Unlocking the secrets of γ Doradus ~~and δ Scuti~~ stars using échelle diagrams

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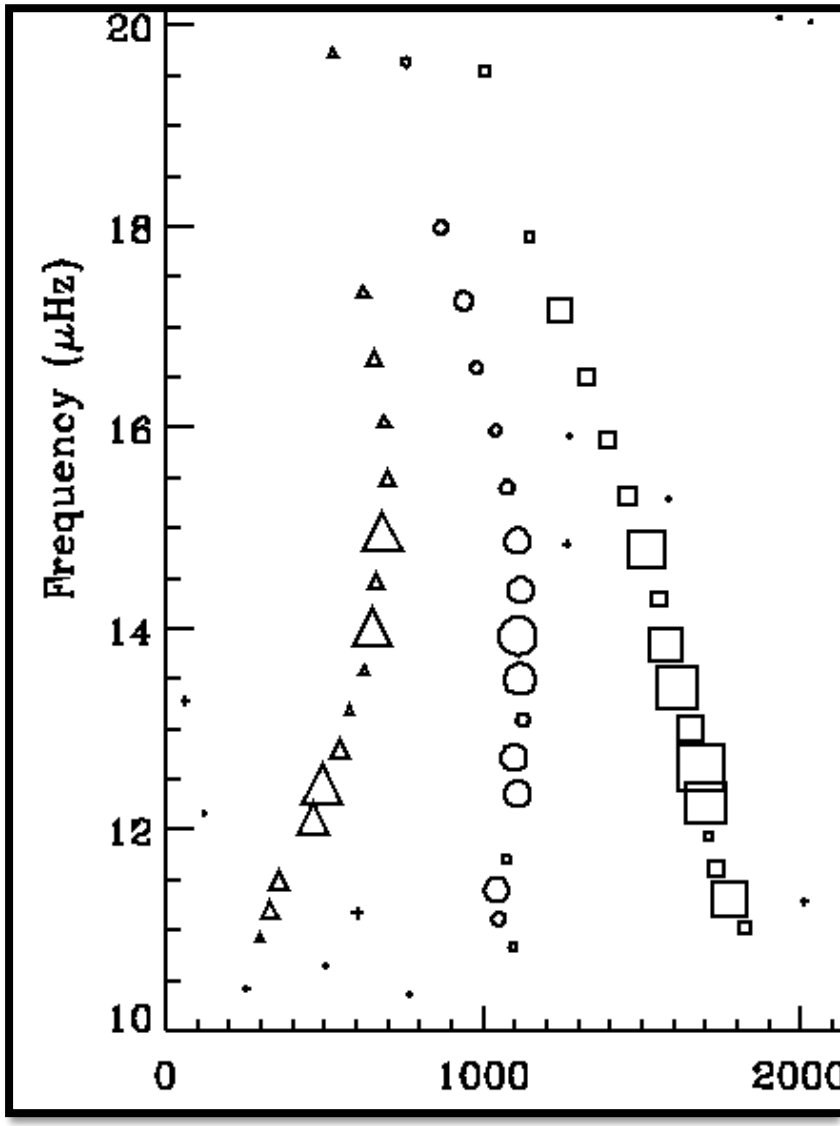
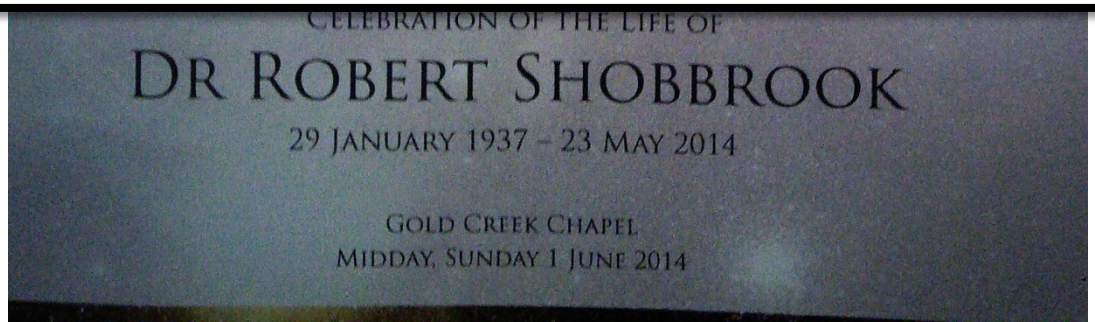
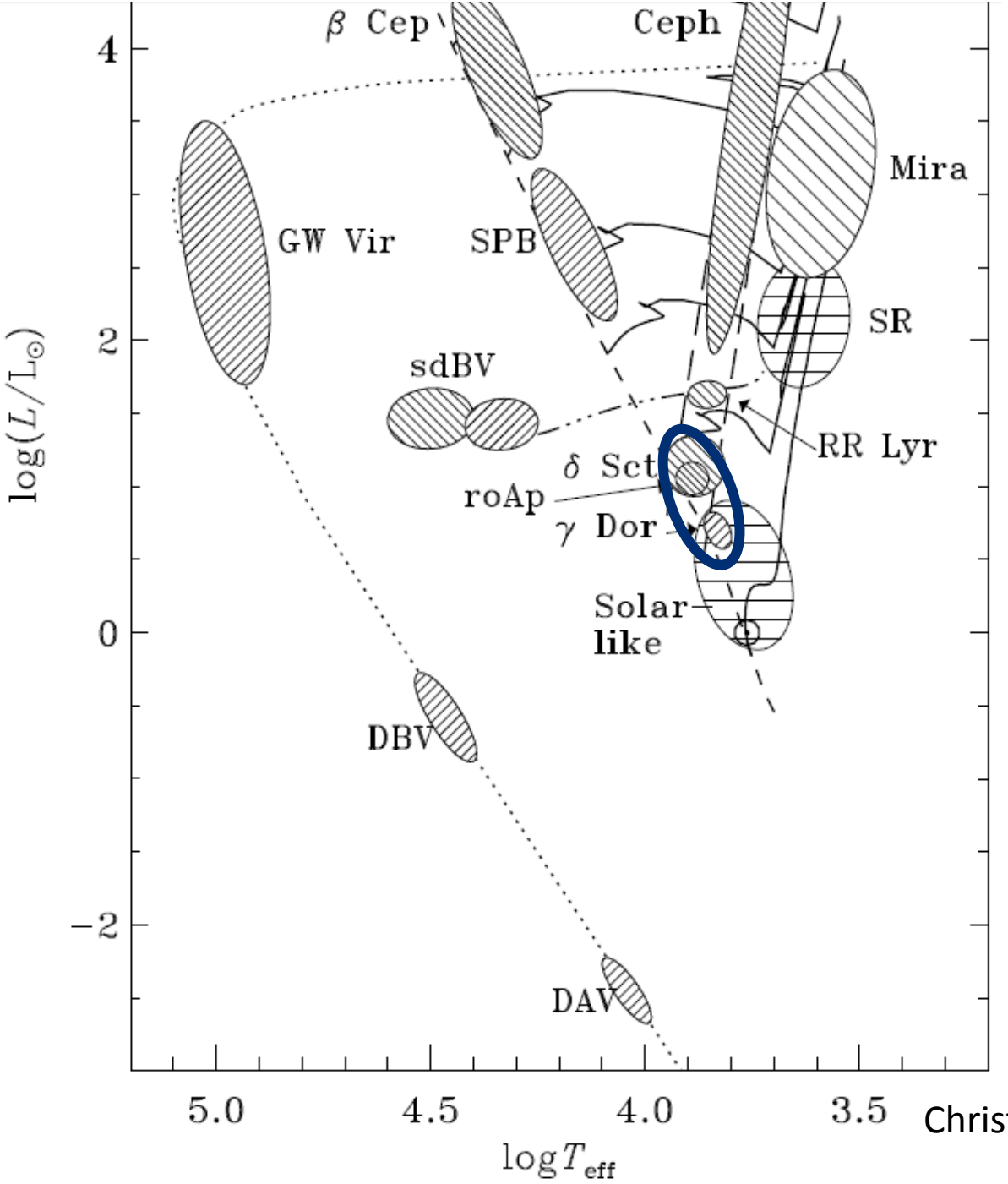


Mon. Not. R. Astron. Soc. **333,** 251–261 (2002)

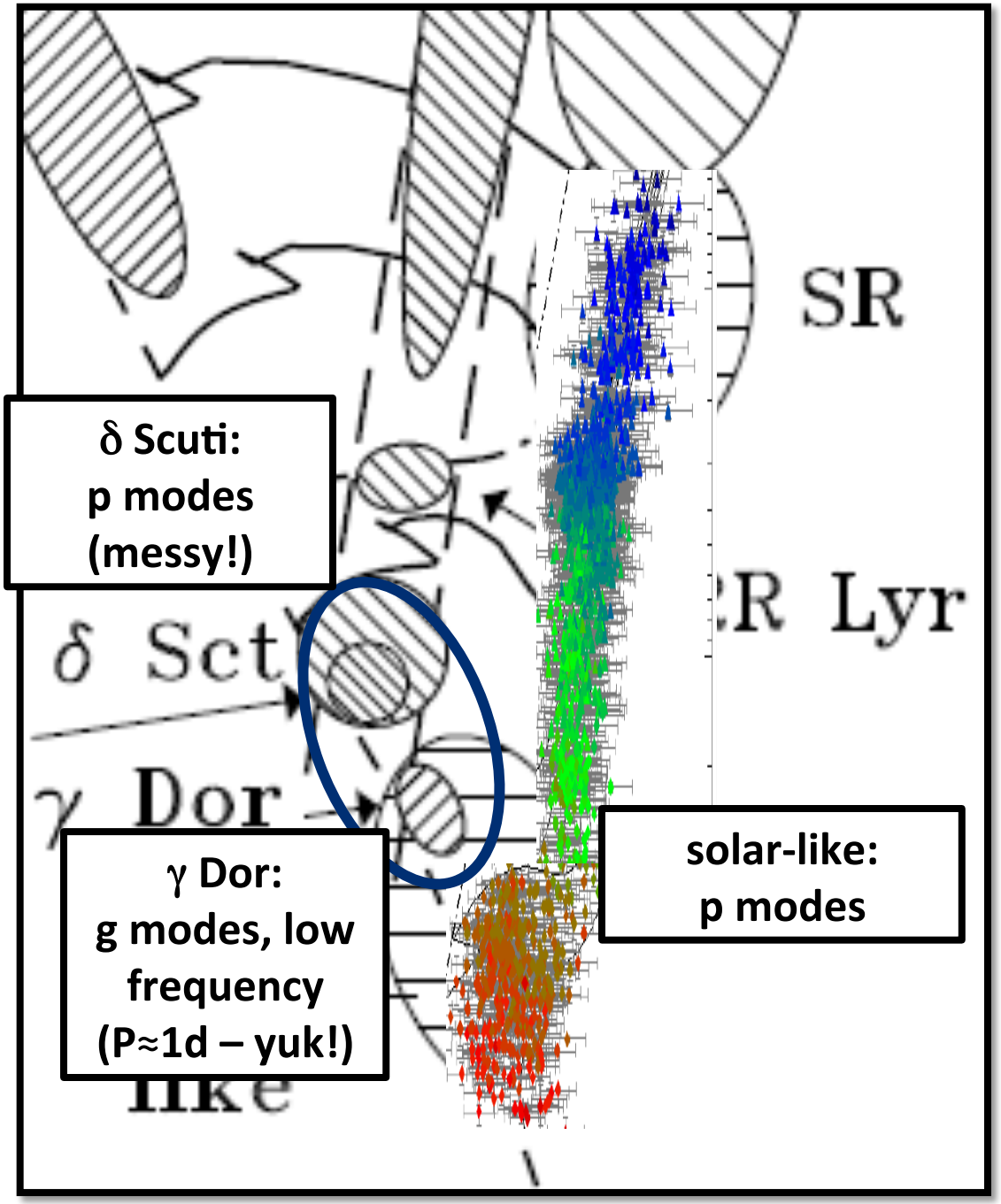
On the relationship between the δ Scuti and γ Doradus pulsators

G. Handler[1★] and R. R. Shobbrook[2,3]

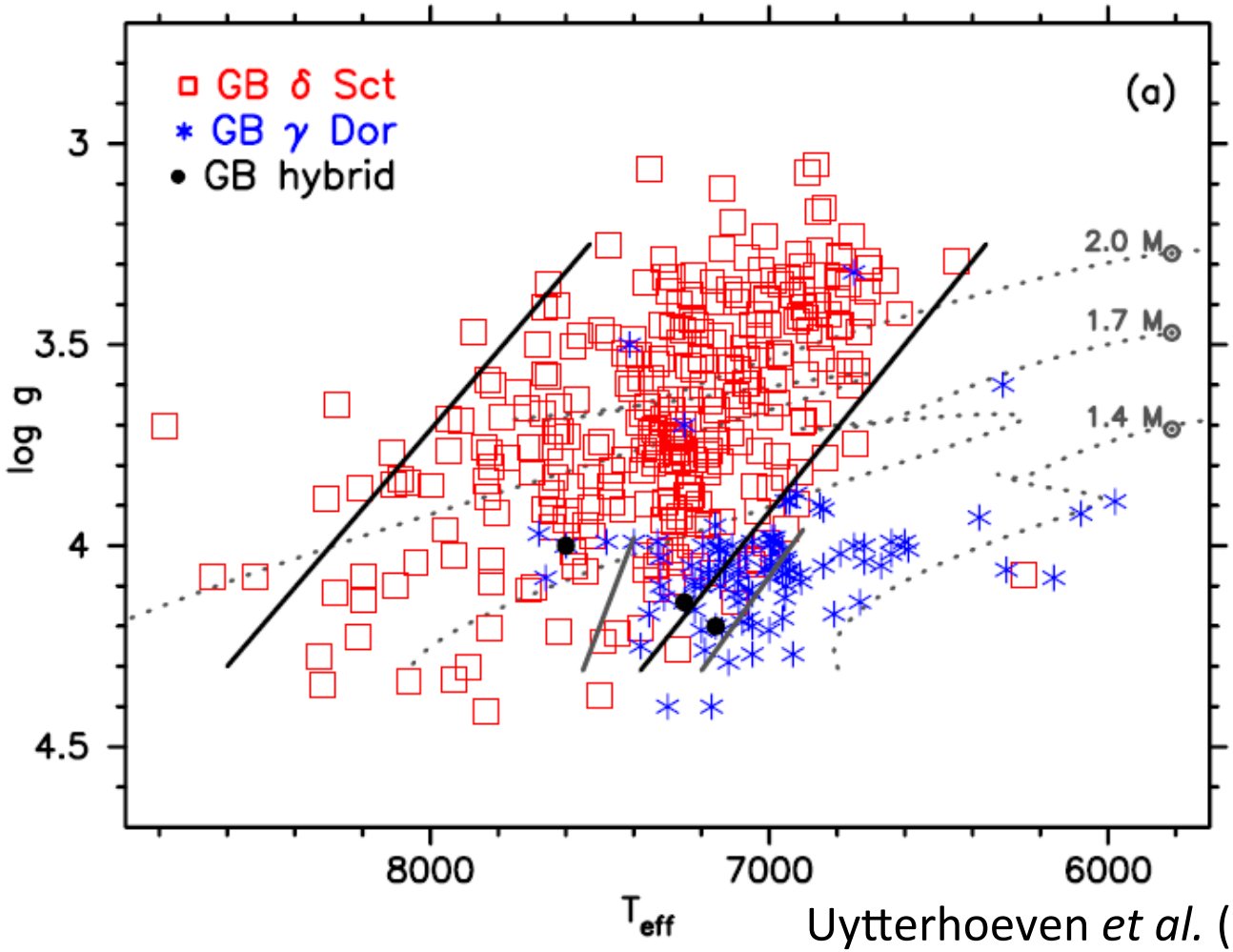




Christensen-Dalsgaard


SR
δ Scuti:
p modes
(messy!)
δ Sct
γ Dor
γ Dor:
g modes, low
frequency
(P≈1d – yuk!)
solar-like:
p modes

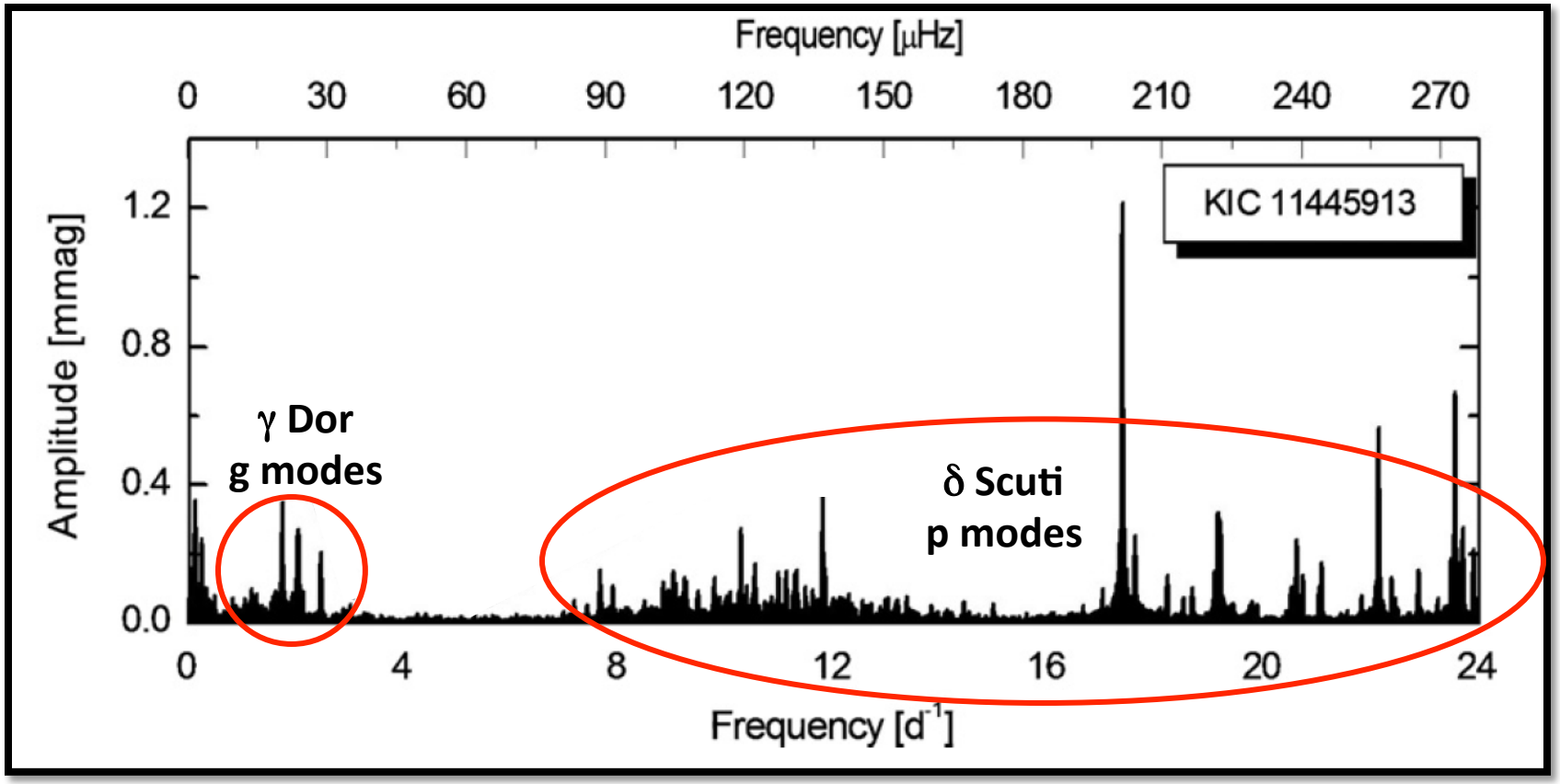
Ground-based observations



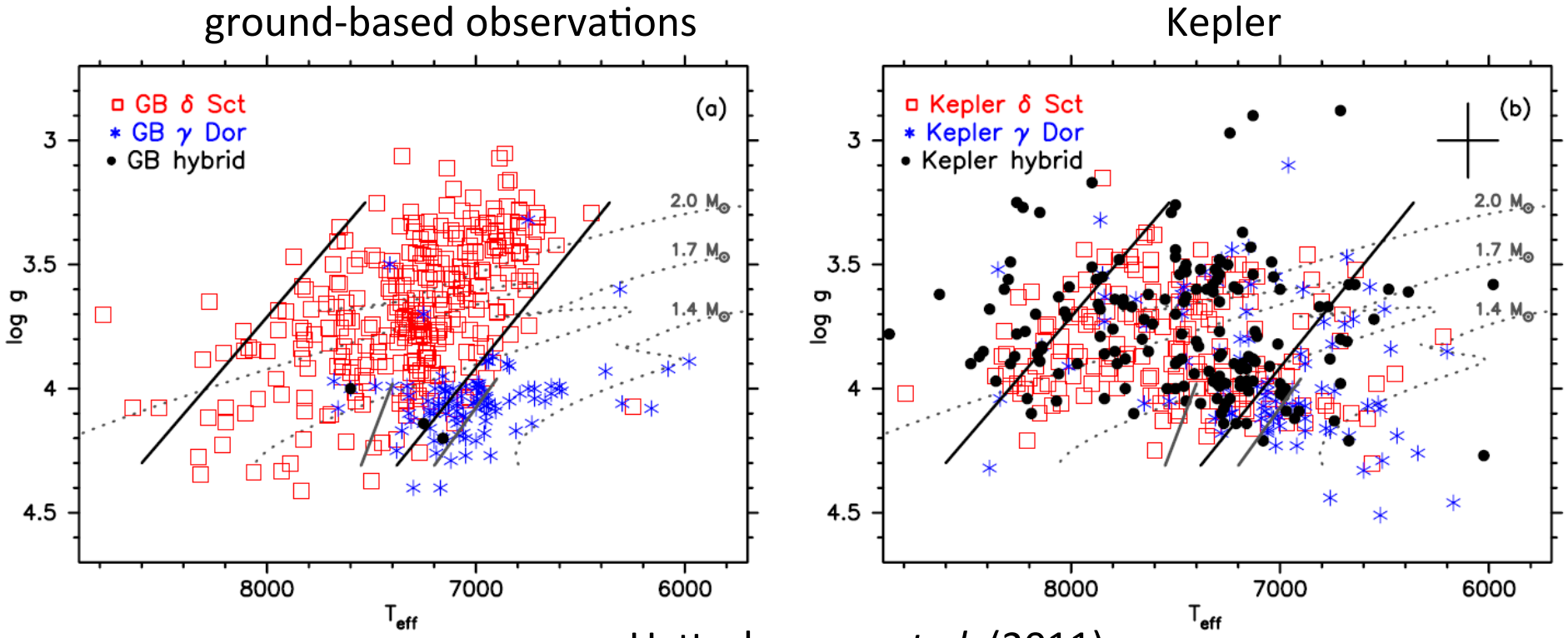
Uytterhoeven *et al.* (2011)

hybrids were predicted theoretically (Dupret et al. 2005)

What did Kepler find?



Grigahcène *et al.* (2010)

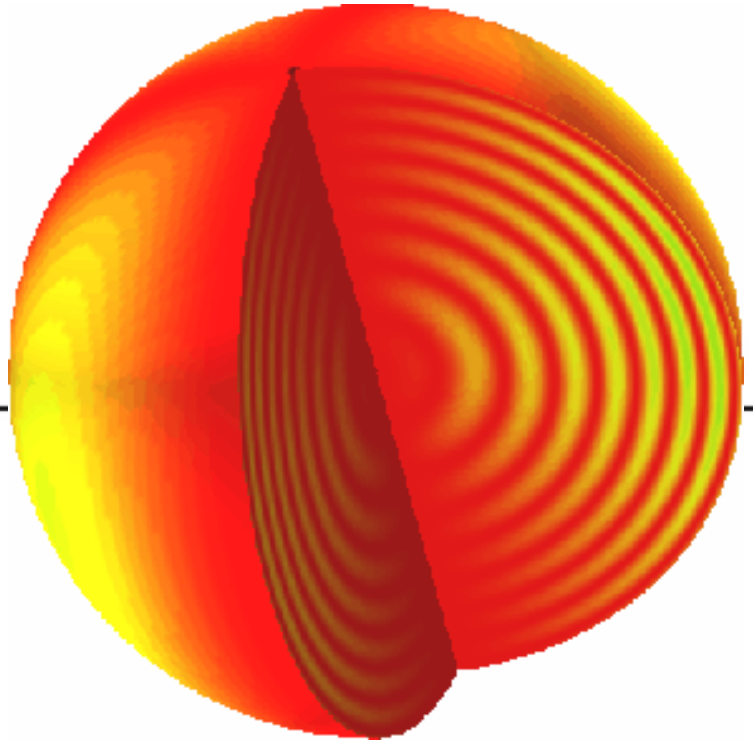


Uytterhoeven *et al.* (2011)

see also Hareter *et* al. (2010, 2012, CoRoT), Balona *et al*. (2011), Tkachenko *et al.* (2013), Bradley *et al.* (2013), Balona (2014)

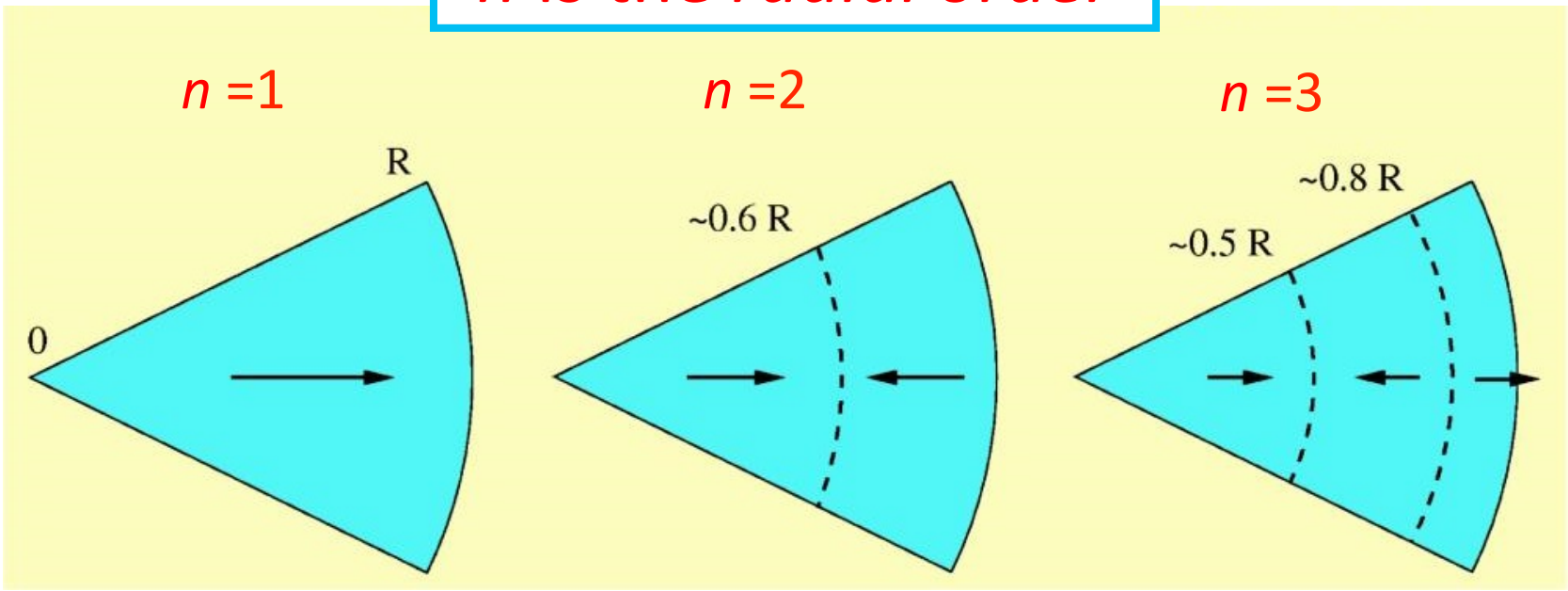
g-mode (γ Dor) pulsations are very common!
(often as hybrids).
Does this open the way for asteroseismology of ordinary intermediate-mass stars?!

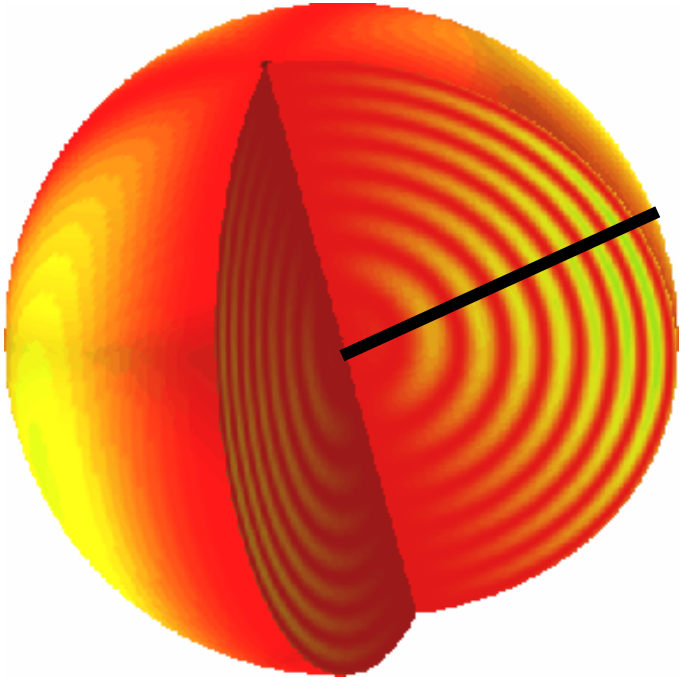
To do asterosesimology we need mode identification



what are
n , ℓ & m?

n is the *radial order*

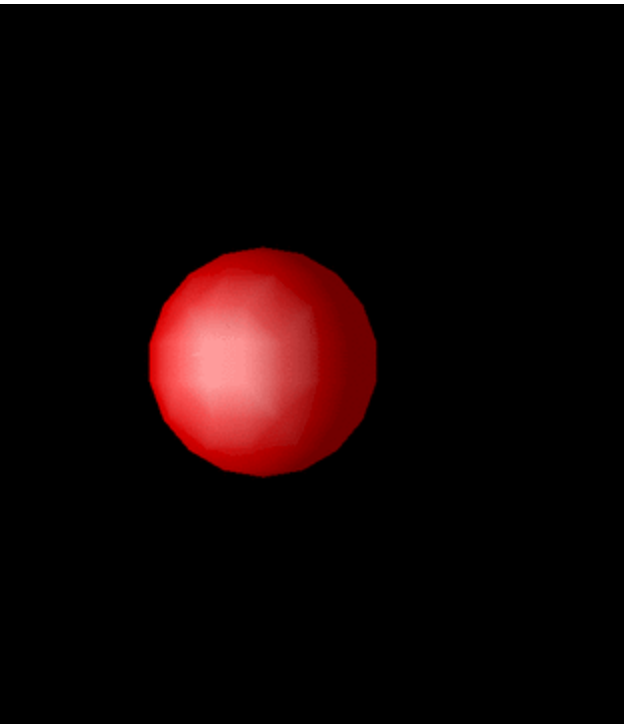


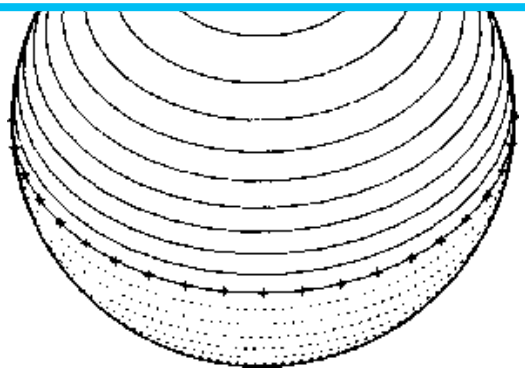


n =18

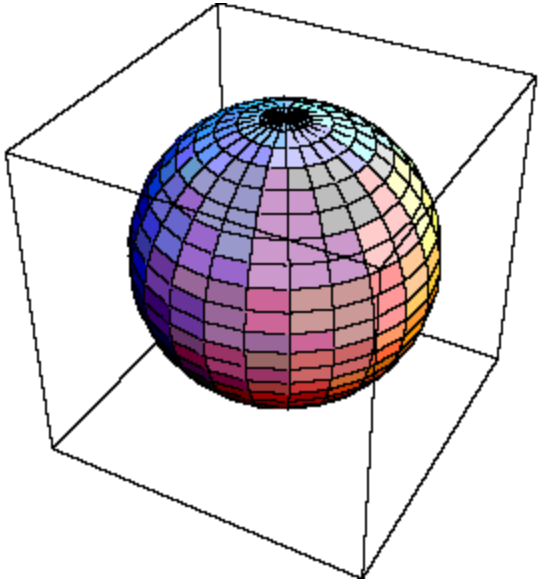
ℓ is the number of nodal lines on the surface (*angular degree*)

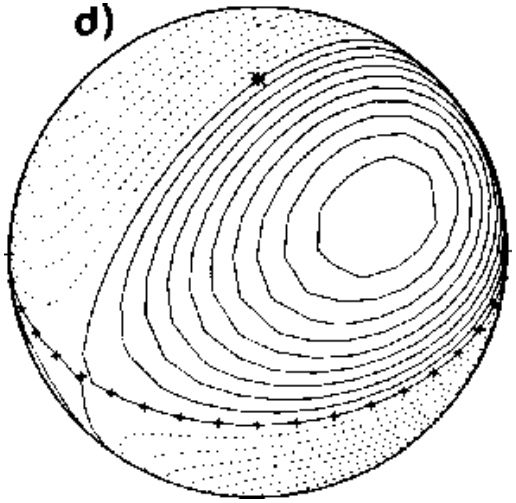
ℓ =0
(radial modes)



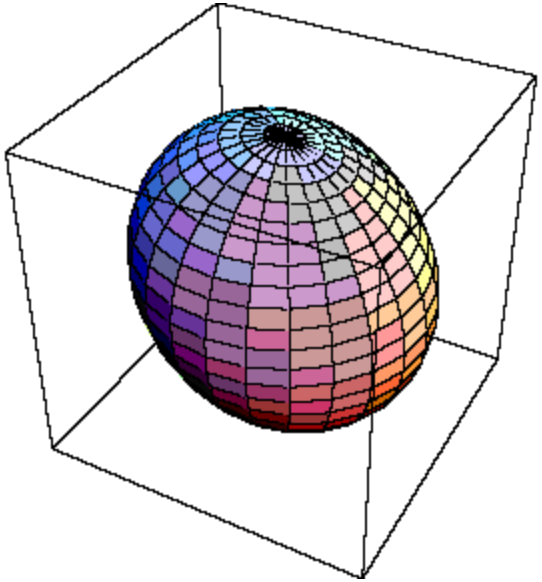


ℓ =1



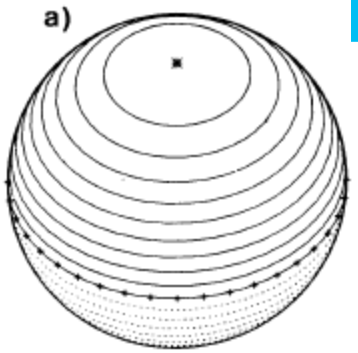


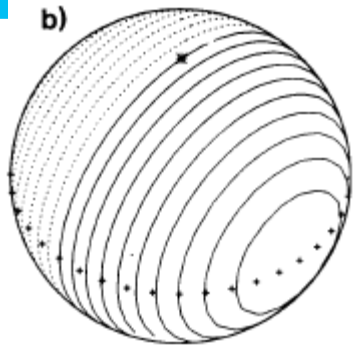
ℓ =2



m is the number of nodal lines crossing the equator.

$m = 0, \pm 1, \ldots, \pm \ell$

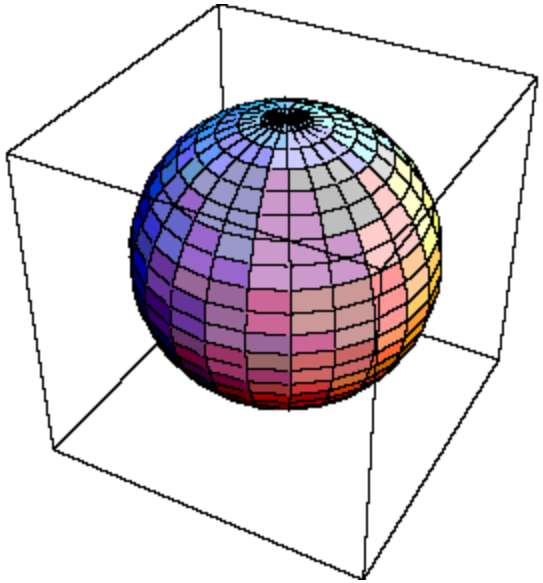


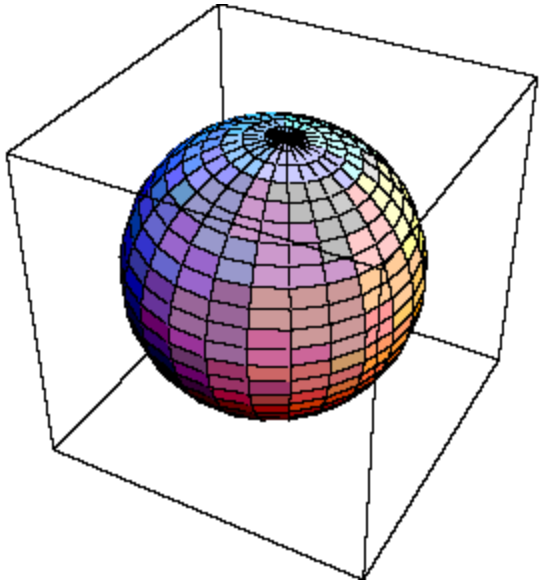


$\ell = 1, m = 0$

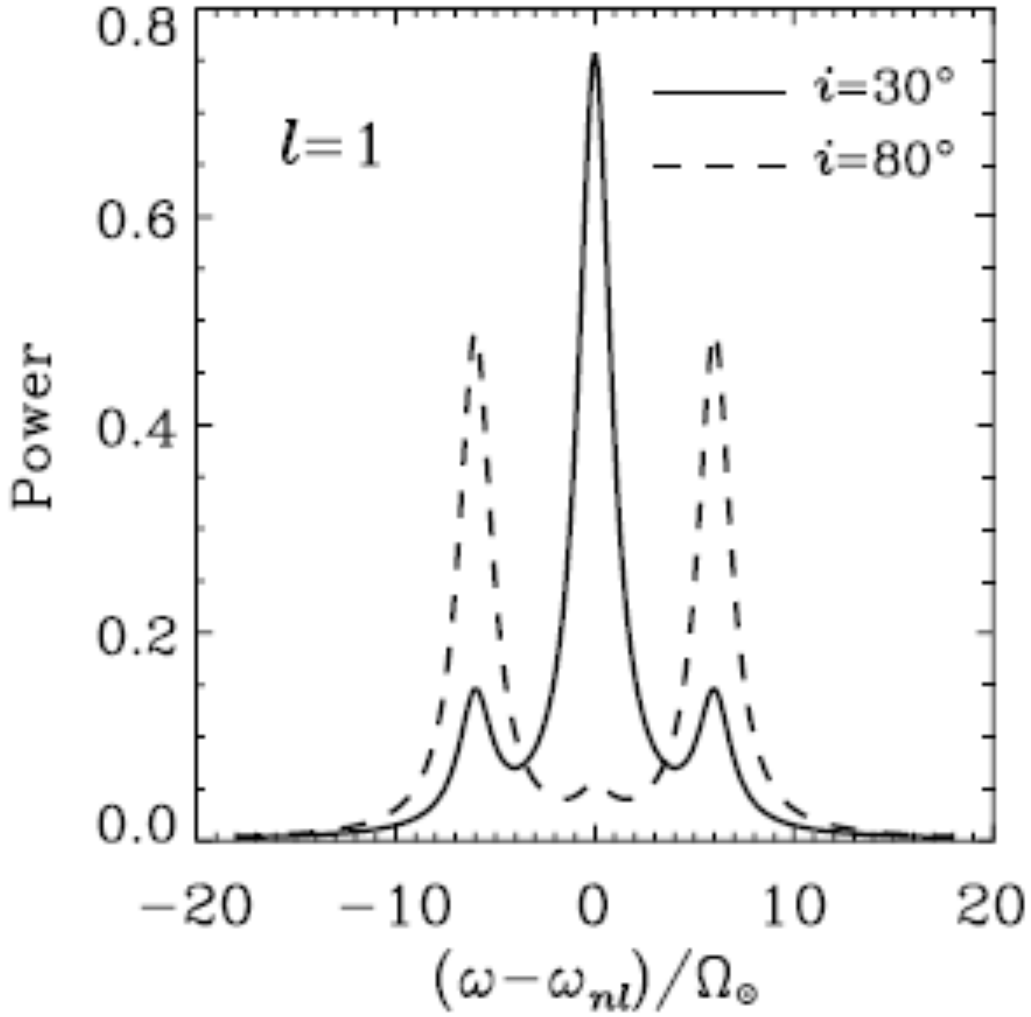
unless symmetry is broken, mode frequency does not depend on *m*

$\ell = 1, m = \pm 1$





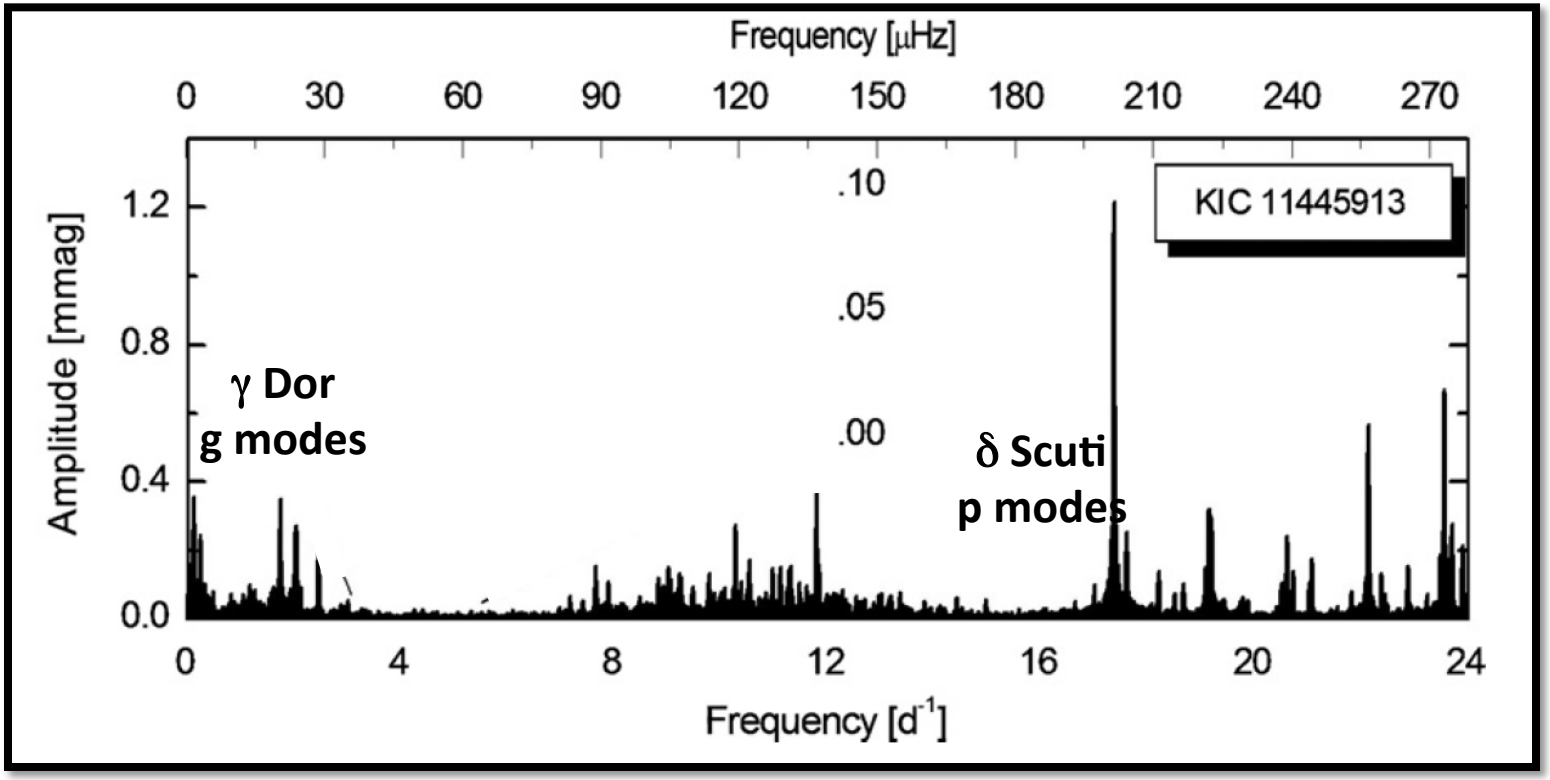
rotational splitting of ℓ= 1



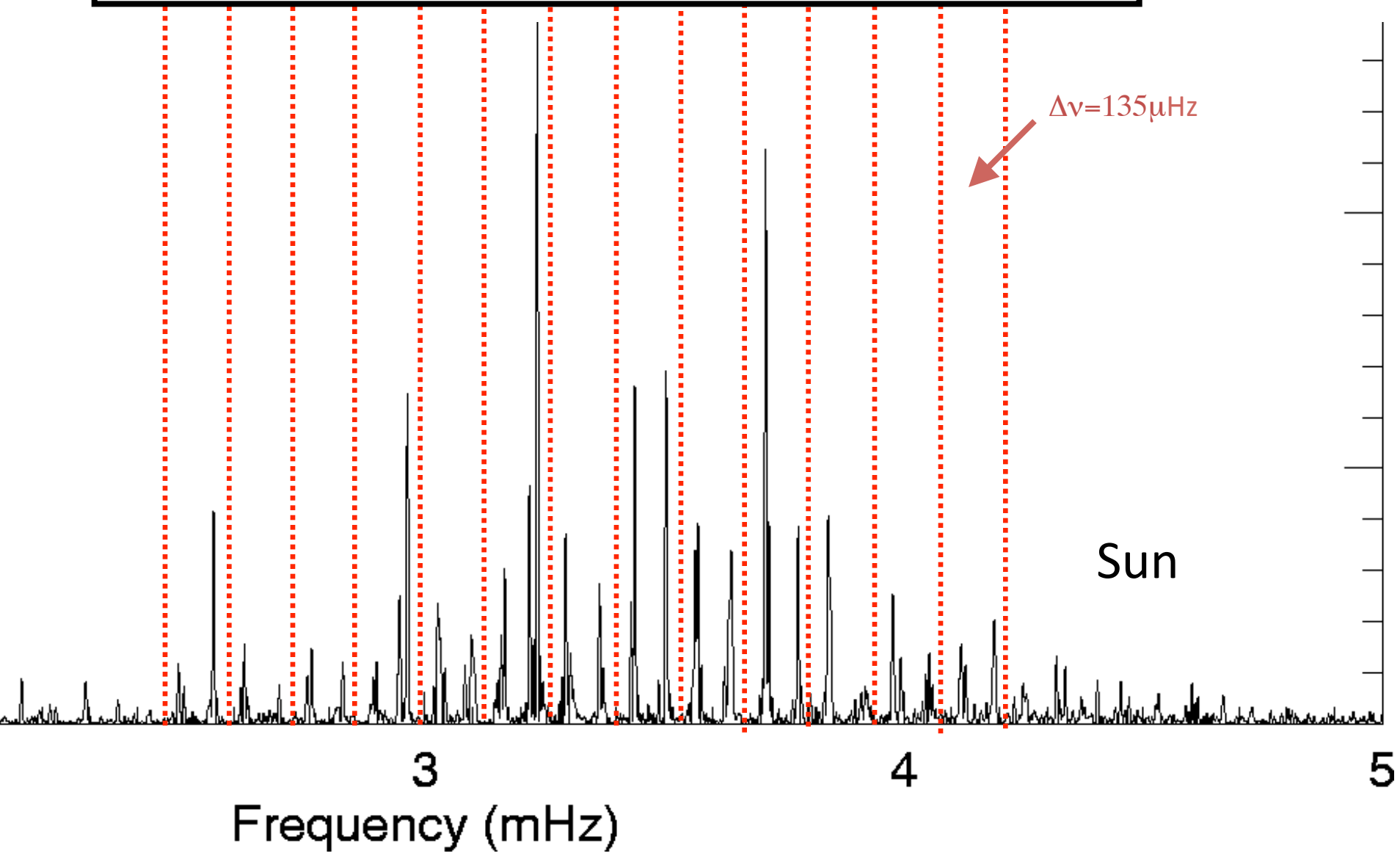
Gizon & Solanki (2003)

How do we identify modes?

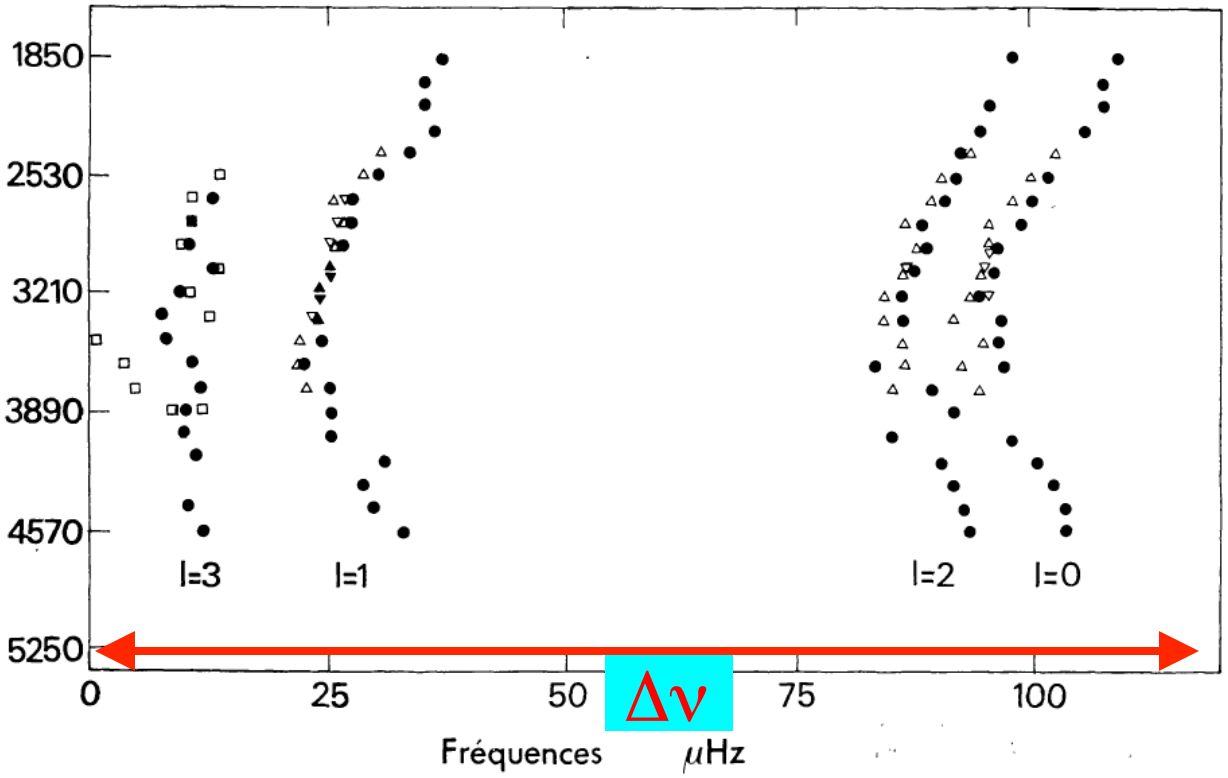
- need adequate frequency resolution
- look for patterns, be guided by theory
- much easier if all (or most) modes are excited, and if rotation is not too rapid



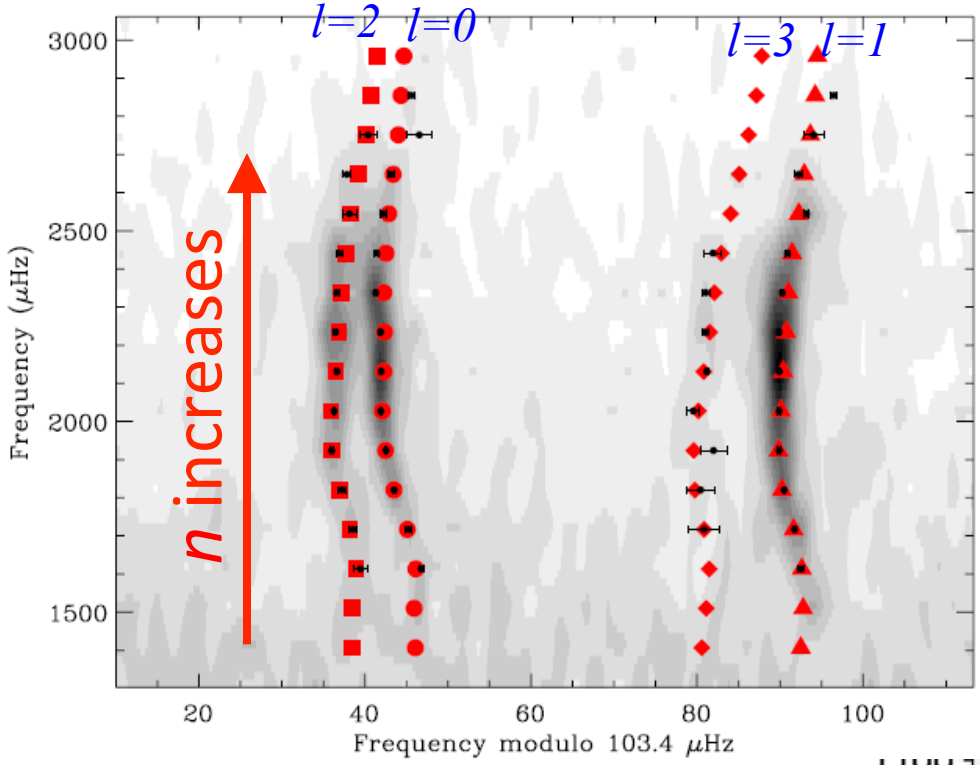
p modes are approximately equally spaced in frequency (for large *n*)



The échelle diagram:



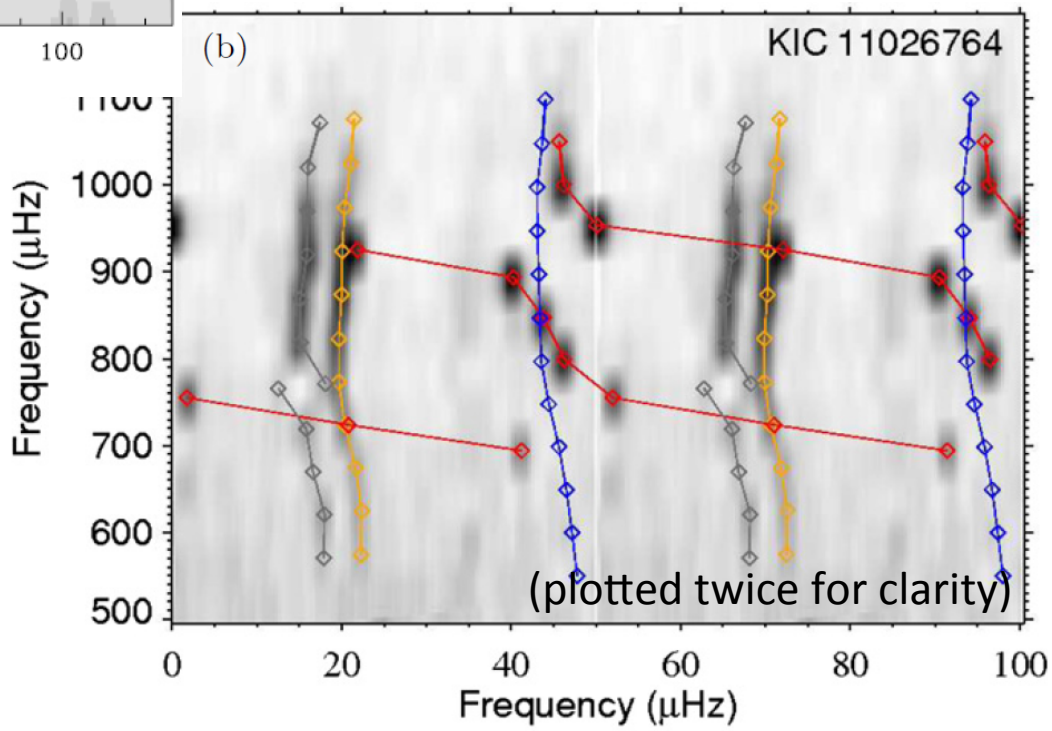
Grec *et al.* (1983)



16 Cyg A (Metcalfe et al. 2012)

identification of p modes in Sun-like stars is usually easy (not true for δ Scuti pulsations, which have low *n*)

G subgiant (Benomar et al. 2013)



Asymptotic pattern of g modes (*n* large):

- NB: ℓ =0 (radial) g modes don't exist
- the $\ell \geq 1$ (non-radial) overtones are approximately equally spaced in *period* (ΔP)
- but the period spacing depends on ℓ:

$$\Delta P \approx [\ell(\ell+1)]^{-½}$$

so for g modes, we need a different échelle diagram for each value of ℓ

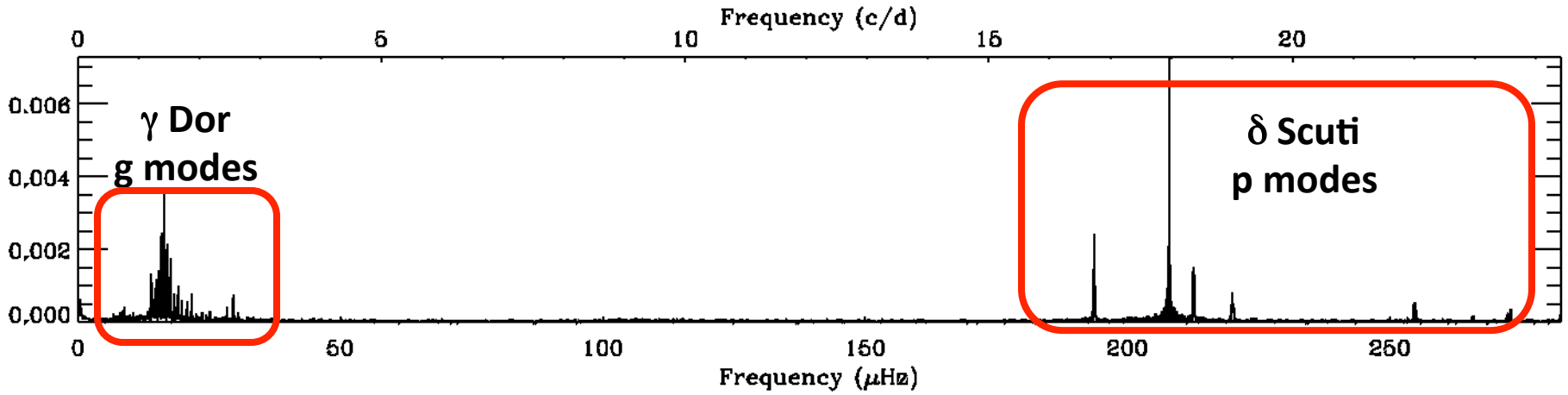
Previous studies of individual CoRoT & *Kepler* γ Dor stars:

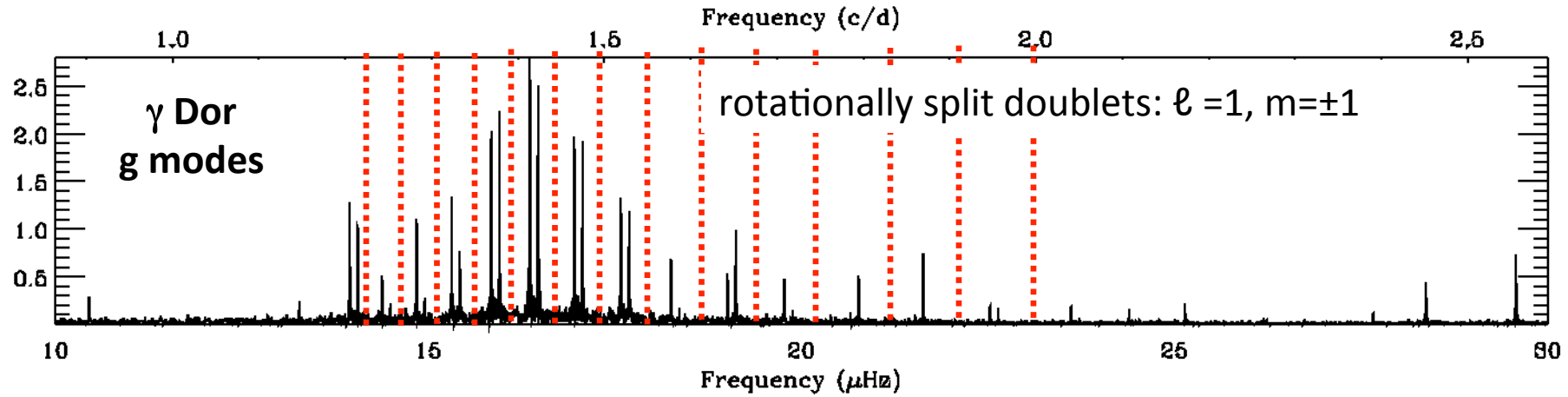
- HD 49434 (Chapellier *et al.* 2011)
- CoRoT 105733033 (Chapellier *et al.* 2012)
- KIC 8054146 (Breger *et al.* 2012)
- KIC 11285625 (Debosscher *et al.* 2013)
- KIC 6761539 (Herzberg *et al.* 2013)
- CoRoT 102918586 (Maceroni *et al.* 2013)
- KIC 6462033 (Ulusoy *et al.* 2014)
- KIC 11145123 (Kurtz *et al.* 2014)

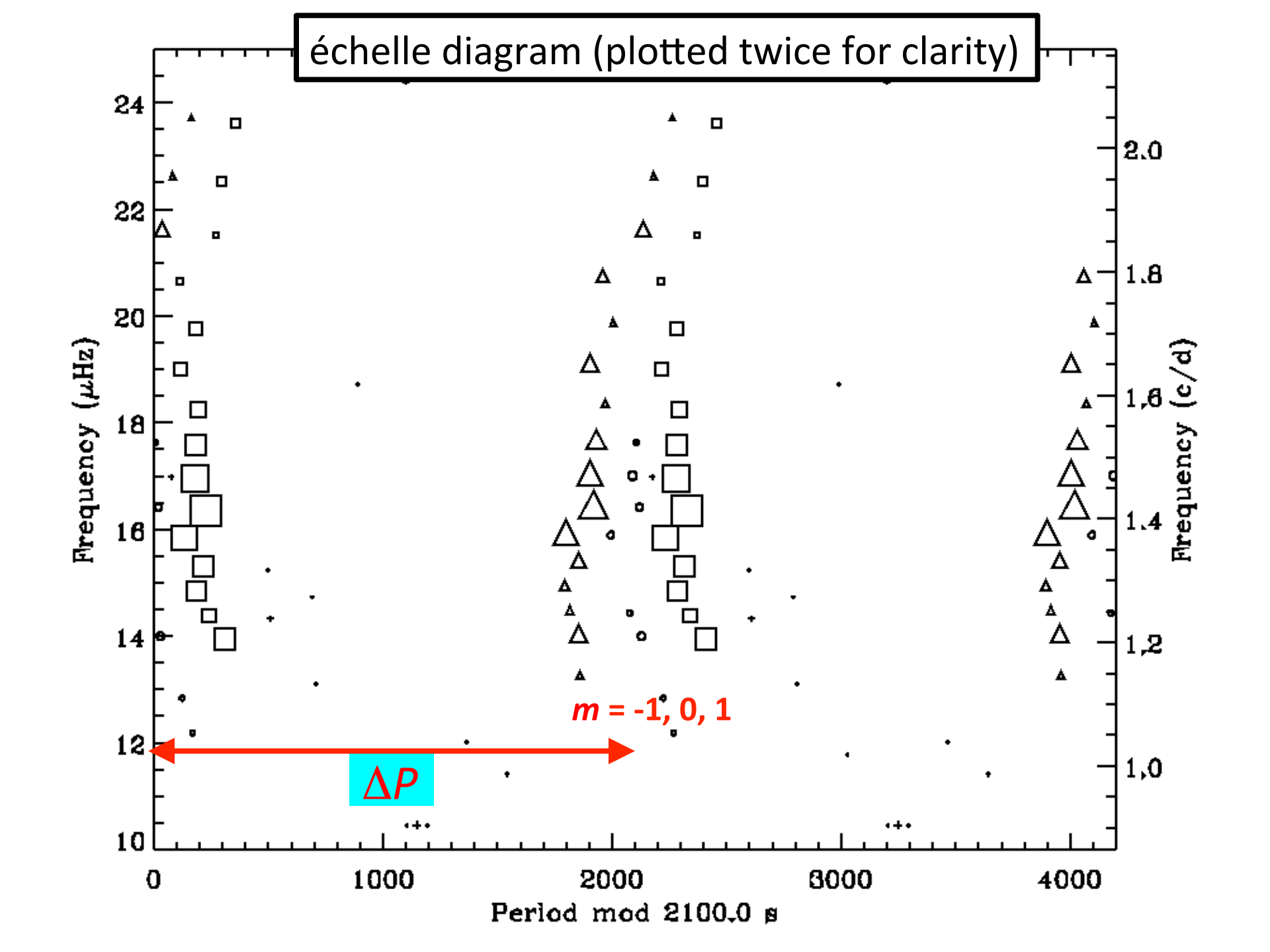
- also see Poster 21 by Van Reeth, Tkachenko & Aerts

Asteroseismic measurement of surface-to-core rotation in a main sequence A star, KIC 11145123

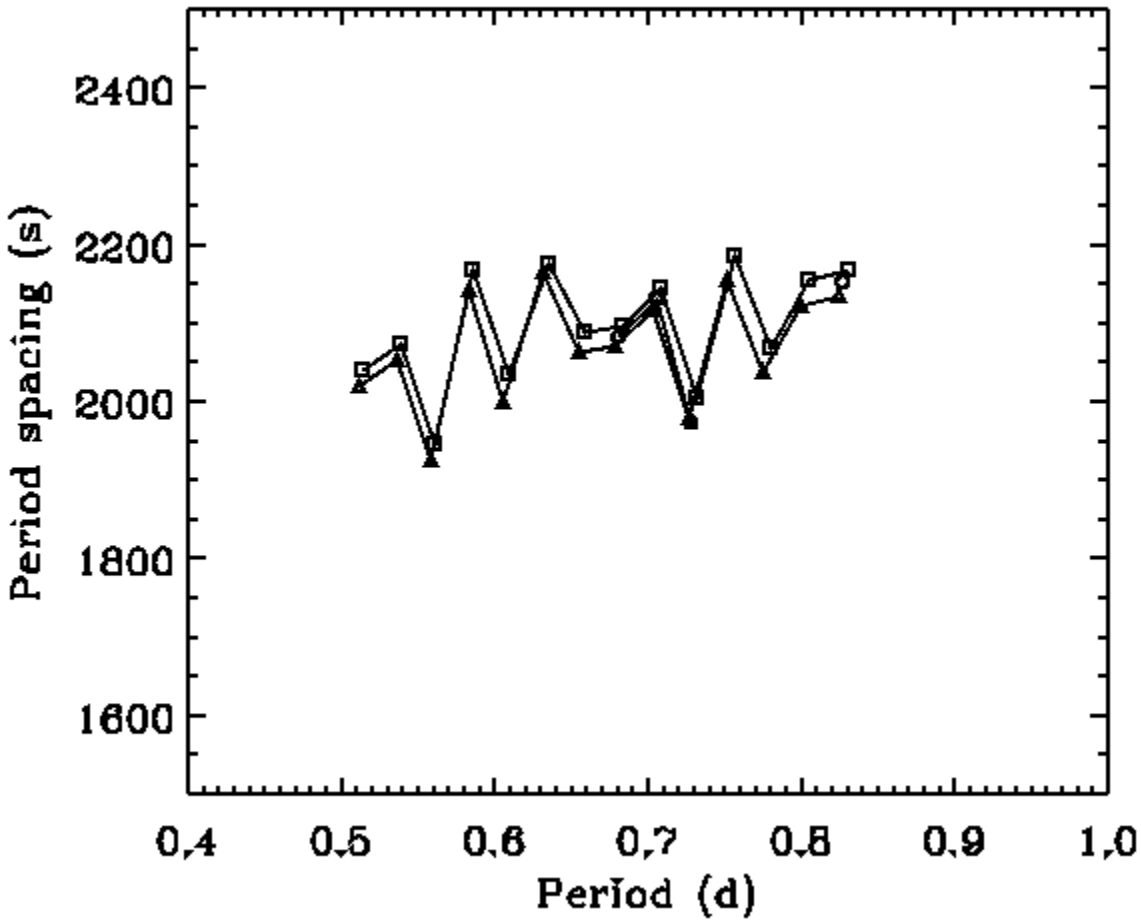
Donald W. Kurtz[1], Hideyuki Saio[2], Masao Takata[3], Hiromoto Shibahashi[3], Simon J. Murphy[1,4], Takashi Sekii[5]



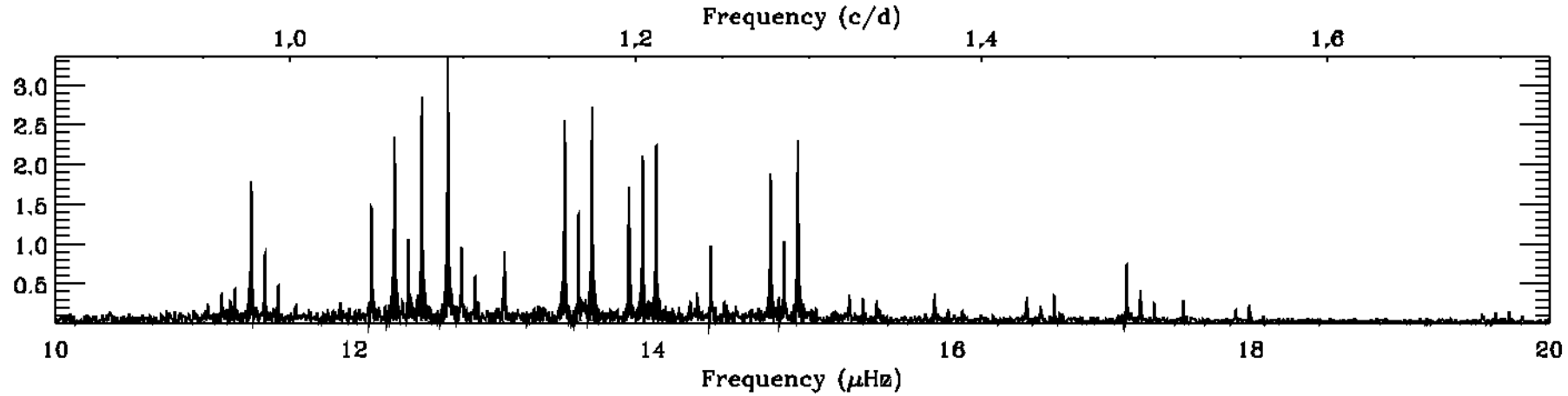



échelle diagram (plotted twice for clarity)
Frequency (μHz)
Frequency (c/d)
Period mod 2100.0 s
m = -1, 0, 1
ΔP
24
22
20
18
16
14
12
10
2.0
1.8
1.6
1.4
1.2
1.0
0
1000
2000
3000
4000

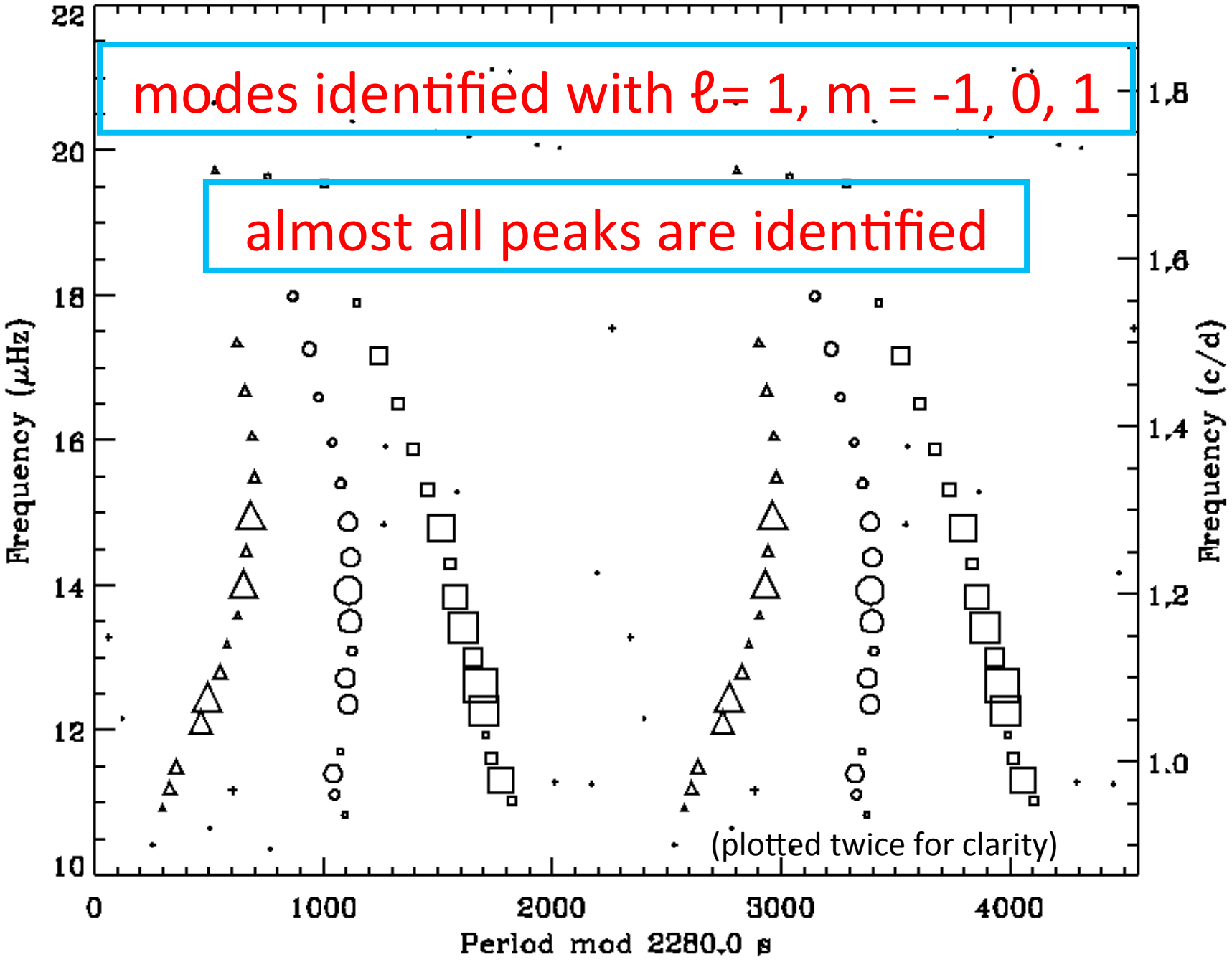
“wiggles” in échelle diagram, also show up in period spacings:



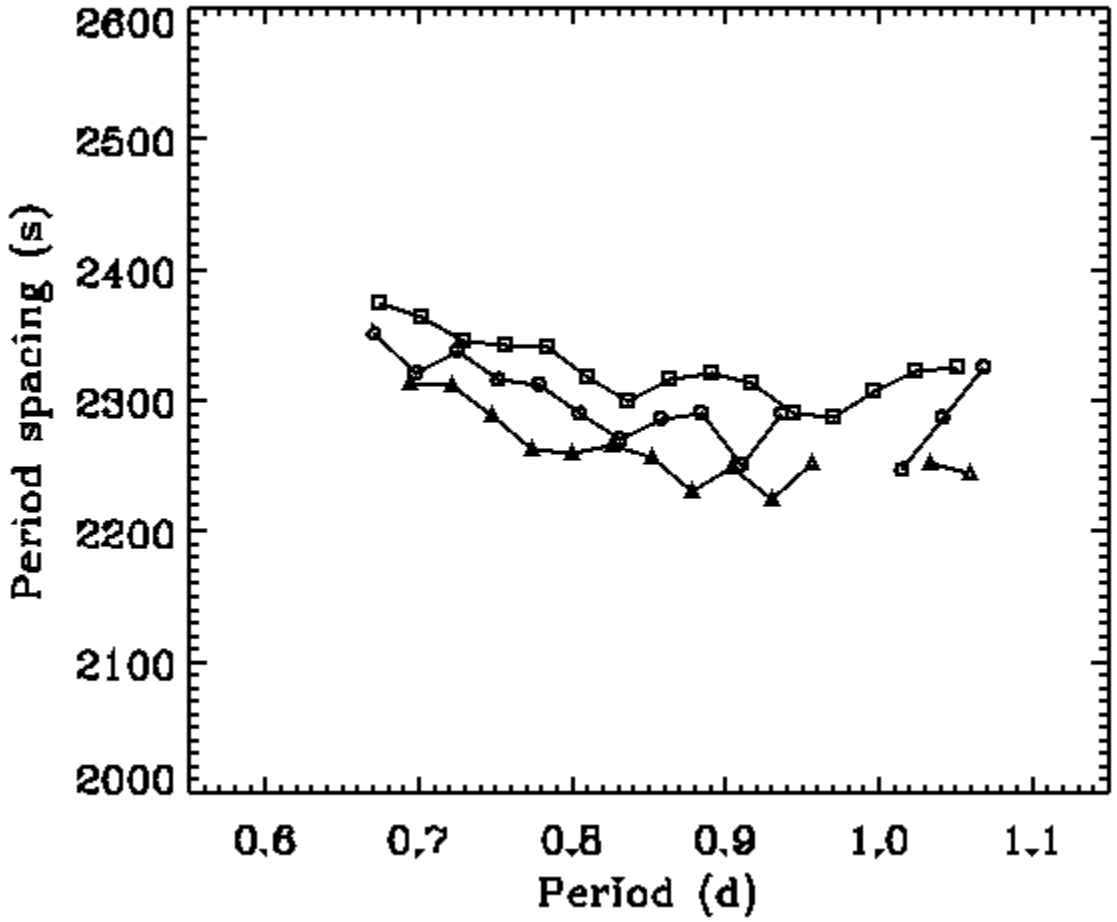
Star 2. (also found by Don)



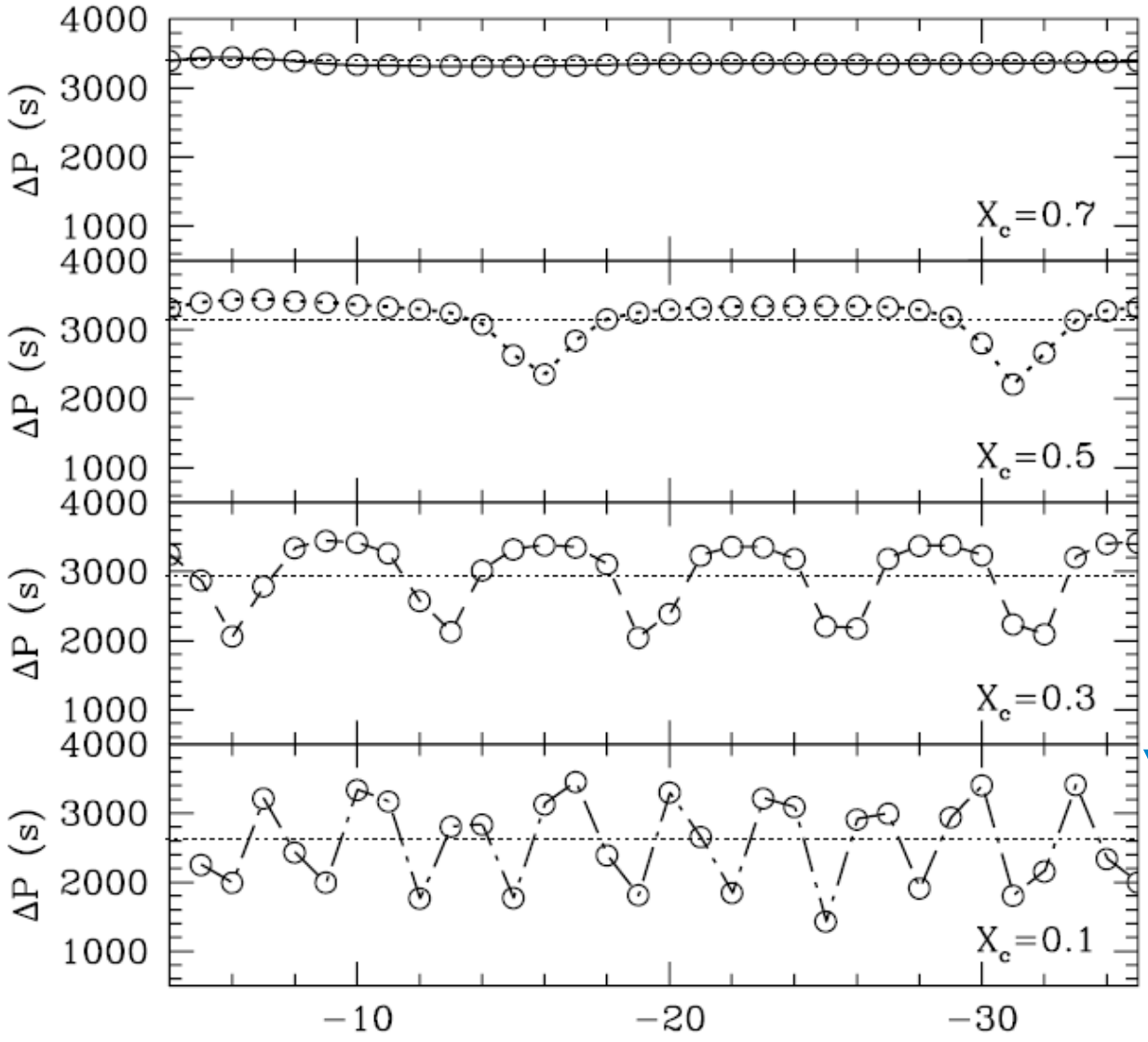
shows ℓ =1 triplets (intermediate inclination)
and somewhat faster rotation


modes identified with ℓ= 1, m = -1, 0, 1
almost all peaks are identified
(plotted twice for clarity)
Frequency (μHz)
Frequency (c/d)
Period mod 2280.0 s
22
20
18
16
14
12
10
1.8
1.6
1.4
1.2
1.0
0
1000
2000
3000
4000

again, “wiggles” in échelle diagram show up in period spacings:



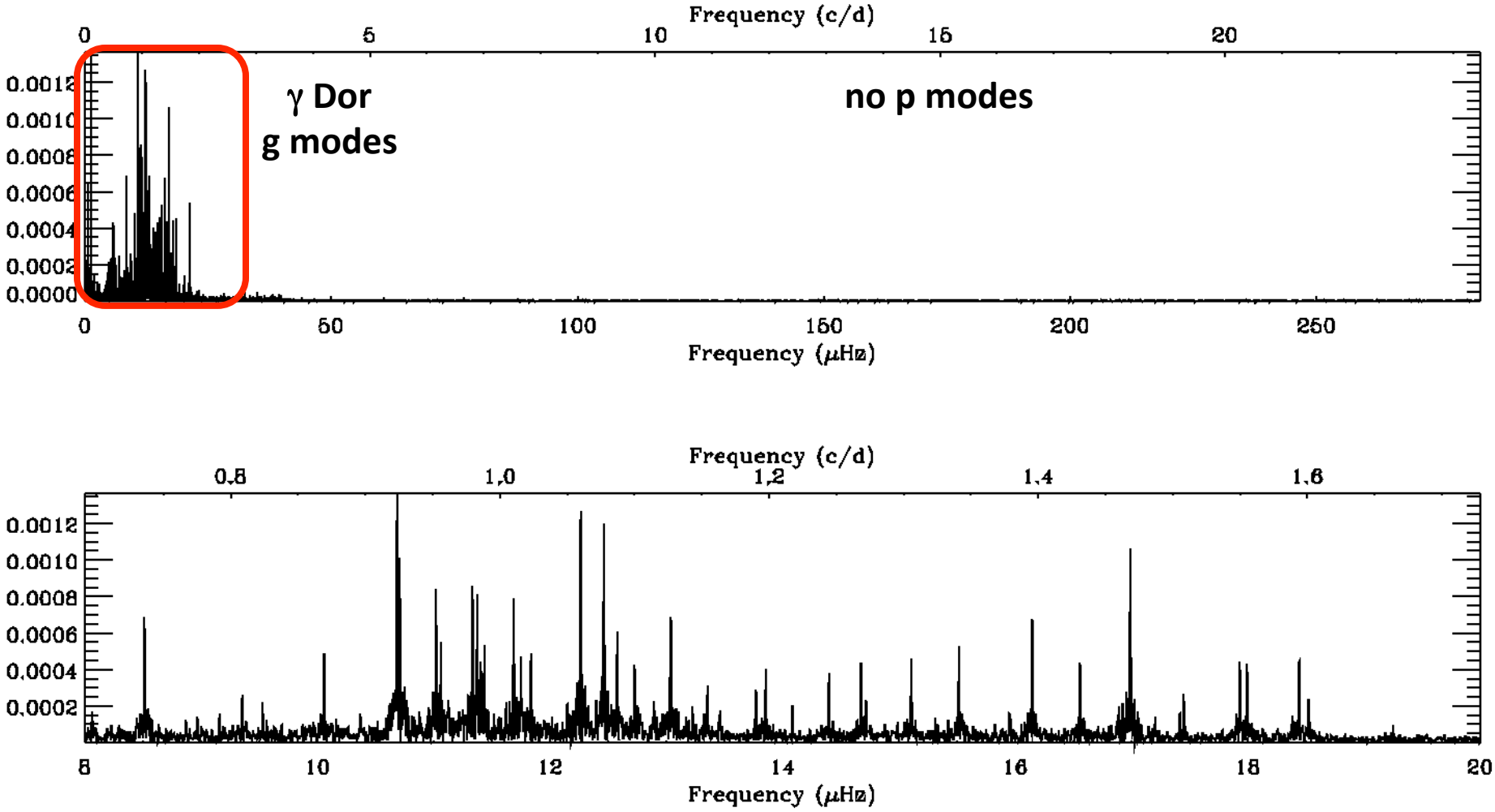
What causes irregularities in the period spacing?

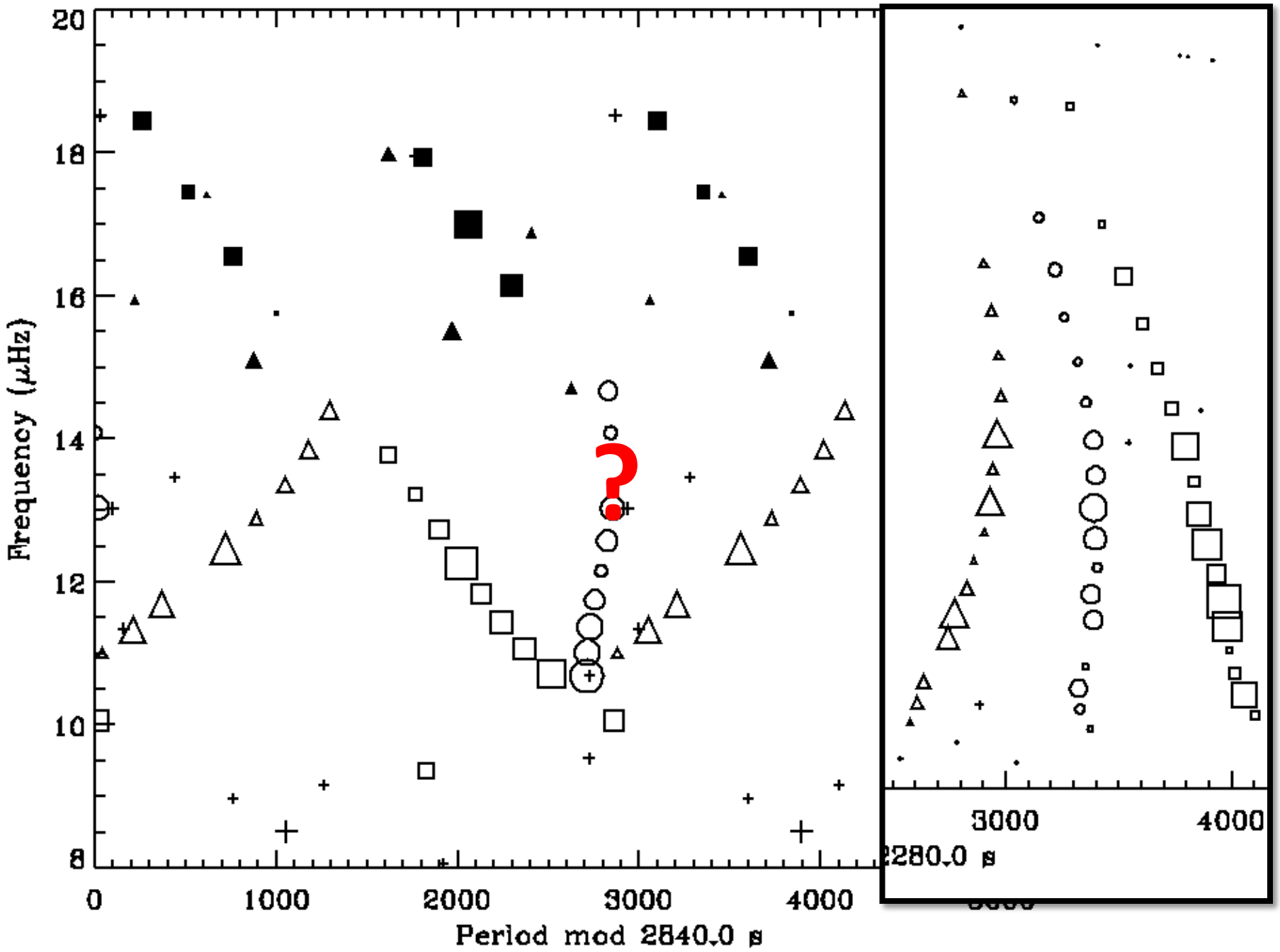


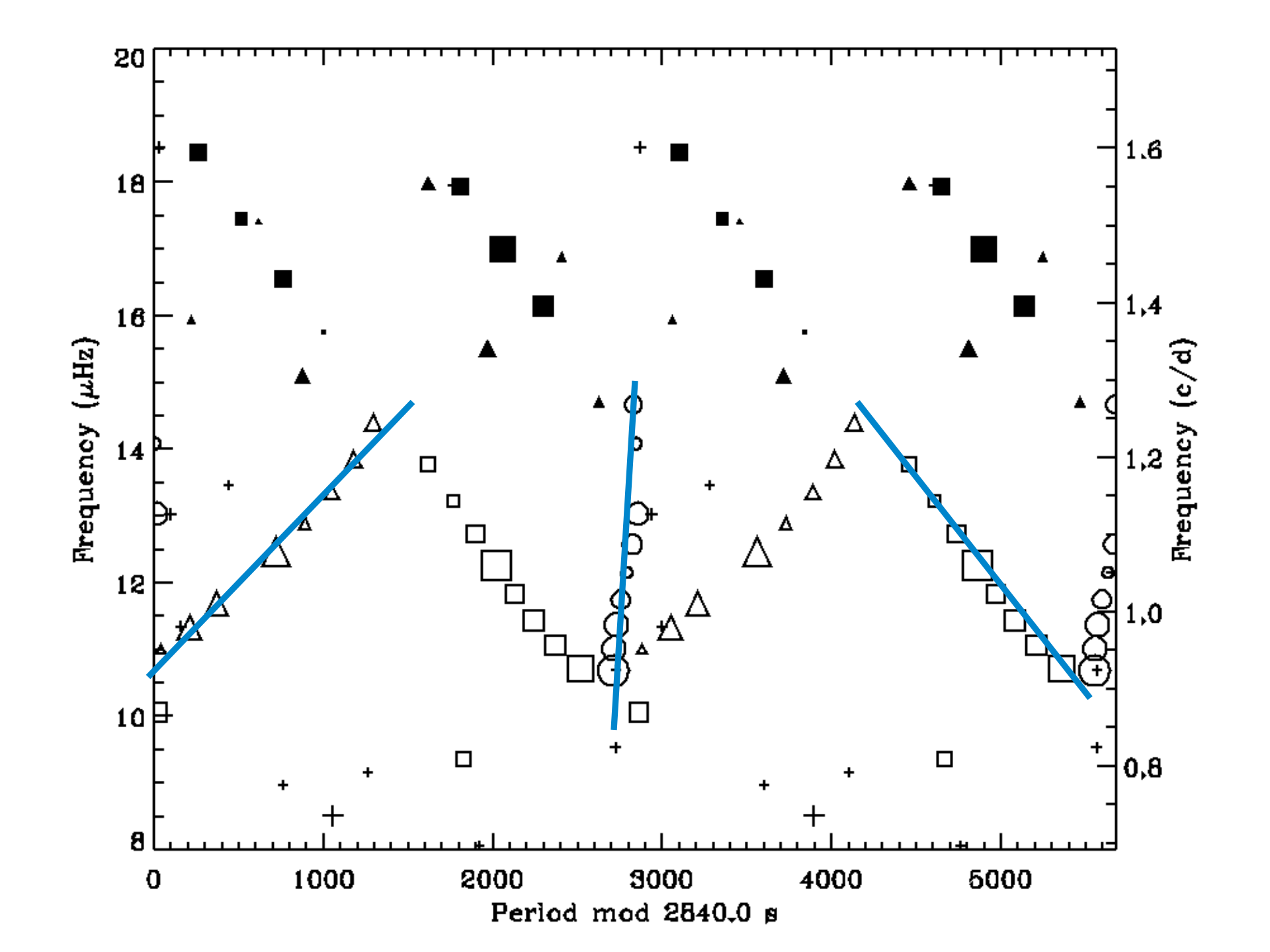
ℓ =1 period spacing for evolving 1.6 $M_\odot$ model (Miglio et al. 2008)

the irregularities are caused by the gradient in chemical composition just outside convective core ("mode trapping"). Mode trapping is well studied in WDs, sdBs and SPBs.

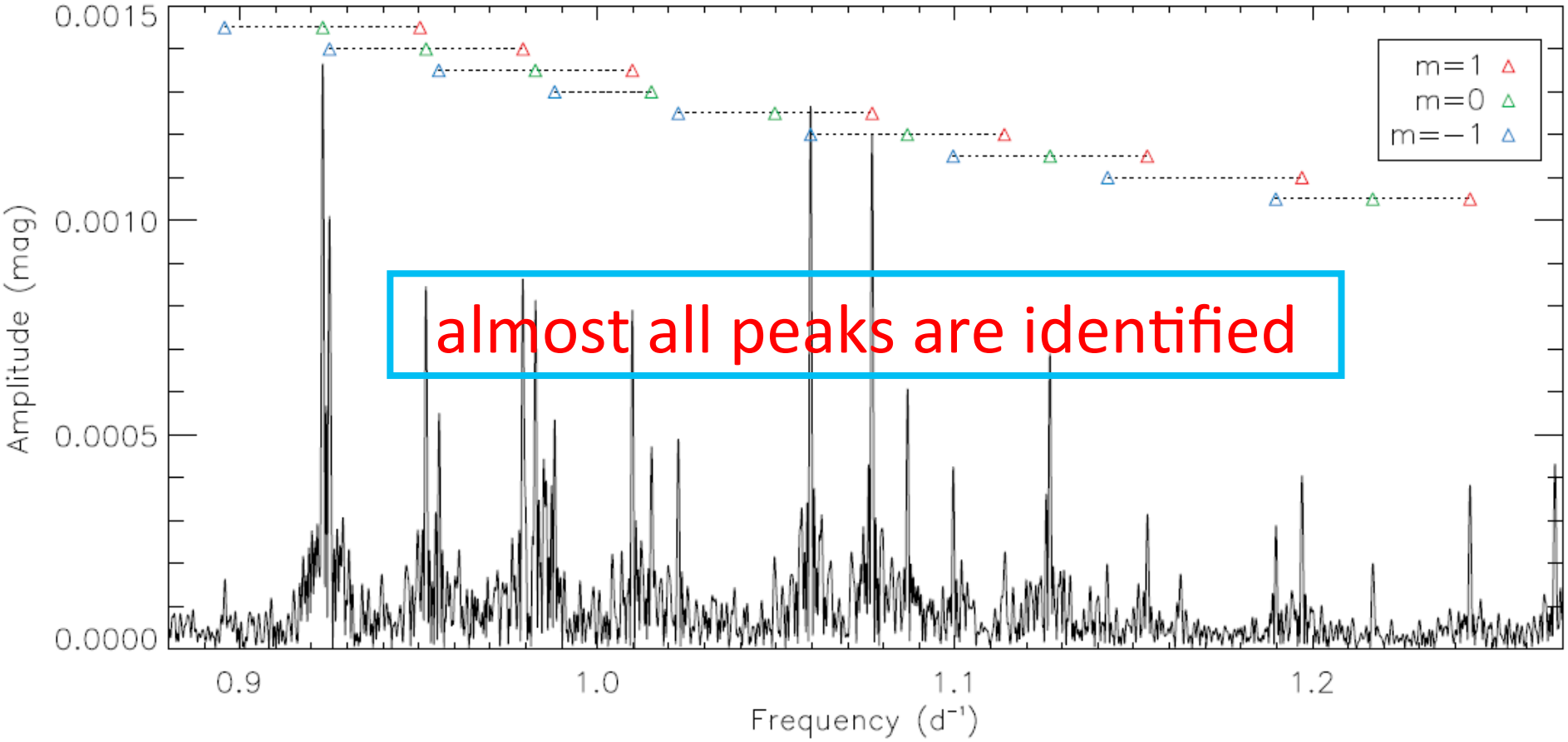
3. Isabel's star




20
18
16
14
12
10
8
Frequency (μHz)
0
1000
2000
3000
4000
Period mod 2840.0 s
?
3000
4000
2280.0 s

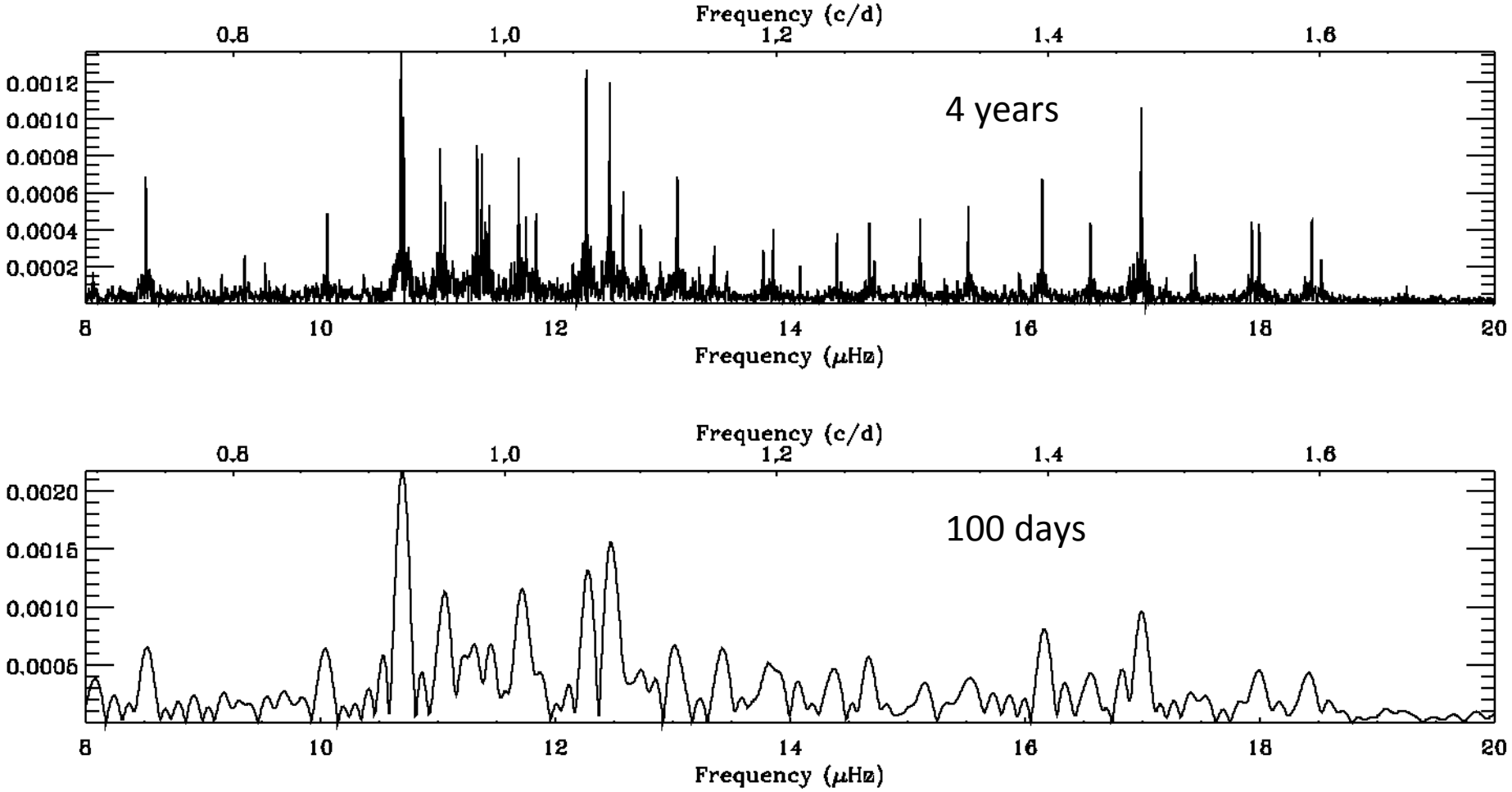

20
18
16
14
12
10
8
Frequency (μHz)
1.6
1.4
1.2
1.0
0.8
Frequency (c/d)
0
1000
2000
3000
4000
5000
Period mod 2540.0 s

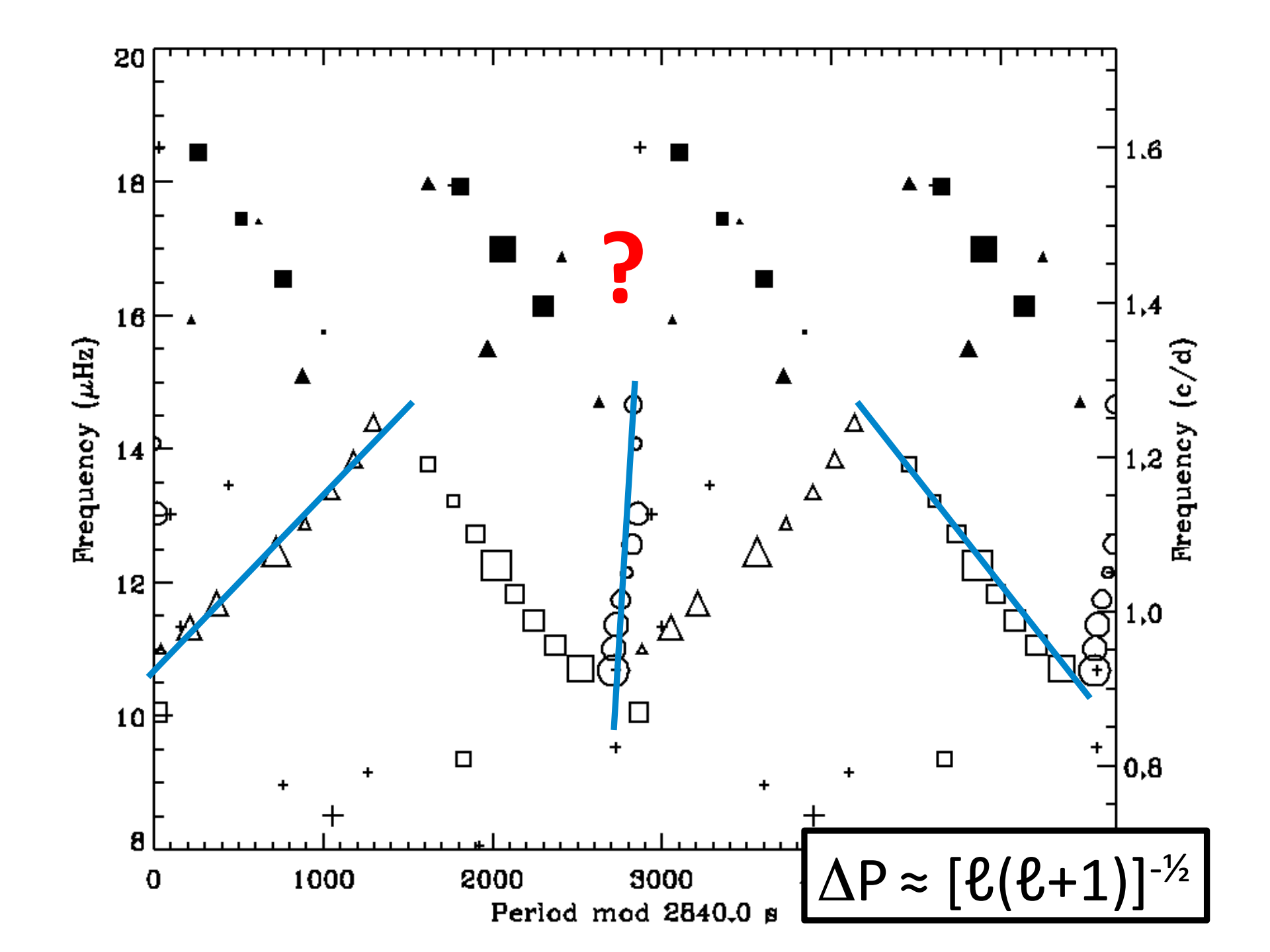
Isabel's star: rotational splitting causes overlap

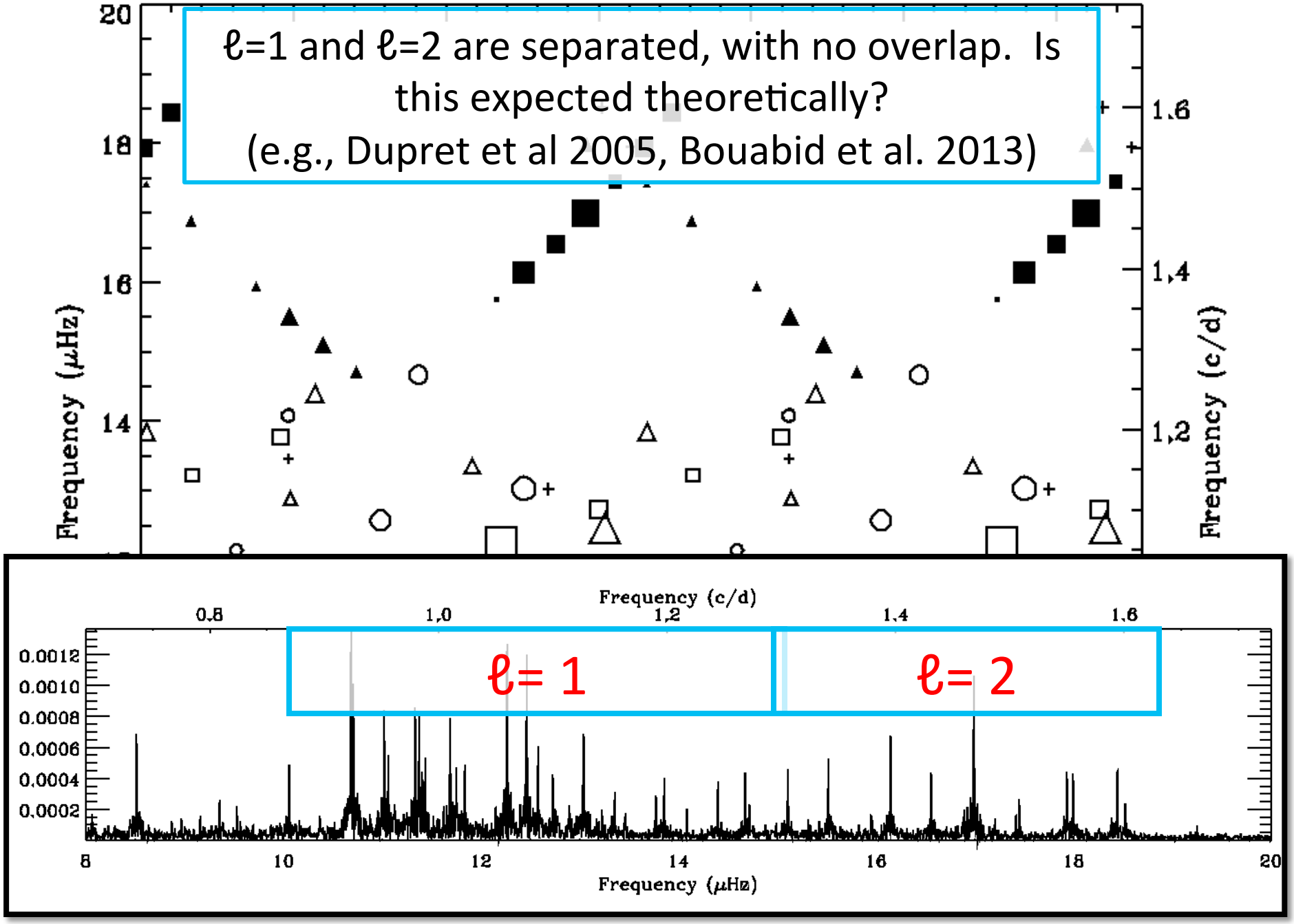


rotational splitting is 0.013 c/d = 0.15 μHz
(2.7 times faster than Don's star)

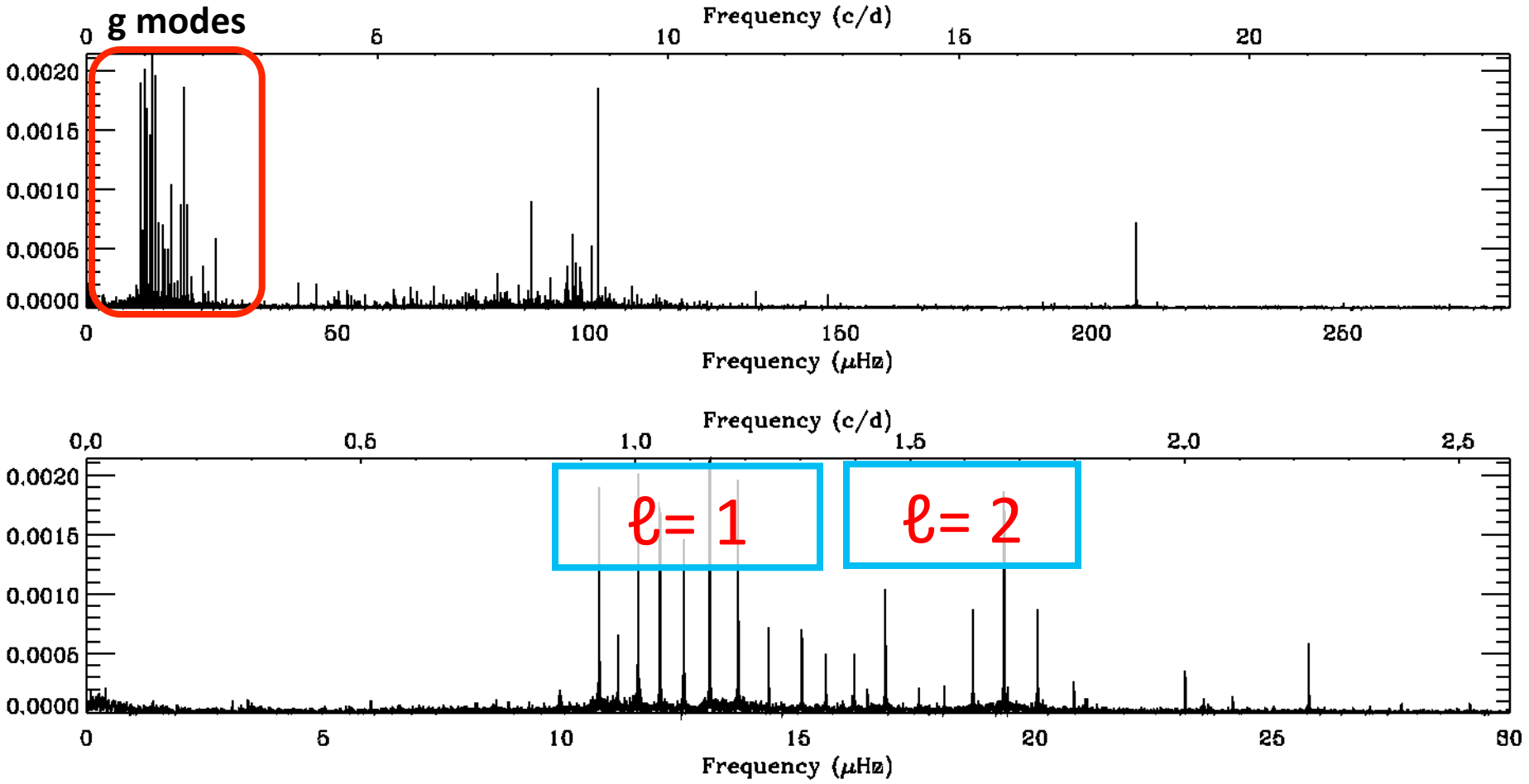
NB: we needed high frequency resolution

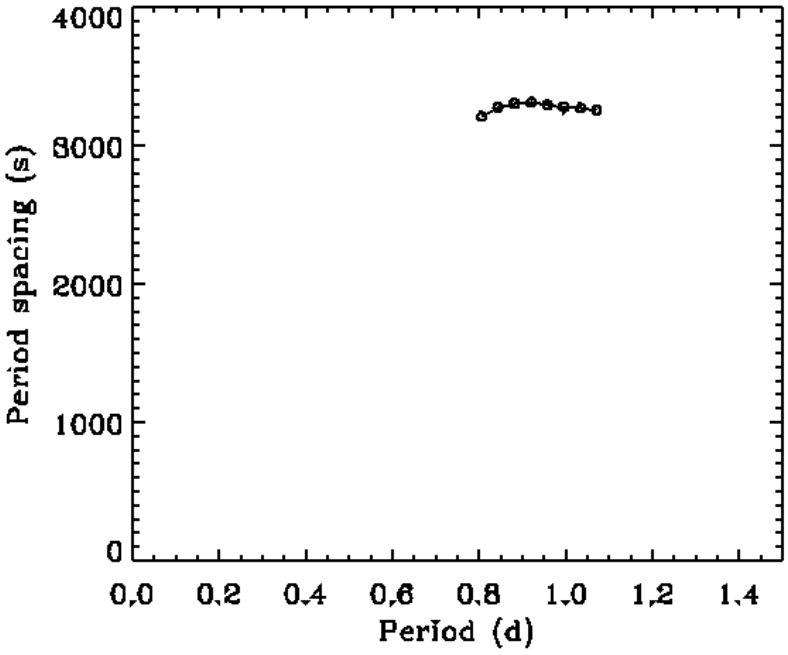


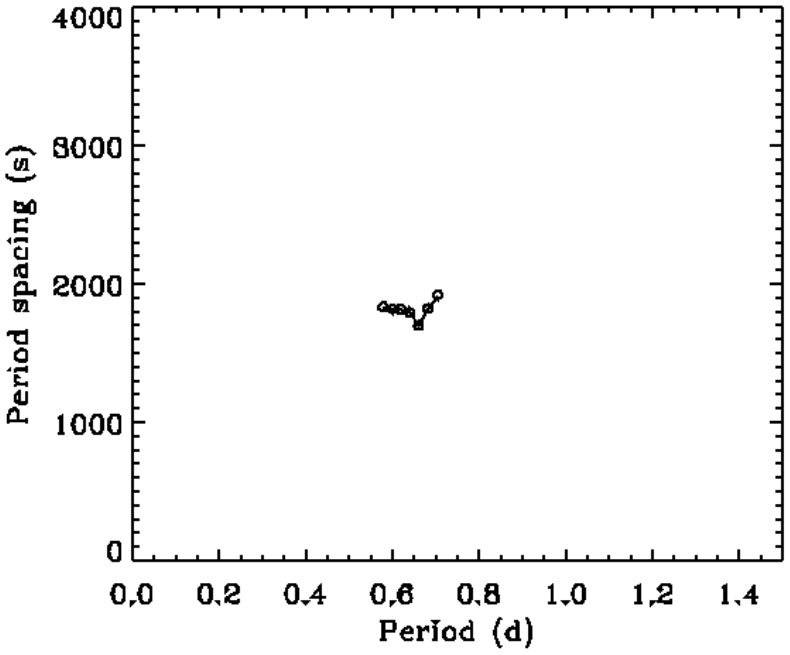

20
18
16
14
12
10
8
Frequency (μHz)
1.6
1.4
1.2
1.0
0.8
Frequency (c/d)
?
0
1000
2000
3000
Period mod 2540.0 s
ΔP ≈ [ℓ(ℓ+1)]^-½

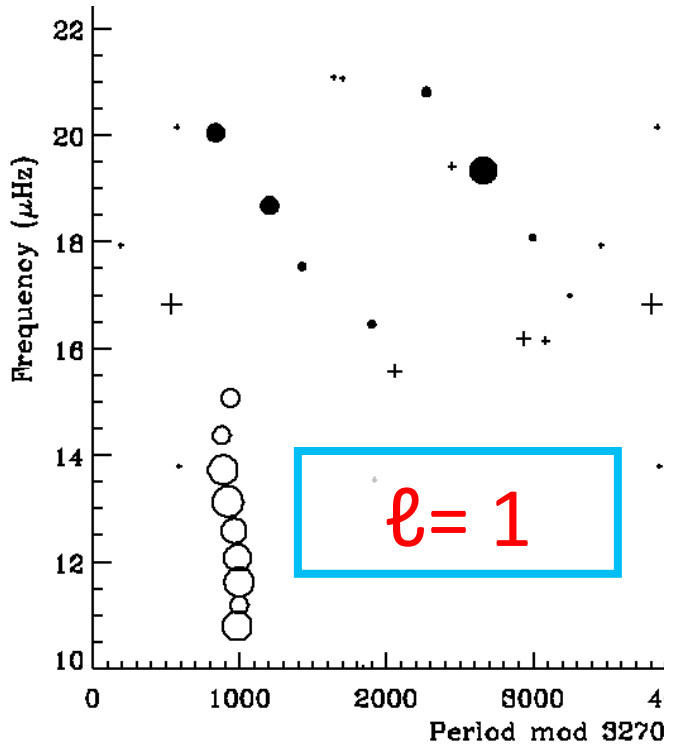

ℓ=1 and ℓ=2 are separated, with no overlap. Is this expected theoretically?
(e.g., Dupret et al 2005, Bouabid et al. 2013)
Frequency (μHz)
Frequency (c/d)
20
18
16
14
1.6
1.4
1.2
Frequency (c/d)
0.8
1.0
1.2
1.4
1.6
ℓ= 1
ℓ= 2
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
8
10
12
14
16
18
20
Frequency (μHz)

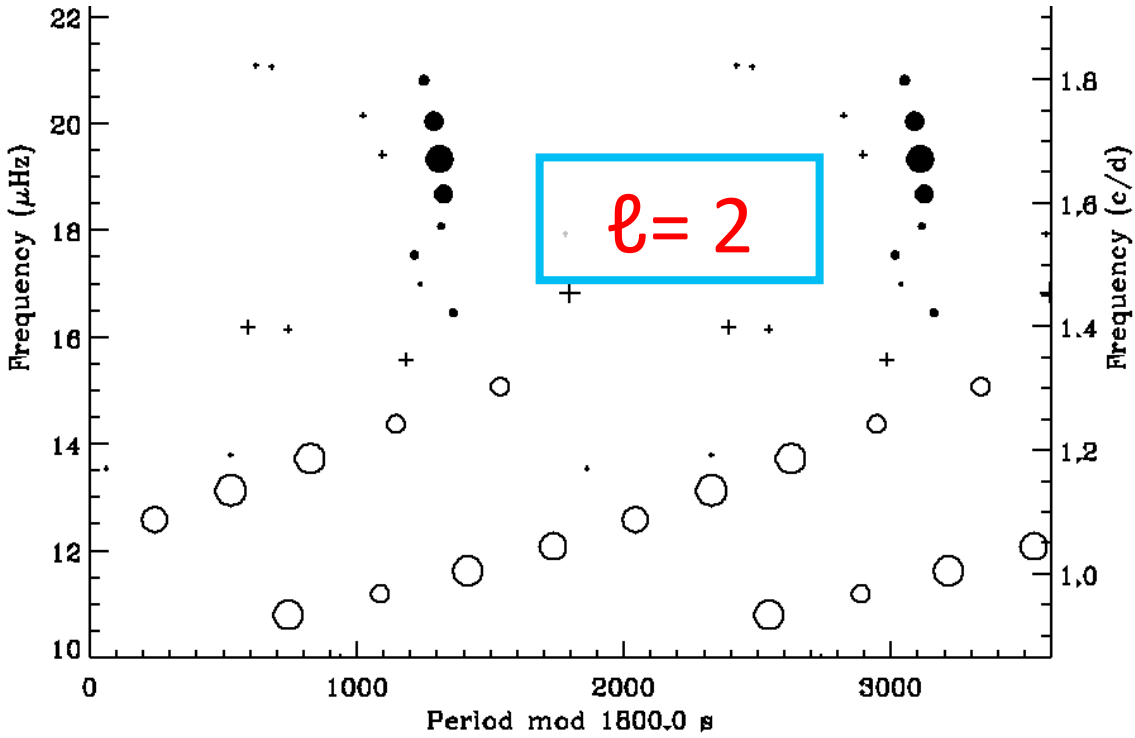
4. another star with ℓ=1 and ℓ=2



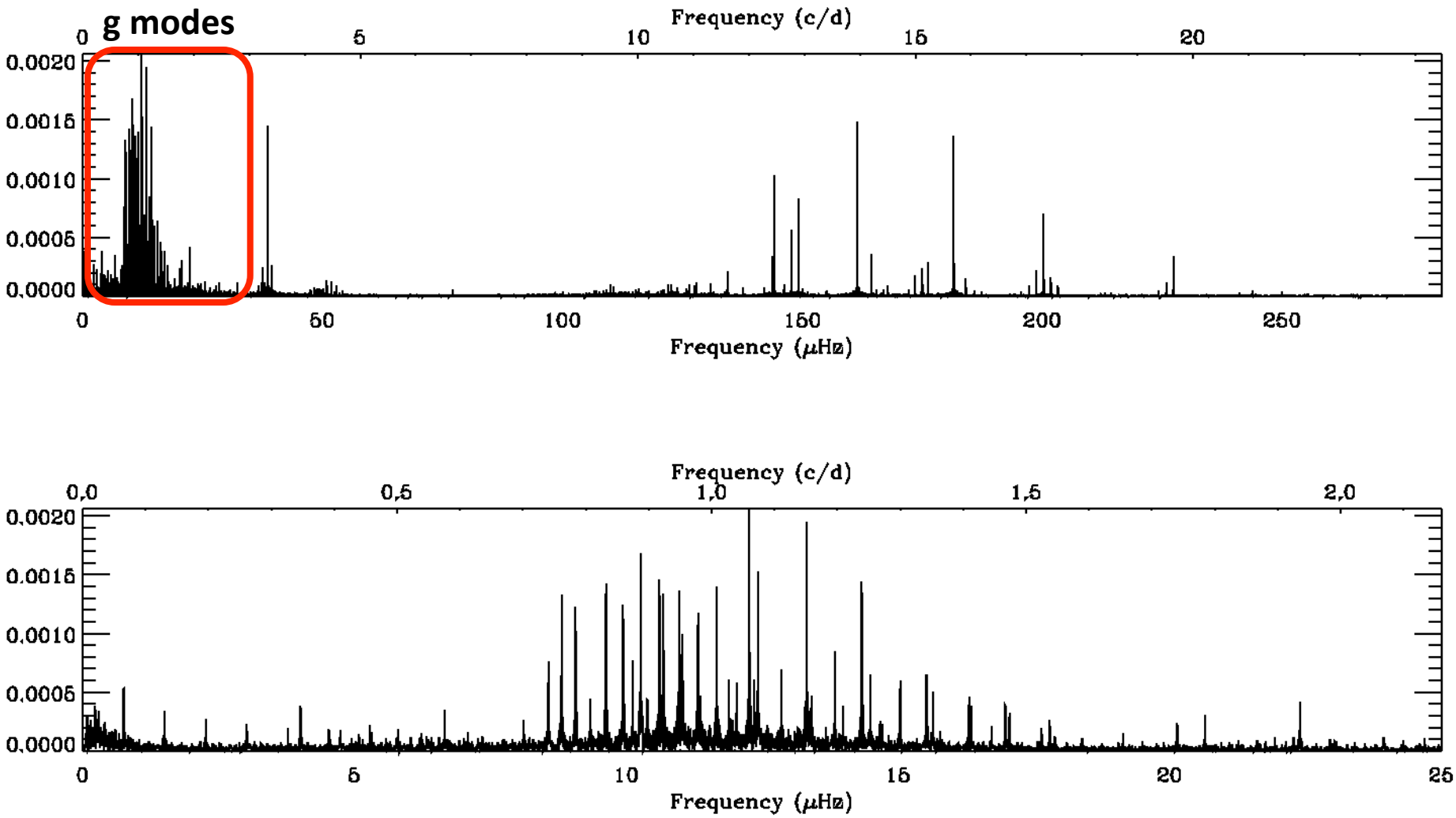

Period spacing (s)
Period (d)

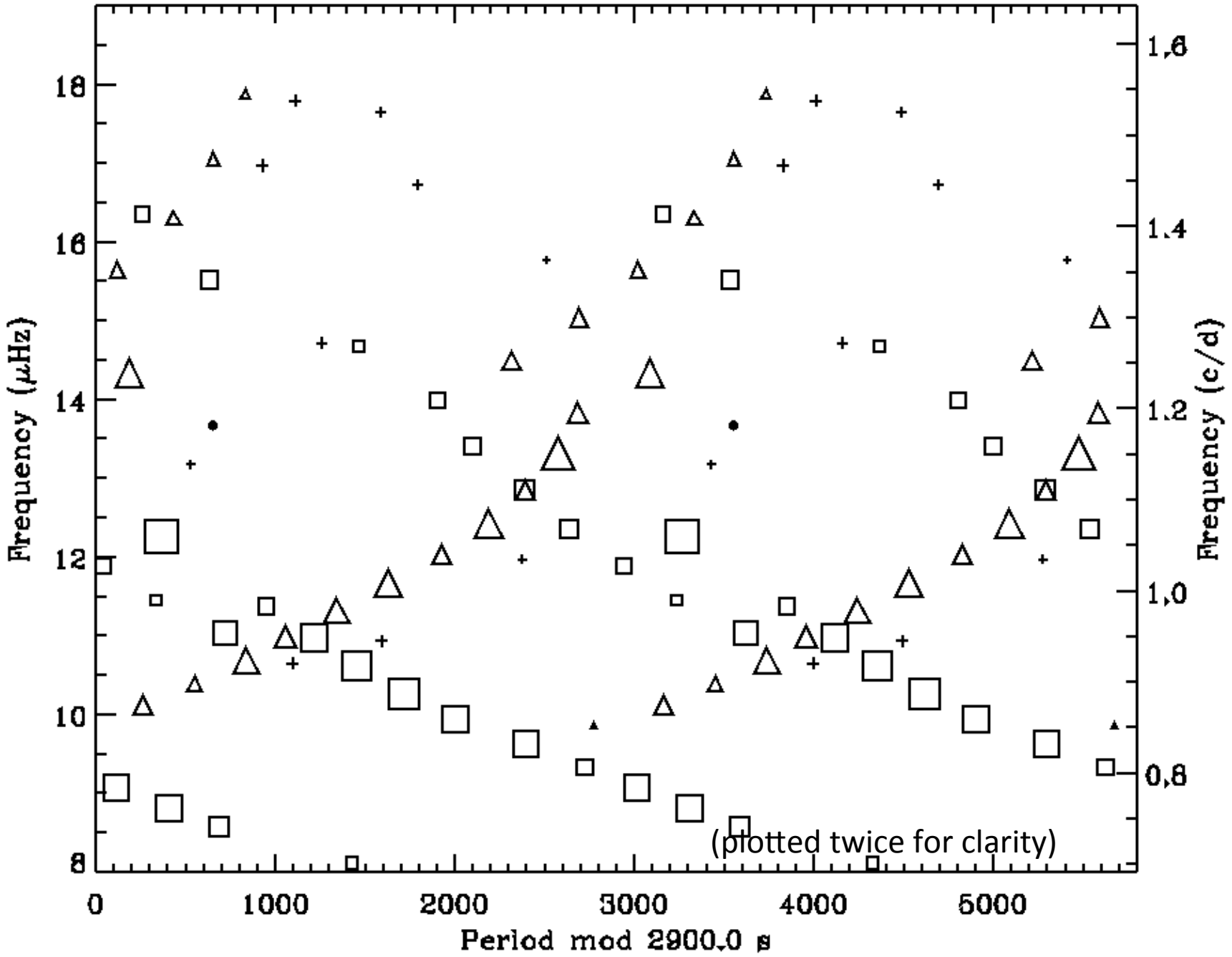

Period spacing (s)
Period (d)

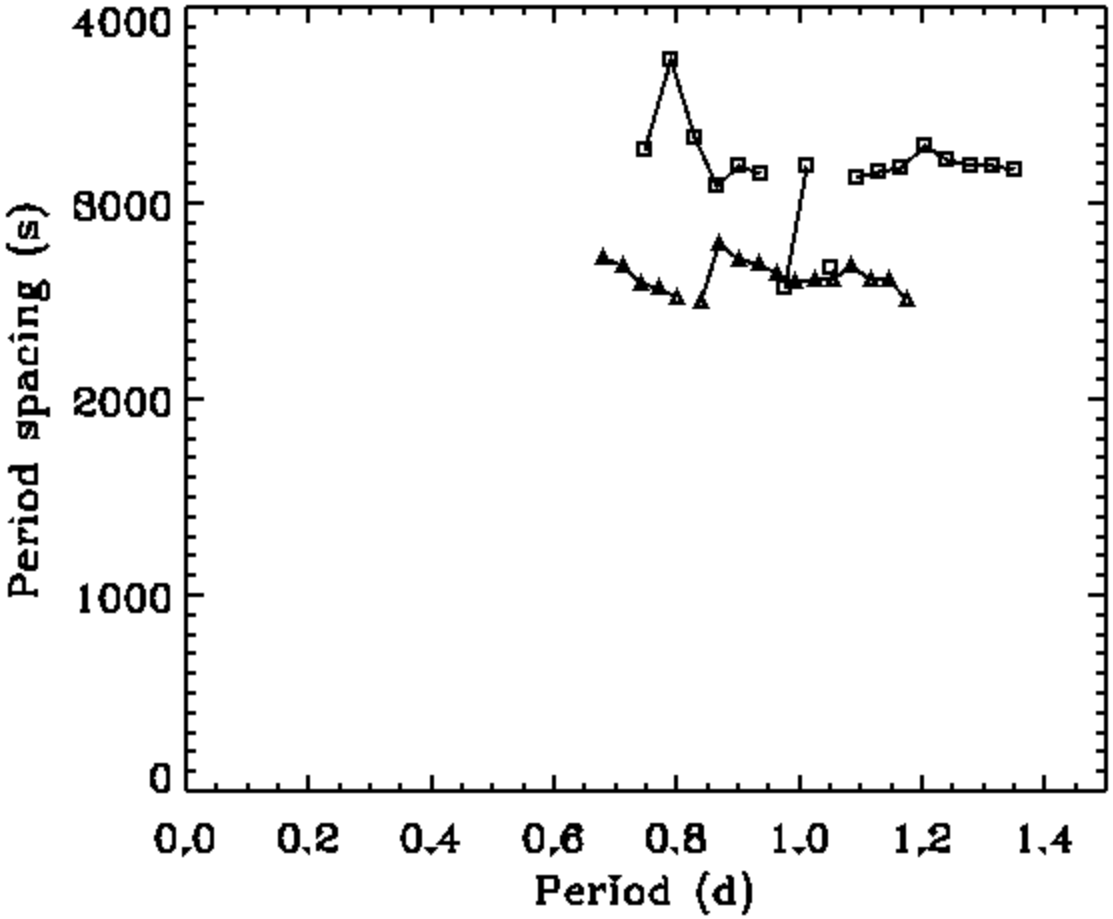

Frequency (μHz)
Period mod 3270
ℓ= 1


Frequency (μHz)
Frequency (c/d)
Period mod 1800.0 s
ℓ= 2

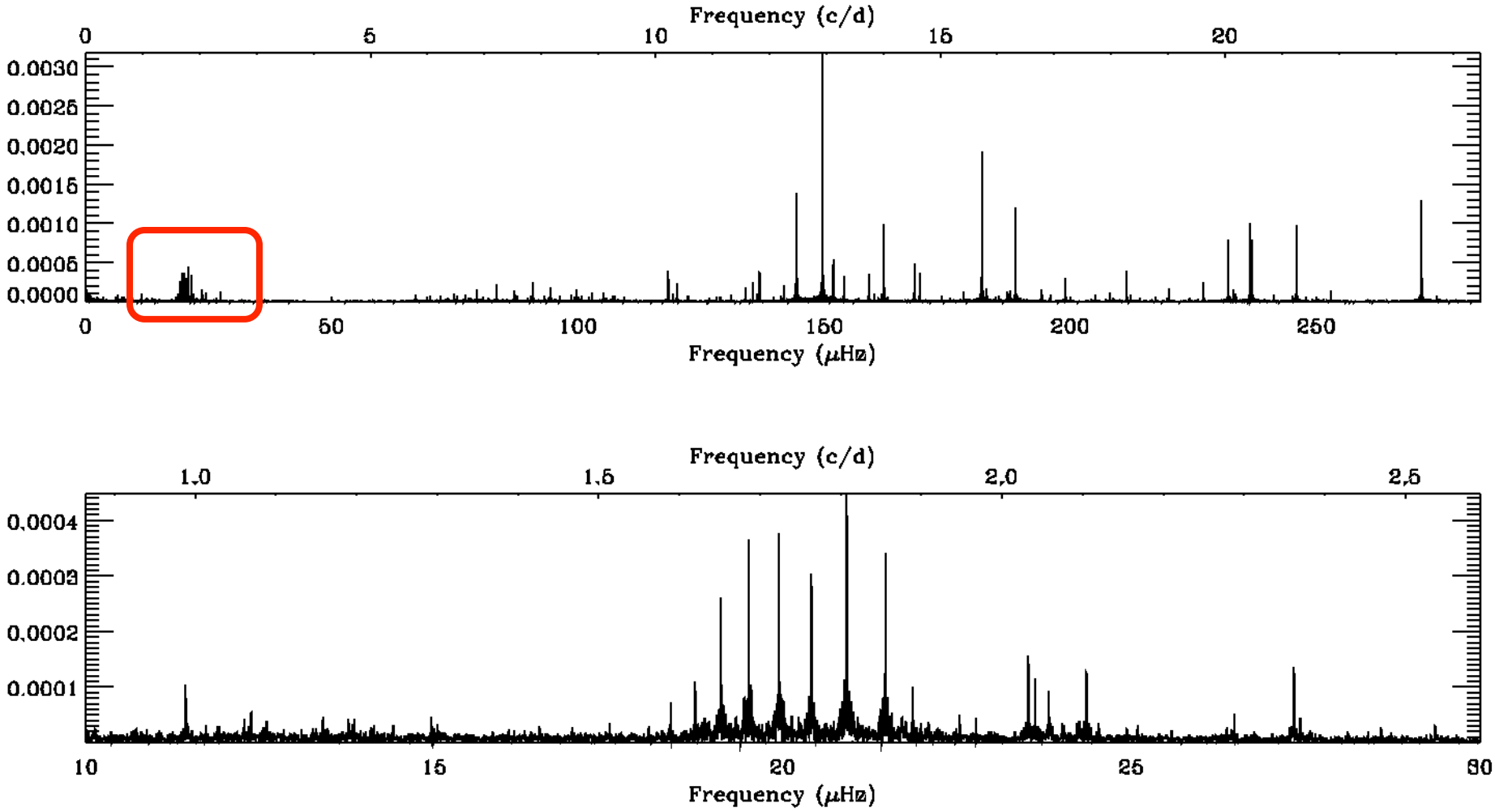
5. more wiggles

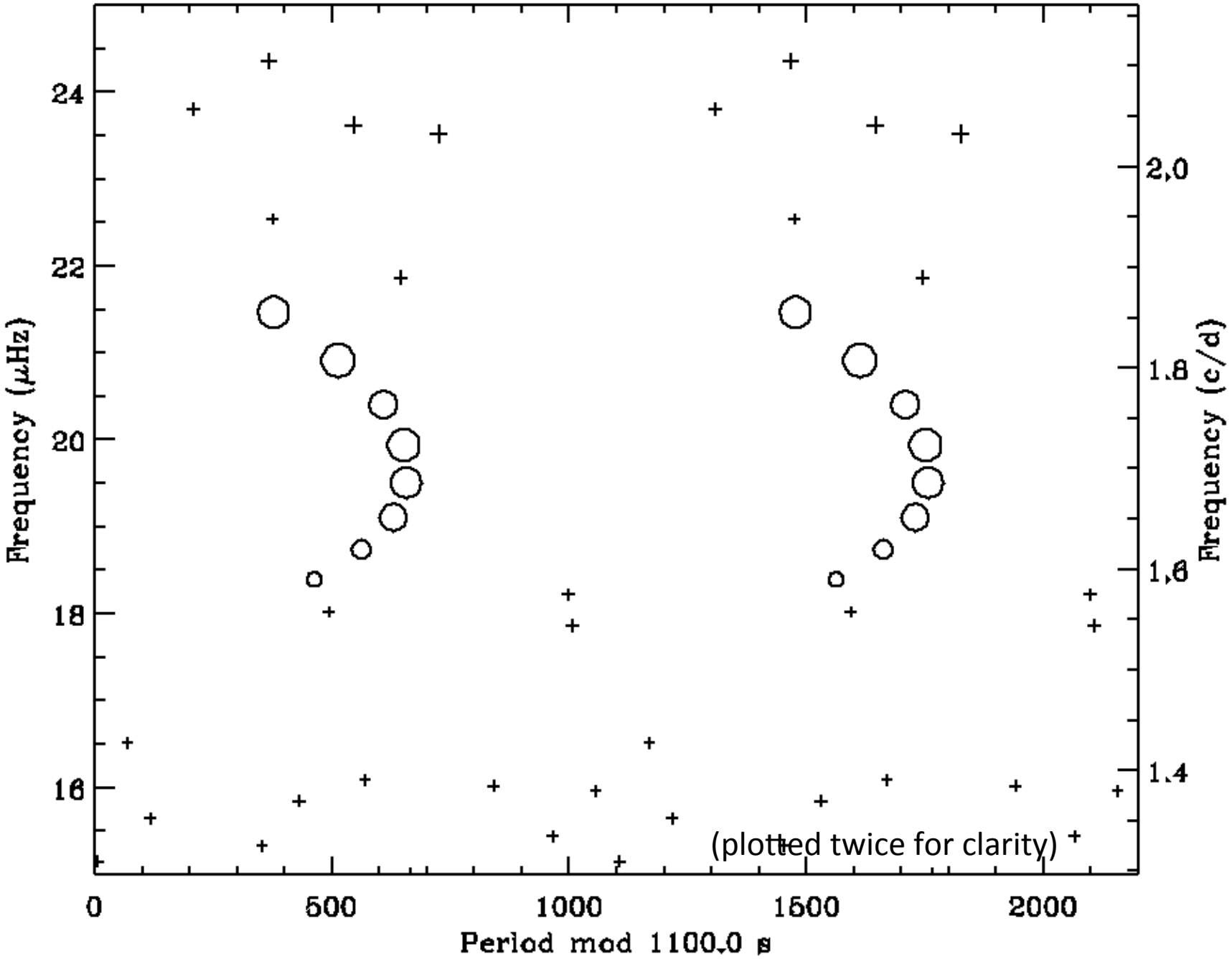



Frequency (μHz)
Frequency (c/d)
Period mod 2900.0 s
0
1000
2000
3000
4000
5000
8
10
12
14
16
18
0.8
1.0
1.2
1.4
1.6
(plotted twice for clarity)

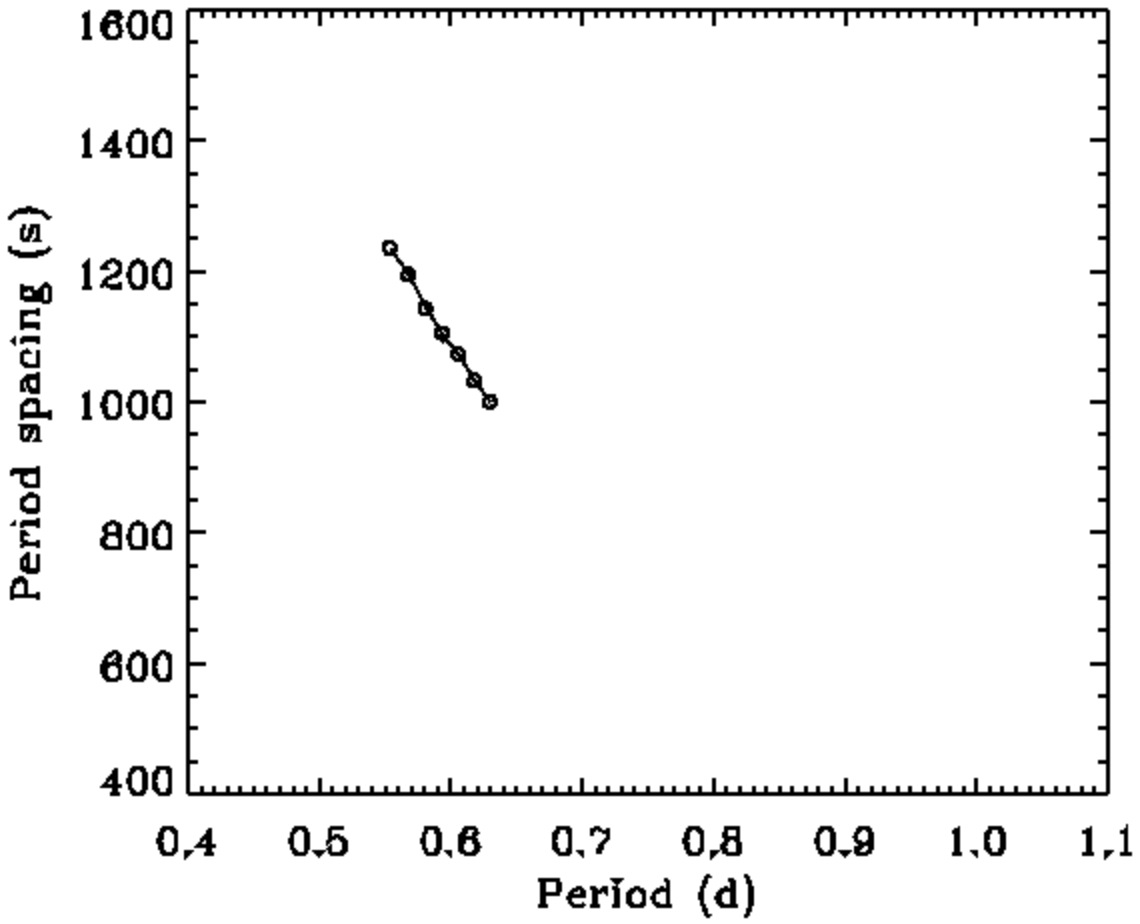

4000
3000
2000
1000
0
Period spacing (s)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Period (d)

6. and now something different:



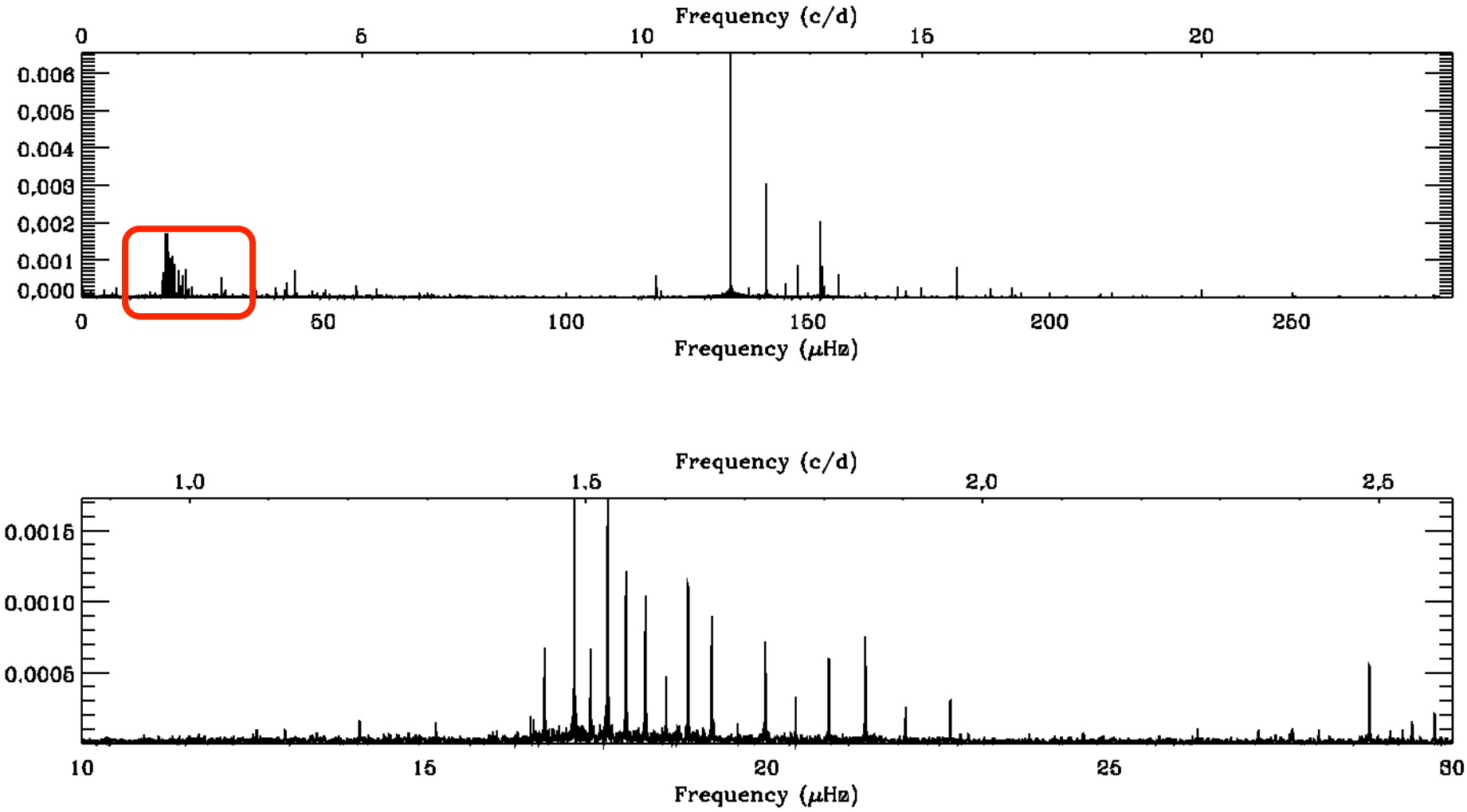

24
22
20
18
16
Frequency (μHz)
2.0
1.8
1.6
1.4
Frequency (c/d)
0
500
1000
1500
2000
Period mod 1100.0 s
(plotted twice for clarity)

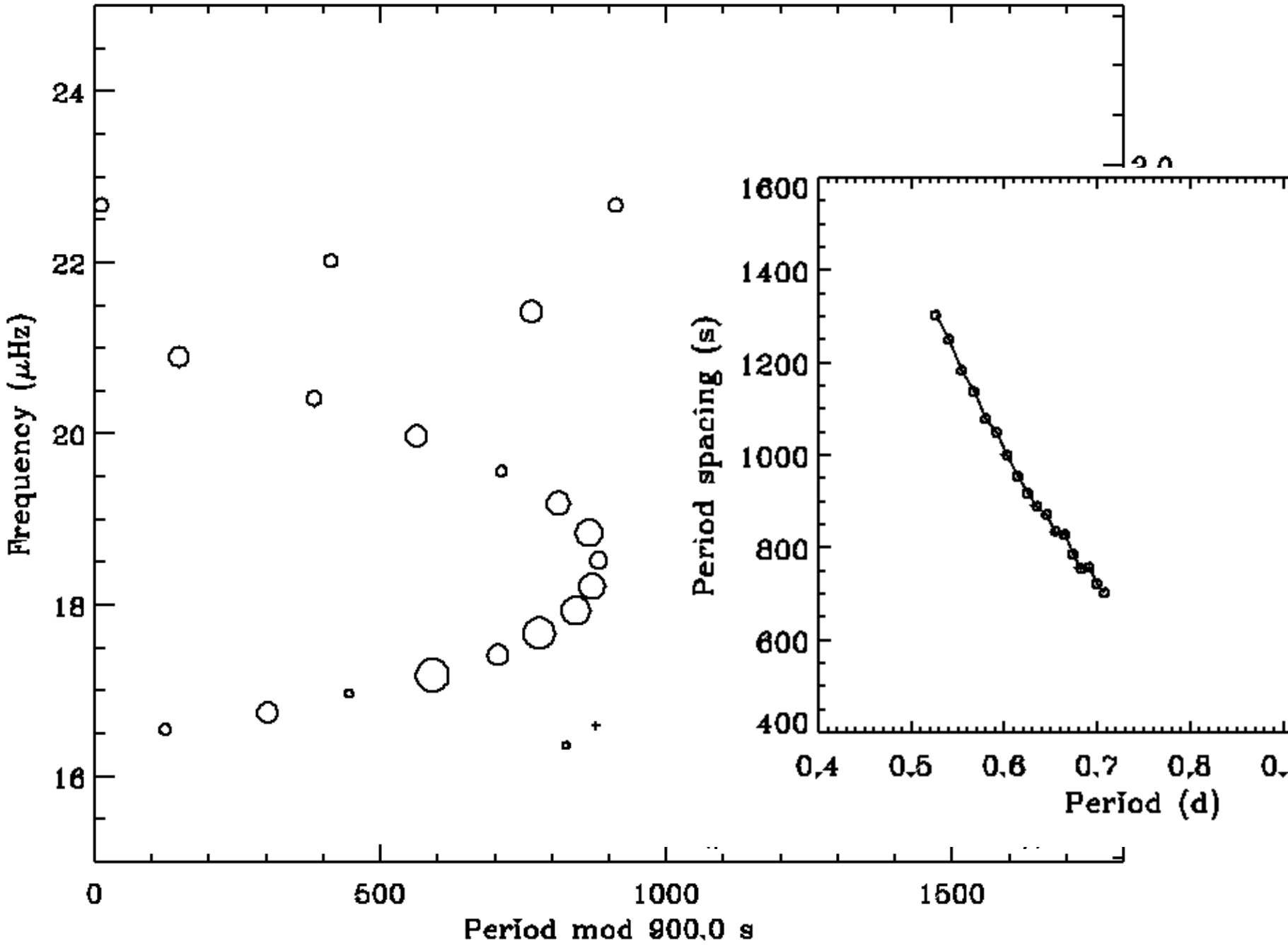
period spacing is *decreasing strongly* with period



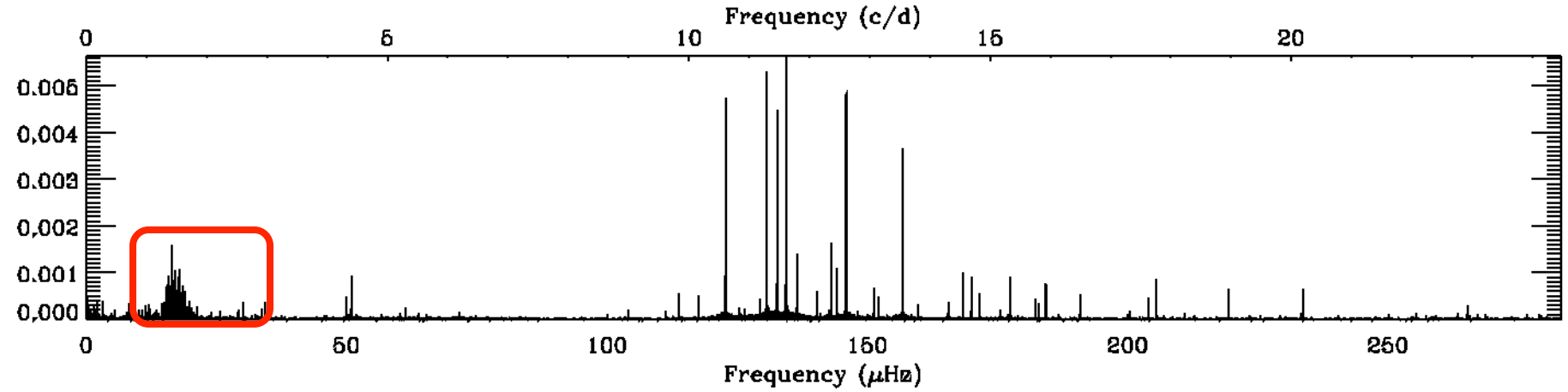
this must be some rare and exotic behaviour?

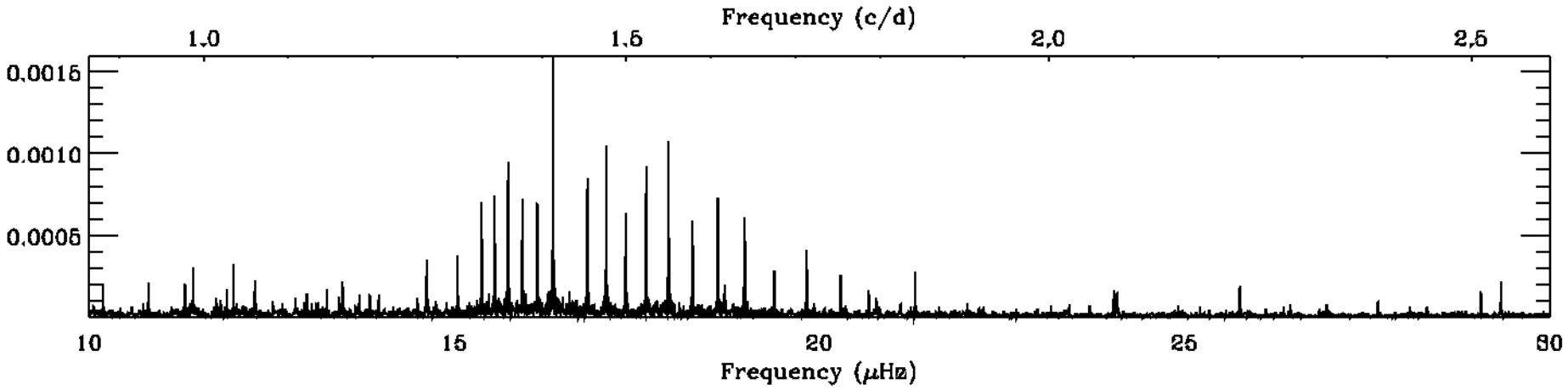
7. another example

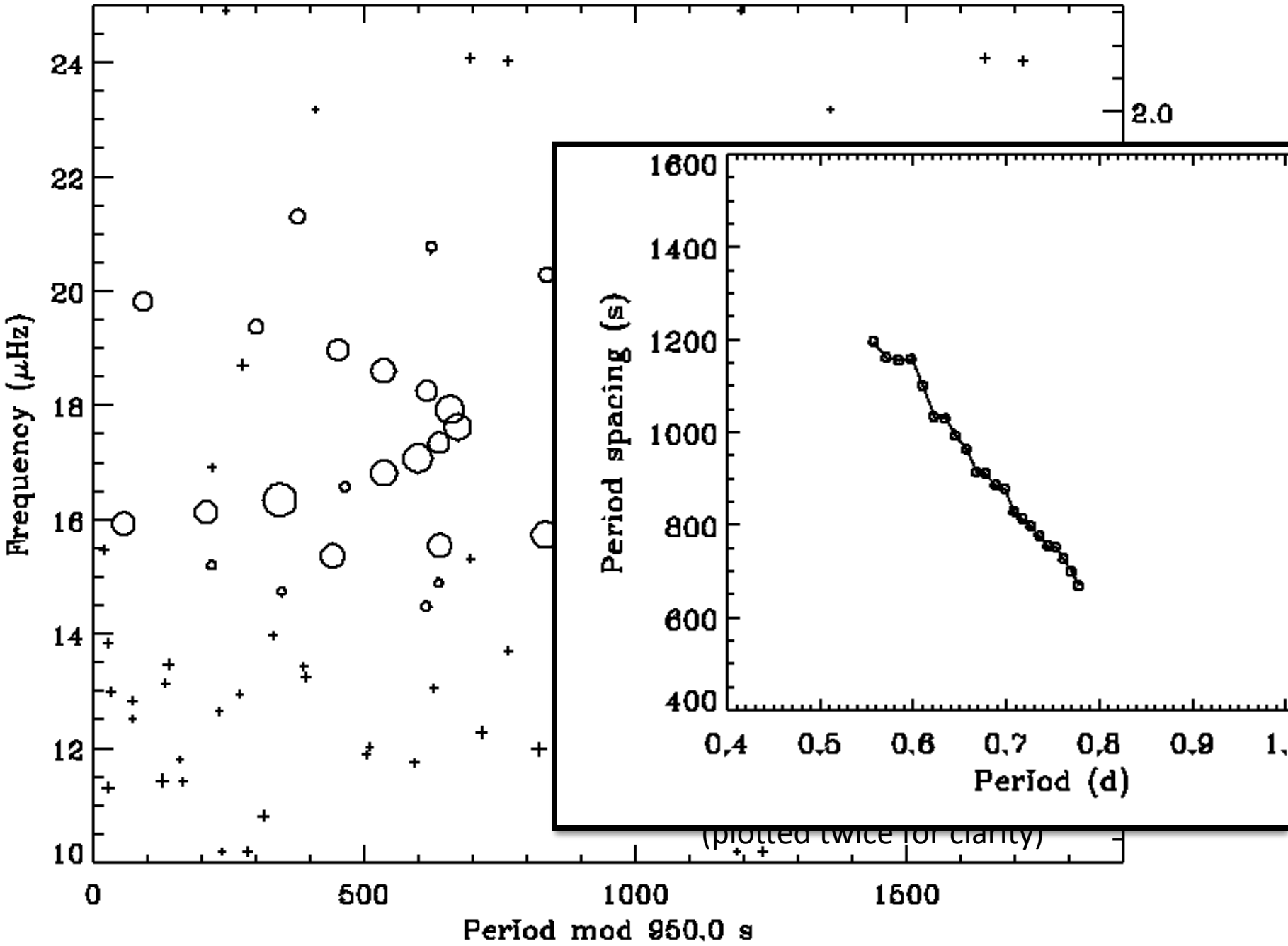



24
22
20
18
16
Frequency (μHz)
0
500
1000
1500
Period mod 900.0 s
1600
1400
1200
1000
800
600
400
Period spacing (s)
0.4
0.5
0.6
0.7
0.8
Period (d)

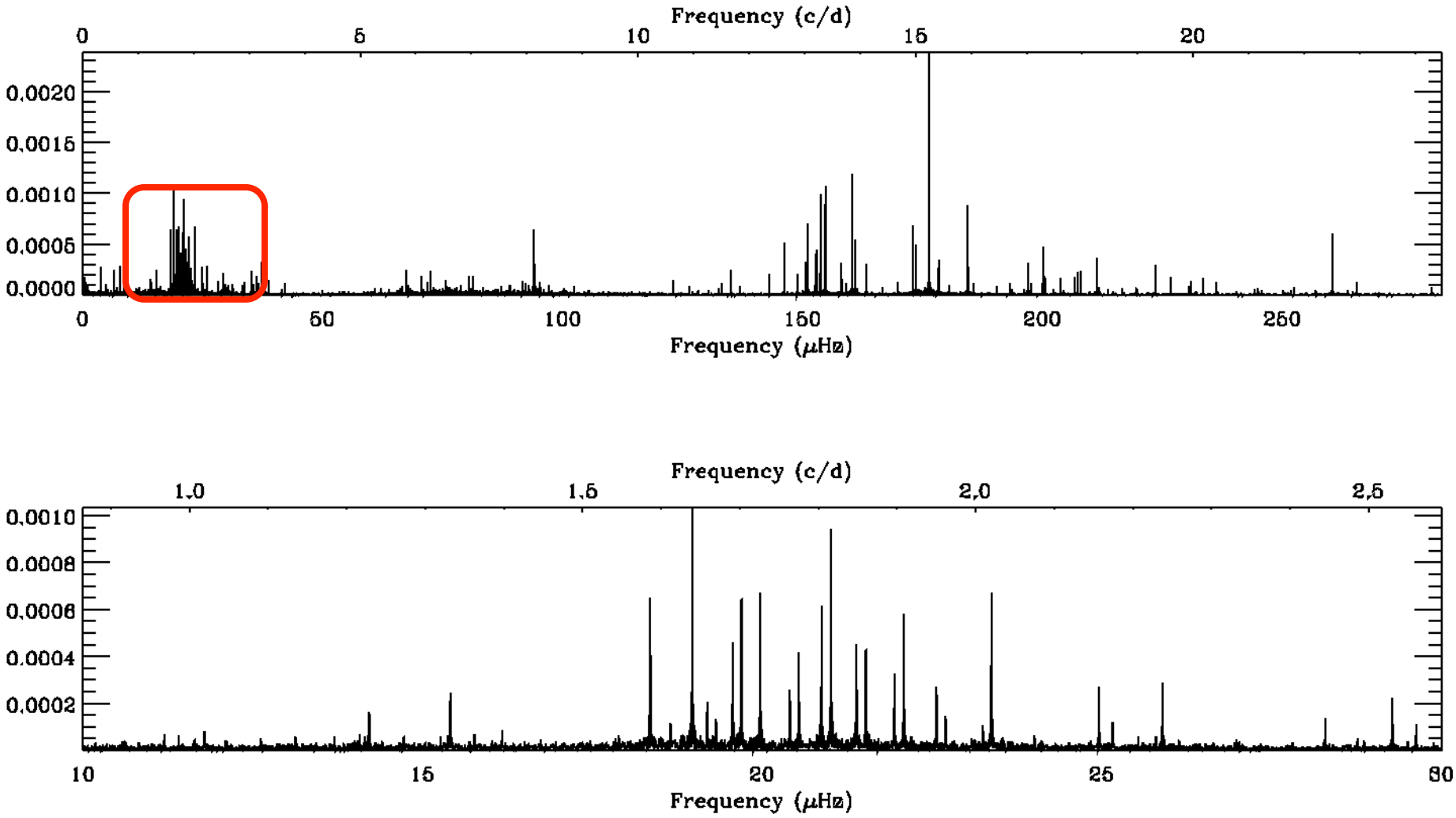
8. and another one

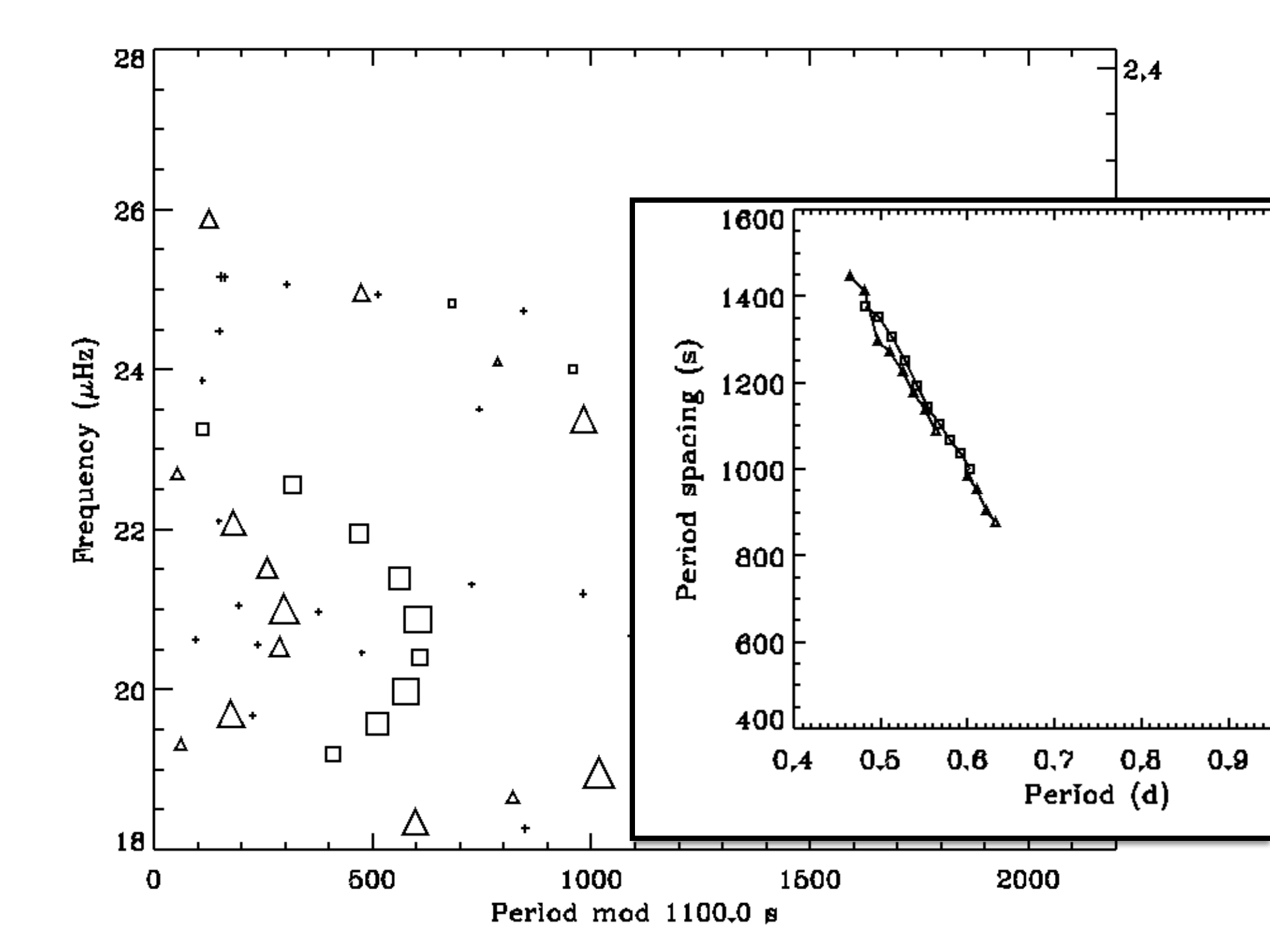




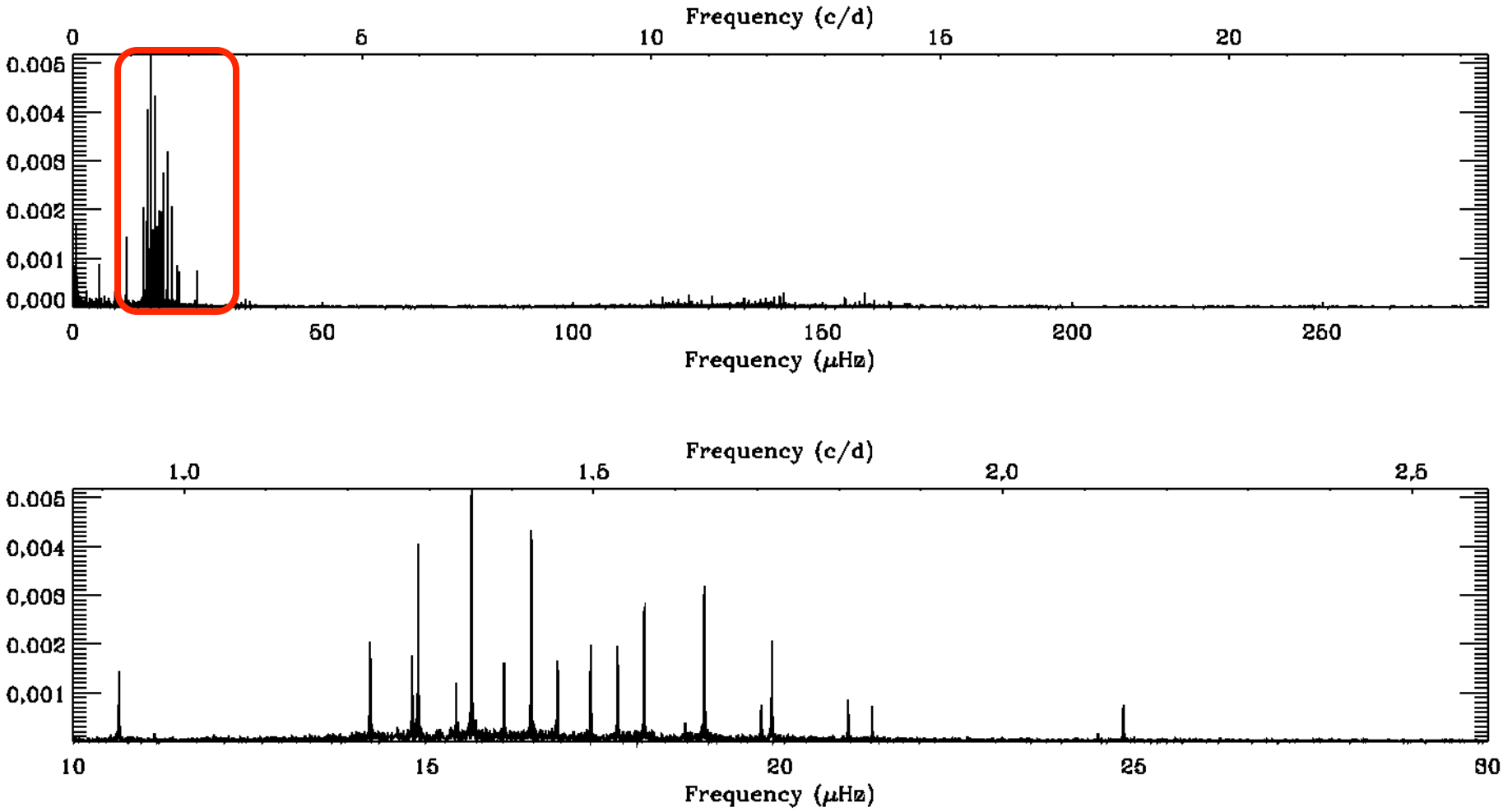

Frequency (μHz)
Period mod 950.0 s
Period spacing (s)
Period (d)
(plotted twice for clarity)

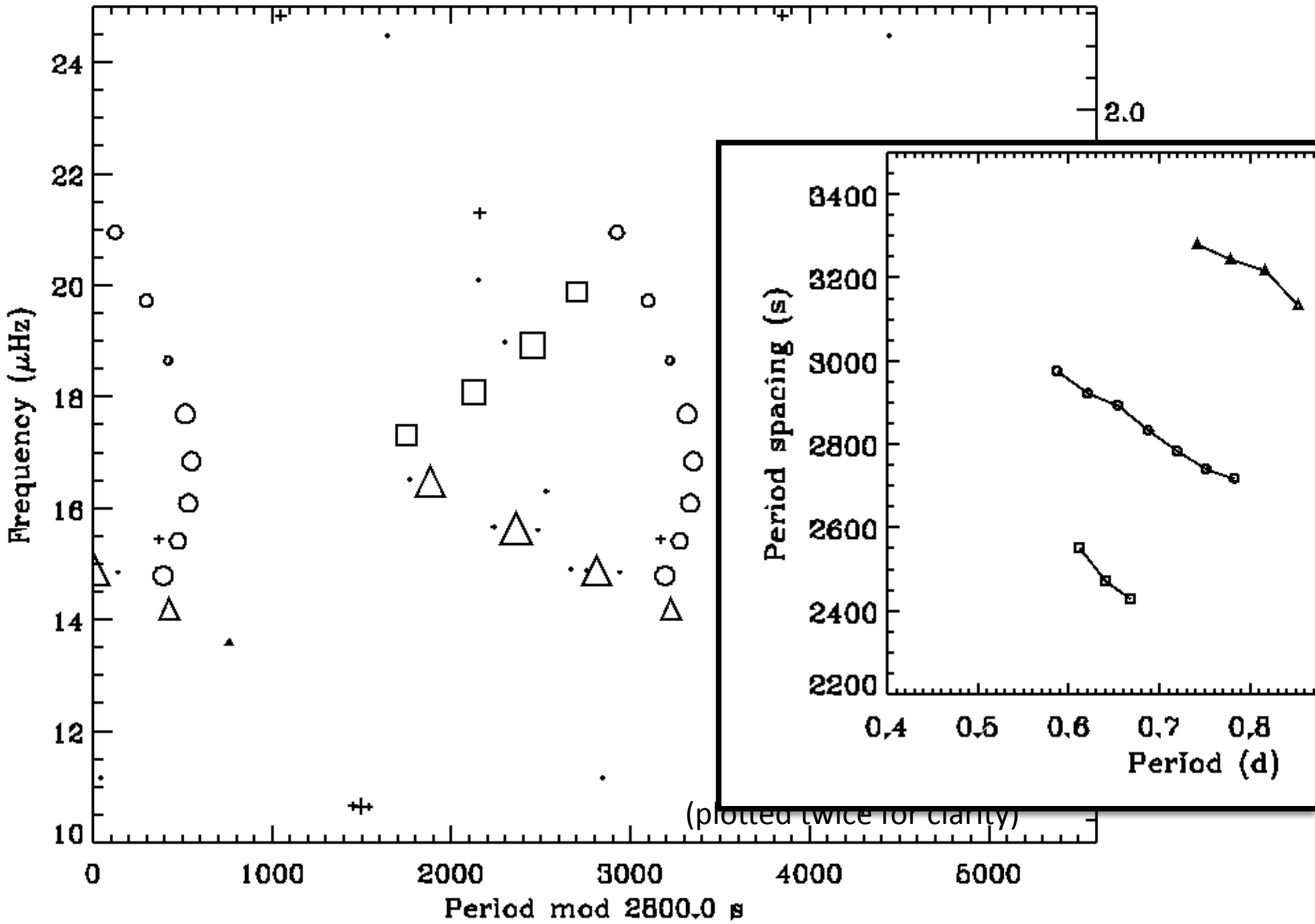
9. yet another, with doublets




28
26
24
22
20
18
Frequency (μHz)
0
500
1000
1500
2000
Period mod 1100.0 s
2,4
1600
1400
1200
1000
800
600
400
Period spacing (s)
0,4
0,5
0,6
0,7
0,8
0,9
Period (d)

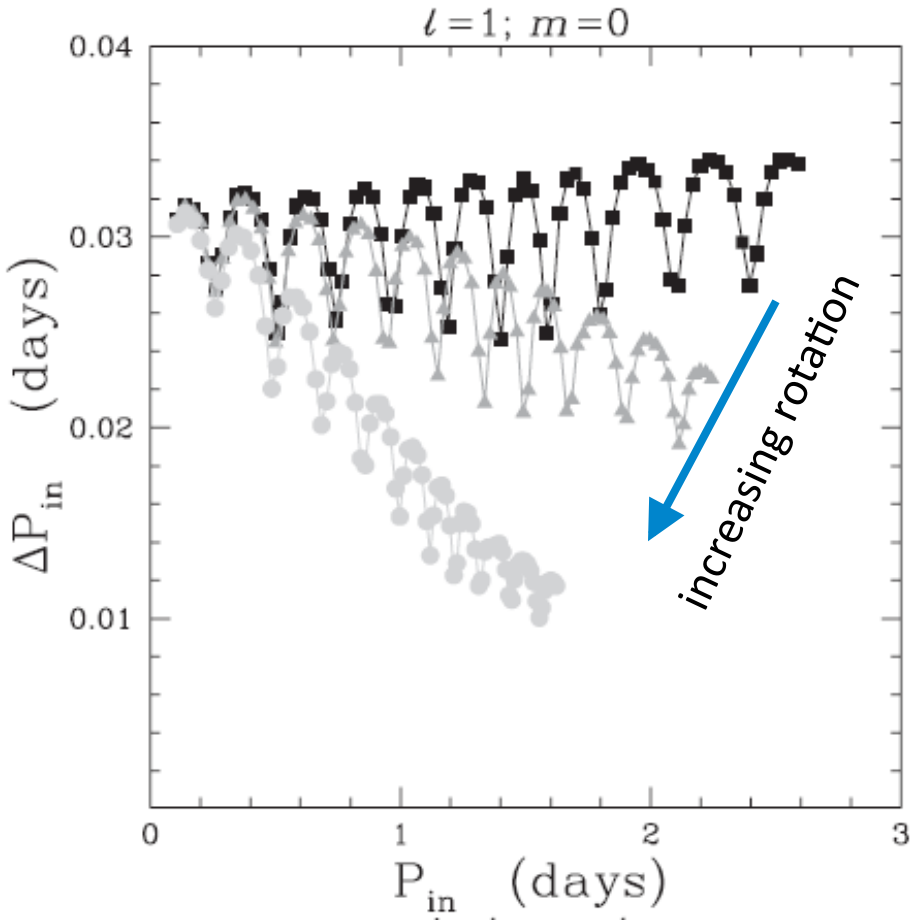
10. one with triplets





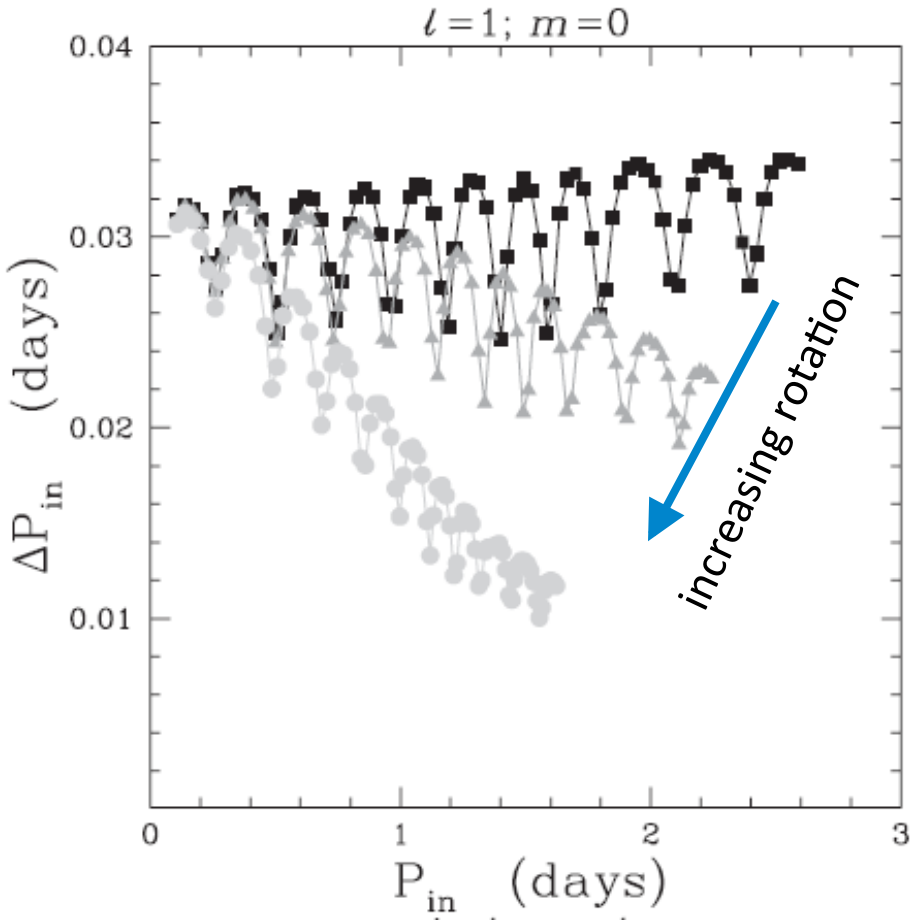
(plotted twice for clarity)

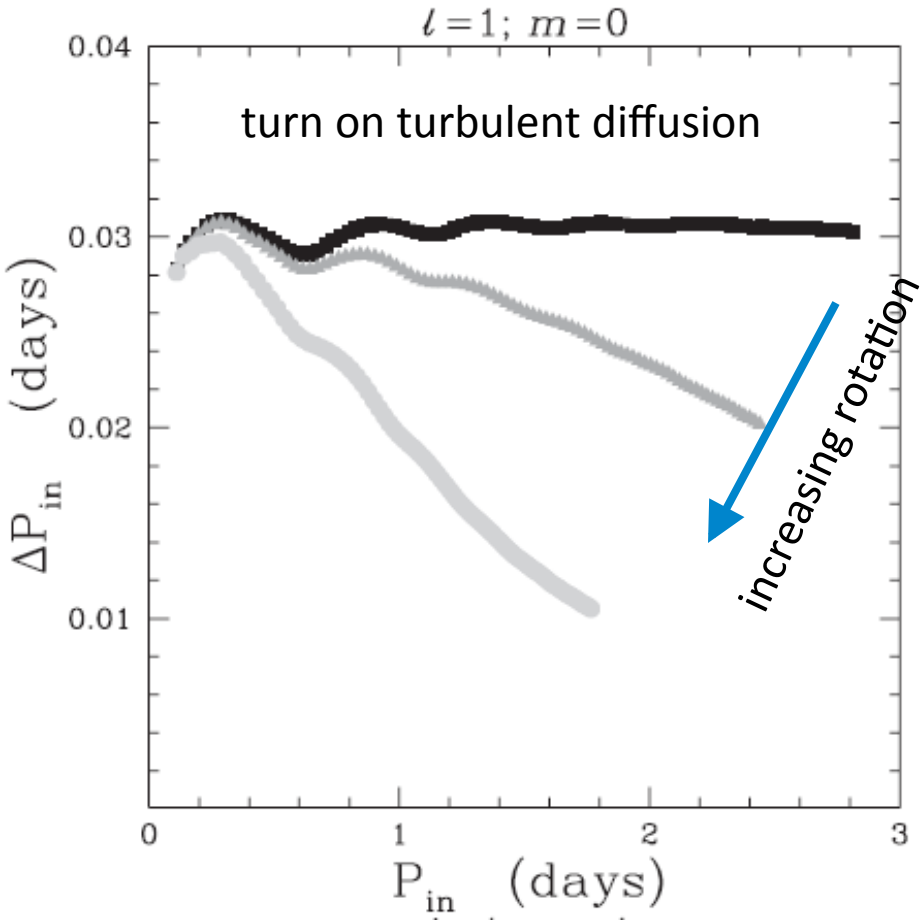
What causes this effect?



Bouabid et al. (2013)

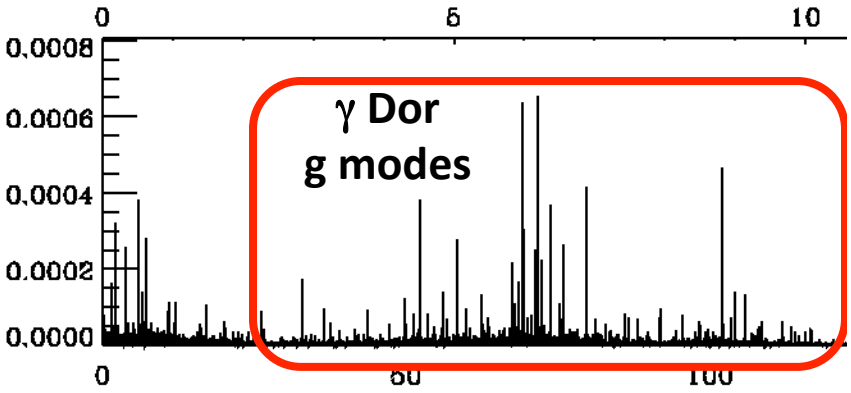
Mixing outside the core smooths the irregularities:

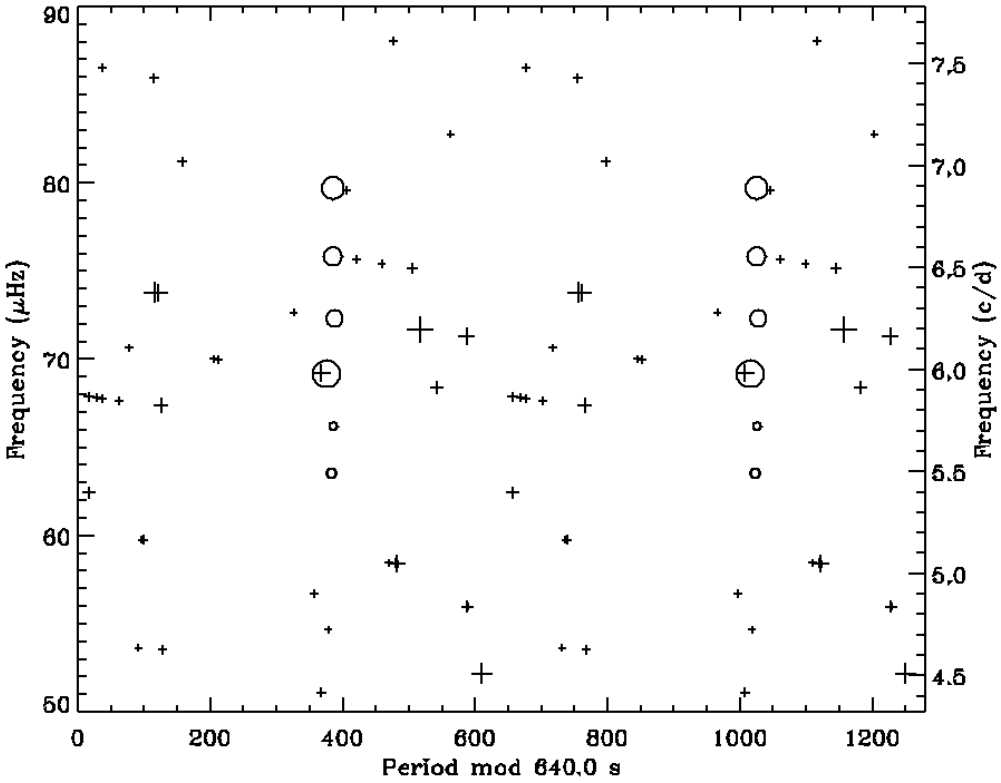




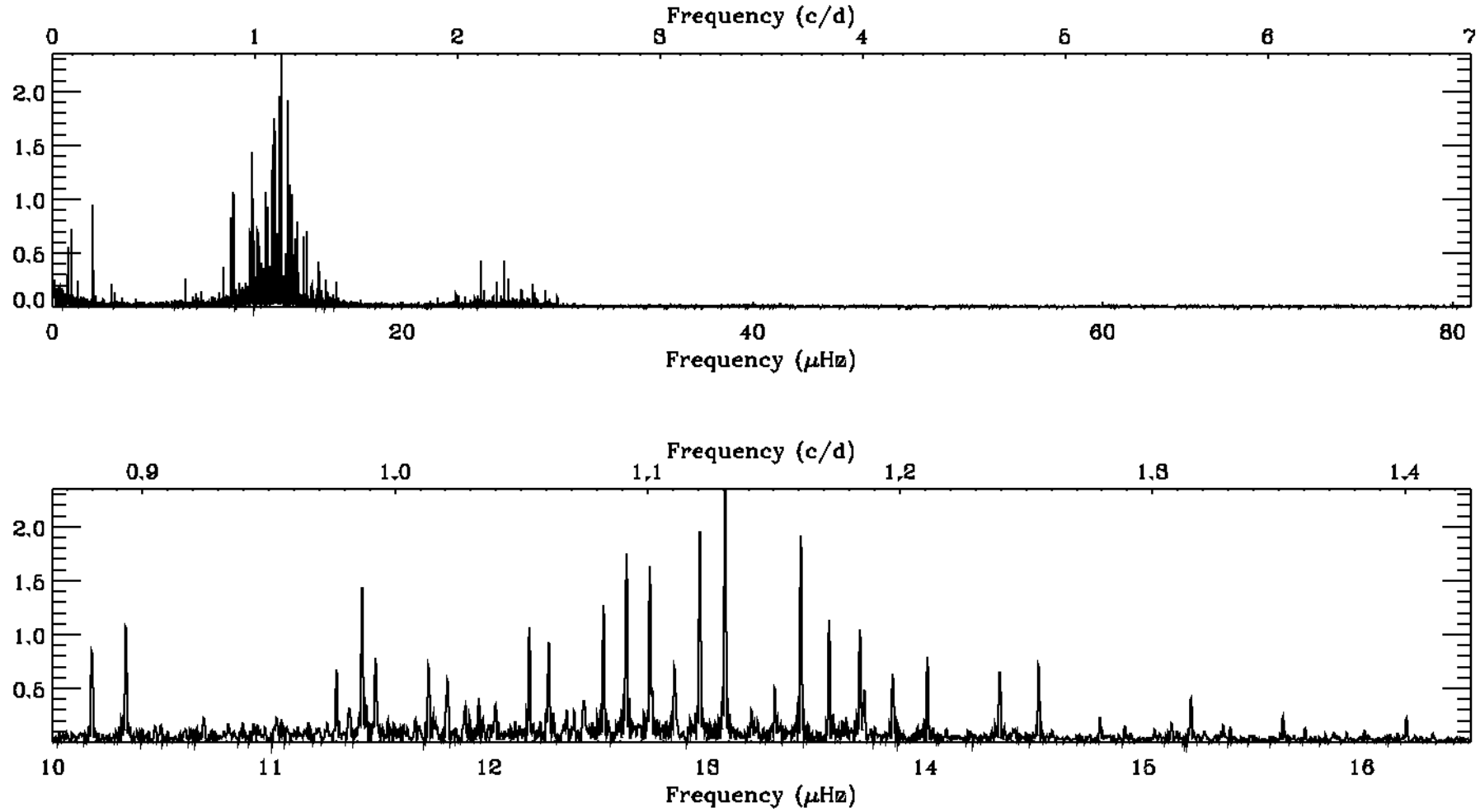
Bouabid et al. (2013)

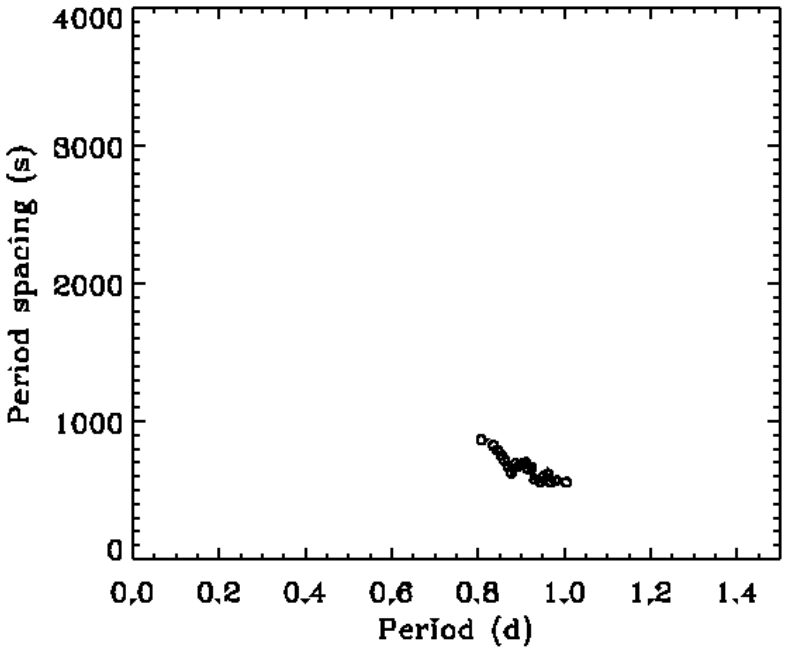
11. higher frequencies (evolved star)

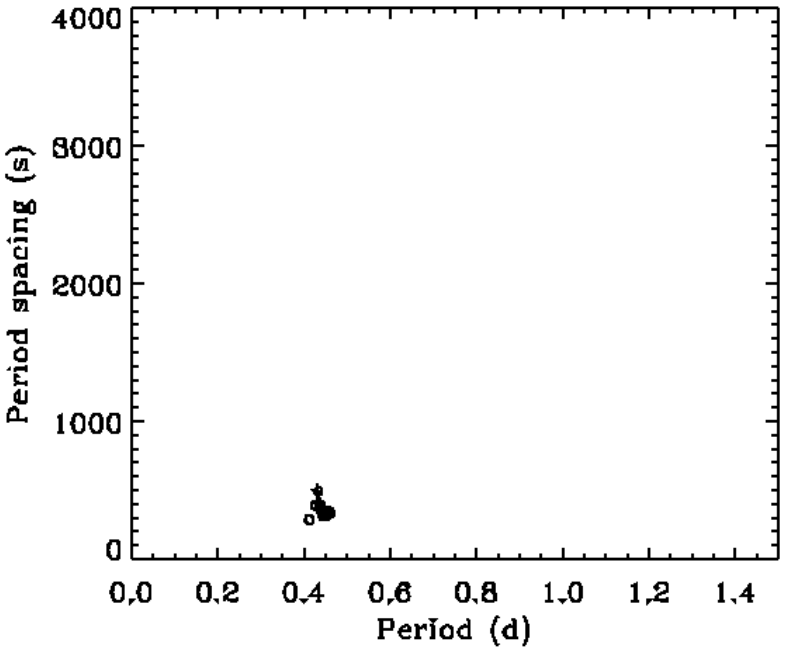


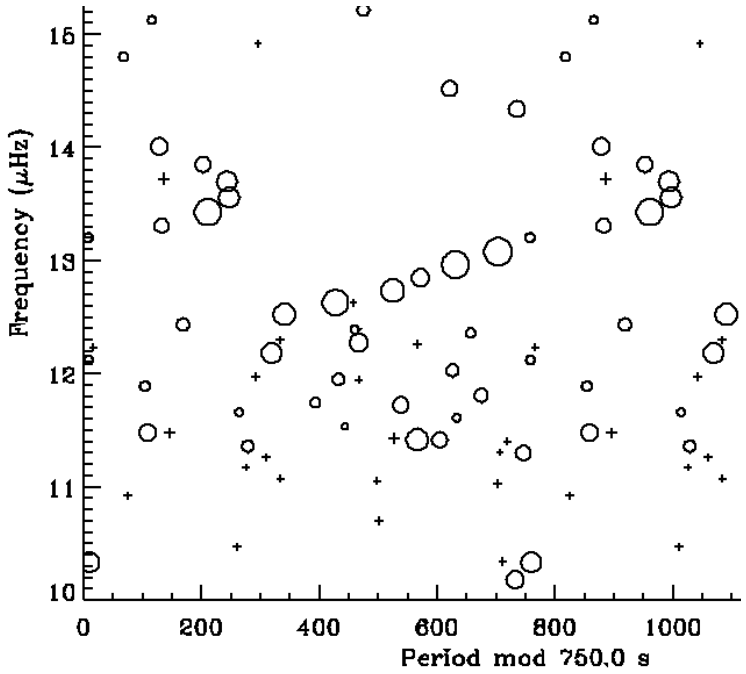


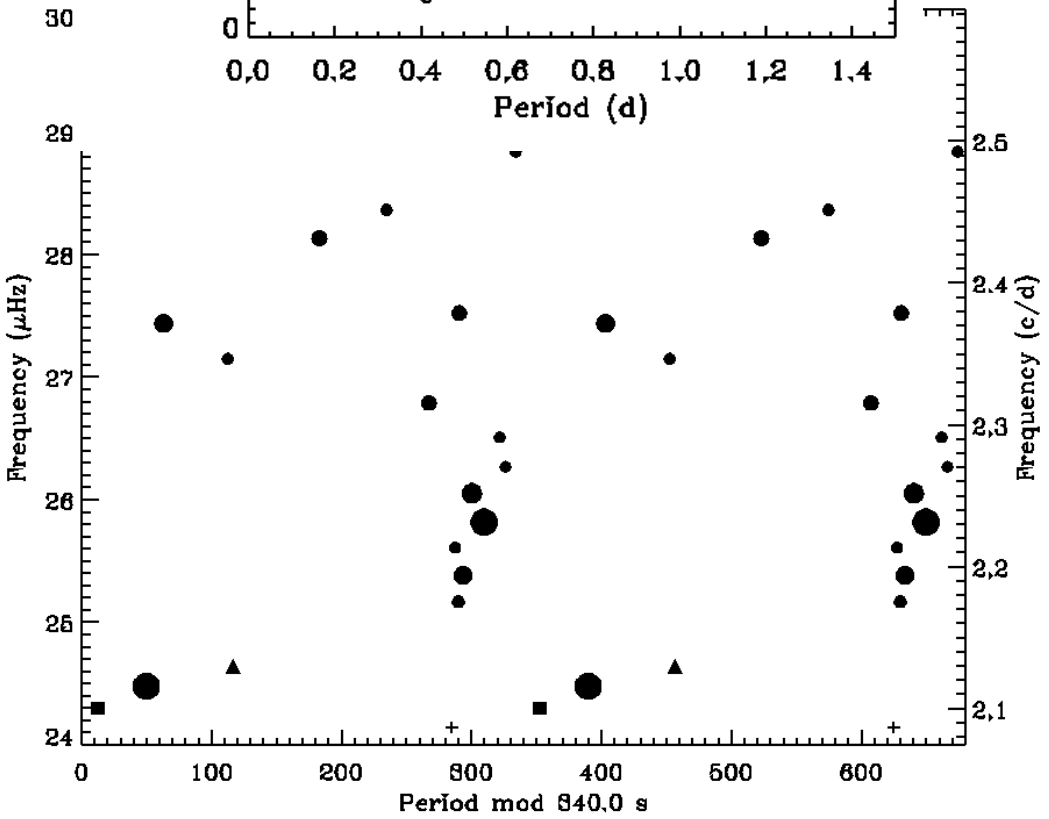
one more for luck



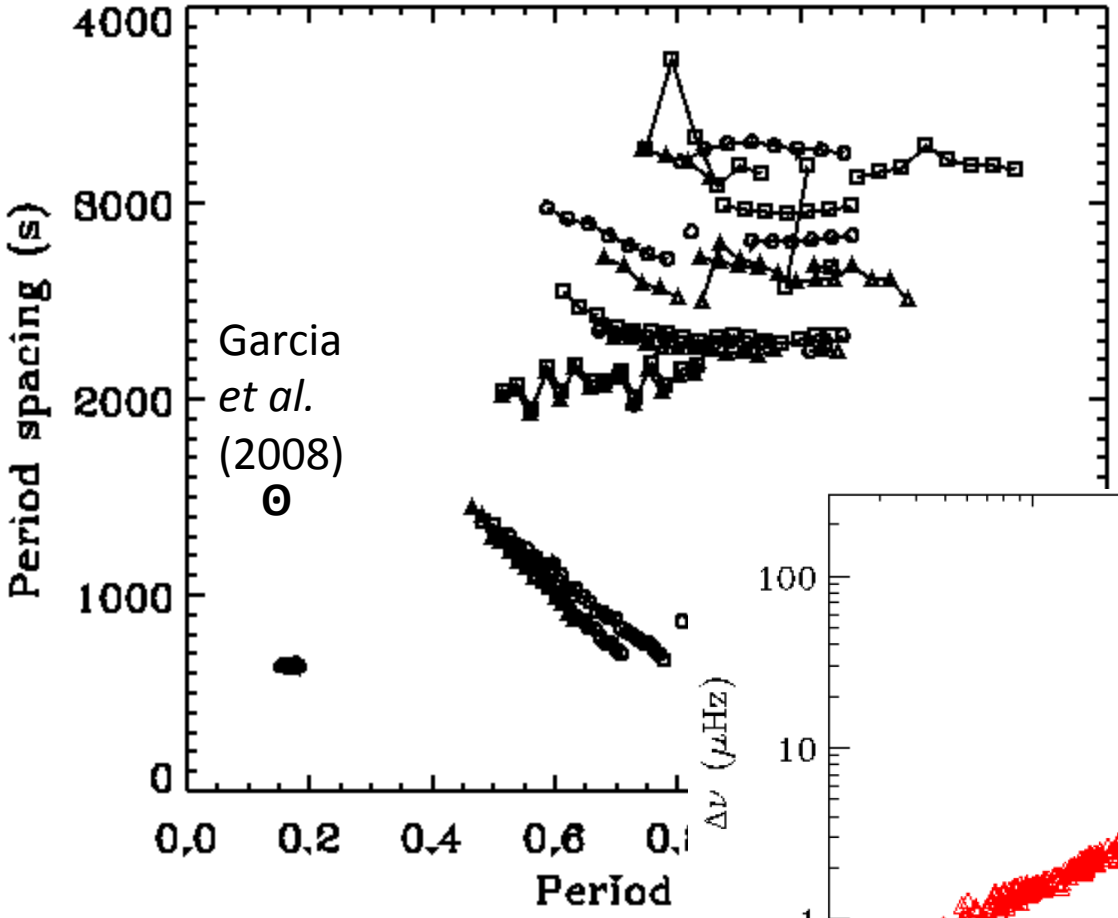

Period spacing (s)
Period (d)


Period spacing (s)
Period (d)

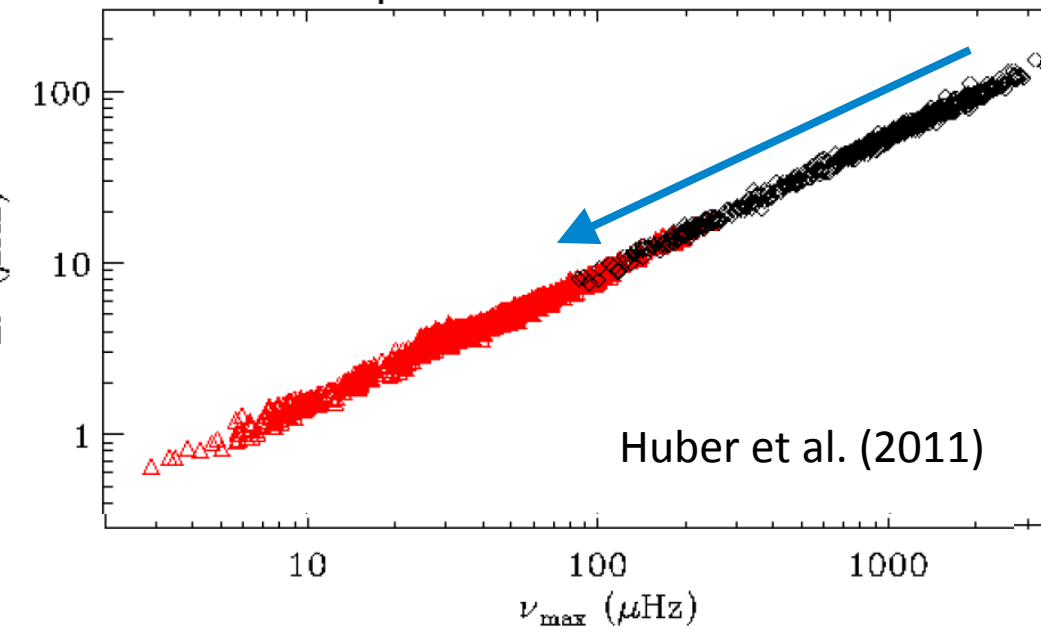

Frequency (μHz)
Period mod 750.0 s


Frequency (μHz)
Frequency (c/d)
Period mod 840.0 s

12 stars in one diagram

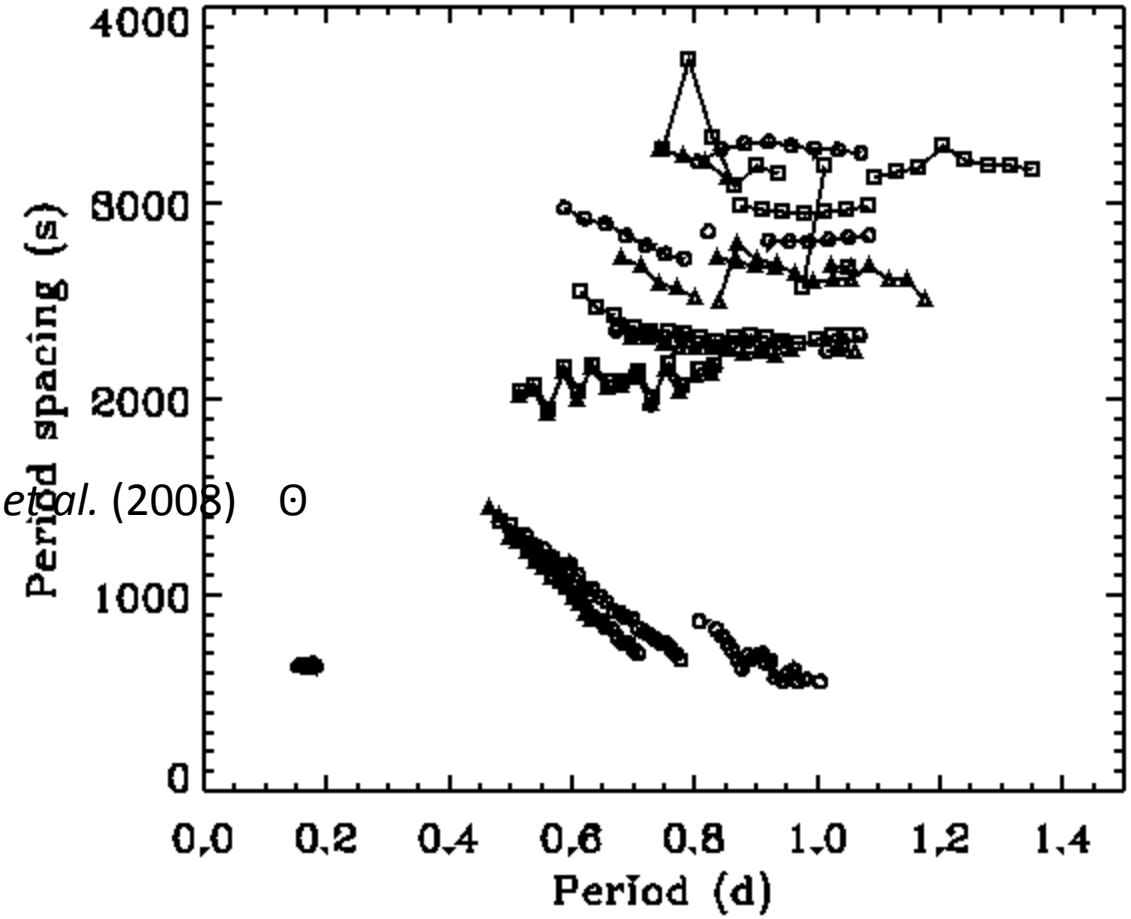


Garcia *et al.* (2008)



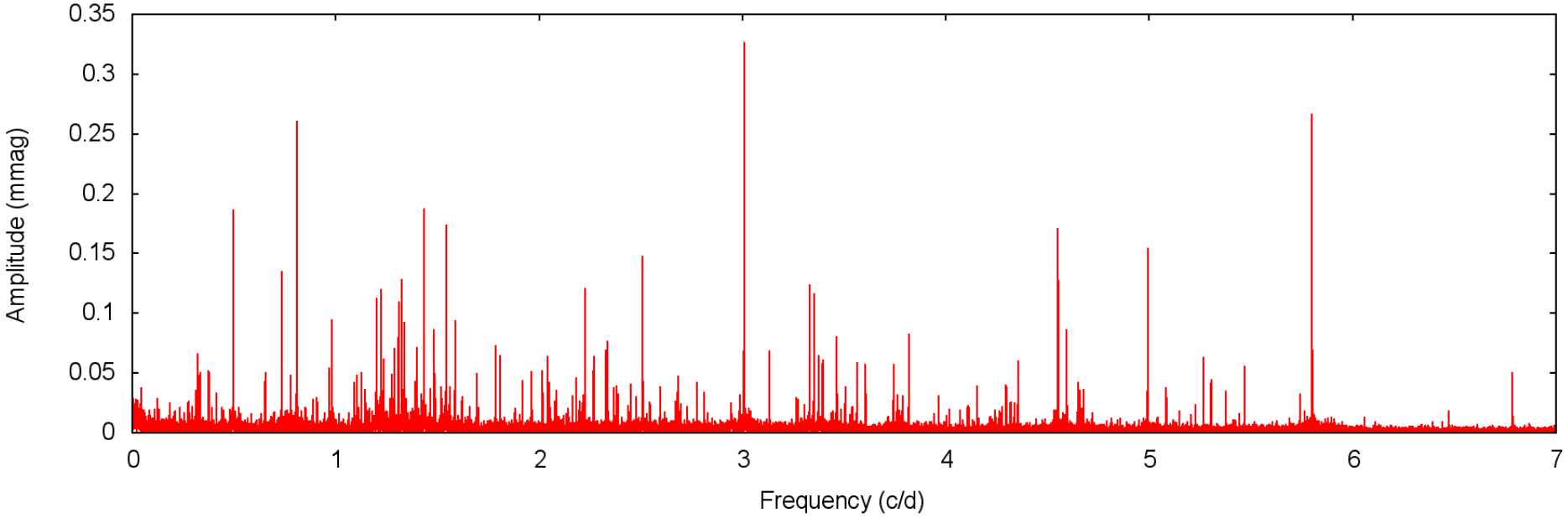
Huber et al. (2011)

12 stars in one diagram



Garcia *et al.* (2008) Θ

but note that lots of stars are a mess:



Conclusions

- some γ Dor pulsations show clear period spacings (and lots don't)
- some show structure in period spacing (good!)
- in some, the period spacing decreases with period
- lots more work to do!