eff} from 22000 K (left) to 38000 K (right)]

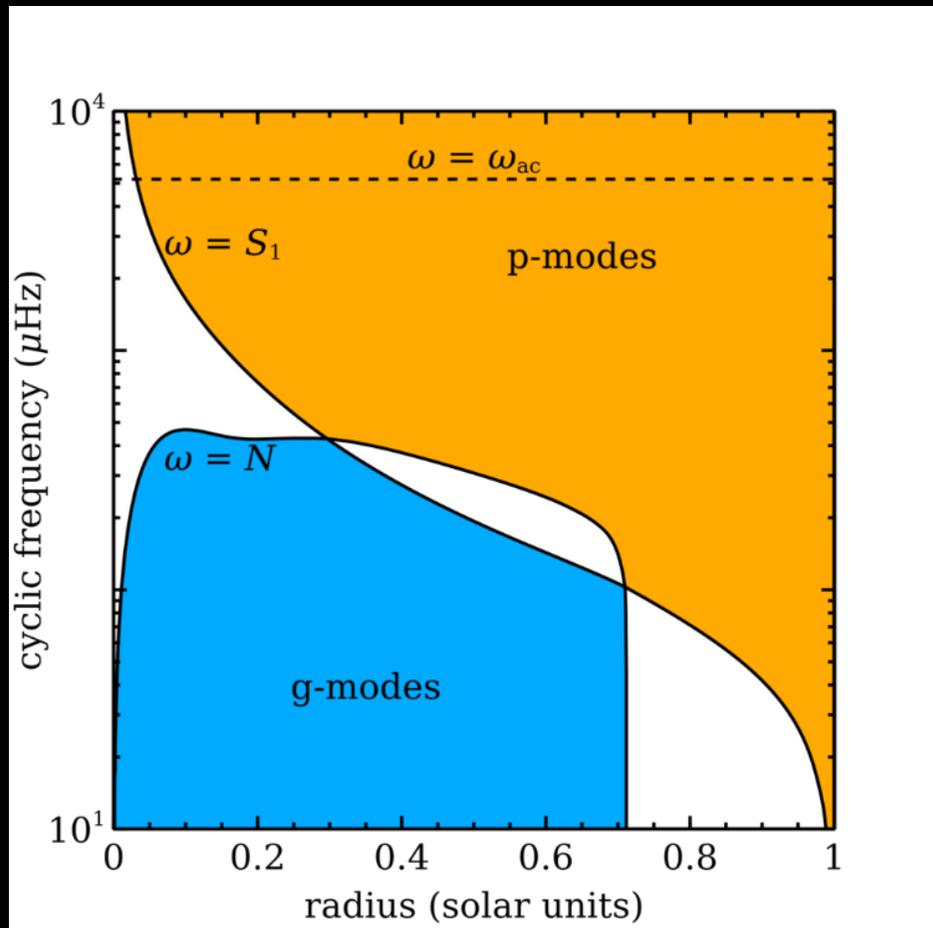
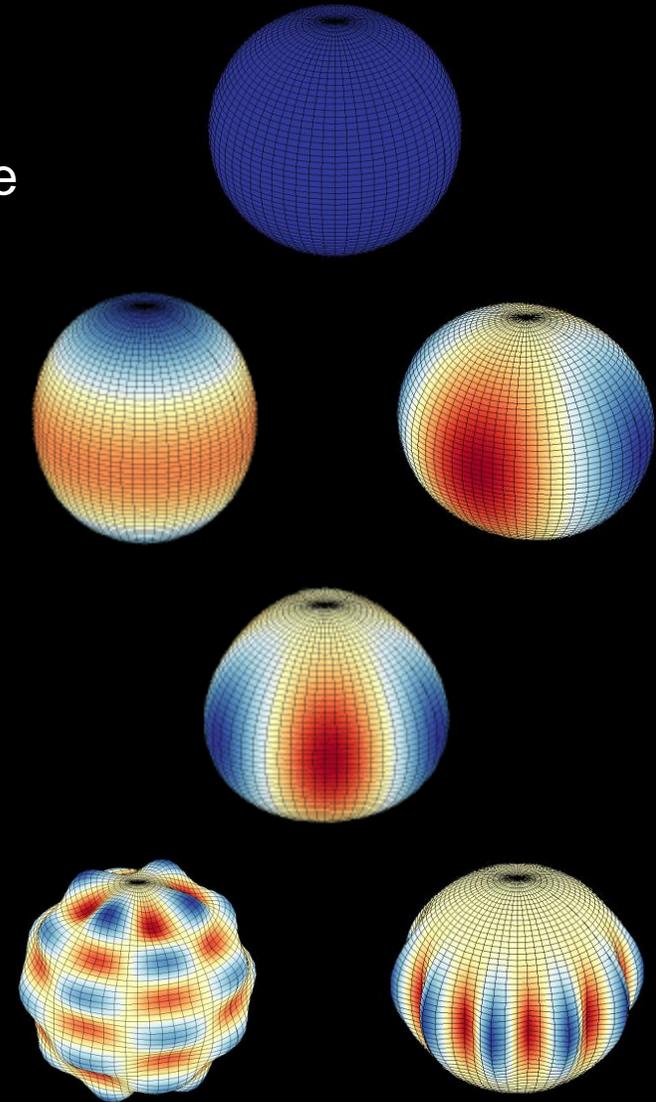
Modi p e modi g

Per le stelle le onde sismiche possono essere di due tipi:

onde di pressione ("modi p") oppure

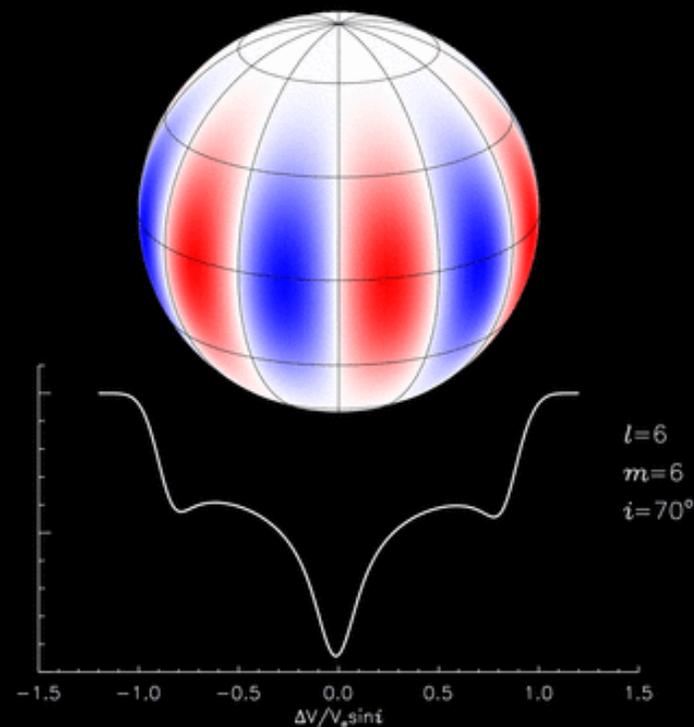
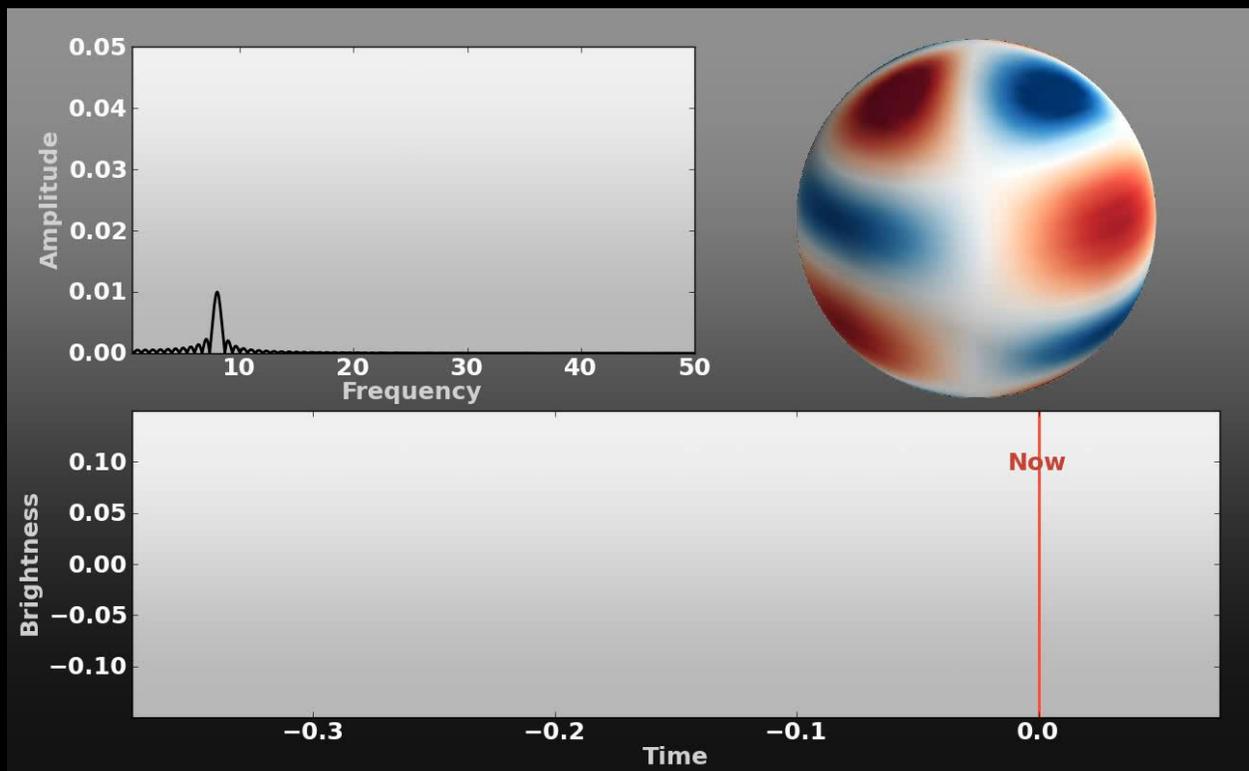
onde di gravità ("modi g")

a seconda che la forza di richiamo sia data dalla pressione o dalla forza di gravità.

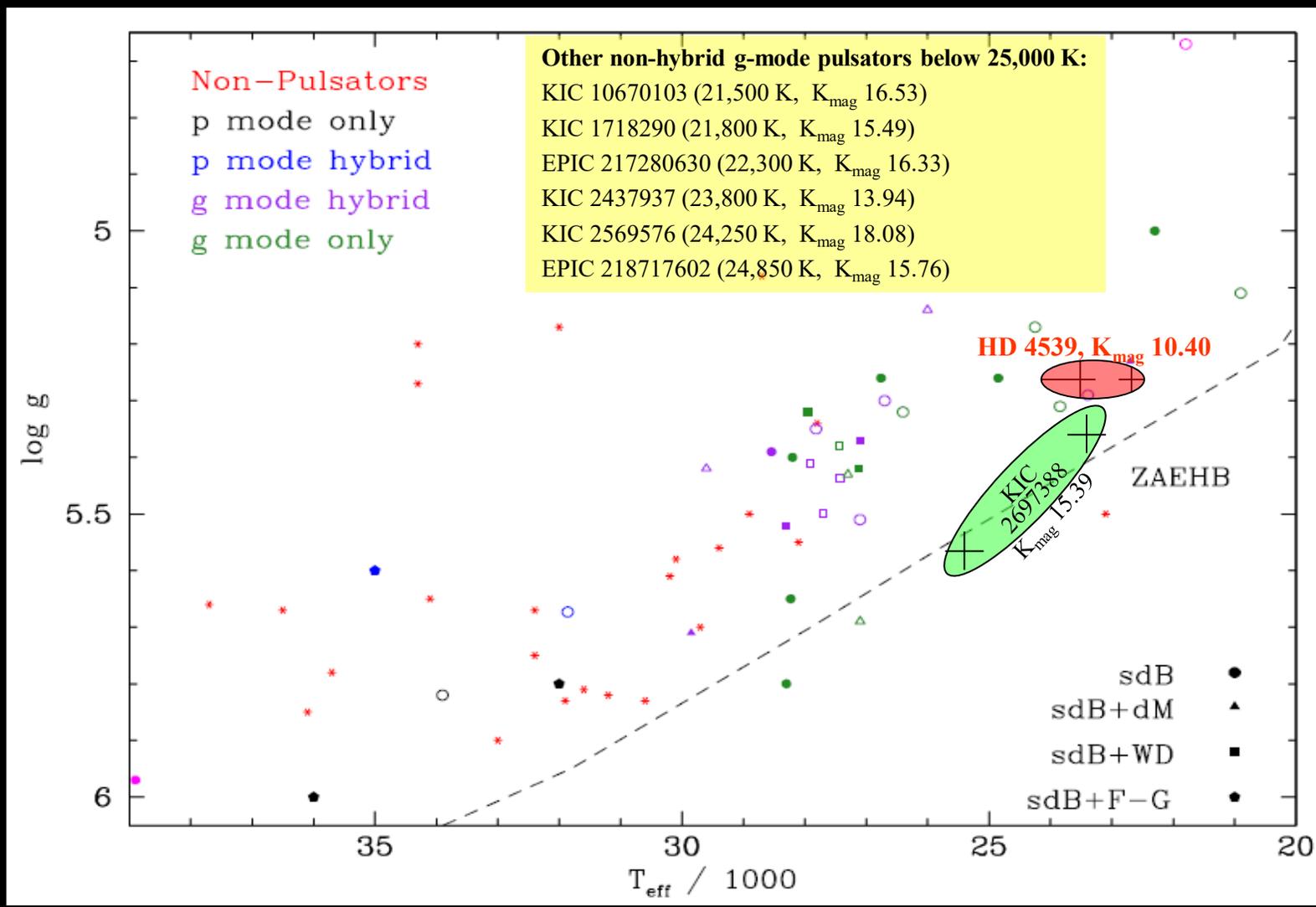


Da un punto di vista osservativo, quello che si può misurare sono i periodi (o le frequenze) di pulsazione e le ampiezze.

Sia ampiezze fotometriche dalle curve di luce, sia ampiezze di velocità radiale dalle curve di velocità radiale.

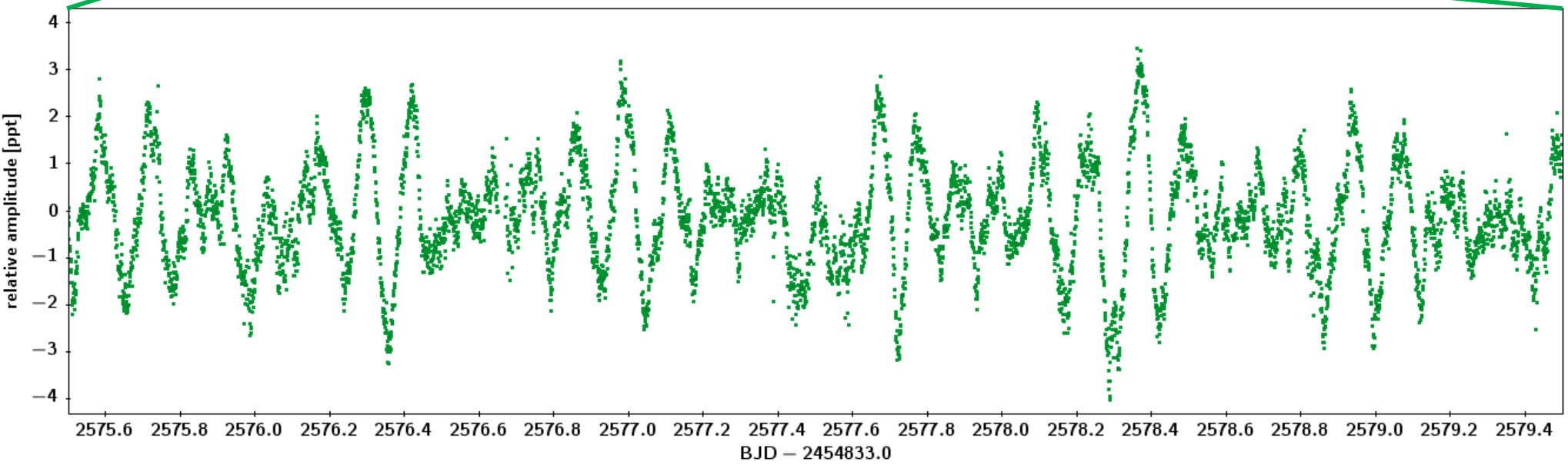
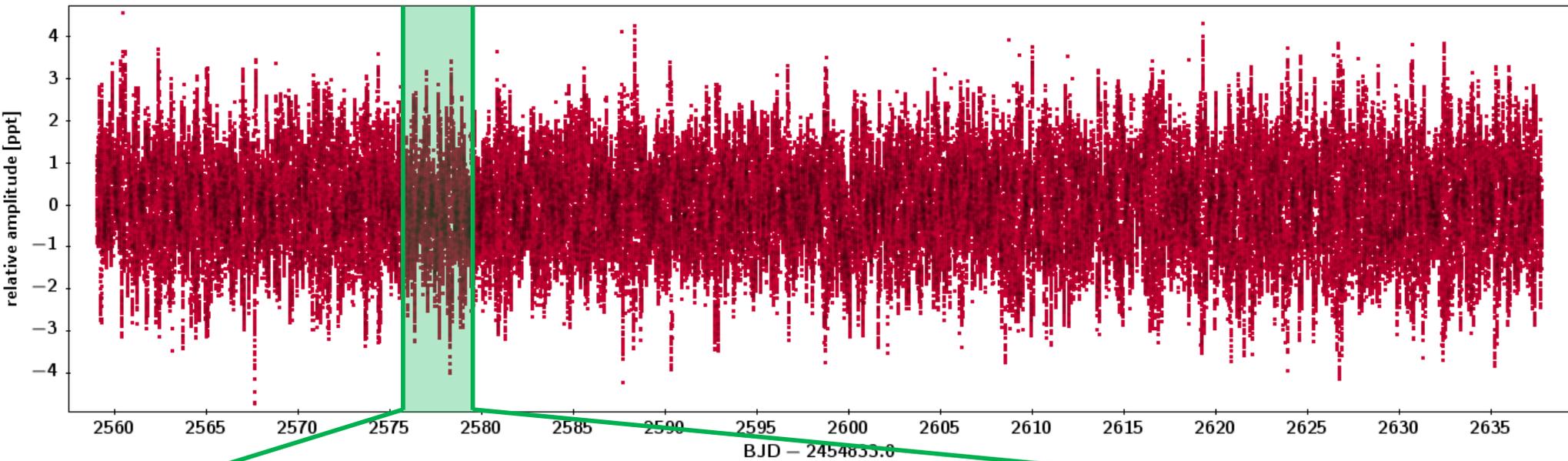


La misura delle frequenze e ampiezze di pulsazione è proprio ciò che è stato fatto con HD4539 (alias PG0044+097 o EPIC220641886), una fra le + brillanti e studiate “subnane calde” conosciute ($V=10.2$) che è stata osservata dal telescopio spaziale Kepler/K2.

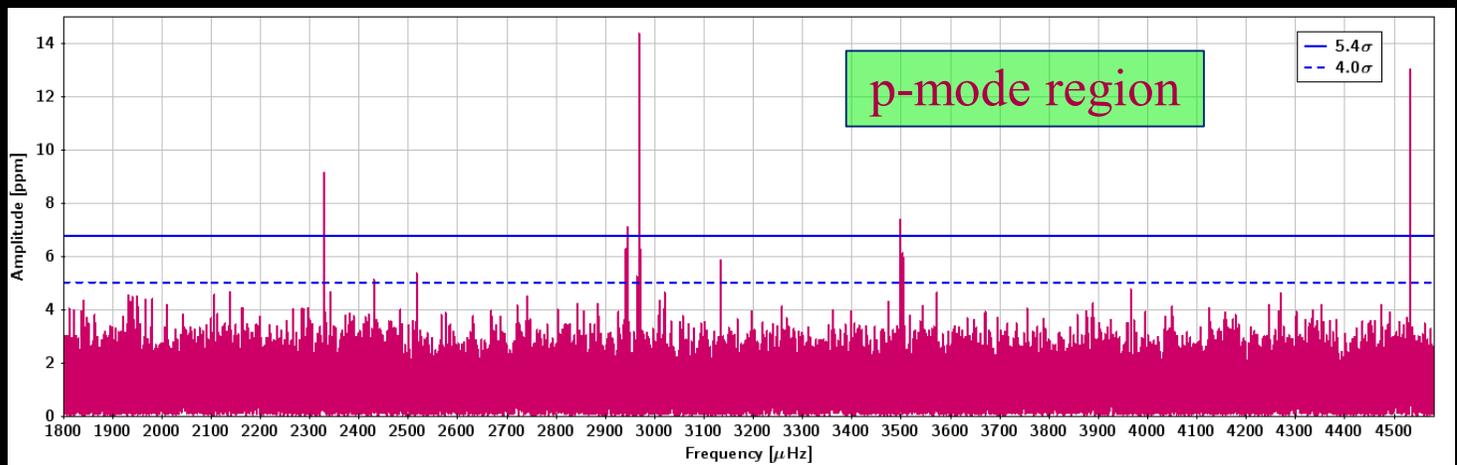
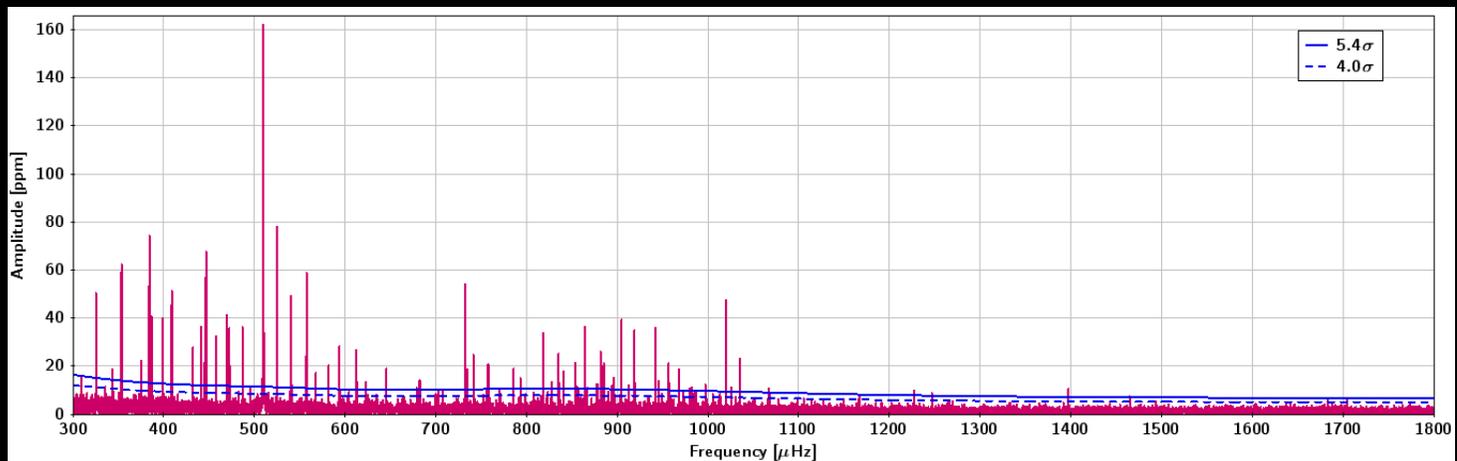
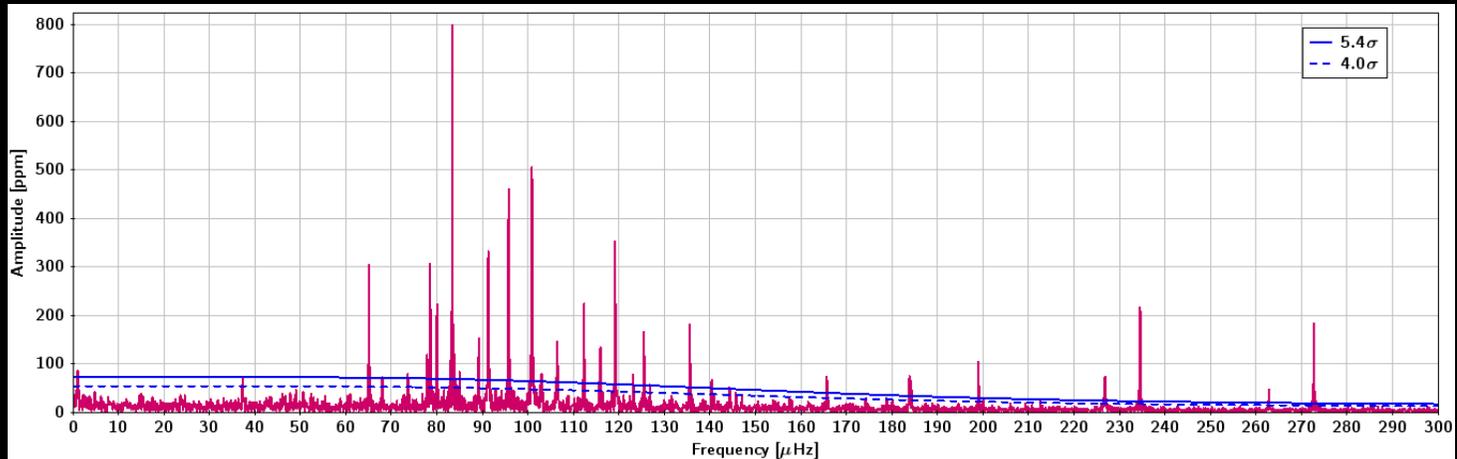


adapted from Reed+2018

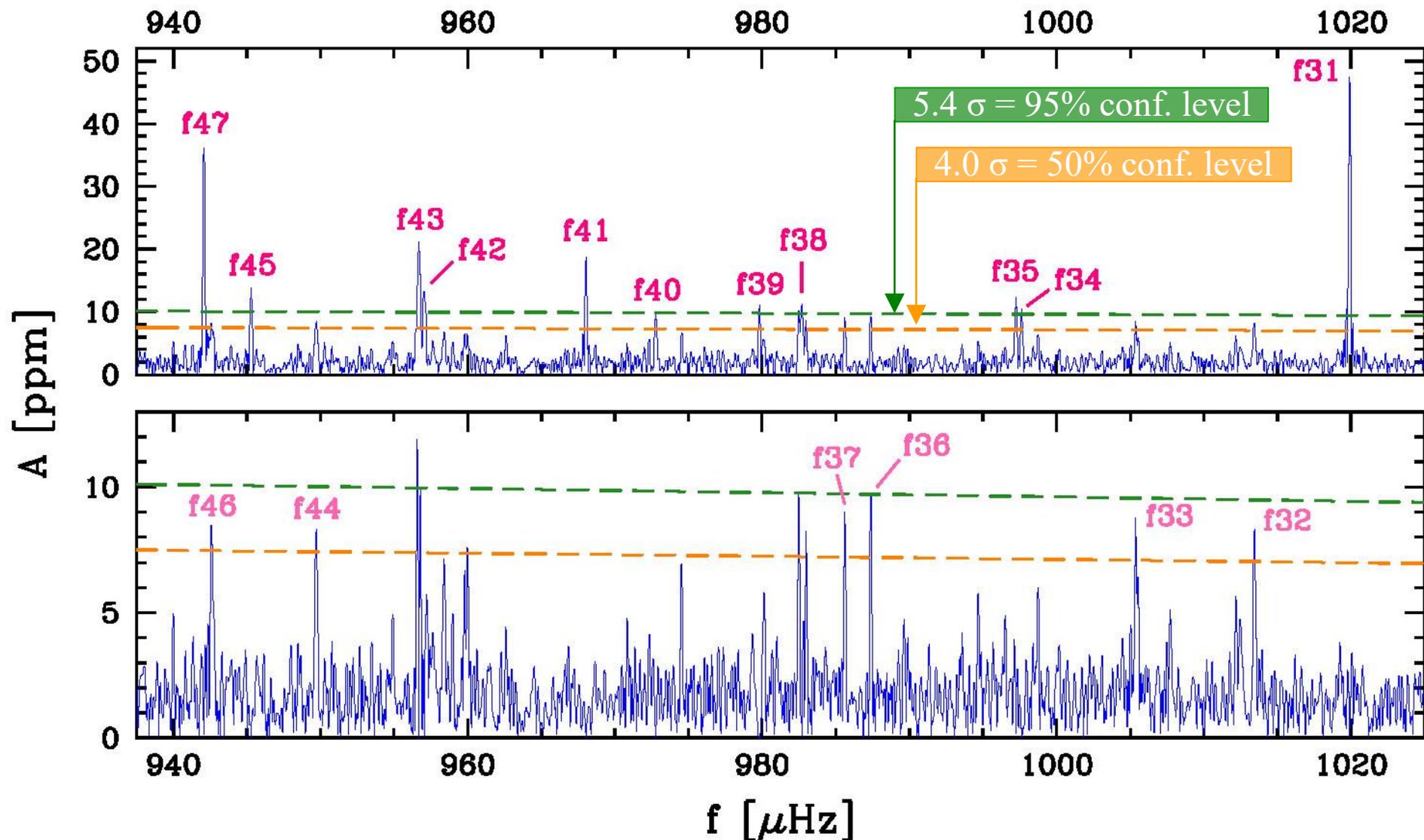
The K2 light curve: 78.7 days



Amplitude spectrum



pulsation frequency 2-step extraction



ID	F [μHz]	P [s]	A [ppm]	l	n	Notes
f1	4531.833	220.66	13.1	—	—	
(f2	3503.332	285.44	6.2	—	—)	
(f3	3499.973	285.72	5.2	—	—)	
f4	3497.986	285.88	7.3	—	—	MR
(f5	3133.521	319.13	5.2	—	—)	
f6	2969.824	336.72	8.6	—	—	
f7	2969.661	336.74	7.6	—	—	
f8	2968.864	336.83	9.8	—	—	
f9	2968.701	336.85	7.3	—	—	
f10	2968.444	336.88	12.4	—	—	
(f11	2963.608	337.43	5.3	—	—)	
f12	2945.414	339.51	7.5	—	—	
(f13	2941.457	339.97	6.0	—	—)	
(f14	2516.795	397.33	4.9	—	—)	
f15	2329.916	429.20	9.4	—	—	MR
approximate boundary between p- and g-modes						
(f16	1704.969	586.52	6.3	—	—)	
(f17	1683.290	594.07	5.5	—	—)	
f18	1465.086	682.55	7.7	—	—	
f19	1397.473	715.58	10.4	—	—	
f20	1246.915	801.98	9.0	—	—	
f21	1227.676	814.55	8.3	—	—	
f22	1227.170	814.88	9.5	—	—	
(f23	1226.799	815.13	6.0	—	—)	
f24	1166.801	857.04	7.6	—	—	MR
(f25	1105.843	904.29	6.2	10	27)	TI
(f26	1077.765	927.85	6.6	9	25)	or l=12, n=34
(f27	1067.695	936.60	7.0	—	—)	
f28	1067.503	936.77	9.7	10	28	TI
f29	1034.893	966.28	22.8	9	26	TI; NoR
f30	1025.764	974.88	11.6	—	—	
f31	1019.899	980.49	48.4	12	36	TI; NoR
(f32	1013.432	986.75	8.5	—	—)	
(f33	1005.356	994.67	8.7	7	21)	or l=8, n=23
f34	997.620	1002.39	9.7	9	27	or l=10, n=30
f35	997.230	1002.78	12.5	10	30	or l=9, n=27
(f36	987.372	1012.79	9.6	—	—)	
(f37	985.603	1014.61	9.1	—	—)	
f38	982.680	1017.63	11.0	6	18	TI; MR
f39	979.808	1020.61	10.1	—	—	
f40	972.769	1027.99	9.5	—	—	
f41	968.027	1033.03	18.5	12	38	TI; NoR
f42	957.031	1044.90	16.5	—	—	
f43	956.670	1045.29	24.0	—	—	MR
(f44	949.703	1052.96	8.4	—	—)	
f45	945.282	1057.89	13.7	—	—	
(f46	942.577	1060.92	8.8	—	—)	
f47	942.061	1061.50	36.7	12	39	TI
f48	919.003	1088.14	34.8	12	40	or l=7, n=23; SR
f49	912.554	1095.83	12.6	—	—	
f50	904.752	1105.28	39.3	10	33	TI; NoR
(f51	902.985	1107.44	9.4	—	—)	
(f52	896.904	1114.95	8.4	9	30)	or l=12, n=41
f53	896.305	1115.69	14.5	12	41	or l=9, n=30
f54	894.152	1118.38	11.8	—	—	
(f55	890.156	1123.40	9.5	8	26)	TI
f56	885.065	1129.86	20.7	6	20	TI MR
f57	881.686	1134.19	26.6	7	24	TI
f58	879.016	1137.64	11.0	10	34	TI
f59	877.037	1140.20	12.8	12	42	TI
f60	867.057	1153.33	11.7	9	31	TI
f61	864.231	1157.10	36.8	—	—	MR

ID	F [μHz]	P [s]	A [ppm]	l	n	Notes
(f62	857.000	1166.86	9.5	8	27)	TI
f63	855.757	1168.56	11.1	12	43	or l=10, n=35
f64	853.968	1171.00	21.2	10	35	or l=12, n=43
f65	841.157	1188.84	18.5	9	32	TI
(f66	836.247	1195.82	9.6	—	—)	
f67	835.861	1196.37	11.0	—	—	
f68	835.416	1197.01	24.4	12	44	TI
f69	828.161	1207.49	13.4	8	28	or l=10, n=36
(f70	823.361	1214.53	8.7	—	—)	
f71	818.056	1222.41	33.8	12	45	or l=9, n=33; or l=7, n=26
(f72	808.031	1237.58	8.8	10	37)	or l=6, n=22
(f73	798.261	1252.72	8.8	8	29)	or l=12, n=46, SR
f74	793.296	1260.56	14.5	9	34	TI
f75	785.720	1272.72	19.6	7	27	TI
(f76	771.070	1296.90	8.0	—	—)	
f77	770.607	1297.68	10.7	9	35	TI, SR
(f78	770.277	1298.23	8.4	—	—)	
f79	757.778	1319.65	19.5	7	28	TI
f80	756.461	1321.95	10.7	—	—	
(f81	752.619	1328.69	8.3	—	—)	
f82	741.650	1348.34	24.2	6	24	TI
f83	734.678	1361.14	19.1	12	50	TI
f84	732.627	1364.95	28.8	—	—	
f85	732.476	1365.23	52.4	7	29	TI
(f86	707.210	1414.01	8.6	12	52)	or l=7, n=30
(f87	702.790	1422.90	8.8	8	33)	TI
(f88	700.061	1428.45	8.8	—	—)	
f89	682.352	1465.52	13.3	8	34	TI
f90	681.253	1467.88	11.6	12	54	TI
f91	679.234	1472.25	10.8	10	44	TI
f92	645.689	1548.73	19.4	8	36	or l=12, n=57
(f93	634.943	1574.95	9.0	12	58)	or l=6, n=28
(f94	625.742	1598.10	7.3	7	34)	TI
f95	622.754	1605.77	14.0	10	48	or l=12, n=59
f96	613.476	1630.05	13.1	9	44	or l=12, n=60 or l=6, n=29
f97	611.943	1634.14	26.4	8	38	
(f98	604.148	1655.22	10.2	12	61)	TI
f99	593.813	1684.03	16.4	6	30	or l=12, n=62
f100	593.579	1684.70	28.1	12	62	or l=6, n=30; MR
f101	581.916	1718.46	20.6	8	40	
f102	567.798	1761.19	17.4	8	41	
f103	557.560	1793.53	58.1	6	32	SR
f104	541.799	1845.70	12.8	8	43	
f105	540.767	1849.23	31.4	12	68	TI; MR
f106	540.551	1849.97	45.7	6	33	
f107	525.061	1904.54	72.5	6	34	
f108	524.847	1905.32	39.0	10	57	TI
(f109	510.027	1960.68	164.4	6	35	SR
(f110	503.468	1986.22	11.5	5	30)	
(f111	495.961	2016.29	8.1	6	36)	
f112	487.276	2052.22	36.0	5	31	MR
(f113	482.714	2071.62	9.5	6	37)	
f114	472.533	2116.25	35.5	5	32	MR
f115	470.009	2127.62	42.1	6	38	MR
f116	458.005	2183.38	33.6	5	33	or l=6, n=39; or l=4, n=27
f117	446.757	2238.35	69.3	6	40	MR
f118	445.031	2247.03	23.0	5	34	MR
f119	441.287	2266.10	38.6	4	28	NoR
f120	432.204	2313.72	26.2	5	35	MR
f121	409.048	2444.70	52.0	5	37	MR
f122	399.031	2506.07	41.8	4	31	MR
f123	386.847	2585.00	41.3	4	32	MR

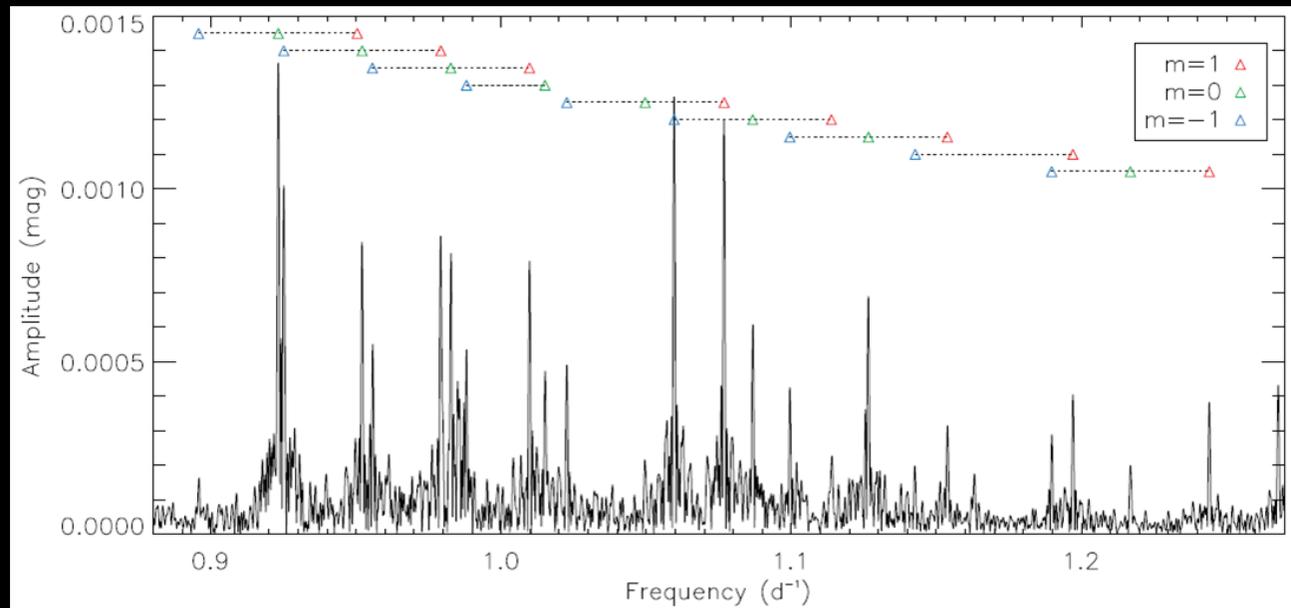
ID	F [μHz]	P [s]	A [ppm]	l	n	Notes
f124	384.362	2601.71	77.3	—	—	SR
f125	374.989	2666.74	20.3	4	33	NoR
f126	353.644	2827.71	61.6	4	35	MR
f127	343.924	2907.62	18.9	4	36	
f128	325.591	3071.34	52.6	4	38	or l=6, n=55; NR
(f129	309.680	3229.14	12.6	4	40)	or l=5, n=49
f130	272.740	3666.50	185.5	2	25	NoR
f131	262.856	3804.37	47.0	2	26	
f132	234.551	4263.47	217.1	2	29	NoR
f133	226.883	4407.56	83.4	—	—	
f134	226.772	4409.72	79.5	2	30	
(f135	212.630	4703.01	21.6	2	32)	
(f136	200.065	4998.36	26.3	2	34)	or l=1, n=20
f137	199.019	5024.65	103.8	1	20	or l=2, n=34; NR
f138	184.250	5427.40	52.0	—	—	
f139	183.842	5439.44	69.5	2	37	MR
(f140	178.849	5591.29	30.8	2	38)	
(f141	174.249	5738.90	28.8	2	39)	
f142	165.701	6034.97	74.8	2	41	
(f143	145.725	6862.25	42.8	1	27)	
f144	144.346	6927.78	49.1	2	47	
f145	140.381	7123.45	68.7	1	28	
f146	135.588	7375.29	180.0	2	50	or l=1, n=29
f147	126.811	7885.73	55.7	1	31	
f148	125.496	7968.39	163.3	2	54	
f149	123.141	8120.80	75.9	2	55	or l=1, n=32
f150	119.146	8393.06	355.3	1	33	or l=2, n=57; MR
f151	115.962	8623.53	131.4	1	34	
f152	115.645	8647.18	62.5	—	—	
f153	112.324	8902.79	223.3	1	35	MR
f154	106.398	9398.65	150.4	1	37	SR
f155	102.991	9709.61	73.2	1	38	TI
f156	102.856	9722.33	70.1	2	66	TI
f157	100.875	9913.29	502.5	1	39	SR
f158	95.776	10440.98	457.4	1	41	MR
(f159	92.884	10766.12	50.9	2	73)	
f160	91.298	10953.08	322.4	1	43	SR
f161	89.230	11207.02	146.6	1	44	
f162	85.032	11760.31	81.3	1	46	TI
f163	83.396	11990.97	796.1	1	47	NoR
f164	80.035	12494.57	231.9	1	49	
f165	78.508	12737.50	321.9	1	50	or l=2, n=86; MR
f166	77.842	12846.60	144.5	2	87	
f167	73.613	13584.56	74.9	2	92	or l=1, n=53
f168	68.027	14700.08	71.5	2	99	or l=1, n=58
f169	65.073	15367.46	306.0	2	104	or l=1, n=60

124 robust detections
 (>95% confidence level)
 + 45 candidates
 (>50% confidence level)

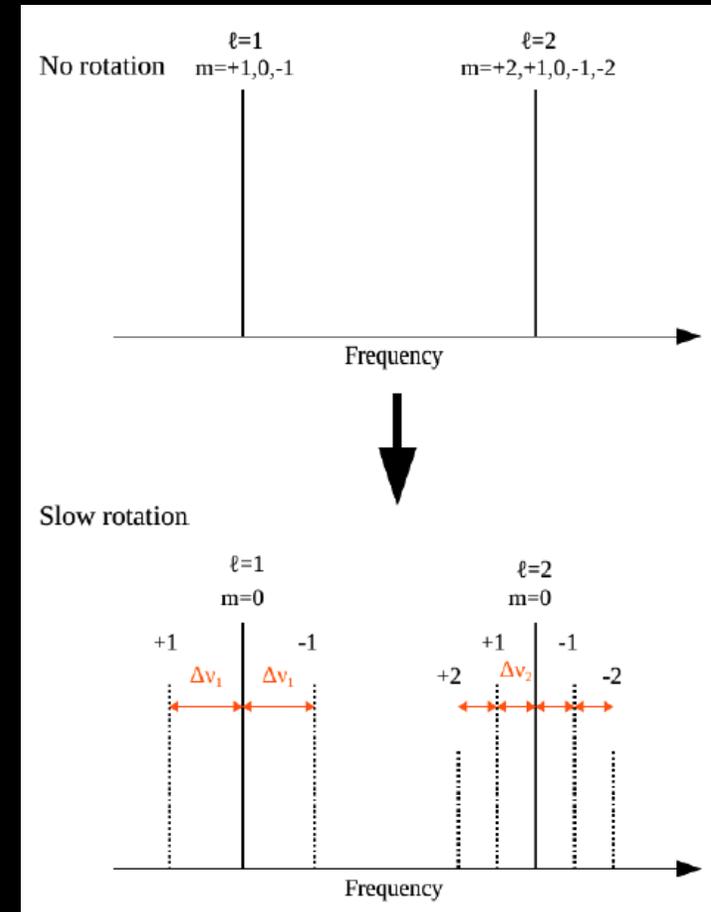
Ma cosa si cerca nel periodogramma ?

Principalmente 2 cose che servono a «identificare» i modi [cioè determinare n (ordine radiale), l (grado) e m (ordine azimutale)]:

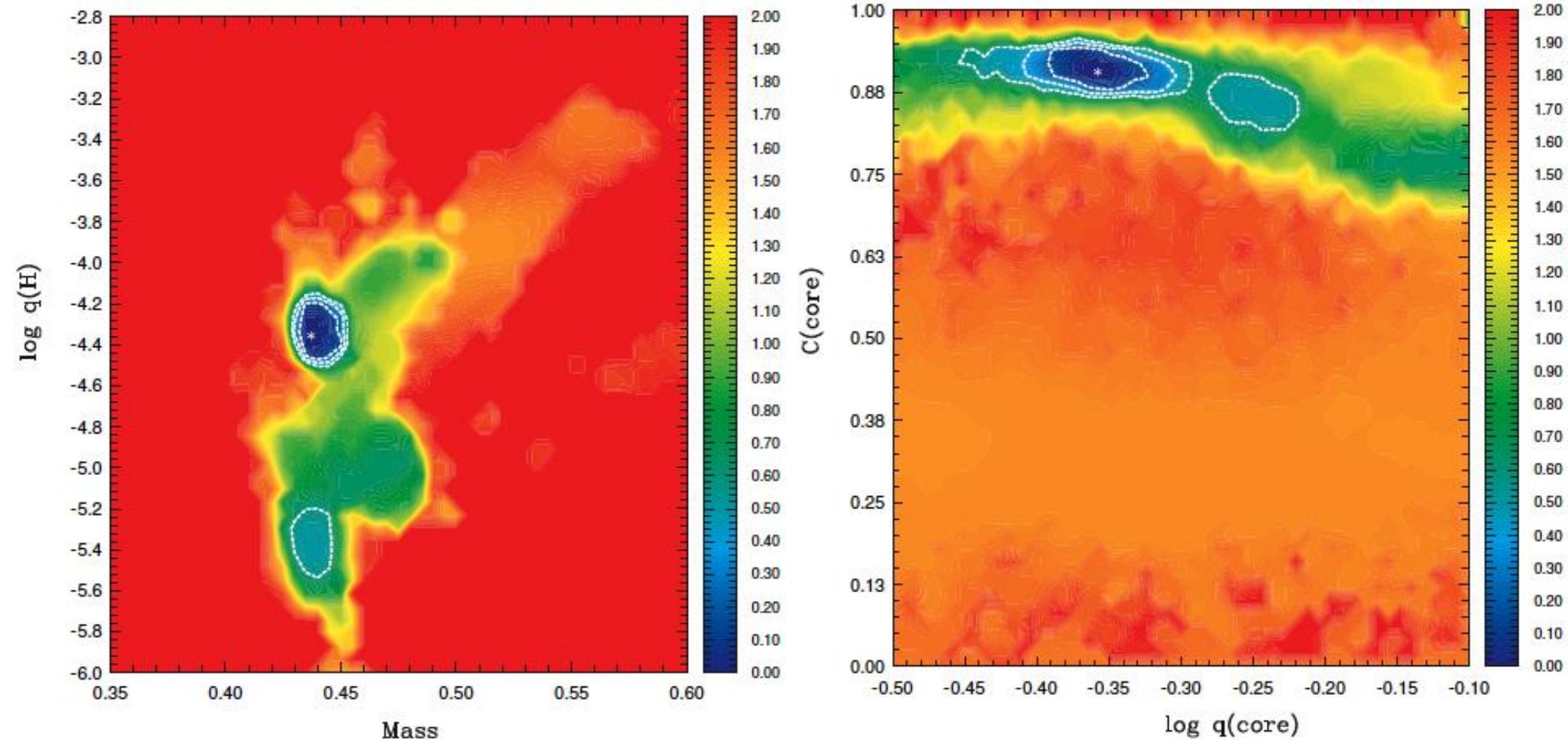
- a) *splitting rotazionale delle frequenze* (equispaziatura delle frequenze) da cui si ricava direttamente il periodo di rotazione (+ ev. rotaz. differenziale)
- b) *Equispaziatura dei periodi per i modi g* (o equisp. delle frequenze per i modi p)



Spettro di ampiezza di una γ Doradus (da Bedding+2014)

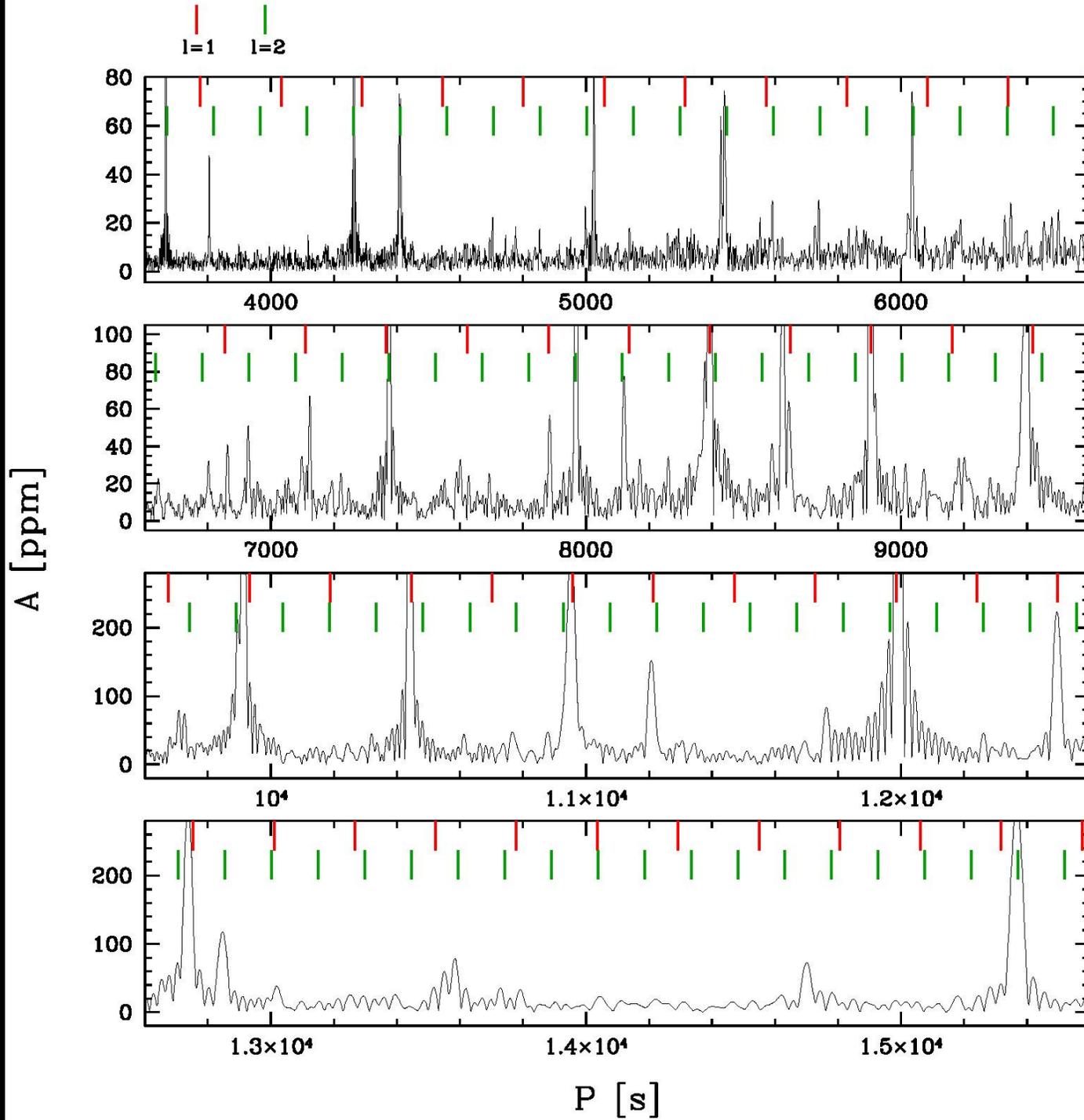


E una volta identificate le frequenze, dal confronto con le frequenze teoriche si possono ottenere vari parametri stellari ...



Esempio da Van Grootel+2018 sulla sdB PG 1219+534

Period spacing 1



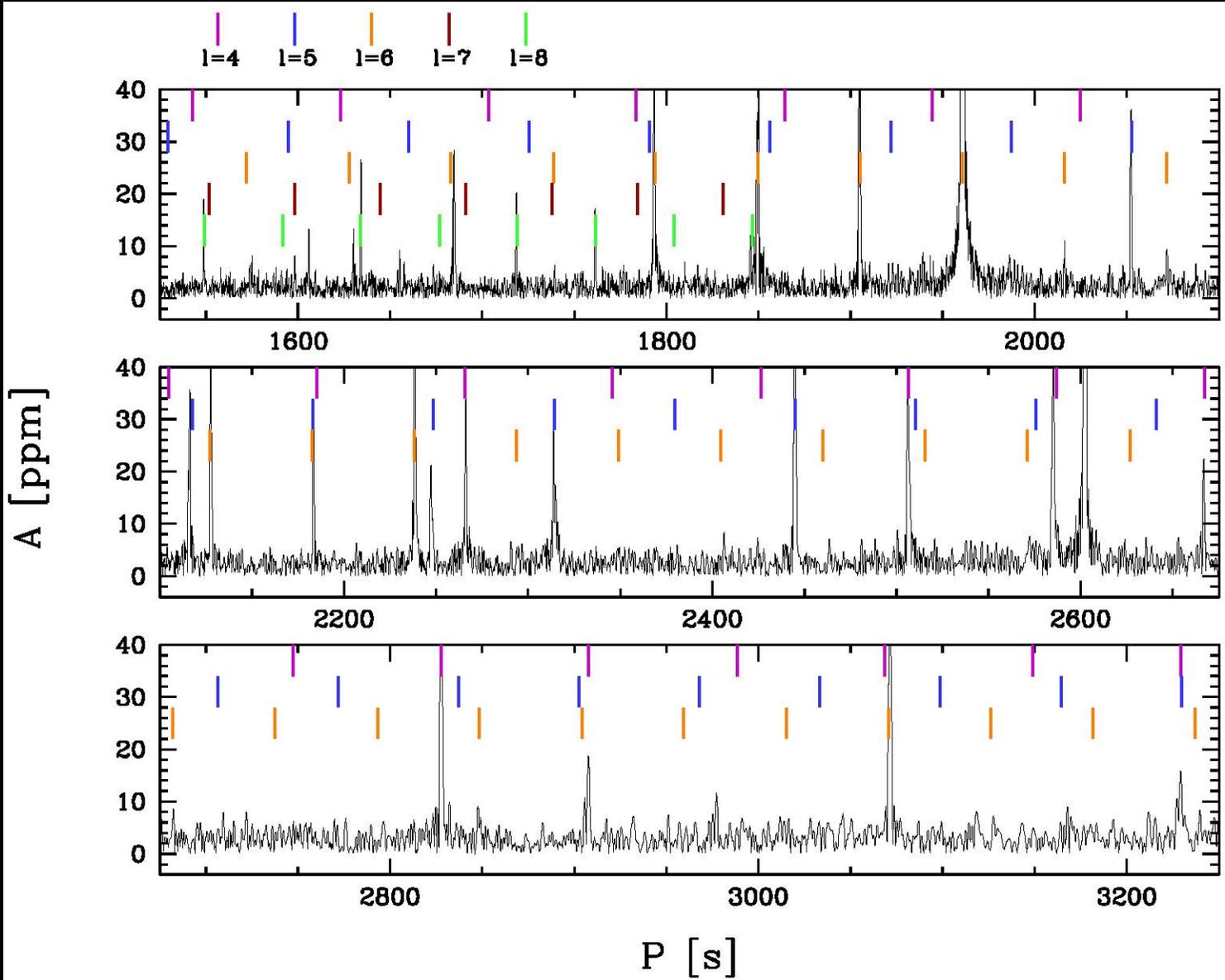
$$\Delta P_l = \Delta\pi / (l(l+1))^{0.5} + \Delta\pi \approx 350 \text{ s}$$

(e.g. Reed+2011 + other papers)

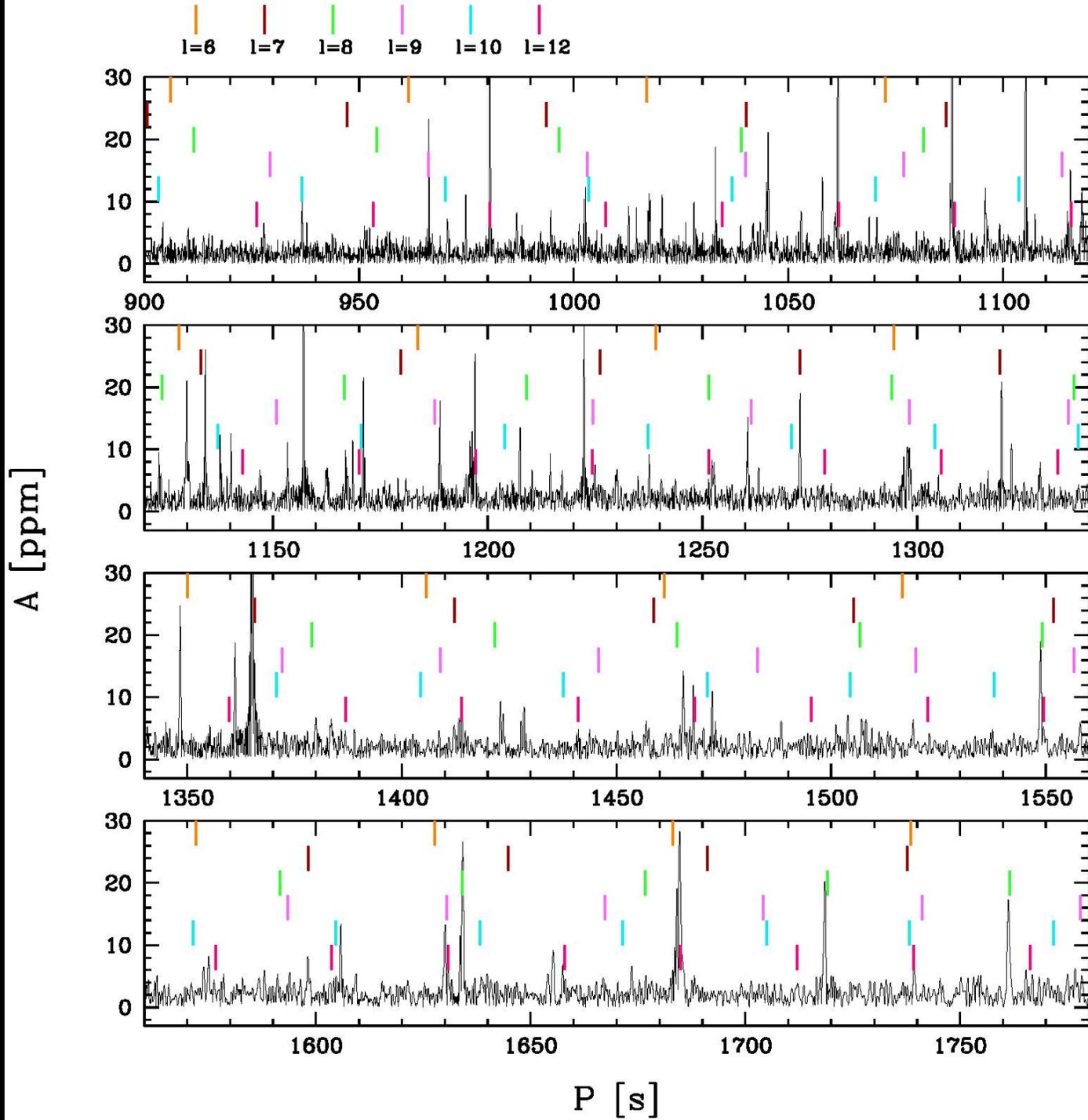
$$\begin{aligned} \Delta P_1 &\approx 250 \text{ s} \\ \Delta P_2 &\approx 140 \text{ s} \\ \Delta P_3 &\approx 100 \text{ s} \\ \Delta P_4 &\approx 80 \text{ s} \end{aligned}$$

$$\begin{aligned} &\dots \\ \Delta P_{11} &\approx 30.5 \text{ s} \\ \Delta P_{12} &\approx 28.0 \text{ s} \end{aligned}$$

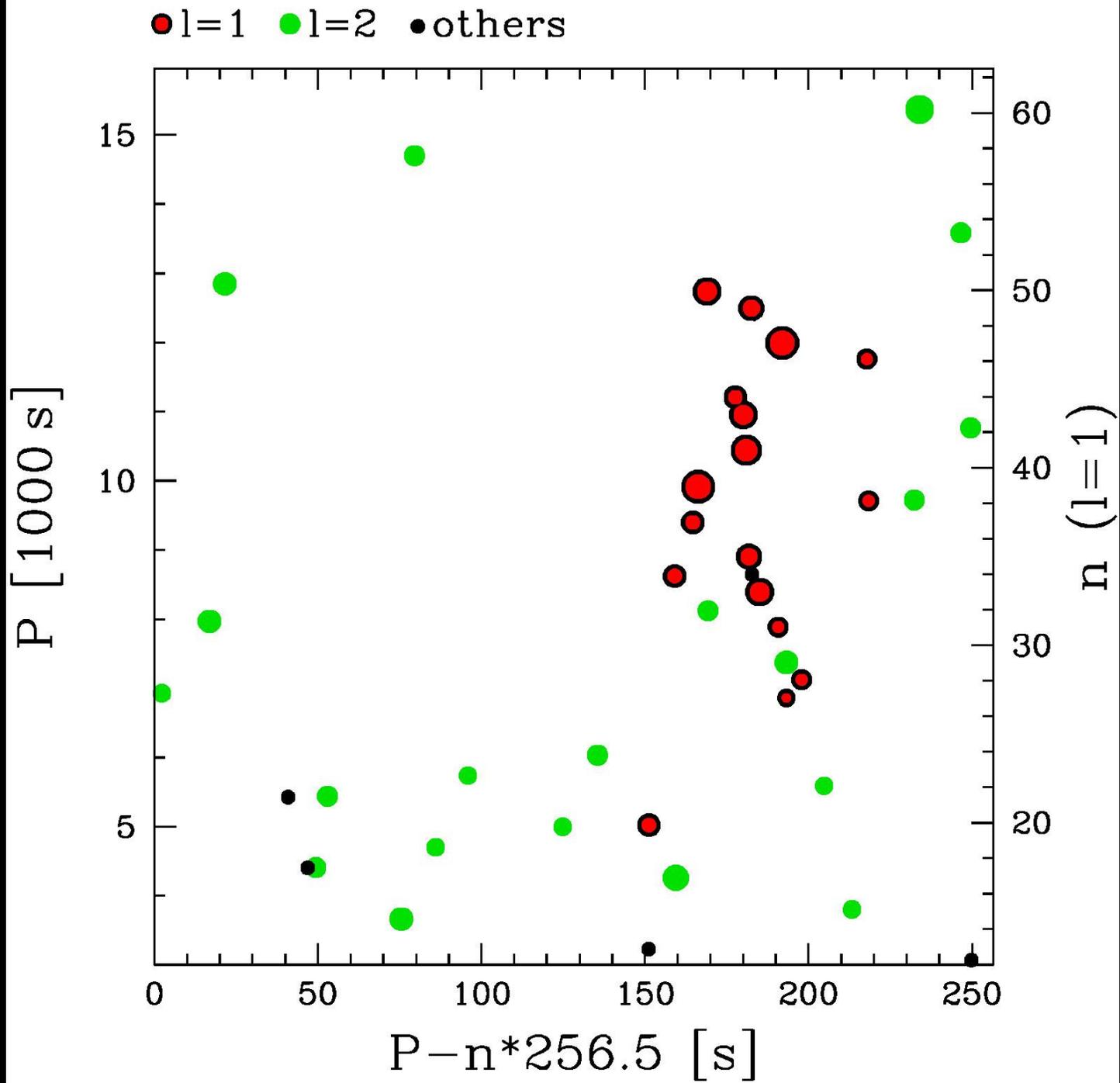
Period spacing 2



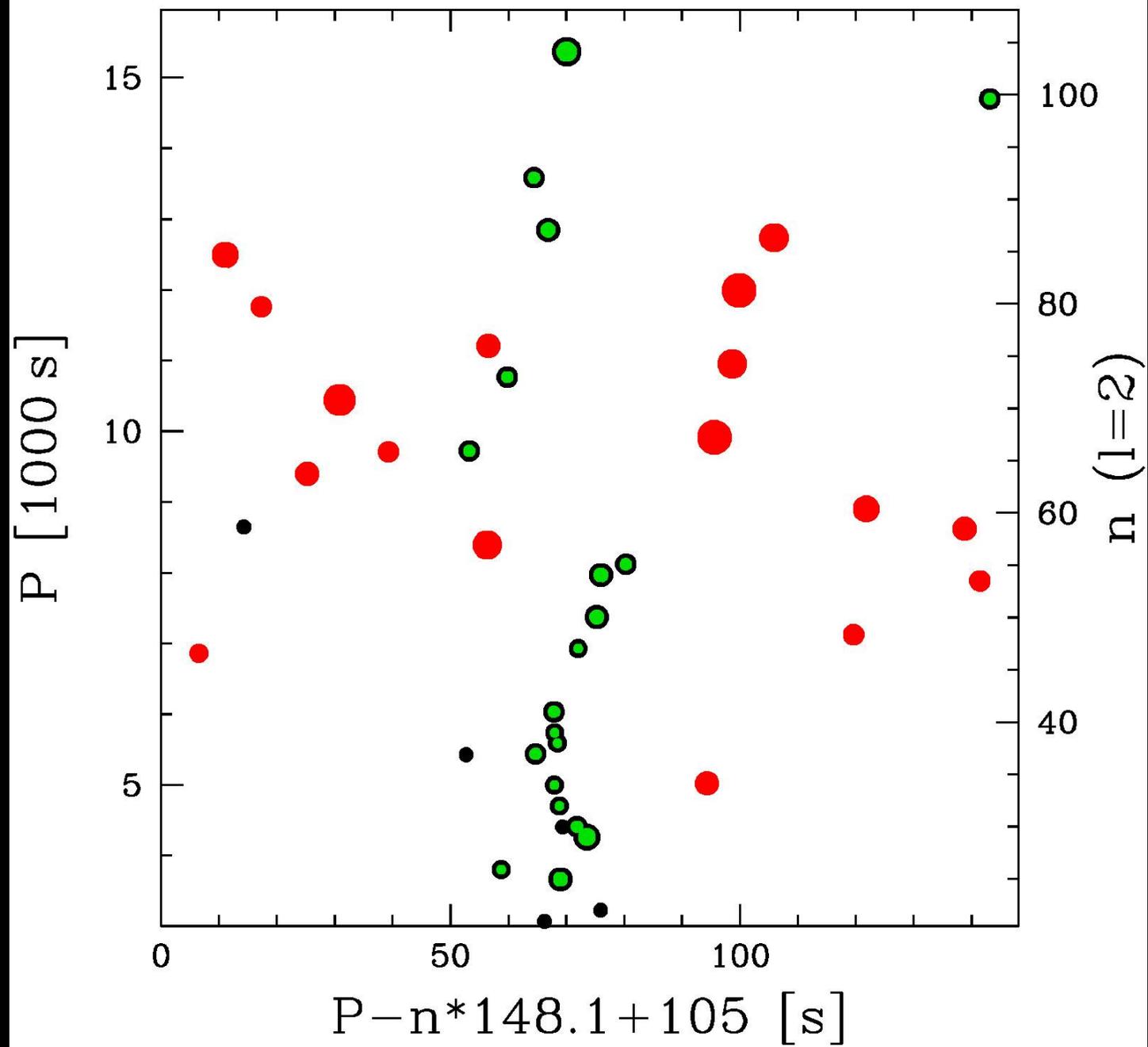
Period spacing 3



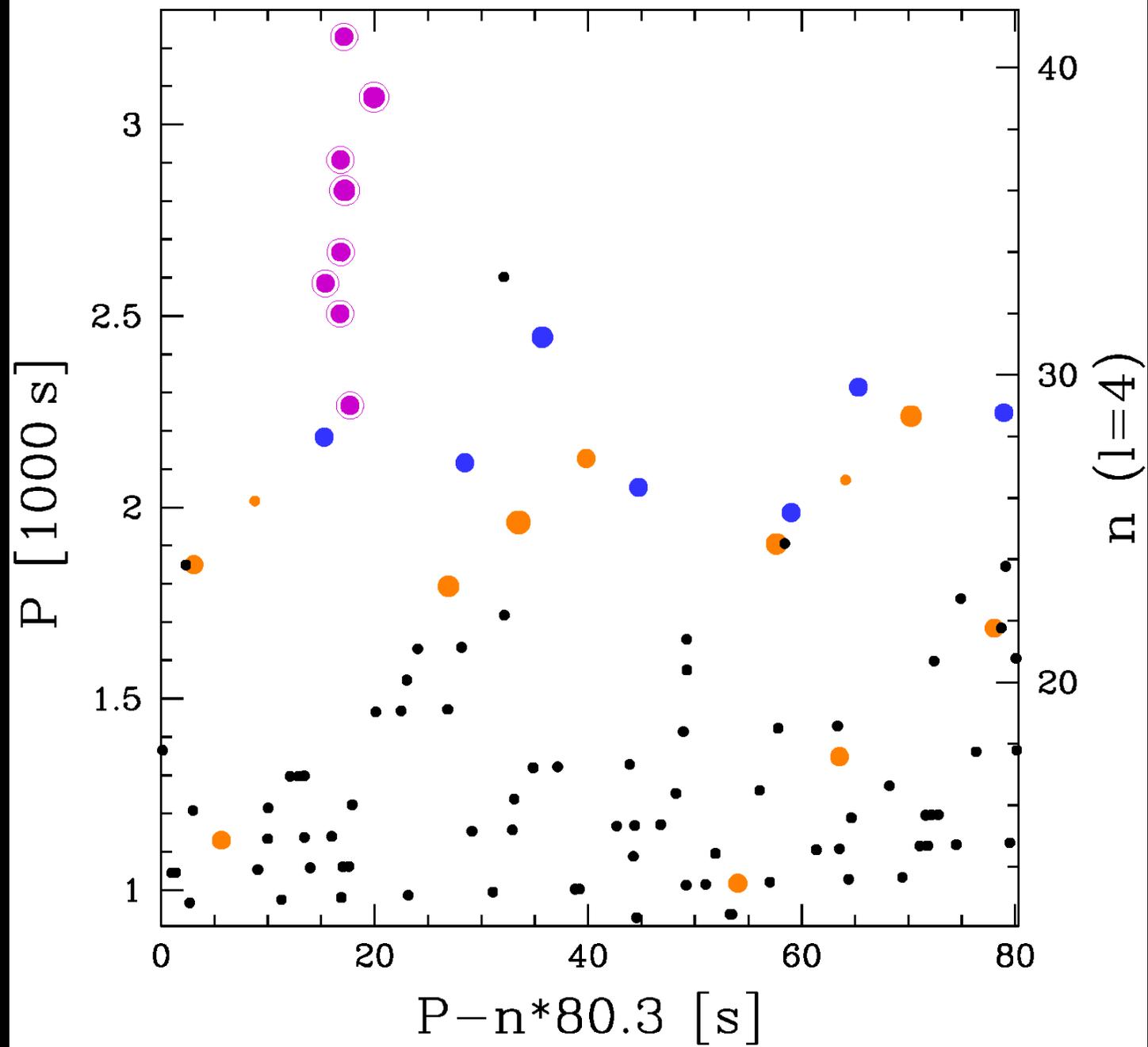
Echelle diagram $l=1$



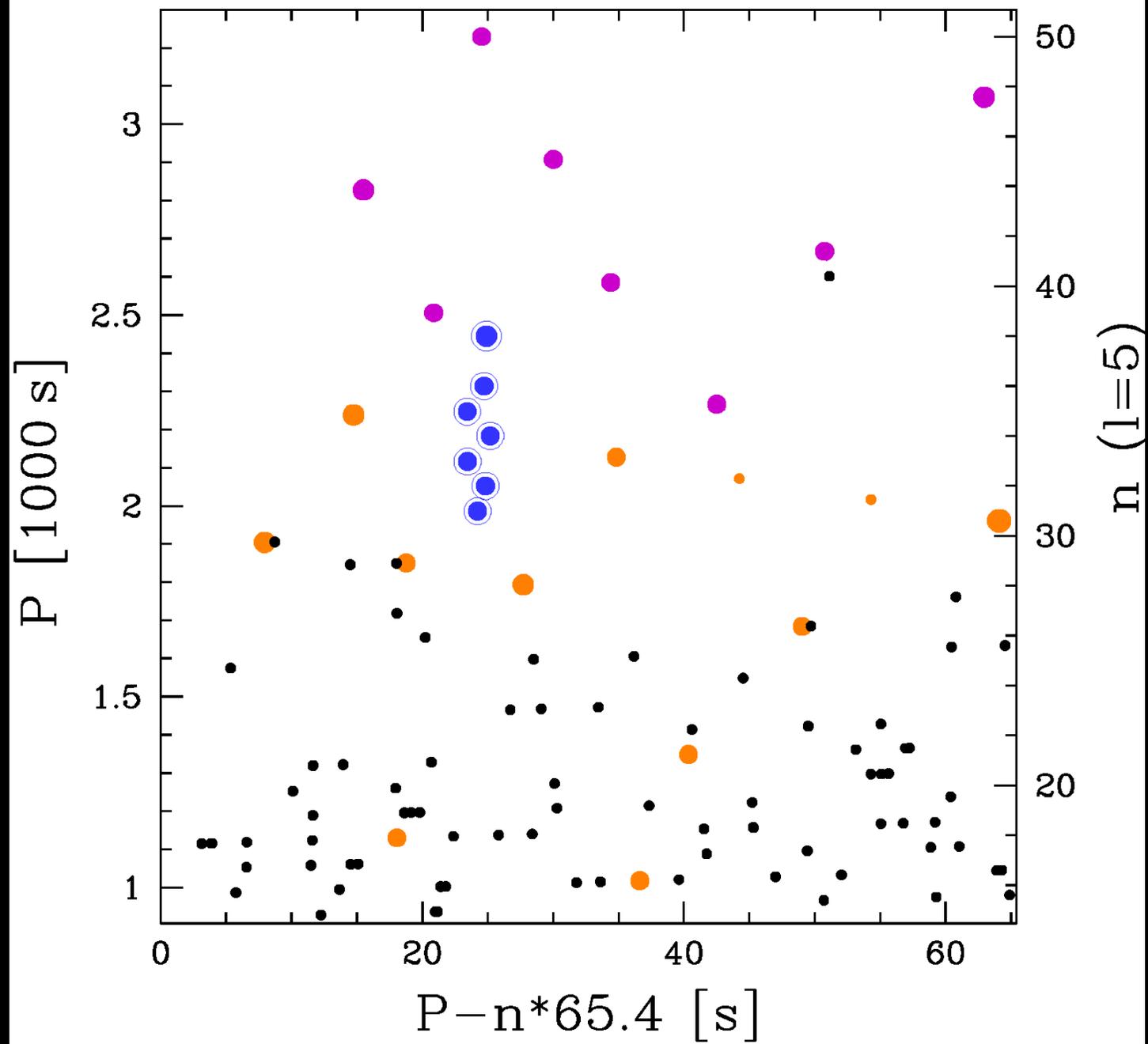
● $l=1$ ● $l=2$ ● others



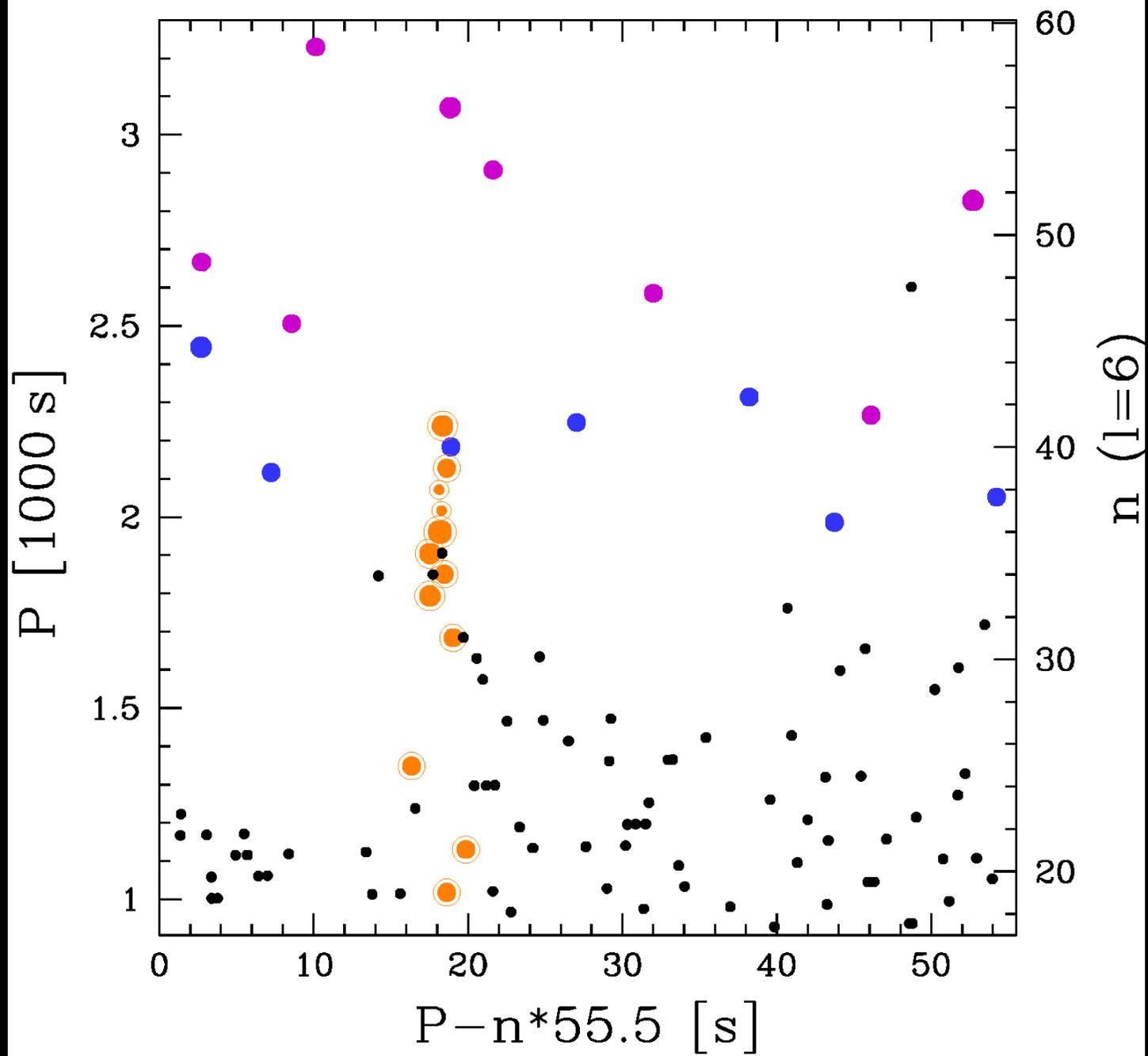
● $l=4$ ● $l=5$ ● $l=6$ ● others



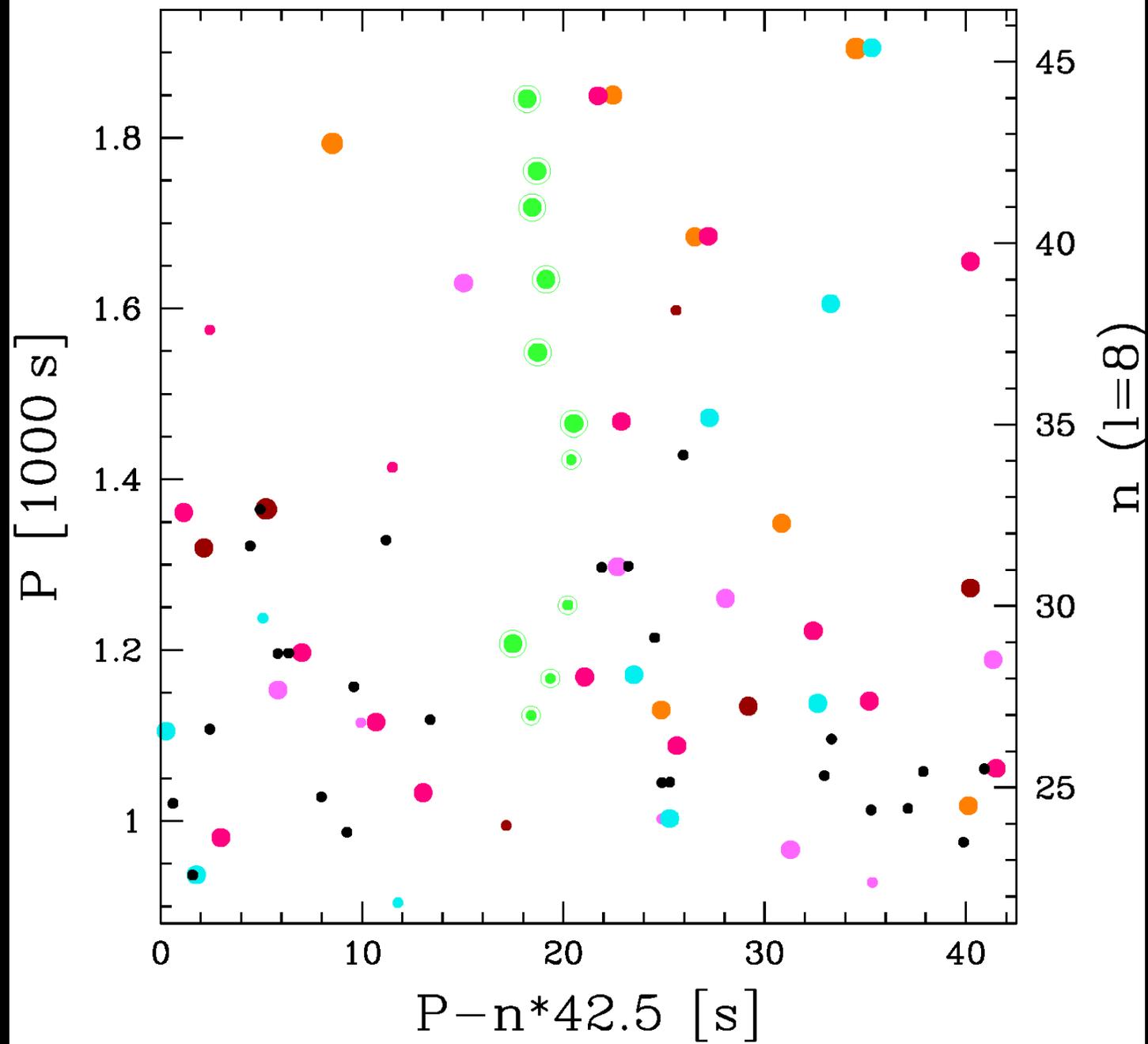
● $l=4$ ● $l=5$ ● $l=6$ ● others



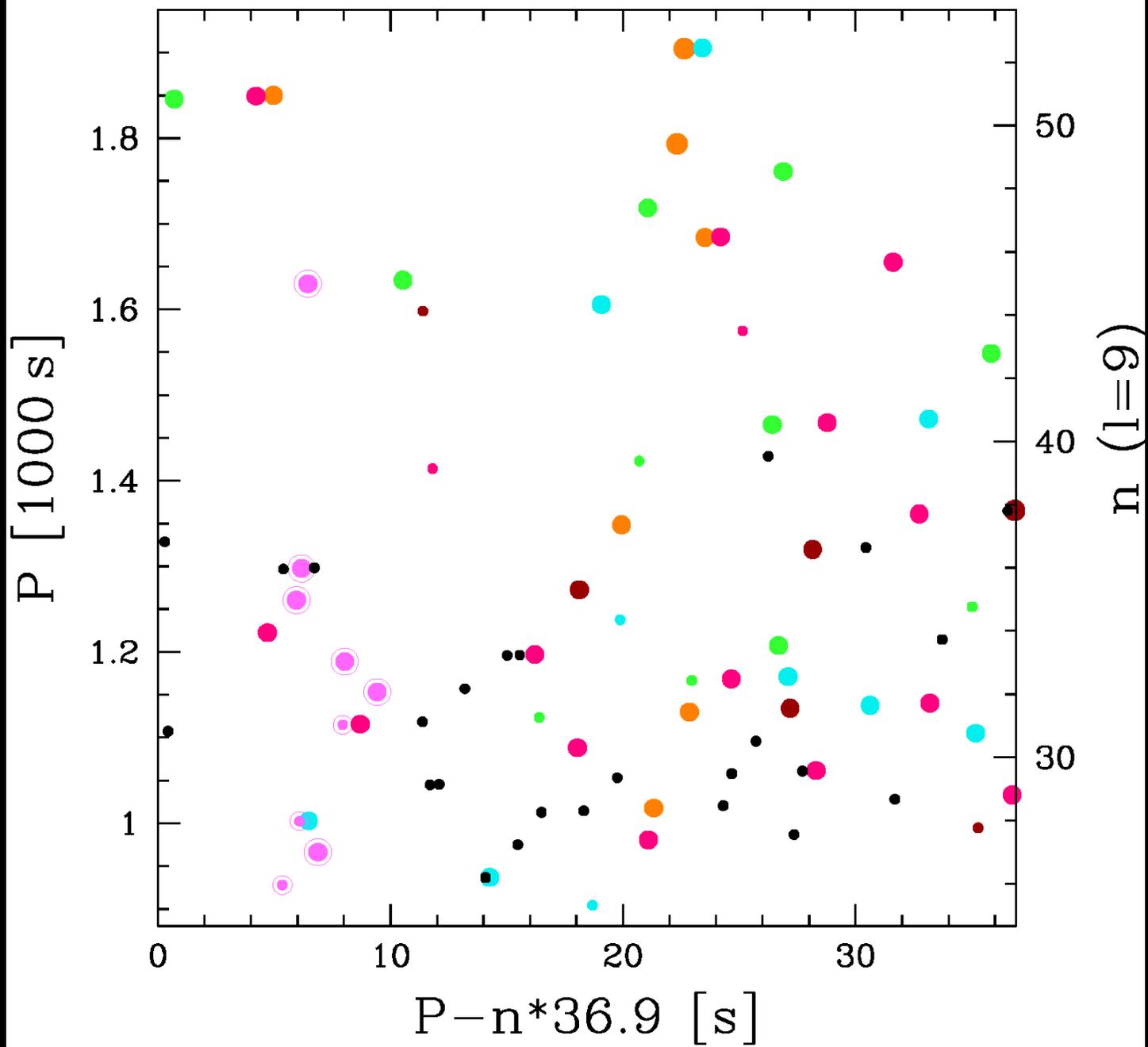
● $l=4$ ● $l=5$ ● $l=6$ ● others



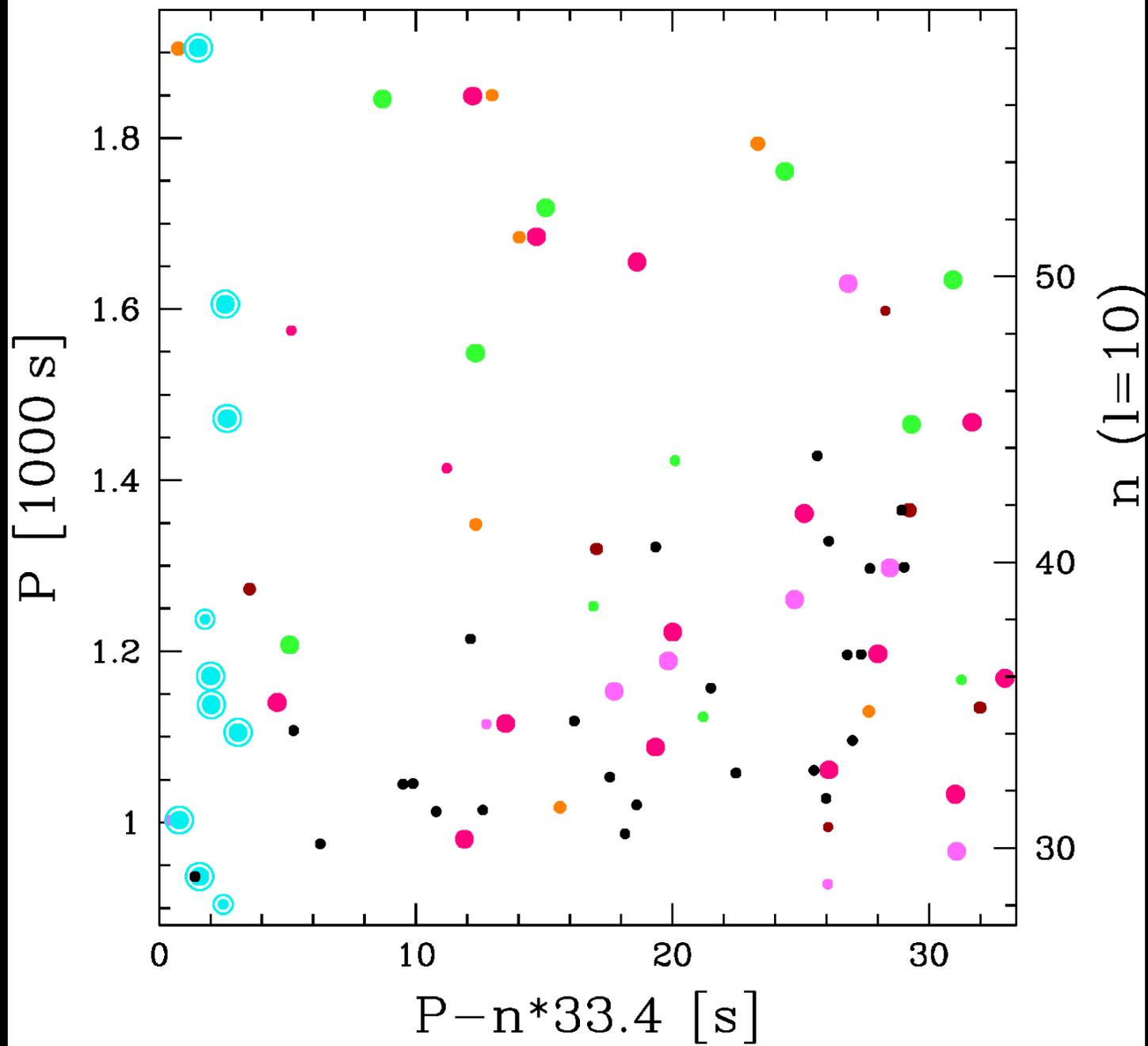
● l=6 ● l=7 ● l=8 ● l=9 ● l=10 ● l=12 ● unknown



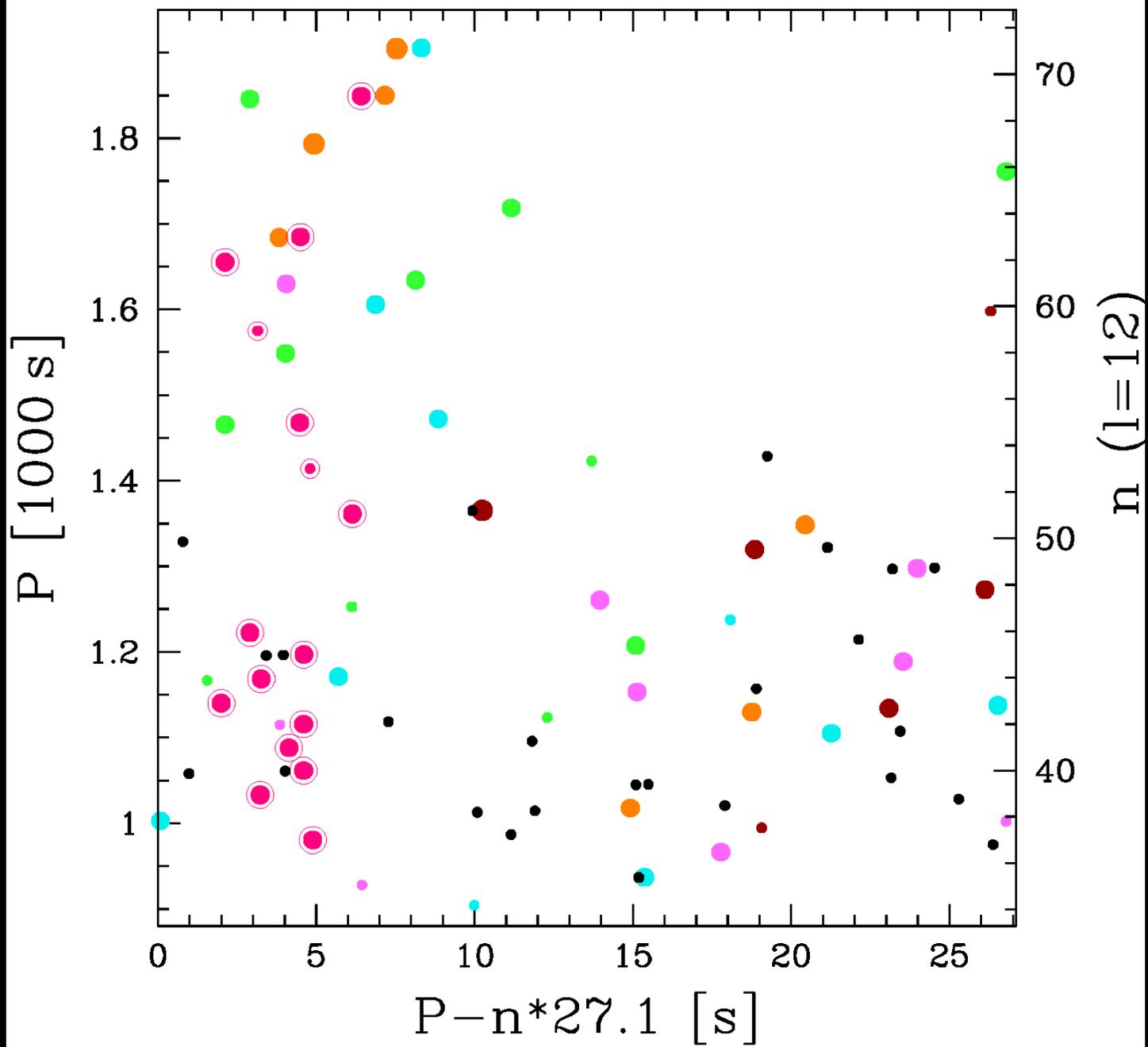
● l=6 ● l=7 ● l=8 ● l=9 ● l=10 ● l=12 ● unknown

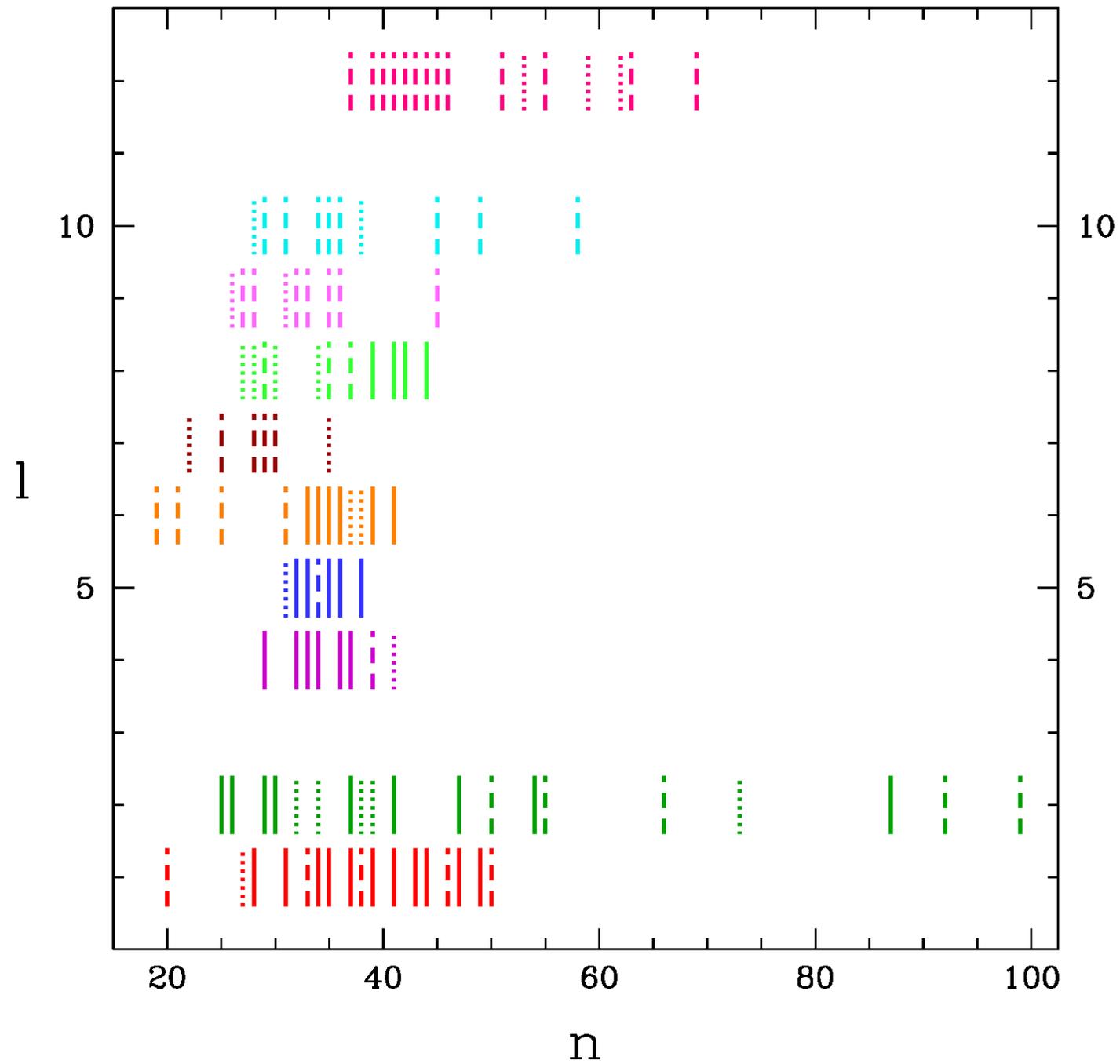


● l=6 ● l=7 ● l=8 ● l=9 ● l=10 ● l=12 ● unknown

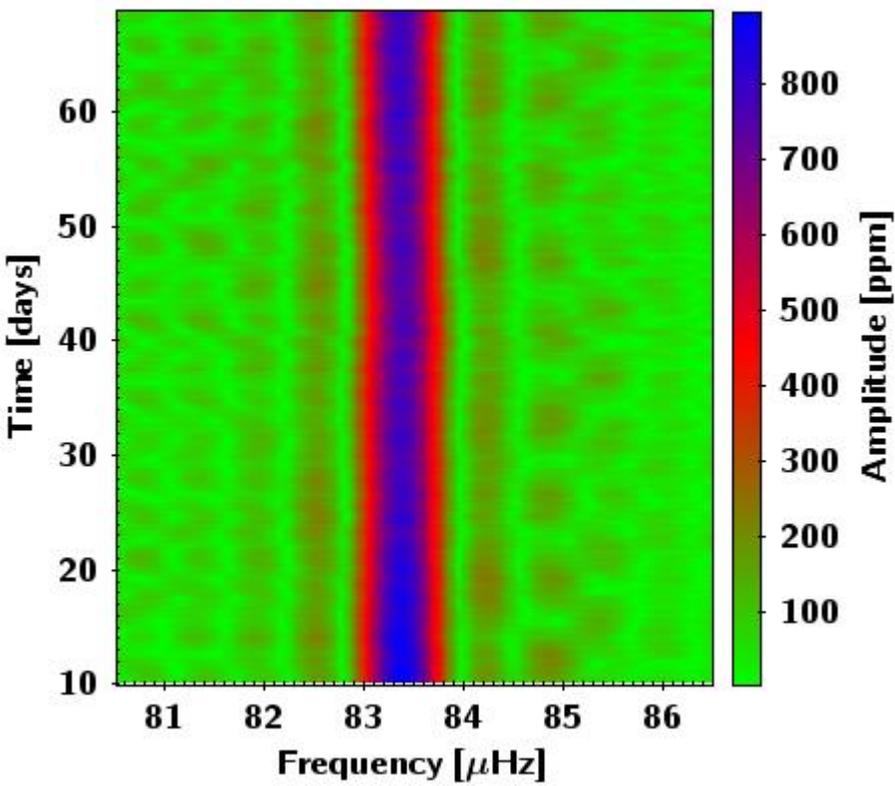
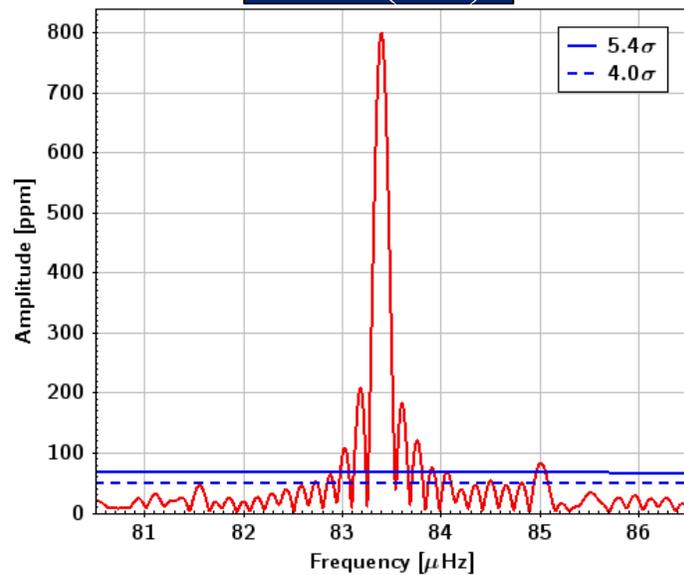


● l=6 ● l=7 ● l=8 ● l=9 ● l=10 ● l=12 ● unknown



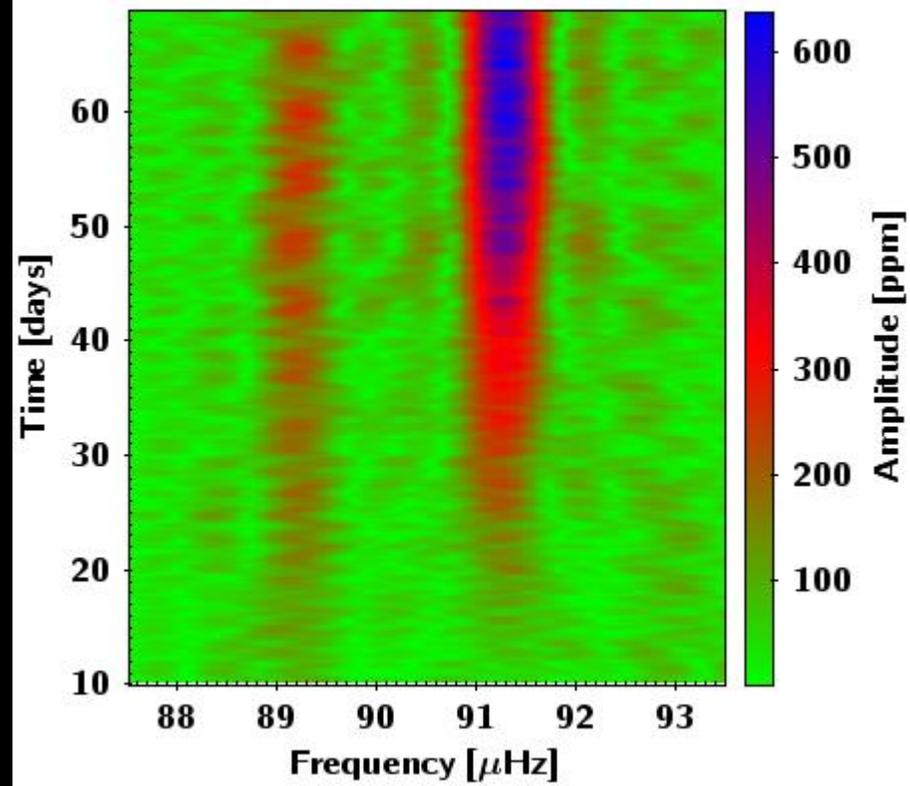
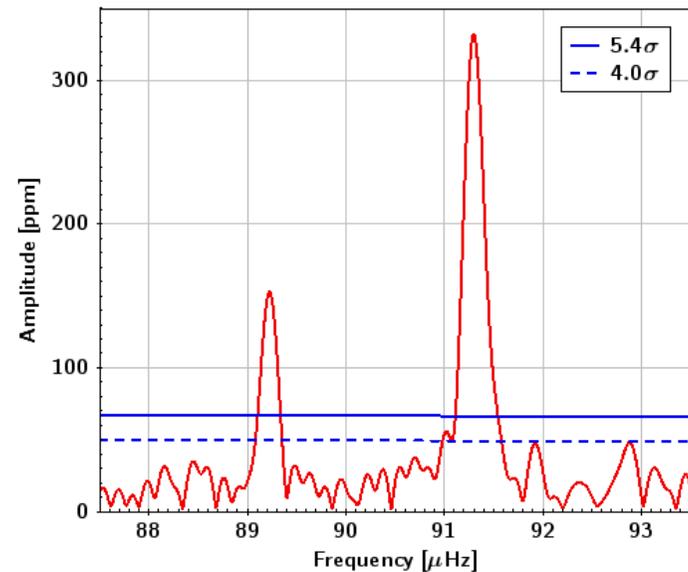


f163 (l=1)

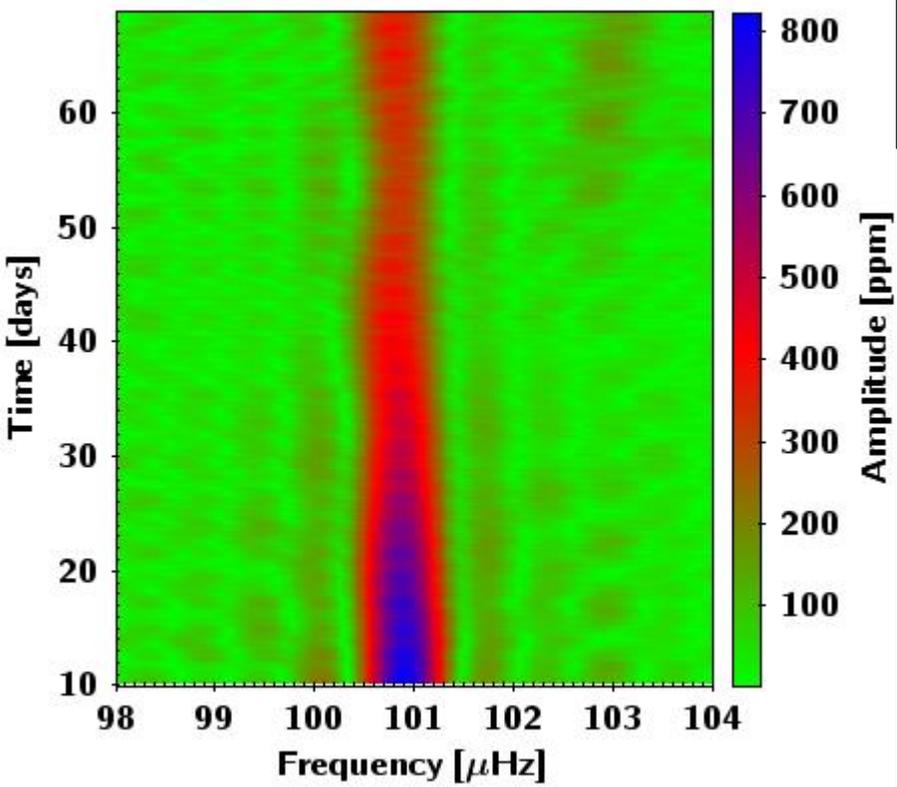
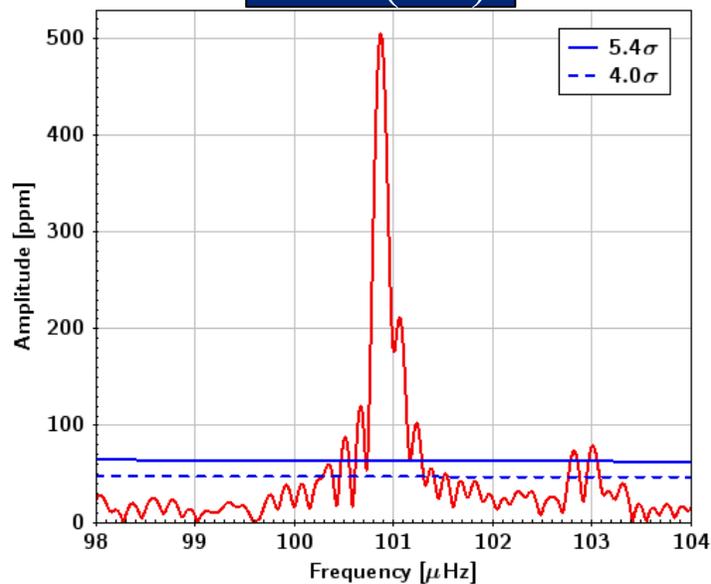


Sliding FTs 1

f161 (l=1) and f160 (l=1)

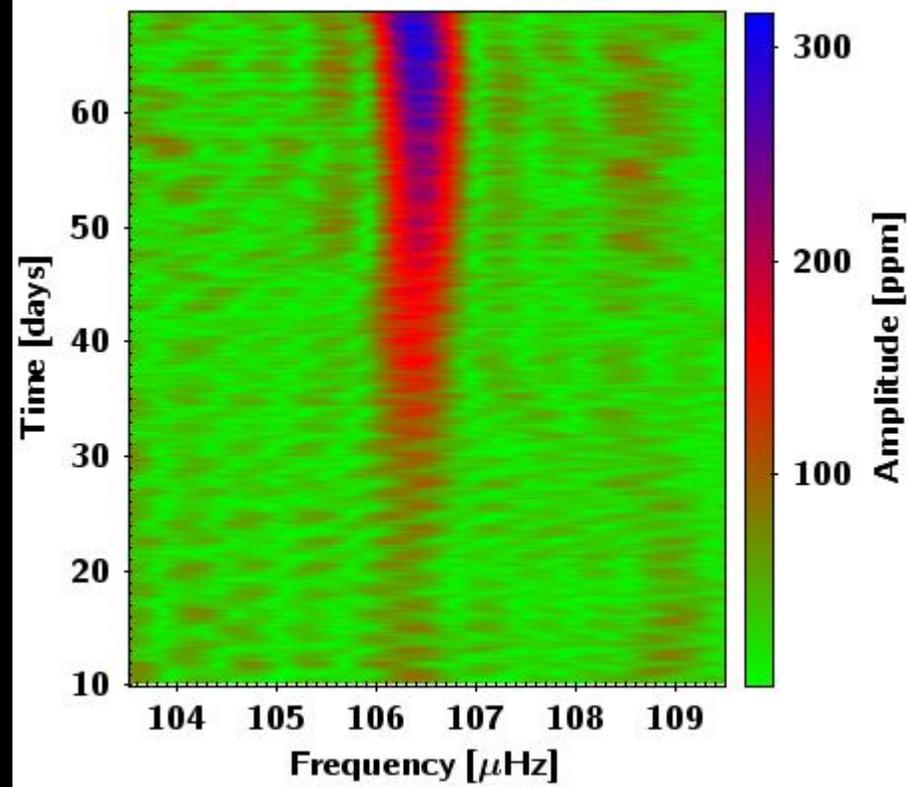
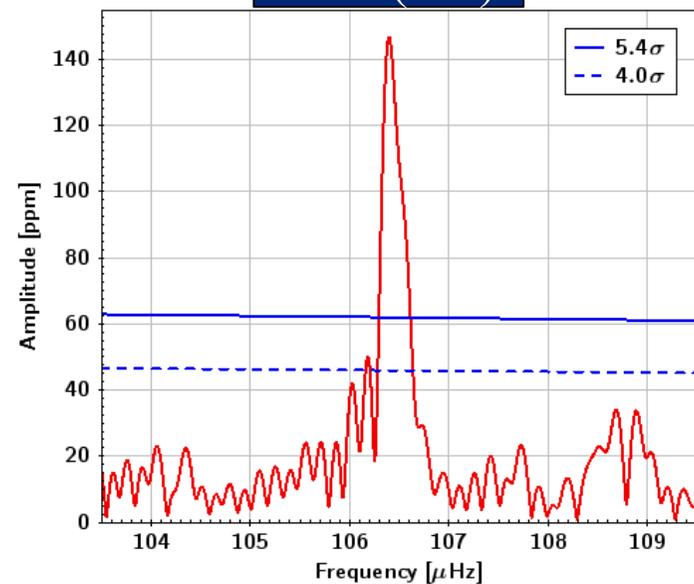


f157 (l=1)

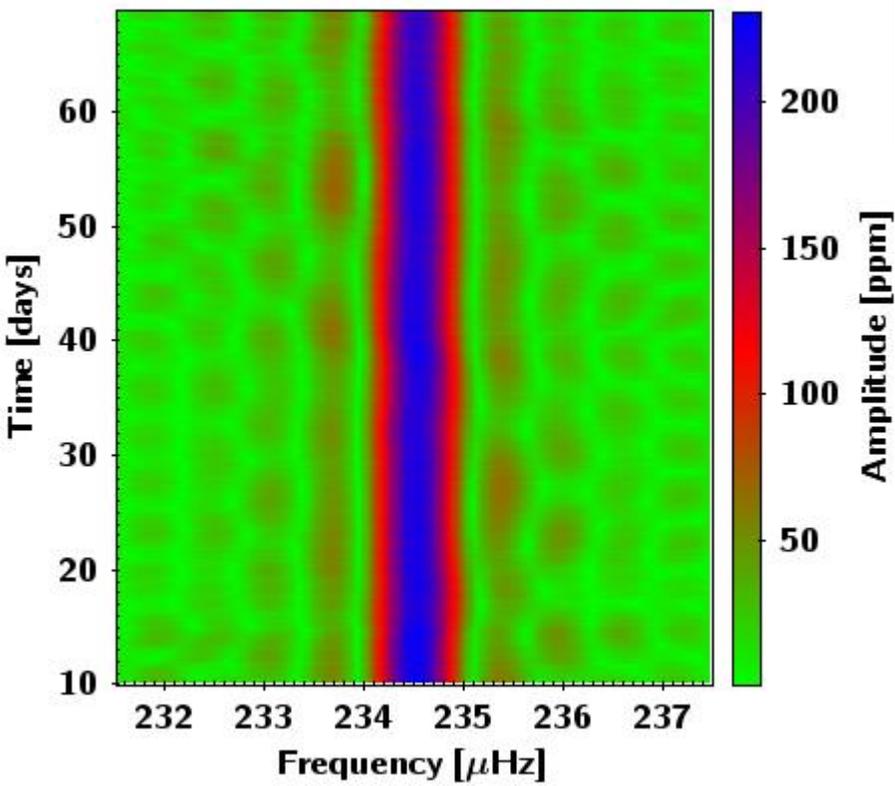
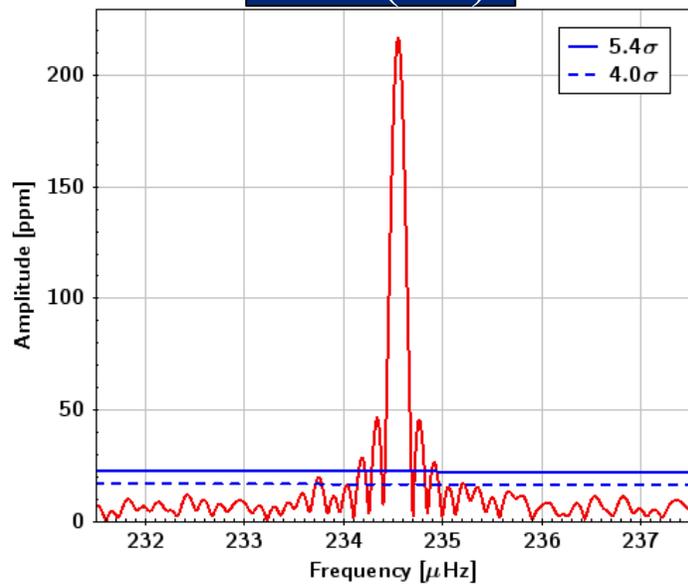


Sliding FTs 2

f154 (l=1)

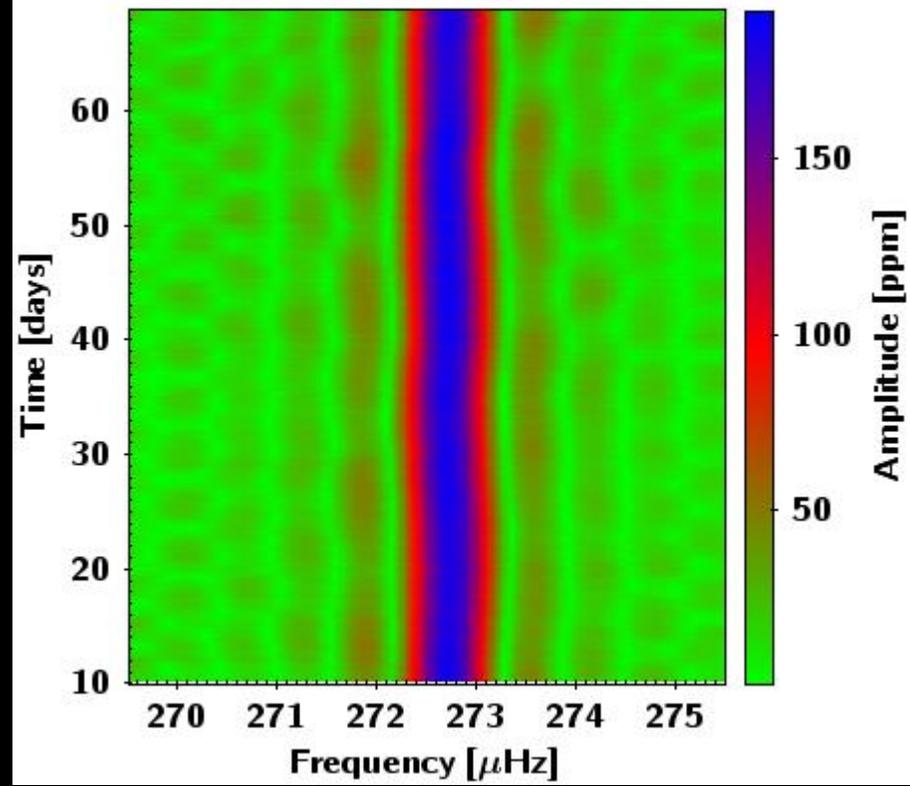
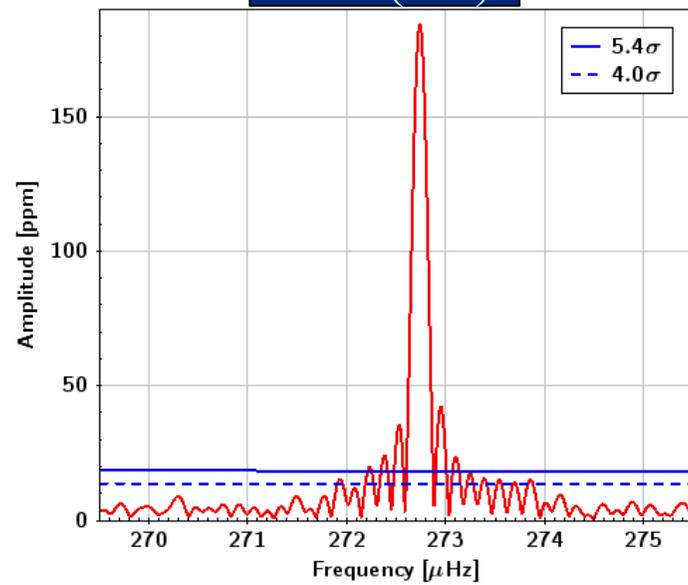


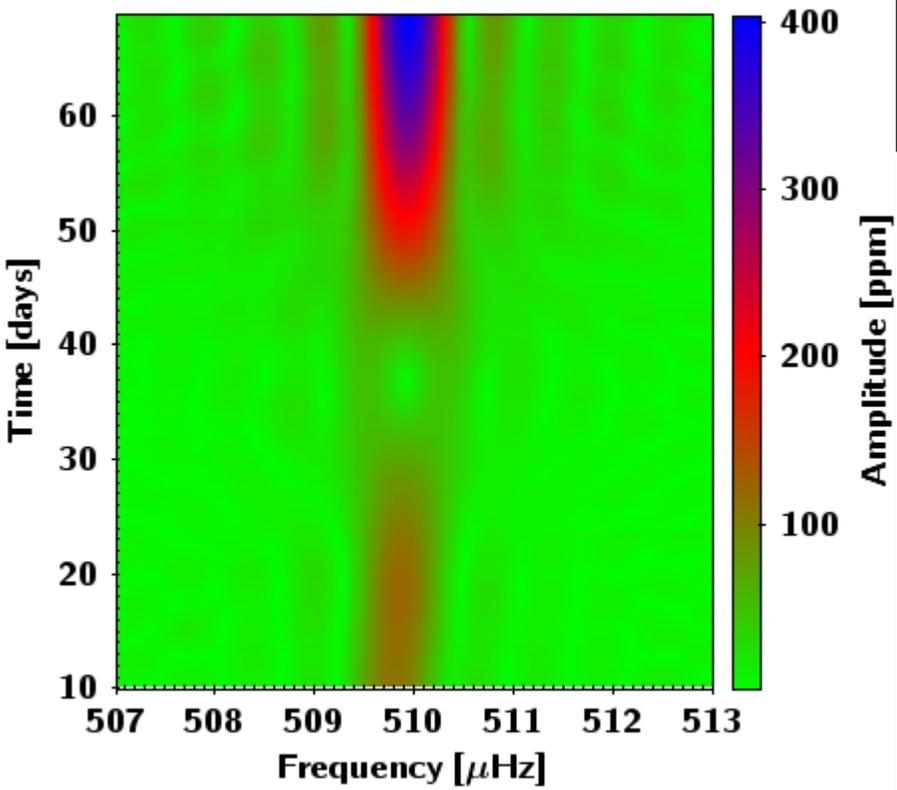
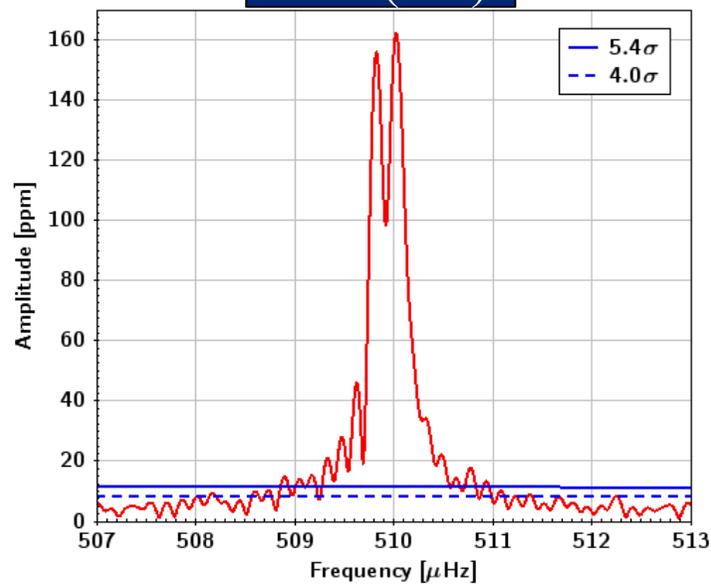
f132 (l=2)



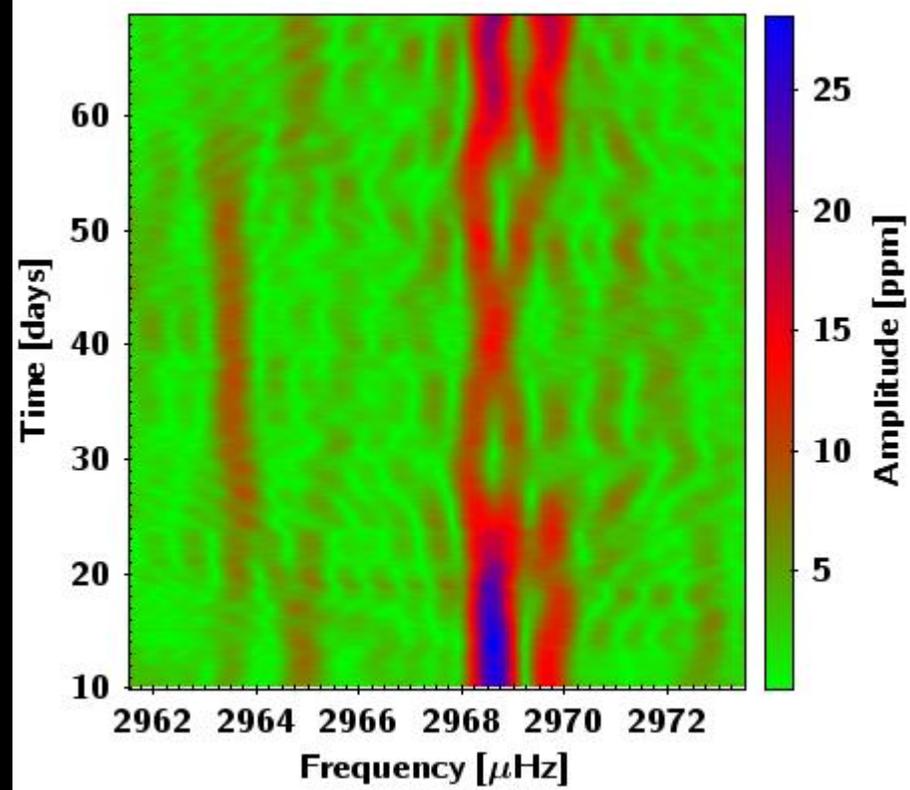
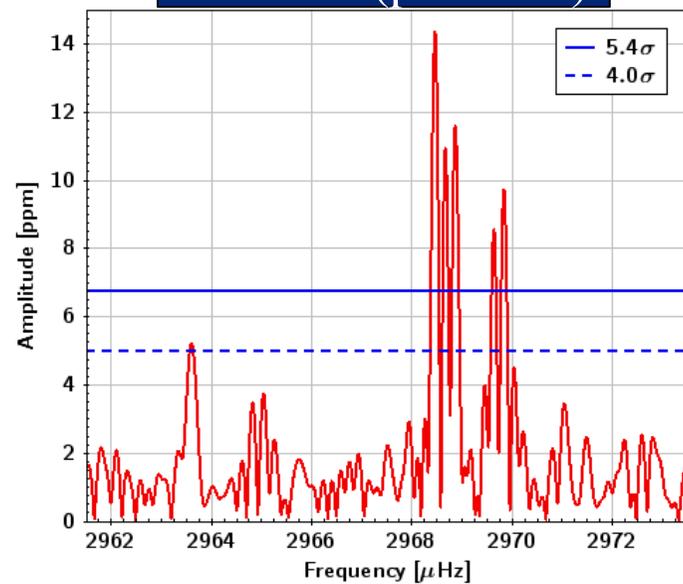
Sliding FTs 3

f130 (l=2)

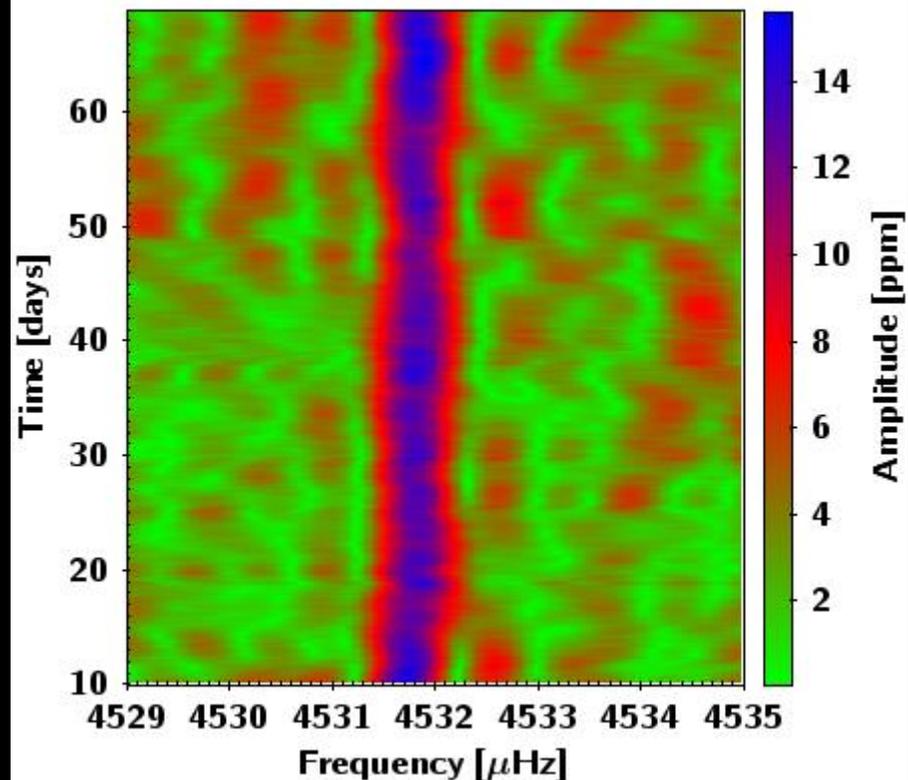
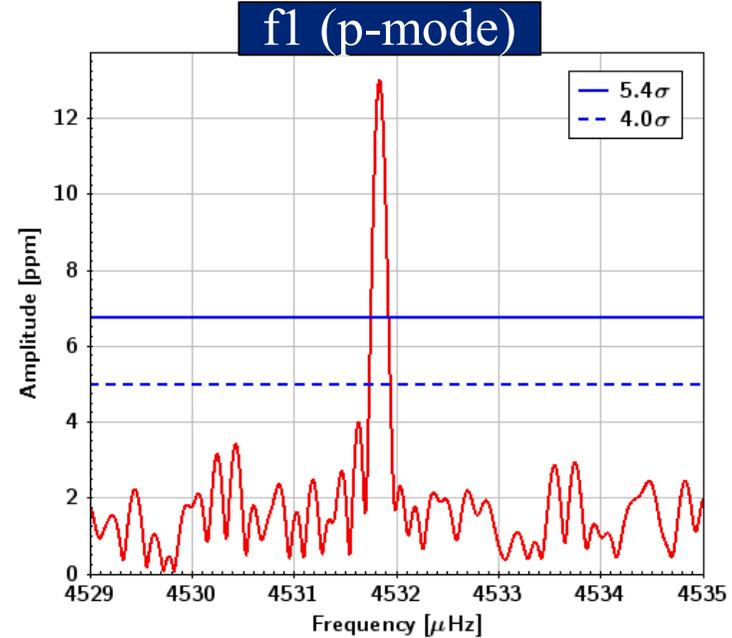


f109 (l=6)

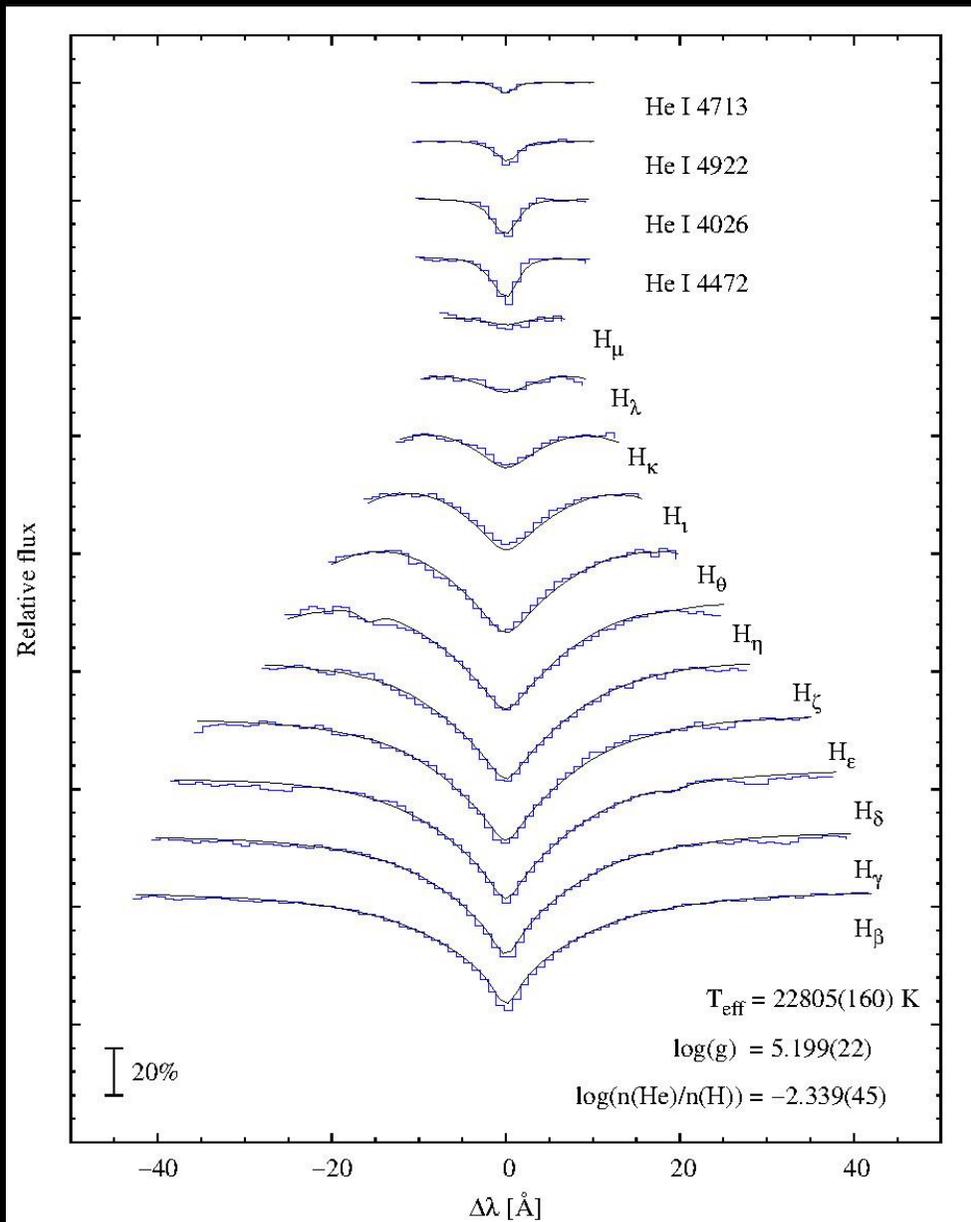
Sliding FTs 4

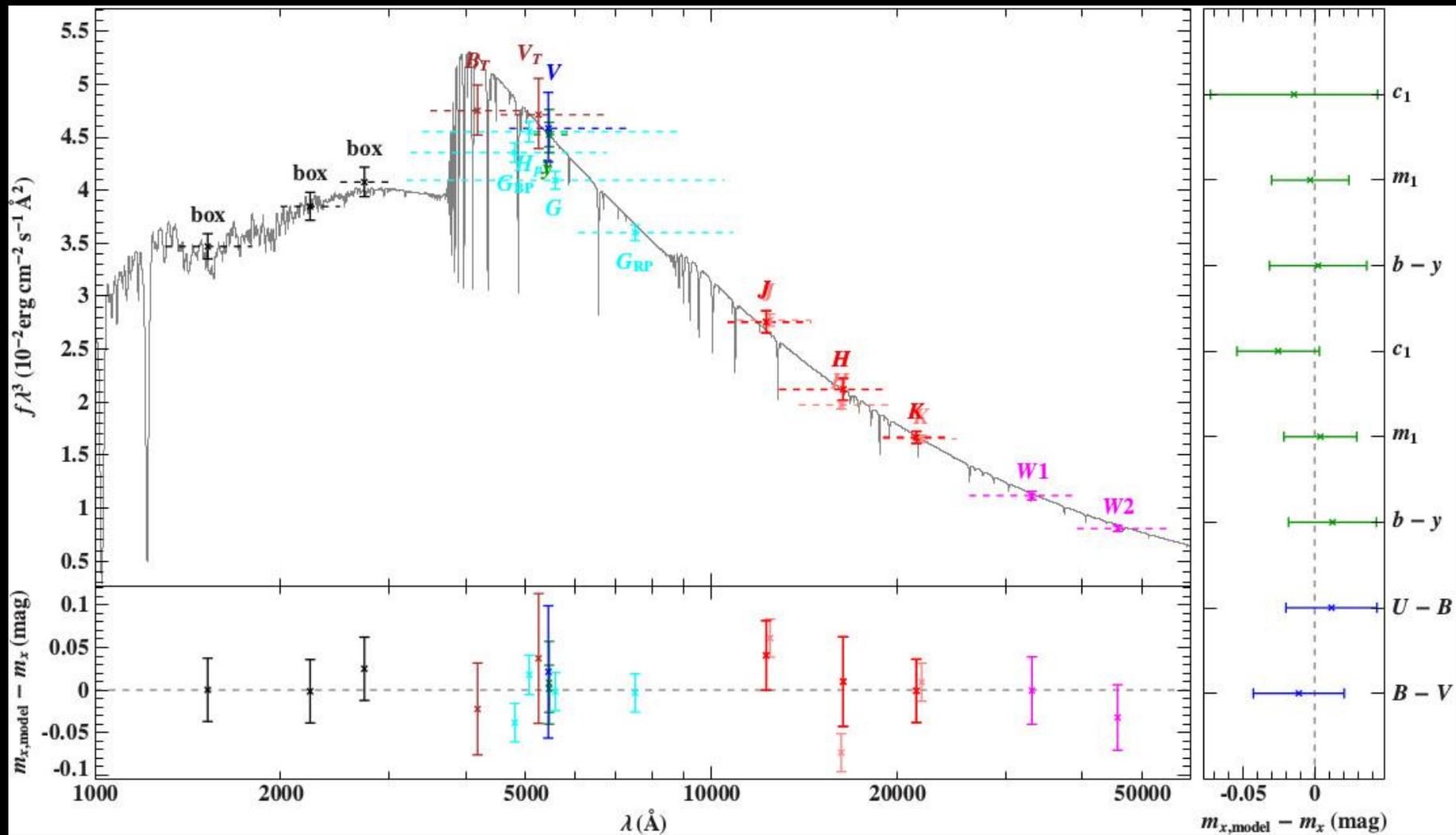
f11 to f6 (p-modes)

Sliding FTs 5



ALFOSC@NOT: 3 low-resolution spectra





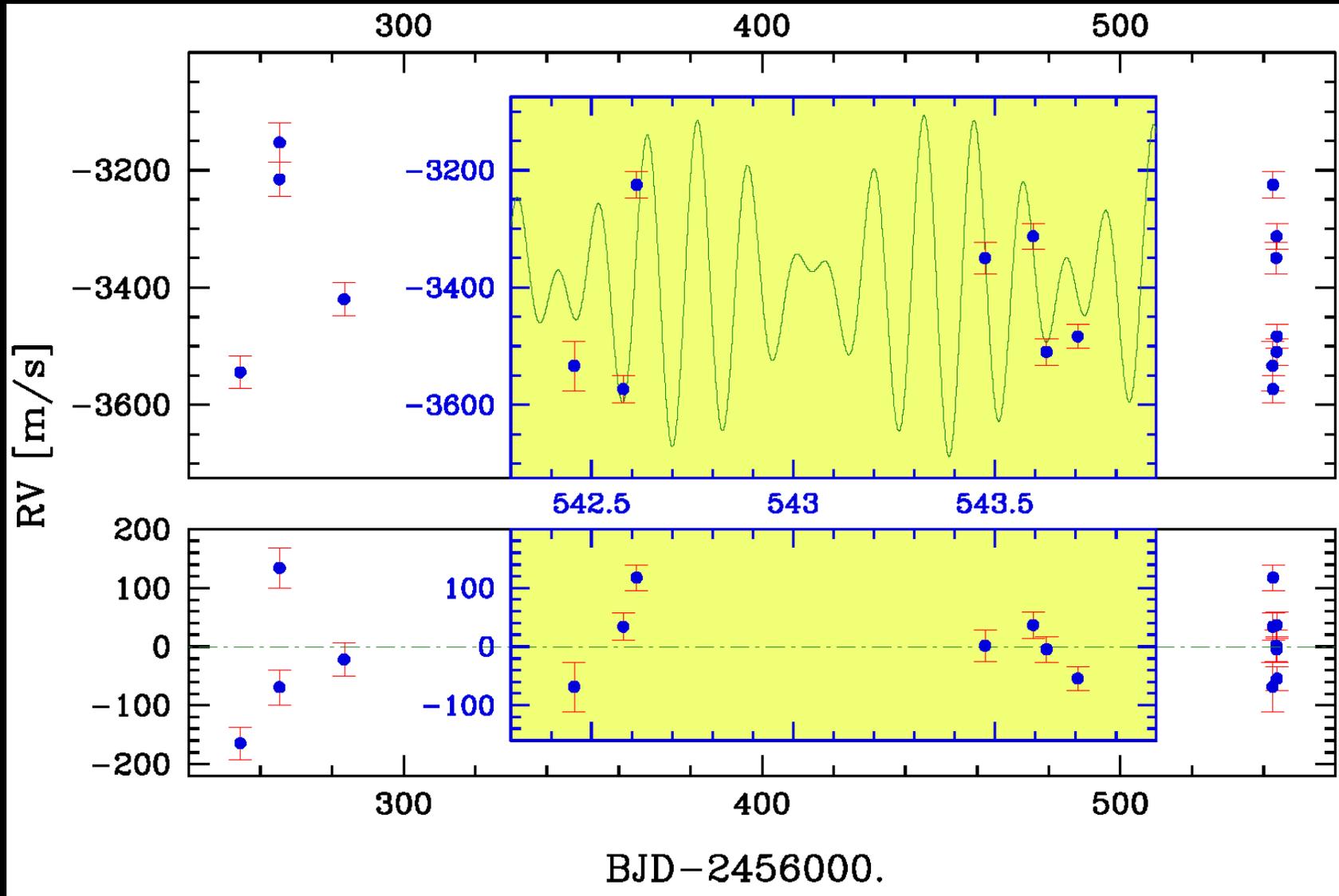
from $\left\{ \begin{array}{l} \log g = 5.20 \pm 0.05 \\ \varpi = 5.384 \pm 0.132 \text{ mas} \end{array} \right.$

we obtain

$T_{\text{eff}} = 23,470^{+650}_{-210}$
 $E(B-V) < 0.009$
 $\Theta = (6.38^{+0.06}_{-0.10}) \times 10^{-11} \text{ rad}$
 $R = 0.263^{+0.009}_{-0.011} R_{\text{SUN}}$
 $M = g \Theta^2 / (4G\varpi^2) = 0.40 \pm 0.08 M_{\text{SUN}}$

RVs from 11 Harps-N spectra:

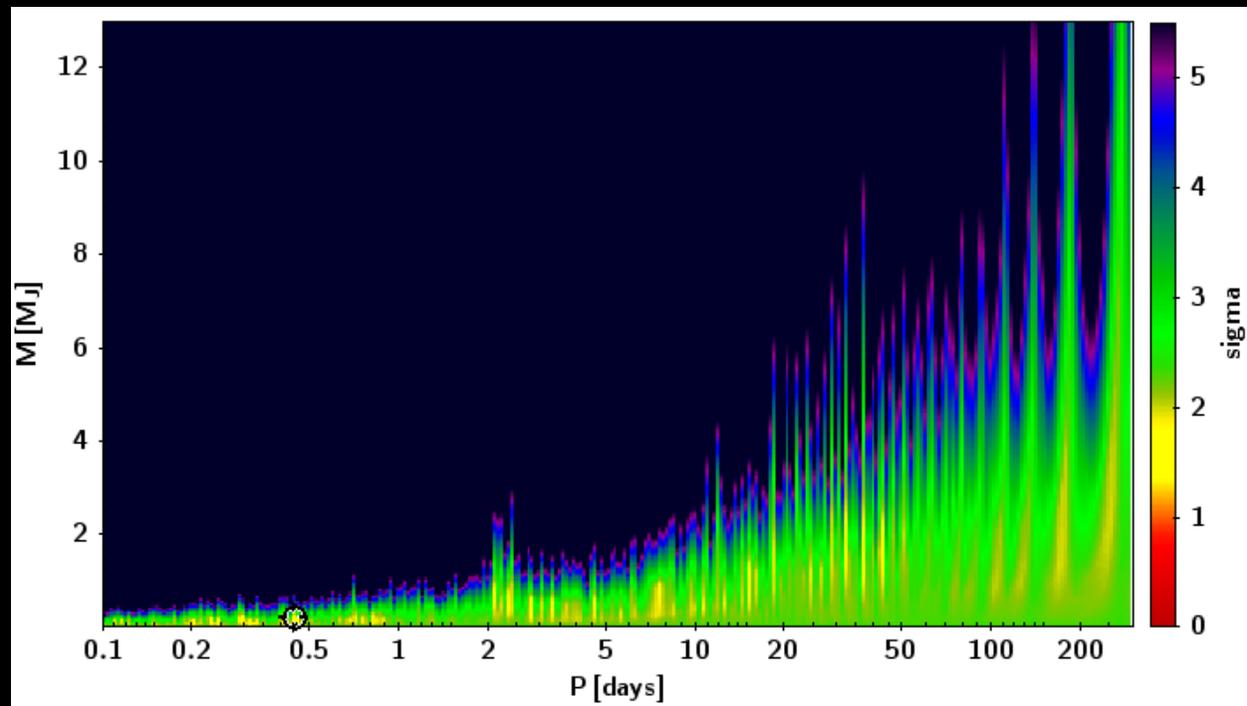
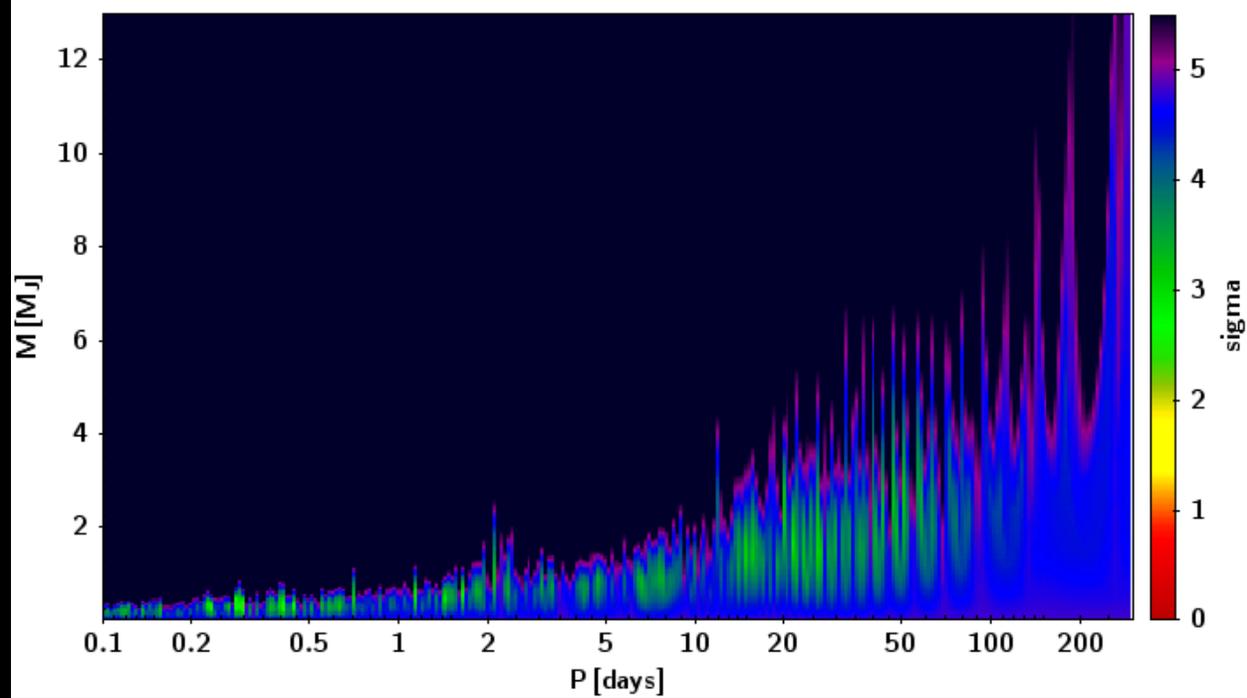
a reasonable fit is obtained when using only 3 main pulsation frequencies



Limiti alla presenza di un compagno di piccola massa (substellare)

La presenza di un compagno potrebbe spiegare la fortissima perdita di massa dei progenitori di queste stelle, quando si trovavano in prossimità della massima espansione di gigante rossa.

Al momento non ci sono altre spiegazioni plausibili.



A large orchestra and choir performing in a concert hall. The orchestra is seated in the foreground, playing various instruments including violins, violas, cellos, and double basses. The choir is positioned on a raised platform in the background, holding sheet music. The conductor is visible in the center of the orchestra, facing the musicians. The text "Grazie dell'attenzione" is overlaid on the image in white, centered horizontally.

Grazie dell'attenzione