irfu
cea
saclay

Service d'Astrophysique
Laboratoire AIM

New insights on

The solar Core

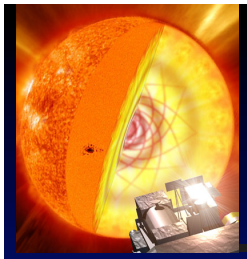
R.A. García

Laboratoire AIM, Service d'Astrophysique, CEA Saclay, France

In collaboration with:

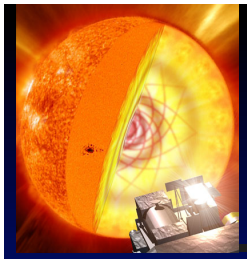
D. Salabert, J. Ballot, A. Eff-Darwich, R. Garrido, A. Jiménez, S. Mathis, S. Mathur, A. Moya, P.L. Pallé, C. Régulo, K. Sato, J.C. Suárez and S. Turck-Chièze

Good luck Spain!!!



Historical summary

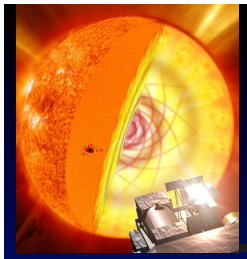
g-mode research



Looking for individual g modes

- **With helioseismology (early days…):**
  - Starting in early 80s (see reviews by Hill et al. 1991 & Pallé 1991)
    [Delache & Scherrer 1983; Frohlich & Delache 1984; Isaak et al. 1984; Pallé & Roca Cortés 1984…]

- **Since 1995: with SoHO and ground-based networks (BiSON & GONG)**
  - Only upper limits (1cm/s at 200 μHz) [Appourchaux et al. 2000; Gabriel et al. 2002]
  - Some patterns found in GOLF (Candidates > 90 to 98% conf. level)
    [Turck-Chièze et al. 2004; Mathur et al. 2007]
  - Peak at 220.7 Hz found in VIRGO and GOLF.
    - ✓ Stable during 13 years. Solar origin [Jiménez & García 2009]
  - Searching contemporaneous data (BiSON, GOLF, MDI; splitting = 400 nHz)
    - ✓ Frequentist approach (l=1, n=-4, m=1)
    - ✓ Bayesian approach (l=2, n=-2, m=2) [Broomhall et al. 2010]
  - Searching GOLF data after a new velocity calibration
    - ✓ Some new g-mode candidates [Poster by G. Grec]



Looking for global properties

- **Method: double Fourier analysis**
  - compute the oscillation power spectrum (PS1)

[García et al. 2007]

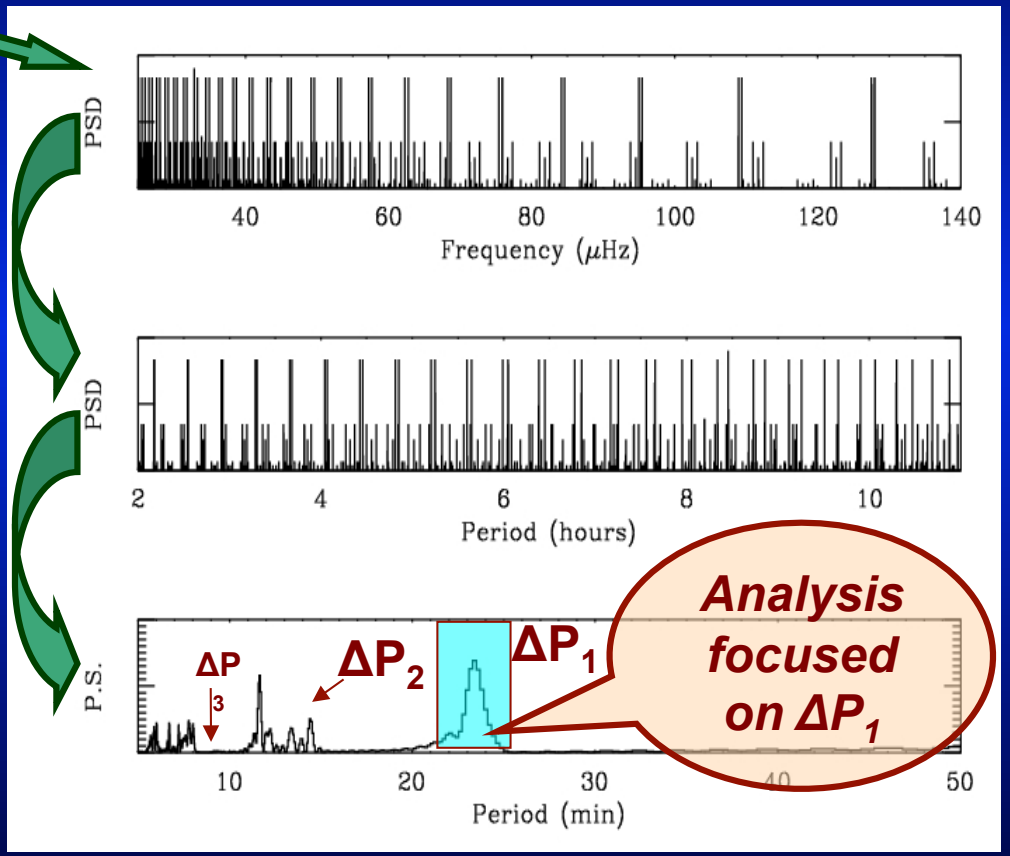
PS expressed in period

- Change the x-axis to periods

Lomb-Scargle periodogram

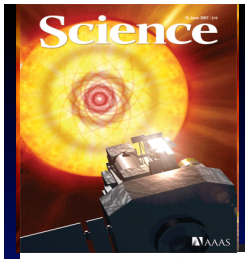
- 2nd spectrum (PS2) obtained

Modelled oscillation power spectrum including modes ℓ = 1, 2 & 3

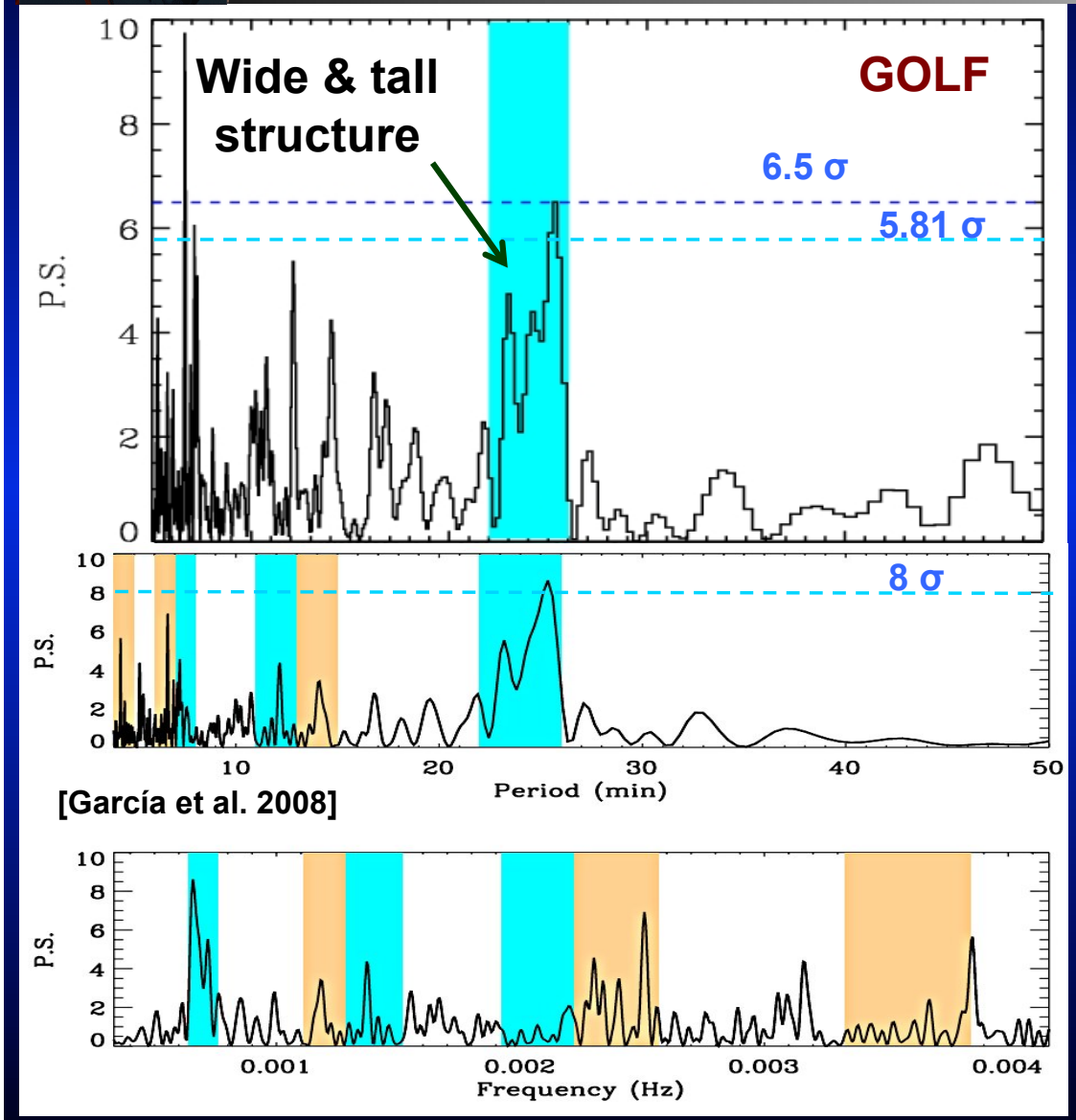


PS2: Method usually used in asteroseismology to look for the large spacing

[Barban et al. 2009; García et al. 2009; Mosser et al. 2009; Chaplin et al. 2010; Bedding et al. 2010…]



PS2 with GOLF

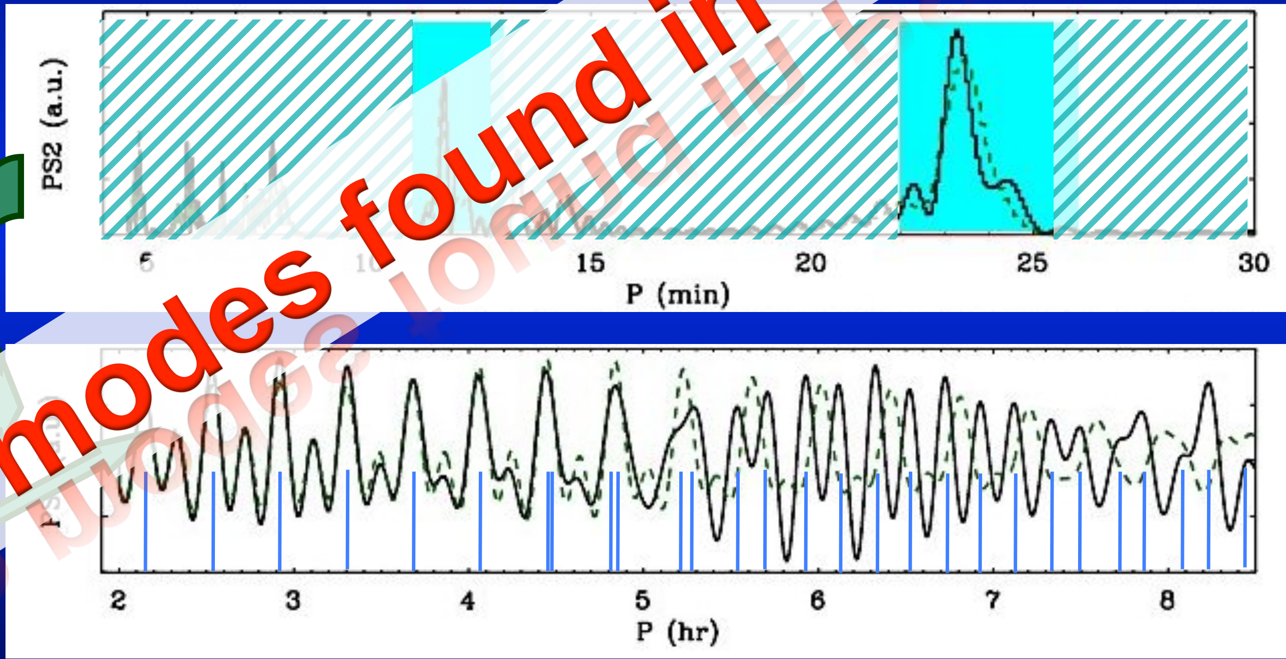


- **Possible fingertips of**
  - Asymptotic properties of =1 g modes [García et al. 2007]
- ***Confidence level***
  - ***99.5 %***
- **Increasing the length of the datasets**
  - **Higher SNR**

Reconstructing the signal

- PS2 = amplitude + <u>phase</u> ← using also this information
- Look for the positions of the maximum of the pattern in the PS1
  - Filter PS2 signal around ΔP_1 and its first harmonics
  - Perform an inverse Fourier transform ($\Sigma_i A_i \sin(2\pi/P_i+\varphi_i)$)

Inverse Fourier Transform

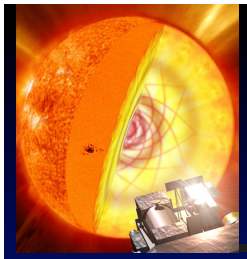


Positions of the pattern compatible with predicted g modes
(model-S, Saclay Seismic & Nice)

But no modes found in PS1

- From the correlation with models with different core rotation rates:
  - Between 3 to 5 Ω_{rad}

- *Confidence level*
  - *99.99 %*



Looking for individual g modes

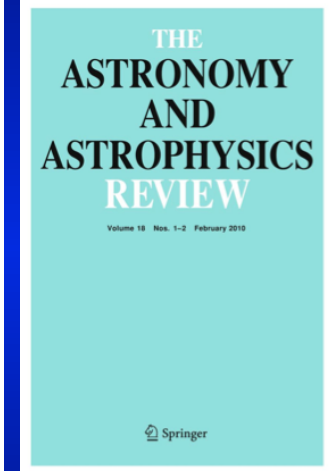
Astron Astrophys Rev
DOI 10.1007/s00159-009-0027-z

[Appourchaux et al. 2010]

REVIEW ARTICLE

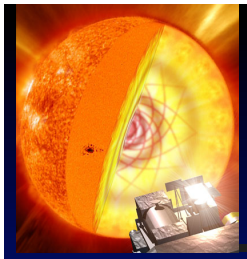
The quest for the solar g modes

T. Appourchaux · K. Belkacem · A.-M. Broomhall · W. J. Chaplin · D. O. Gough · G. Houdek · J. Provost · F. Baudin · P. Boumier · Y. Elsworth · R. A. García · B. N. Andersen · W. Finsterle · C. Fröhlich · A. Gabriel · G. Grec · A. Jiménez · A. Kosovichev · T. Sekii · T. Toutain · S. Turck-Chièze



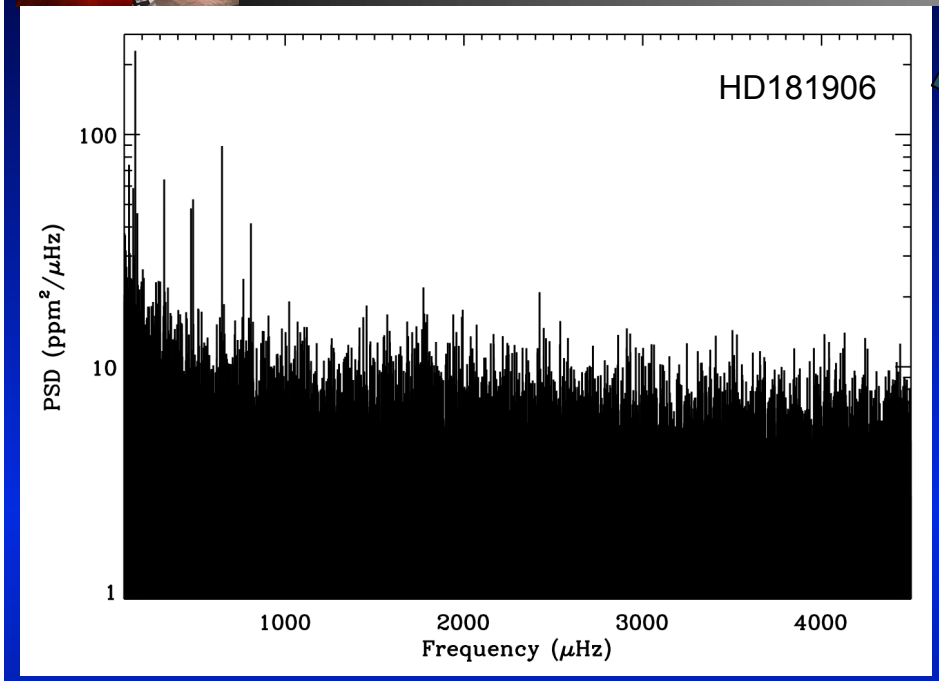
6 Discussion and conclusion

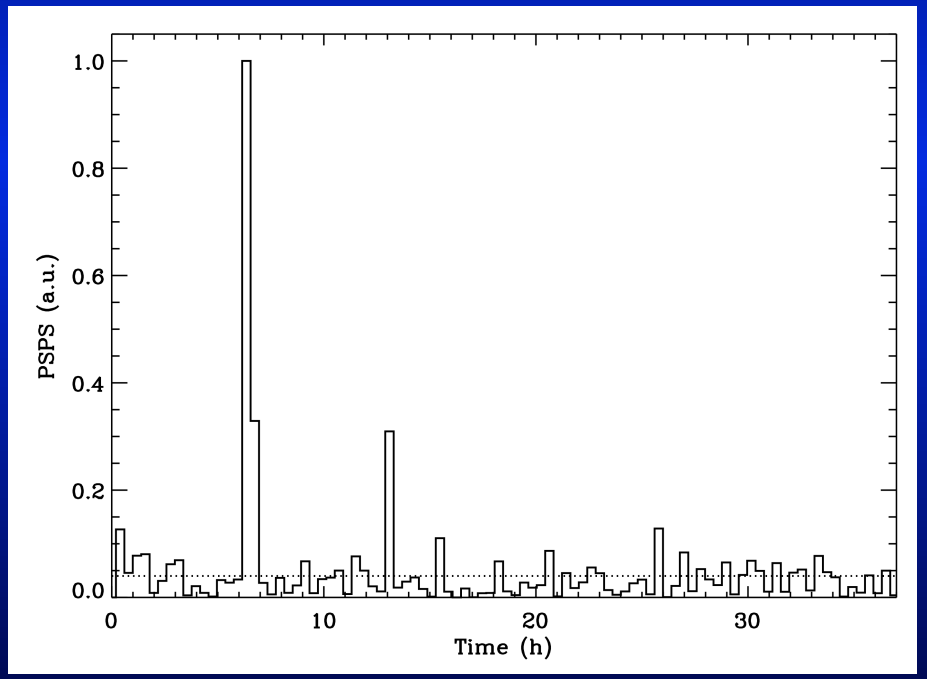
Figure 15 shows the comparison of the best observational measurements with theoretical amplitudes of the g modes. The theoretical g-mode amplitudes range from 10^{-2} mm s^{-1} to a few mm s^{-1}. The most optimistic theoretical mode amplitudes could be collectively detectable, after the collection of more than 10 years of observations of the solar radial velocity. Unfortunately, the detection of individual peaks is very far from being feasible since the only possibility would be to have the most optimistic amplitude larger by 50%, or twice as much in power (Belkacem et al. 2009). Since the noise reduction scales with the observing time T like $\log(T)/\sqrt{T}$, another 80 years or so of data would be required to reduce the actual detection limit by a factor two. The limit does not scale like $1/\sqrt{T}$ because the probability limit is kept constant in a given detection window, while the number of frequency bins in that window increases like T (Appourchaux 1998). At the time of writing, there is indeed a consensus amongst the authors of this review that *there is currently no undisputed detection of solar g modes.*



Can we see the peaks in the PSD that are responsible for ΔP_1?

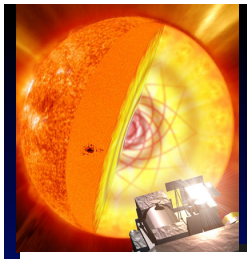
Lessons from Asteroseismology



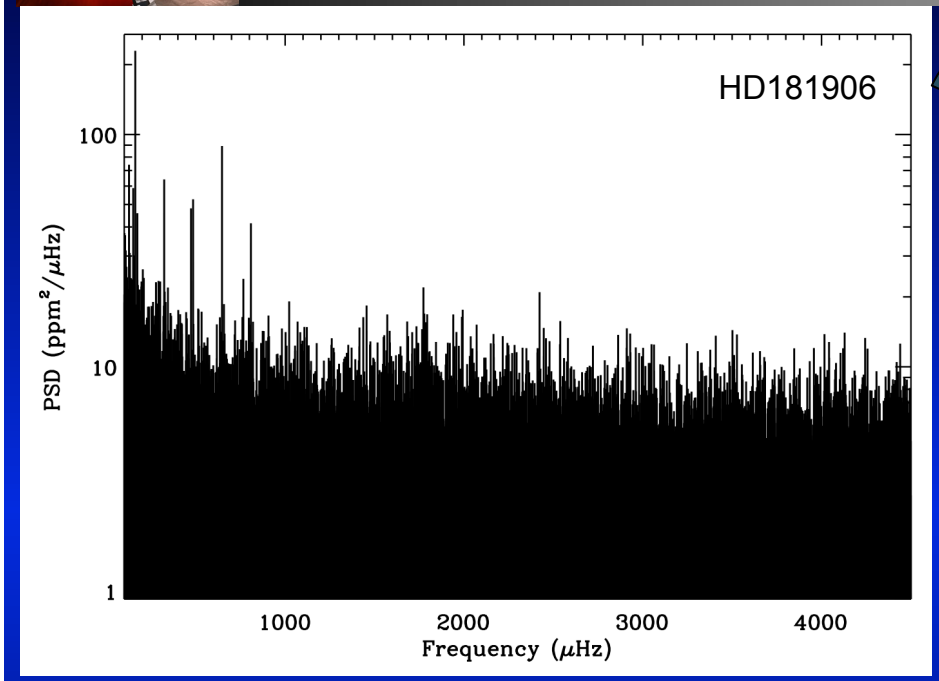


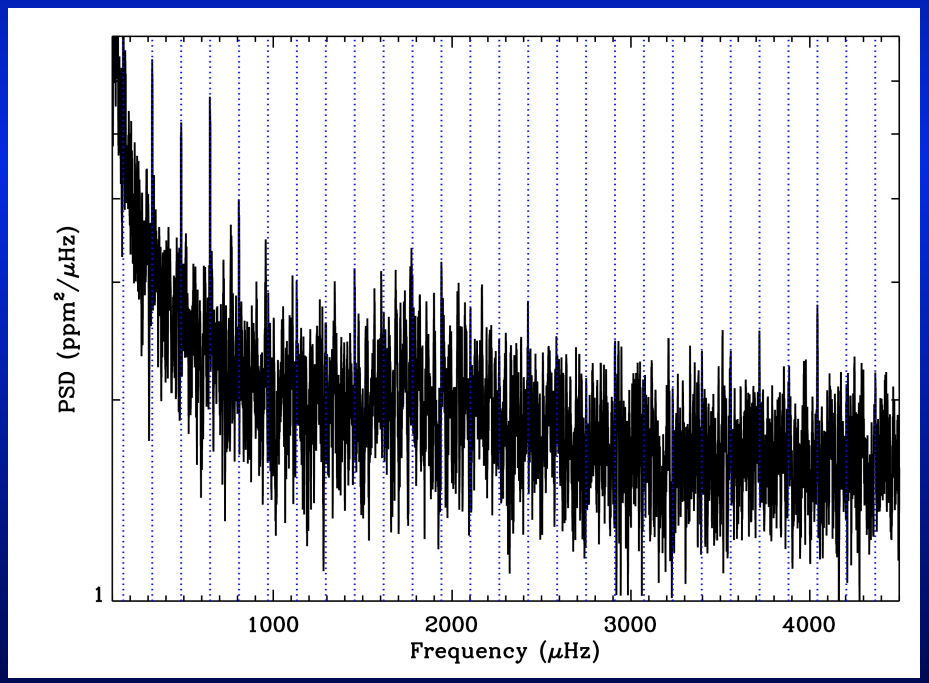
- **IF SNR is small**
  - Difficult to identify any p-mode hump
- **PSPS or autocorrelation**
  - Large separation

[García et al. 2009]



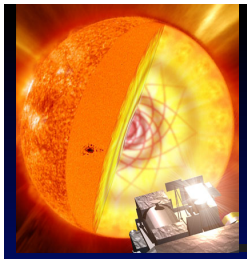
Lessons from Asteroseismology



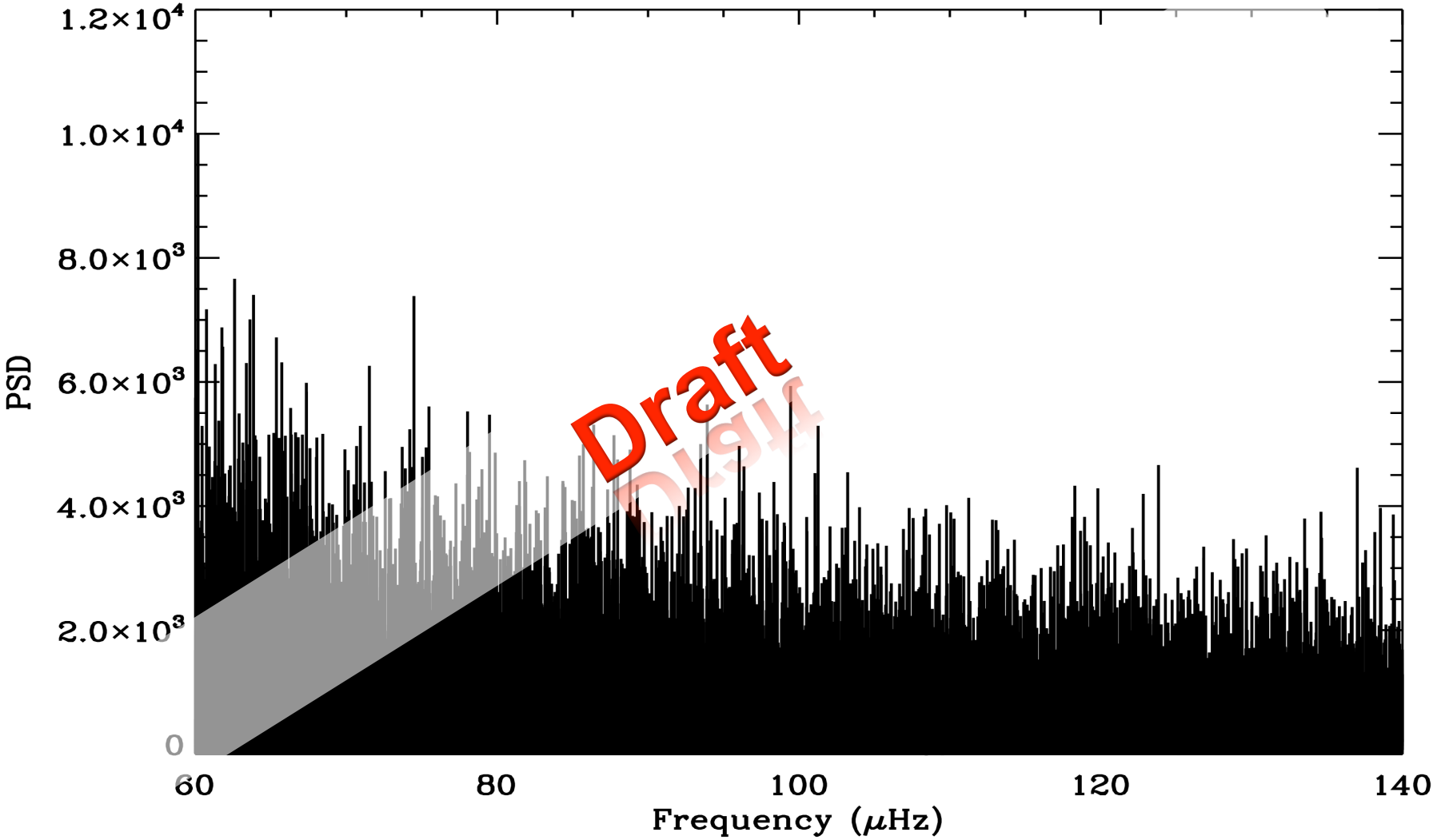


- **IF SNR is small**
  - Difficult to identify any p-mode hump
- **PSPS or autocorrelation**
  - Large separation
- **To help visualizing p-mode hump**
  - PSD is smoothed

[García et al. 2009]



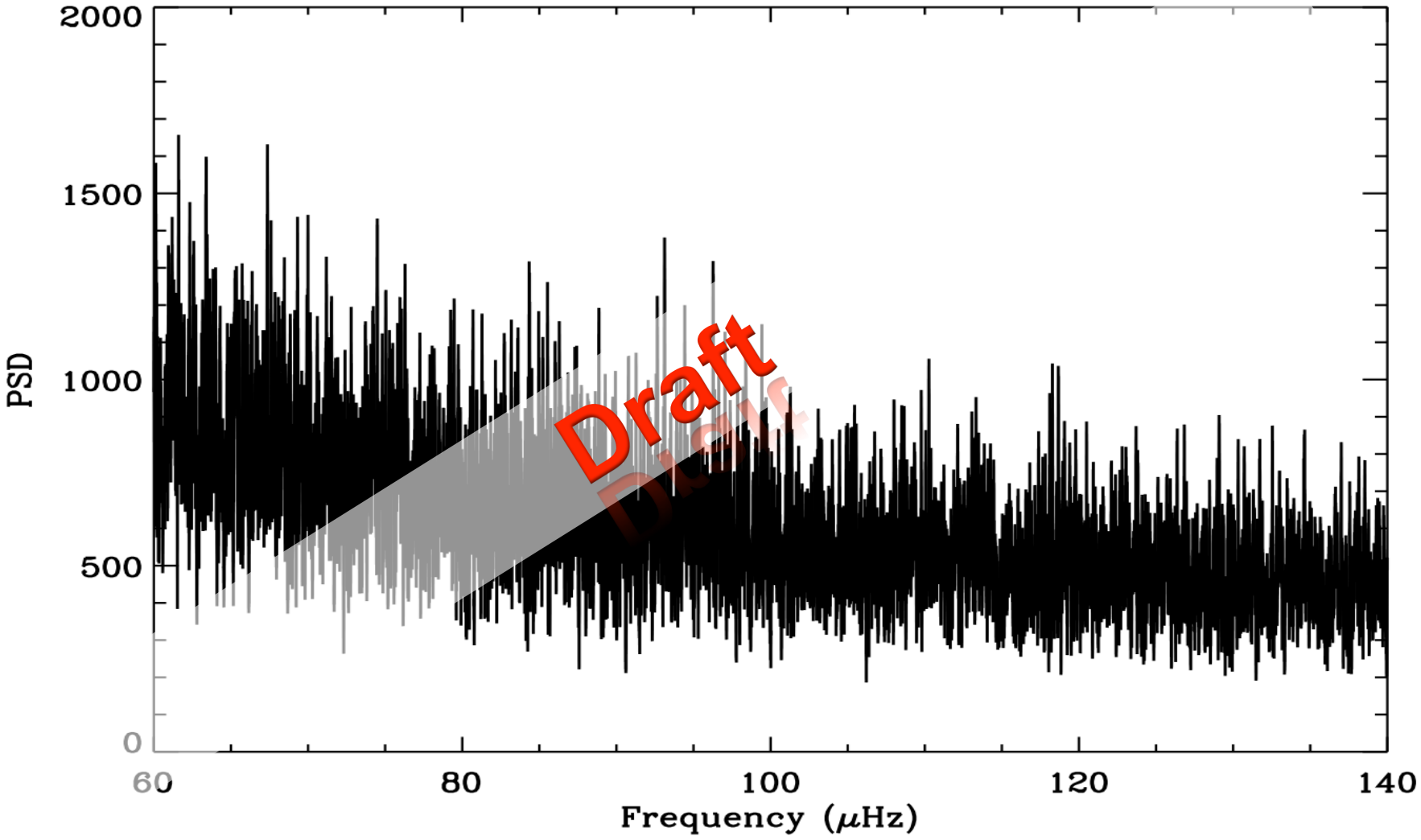
A step forward in individual g-mode search



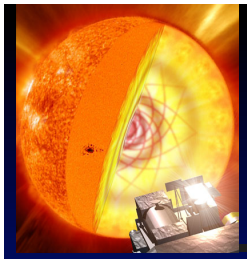
4472 days GOLF velocity data.

Verified also using 5163 days (up to 30/5/2010)

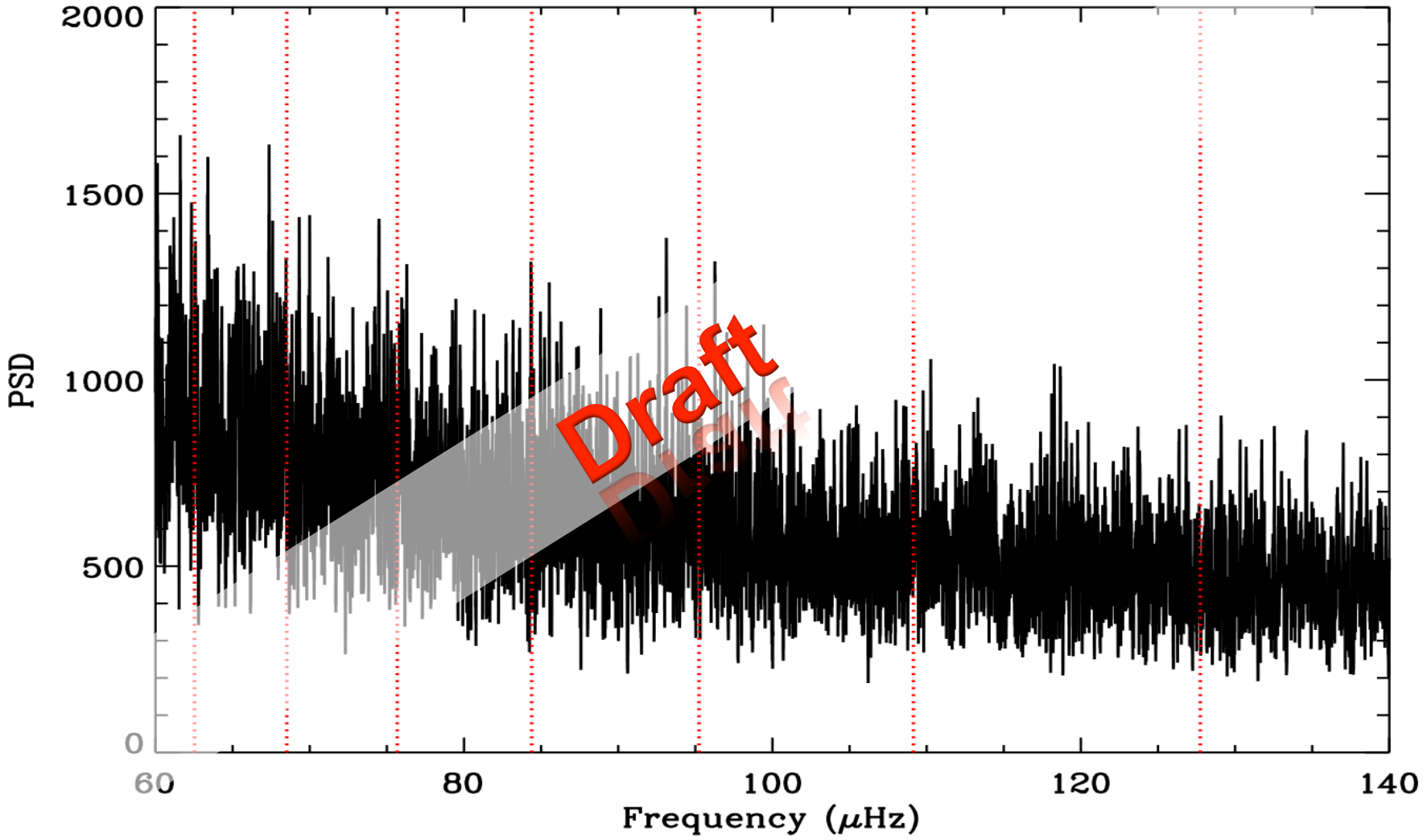
A step forward in individual g-mode search



4472 days GOLF velocity data. Smoothed by a 16 points boxcar

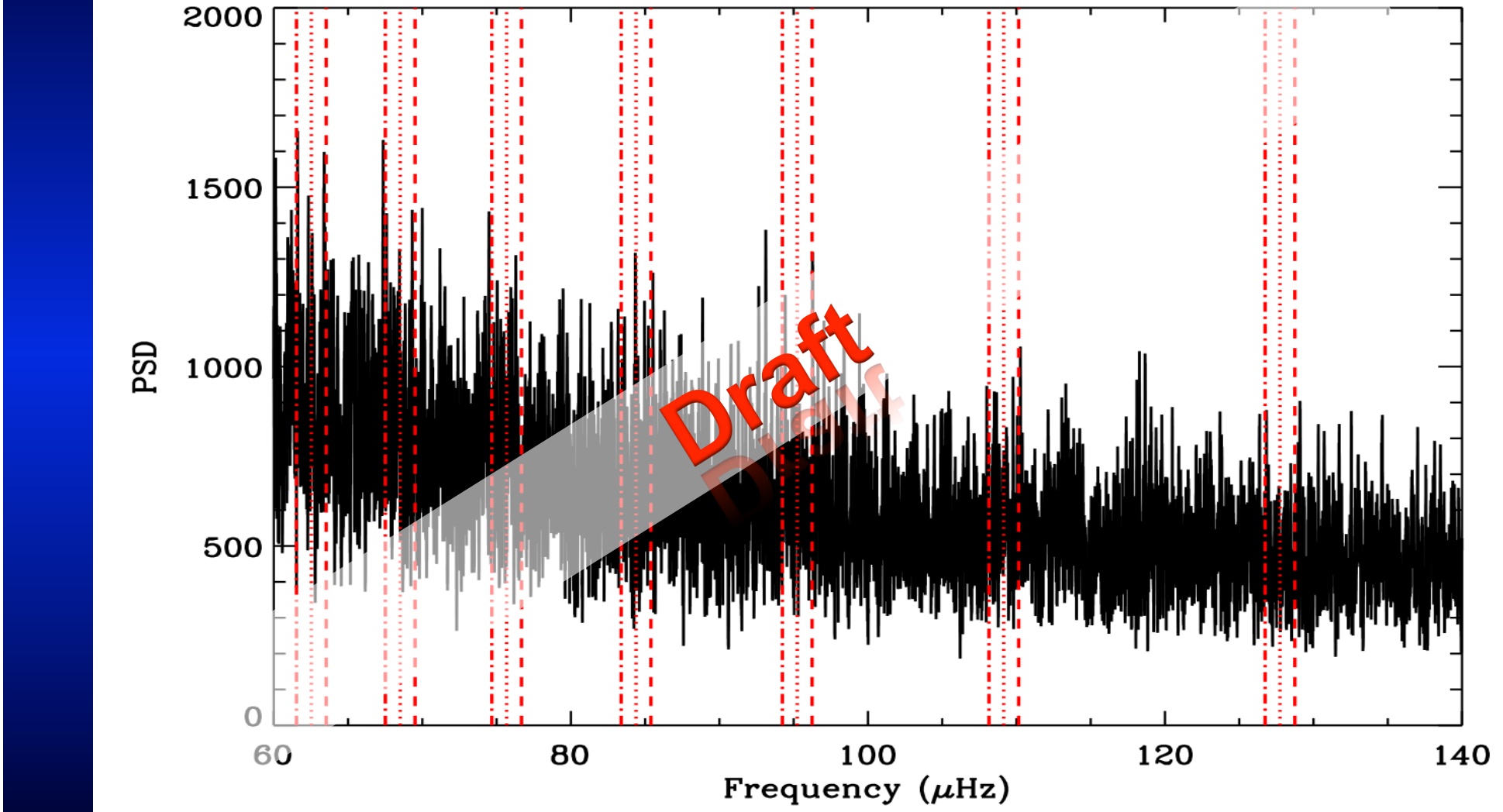


A step forward in individual g-mode search



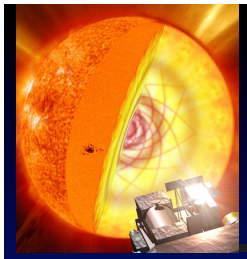
Theoretical Frequencies: Model S or Seismic (difference < 0.05 μHz)

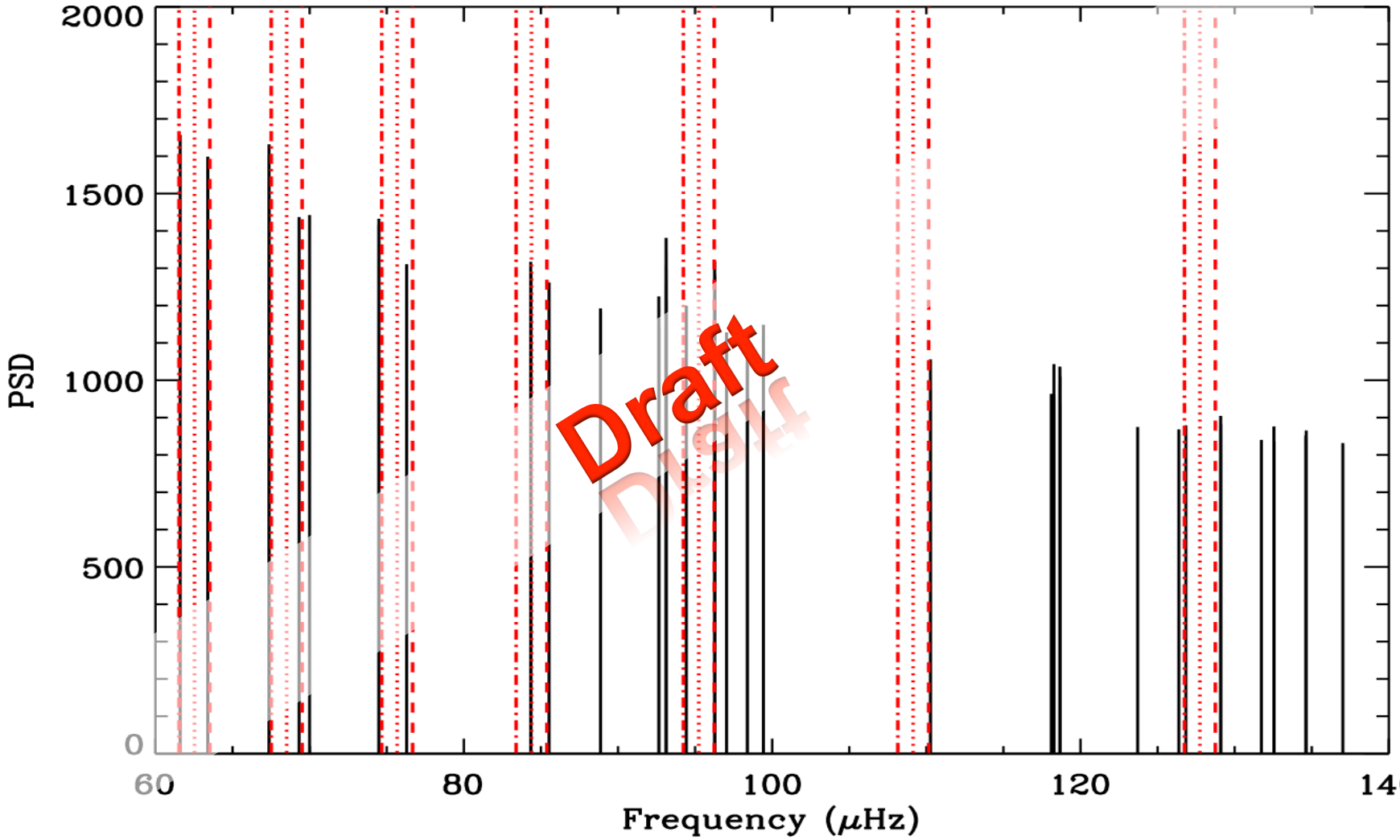
A step forward in individual g-mode search

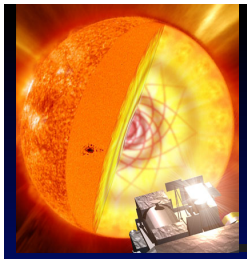


Splitting : 4.5 x Ω_{rad}

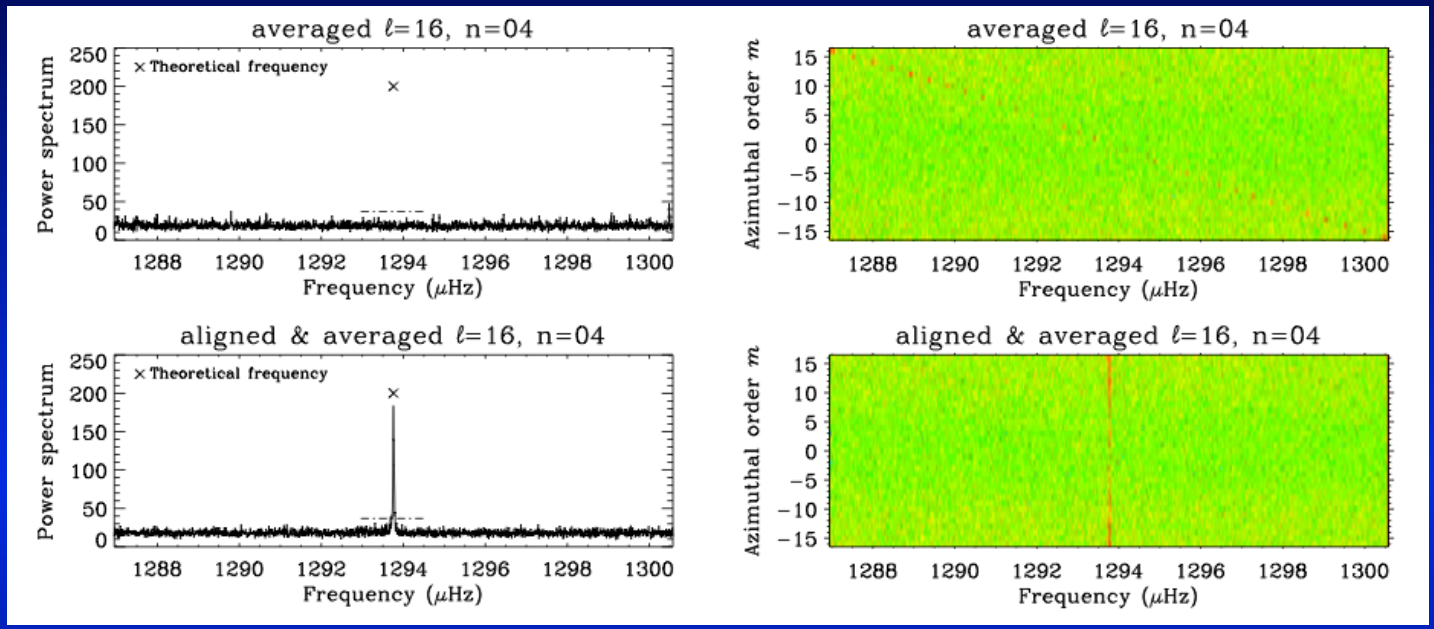
A step forward in individual g-mode search







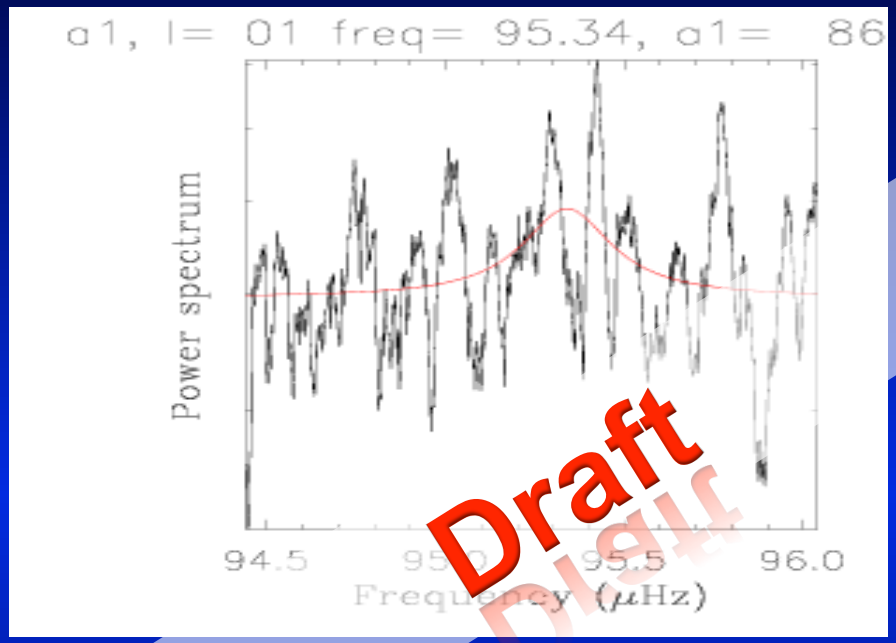
Collapsogram: generalities



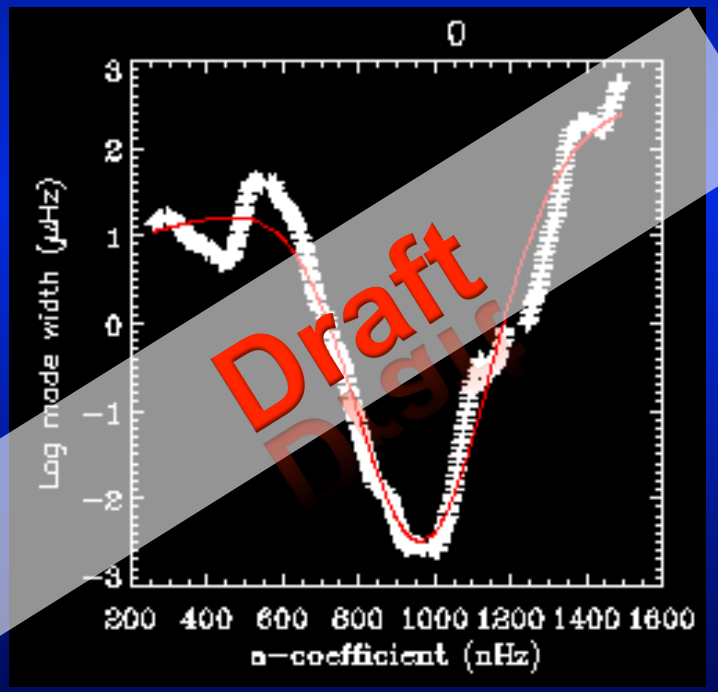
- m-collapsogram originally developed for imaged instruments.
- Consist of shifting each m-component by a quantity proportional to the splitting and adding all.
- Each time a Lorentzian profile is fitted.
- The one with the minimum linewidth or maximum likelihood gives the splitting

[Salabert, Leibacher, Appourchaux & Hill, 2008]

Collapsograms: l=1, n=-6

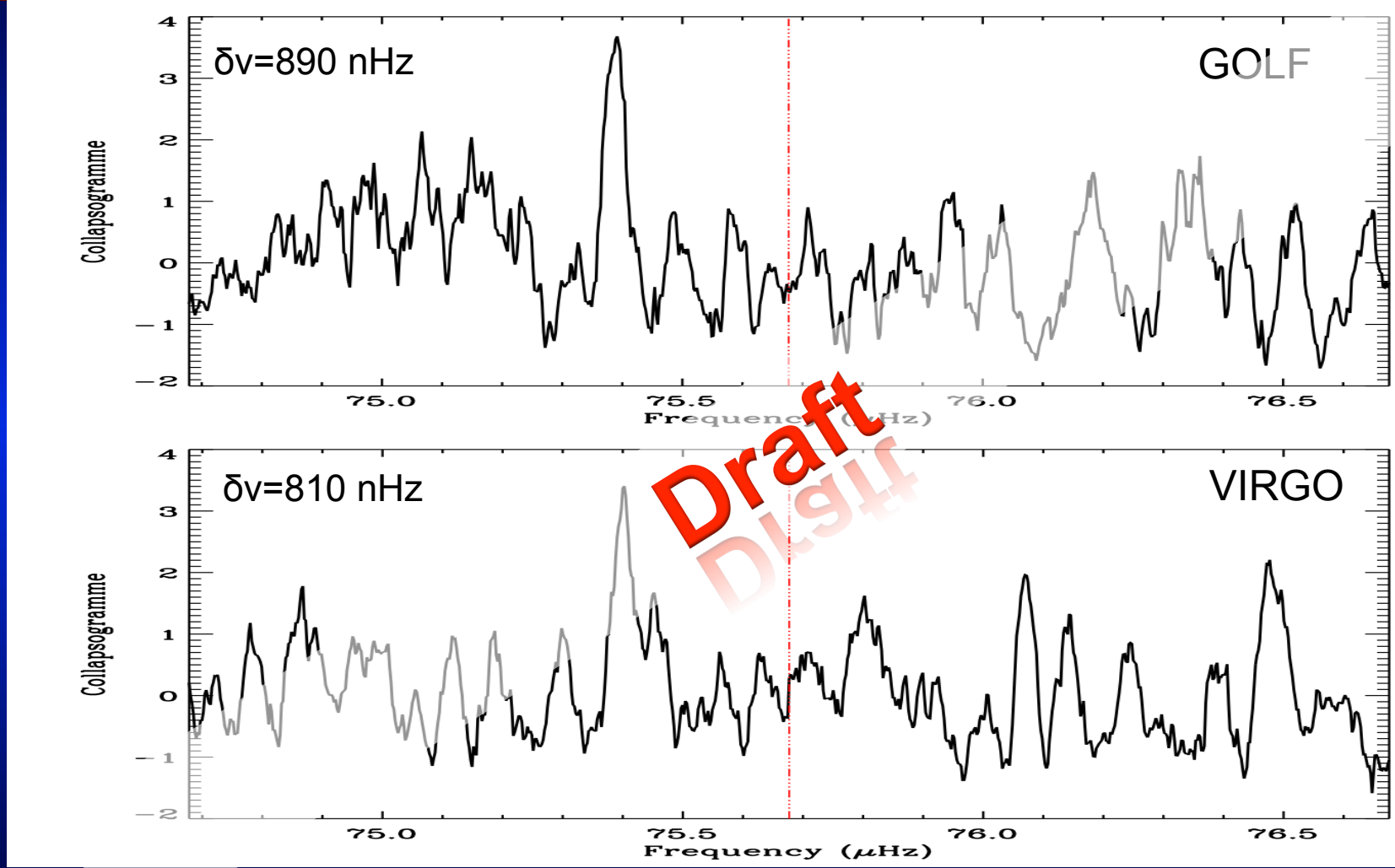


Line width of the fitted peak in the collapsogram

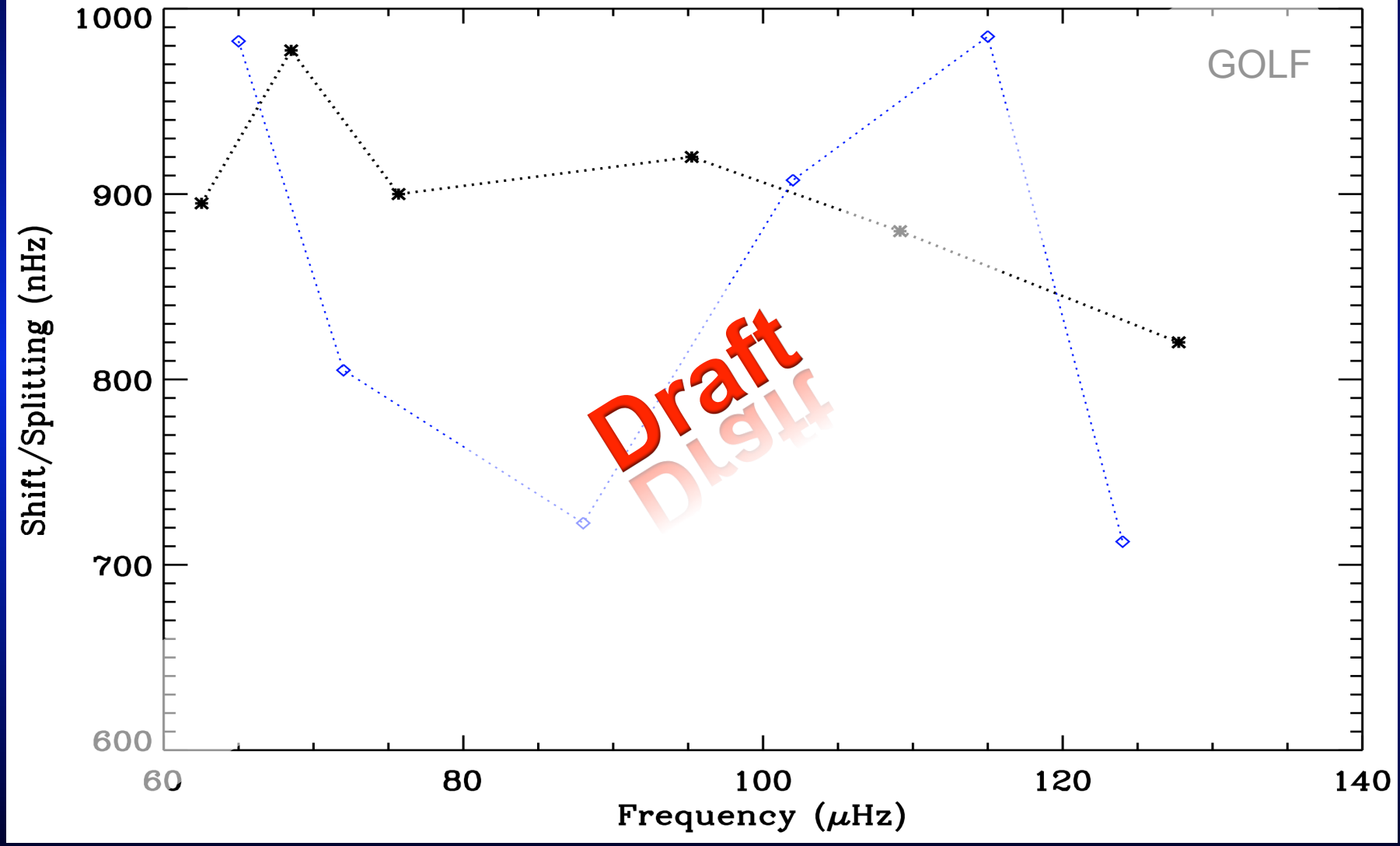


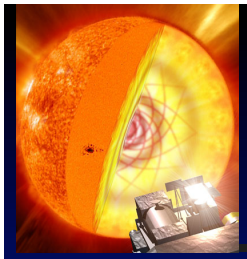
- We duplicate the PSD, we shift one of them we add both and we fit a Lorentzian
- Window: ±1 μHz
- Splittings between 0.5 and 7 times Ω_{rad}
- Retained peak:
  - Fitting with small line-width
  - Splitting obtained from the shift

Collapsograms

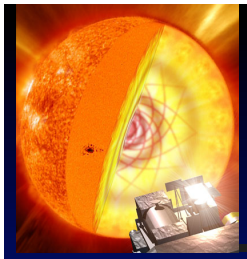


Collapsograms

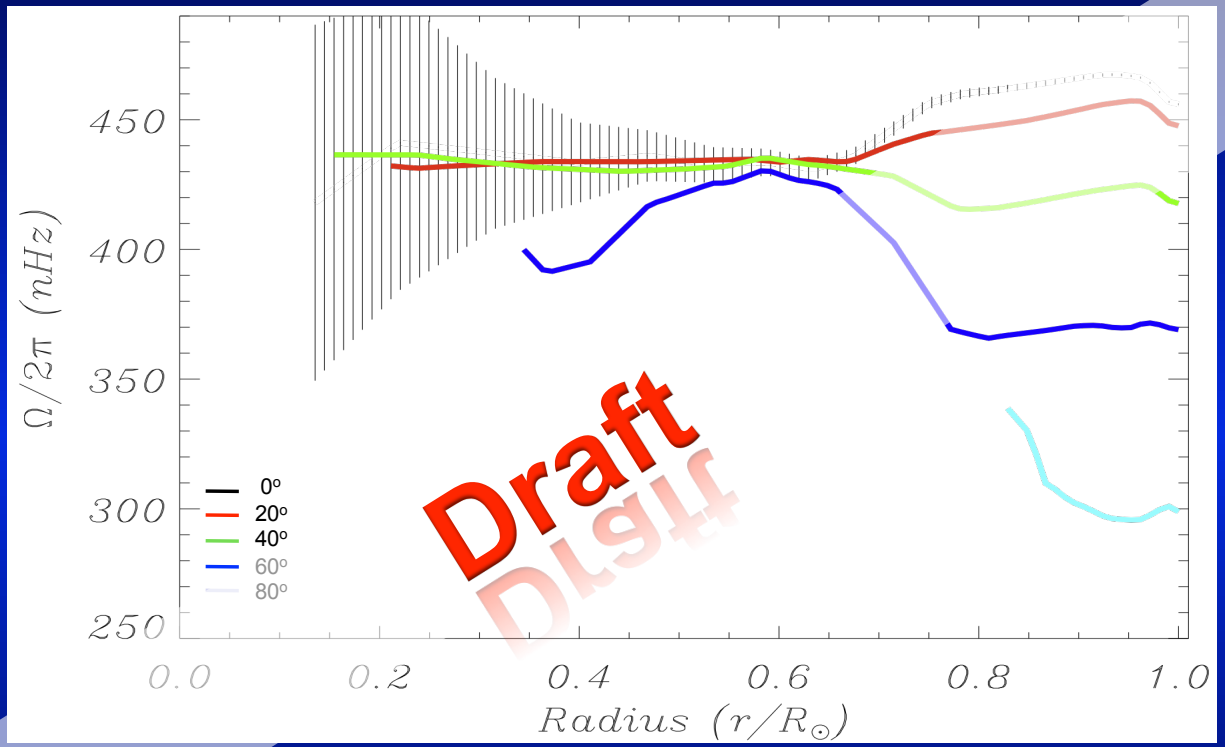




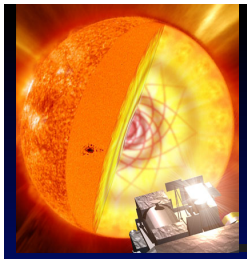
Dynamics of the solar core



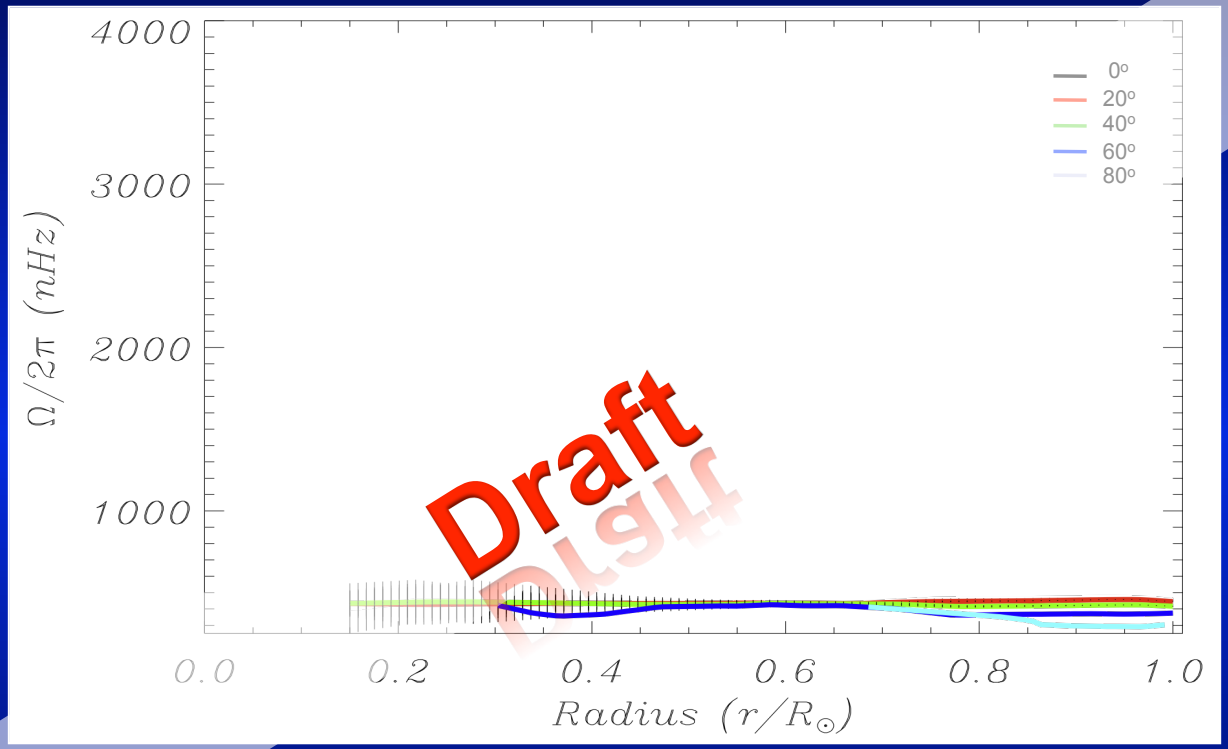
Inversion of rotation



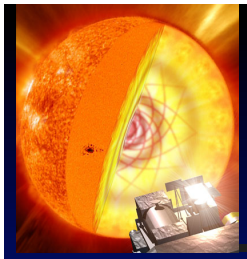
- **Inversion using:**
  - **Modified RLS** [Eff-Darwich et al., 2008]
- **Data:**
  - **GOLF (ℓ ≤ 2)** [García et al. Poster Low-3]
  - **MDI (ℓ ≥ 3)**
  - **4608 days** [Eff-Darwich & Korzennik Poster; Korzennik, Talk]



Inversion of rotation

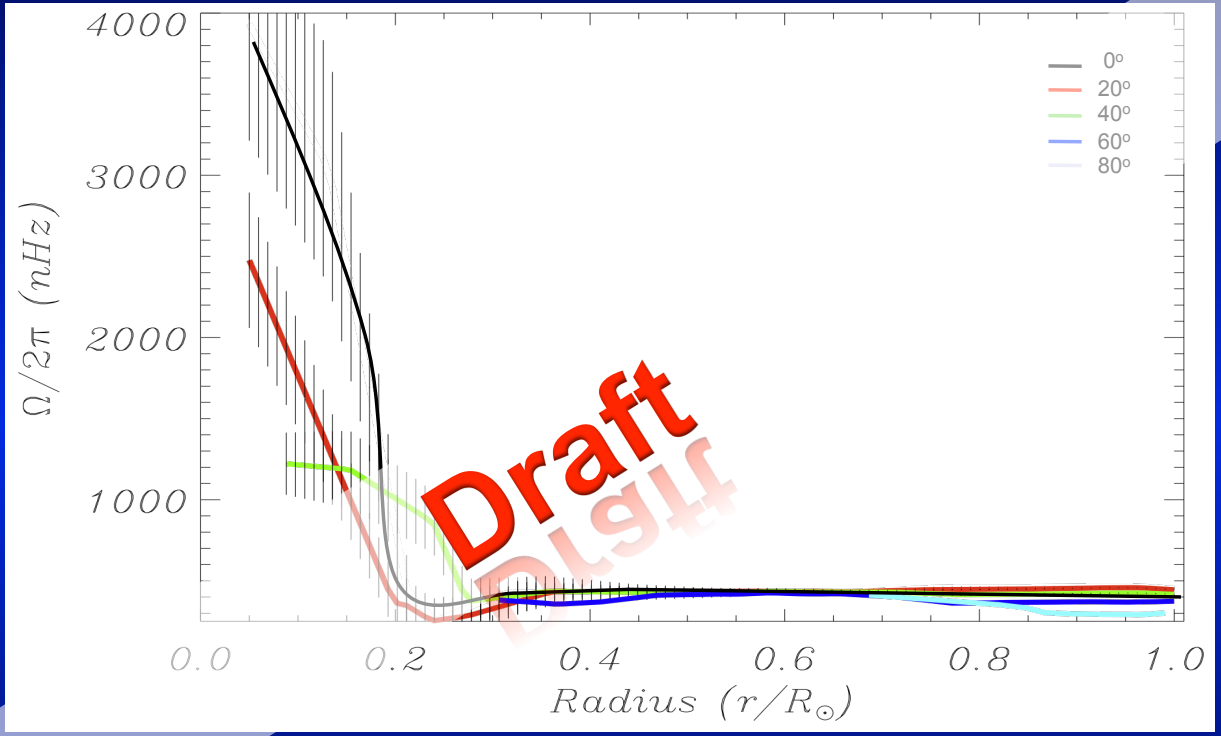


- **Inversion using:**
  - **Modified RLS** [Eff-Darwich et al., 2008]
- **Data:**
  - **GOLF ($\ell \leq 2$)** [García et al. Poster Low-3]
  - **MDI ($\ell \geq 3$)**
  - **4608 days** [Eff-Darwich & Korzennik Poster; Korzennik, Talk]

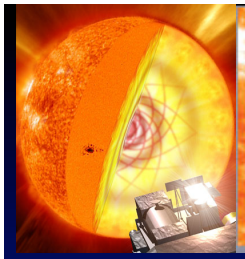


Inversion of rotation

Adding 5 g modes l=1 (n=-4, -6, -8, -9 , -10)



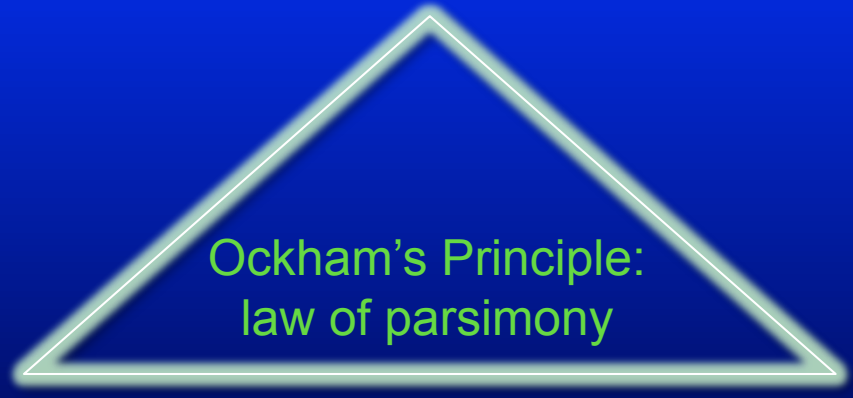
- **Inversion using:**
  - **Modified RLS** [Eff-Darwich et al., 2008]
- **Data:**
  - **GOLF ($\ell \leq 2$)** [García et al. Poster Low-3]
  - **MDI ($\ell \geq 3$)**
  - **4608 days** [Eff-Darwich & Korzennik Poster; Korzennik, Talk]



CONCLUSIONS

- **Using common asteroseismic methodologies**
- **We have identified, for the first time, individual l=1 g modes:**
  - **Equidistant in Period (99.99 % confidence level)**
  - **Split in frequency ~900 nHz**
  - **Nearby l=1 predicted frequencies (model S, Saclay Seismic, Nice)**

g modes



Pure noise

Convection

William Ockham: "entities should not be multiplied unnecessarily".
Isaac Newton: "We are to admit no more **causes** of natural things than such as are both true and sufficient to explain their appearances."