HD49933:

$$T = \frac{10 - 14.3X}{M^3} \cdot 10^9\, yr$$

$$V \sin(i) = 10.9\,\mathrm{km/s}$$

$$R \approx 1.5 R_{Sun} \rightarrow P_{rot} \approx 7.0\mathrm{d}$$

$$\Delta \nu_0 \approx 135 \mu Hz \sqrt{M / R^3}$$

$$\Delta \nu_0 \approx 88.7\,\mu\mathrm{Hz}$$

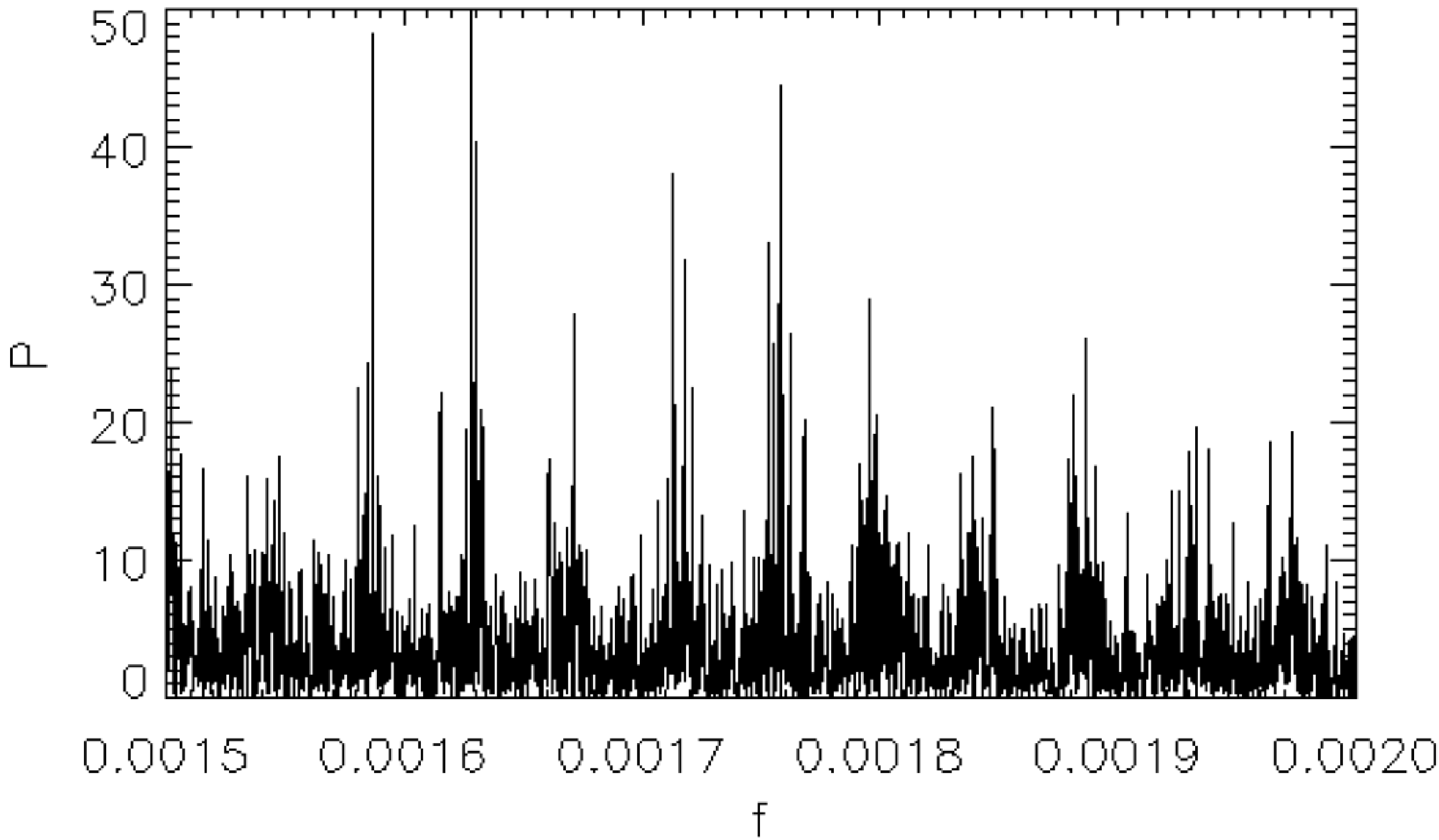
$$\varepsilon \approx 1$$

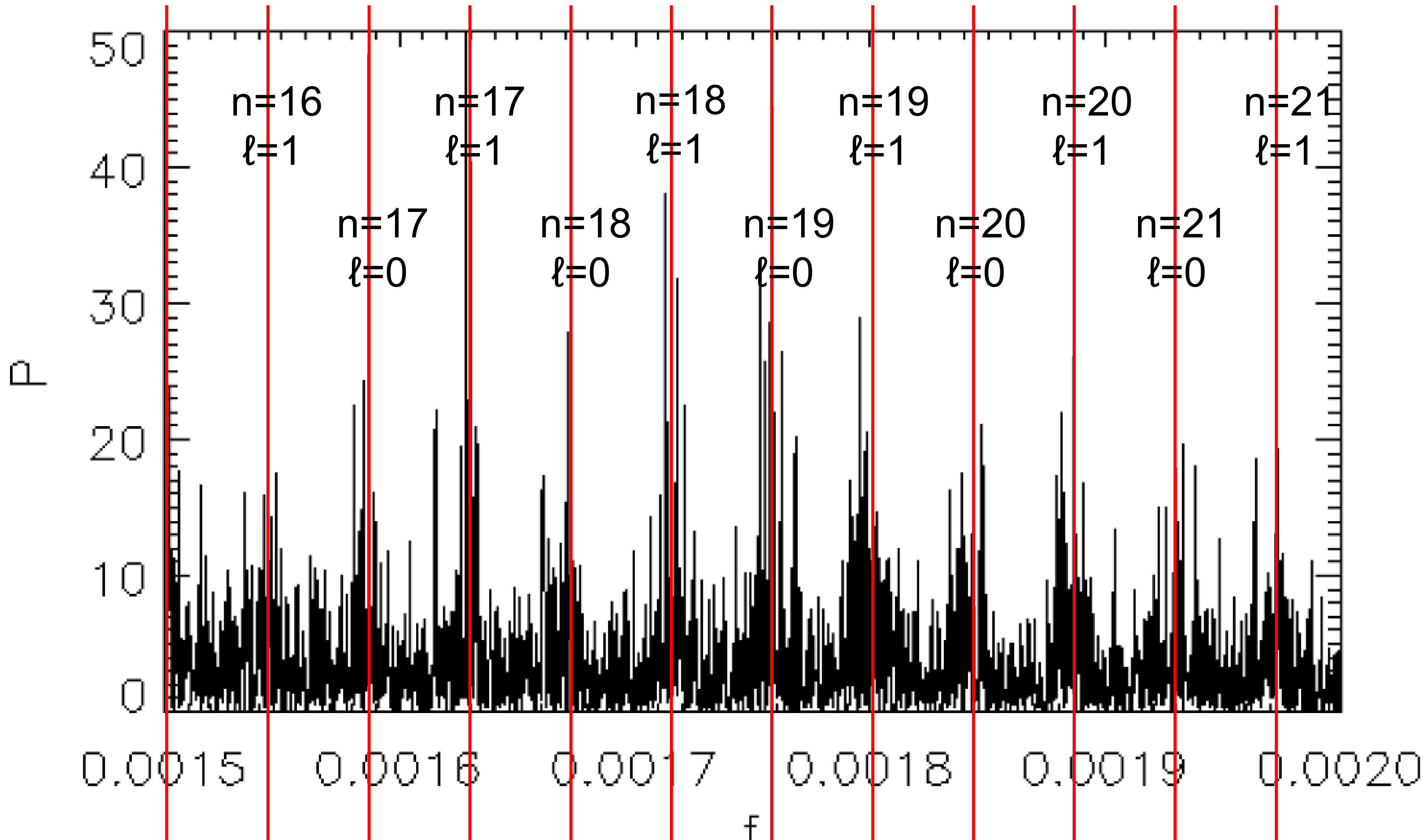
$$\nu_{n,l} = \Delta \nu (n + \frac{1}{2} l + \varepsilon) - l(l+1) D_0$$

Identify the dominant modes in the spectrum

What is its Mass, age and Radius?
What is its rotation period and inclination?

dI/I ~ 0.001– 0.003 for Sunspots
Are the spots on HD49933 of similar size?

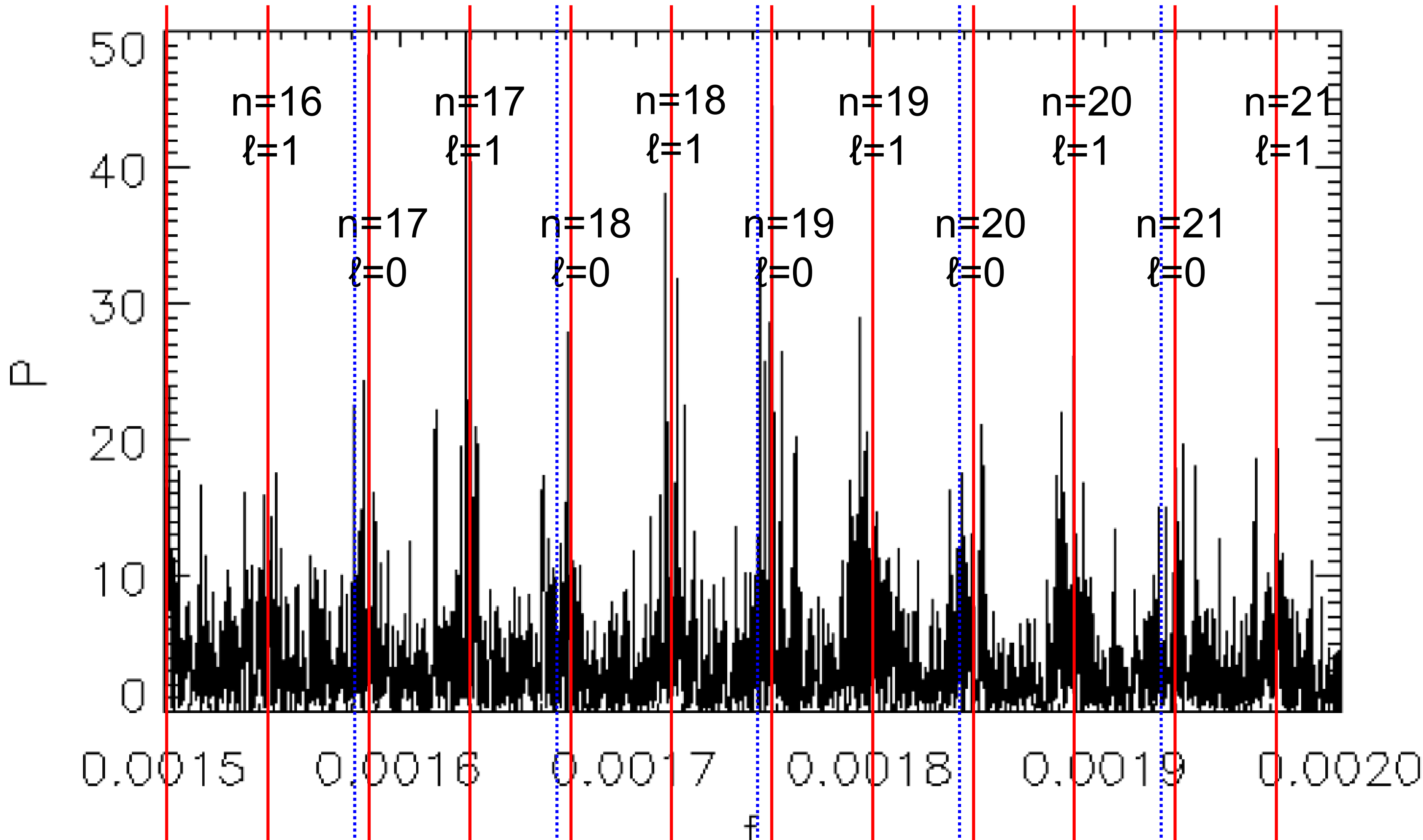

P
0
10
20
30
40
50
0.0015
0.0016
0.0017
0.0018
0.0019
0.0020
f



$\Delta\nu_0 = 85.6\ \mu Hz$

CoRoT: HD 49933

$\Delta\nu_0 = 85.6\ \mu Hz$

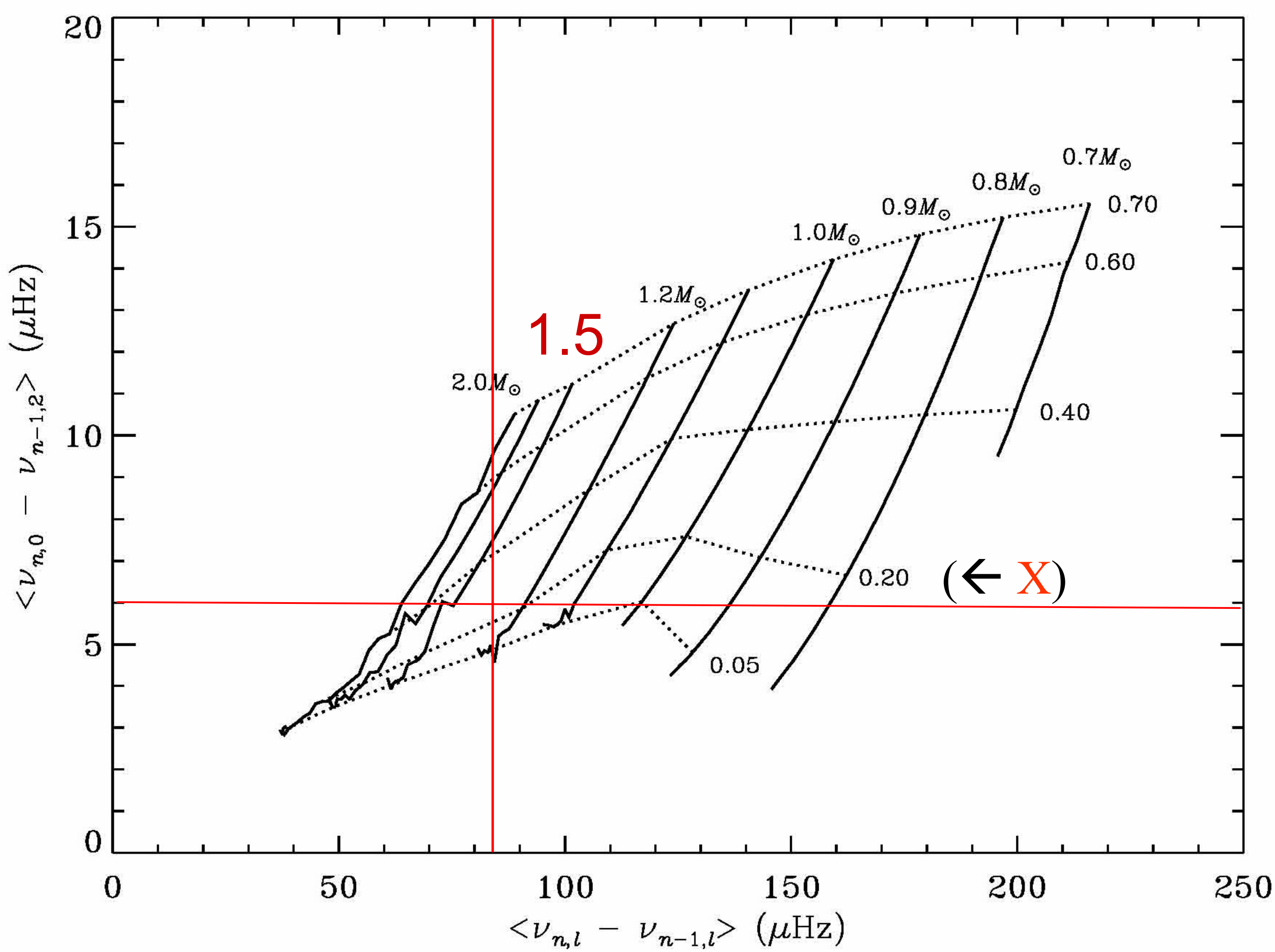


Small separation ~ 6 μHz

Theoretical Separations from stellar models:

Small Separation

(δ_{02})



M ~ 1.3

X ~ 0.23

Large Frequency Separation

HD49933:

$$T = \frac{10 - 14.3X}{M^3} \cdot 10^9\,yr$$

$$V \sin(i) = 10.9\,\mathrm{km/s}$$

$$R \approx 1.5 R_{Sun} \rightarrow P_{rot} \approx 7.0\mathrm{d}$$

$$\Delta\nu_0 \approx 135\,\mu Hz \sqrt{M / R^3}$$

$$\Delta\nu_0 \approx 88.7\,\mu\mathrm{Hz}$$

$$\varepsilon \approx 1$$

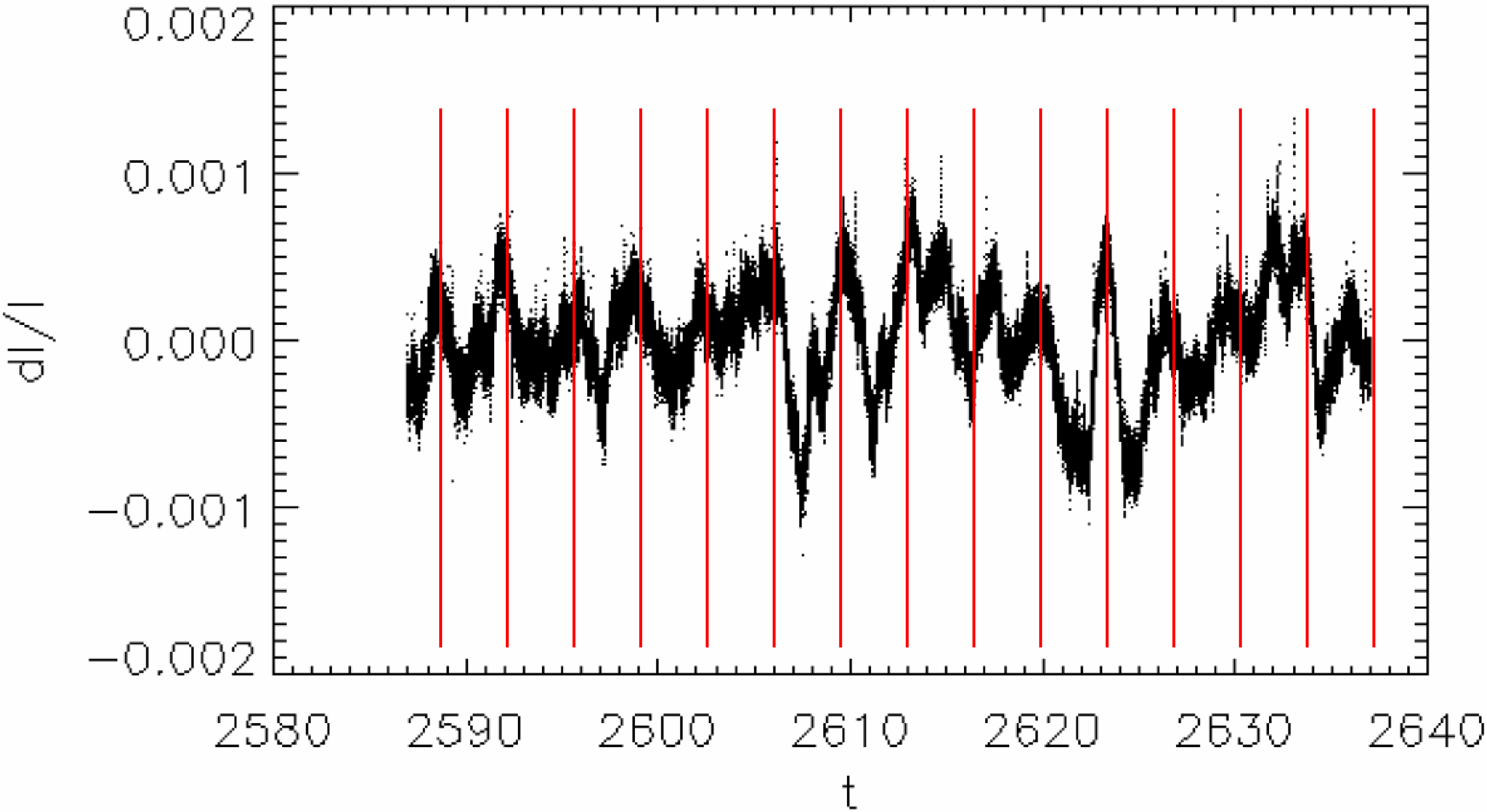
$$\nu_{n,l} = \Delta\nu\left(n + \frac{1}{2} l + \varepsilon\right) - l(l+1) D_0$$

Identify the dominant modes in the spectrum

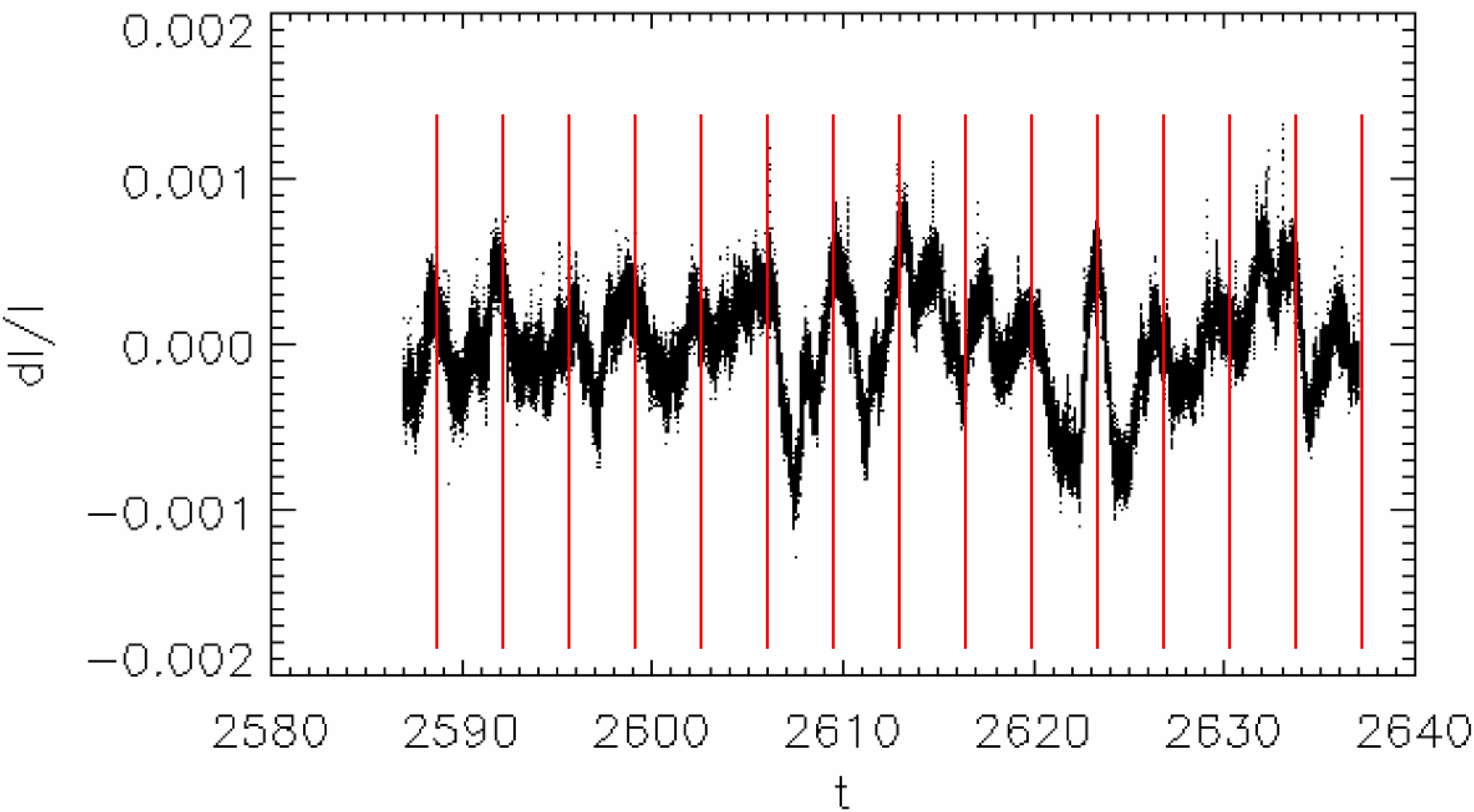
What is its Mass, age and Radius?

M ~ 1.3 M_{sun} ; R ~ 1.5 R_{sun} ; Age ~ 3.1x10^9 yr

$R/R_{sun} = 1.50$
$V\sin(i) = 10.9$ km/s → $P_{ROT} = 7.0$ d



$P_{ROT} \approx 3.5$ d
$\sin(i) \approx 0.5$ → $i \approx 30°$



Typical spot size: 0.0005
Large spots: 0.0015

CoRoT: HD 49933

Typical spot size: 0.0005
Large spots: 0.0015

$$d_{spot}^2 = 0.0005 \times d_{star}^2 \rightarrow d_{spot} \sim 50000\text{km}$$

$$d_{spot}^2 = 0.0015 \times d_{star}^2 \rightarrow d_{spot} \sim 80000\text{km}$$

Same size as sunspots!

CoRoT: HD 49933

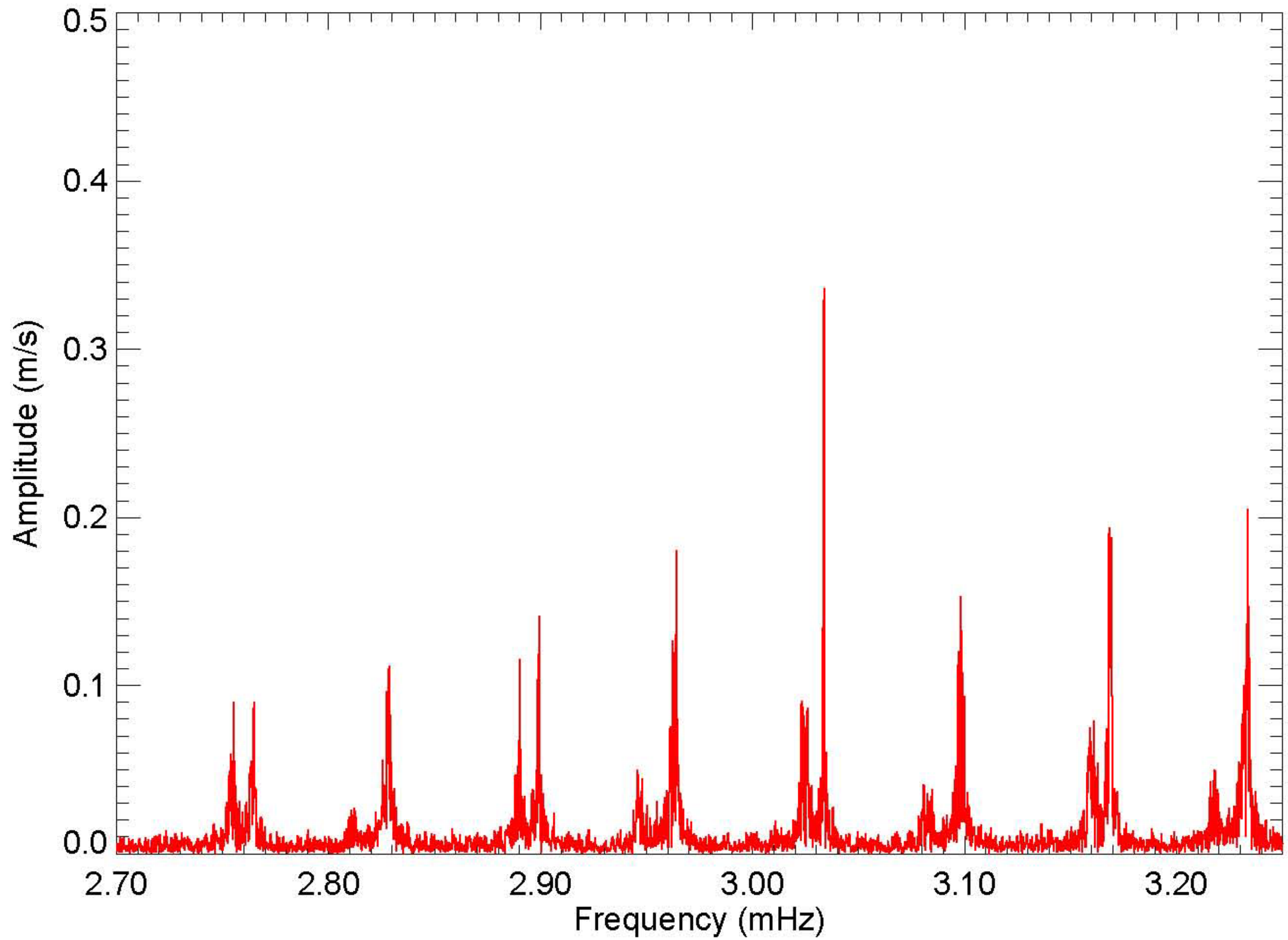
$\Delta\nu_0$ = 85.6 μHz
ρ/ρ_{sun} = 0.402
M/M_{sun} = 1.3
R/R_{sun} = 1.5
$P_{ROT} \approx 3.5$ d
$i \approx 30^o$

Typical spot size: 0.0005 (D ≈ 50,000 km)
Large spots: 0.0015 (D ≈ 80,000 km)

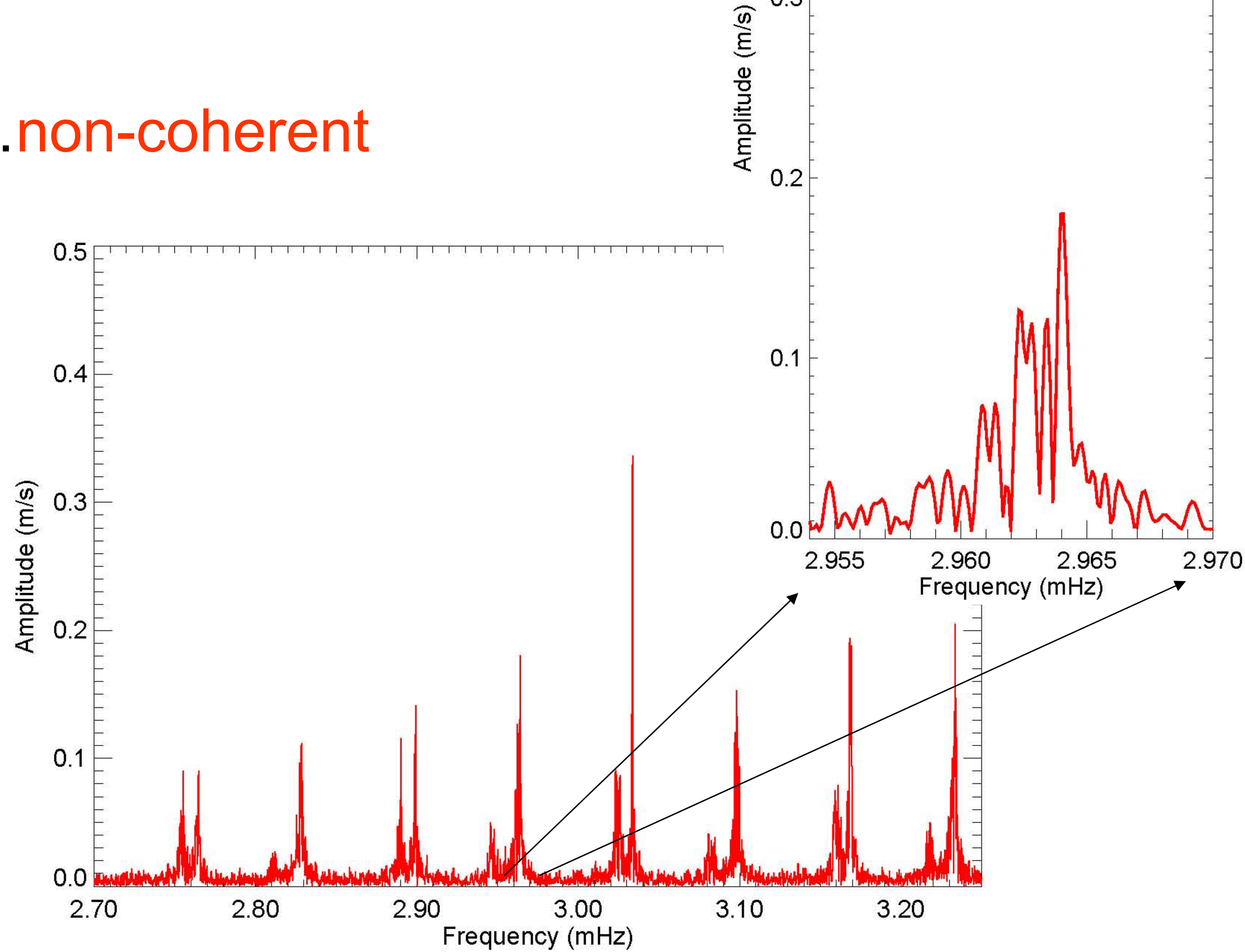
T_{eff} = 6460 ± 150 K

Hipparcos: L/L_{sun} = 3.5 ± 0.25
R/R_{sun} = 1.50 ± 0.09

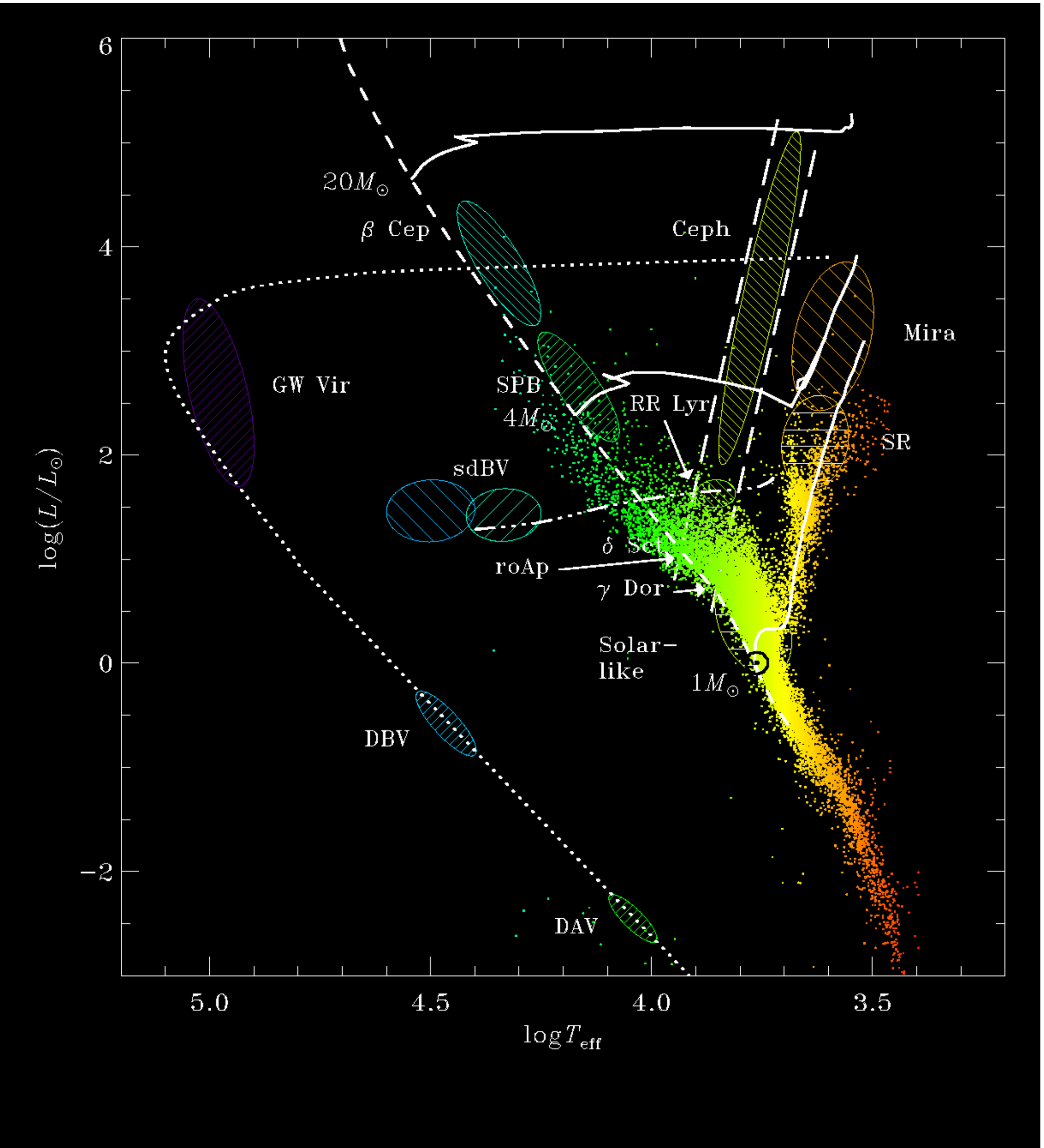
Solar-like oscillations are..



…non-coherent



The HR-diagram: Many types of pulsating stars



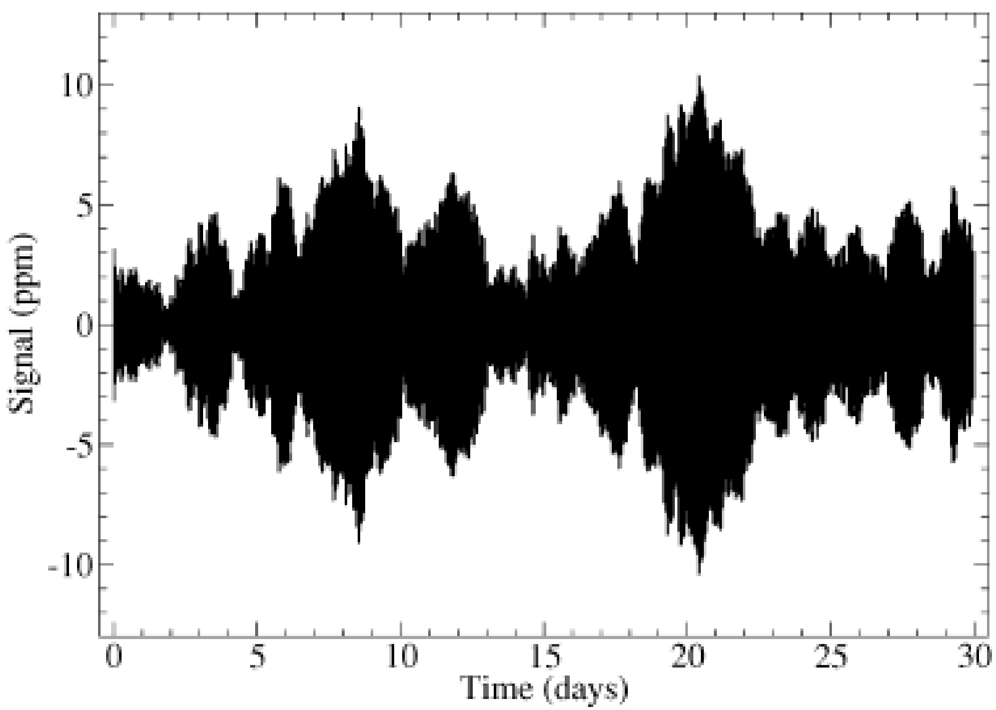
The Kappa-mechanism:

- Delta Scuti
- Beta Cepheid
- Cepheids
- RR Lyrae

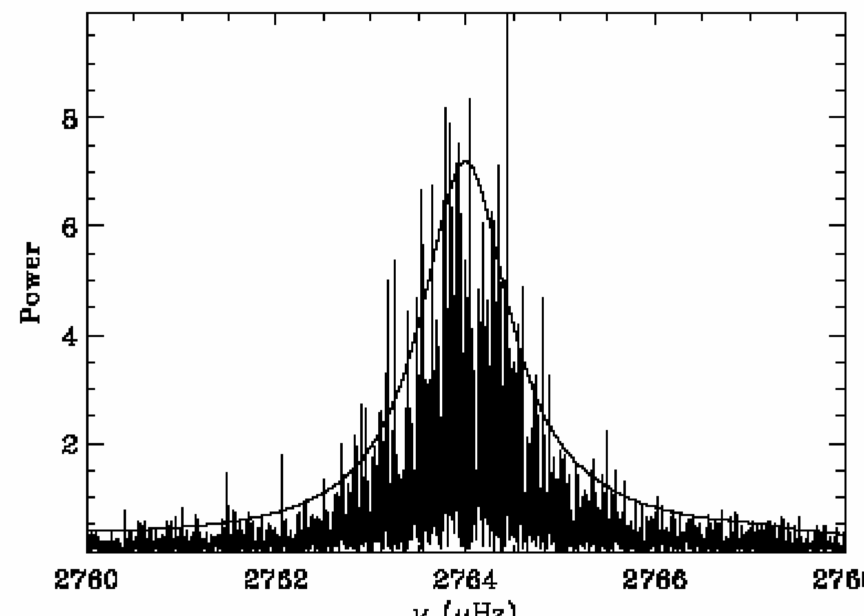
Coherent oscillations

Solar-like oscillations

- The oscillations are actually stable modes stochastically excited by convection
- Random excitation and exponential decay → Lorentz Profile



A single, stochastic mode



The Sun – fit multiplied by 3

Solar-like oscillations

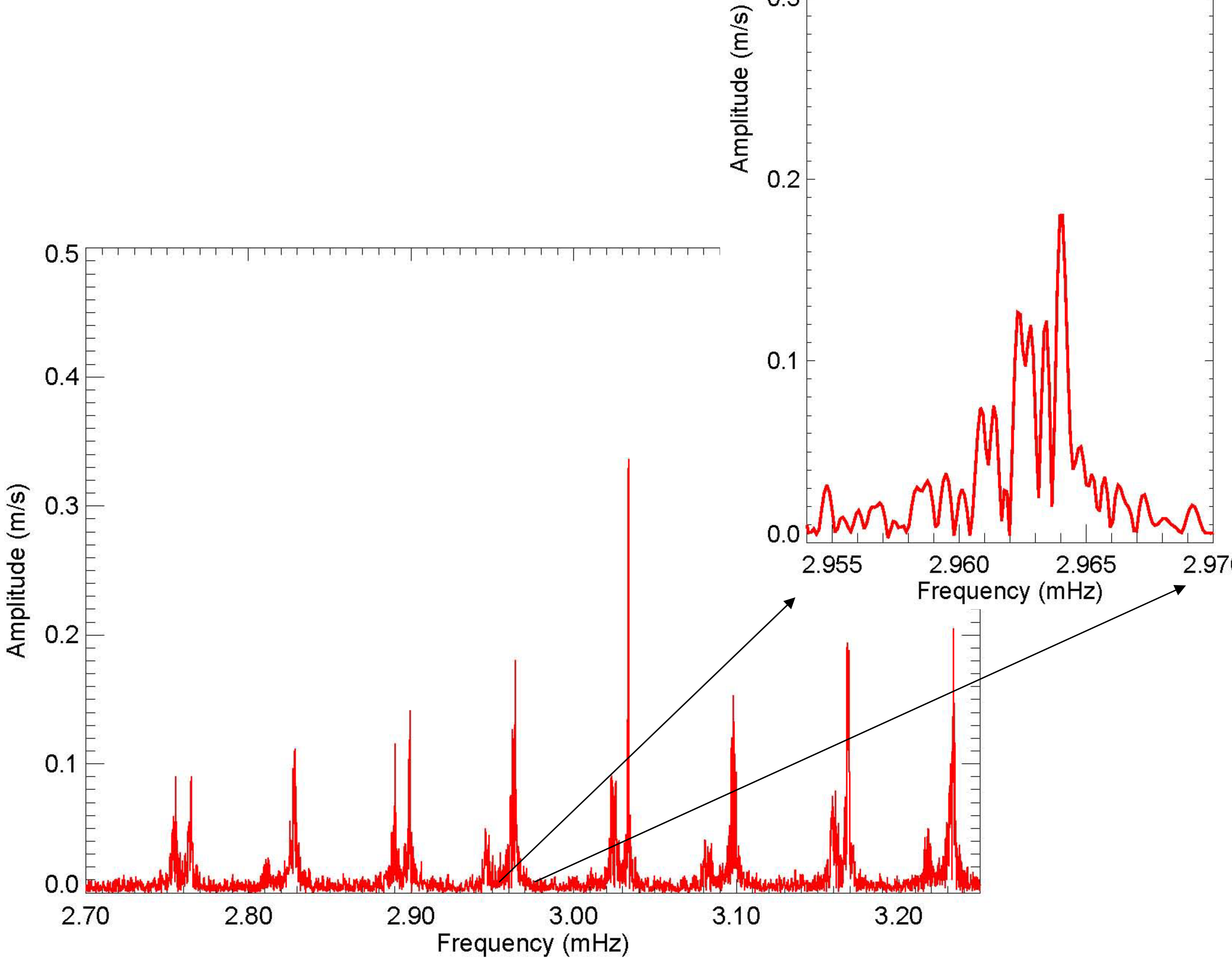
- The width of the Lorentzian depends on the

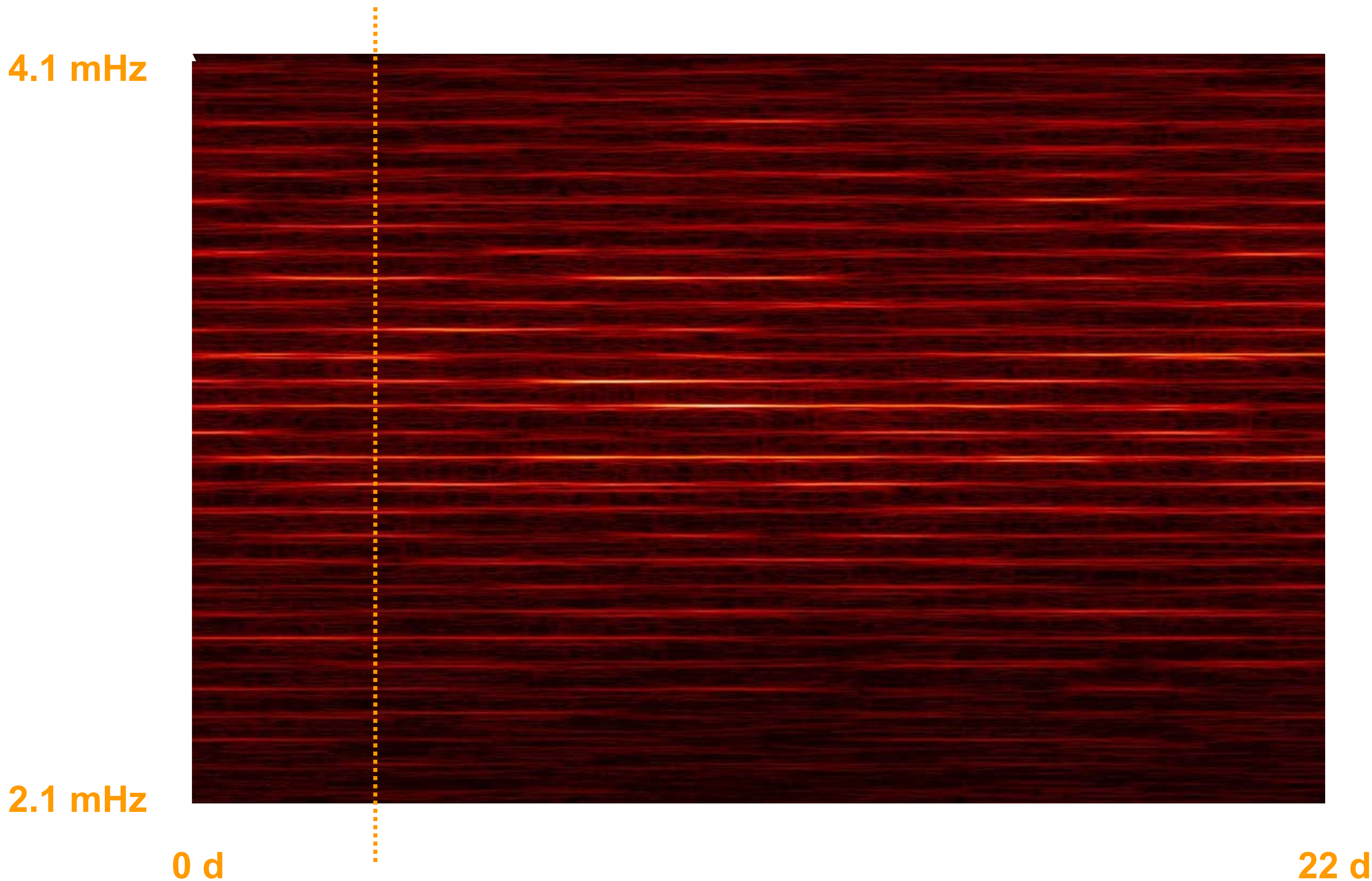
  mode lifetime

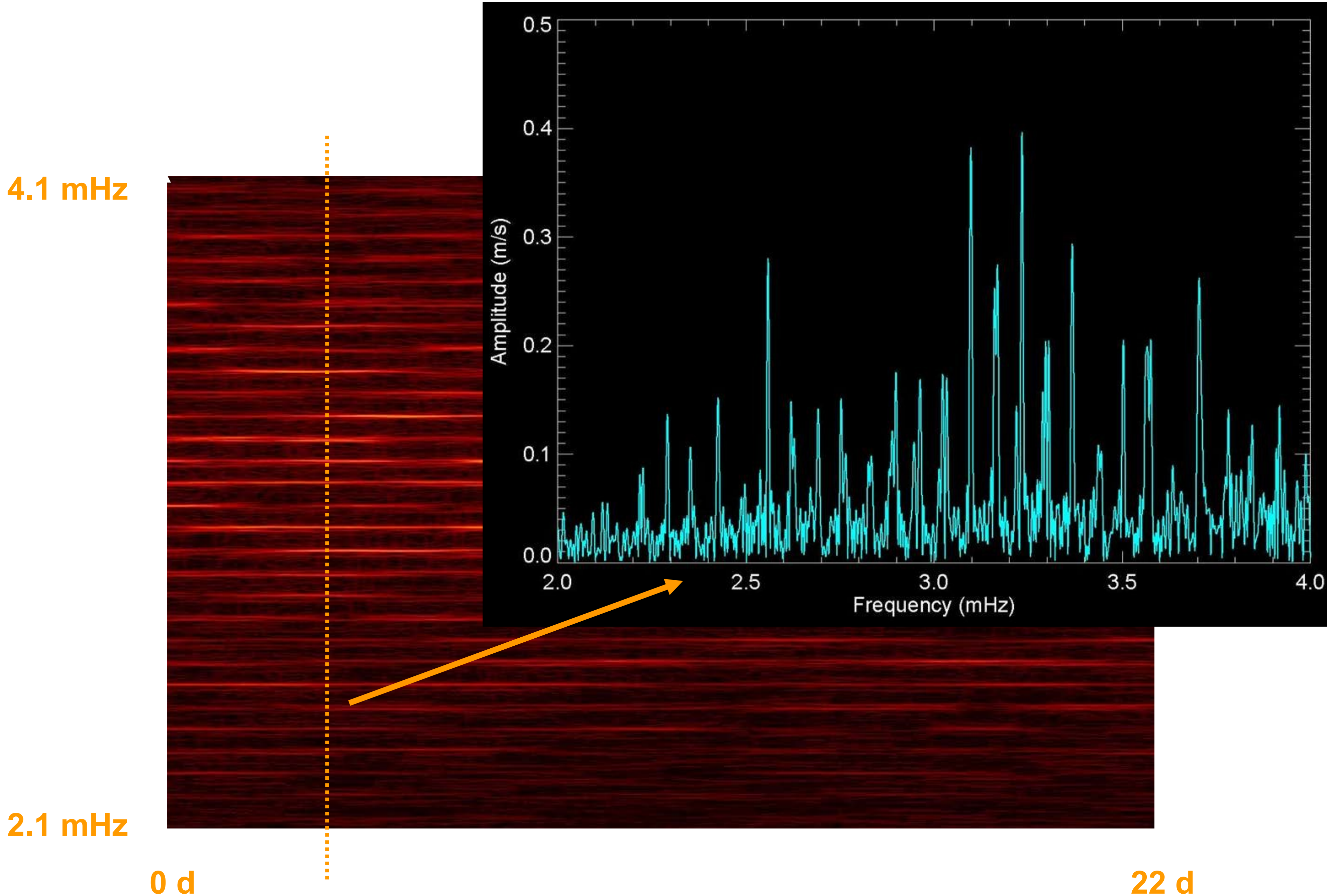
- Typically a couple of days – but not yet well-understood

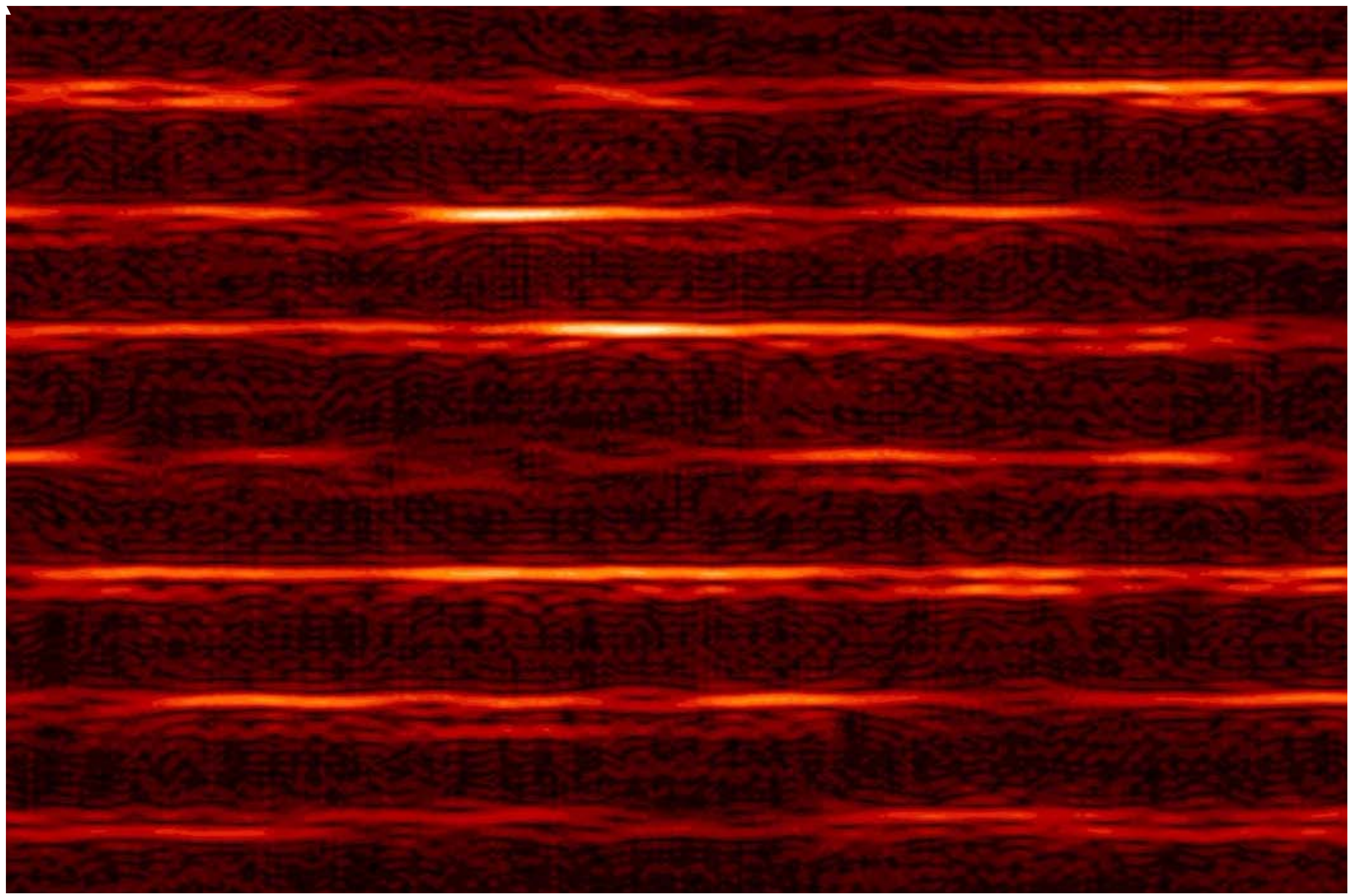
- Typically not resolved in ground-based campaigns on solar-like stars

  – requires observations over many lifetimes, which we so far only have for the Sun

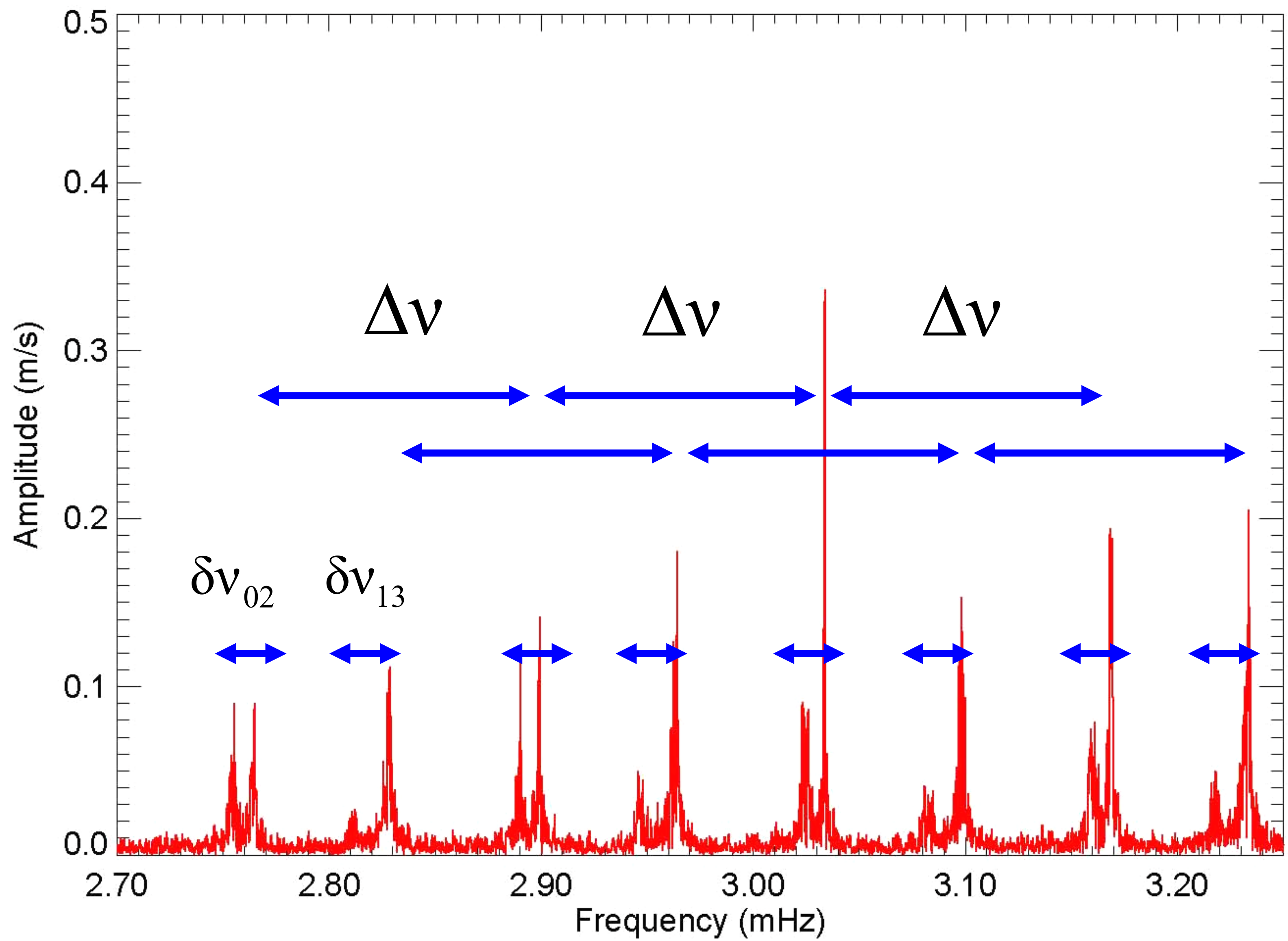

Amplitude (m/s)
0.0
0.1
0.2
0.3
0.4
0.5
2.70
2.80
2.90
3.00
3.10
3.20
Frequency (mHz)
Amplitude (m/s)
0.0
0.1
0.2
2.955
2.960
2.965
2.970
Frequency (mHz)


4.1 mHz
2.1 mHz
0 d
22 d


4.1 mHz
2.1 mHz
0 d
22 d
Amplitude (m/s)
0.0
0.1
0.2
0.3
0.4
0.5
2.0
2.5
3.0
3.5
4.0
Frequency (mHz)

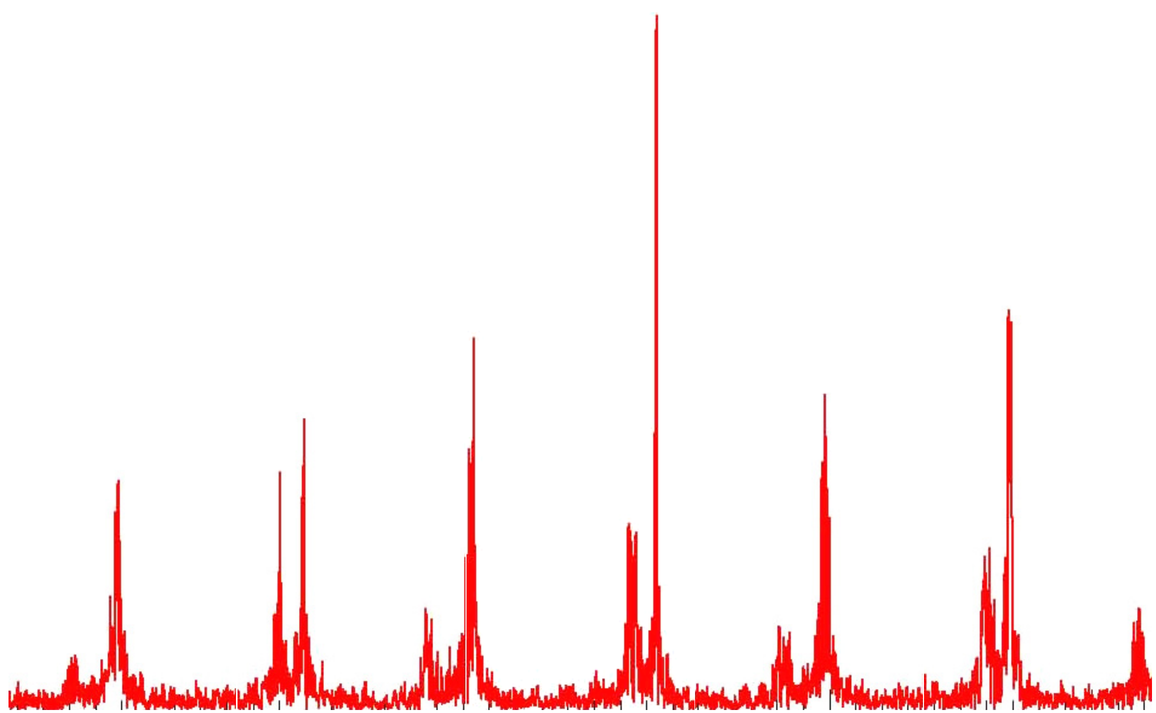

3.35 mHz
2.85 mHz
0 d
22 d

Determine the large Separation



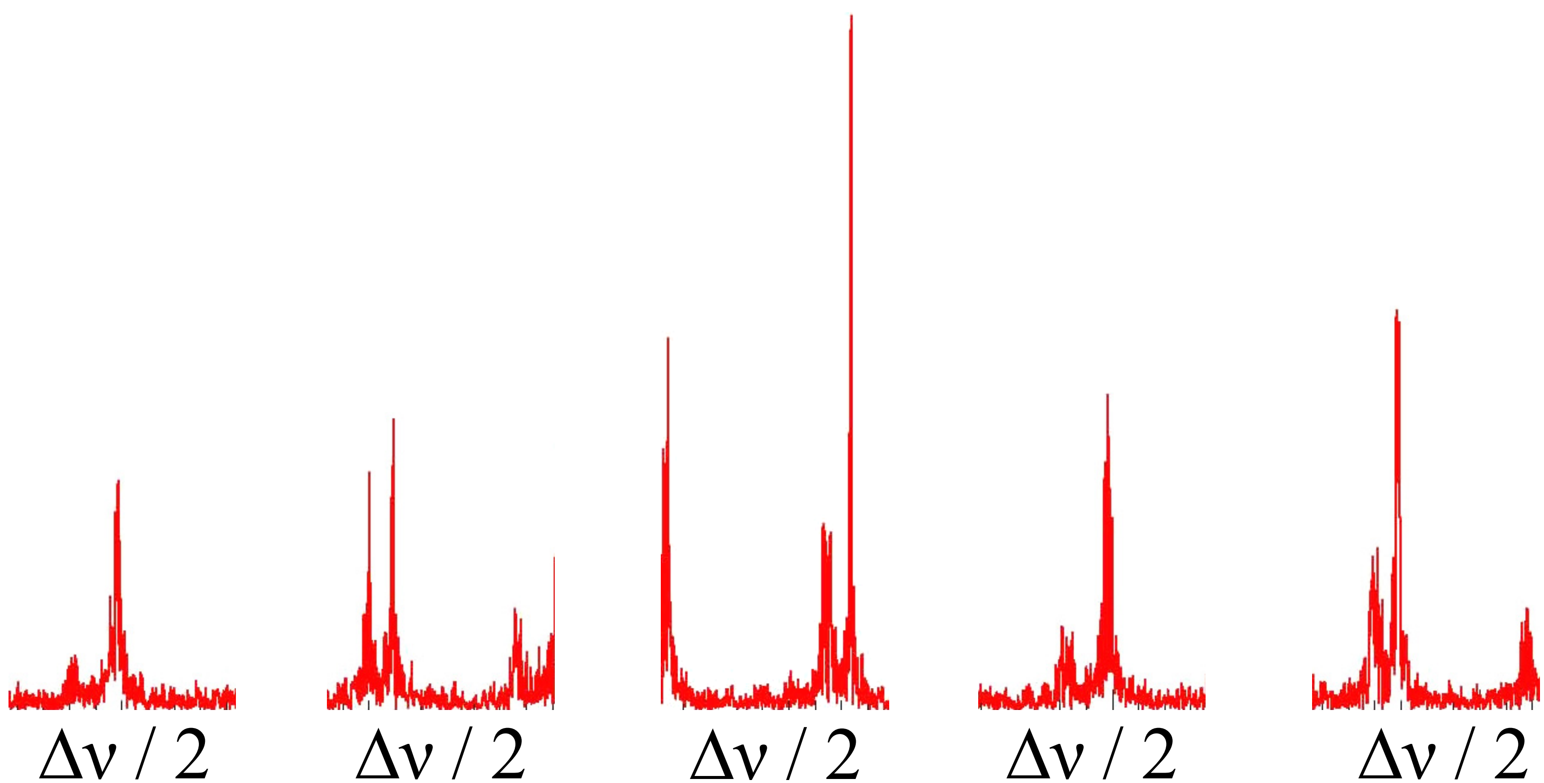
Determine the large Separation

1. Take one value for $\Delta\nu$ (first guess)



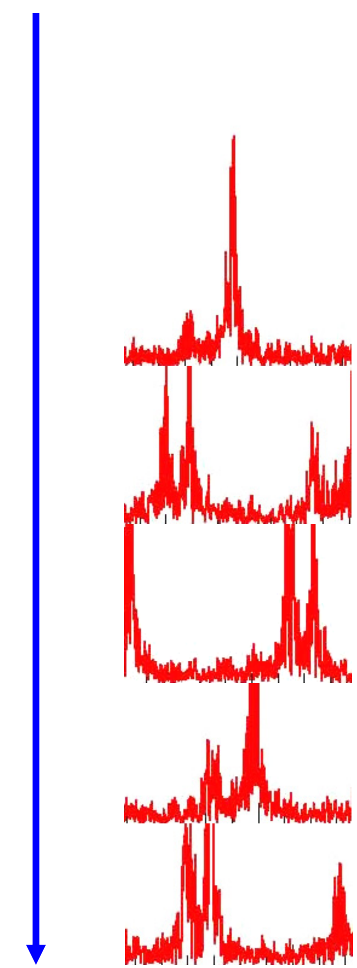
Determine the large Separation

1. Take one value for $\Delta\nu$
2. Cut the spectrum into bins of $\Delta\nu / 2$



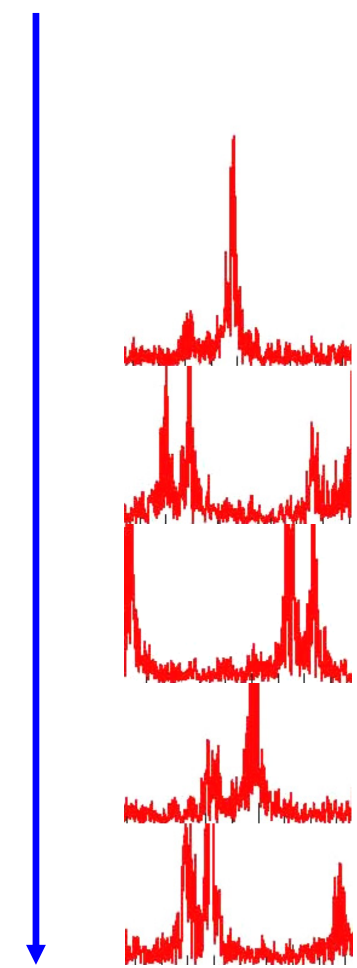
Determine the large Separation

1. Take one value for $\Delta\nu$
2. Cut the spectrum into bins of $\Delta\nu / 2$
3. Sum the power of each bin

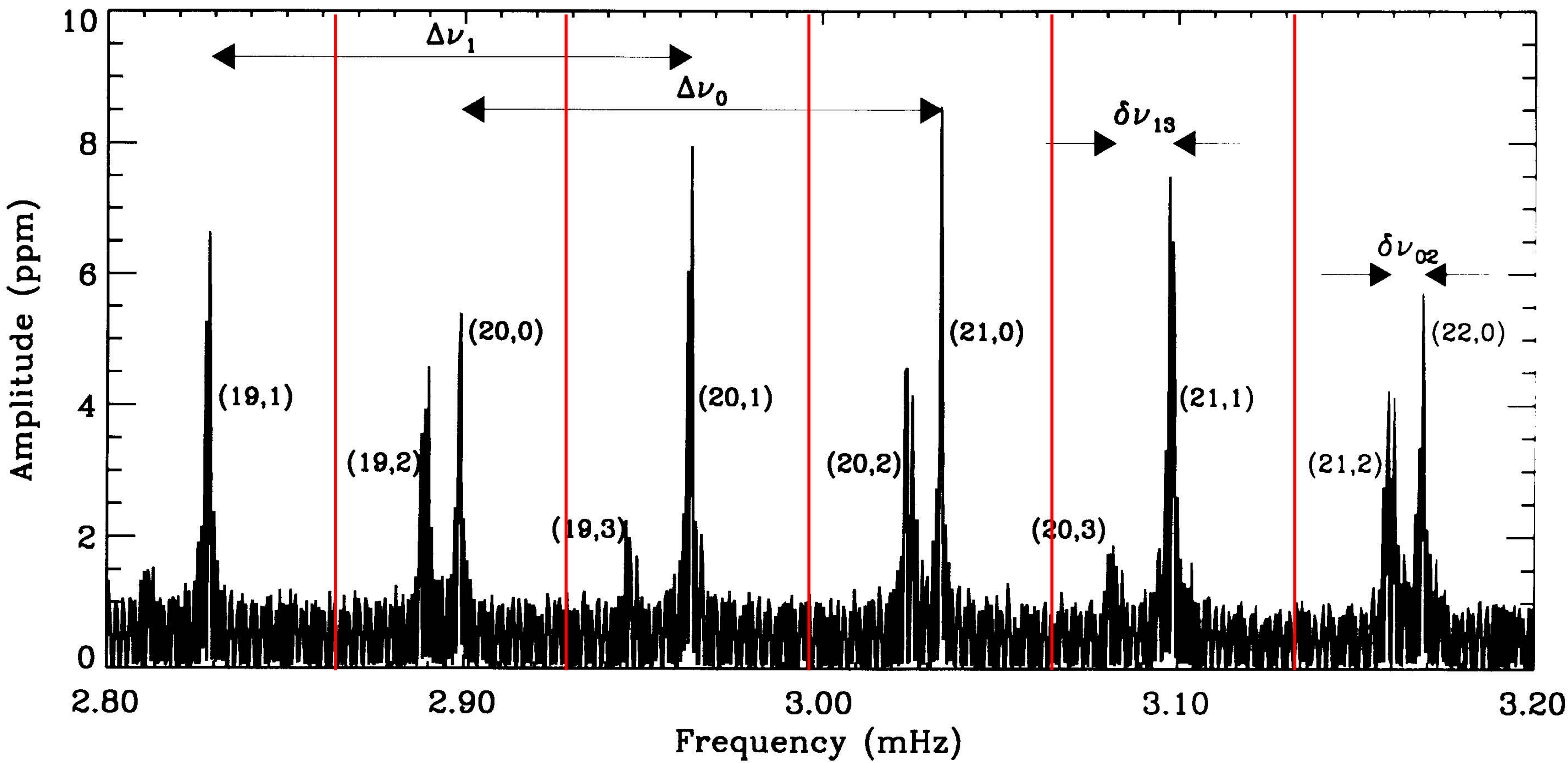


Determine the large Separation

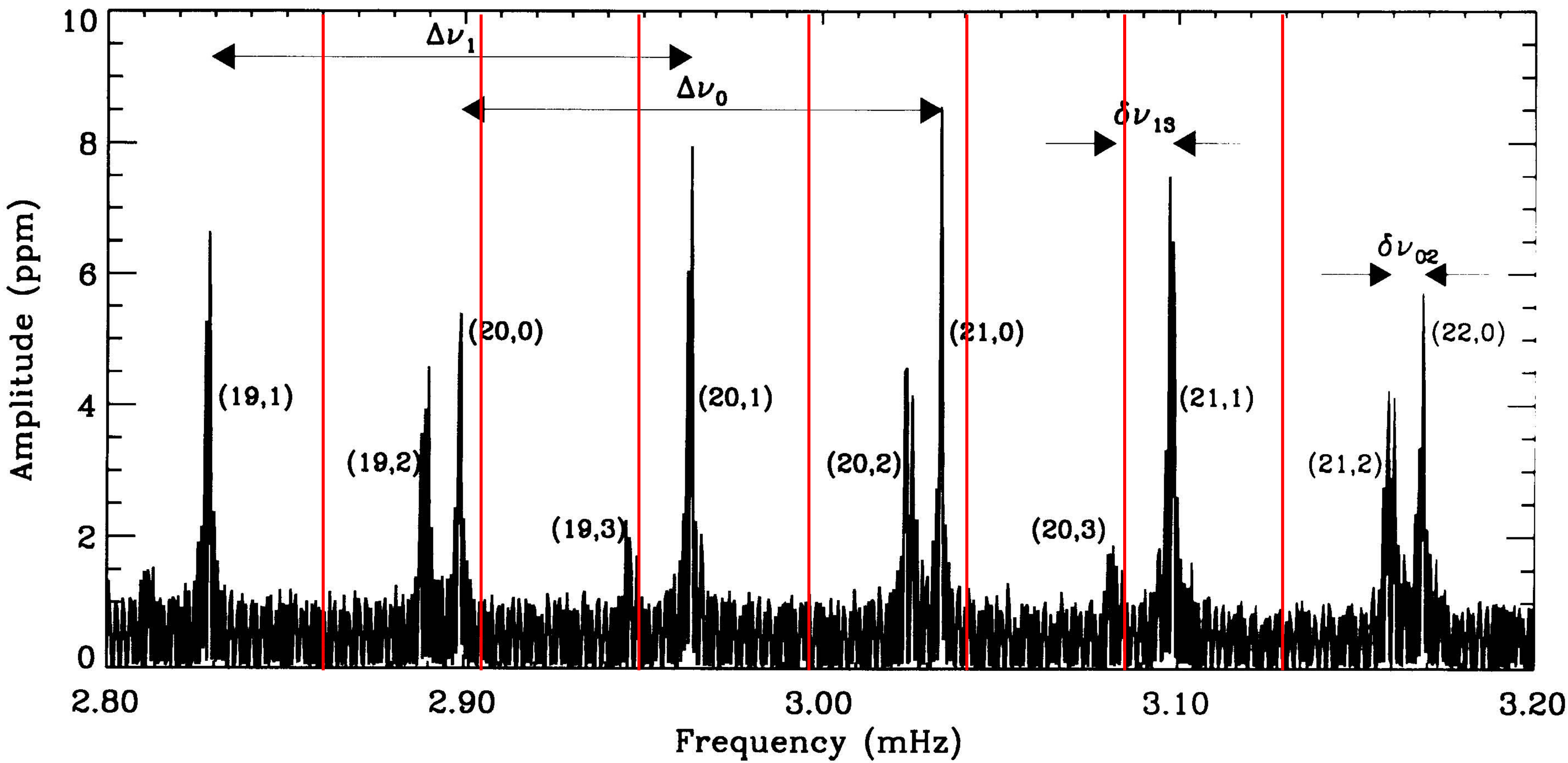
1. Take one value for $\Delta\nu$
2. Cut the spectrum into bins of $\Delta\nu / 2$
3. Sum the power of each bin
4. Find the peak of the summed power



Correct value: l=0,1 same position in each bin

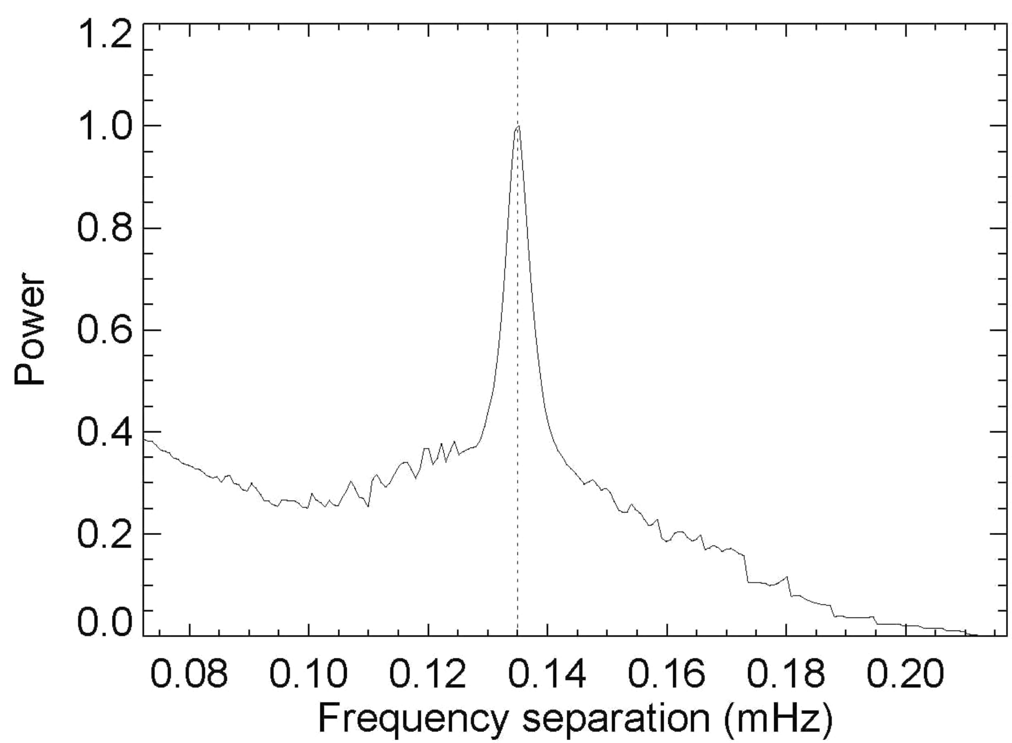


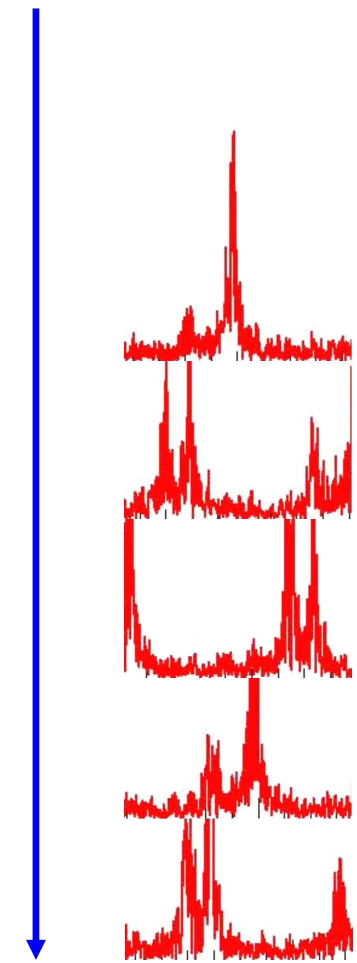
Wrong Large Separation



Determine the large Separation

1. Take one value for $\Delta\nu$
2. Cut the spectrum into bins of $\Delta\nu / 2$
3. Sum the power of each bin
4. Find the peak of the summed power
5. Try for all possible values of $\Delta\nu$





Extract the frequencies (using iterative fitting):

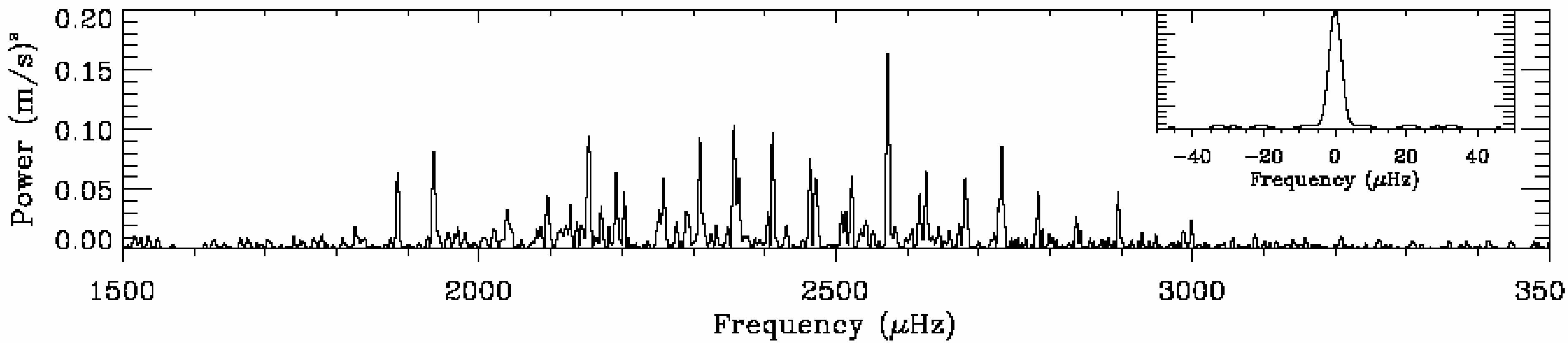


TABLE 1

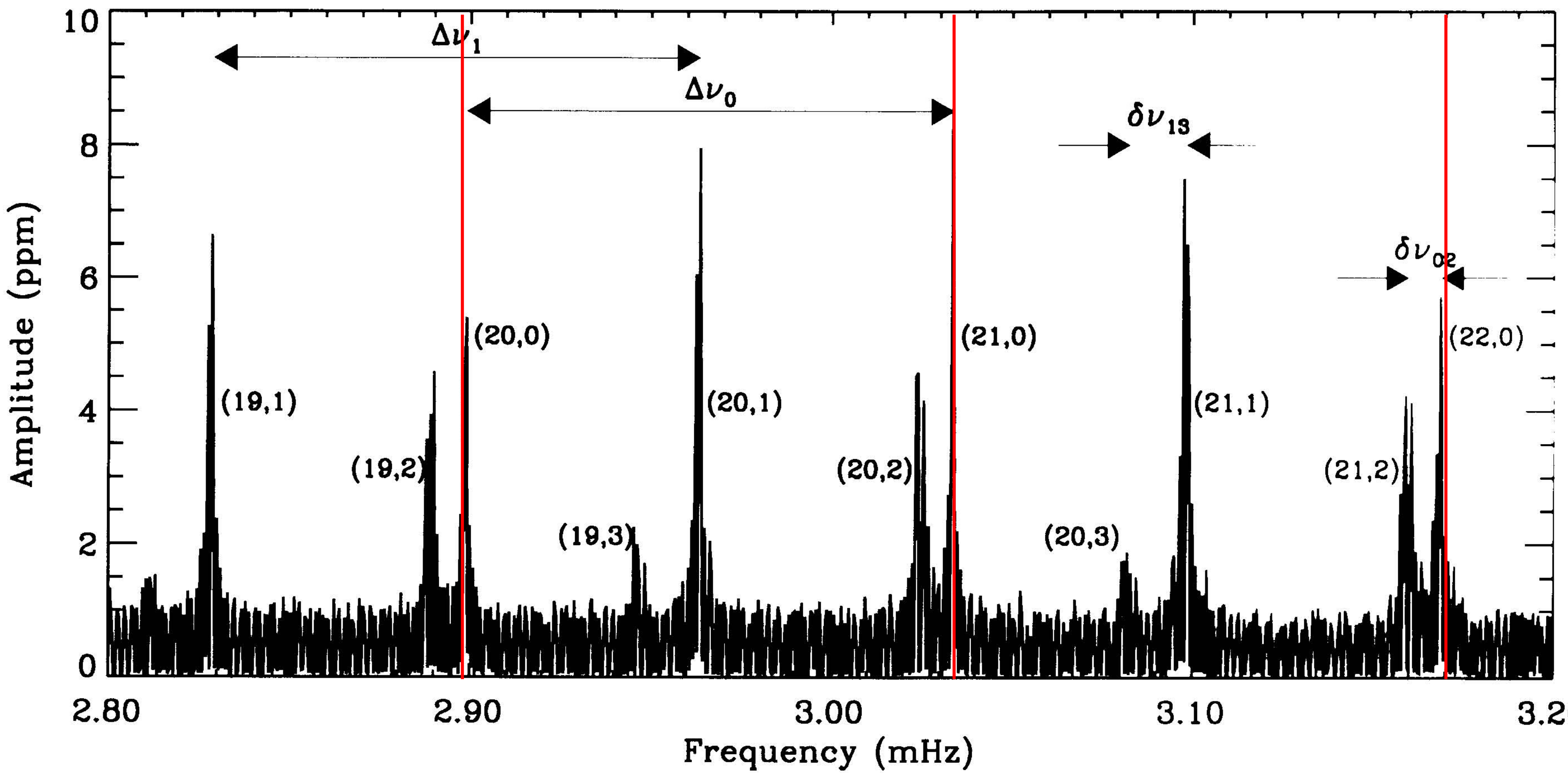
OSCILLATION FREQUENCIES FOR α CEN A (μHz)

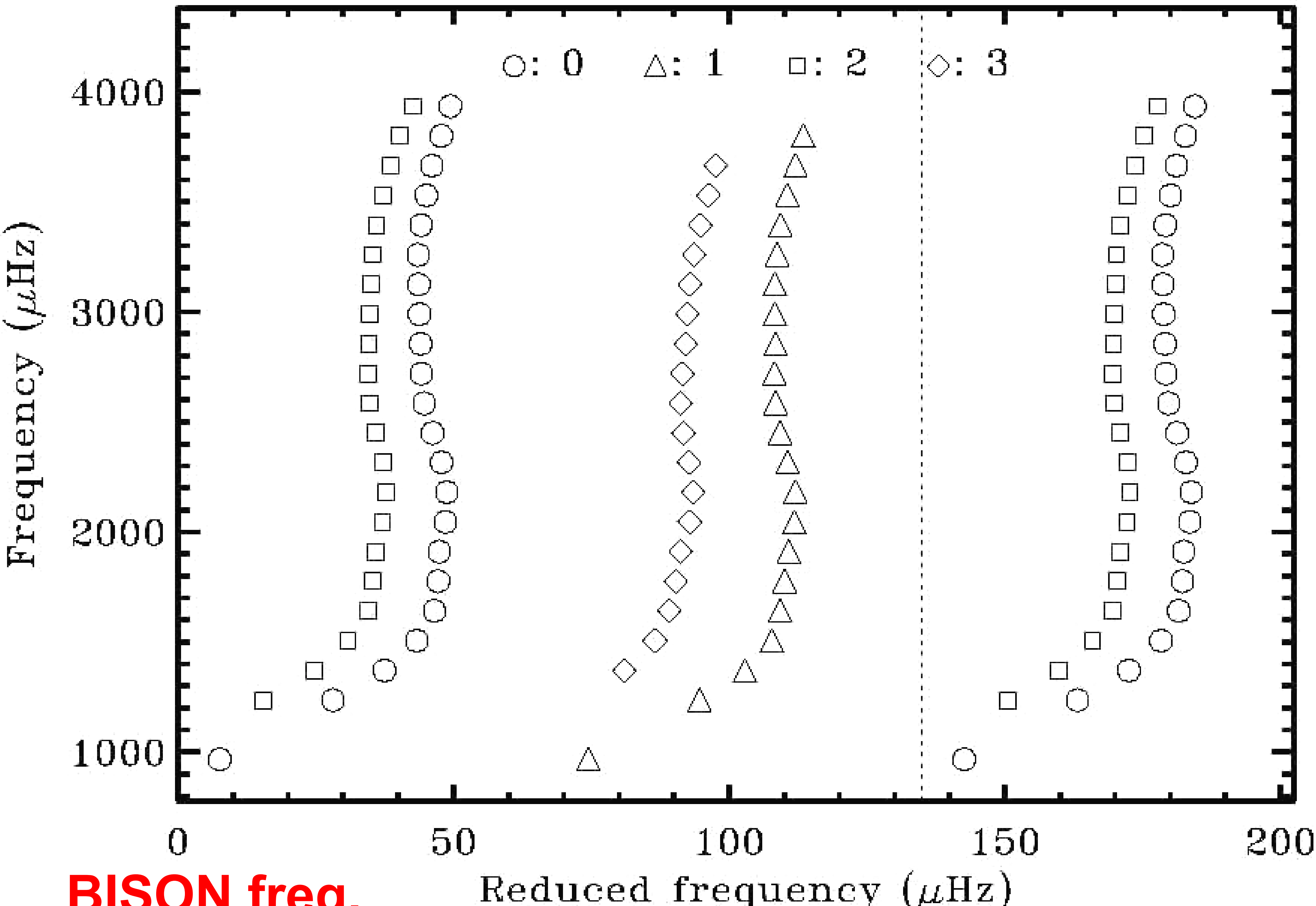
n	$l = 0$	$l = 1$	$l = 2$	$l = 3$
14....................	...	1675.9	...	...
15....................	...	1779.7	1828.6	...
16....................	1839.2	1885.9	1935.7	...
17....................	1943.3	1993.8	2038.9	2082.9
18....................	2045.5	2094.6	2146.3	2193.1
19....................	2152.9	2203.2	2253.4	2296.3
20....................	2258.1	2309.1	2357.3	2404.8
21....................	2364.0	2412.4	2463.4	2507.5
22....................	2471.5	2522.1	2572.7	2616.8
23....................	2572.7	2627.1	2676.8	2723.5
24....................	2682.7	2733.2	2783.4	...
25....................	...	2840.2	...	...
26....................	2895.9	2945.7	2998.3	...
27....................	...	3055.1	...	...

And calculate

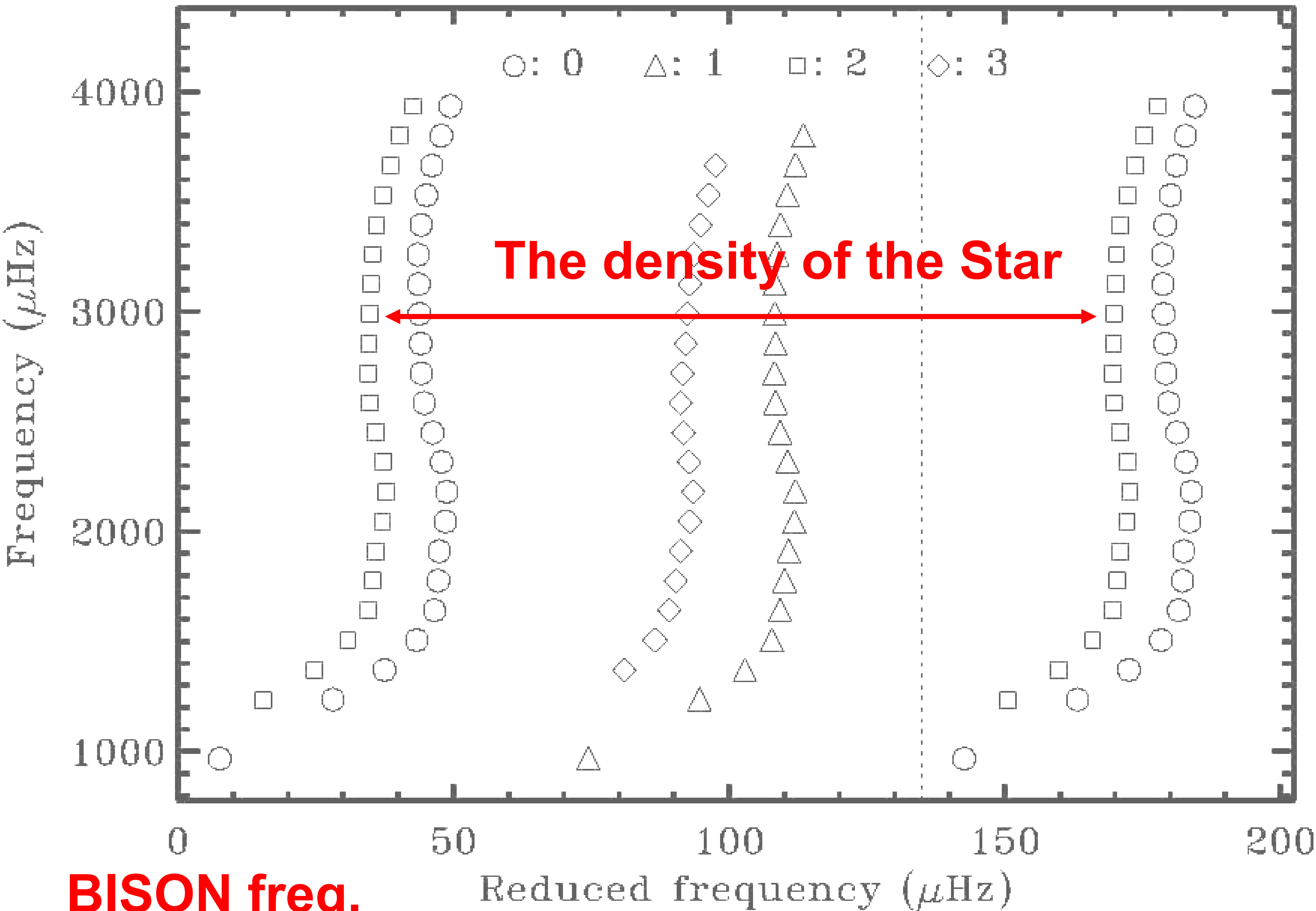
$$\nu \bmod \Delta\nu_0$$

$\nu \bmod \Delta\nu_0$ ~ constant for modes of same l

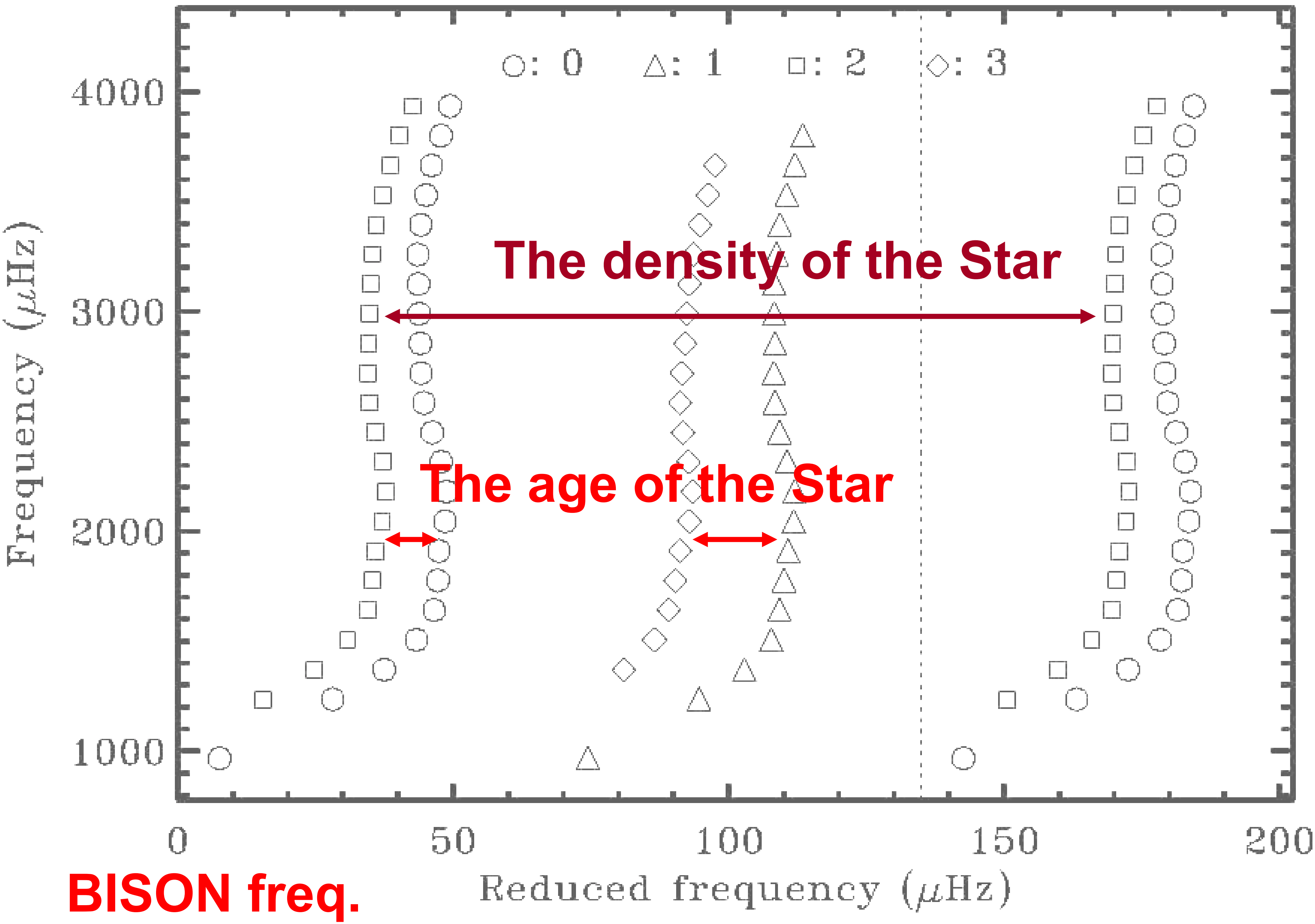


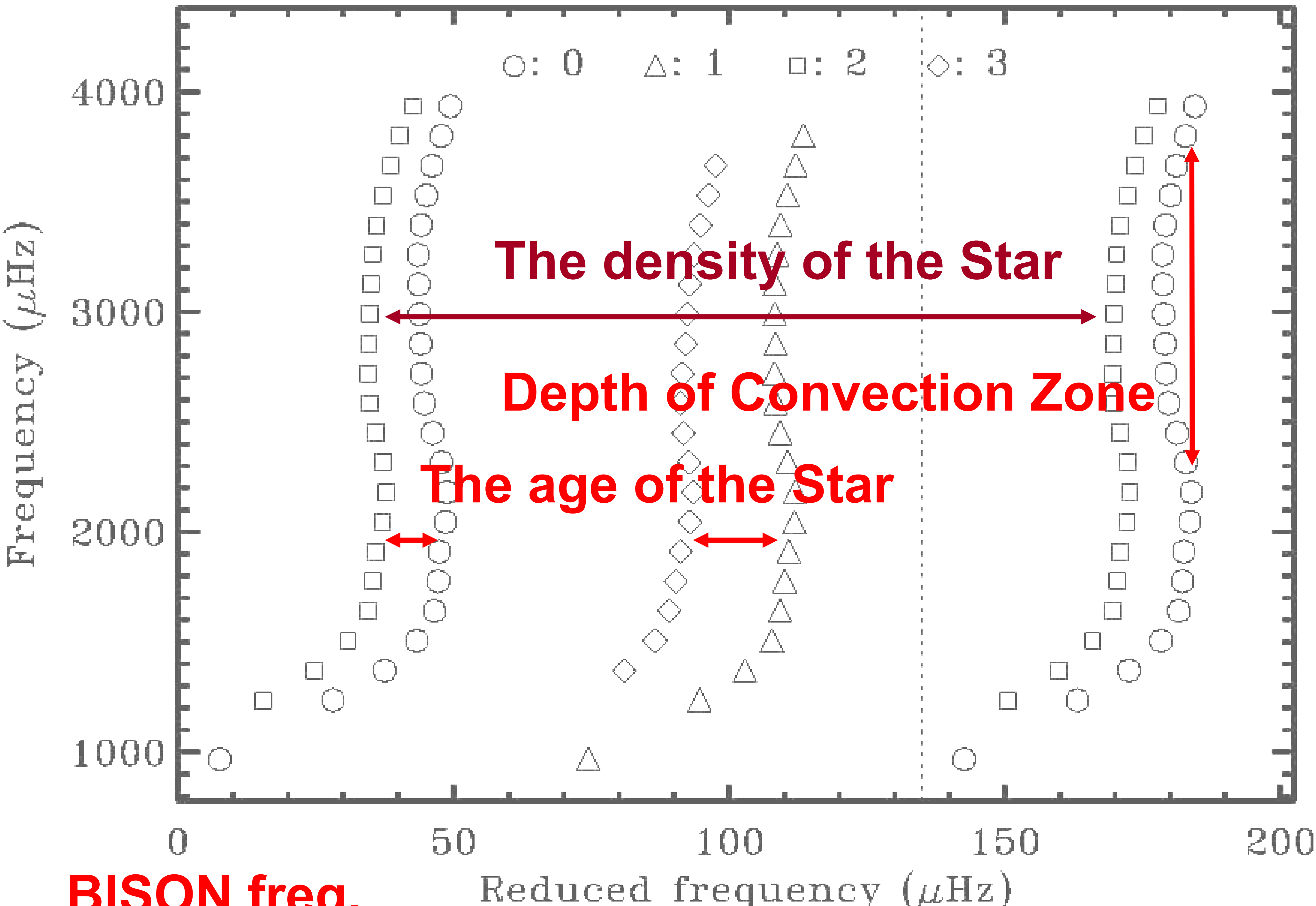

○: 0 △: 1 □: 2 ◇: 3
4000
3000
2000
1000
Frequency (μHz)
0
50
100
150
200
Reduced frequency (μHz)

BISON freq.



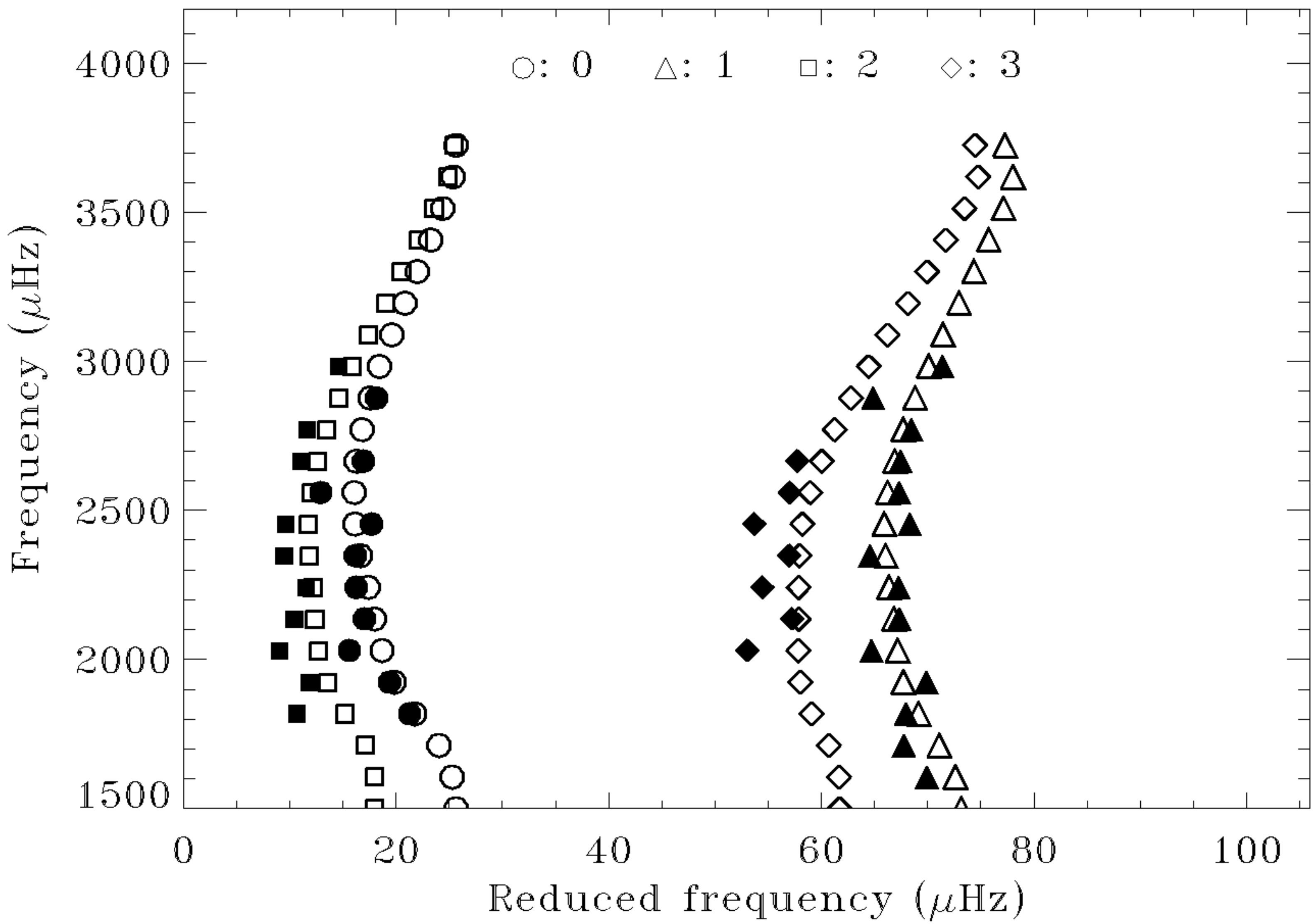
○: 0
△: 1
□: 2
◇: 3
The density of the Star
4000
3000
2000
1000
Frequency (μHz)
0
50
100
150
200
Reduced frequency (μHz)
BISON freq.


○: 0 △: 1 □: 2 ◇: 3
The density of the Star
The age of the Star
Frequency (μHz)
4000
3000
2000
1000
0
50
100
150
200
Reduced frequency (μHz)
BISON freq.

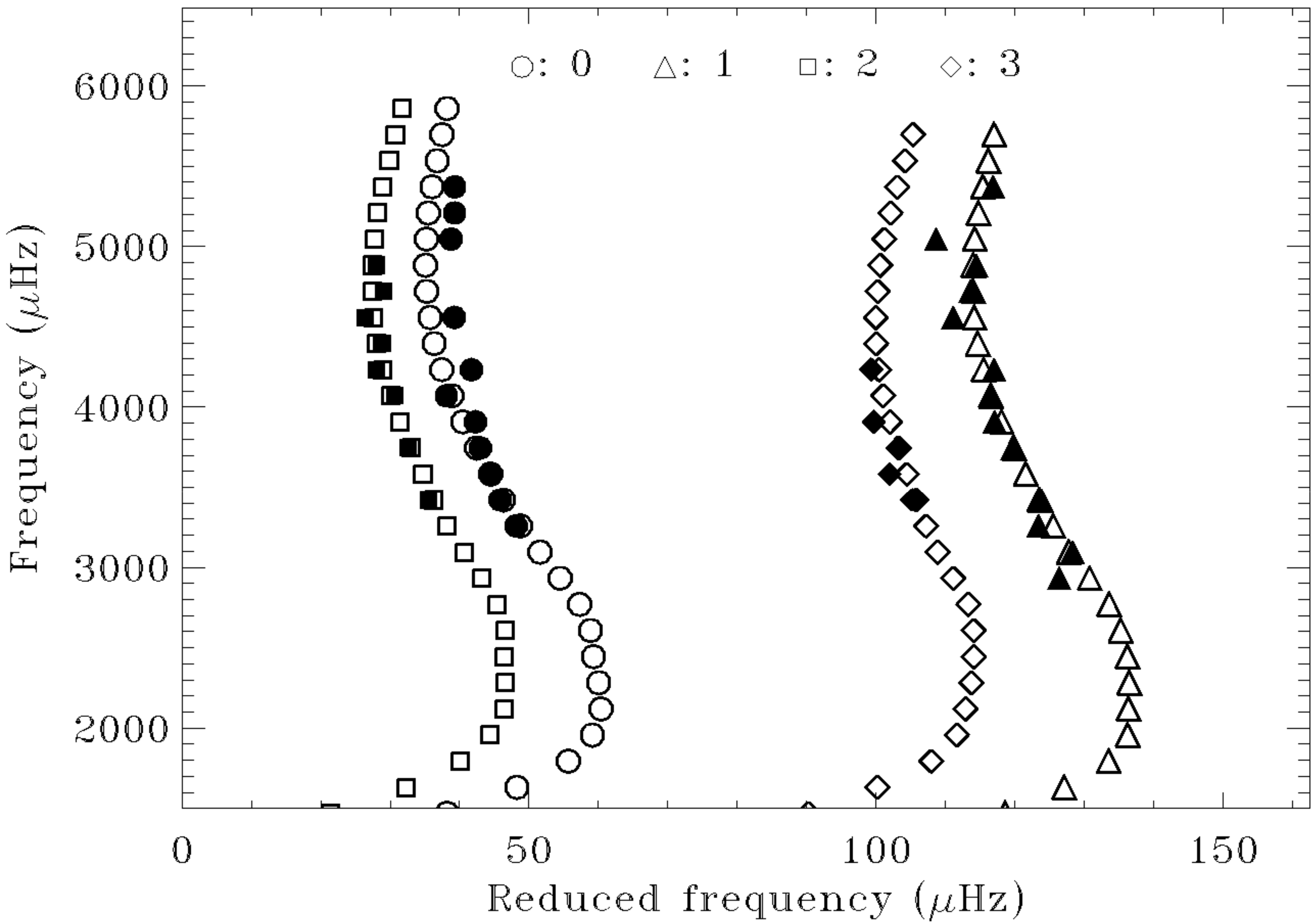

○: 0
△: 1
□: 2
◇: 3
The density of the Star
Depth of Convection Zone
The age of the Star
Frequency (μHz)
4000
3000
2000
1000
0
50
100
150
200
Reduced frequency (μHz)

BISON freq.

α Centauri A

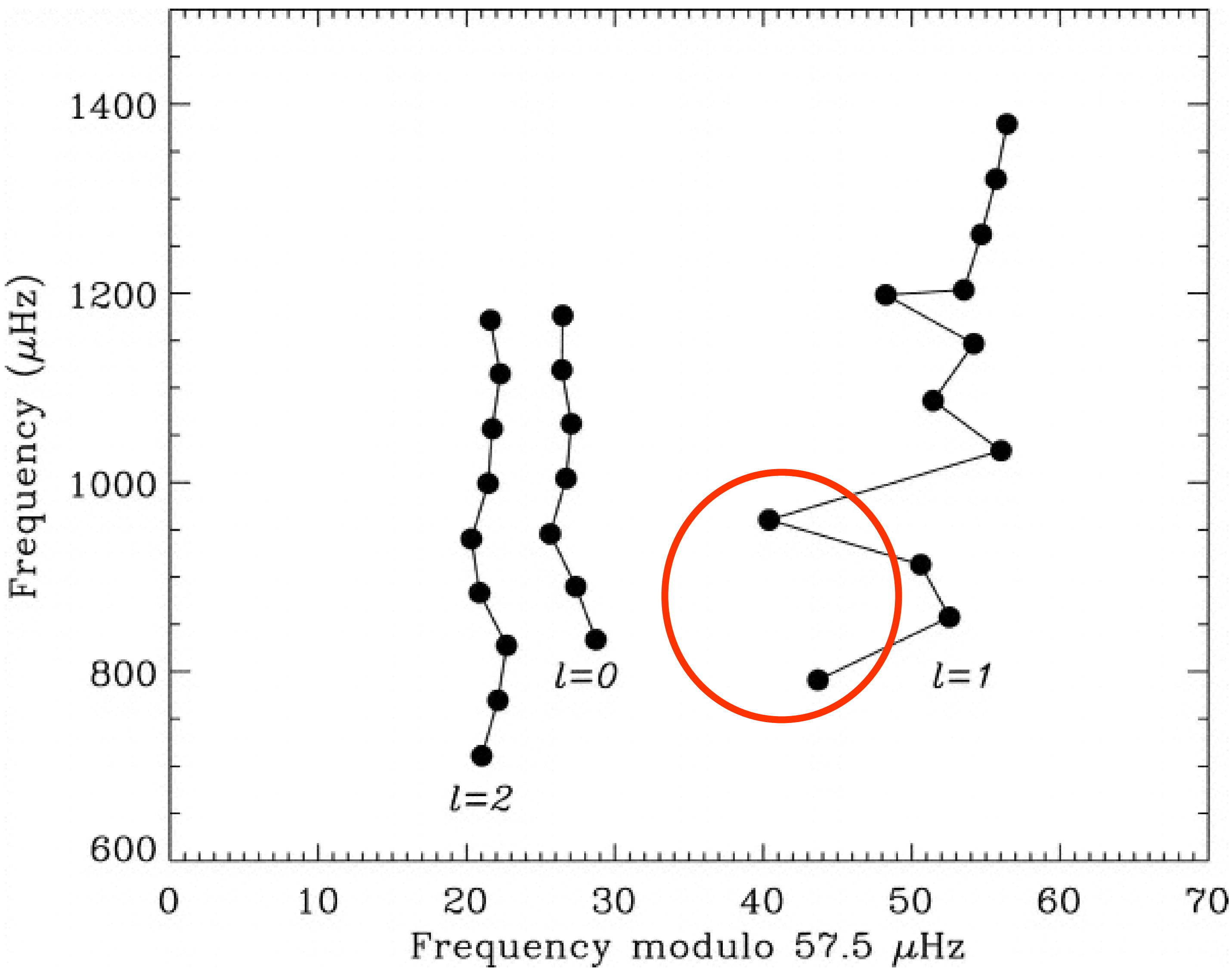

○: 0 △: 1 □: 2 ◇: 3
4000
3500
3000
2500
2000
1500
Frequency (μHz)
0
20
40
60
80
100
Reduced frequency (μHz)

α Centauri B



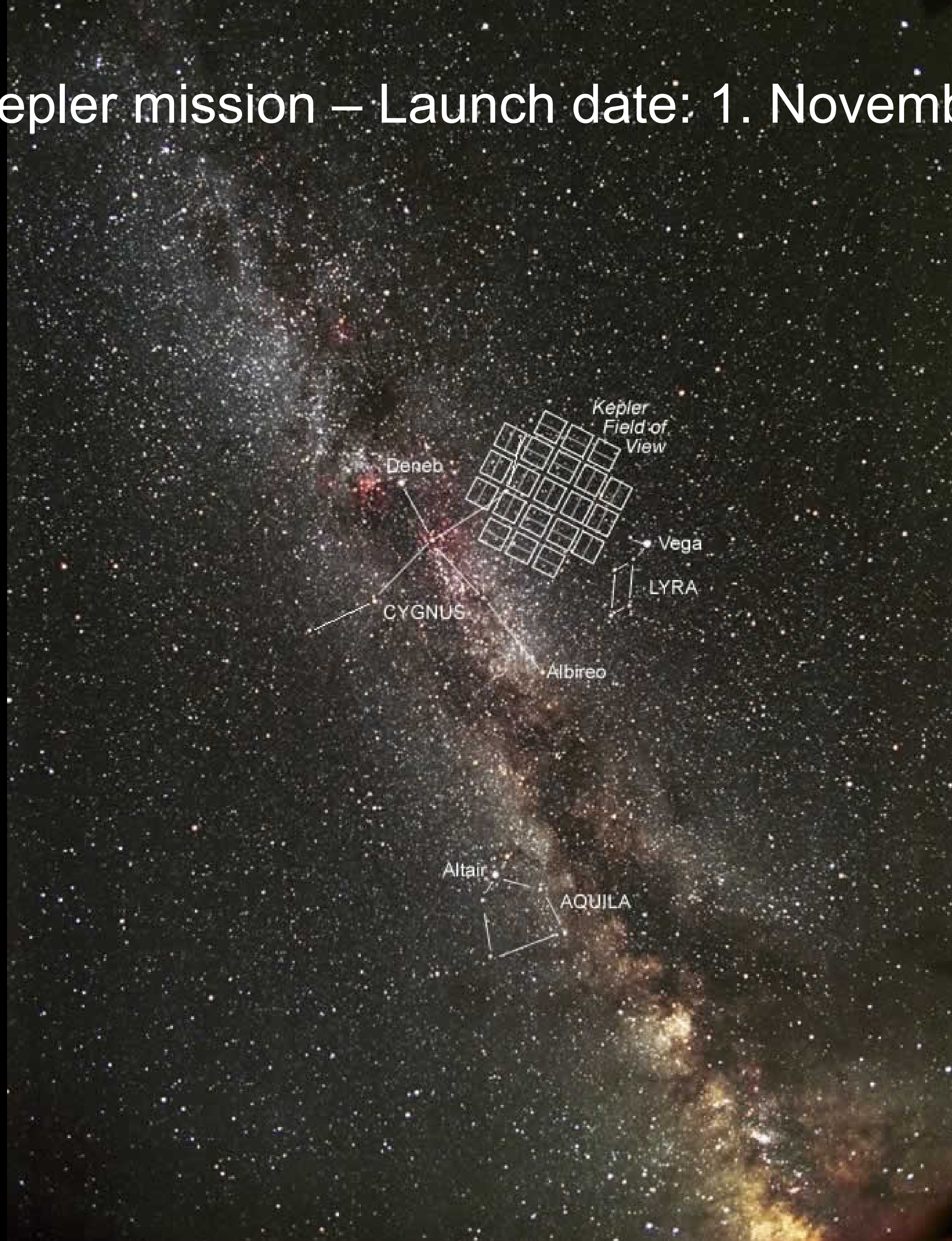
○: 0 △: 1 □: 2 ◇: 3
6000
5000
4000
3000
2000
Frequency (μHz)
0
50
100
150
Reduced frequency (μHz)

Beta Hydri – an evolved star:



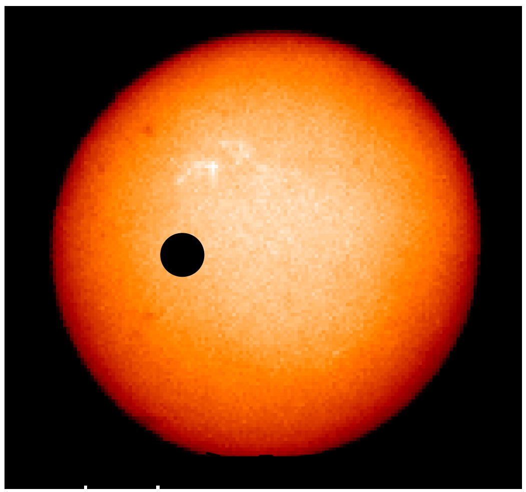
Predicted by theory before before seen in observations

NASA Kepler mission – Launch date: 1. November 2008

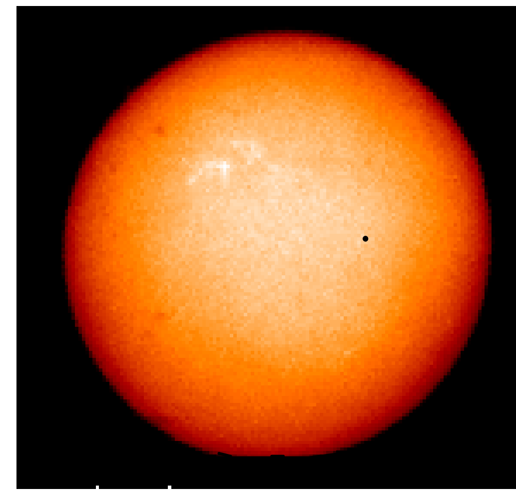


Using Photometry to Detect Earth-Size Planets

- The relative change in brightness (dL/L) is equal to the relative areas (A_{planet}/A_{star})



Jupiter:
1% area of the Sun (1/100)



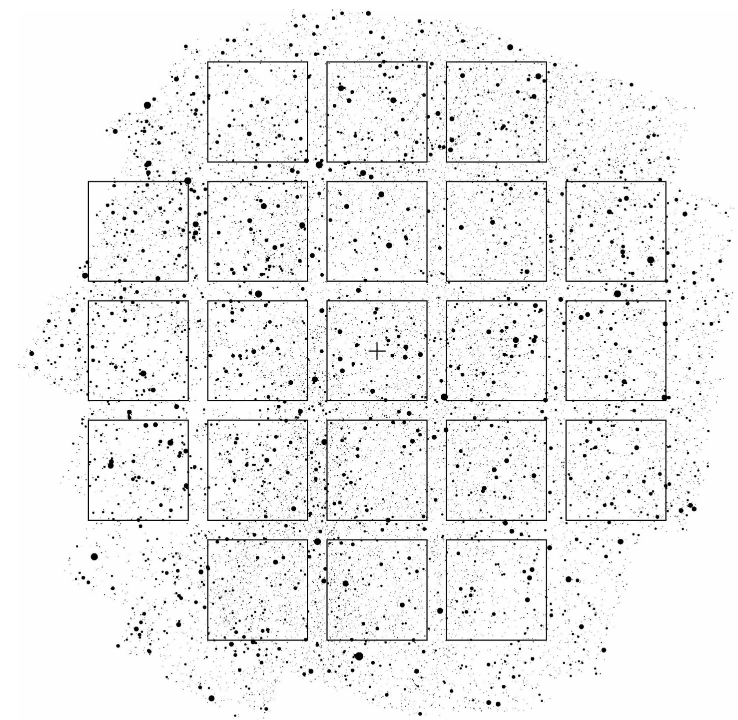
Earth or Venus
0.01% area of the Sun (1/10,000)

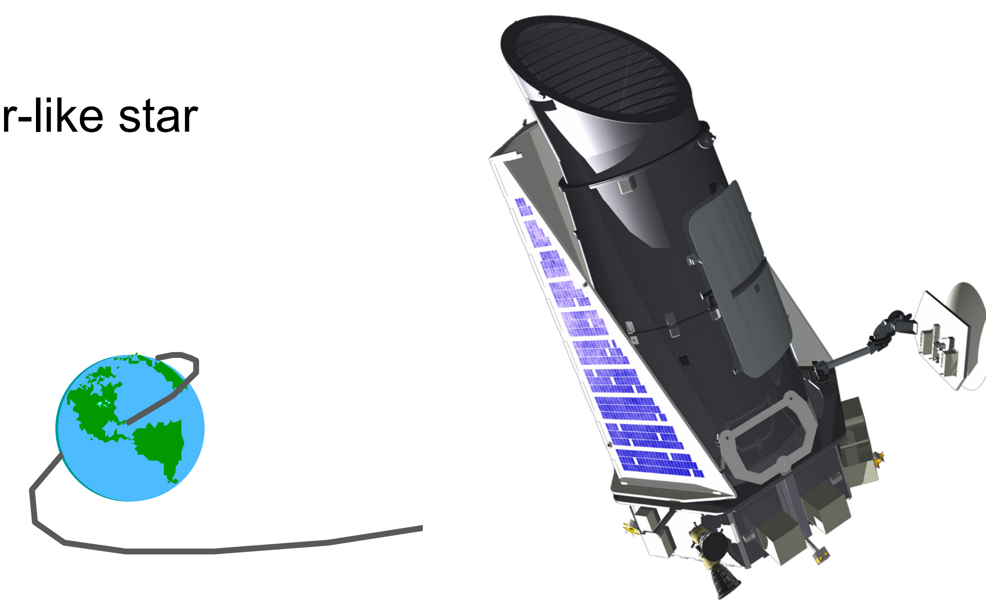
- To measure 0.01% must get above the Earth's atmosphere

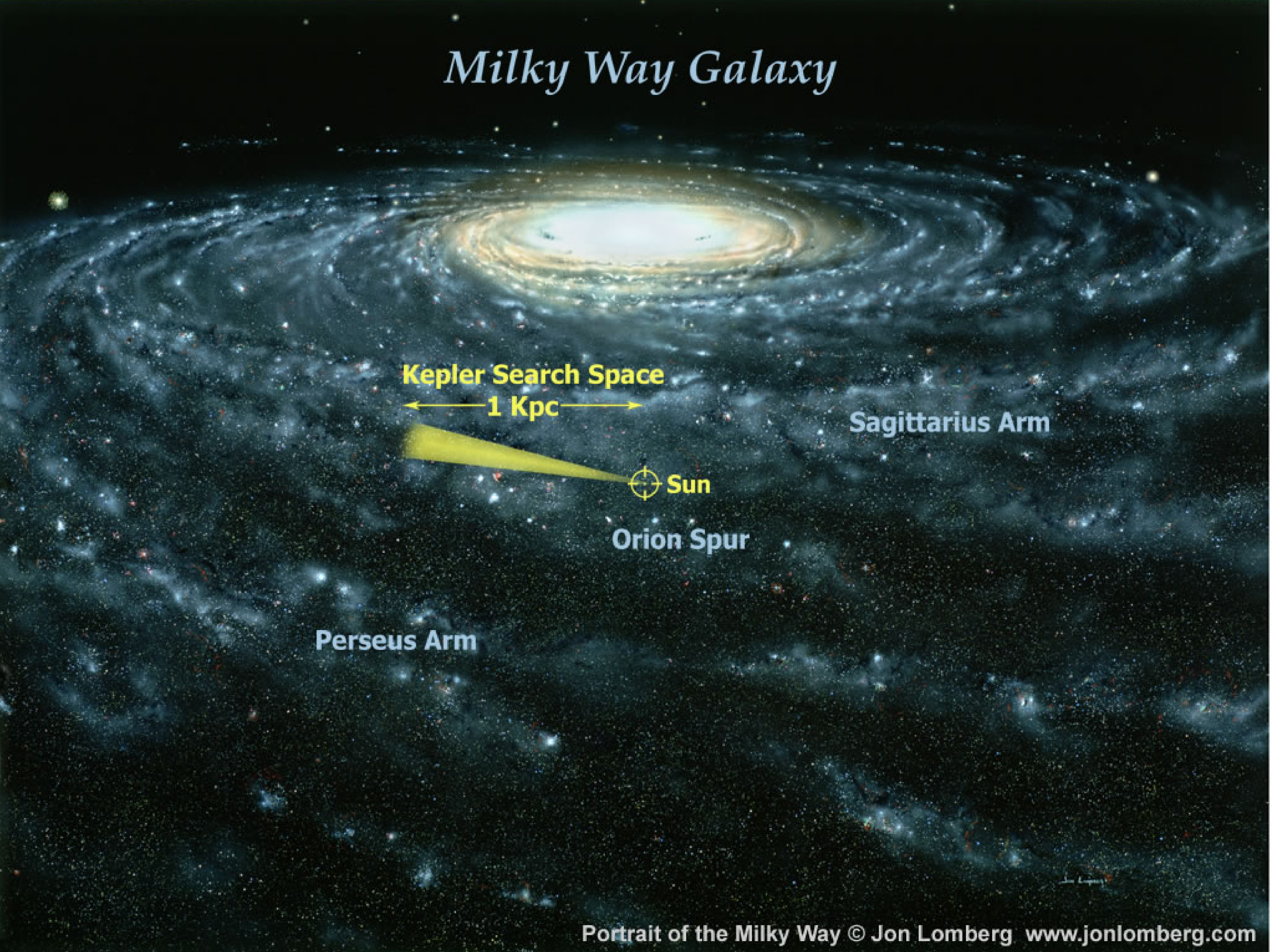
  Require at least 3 transits preferably 4 with same brightness change, duration and temporal separation

- *Kepler* is optimized for finding
  habitable planets (0.5 to 10 M_{Earth})
  in the HZ (near 1 AU) of solar-like stars

- Continuously and simultaneously
  monitor 170,000 main-sequence stars
- Use a one-meter telescope:
  FOV >100 deg^2 with an array of 42 CCD
- Photometric precision:
  Noise < 20 ppm in 6.5 hours V = 12 solar-like star
  => 4s detection for Earth-size transit
- Mission:
  Heliocentric orbit for continuous viewing
  $\geq$ 4 year duration

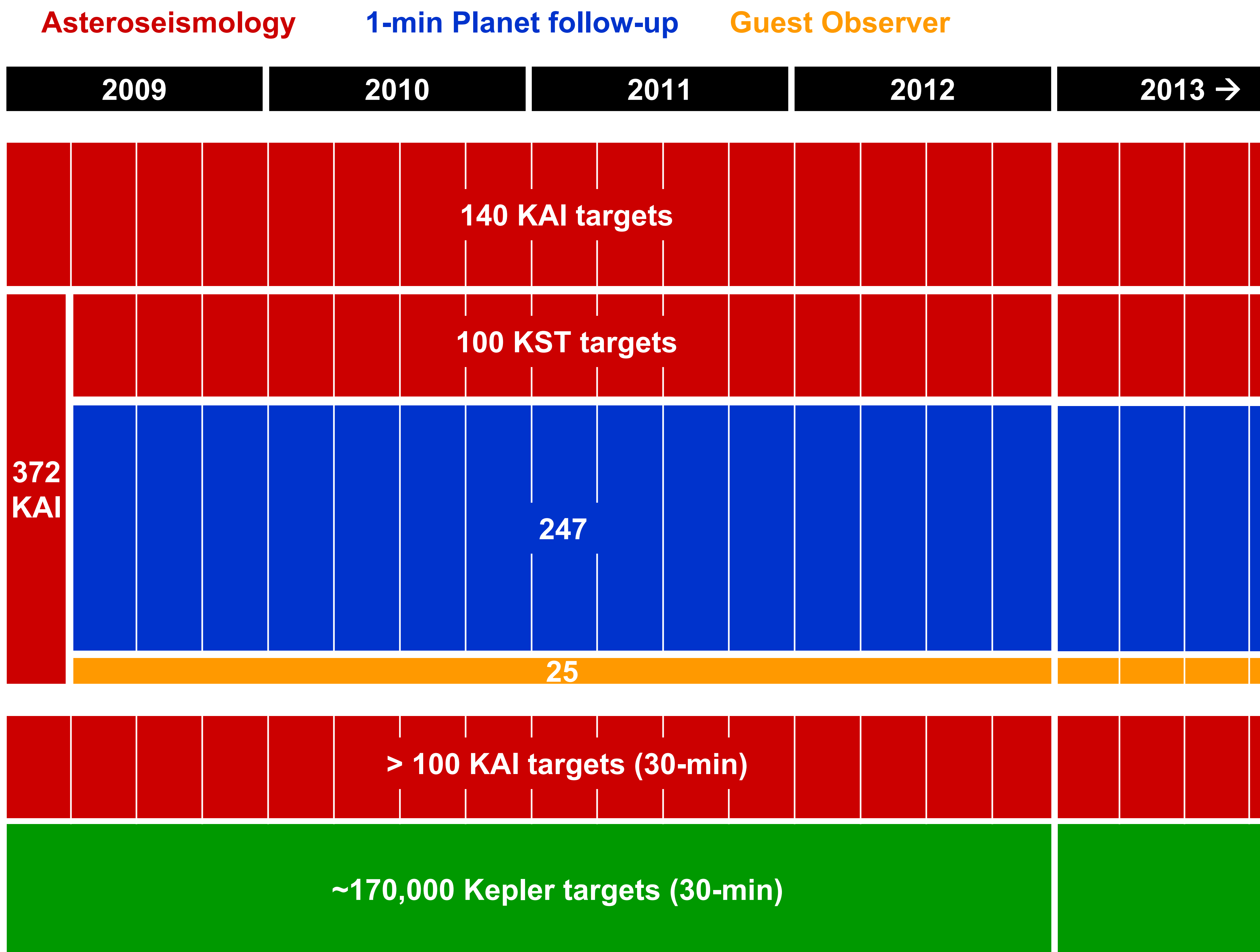





Milky Way Galaxy
Kepler Search Space
1 Kpc
Sagittarius Arm
Sun
Orion Spur
Perseus Arm
Portrait of the Milky Way © Jon Lomberg www.jonlomberg.com

Goals of Kepler asteroseismology

- 170000 stars at low cadence (30 min)
- 512 stars at high cadence (1 min)
- Data for Radii Programme (KAI / KASOC)



Asteroseismology
1-min Planet follow-up
Guest Observer
2009
2010
2011
2012
2013 →
140 KAI targets
372 KAI
100 KST targets
247
25
> 100 KAI targets (30-min)
~170,000 Kepler targets (30-min)