Sismologie solaire & stellaire

Résultats et perspectives

F. Baudin

Plus précisément

- petit historique

- moyens d'observation et d'analyse

- résultats solaires puis stellaires:

- en vrac (observation/théorie, rotation, champ magnétique...)

- la saga des modes g solaires

- l'épopée des géantes rouges

- perspectives

VELOCITY FIELDS IN THE SOLAR ATMOSPHERE
I. PRELIMINARY REPORT*

ROBERT B. LEIGHTON, ROBERT W. NOYES, AND GEORGE W. SIMON
California Institute of Technology, Pasadena, California
Received October 16, 1961

ABSTRACT

Velocity fields in the solar atmosphere have been detected and measured by an adaptation of a technique previously used for measuring magnetic fields. Data obtained during the summers of 1960 and 1961 have been partially analyzed and yield the following principal results:

1. Large "cells" of horizontally moving material are distributed roughly uniformly over the entire solar surface. The motions within each cell suggest a (horizontal) outward flow from a source inside the cell. Typical diameters are 1.6×10^4 km; spacings between centers, 3×10^4 km ($\sim 5 \times 10^3$ cells over the solar surface); r.m.s. velocities of outflow, 0.5 km sec^{-1}; lifetimes, 10^4–10^5 sec. There is a similarity in appearance to the Ca^+ network. The appearance and properties of these cells suggest that they are a surface manifestation of a "supergranulation" pattern of convective currents which come from relatively great depths inside the sun.

2. A distinct correlation is observed between local brightness fluctuations and vertical velocities: bright elements tend to move upward, at the levels at which the lines Fe λ 6102 and Ca λ 6103 are formed. In the line Ca λ 6103, the correlation coefficient is ~0.5. This correlation appears to reverse in sign in the height range spanned by the Doppler wings of the Na D_1 line and remains reversed at levels up to that of Ca^+ λ 8542. At the level of Ca λ 6103, an estimate of the mechanical energy transport yields the rather large value 2 W cm^{-2}.

3. The characteristic "cell size" of the vertical velocities appears to increase with height from ~1700 km at the level of Fe λ 6102 to ~3500 km at that of Na λ 5896. The r.m.s. vertical velocity of ~0.4 km sec^{-1} appears nearly constant over this height range.

4. The vertical velocities exhibit a striking repetitive time correlation, with a period $T = 296 \pm 3$ sec. This quasi-sinusoidal motion has been followed for three full periods in the line Ca λ 6103, and is also clearly present in Fe λ 6102, Na λ 5896, and other lines. The energy contained in this oscillatory motion is about 160 J cm^{-2}; the "losses" can apparently be compensated for by the energy transport (2).

5. A similar repetitive time correlation, with nearly the same period, seems to be present in the *brightness fluctuations* observed on ordinary spectroheliograms taken at the center of the Na D_1 line. We believe that we are observing the transformation of potential energy into wave energy through the brightness-velocity correlation in the photosphere, the upward propagation of this energy by waves of rather well-defined frequency, and its dissipation into heat in the lower chromosphere.

6. Doppler velocities have been observed at various heights in the upper chromosphere by means of the Hα line. At great heights one finds a granular structure with a mean size of about 3600 km, but at lower levels one finds predominantly *downward* motions, which are concentrated in "tunnels" which presumably follow magnetic lines of force and are geometrically related to the Ca^+ network. The Doppler field changes its appearance *very rapidly* at higher levels, typical lifetimes being about 30 *seconds*.

In an earlier paper, Leighton (1959) described a method for obtaining "spectroheliograms" whose density variation indicated the presence of Zeeman splitting due to longitudinal magnetic fields on the sun rather than actual light-intensity variations. This method is readily applicable to measurements of Doppler shifts as well as Zeeman splitting, giving a "spectroheliogram" of the line-of-sight velocity field in the region of line formation. The present paper describes some of the velocity observations made in this way during the summers of 1960 and 1961. Some of the results have been reported by Leighton (1960, 1961).

I. OBSERVATIONAL TECHNIQUES

The specific details of the method were described in the above-mentioned paper, so we shall give here only a brief description of how it has been adapted to the measurement of Doppler shifts.

* Supported in part by the joint program of the Office of Naval Research and the U.S. Atomic Energy Commission.

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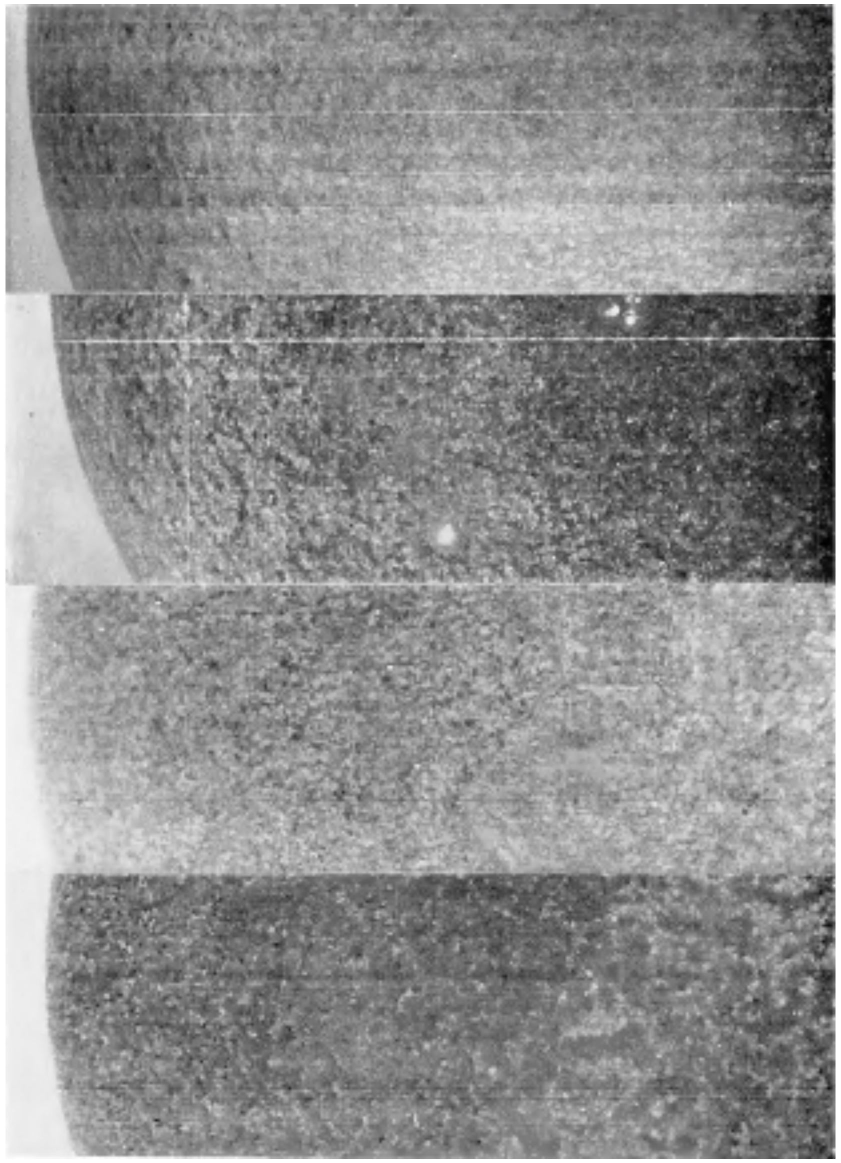
Un peu d'histoire (le cas solaire)



Leighton, Noyes & Simon 1962

Un peu d'histoire
(le cas solaire)

OBSERVATIONAL STUDY OF MACROSCOPIC INHOMOGENEITIES IN THE SOLAR ATMOSPHERE

III. VERTICAL OSCILLATORY MOTIONS IN THE SOLAR PHOTOSPHERE

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Received Janury 20, 1962; revised March 19, 1962

ABSTRACT

We have studied the Doppler displacements in two time sequences of spectrograms, one showing Fe I 5171.61, Mg I 5172.70 (b_2), and Ti I 5173.75 at the center of the solar disk, the other showing Fe I 5324.19 at the limb.

At the center we find that the velocity field consists mainly of short-lived oscillations of small elements of the solar atmosphere. The r.m.s. velocity amplitudes are 0.42 and 0.81 km/sec at low and high levels, respectively. The periods of the vertical oscillations cover roughly the range 200–300 seconds, with a mean value around 242 sec. The periods seem to decrease with height in the atmosphere. An autocorrelation study shows also that the vertical velocity field is dominated by periodic oscillations, the time-correlation function having a strong positive peak at 300 seconds from the origin. The study of the time lags of oscillations between strong and faint lines suggests that they are of a type intermediate between progressive sonic waves (for the shorter periods) and standing waves (for the longer periods). Gradual transition from the first type to the second seems to occur during the life of a given oscillation. There is an indication that the individual oscillations are associated with individual granules.

Near the limb, the observed horizontal motions consist of slowly changing velocities of the order of 0.5 km/sec in large surface elements, on which are superposed smaller random velocities of short duration. Oscillations rapidly disappear away from the center of the disk. The horizontal and vertical observable motions appear to be physically independent.

Evans & Michard 1962a

CORRELATIONS IN THE TIME VARIATIONS OF MACROSCOPIC INHOMOGENEITIES IN THE SOLAR ATMOSPHERE

In Paper III of a series being published in this *Journal* (Evans and Michard 1962), two of us described the oscillatory vertical motions of small photospheric elements as observed at the center of the solar disk. This study was made by picking up "individual oscillations" and directly measuring some properties, such as amplitude, period, time-lag between different lines, and individual association with granules.

While this approach was quick and sufficient to reveal the most prominent features of the solar velocity field, it fell far short of exhausting the information content of the observations. We have therefore embarked upon a study of the correlation functions and power spectra of the time variations in velocities and the brightnesses at the line centers and in the continuum. The work is well advanced, and we present here some of the more interesting results. The observations on which they are based have been described by Evans and Michard in Papers I and III.

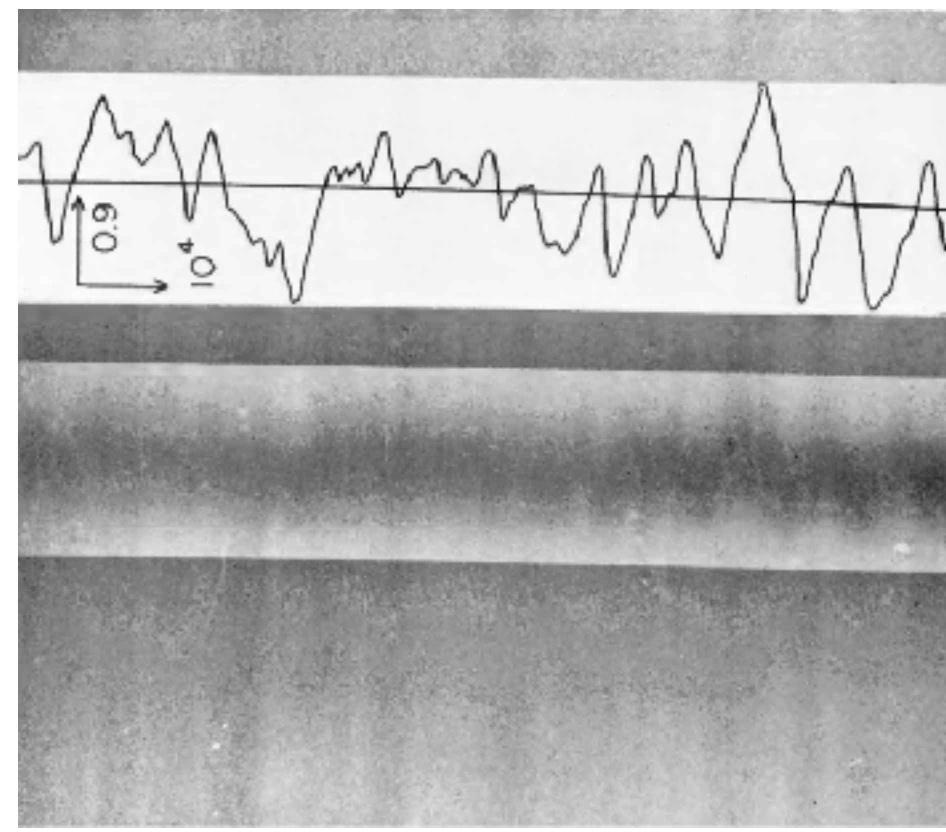
To obtain *one* point at lag Δt in a time-correlation curve, we calculated the *coefficient of correlation* ρ between the two sets of measurements made on two spectra taken at an interval Δt. The two sets contain generally measurements at 150 or 200 points 1000 km apart on the sun. For each Δt there are, of course, a number, n, of values of ρ available, n being something between 30 and 1, depending on Δt and the particular set of data. The r.m.s. deviation of individual ρ-values is in all cases around 0.10. Therefore, our time-correlation curves are very precise up to that Δt value where n falls below about 10.

The calculation of power spectra is not yet completed, but the AC (autocorrelations)- and CC (cross-correlations)-curves are sufficient to show the main results. Some of the most interesting AC- and CC-curves are presented in Figure 1 and commented upon in the following. The CC-curves have been separated into their *odd* and *even* parts. Let us recall here that if two periodic functions with identical period are cross-correlated, the odd and even parts of the CC-curve should be periodic, remain in quadrature, and have amplitudes in a ratio equal to $tg\ \phi$, ϕ being the phase lag. We might expect the CC-curves to have this behavior at small Δt, since the observed variations contain a sizable proportion of coherent periodic changes of equal periods and systematic ϕ's.

1. *Velocities.*—The AC-curves for the lines formed around the temperature minimum between photosphere and chromosphere (8514.08 Fe I, 5173.75 Ti I, and 5172.70 Mg I are shown) indicate an enormous predominance of oscillations in a very limited range of period. Most of these oscillations do not last for more than one to two periods, as shown by the initial decay of the AC-curves, but a part seems to persist for much longer, as suggested by the behavior of the AC-curves at large Δt. The CC-curves of velocities in 5173.75 and 5172.70 show a definite time lag for small Δt which disappears at large Δt (motion in b_2 lags behind motion in faint line).

We conclude that the velocity field at these upper photospheric levels contains both progressive oscillations of relatively small lifetimes and standing oscillations of great persistence. The frequency ranges of these two types of motion overlap a great deal, but the progressive type dominates at higher frequencies, while the standing type is more pronounced in the low-frequency range. The mean period of mainly progressive, short-lived oscillations is $\simeq$220 sec (the initial oscillation in the odd part of the CC-curve).

Un peu d'histoire (le cas solaire)



Evans & Michard 1962b

OBSERVATIONAL STUDY OF MACROSCOPIC INHOMOGENEITIES IN THE SOLAR ATMOSPHERE.
V. STATISTICAL STUDY OF THE TIME VARIATIONS OF SOLAR INHOMOGENEITIES (1)

by J. W. Evans
(Sacramento Peak Observatory,
Air Force Cambridge Research Laboratories)

R. Michard, R. Servajean
(Observatoire de Paris-Meudon)

Un peu d'histoire (le cas solaire)

Sommaire. — *A l'aide de séquences de spectres du centre du disque solaire de haute qualité, nous avons étudié par des méthodes statistiques objectives les variations dans le temps des fluctuations de vitesses radiales (" zig-zags ") pour 6 raies de Fraunhofer de diverses intensités et niveaux de formation. Les fluctuations de brillance dans le continu (granulation) et au centre de deux raies, ont été aussi analysées. On a obtenu les corrélations entre toutes ces quantités.*

Les variations dans le temps ont été décrites par les spectres de Fourier correspondants. De même les associations entre diverses grandeurs fluctuantes ont été représentées par les " cohérences » et « différences de phase » de leurs composantes de Fourier en fonction de la fréquence.

Le spectre des vitesses verticales aux niveaux photosphériques élevés est limité à un étroit domaine de fréquence, le maximum étant voisin de $T = 295$ s pour les raies moyennes. Dans ce domaine, les mouvements dans une raie forte (b2) et dans une raie faible (5173, 75 Ti) sont déphasés de quantités trop faibles pour des ondes sonores. Nous suggérons que les déphasages sont liés au stade initial transitoire de mouvements qui tendent vers des ondes stationnaires, à une fréquence de résonance.

L'analyse statistique est compatible avec le fait précédemment observé, que les « granules » brillants déclenchent les oscillations verticales, les évolutions ultérieures de ces deux structures étant indépendantes. Les fluctuations de brillance au centre des raies sont fortement corrélées et presque en quadrature avec les vitesses radiales dans les mêmes raies, pour le domaine de fréquence convenable. Ceci prouve à nouveau que les structures de la haute photosphère ne sont pas dues à la convection mais à des ondes hydrodynamiques.

Dans la basse chromosphère représentée par les raies infrarouges de Ca II, le spectre de Fourier du champ de vitesses se modifie en fonction de l'altitude ; il apparaît une bande de haute fréquence qui, pour 8542 Ca II, contient plus d'énergie que la bande centrée sur 295 s. L'origine physique de cette évolution avec la hauteur est discutée.

Summary. — *From time sequences of high resolution spectra of the center of the solar disk, we have studied by objective statistical methods the time variations of fluctuations in radial velocities (" wiggles ") for 6 Fraunhofer lines of various strengths and atmospheric levels. The fluctuations of brightness in the continuum (" granulation ") and at the centers of 2 lines have also been analysed. The time correlations between all these quantities have been obtained.*

Time variations are described by the corresponding Fourier power spectra. Similarly the associations between various parameters are shown by the " coherences " and " phase shifts " of their Fourier components as a function of frequency.

The power spectrum of vertical velocities at upper photospheric levels is confined to a narrow range of frequencies, peaked at $T = 295$ s for average lines. In this range the motions of a strong line (b2) and of a faint line (5173, 75 Ti) show phase shifts which seem too small for sound waves. It is suggested that the phase shifts are due to the transient initial stages of motions which decay towards standing oscillations, at a resonance frequency.

The statistical analysis is consistent with the previously reported fact that sudden appearances of bright " granules " are the starting agents of vertical oscillations, with further independent decays of the two features. Brightness fluctuations at the centers of Fraunhofer lines are shown to be strongly correlated and nearly in quadrature with velocities in the same lines in the relevant frequency range, further proving that the upper photospheric structures are not due to convection but to hydrodynamic waves.

In the low chromosphere as exemplified by the infrared Ca II lines, the power spectrum of the velocity field changes as a function of height ; it develops a high frequency tail which for 8542 Ca II contains more energy than the peak at $T = 295$ s. The physical origin of this height evolution is briefly discussed.

(1) This paper is part of a series, the first four of which appeared in *The Astrophysical Journal*.

Evans & Michard 1963

Un peu d'histoire (le cas solaire)

Резюме — При помощи последовательностей спектров солнечного диска высокого качества были исследованы объективными статистическими методами изменения во времени флуктуаций лучевых скоростей (" зигзаги ") для 6 фраунгоферовых линий различных интенсивностей и уровней образования. Флуктуации яркости в континууме (грануляции) и в центре двух линий были также анализированы. Были получены соотношения между всеми этими количествами.

Изменения во времени были описаны соответствующими спектрами Фурье. Ассоциации между различными флуктуирующими величинами были также представлены " связностями " и " разницами фазы " их составляющих Фурье в зависимости от частоты.

Спектр вертикальных скоростей на высоких фотосферических уровнях ограничен узкой частотной областью, максимум будучи близок T = 285 s для средних линий. В этой области движения в сильной линии (*b*2) и в слабой линии (5173,75 Ti) дефазированы на незначительные количества для звуковых волн. Мы предполагаем, что сдвиги фаз, связаны с начальной переходящей стадией движений, стремящихся к стационарным волнам с резонансной частотом.

Статистический анализ совместим с прежде наблюденным фактом, что блестящие " грануы " дают начало вертикальным колебаниям, дальнейшие развития этих двух структур будучи независимыми флуктуации яркости в центре линий тесно связаны, и почти как квадрат, с лучевыми скоростями в этих же линиях для области с подходящей частотой. Это доказывает снова, что структуры верхней фотосферы не имеют причиной конвекцию, но гидродинамические волны.

В нижней хромосфере, представленной инфракрасными линиями Ca II, спектр Фурье поля скоростей изменяется в зависимости от высоты ; появляется высокочастотная полоса, которая для 8542 Ca II содержит больше энергии чем полоса с чентром в 295 s. Обсуждена физическая природа этой эволюции с высотой.

I. Introduction.

In 1961, one of us obtained at the Sacramento Peak Observatory a few time sequences of solar spectra under conditions of excellent image quality. An exploration of the time changes in upper photospheric structure had already led R. Leighton (1960 [9]) to the important discovery of vertical oscillations in the solar atmosphere, among other interesting results. The morphological study of the time sequences of spectra, as reported in Paper III of this series, showed various important properties of the atmospheric inhomogeneities (J. Evans, R. Michard, 1962 *c*)[6]. We briefly list these properties, as constant reference will be made later to the results of Paper III :

The prominent vertical oscillations at the center of the disk increase sharply in amplitude with height in the atmosphere, as indicated by line strength. They are confined to periods in the range 200-300 seconds. There is clear evidence of upward propagation of the phase of the motion, mainly for the initial portions of the oscillations.

— Individual oscillations seem to start with a violet shift initiated by the apparition of a granule, the maximum brightness of the continuum feature occuring roughly 40 *s* before the maximum initial violet shift. Then the two features decay independently.

— The velocity field changes rapidly with height ; individual oscillations cannot be clearly recognized in the chromospheric line 8542 Ca II, where the motions have a smaller time constant.

These results were obtained by selecting clearly identifiable features in a set of curves showing the velocities (or brightnesses) as functions of position along the slit and time, then following the individual evolutions of these more prominent features. Accordingly they do not describe the inhomogeneous atmosphere as a whole, since they are surely influenced by our selection criteria and by subjective factors. It seemed important to see if an entirely objective statistical analysis would give consistent results. This is the purpose of the present paper. Further, the brightness fluctuations at the centers of average lines were included in our statistical work. Some of their properties had been discussed in Paper II (J. Evans, R. Michard, 1962 *b*) [5]. An exploratory plate pair in the D 1 line by R. B. Leighton, R. W. Noyes, and G. W. Simon (1962) [10] had strongly suggested brightness oscillations with the same period as velocity oscillations. It seemed worth while, therefore, to study the brightness fluctuations and their relation to velocity fluctuations as thoroughly as our observational material allowed.

The following quantities have been measured and analysed

— on film No. 471 : Velocities in lines 5173, 75 Ti I ; 5172, 70 Mg I (*b*2) ; and 5171, 61 Fe I, Brightness in continuum, Brightnesses at the centers of 5172, 70 Mg I and 5171, 65 Fe I.

— on film No. 568 : Velocities in lines 8514, 08 Fe I ; 8498, 06 Ca II ; and 8542, 13 Ca II.

The time correlations between all quantities

Evans & Michard 1963

Un peu d'histoire
(le cas solaire)

Compréhension physique des oscillations:

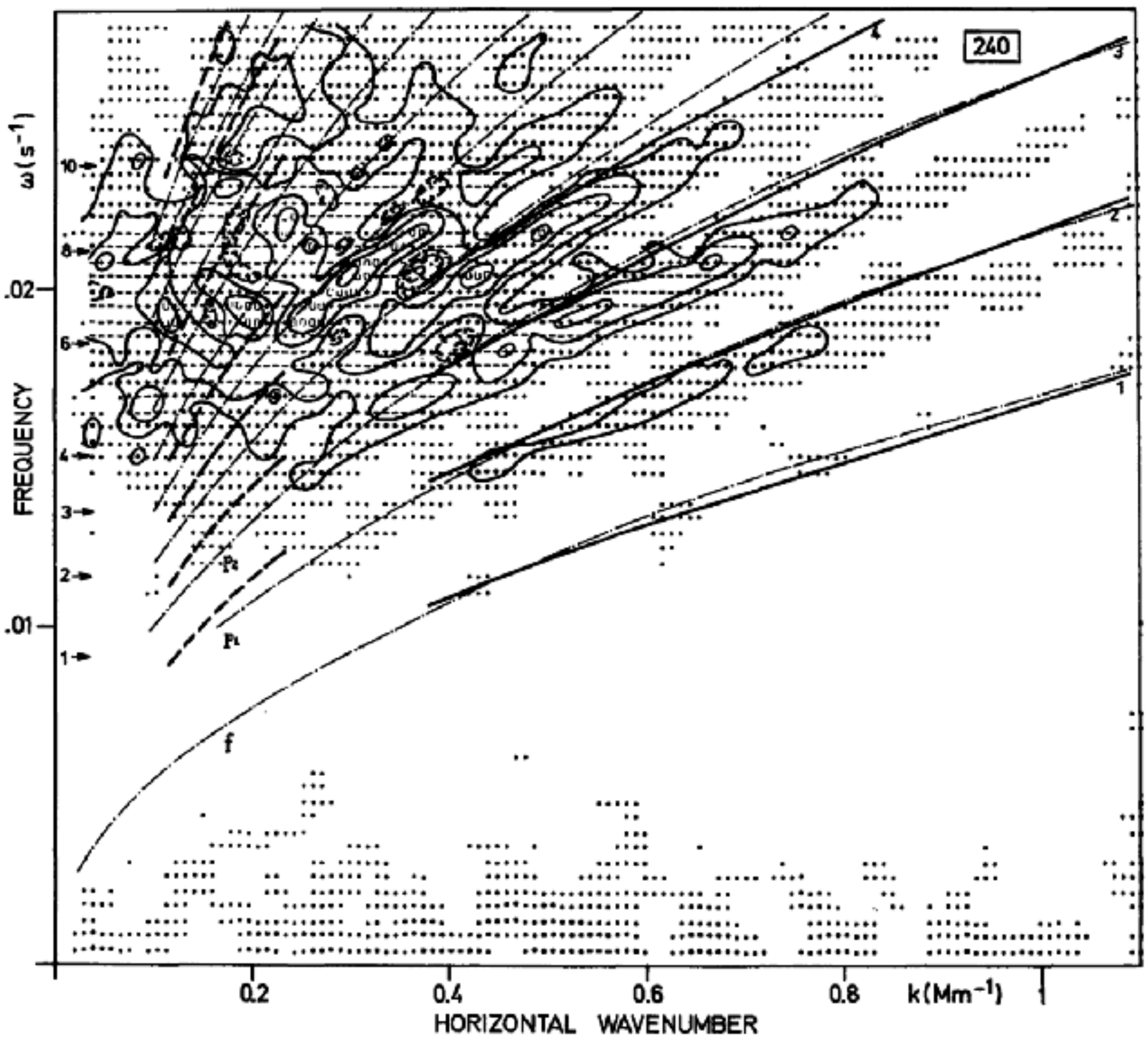
-Ulrich (1970)

-Leibacher & Stein (1971)

Confirmation observationelle?

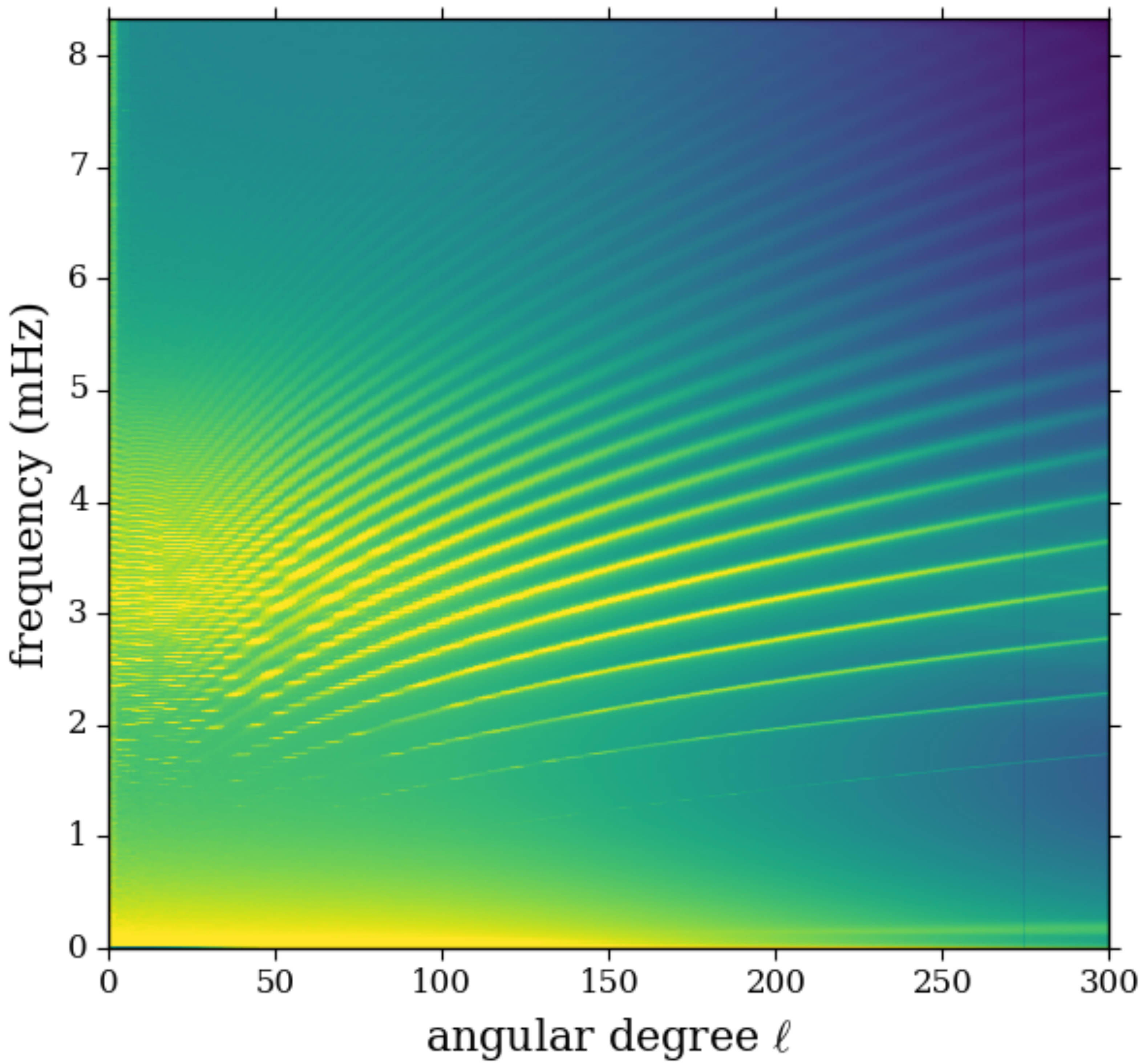
E. Rhodes, étudiant de G. Simon (de Leighton, Noyes & Simon) collecte des observations à Sacramento Peak. Mais...

Un peu d'histoire (le cas solaire)



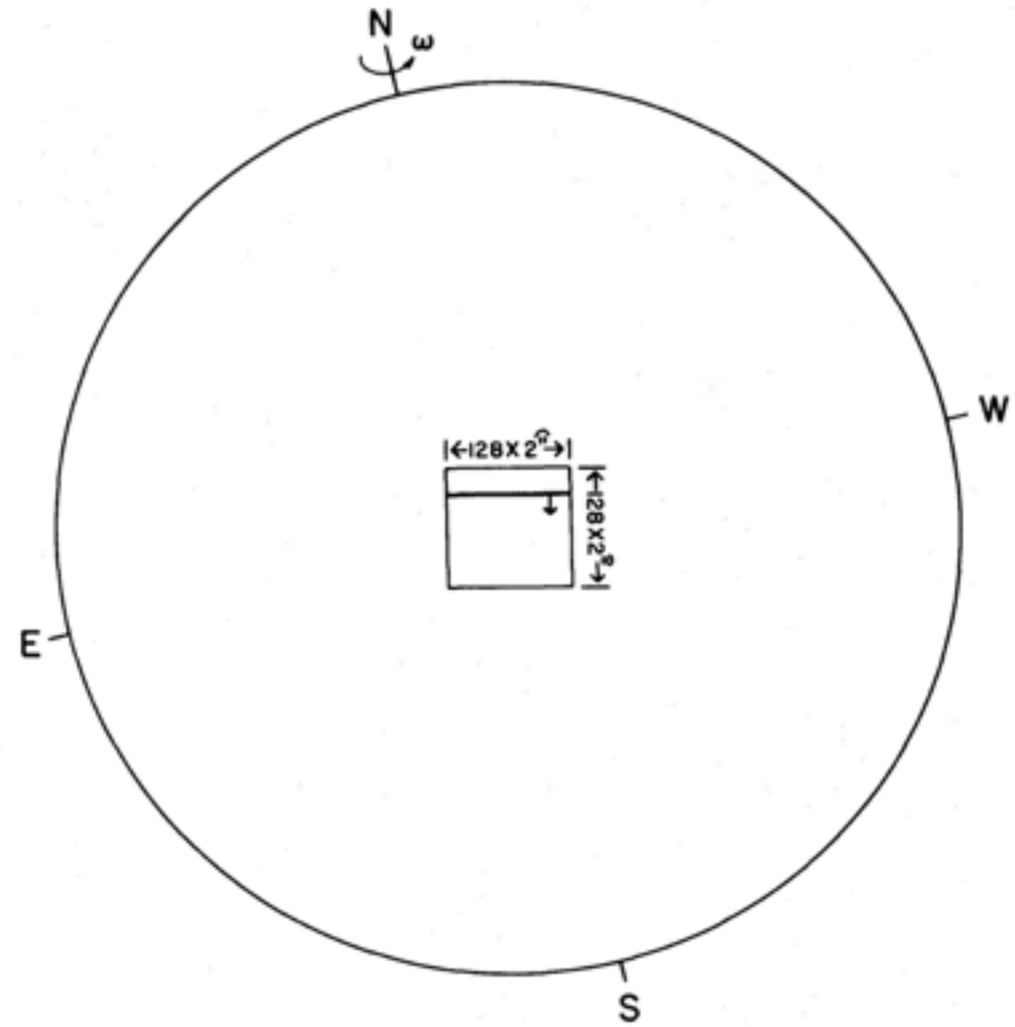
Deubner 1975

Un peu d'histoire



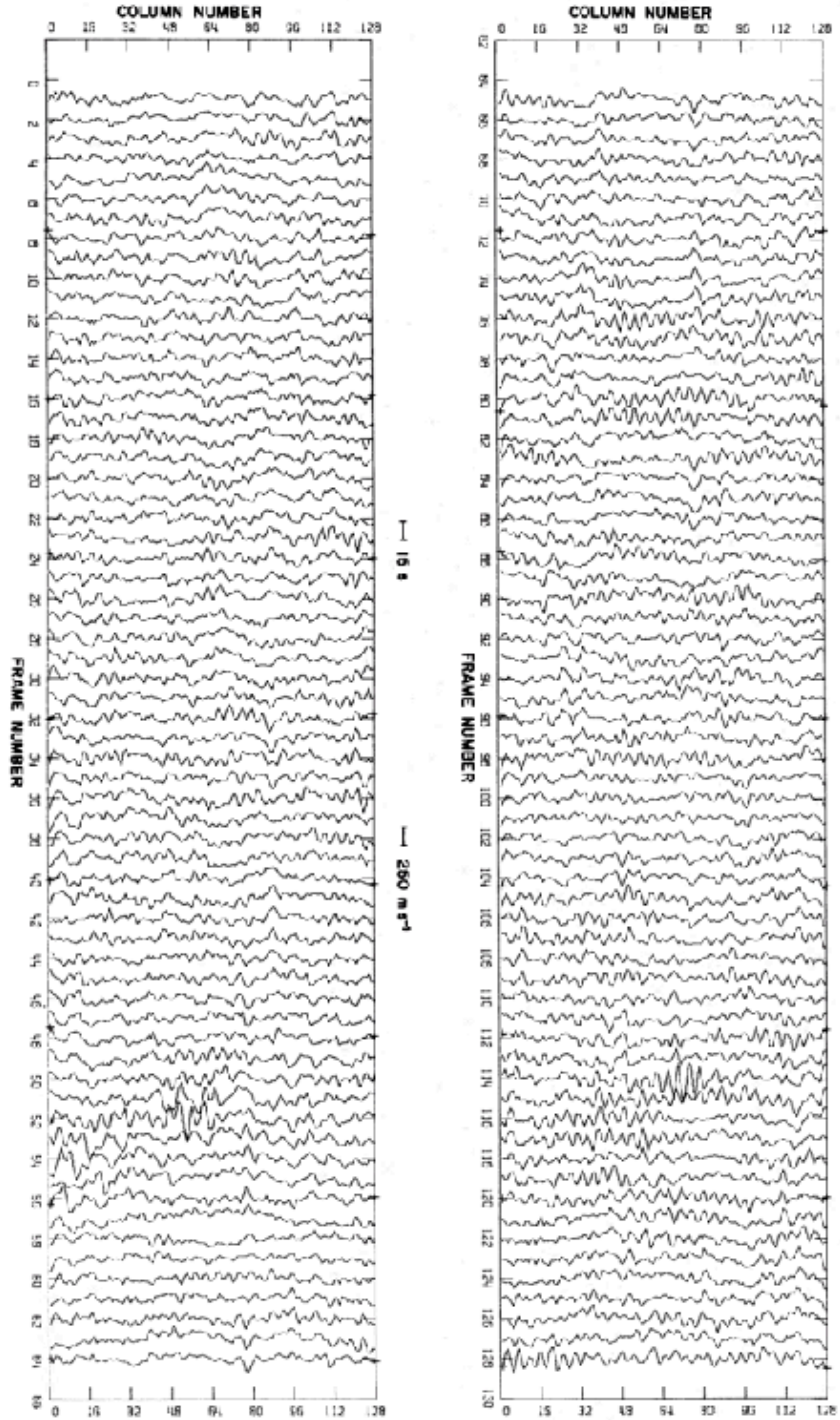
MDI

Un peu d'histoire
(le cas solaire)



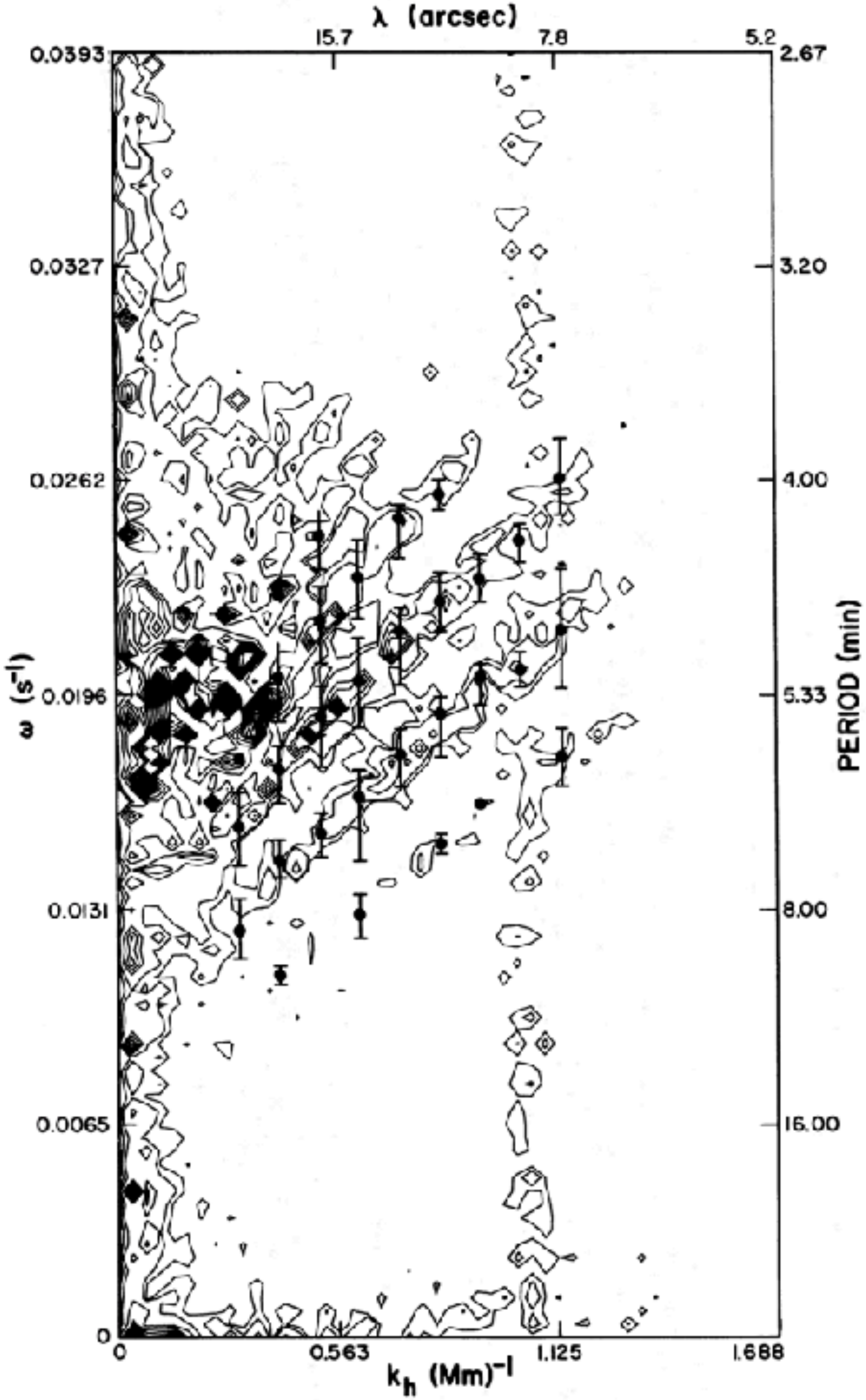
Rhodes, Ulrich & Simon 1977

Un peu d'histoire (le cas solaire)



Rhodes, Ulrich & Simon 1977

Un peu d'histoire (le cas solaire)



Rhodes, Ulrich & Simon 1977

Méthodes d'observation

km at the level of Fe λ 6102 to ~3500 km at that of Na λ 5896. The r.m.s. vertical velocity of ~0.4 km sec^{-1} appears nearly constant over this height range.

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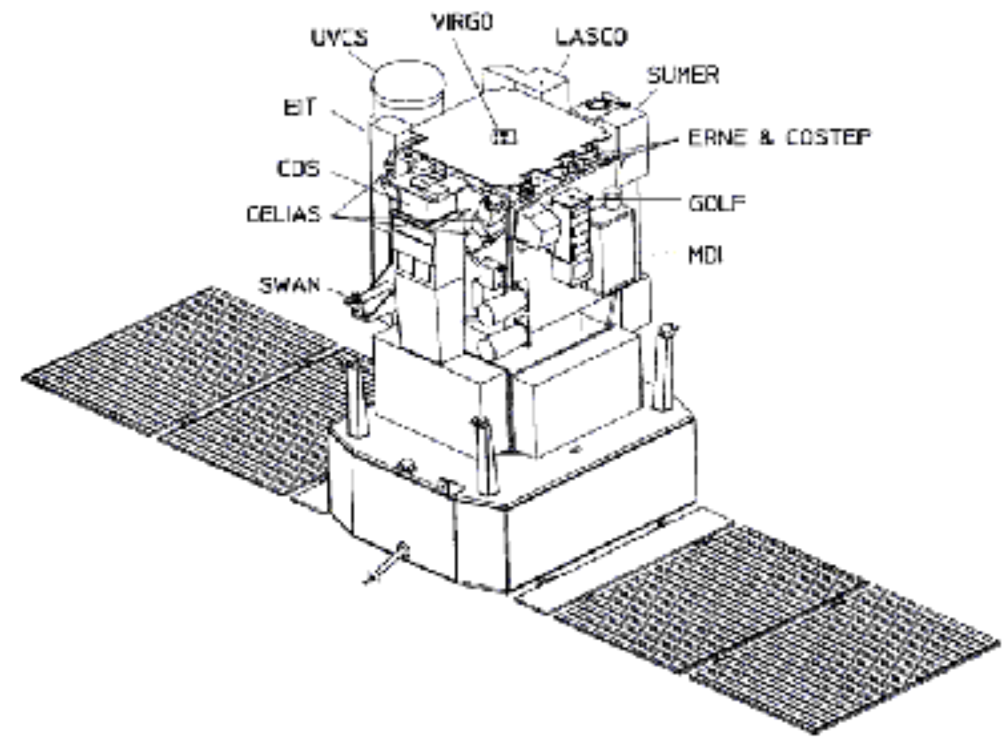
=> observations spectroscopiques (vitesses)

=> observations photométriques (intensité)

Méthodes d'observation



=> observations spectroscopiques (vitesses)
=> observations photométriques (intensité)

Un bon exemple: SOHO

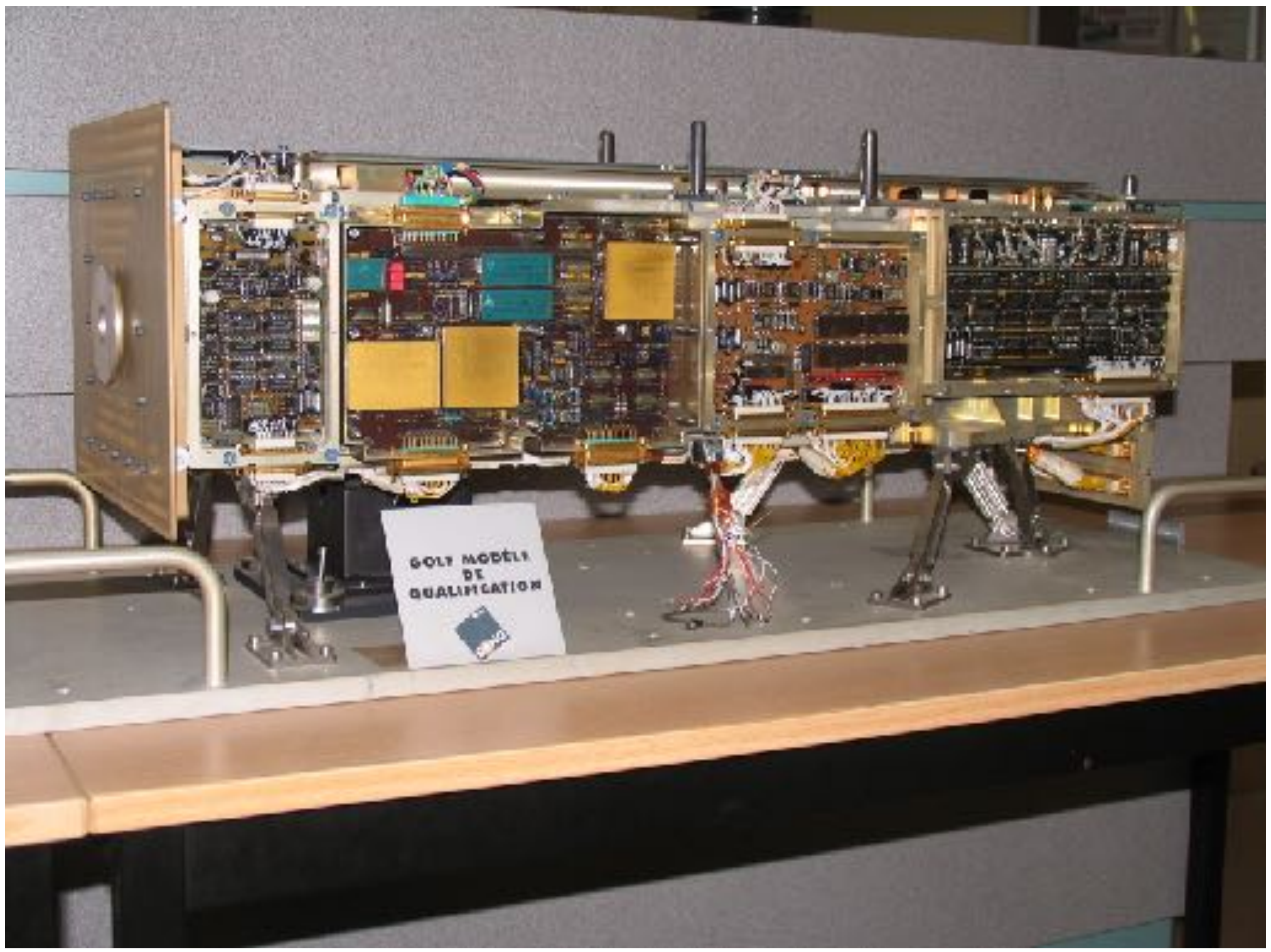
- GOLF (Global Oscillation at Low Frequency): mesure de vitesse (par effet Doppler) intégrée sur tout le disque
- VIRGO (Variability of solar Irradiance and Gravity Oscillations): mesures (ultra-précises) de variation d'intensité

Méthodes d'observation

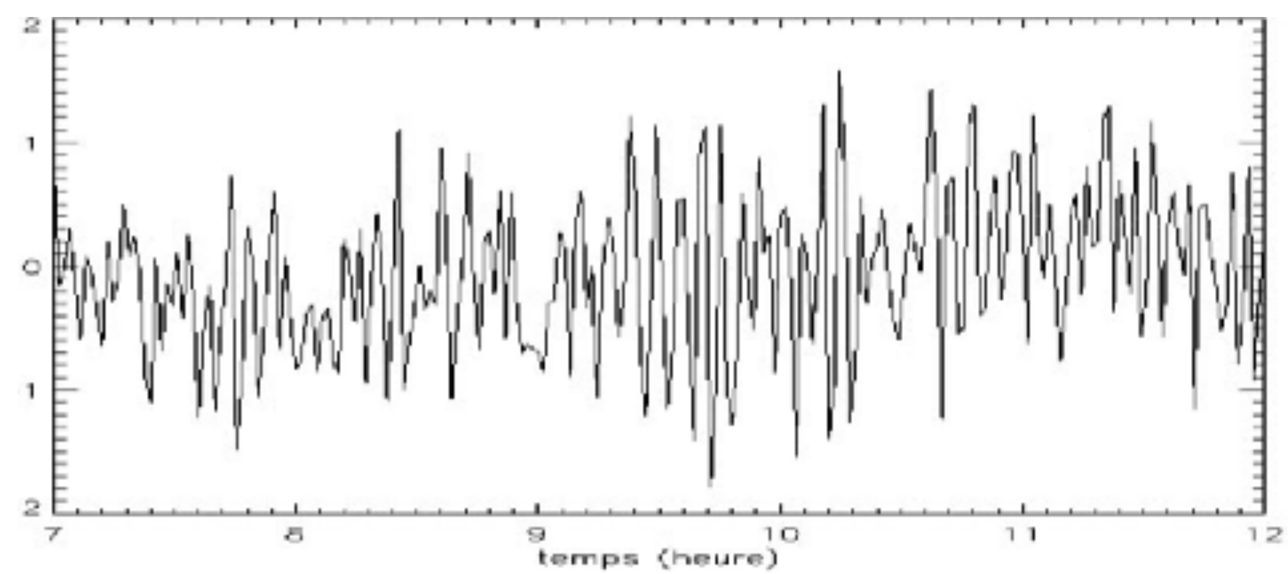
Un autre exemple: HARPS

spectro au sol (version Sud et Nord)

Méthodes d'observation



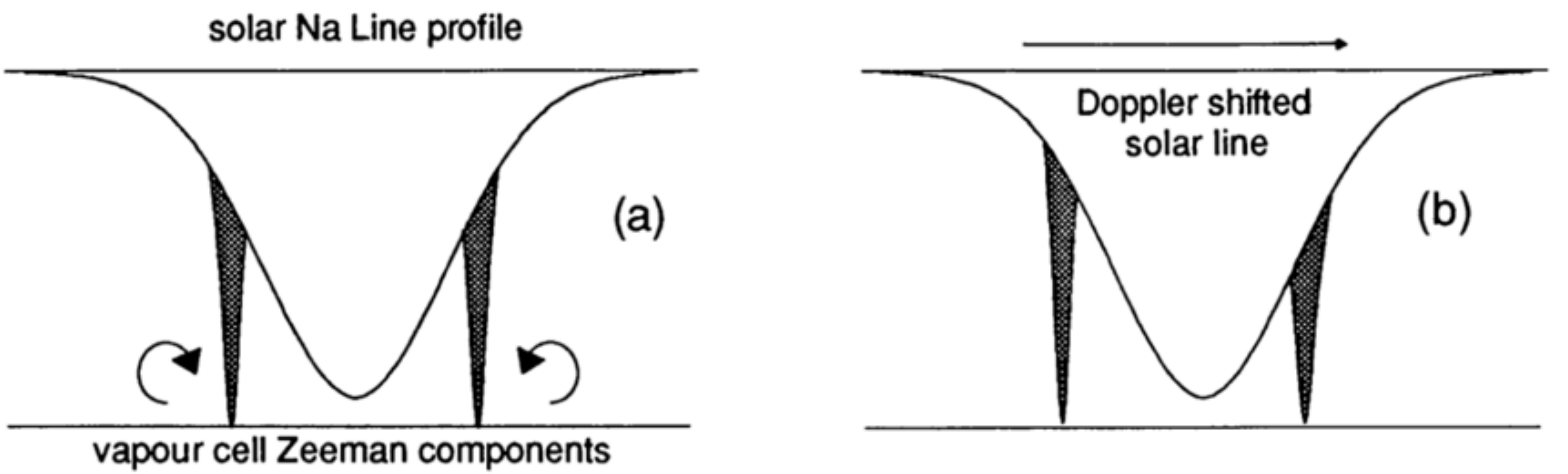
GOLF: spectroscope à résonance



Ordre de grandeur de l'amplitude des modes: v~10 cm/s

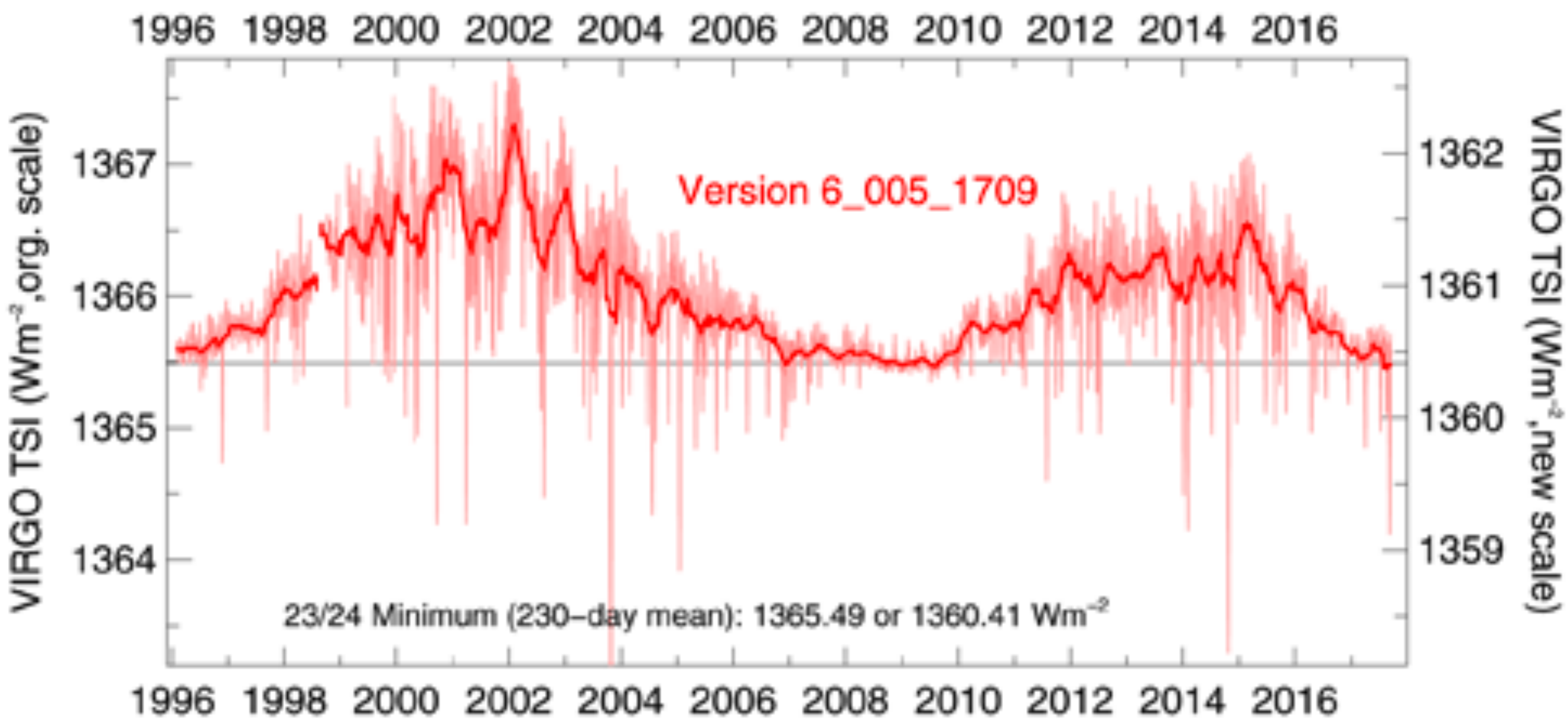
Méthodes d'observation

GOLF: spectroscope à résonance



Méthodes d'observation

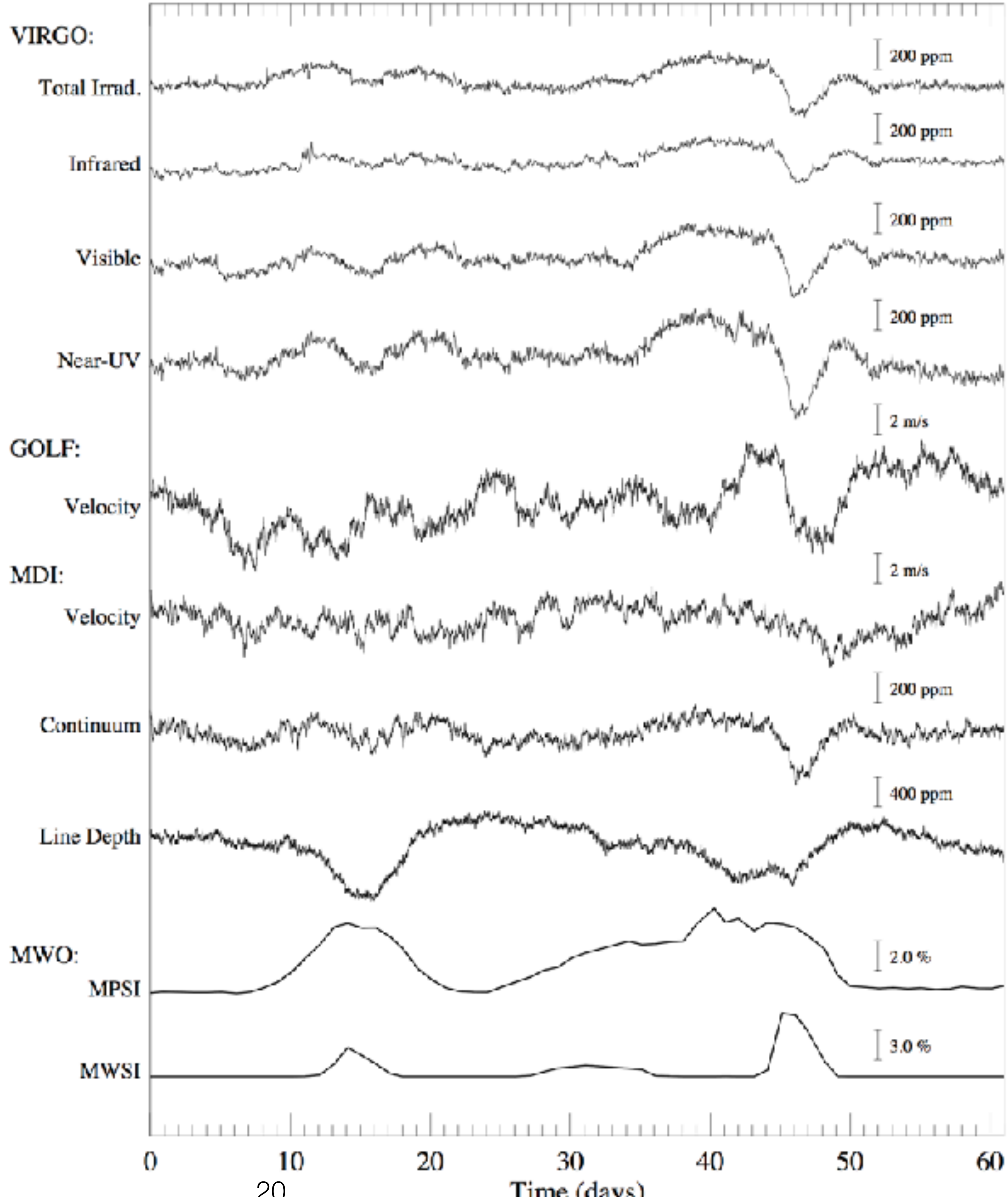
VIRGO = SPM + LOI + DIARAD + PMO6



Ordre de grandeur de l'amplitude des modes: $\Delta I/I$~ppm

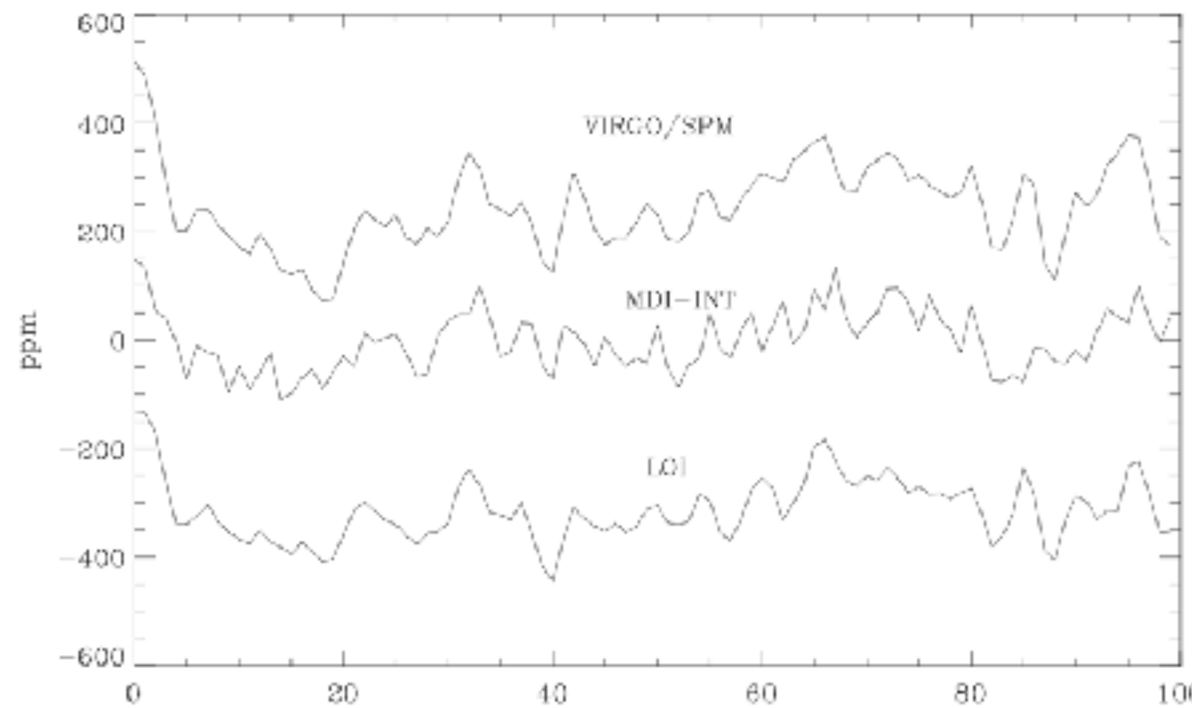
Méthodes d'observation

GOLF
+MDI
+VIRGO
=SOHO/Sismo

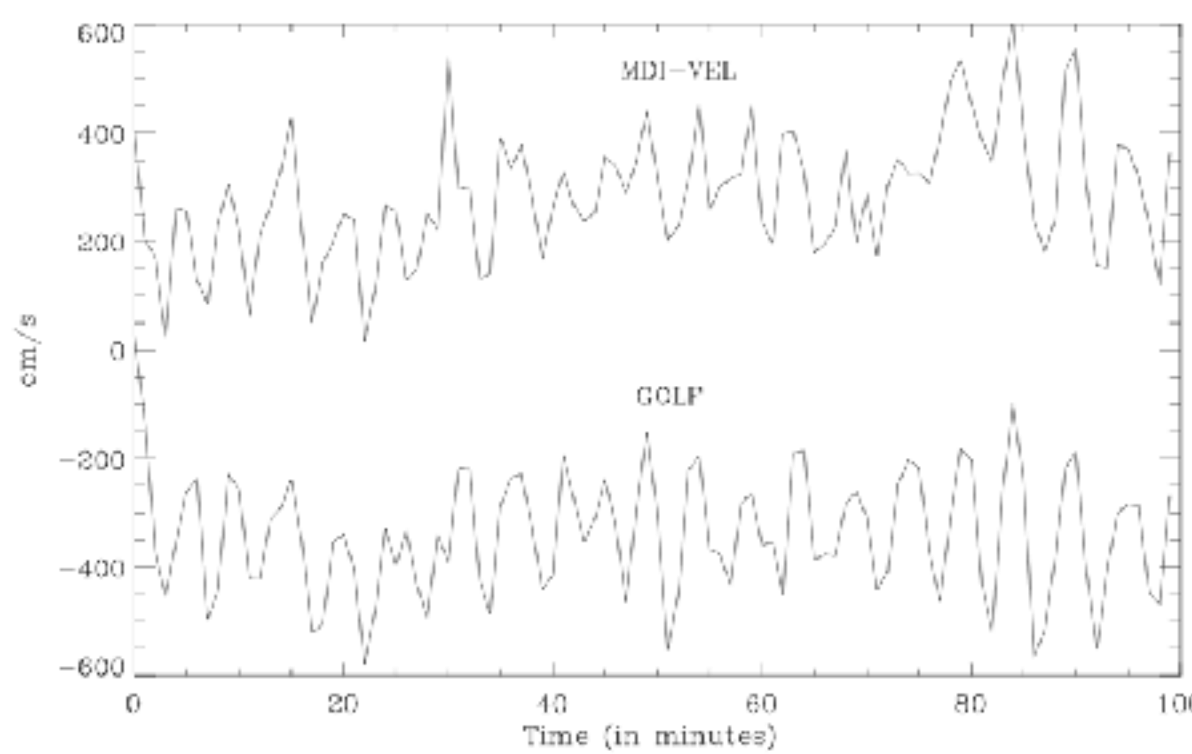


Méthodes d'observation

Photométrie:
simplicité de l'instrumentation
rapport S/B moyen



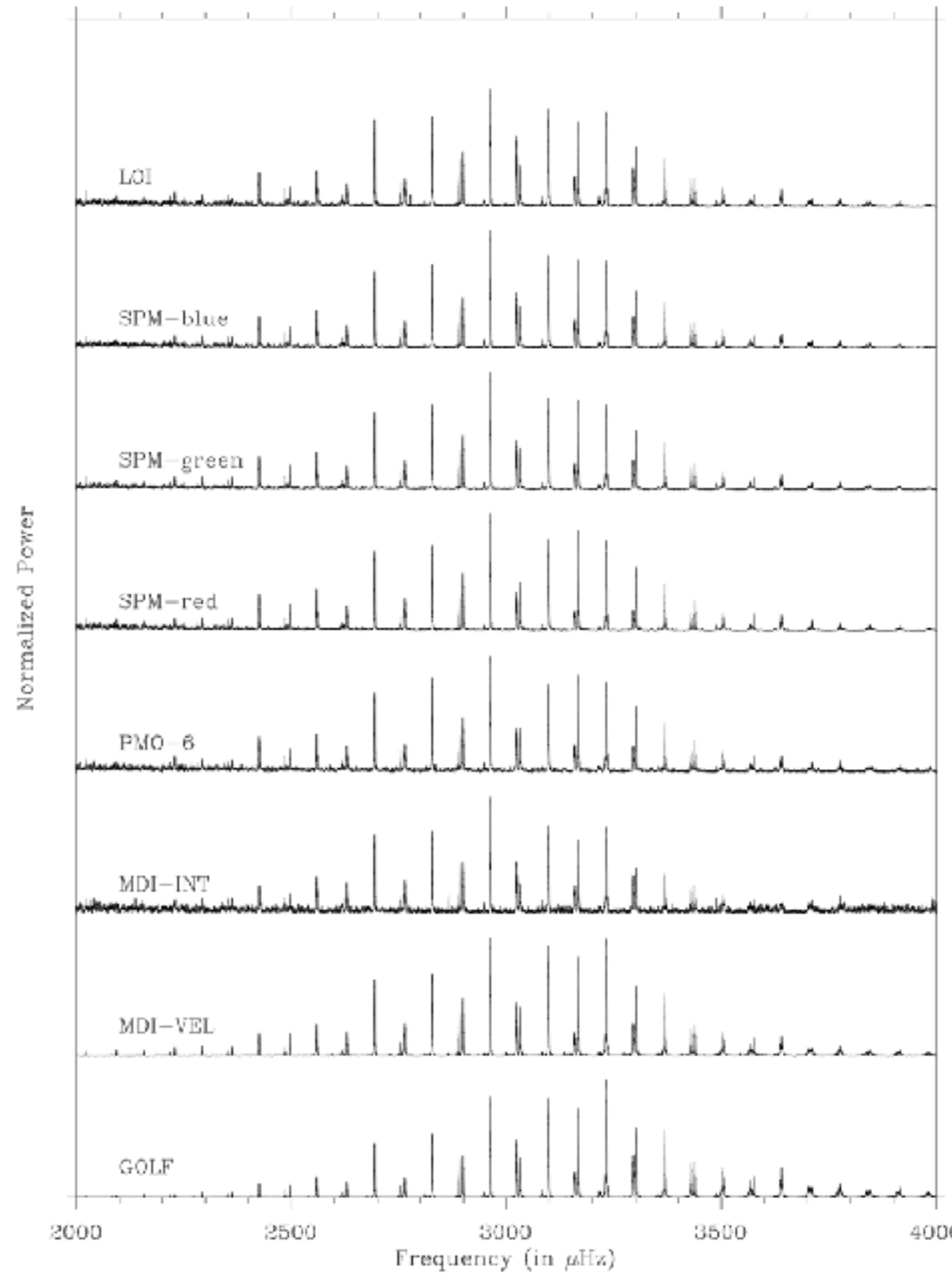
Spectroscopie:
complexité de l'instrumentation
rapport S/B excellent



Méthodes d'observation

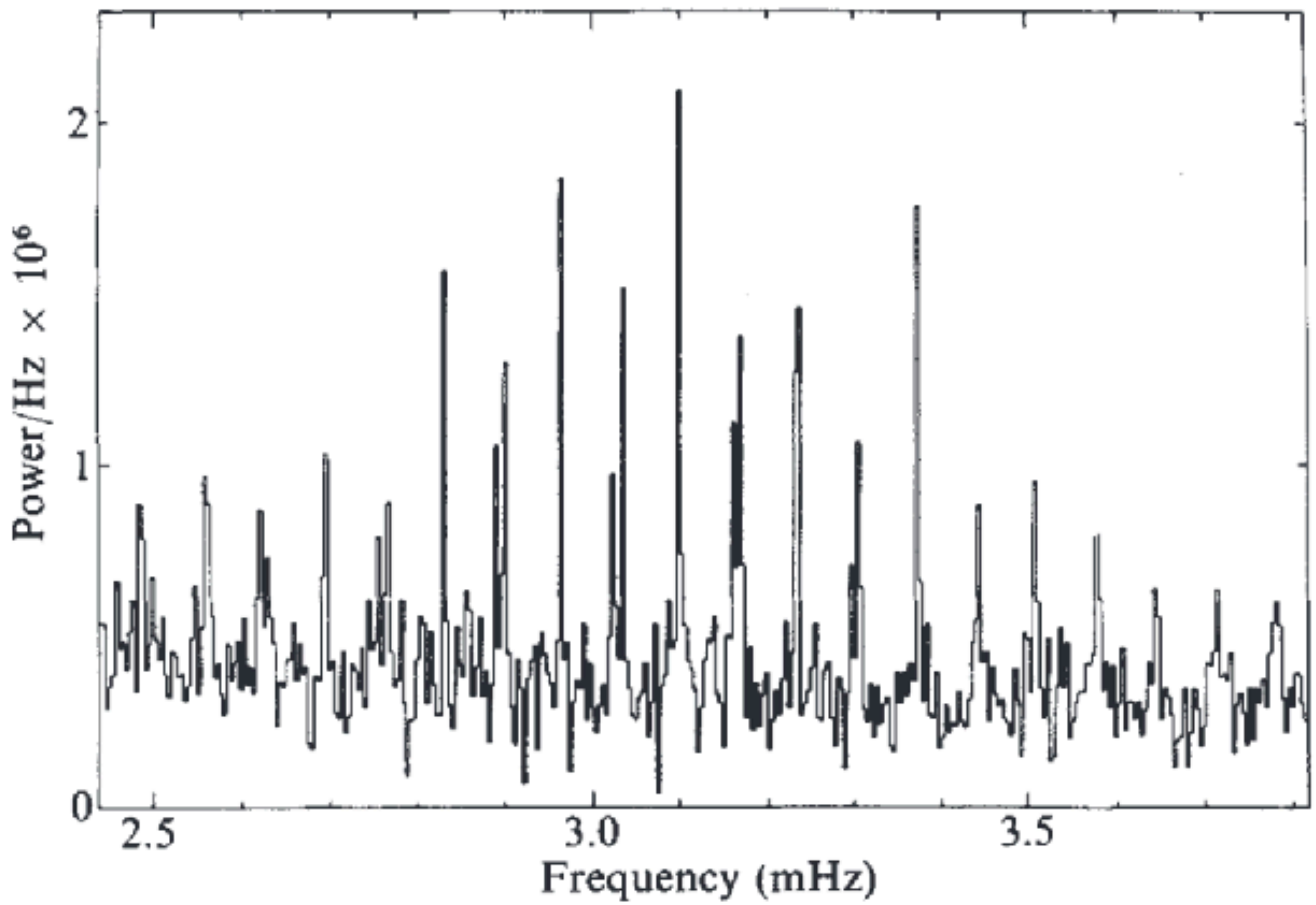
Photométrie:
simplicité de l'instrumentation
rapport S/B moyen

Spectroscopie:
complexité de l'instrumentation
rapport S/B excellent



Méthodes d'observation

Photométrie:
simplicité de l'instrumentation
rapport S/B moyen

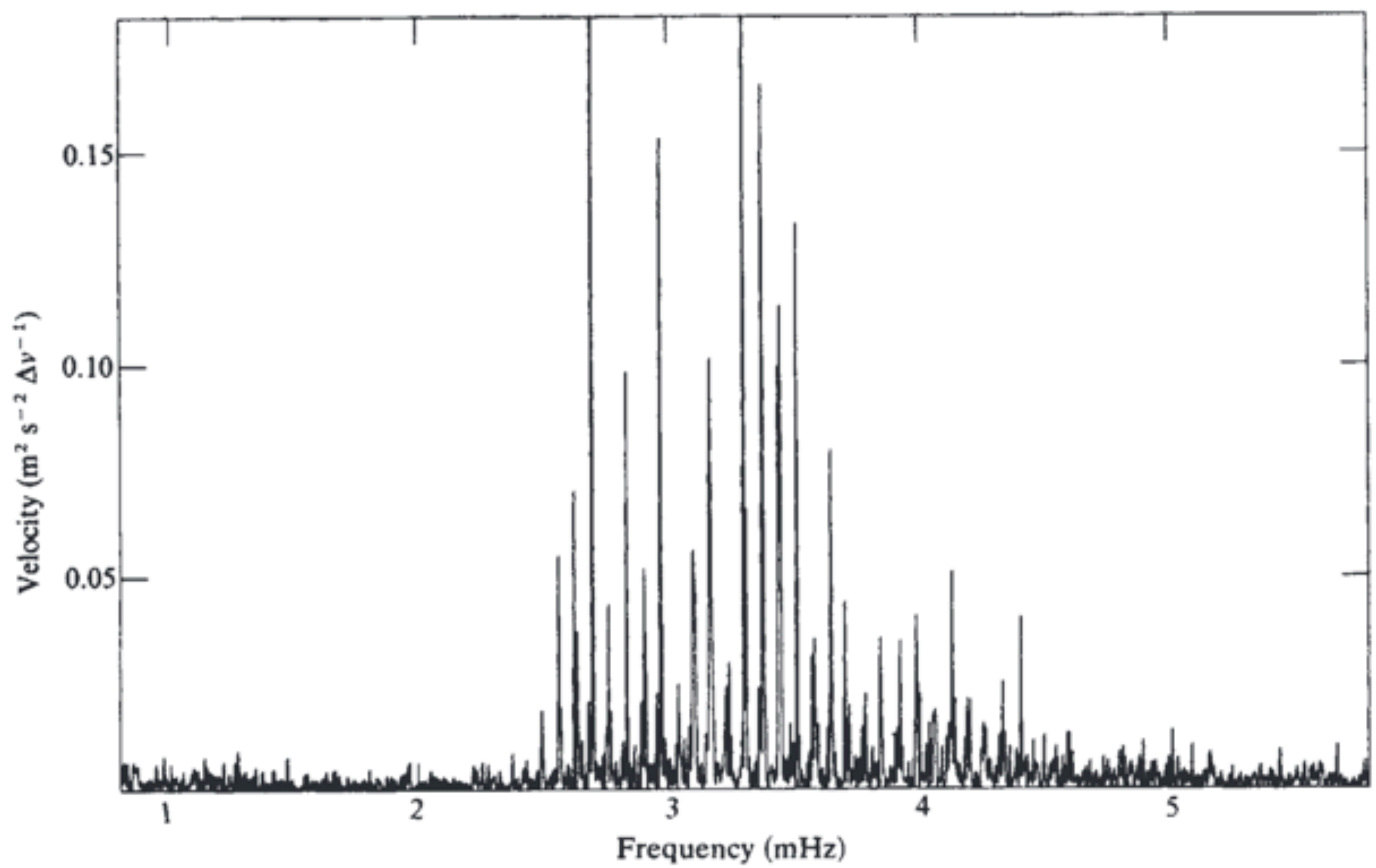


Instrument ACRIM

Woodard & Hudson 1983

Méthodes d'observation

Spectroscopie:
complexité de l'instrumentation
rapport S/B excellent

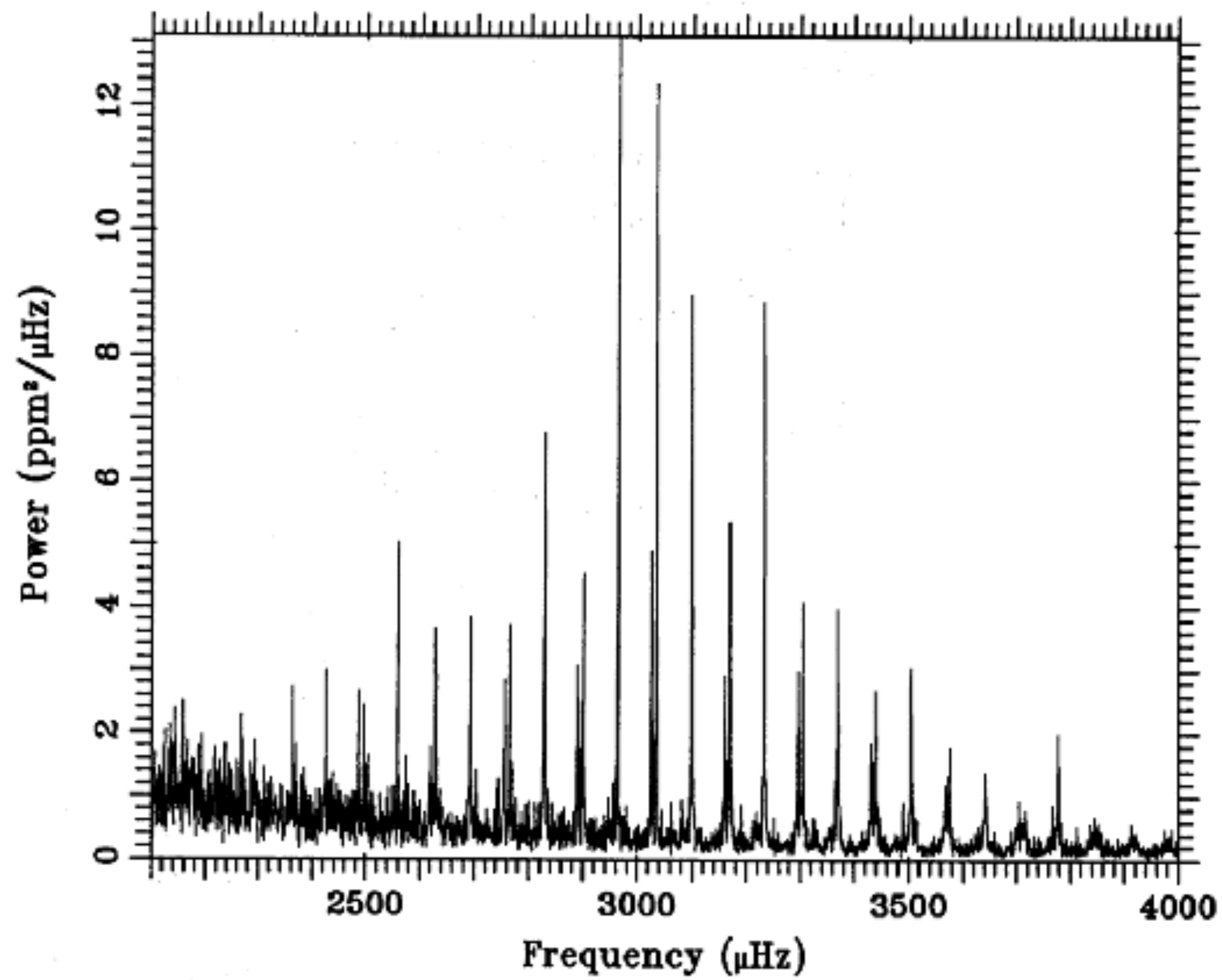


Observation depuis le pôle Sud

Grec et al 1980

Méthodes d'observation

Photométrie:
simplicité de l'instrumentation
rapport S/B moyen

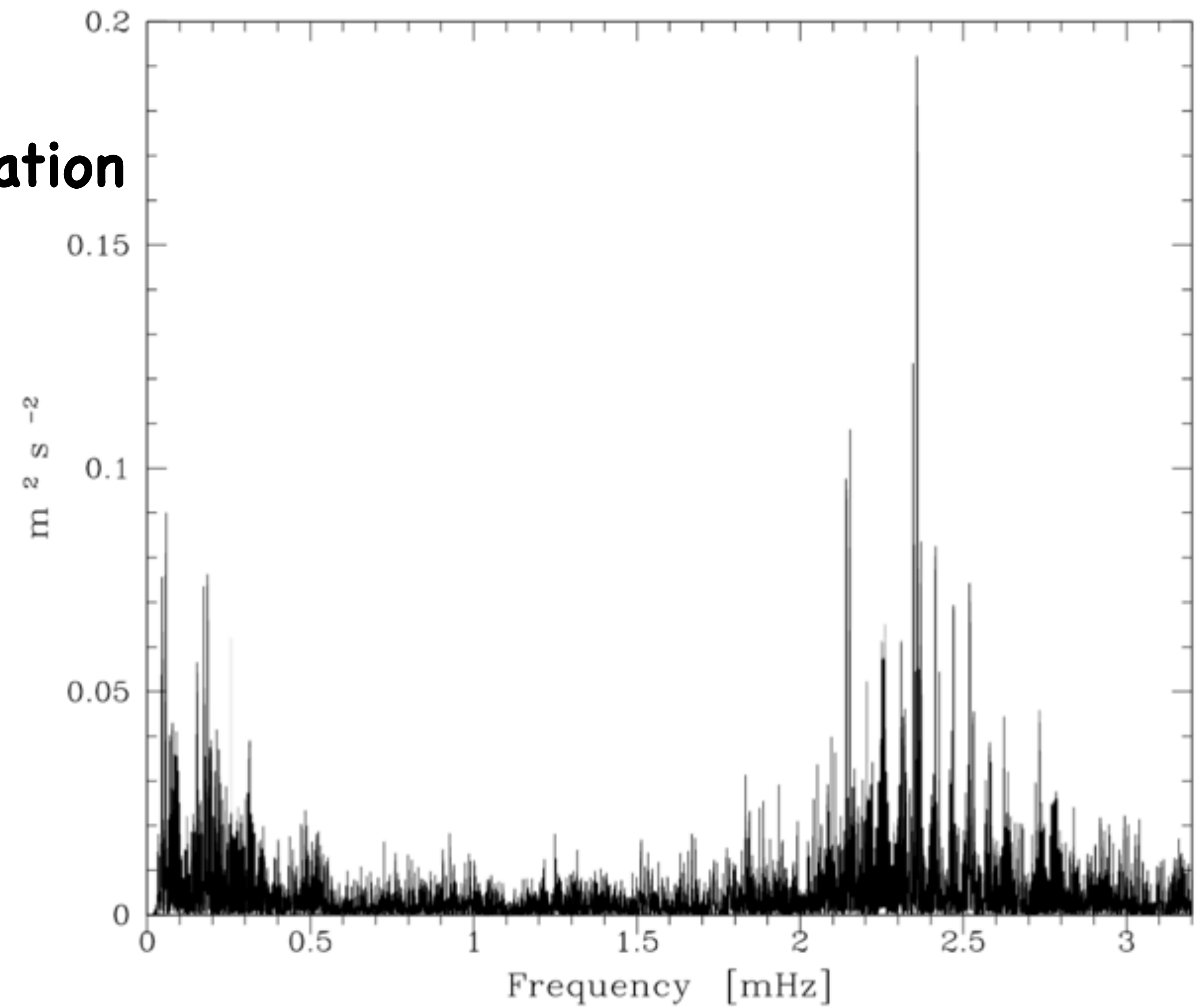


Instrument IPHIR

Toutain & Fröhlich 1992

Méthodes d'observation

Spectroscopie:
complexité de l'instrumentation
bon rapport S/B



Observations spectro sol stellaires
α Cen A

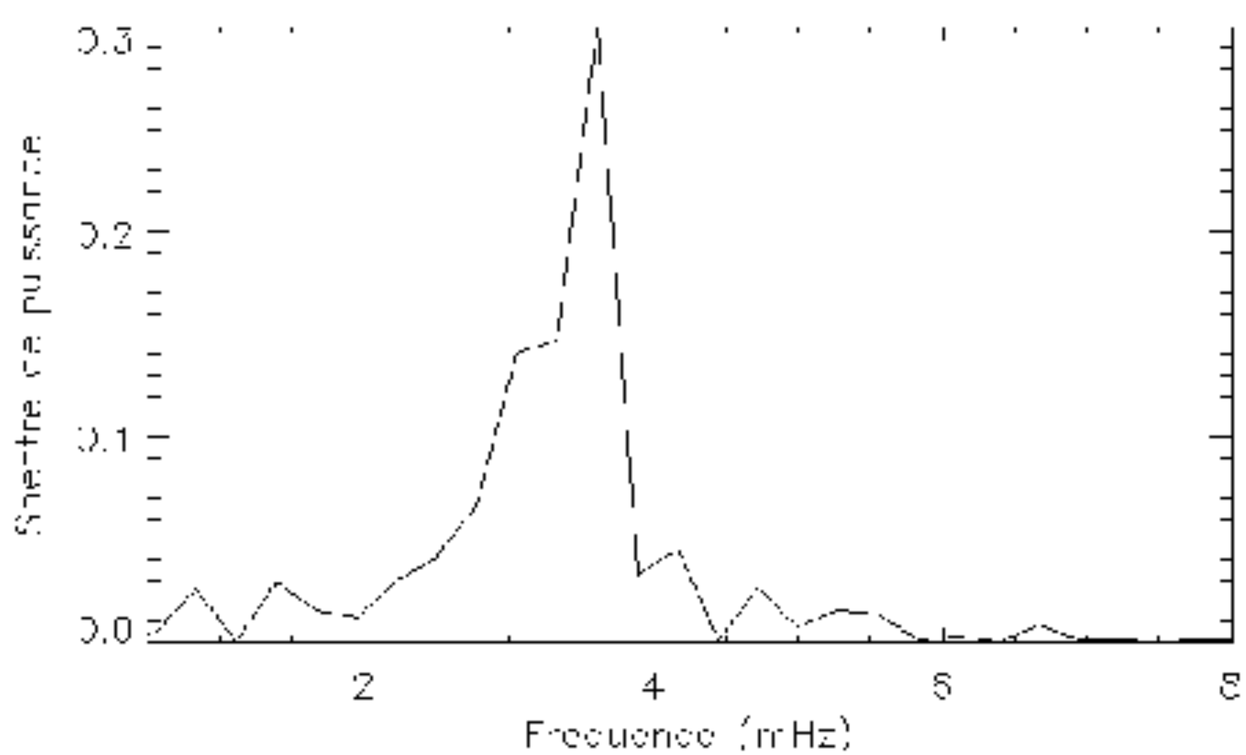
Bouchy & Carrier 2002

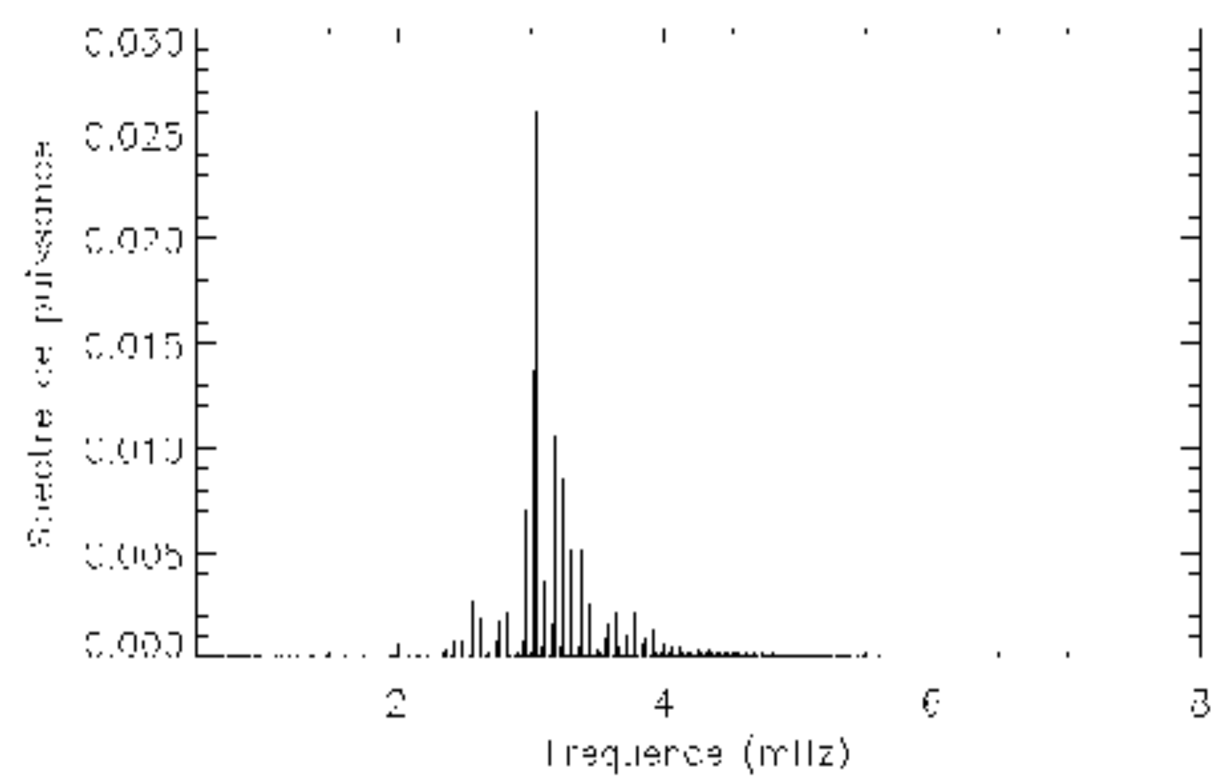
Méthodes d'analyse

Transformée de Fourier

s(t) => S(ν)

Importance de la durée d'observation





Méthodes d'analyse

Transformée de Fourier

s(t) => S(ν)

Importance de la continuité des observation

$$s_0(t) = \cos(2\pi\nu_0 t)$$

$$s(t) = s_0(t) \times W(t) \Rightarrow \hat{S}(\nu) = \hat{S}_0(\nu) * \hat{W}(\nu)$$

$$W(t) = \Pi_T * \sum_n \delta(t - nt_0) = \Pi_T * III(nt_0)$$

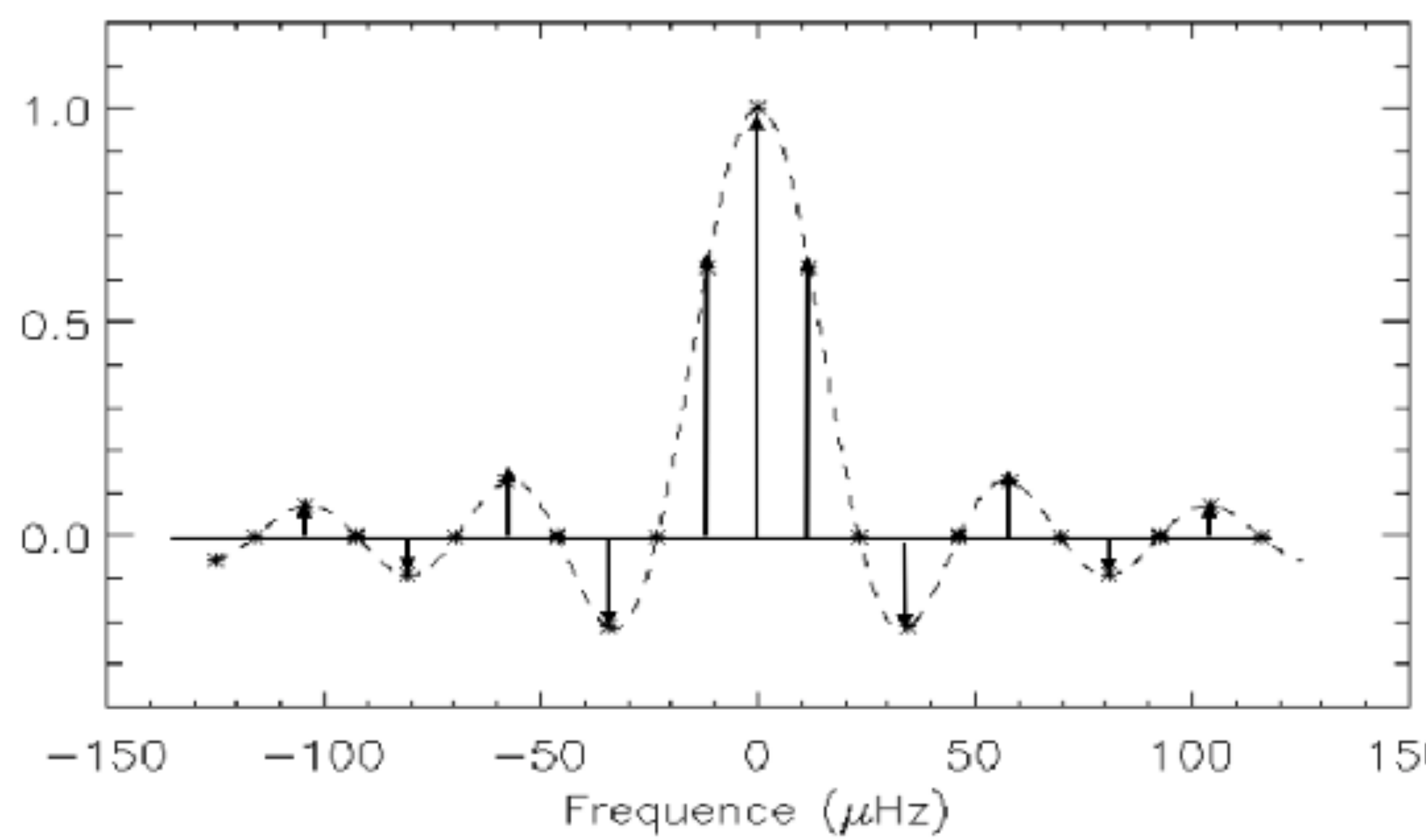
Méthodes d'analyse

Transformée de Fourier

s(t) => S(ν)

Importance de la continuité des observation

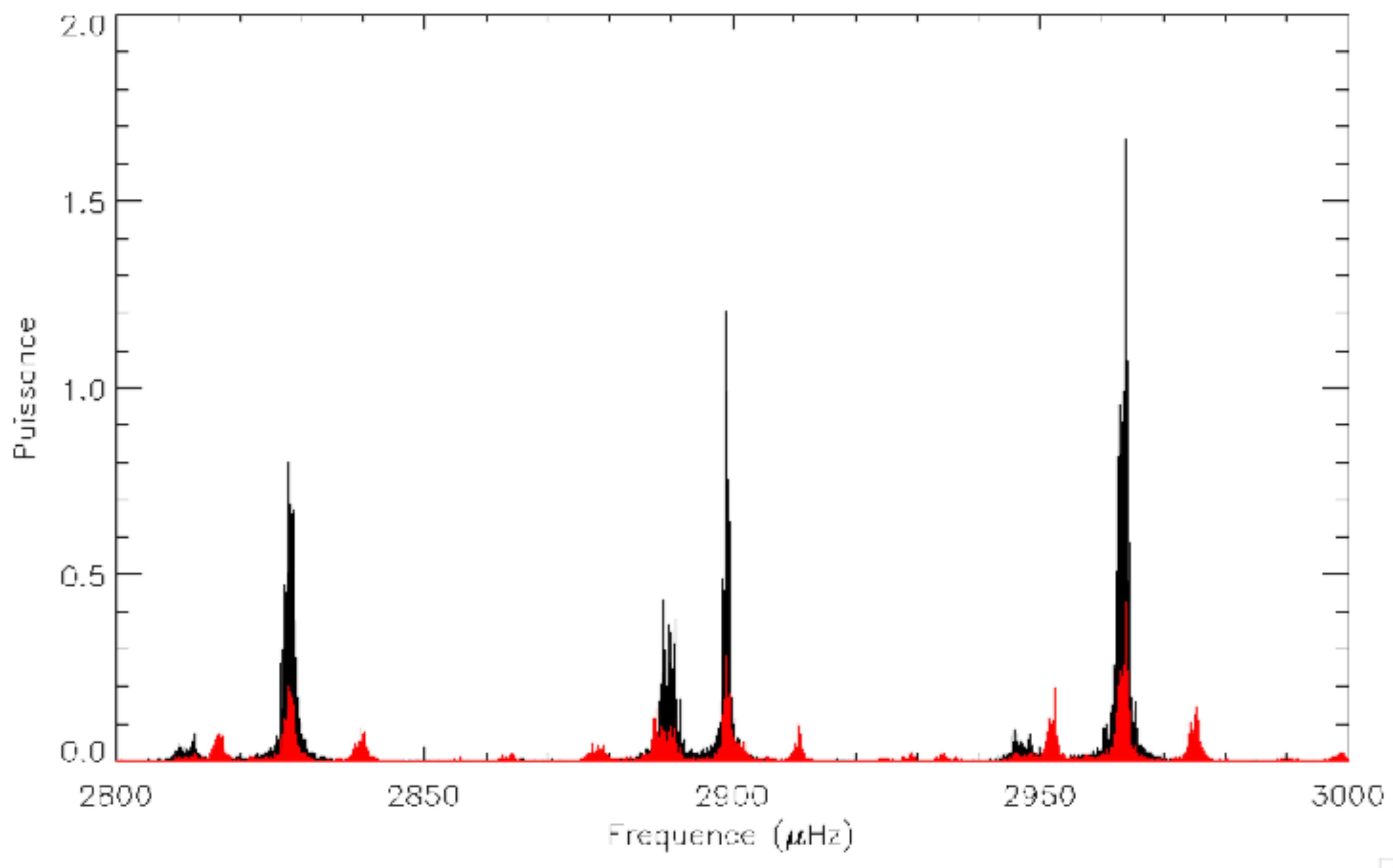
$$\hat{W}(\nu) = T\mathrm{sinc}(\pi\nu T) \times \frac{1}{t_0} III(nf_0)$$



Méthodes d'analyse

Transformée de Fourier

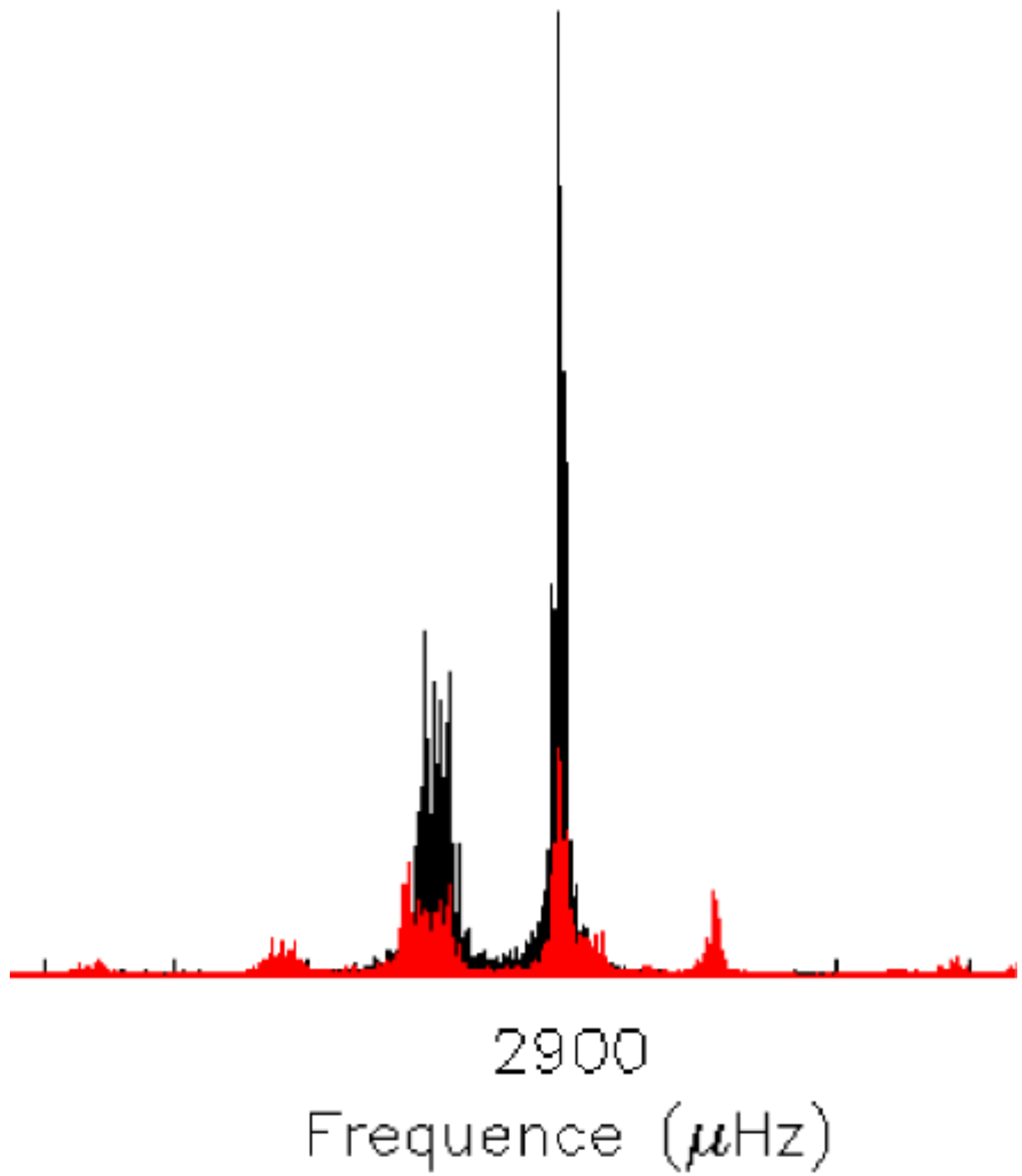
s(t) => S(ν)



Méthodes d'analyse

Transformée de Fourier

s(t) => S(ν)



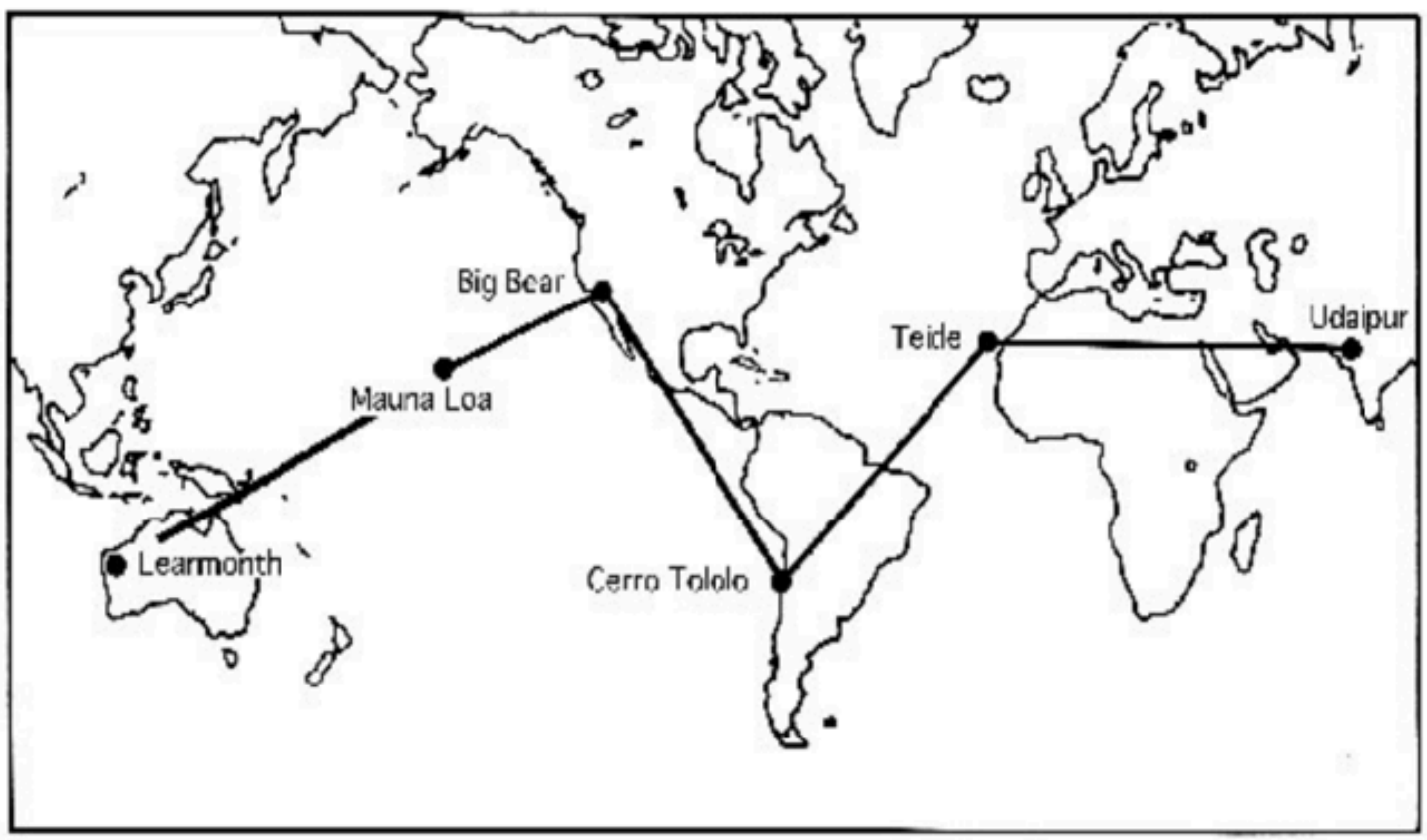
Espace ou réseau

Missions spatiales: ACRIM/SMM, Phobos/IPHIR, SOHO, MOST, CoRoT, Kepler…

Espace ou réseau

Missions spatiales: ACRIM/SMM, Phobos/IPHIR, SOHO, MOST, CoRoT, Kepler...

Réseau au sol: BiSON, IRIS, GONG, SONG



Espace ou réseau

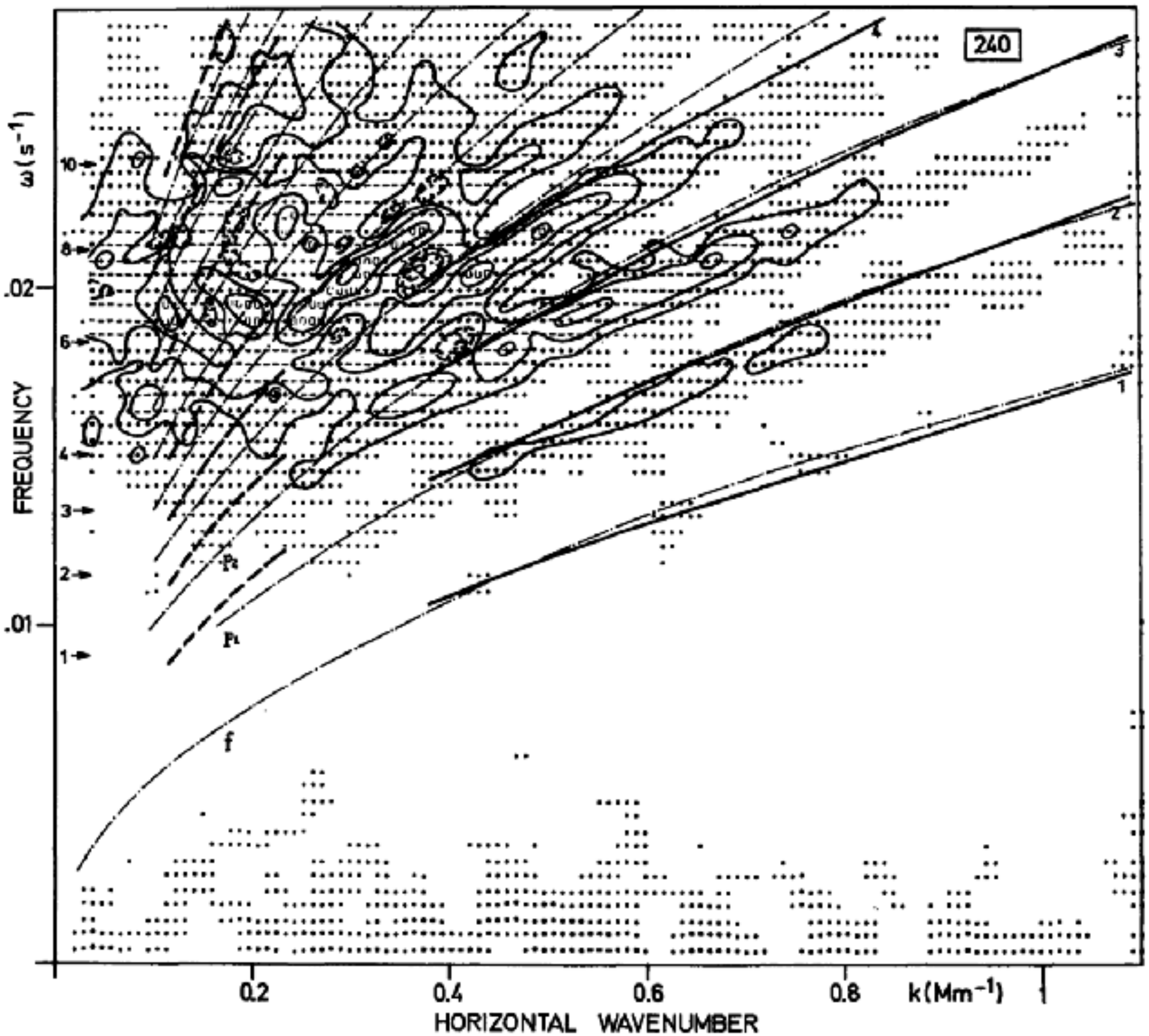
Missions spatiales: ACRIM/SMM, Phobos/IPHIR, SOHO

Réseaux au sol: BiSON, IRIS, GONG

Réseau BiSON

Petite respiration

Résultats héliosismiques

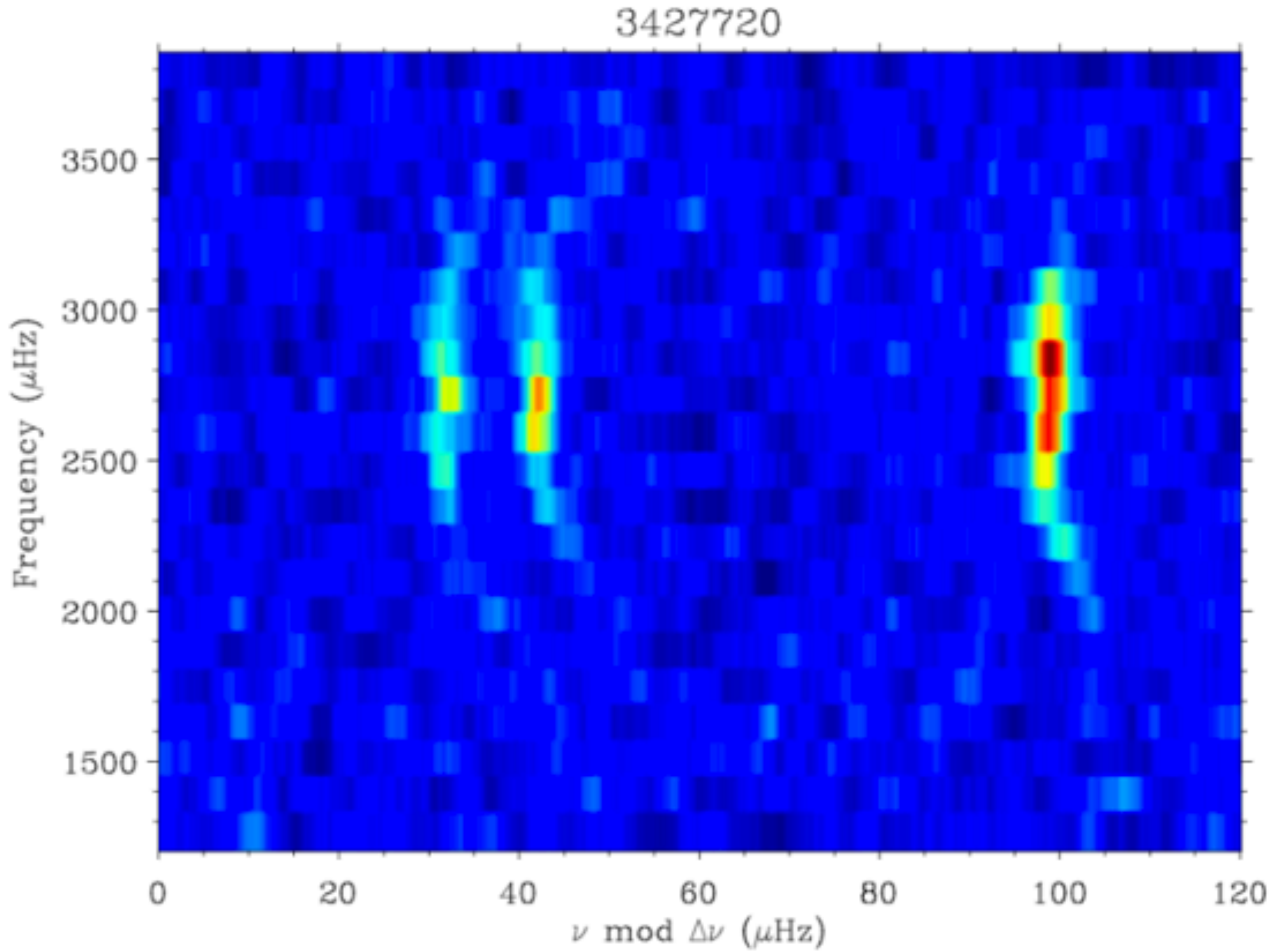


Fréquences observées pas loin des fréquences théoriques…

On a tout compris ?!?

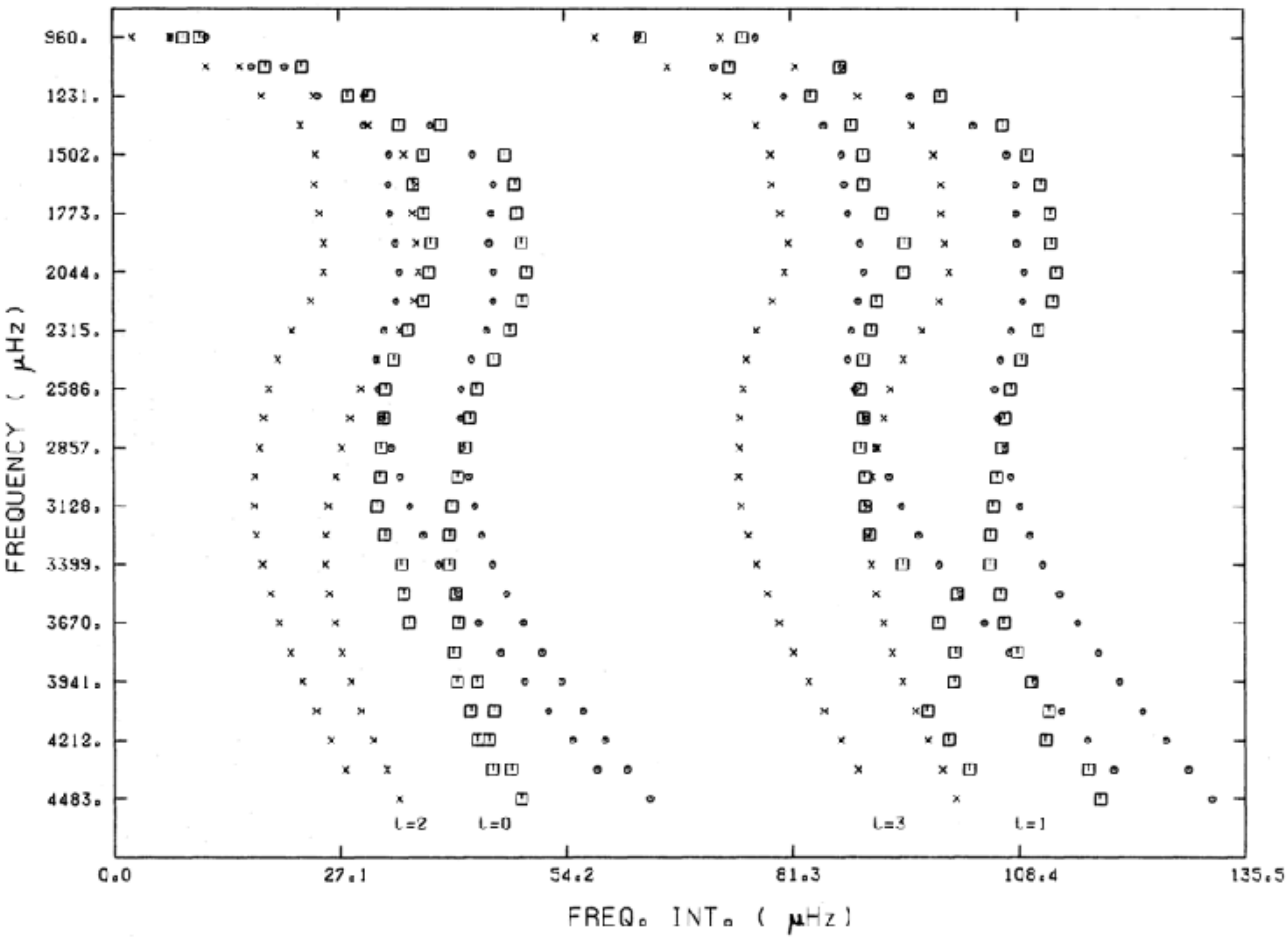
Deubner 1975

Résultats héliosismiques



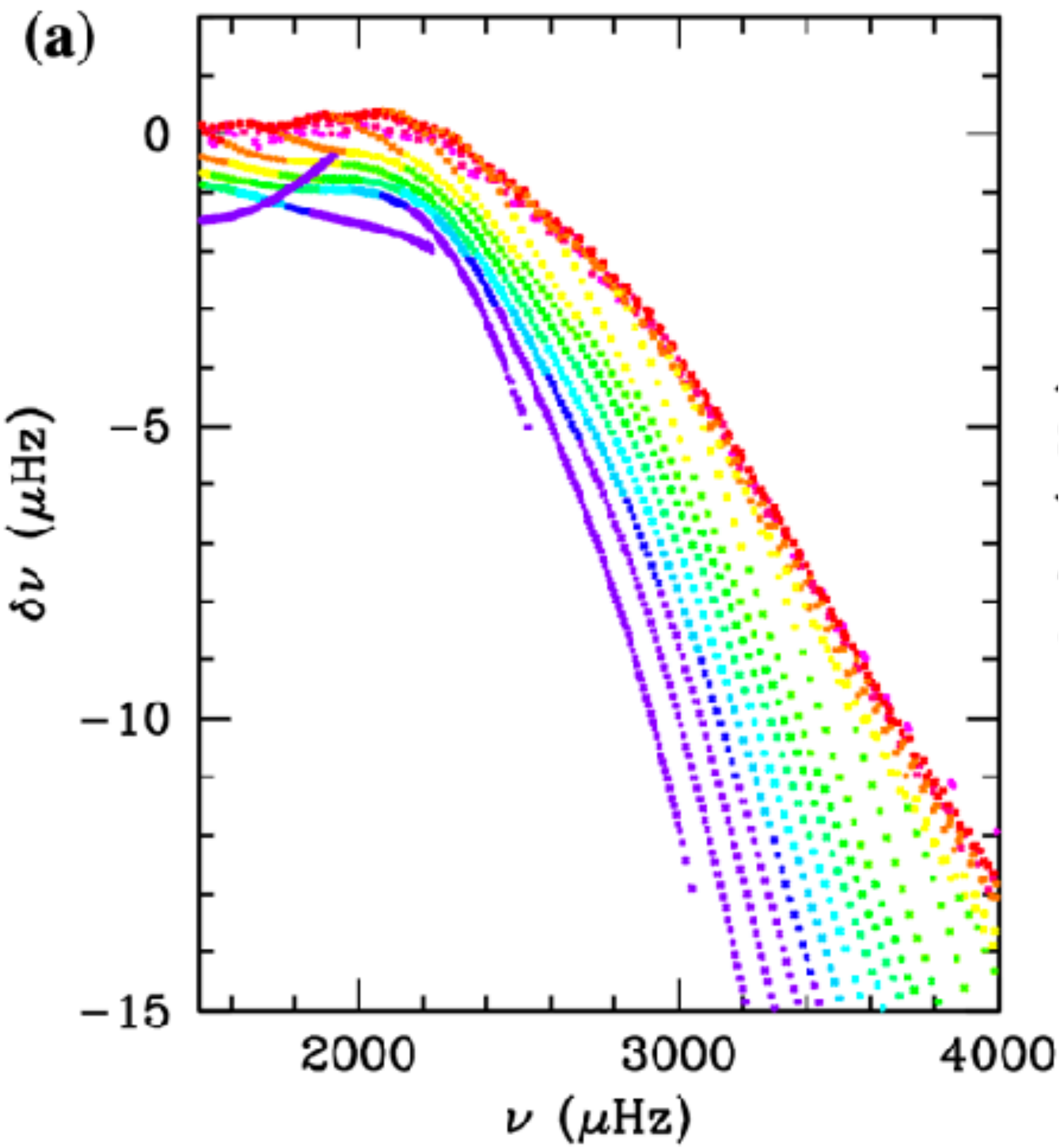
Une autre manière de visualiser la régularité des modes (de bas degré): le diagramme échelle

Observation/théorie



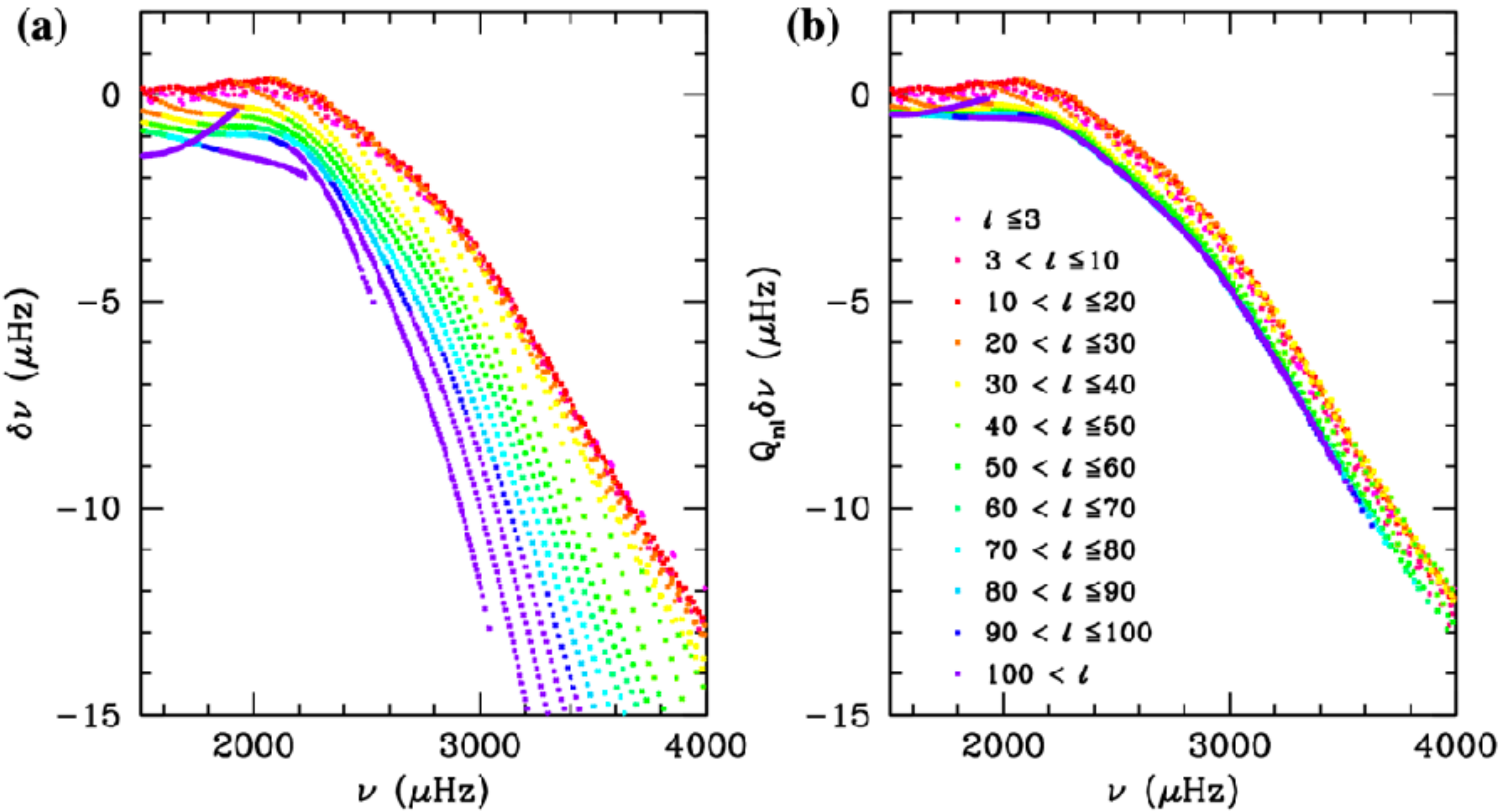
Anguera Gubau et al 1992

Observation/théorie



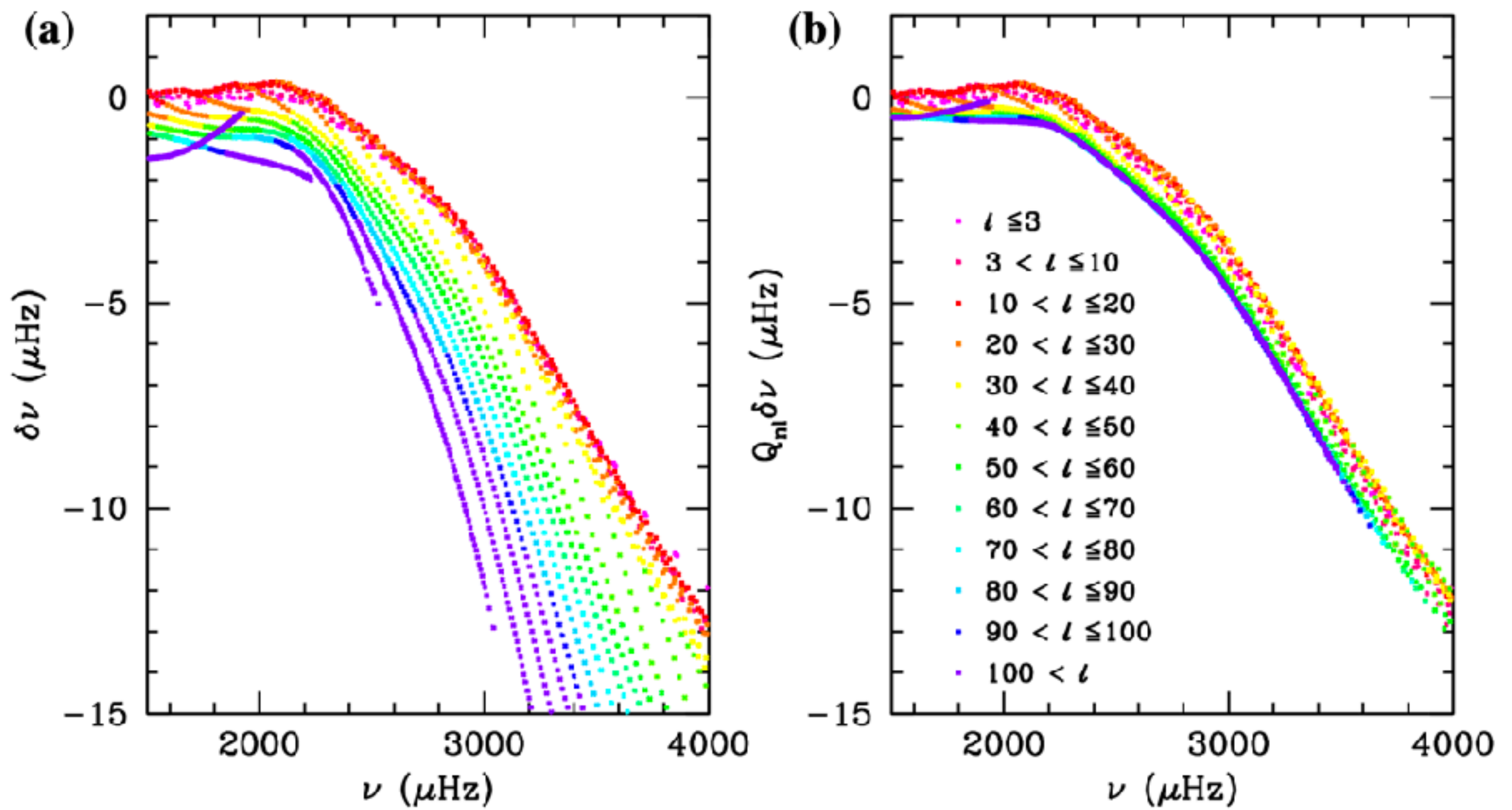
Basu 2016

Observation/théorie



Basu 2016

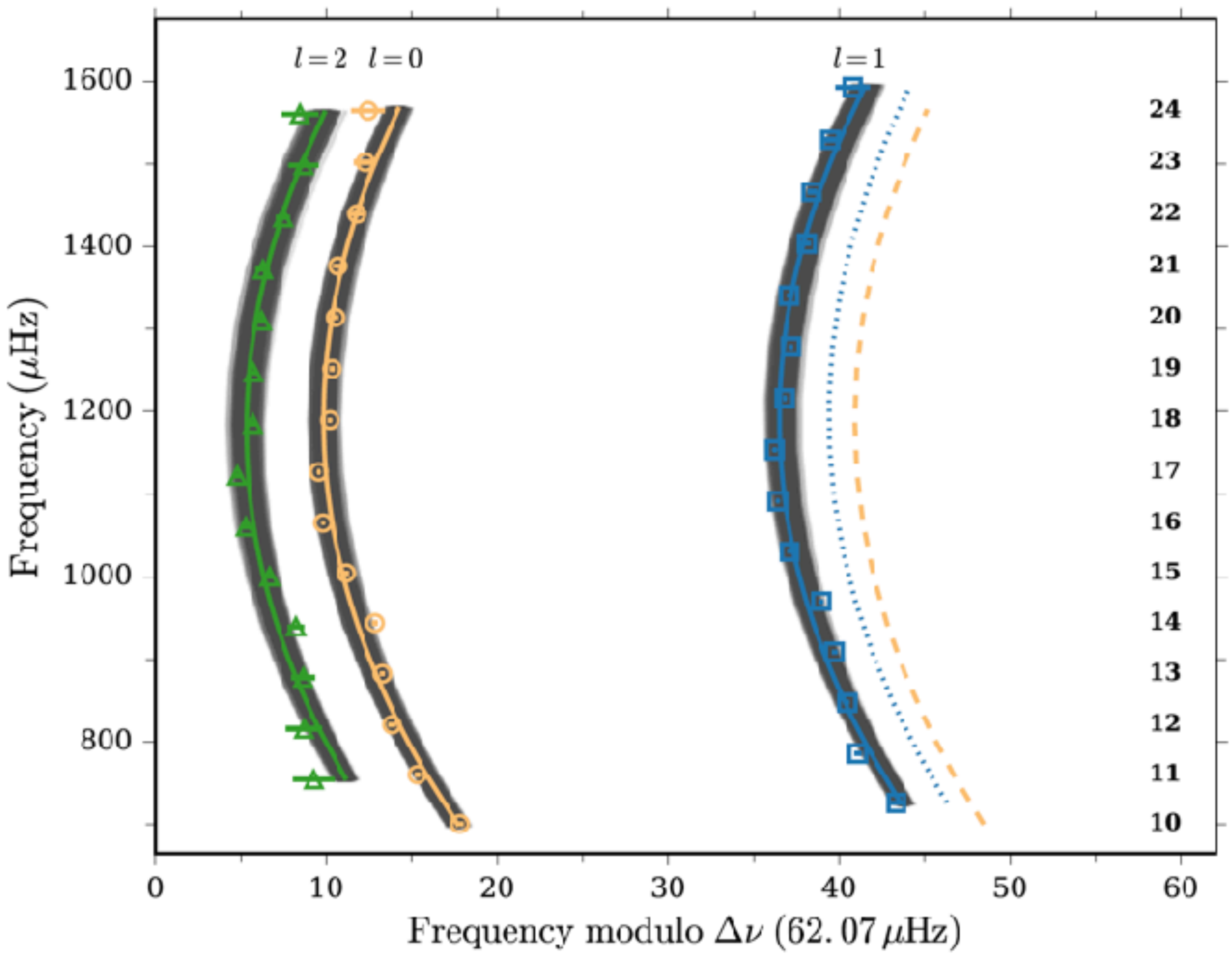
Observation/théorie



=> Mauvaise description des couches les plus externes (effets non-adiabatiques)

Basu 2016

Et l'astérosismolgie fût...

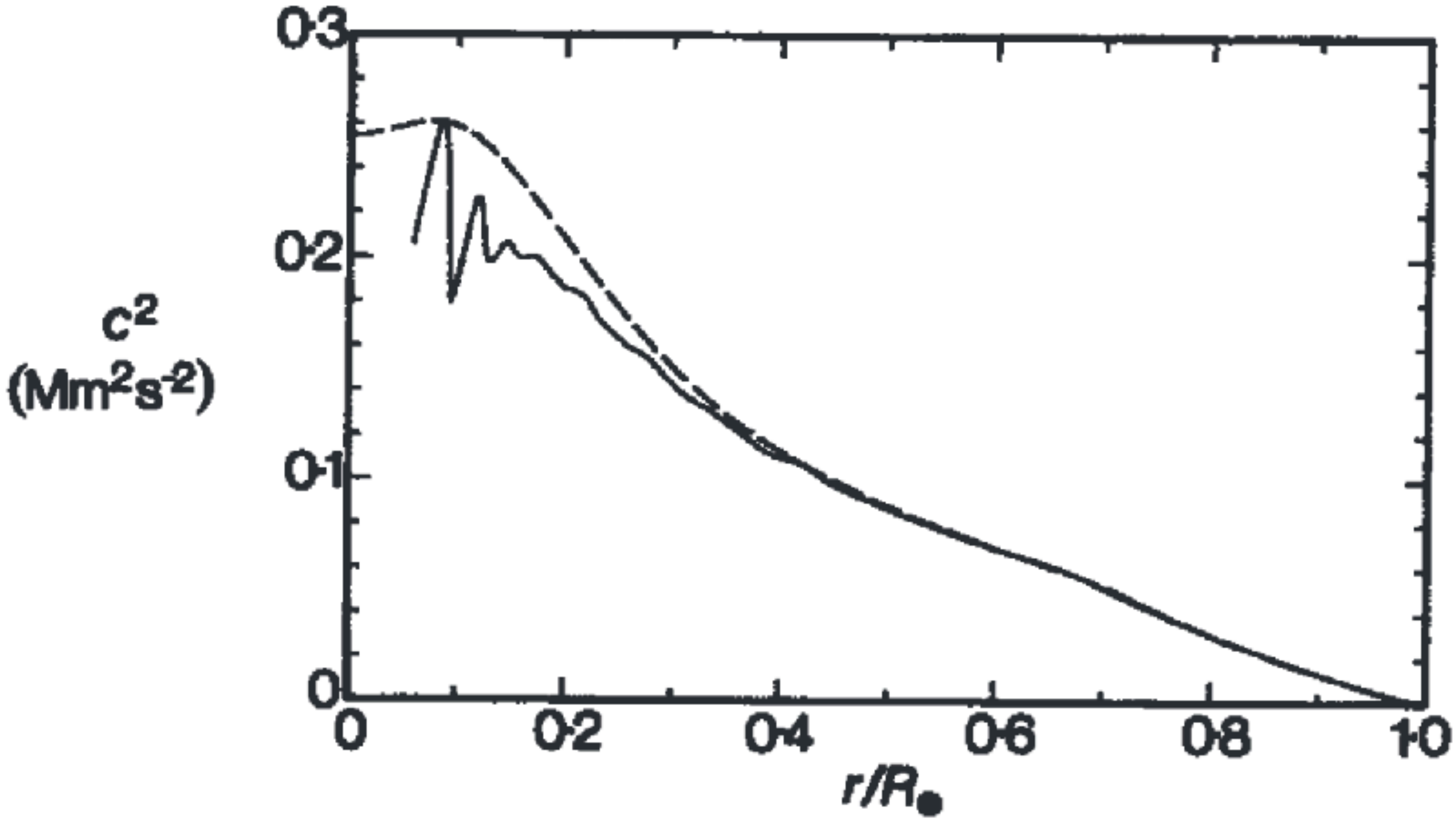


Lund et al 2017

Oscillations => information sur des discontinuité dans la structure interne de l'étoile

Résultats héliosismiques

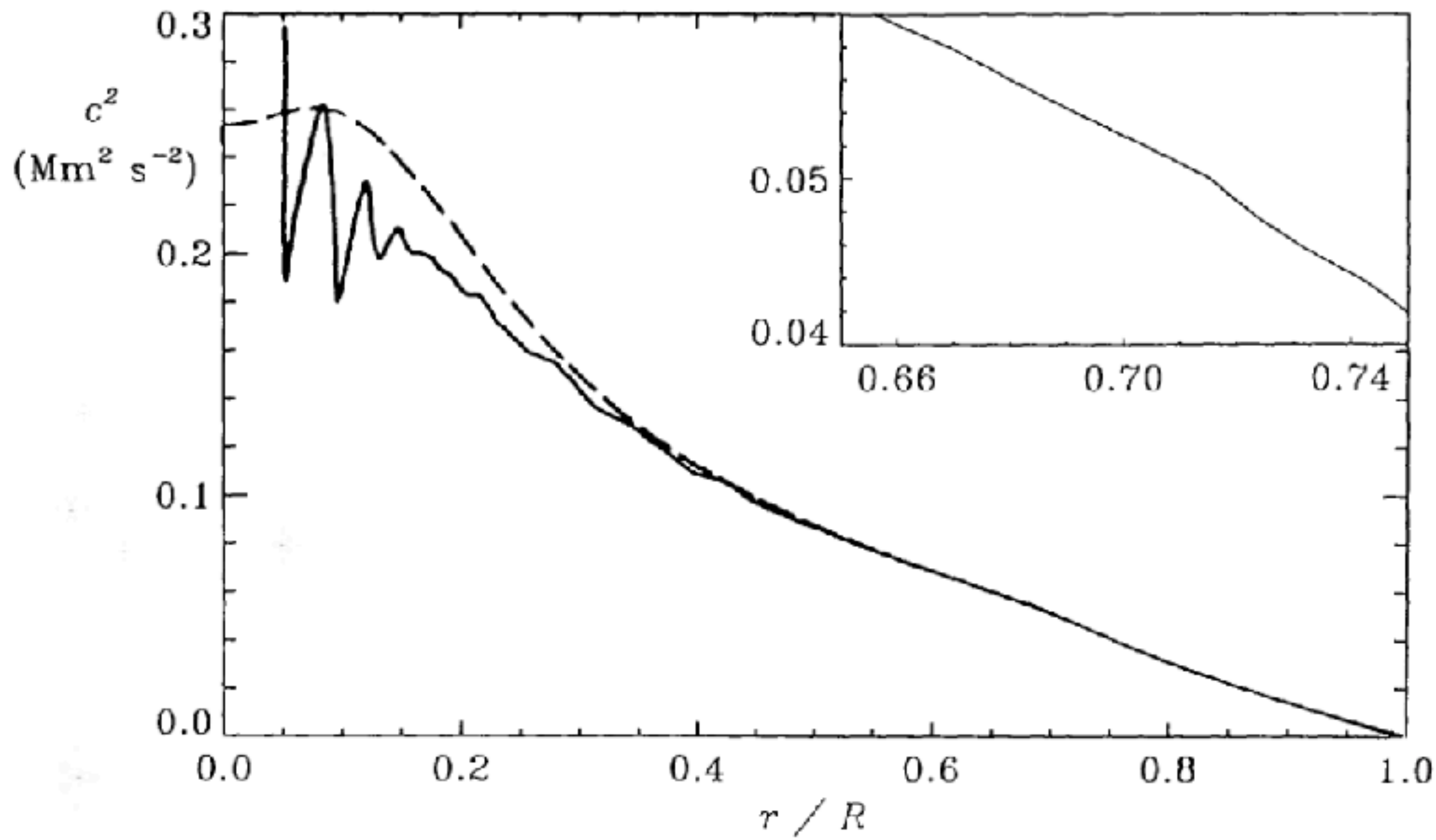
Inversion des fréquences => Vitesse du son en fonction du rayon



Christensen-Dalsgaard et al 1985

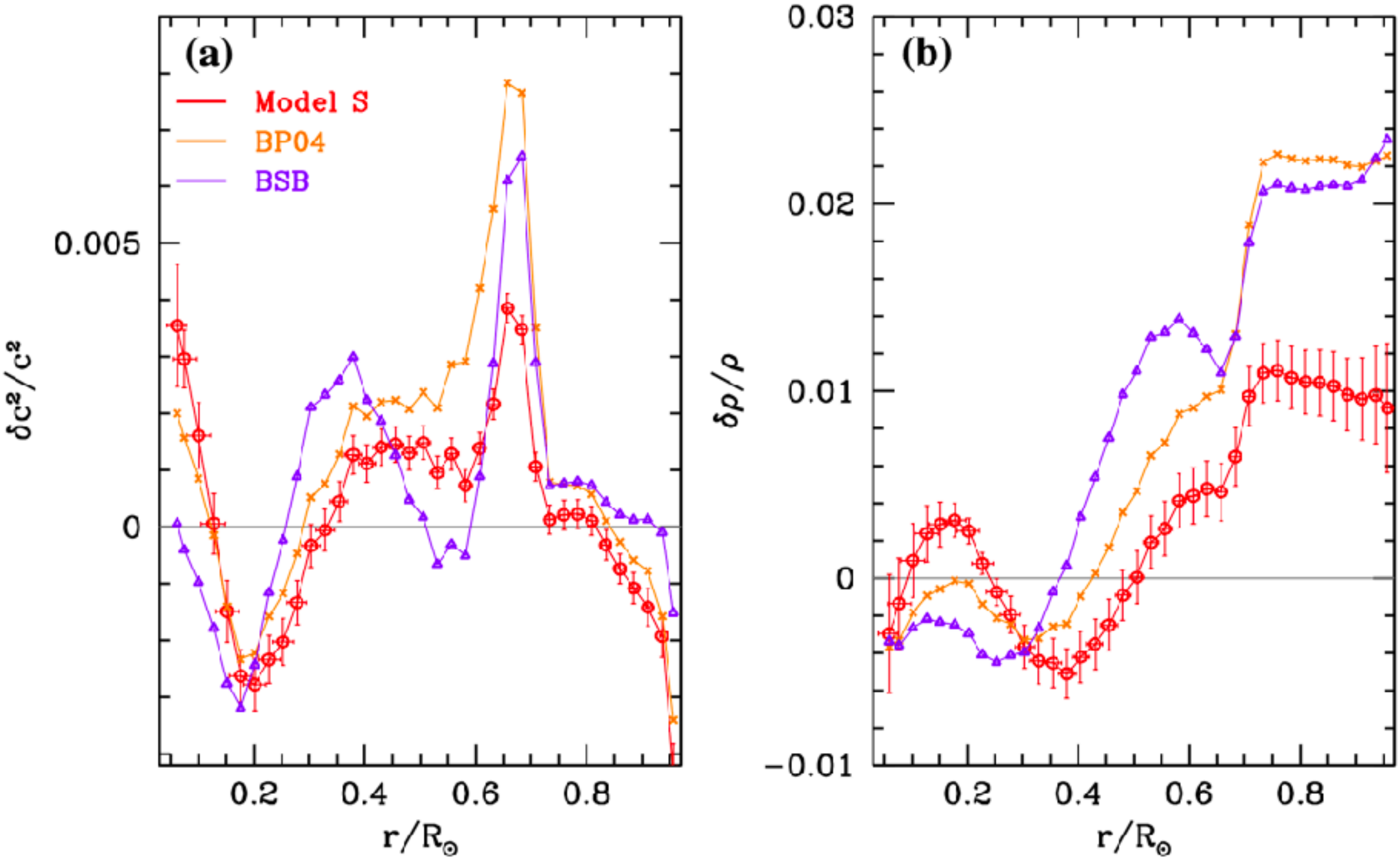
Résultats héliosismiques

Inversion des fréquences => Vitesse du son en fonction du rayon



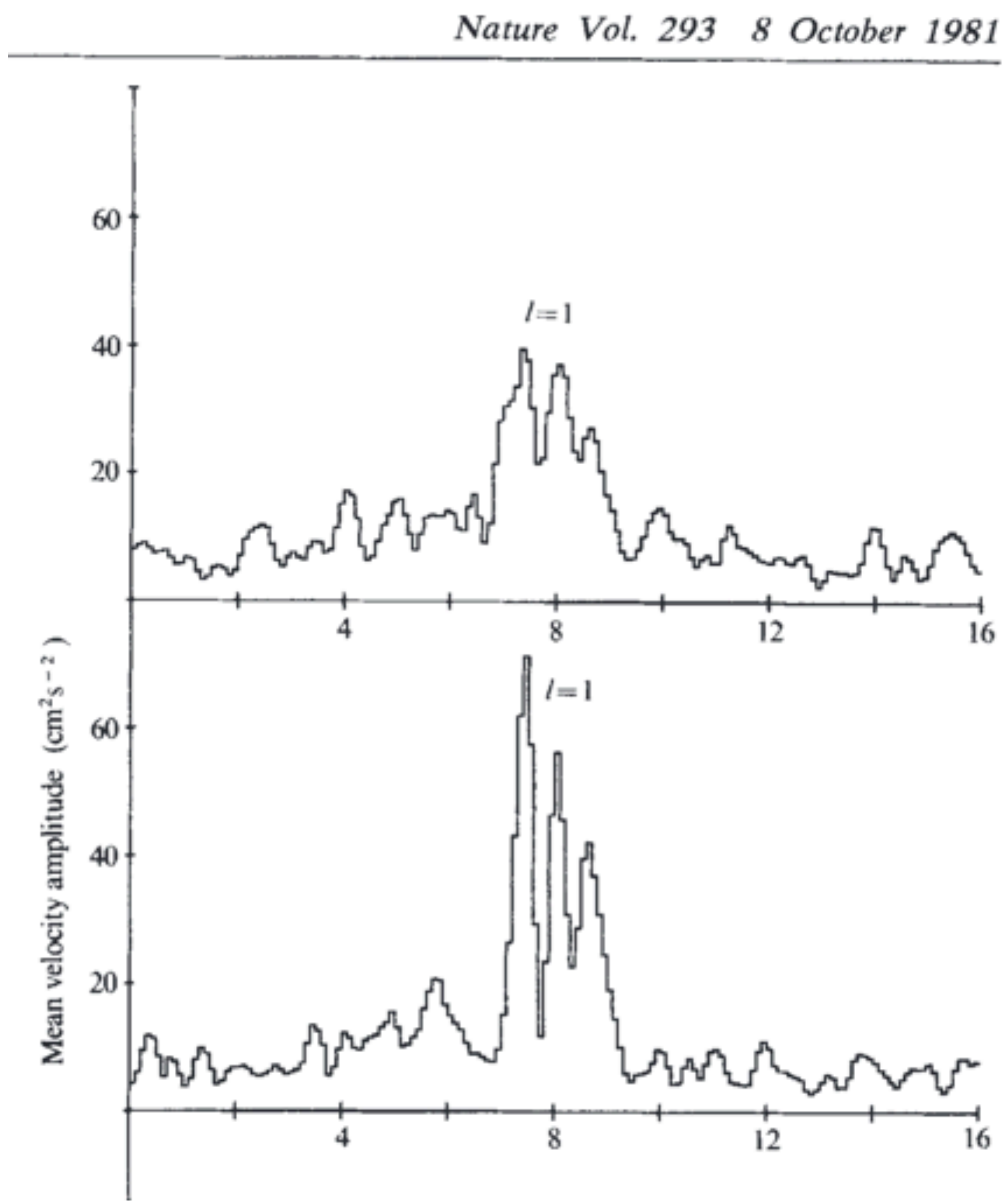
Christensen-Dalsgaard et al 1991

Observation/théorie



Basu 2016

Résultats héliosismiques

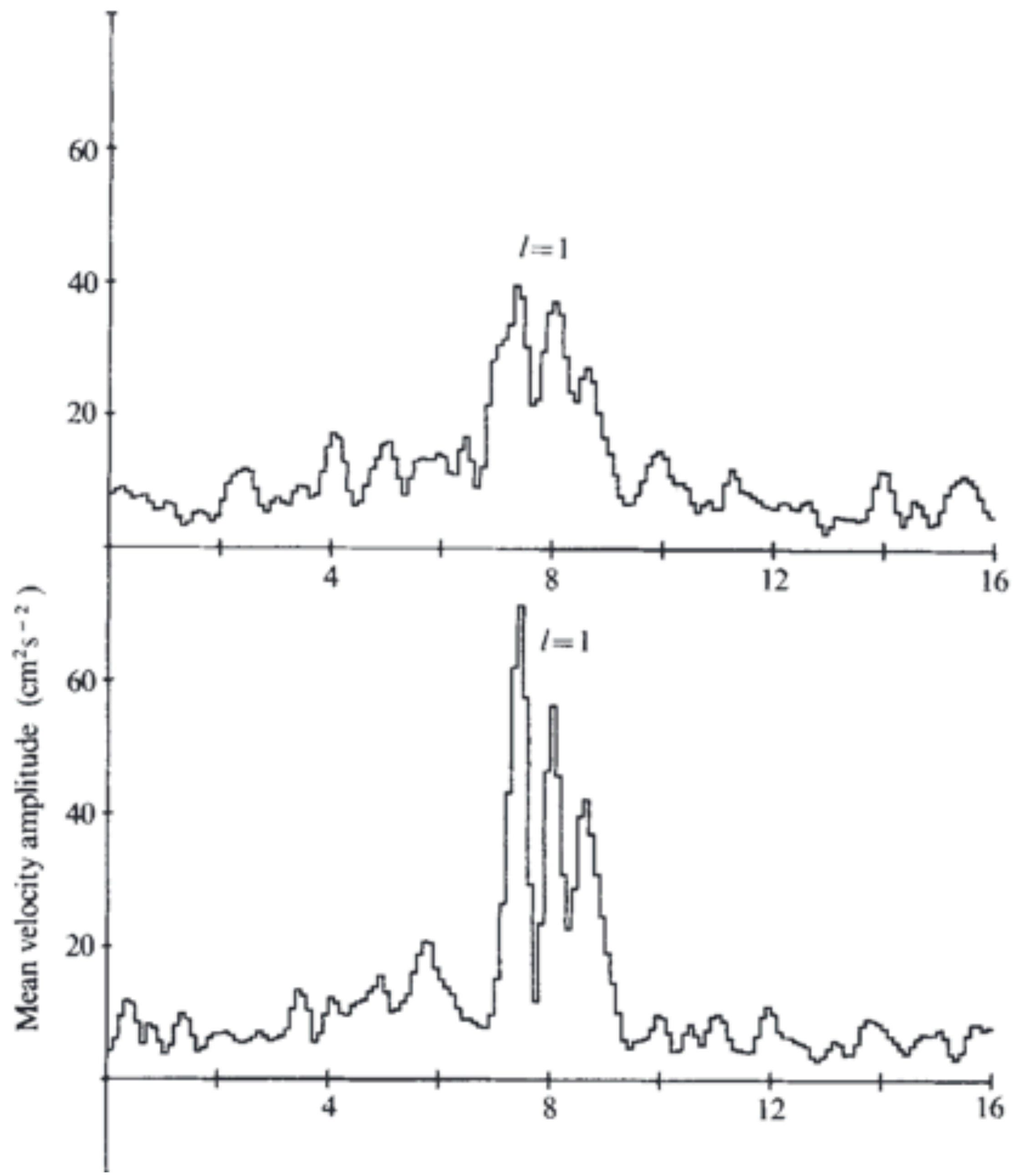


=> rotation du coeur en 13j

Claverie et al 1981

Résultats héliosismiques

Nature Vol. 293 8 October 1981



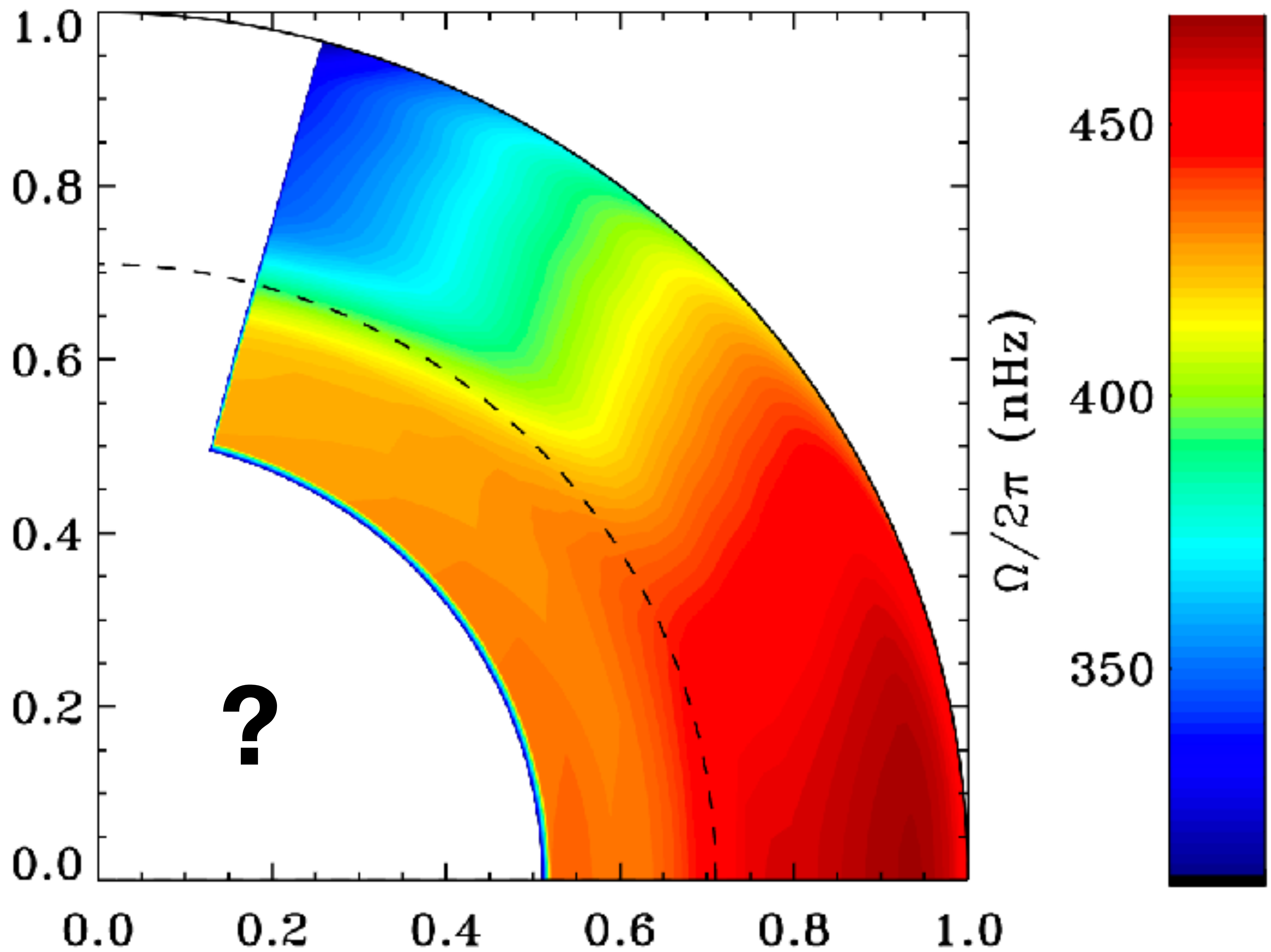
=> rotation du coeur en 13j

observing conditions during the 1980 season and a possibly noisy source as the measurements were made during the solar maximum. The widths of the $l=0$ and $l=1$ peaks (0.5 μHz) should be compared with the intrinsic resolution of the data set of $\sim 1/T$ (0.43 μHz) where T is the length of the set in seconds. Hence the width observed is consistent with the intrinsic frequency resolution and thus indicative of high Q oscillations.

Assuming that all the splitting determinations have equal statistical weight yields a mean value of 0.75 μHz. This should be compared with the anticipated uniform rotation value of 0.4 μHz. The core of the Sun therefore indisputably rotates faster than the observed surface. Such a result eliminates some of the theories of differential rotations of the solar surface, as these require that the solar interior rotates more slowly than the

Claverie et al 1981

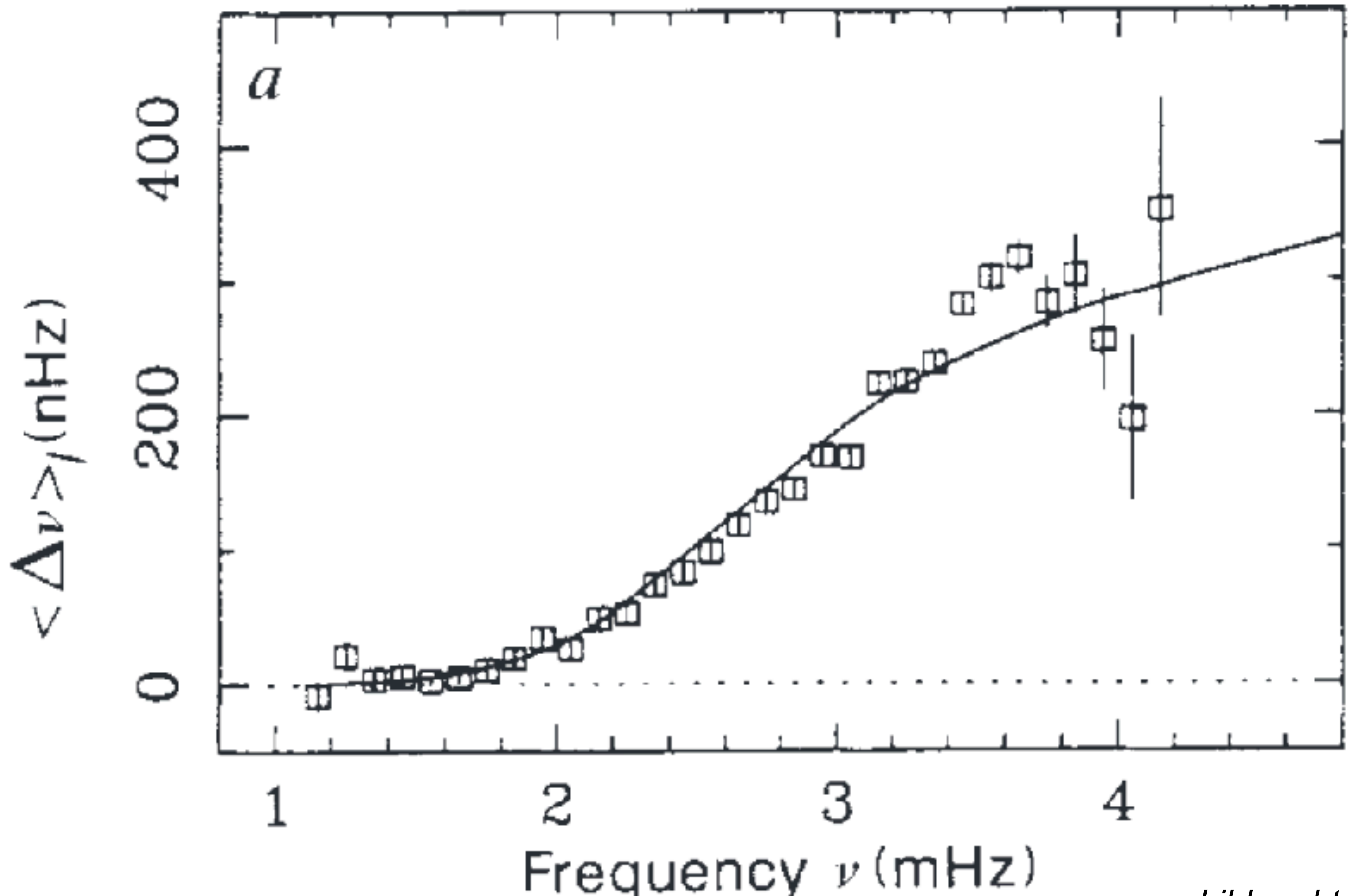
Résultats héliosismiques



Basu 2016

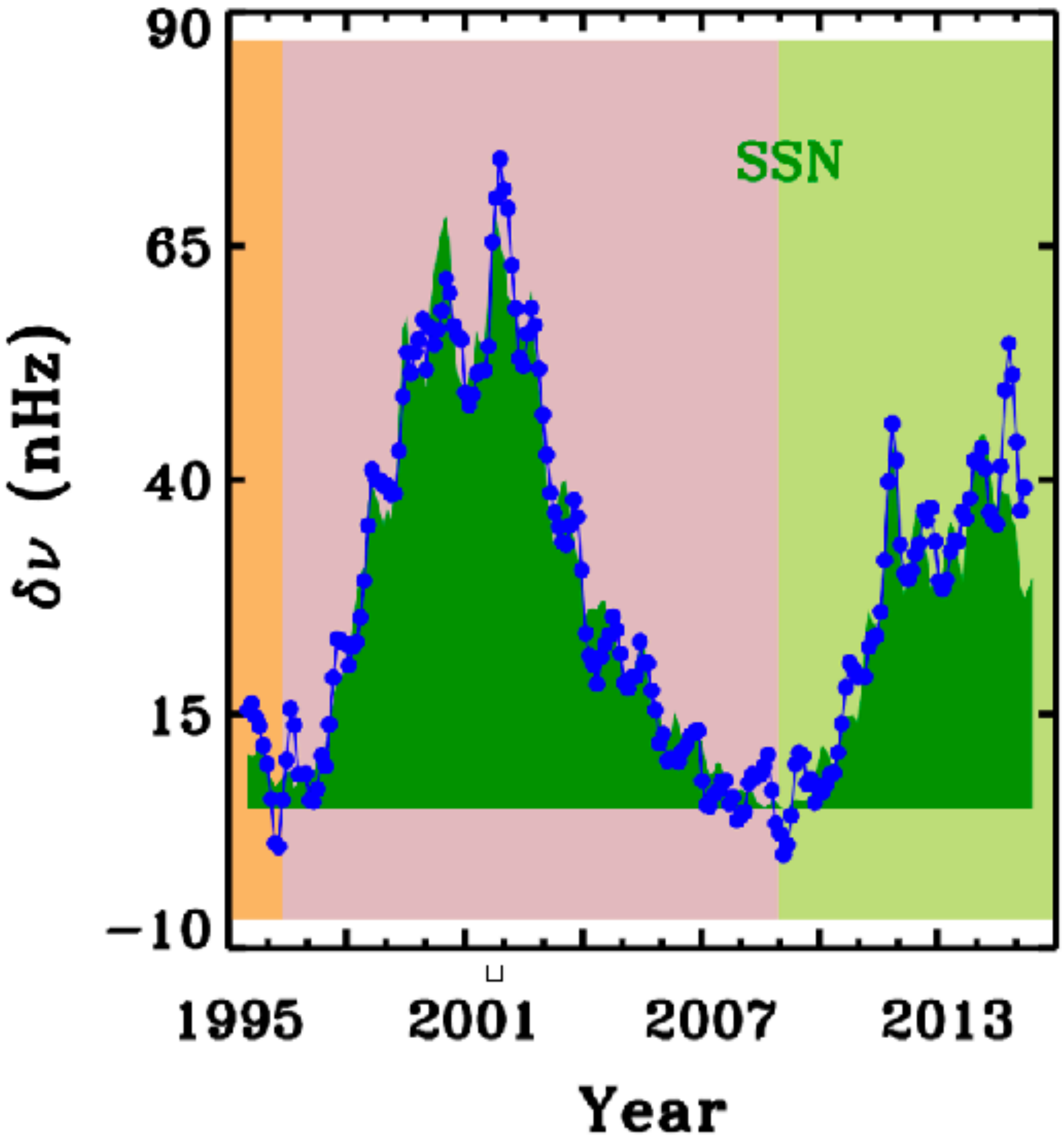
Entrée en scène du champ magnétique

Variation de fréquence au cours du cycle magnétique



Libbrecht & Woodard 1990

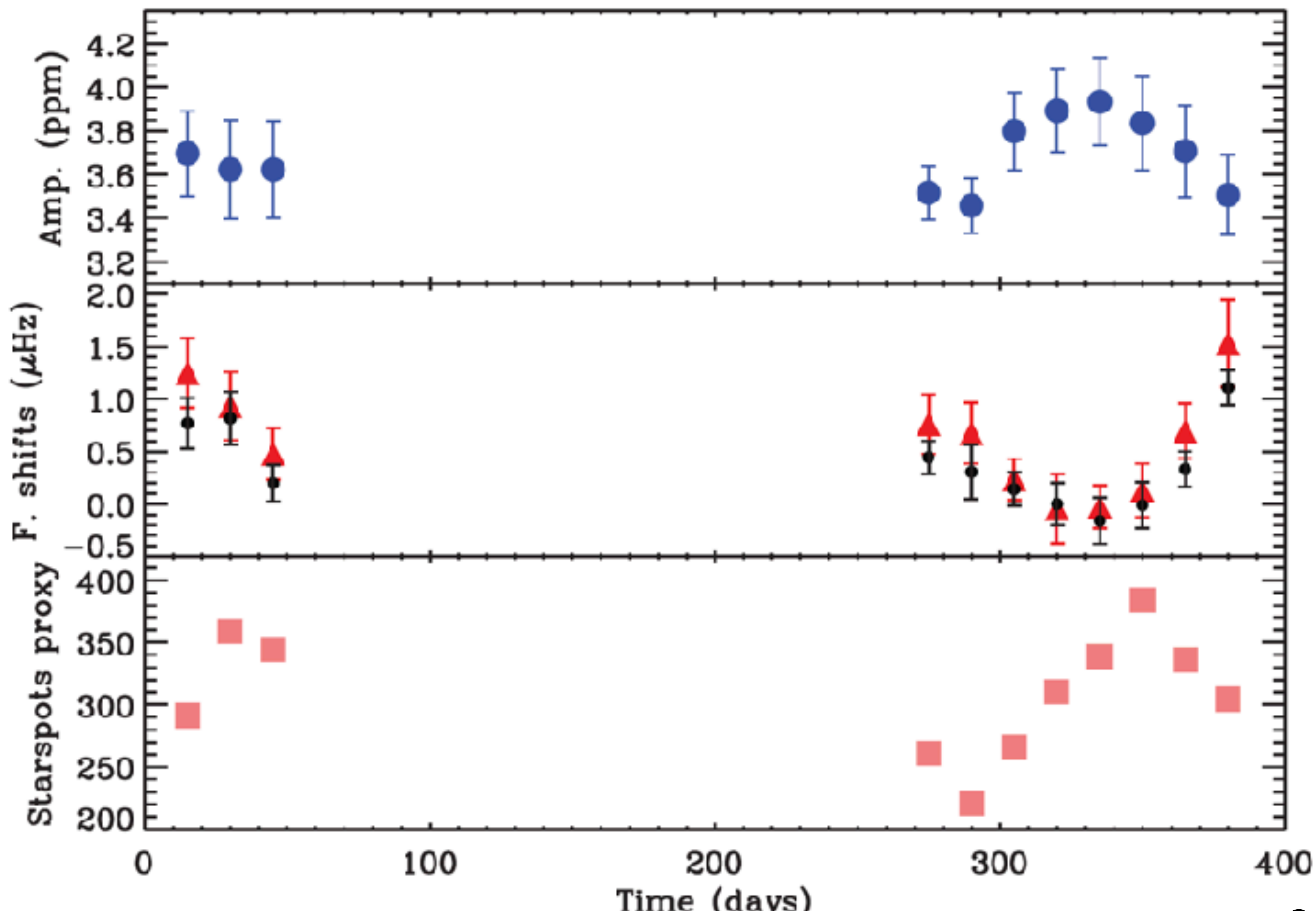
Entrée en scène du champ magnétique



Fréquences des modes d'oscillation corrélées avec le champ magnétique

Basu 2016

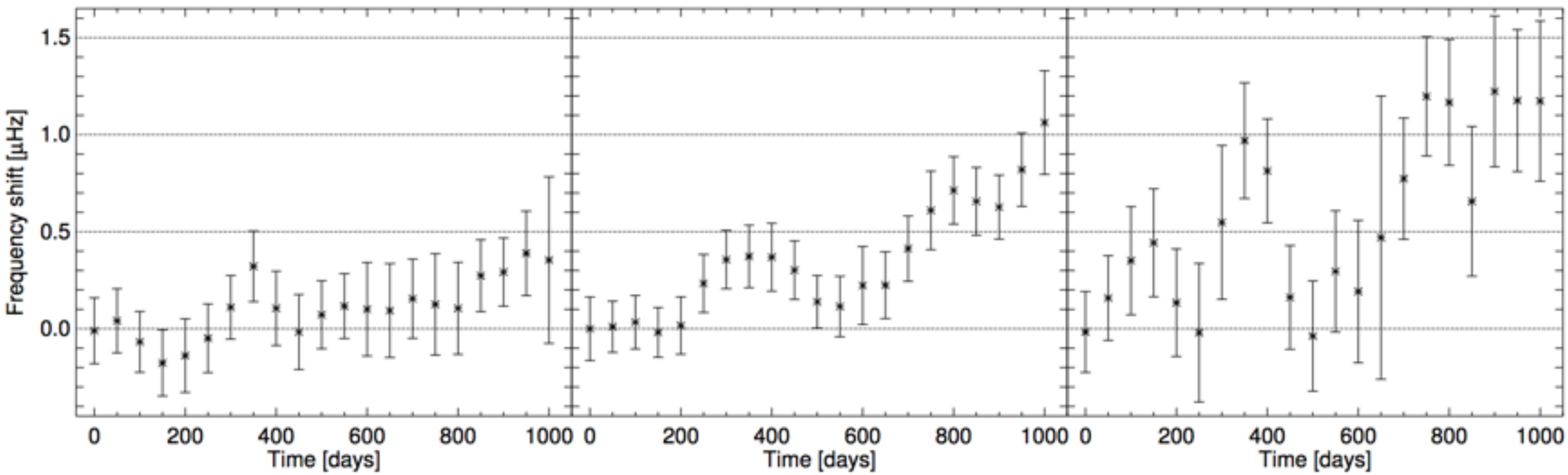
Entrée en scène du champ magnétique



Garcia et al 2010

Variations de fréquences anti-corrélées avec l'amplitude et corrélées avec un indice d'activité magnétique

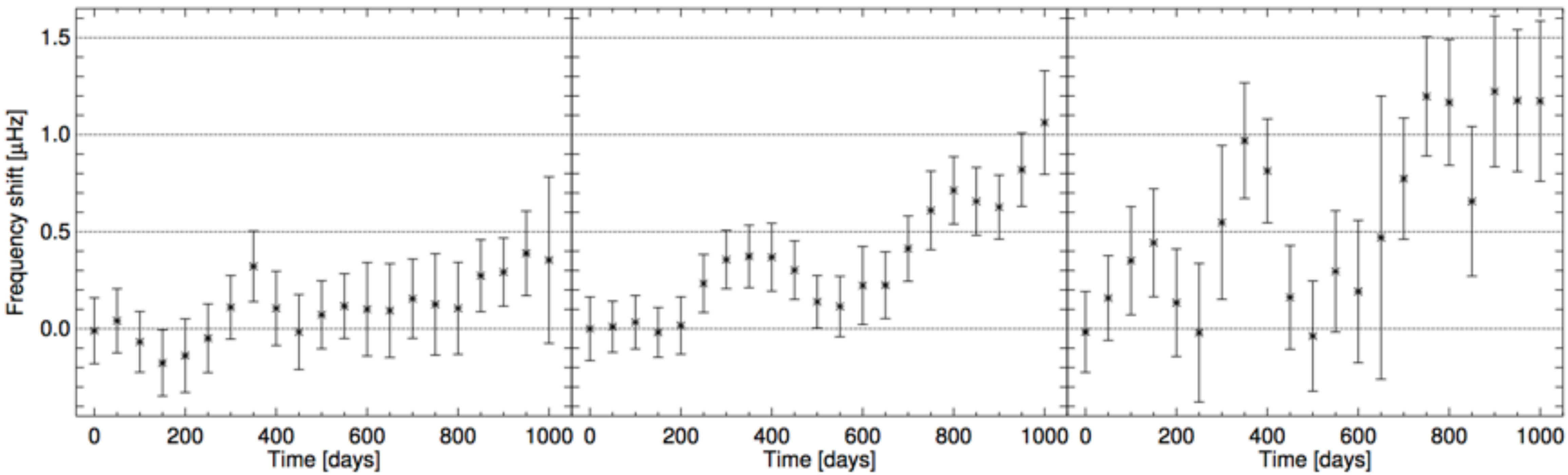
Les péripéties magnétiques



Kiefer et al 2017

Variations de fréquences pour 23 étoiles sur 24

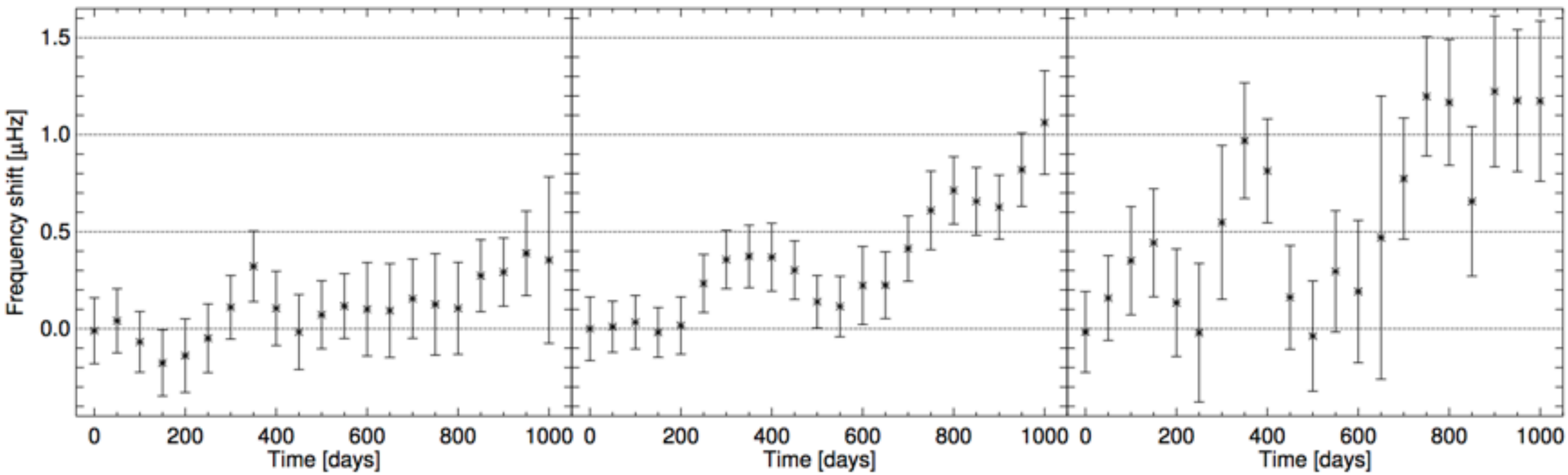
Les péripéties magnétiques



Variations de fréquences pour 23 étoiles sur 24
Variations de fréquences anti-corrélées avec l'amplitude pour 7 étoiles sur 24…

Kiefer et al 2017

Les péripéties magnétiques



Variations de fréquences pour 23 étoiles sur 24
Variations de fréquences anti-corrélées avec l'amplitude pour 7 étoiles sur 24…
mais corrélées avec l'amplitude pour 6 étoiles sur 24!

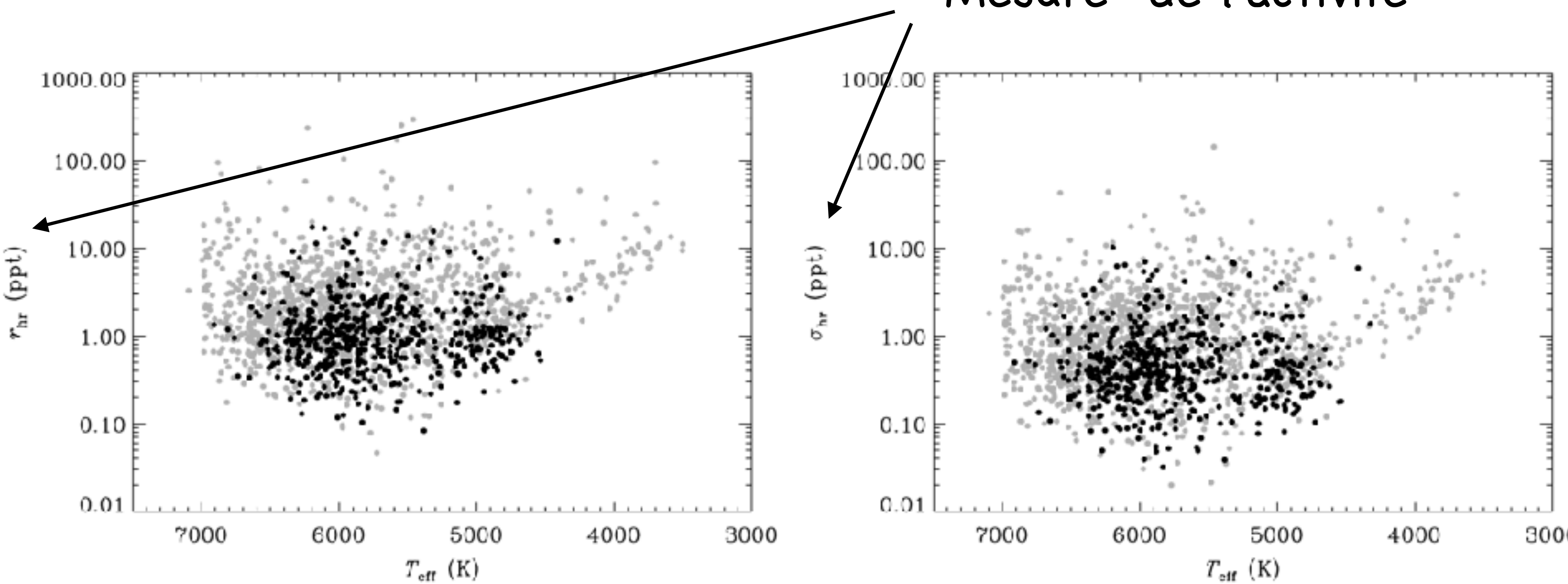
Kiefer et al 2017

Les péripéties magnétiques

Etoiles avec oscillations détectées

Etoiles sans oscillations détectées

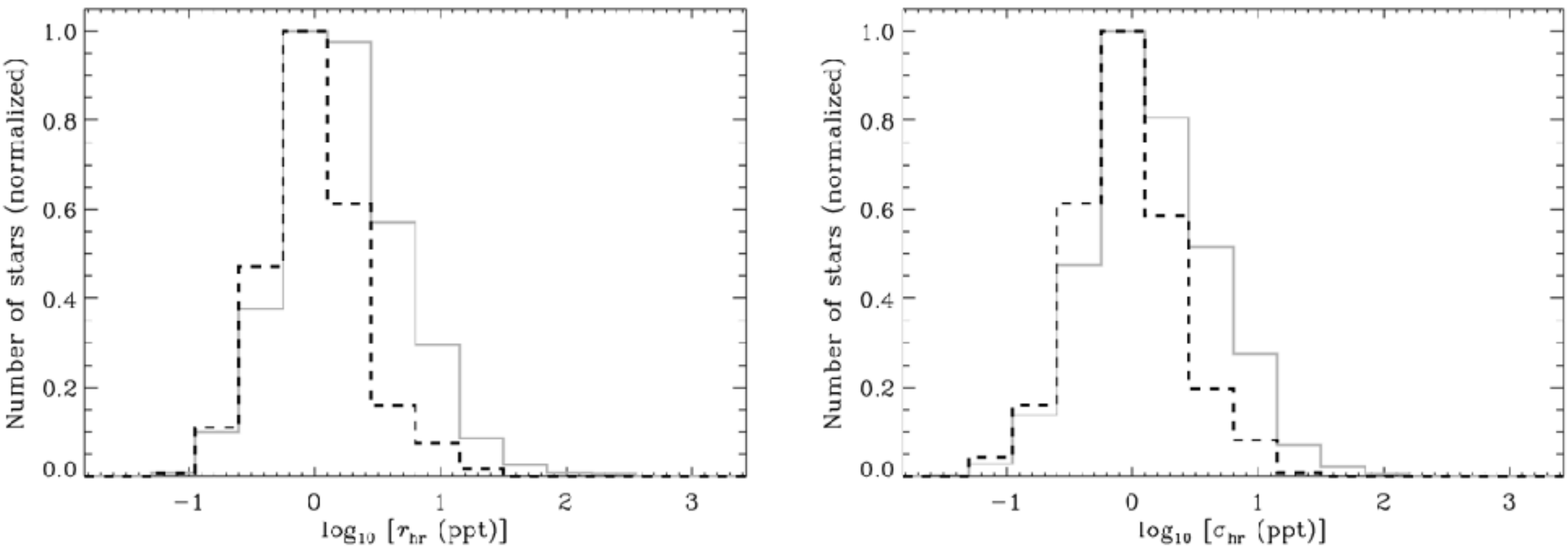
"Mesure" de l'activité



Chaplin et al 2011

Amplitudes des modes d'oscillation
corrélées avec le champ magnétique

Les péripéties magnétiques



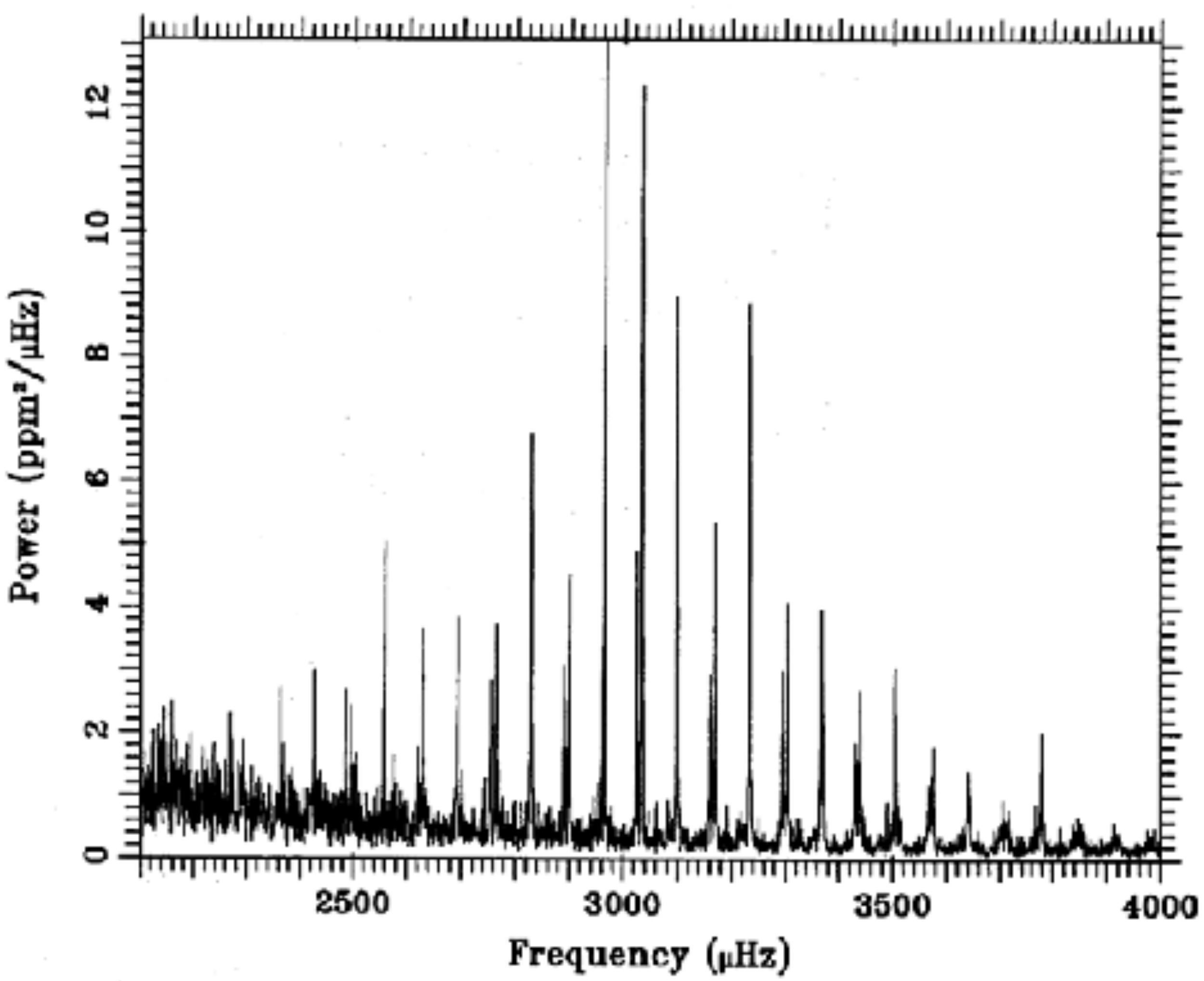
"Mesure" de l'activité

Chaplin et al 2011

Champ magnétique => modes de plus faible amplitude

Etoiles de type solaire

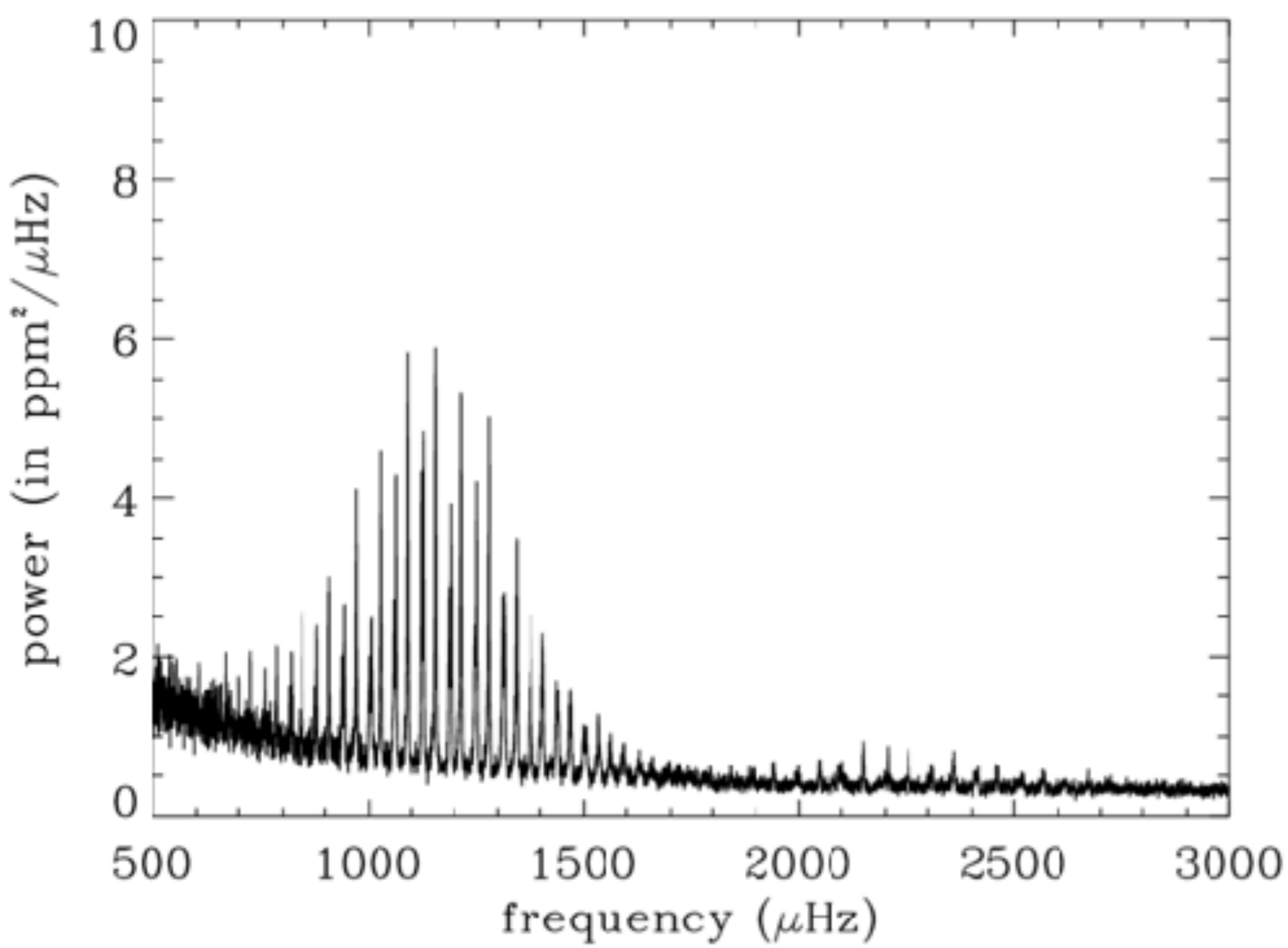
Soleil



Toutain & Fröhlich 1992

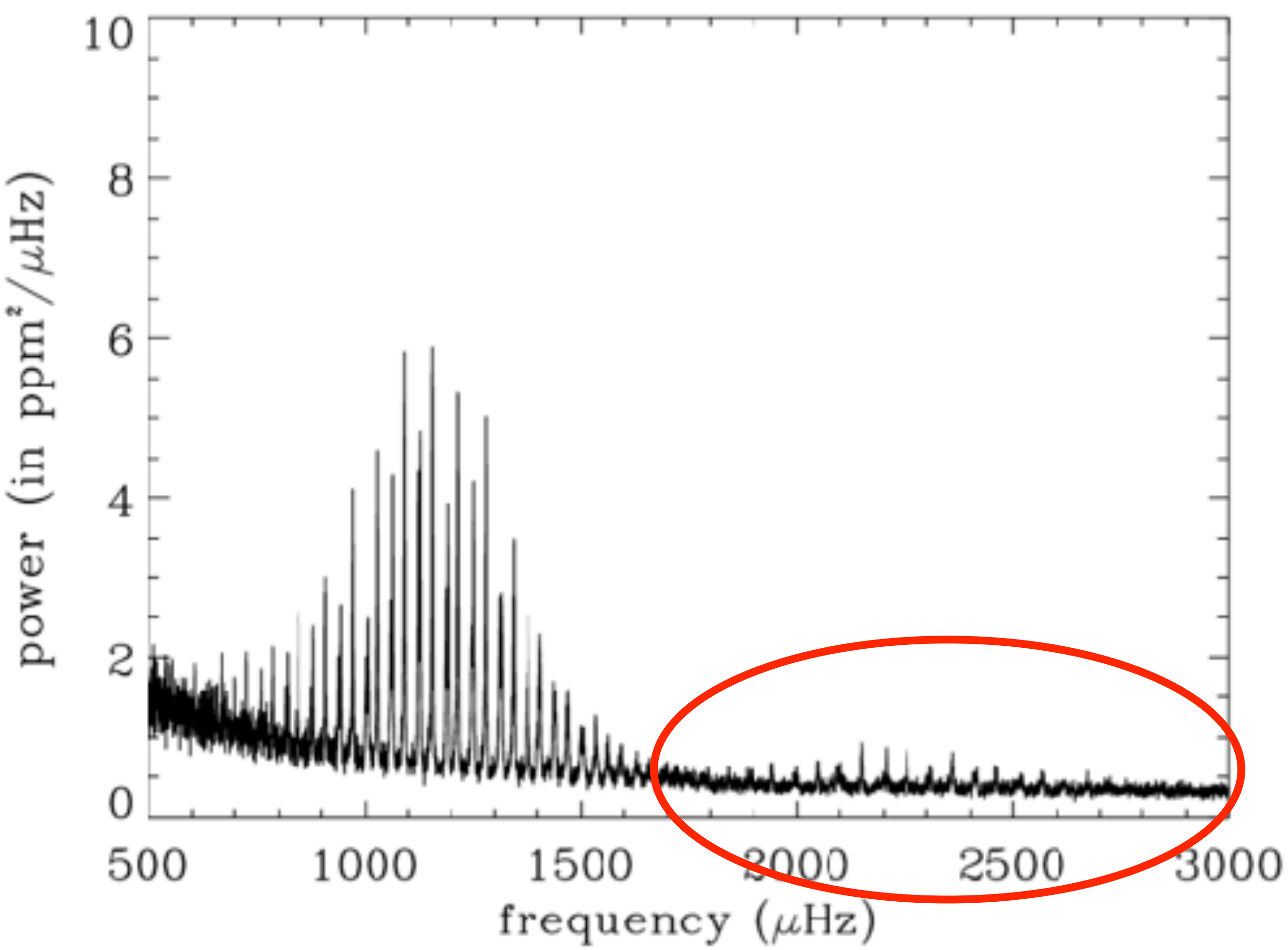
Etoile F8 V

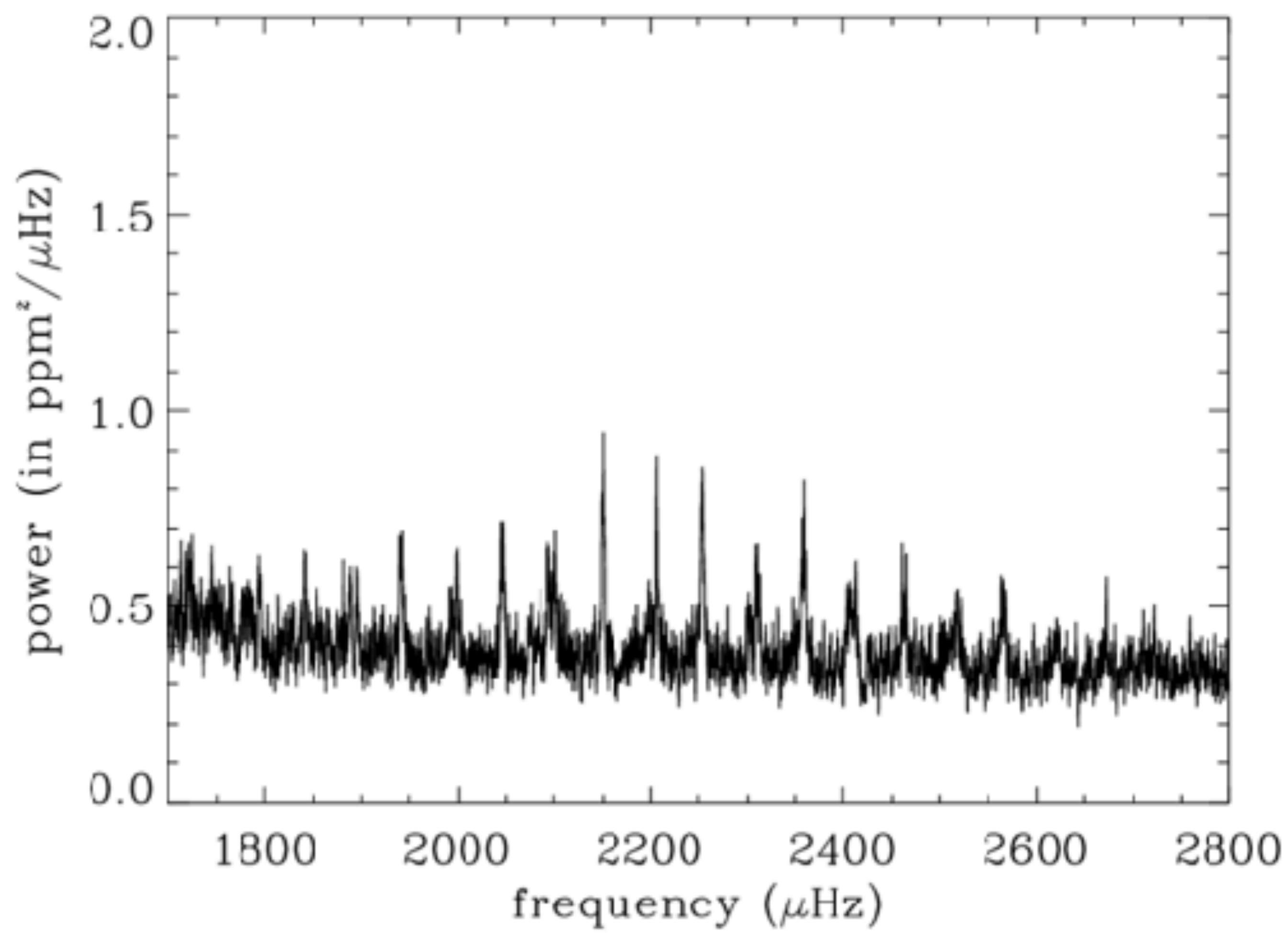
m_V=7.86



Appourchaux et al 2015

Etoiles de type solaire





Appourchaux et al 2015

Et l'astérosismolgie fût…

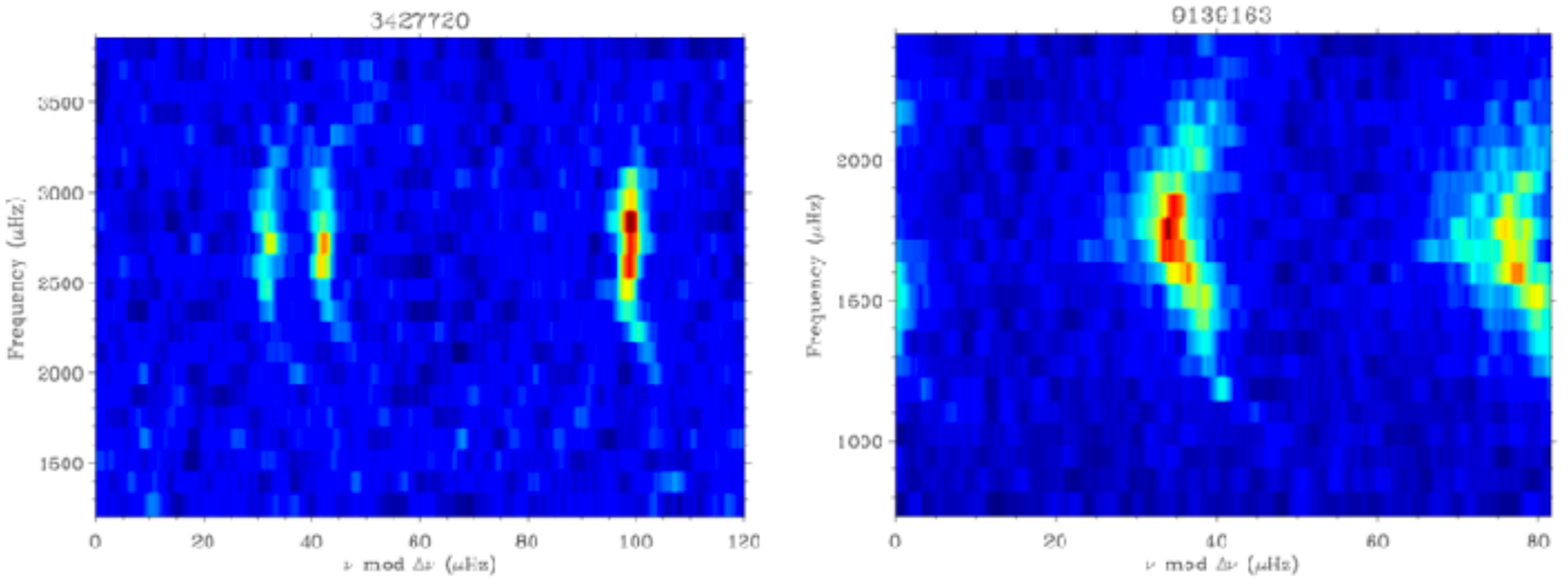
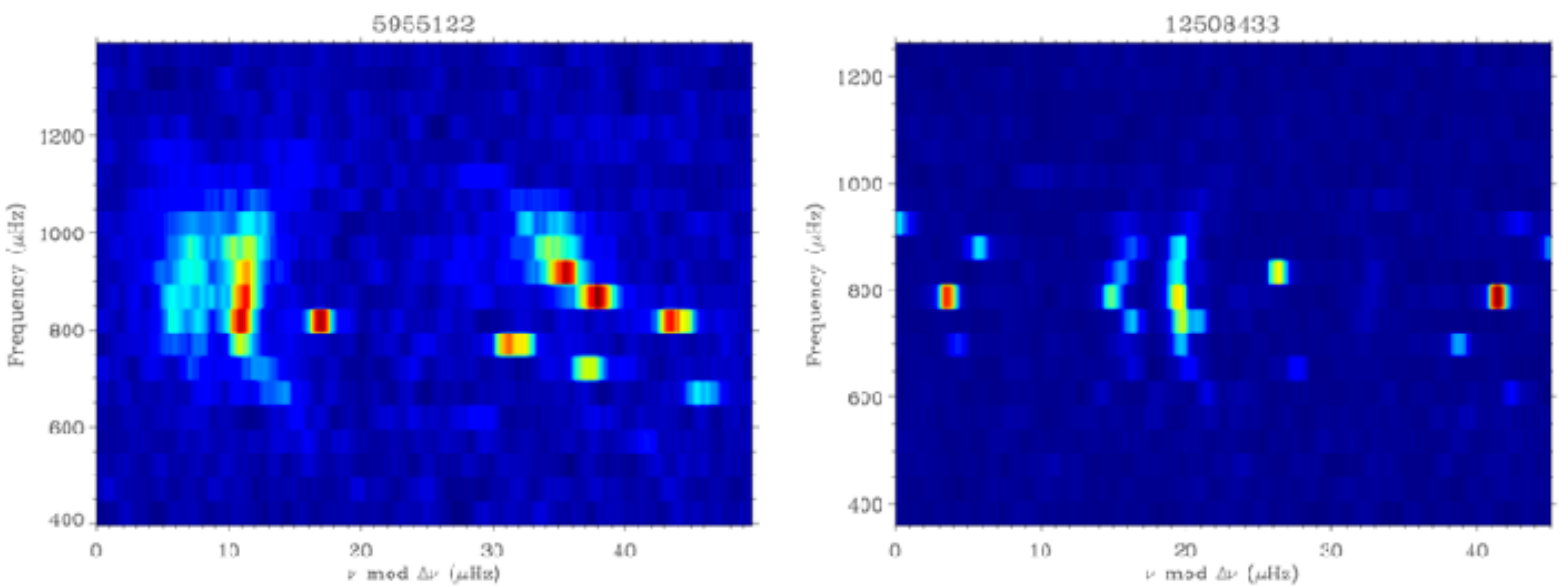


Fig. 1. Echelle diagrams of the power spectra of two *simple* stars (KIC 3427720 and KIC 9139163). The power spectra are normalised by the background and smoothed over 3 μHz.

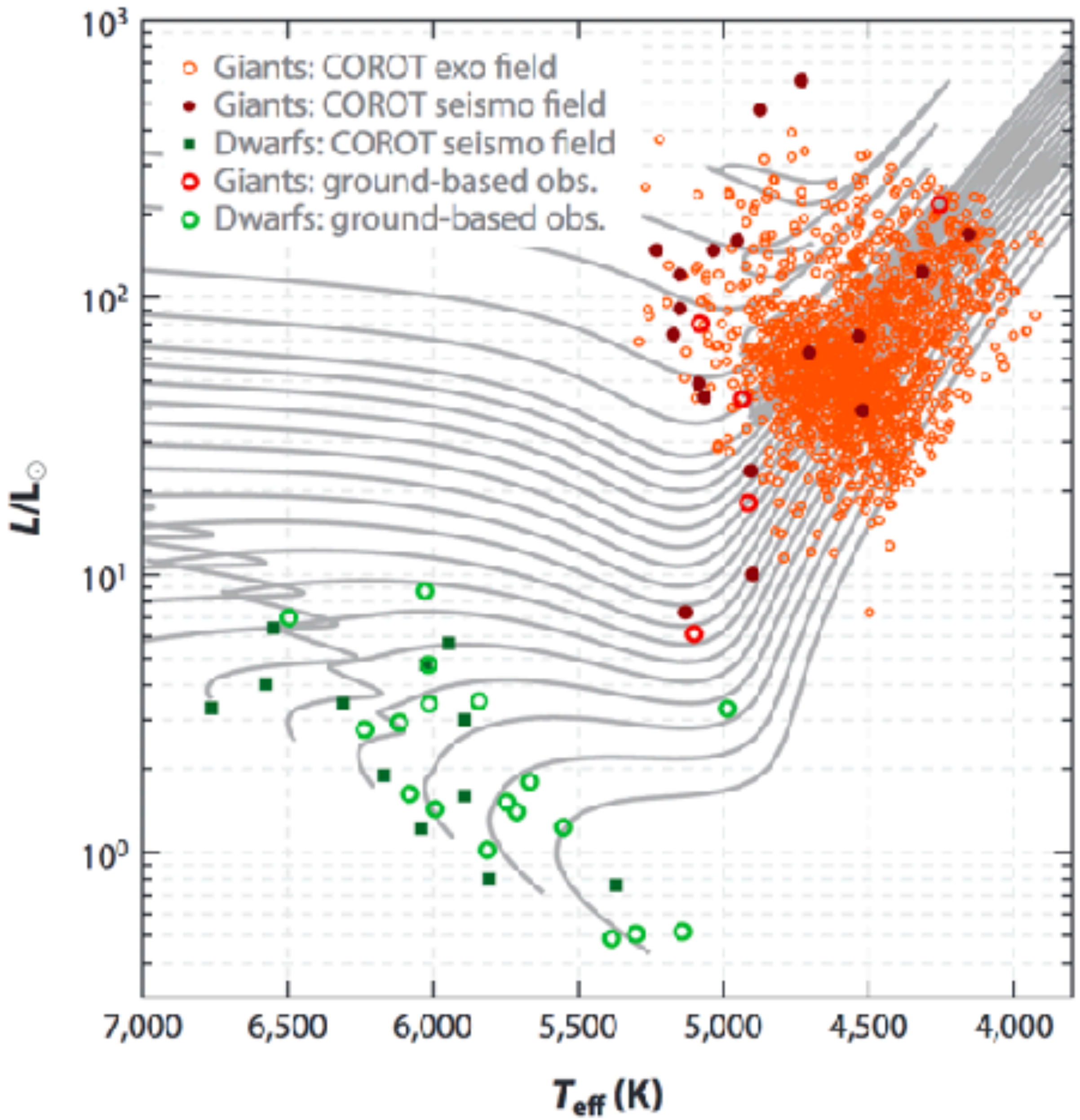


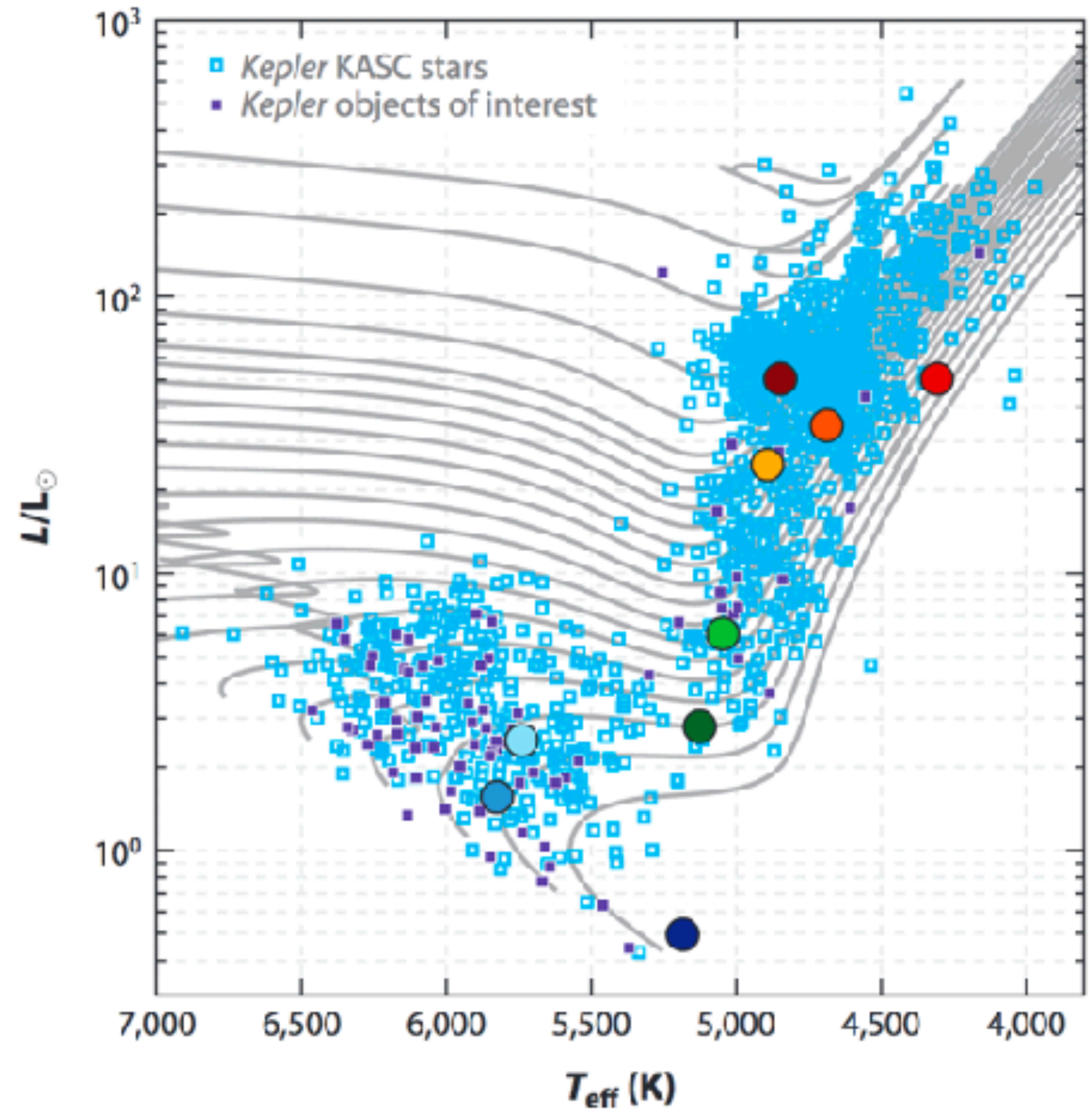
Appourchaux et al 2012

Différents "diagrammes-échelle", plus ou moins compliqués

Et l'astérosismolgie fût...

CoRoT (lancé en 2006) et Kepler (lancé en 2009)

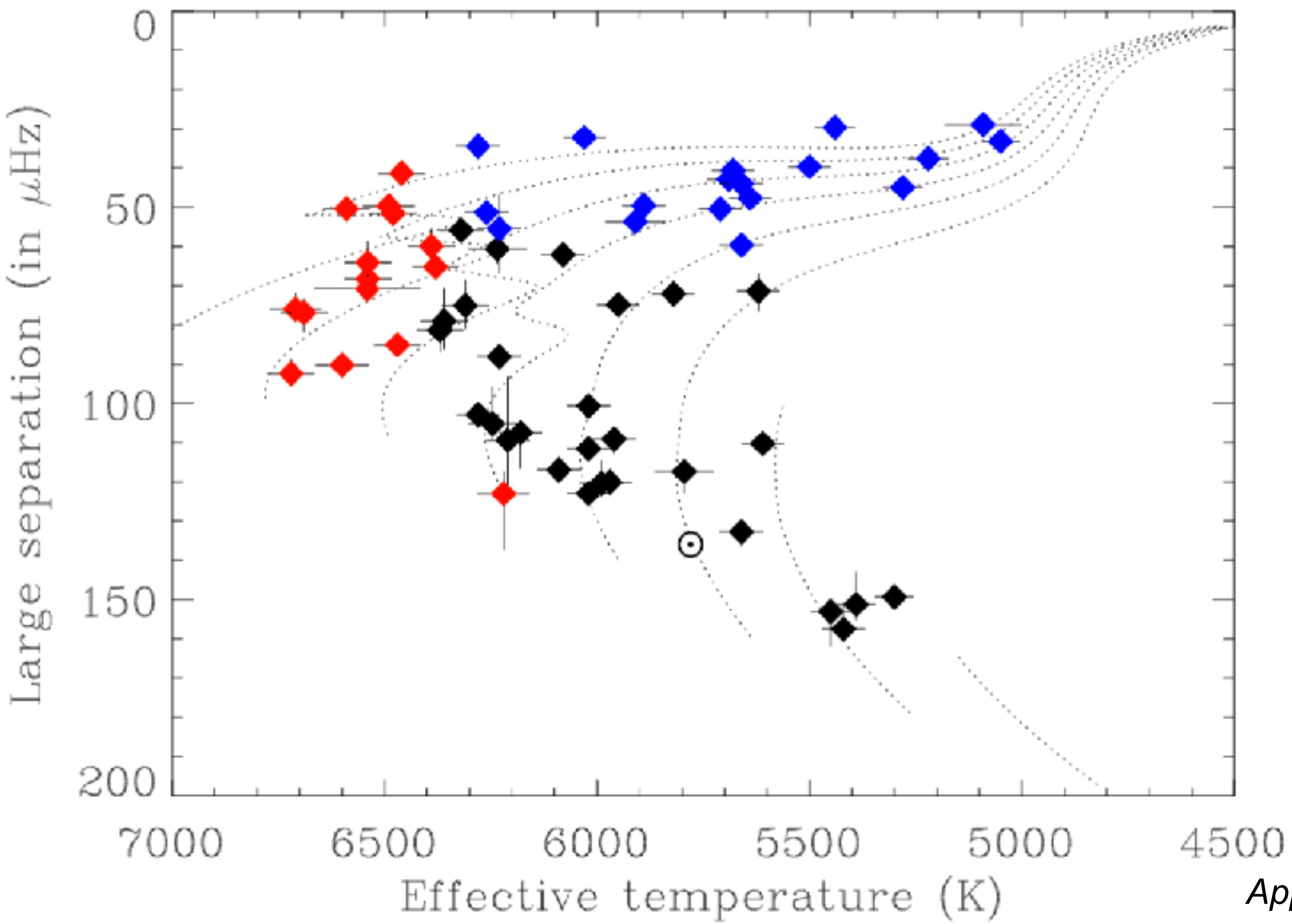




Chaplin & Miglio 2013

Kepler = 66 étoiles de la Séquence Principale sismiques

Et l'astérosismolgie fût...



Etoiles "simples"

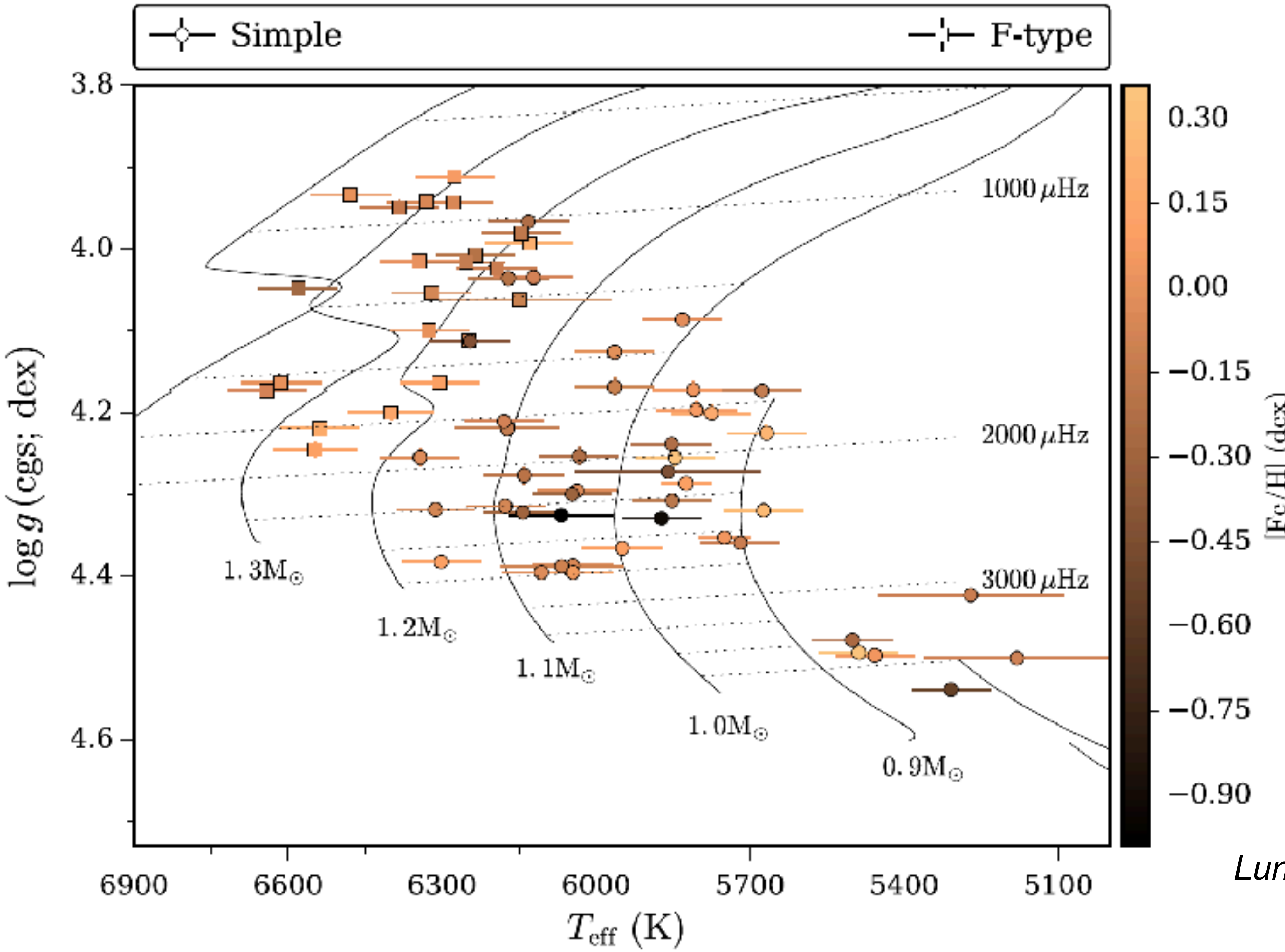
Etoiles avec modes mixtes

Etoiles F

Appourchaux et al 2012

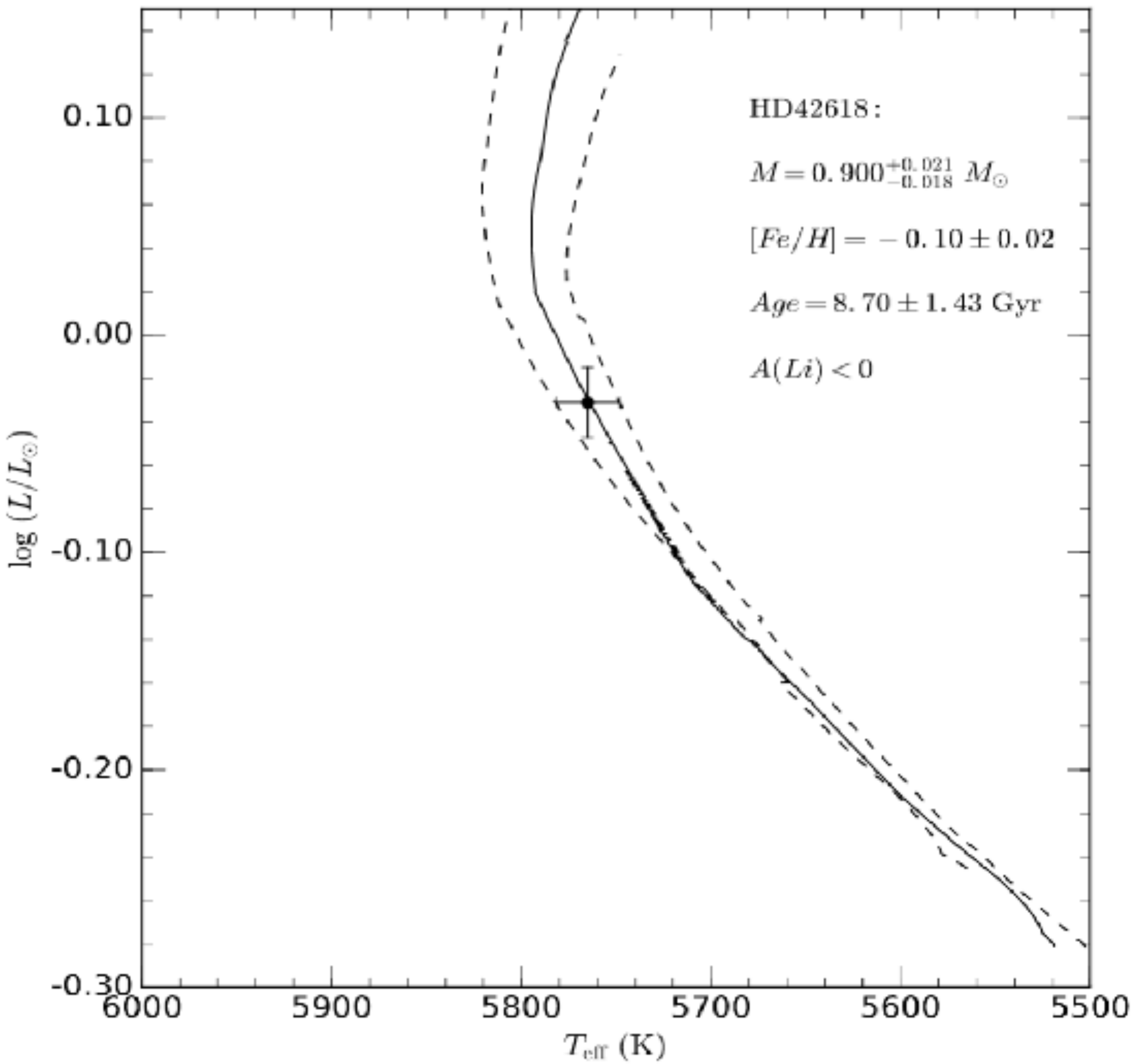
Kepler = 66 étoiles de la Séquence Principale sismiques

Et l'astérosismolgie fût...



Lund et al 2017

Et l'astérosismolgie fût…

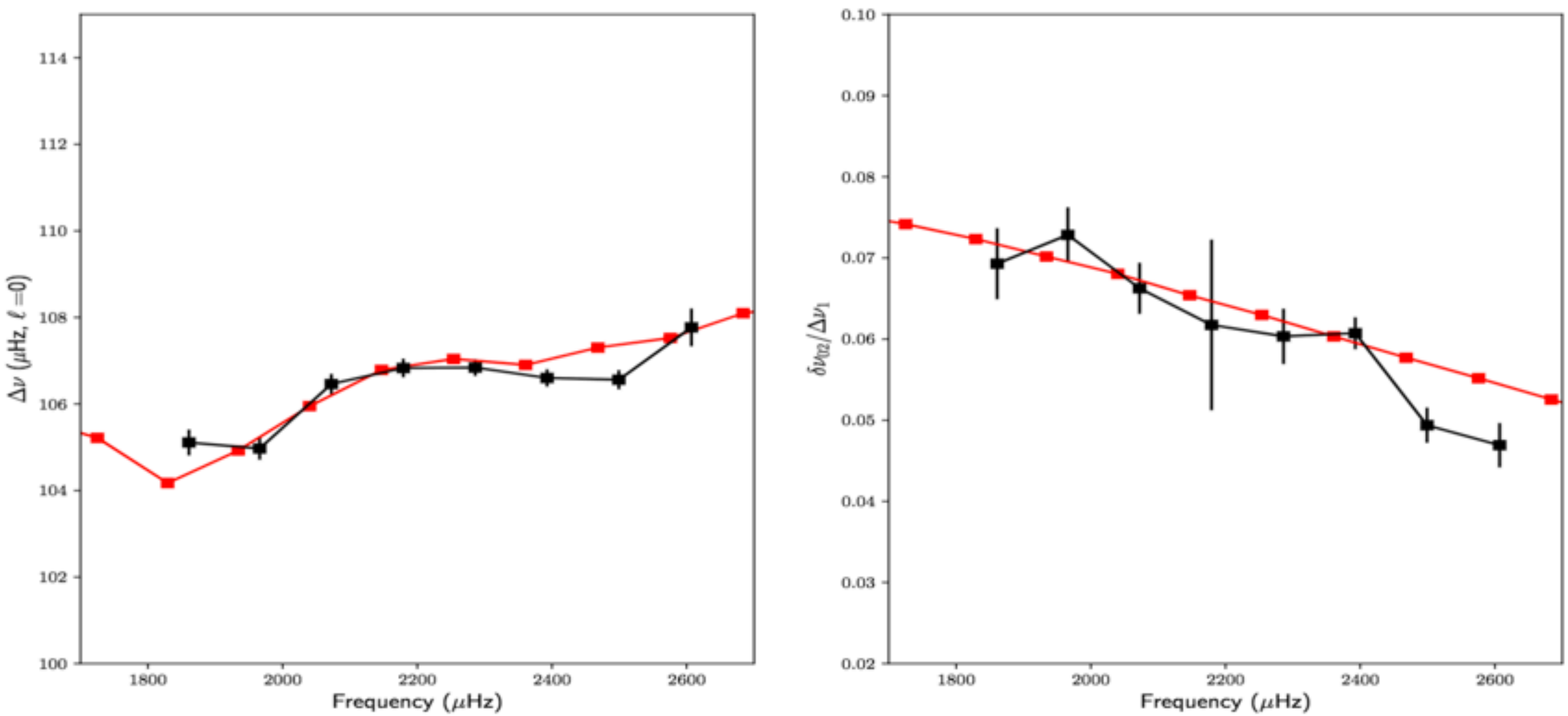


Castro et al 2018

Contraintes dans le diagramme H-R

Et l'astérosismolgie fût...

Contraintes sismiques

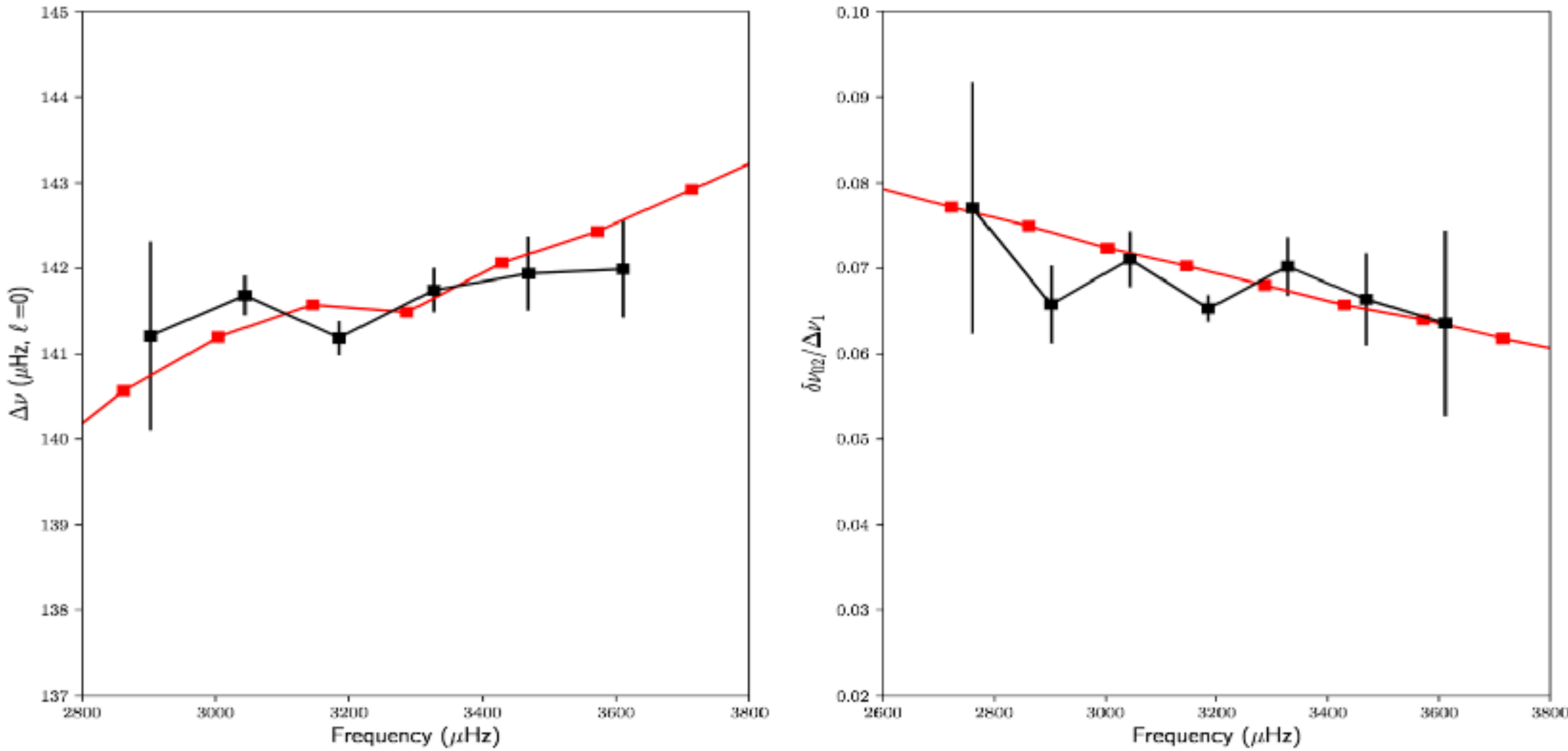


Castro et al 2018

	Mass ($M_\odot$)	Radius ($R_\odot$)	Age (Gyr)
TGEC	1.02 ± 0.02	1.20 ± 0.01	$6.8^{+0.6}_{-0.5}$
CESTAM	1.01 ± 0.02	1.20	6.4 ± 0.3

Et l'astérosismolgie fût…

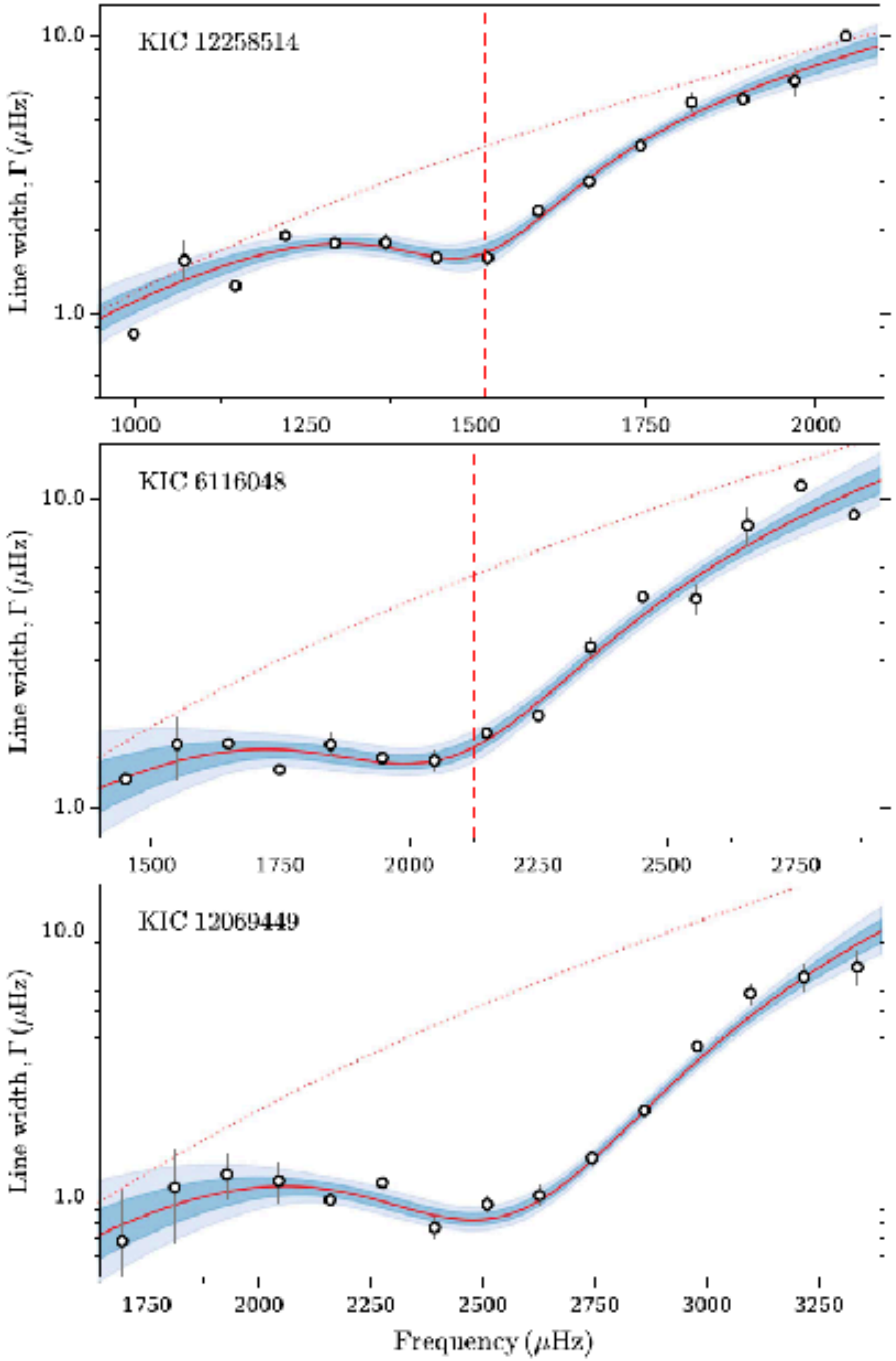
Contraintes sismiques



Castro et al 2018

	Mass ($M_\odot$)	Radius ($R_\odot$)	Age (Gyr)
TGEC	0.92 ± 0.03	0.97 ± 0.01	7.6 ± 2.4
CESTAM	0.94 ± 0.02	0.96	4.9 ± 1.0

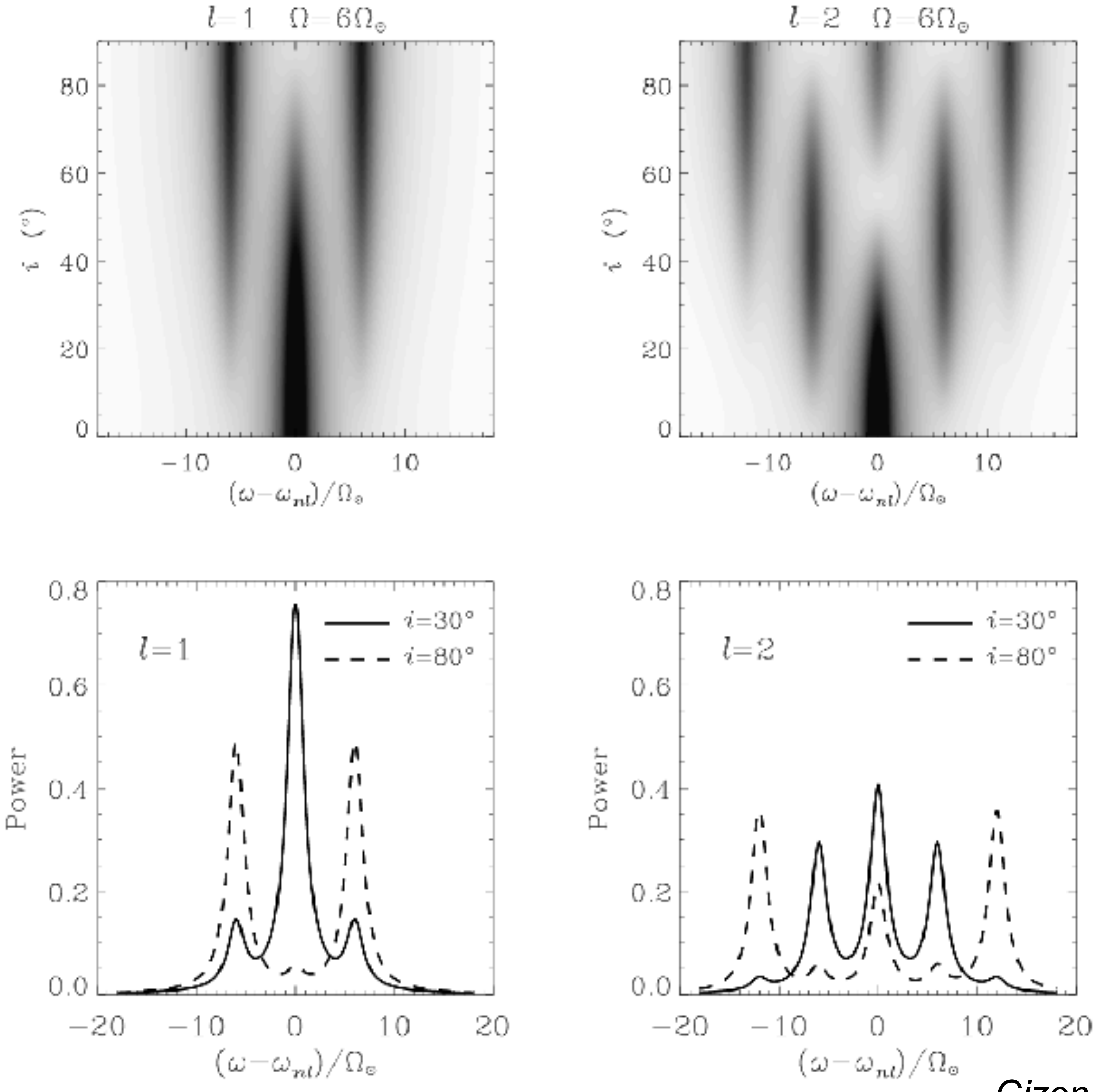
Et l'astérosismolgie fût...



Largeurs des modes
=> information sur l'excitation et l'amortissement des oscillations (convection)

Lund et al 2017

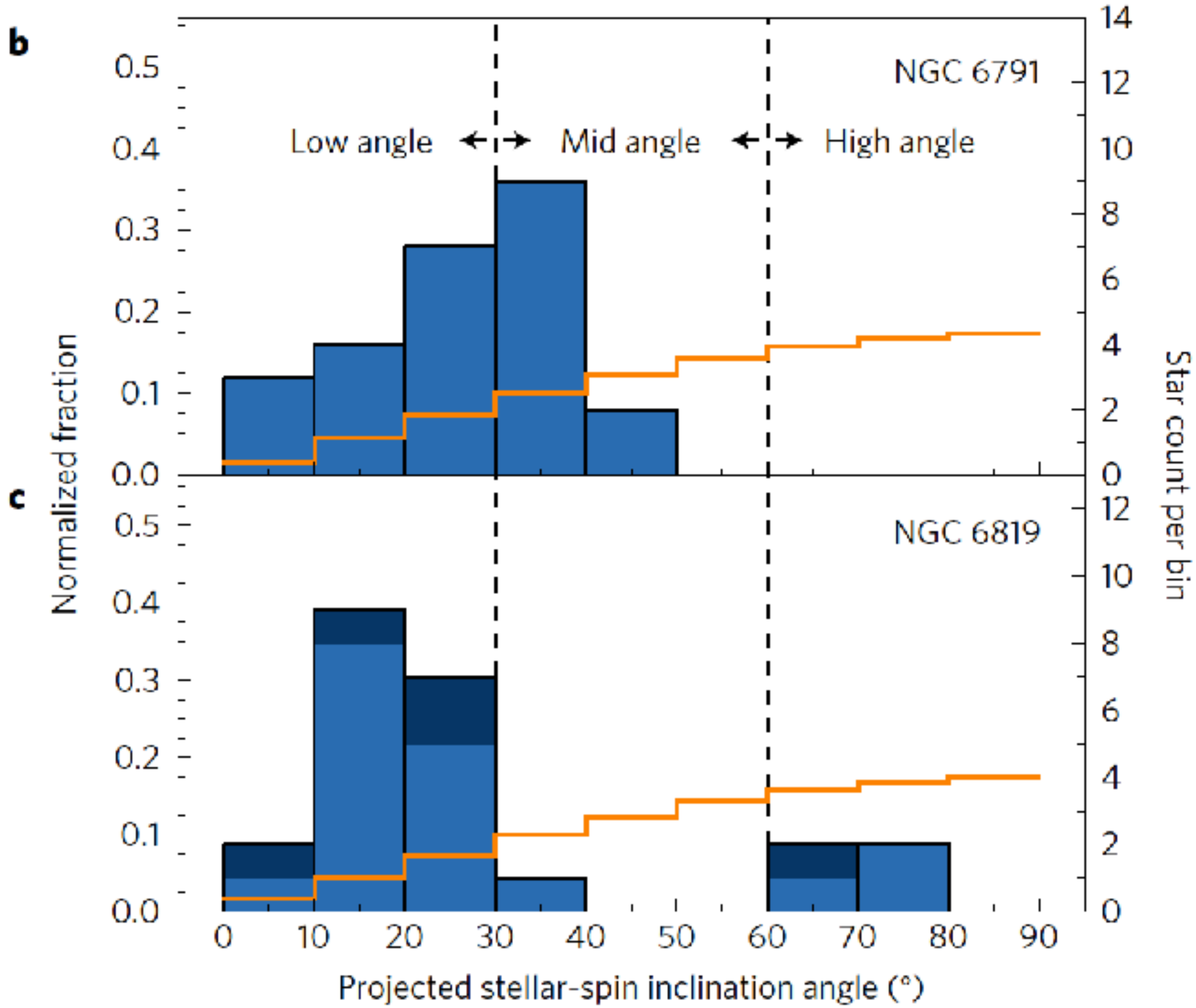
Et l'astérosismolgie fût...



Amplitude relative
des modes (≠m)
=> angle d'inclinaison

Gizon & Solanki 2003

Et l'astérosismolgie fût...



Etoiles alignées dans deux amas ouverts!

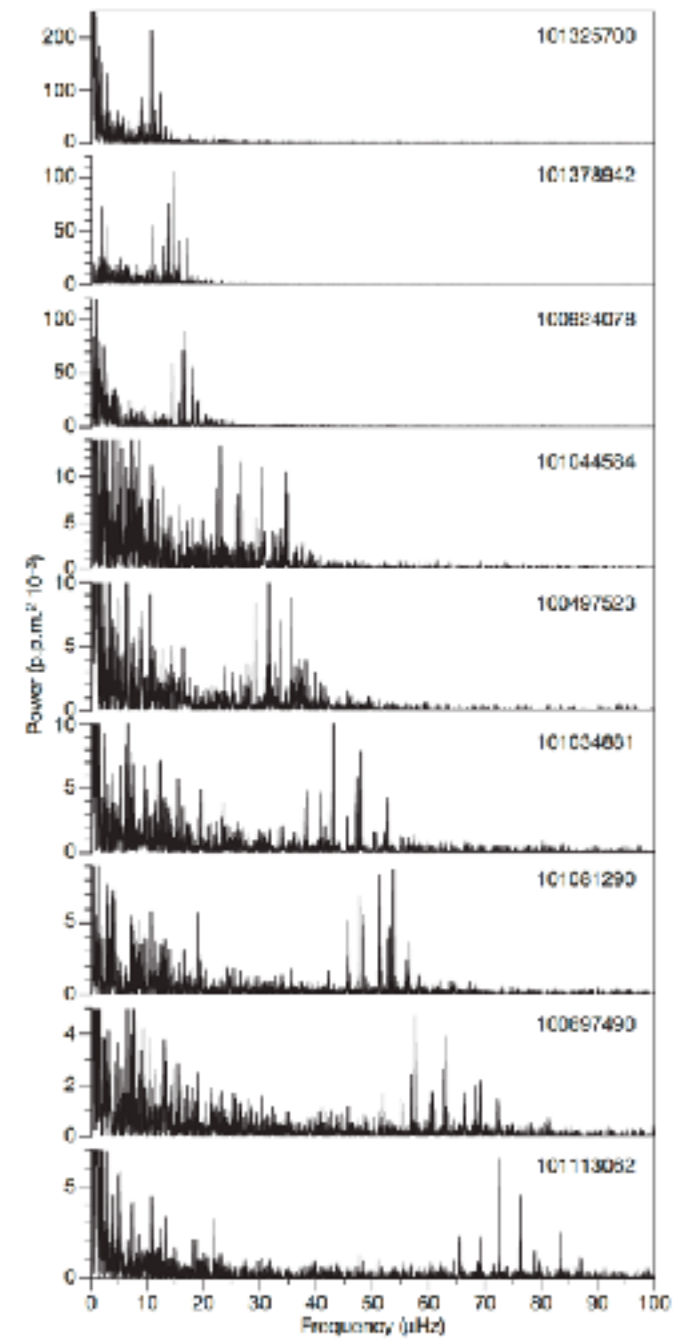
Corsaro et al 2017

Une dernière petite respiration

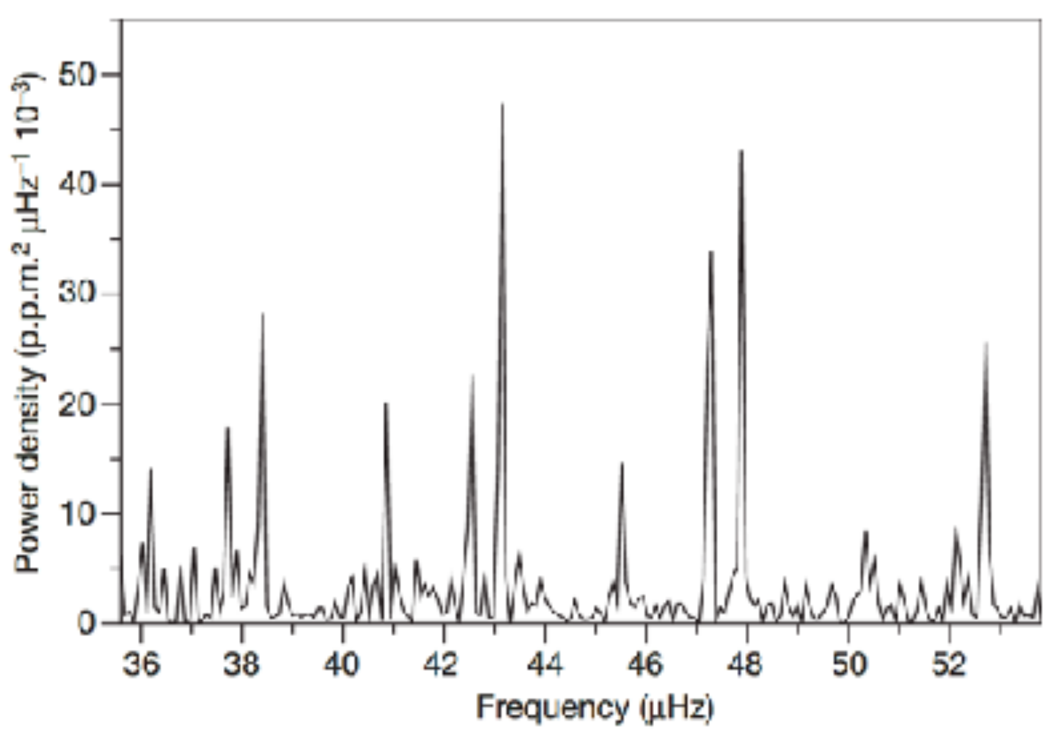
L'épopée des géantes rouges

Dziembowski et al (2001):

"The amplitudes of stochastically excited non-radial modes, including those that are most efficiently trapped in the acoustic cavity, are expected to have values much lower than those of corresponding radial modes."



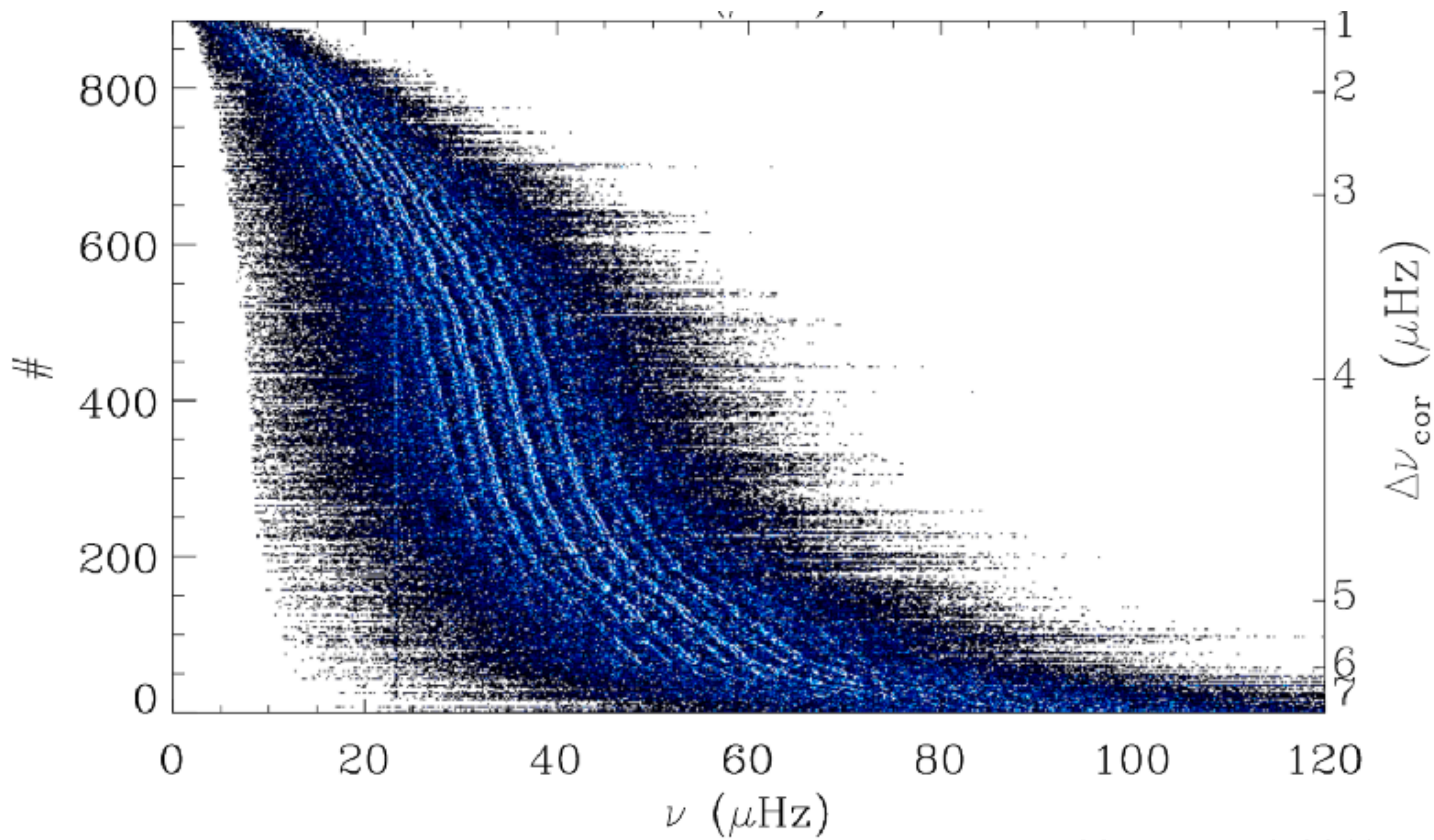
de Ridder et al (2009):



L'épopée des géantes rouges

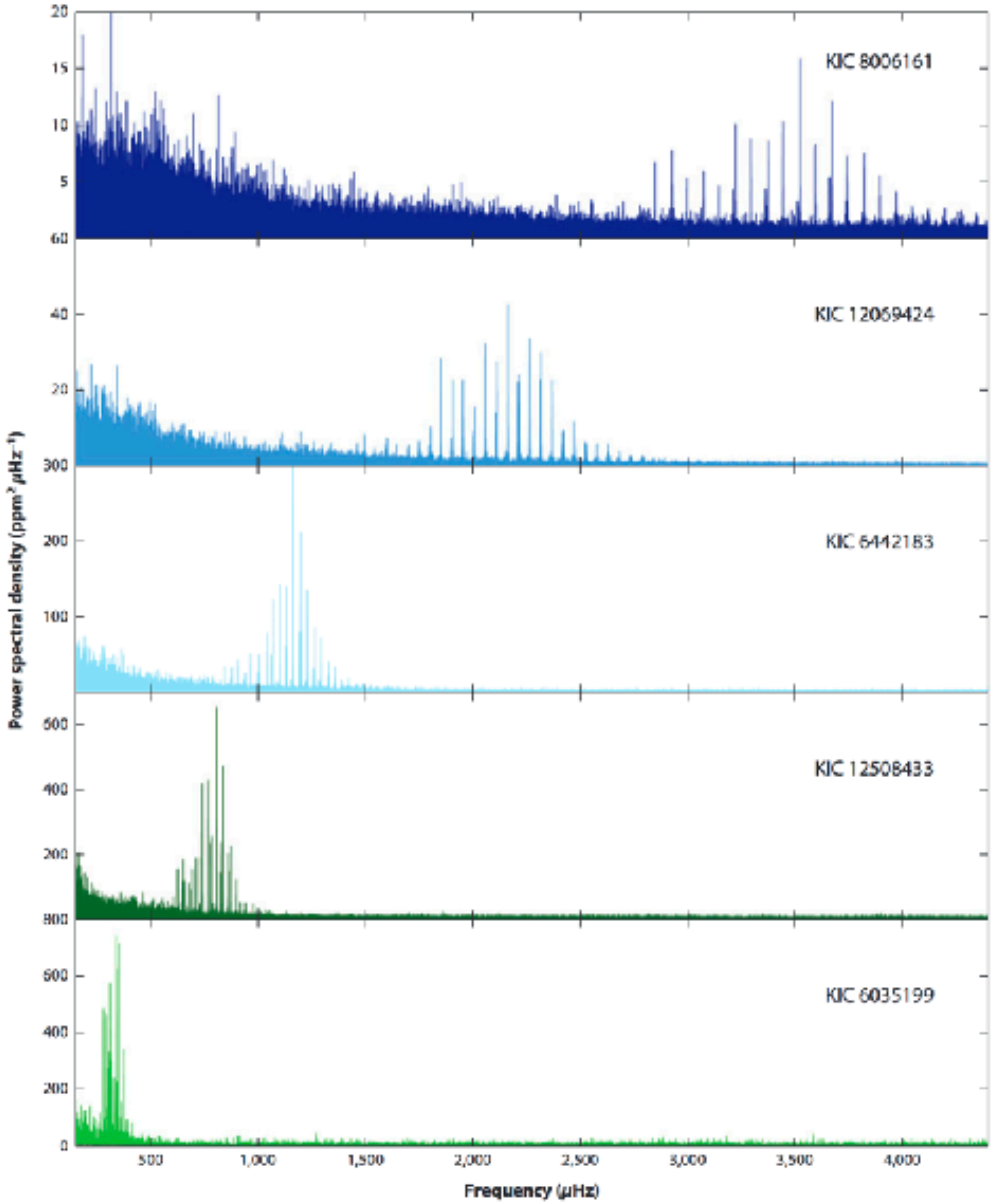
$$\frac{\nu_{n,\ell}}{\Delta\nu} = n + \frac{\ell}{2} + \varepsilon(\Delta\nu) - d_{0\ell}(\Delta\nu) + \frac{\alpha_\ell}{2}\left(n - \frac{\nu_{\max}}{\Delta\nu}\right)^2$$

=> "universal pattern"



Mosser et al. 2011

Le "universal pattern"



Au delà des géantes rouges

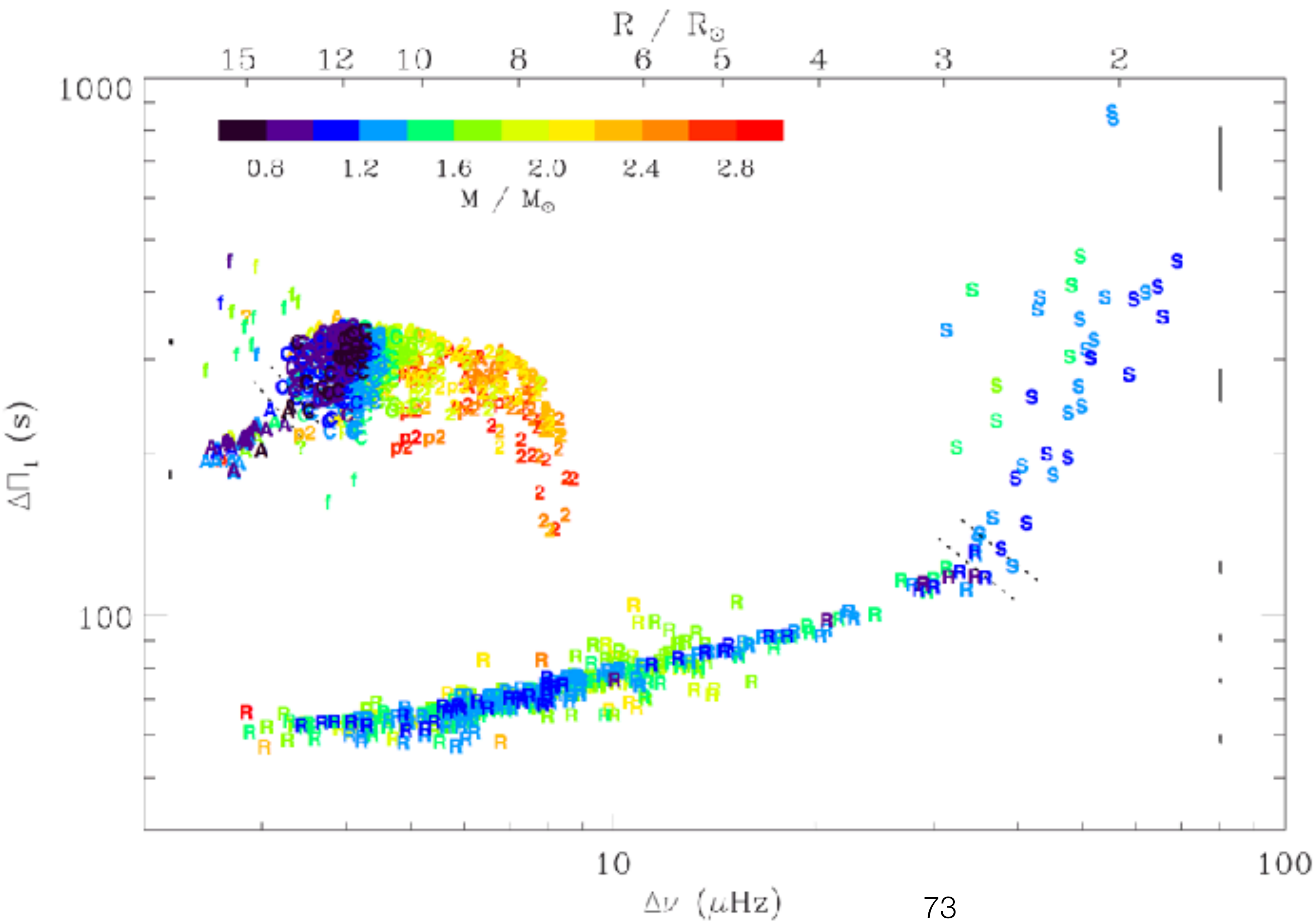
Chaplin & Miglio 2013

L'épopée des géantes rouges

Et les fameux modes mixtes

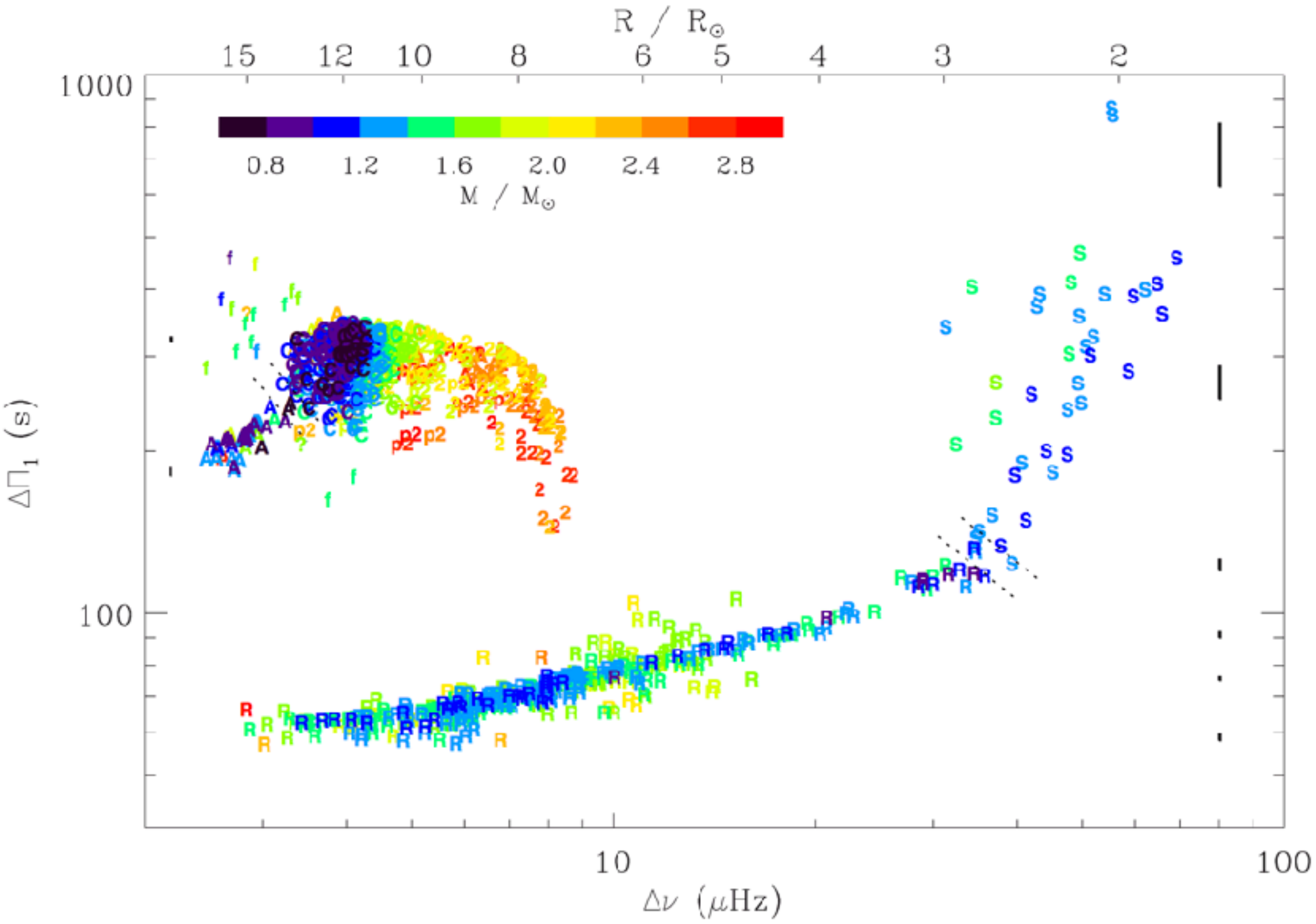
Kepler Detected Gravity-Mode Period Spacings in a Red Giant Star

P. G. Beck,[1*] T. R. Bedding,[2] B. Mosser,[3] D. Stello,[2] R. A. García,[4] T. Kallinger,[5] S. Hekker,[6,7] Y. Elsworth,[6] S. Frandsen,[7] F. Carrier,[1] J. De Ridder,[1] C. Aerts,[1,9] T. R. White,[2] D. Huber,[2] M.-A. Dupret,[10] J. Montalbán,[10] A. Miglio,[10] A. Noels,[10] W. J. Chaplin,[6] H. Kjeldsen,[8] J. Christensen-Dalsgaard,[8] R. L. Gilliland,[11] T. M. Brown,[12] S. D. Kawaler,[13] S. Mathur,[14] J. M. Jenkins[15]



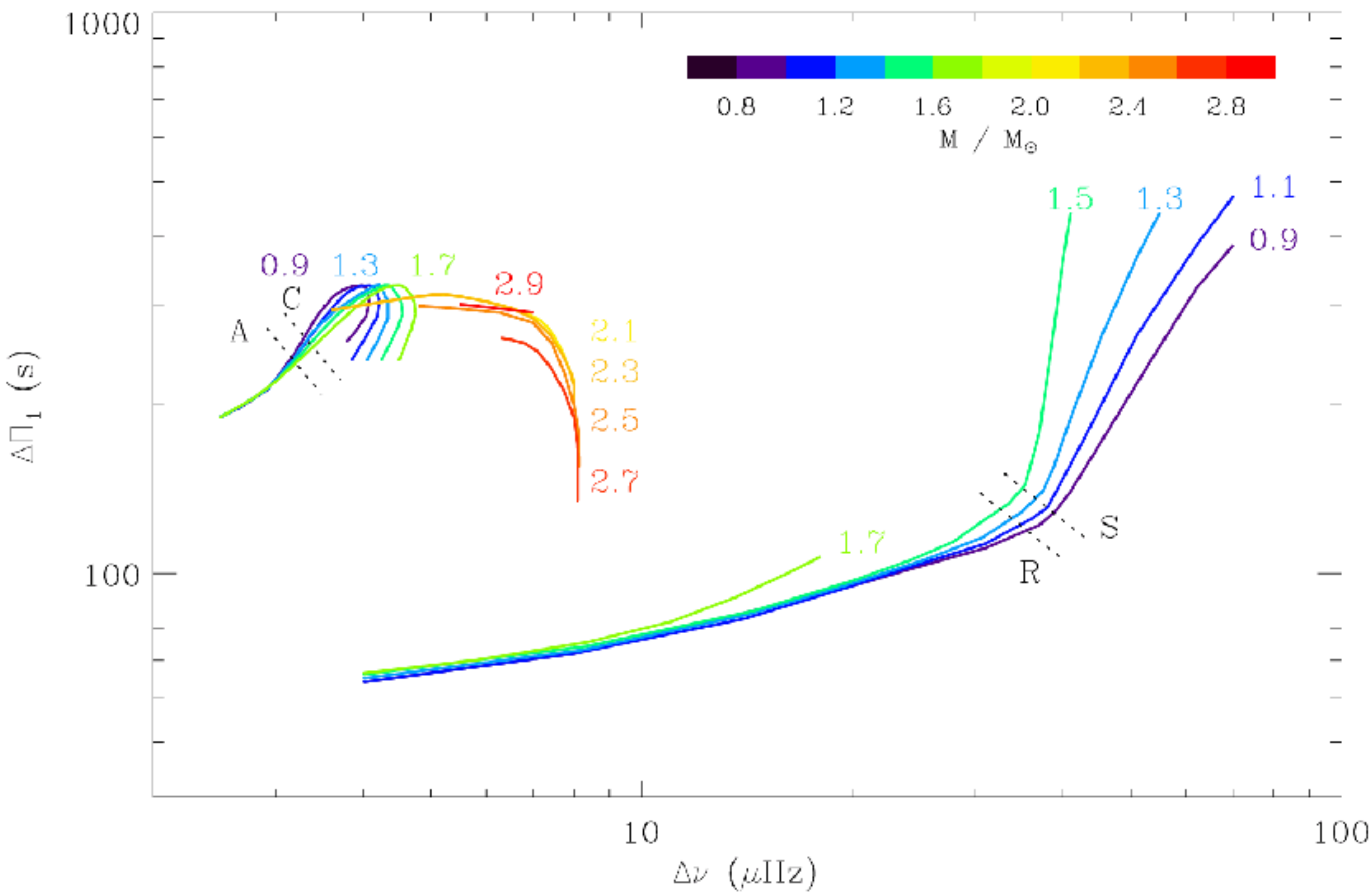
Mosser et al 2014

L'épopée des géantes rouges



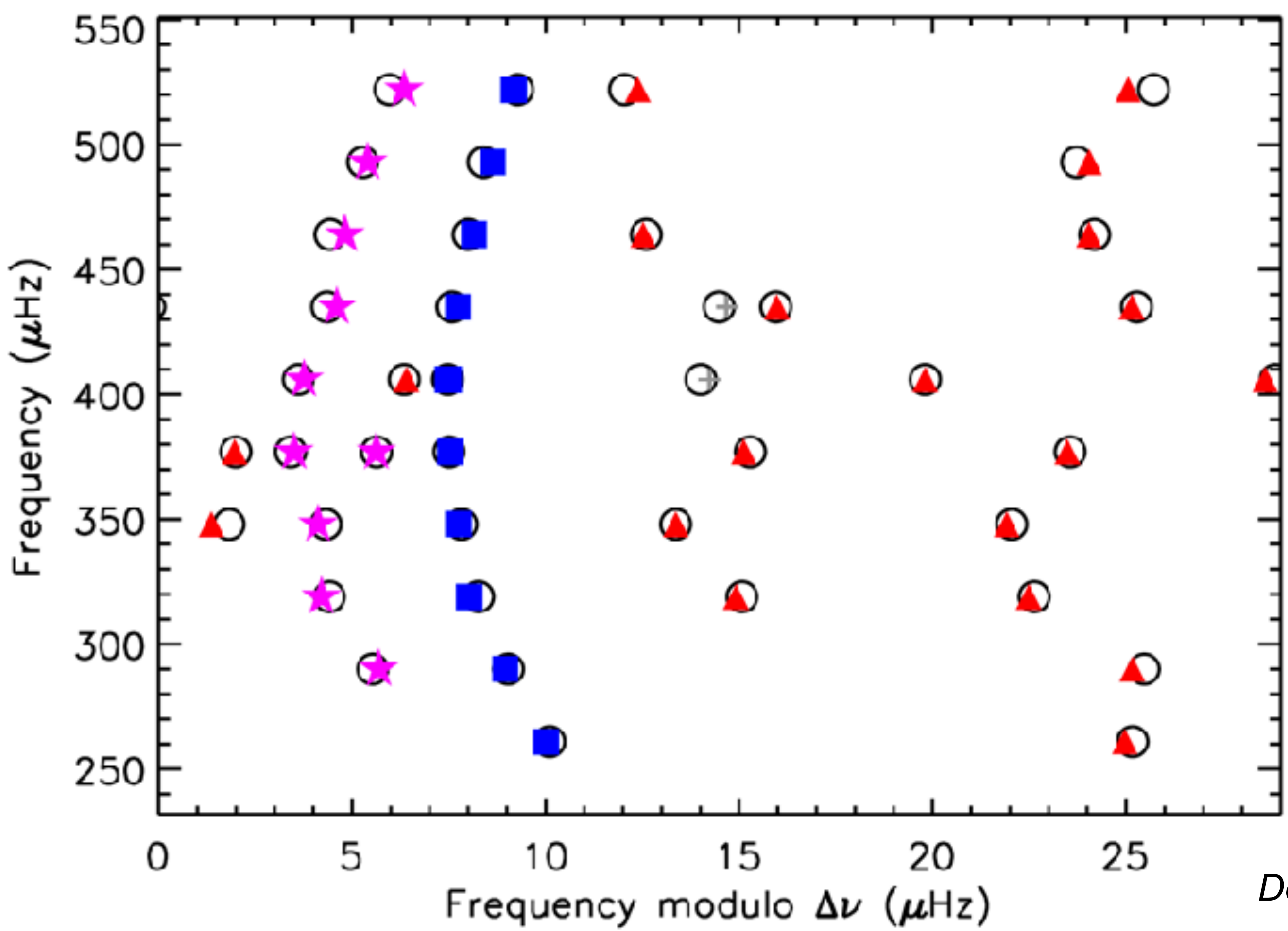
Mosser et al 2014

L'épopée des géantes rouges



Mosser et al 2014

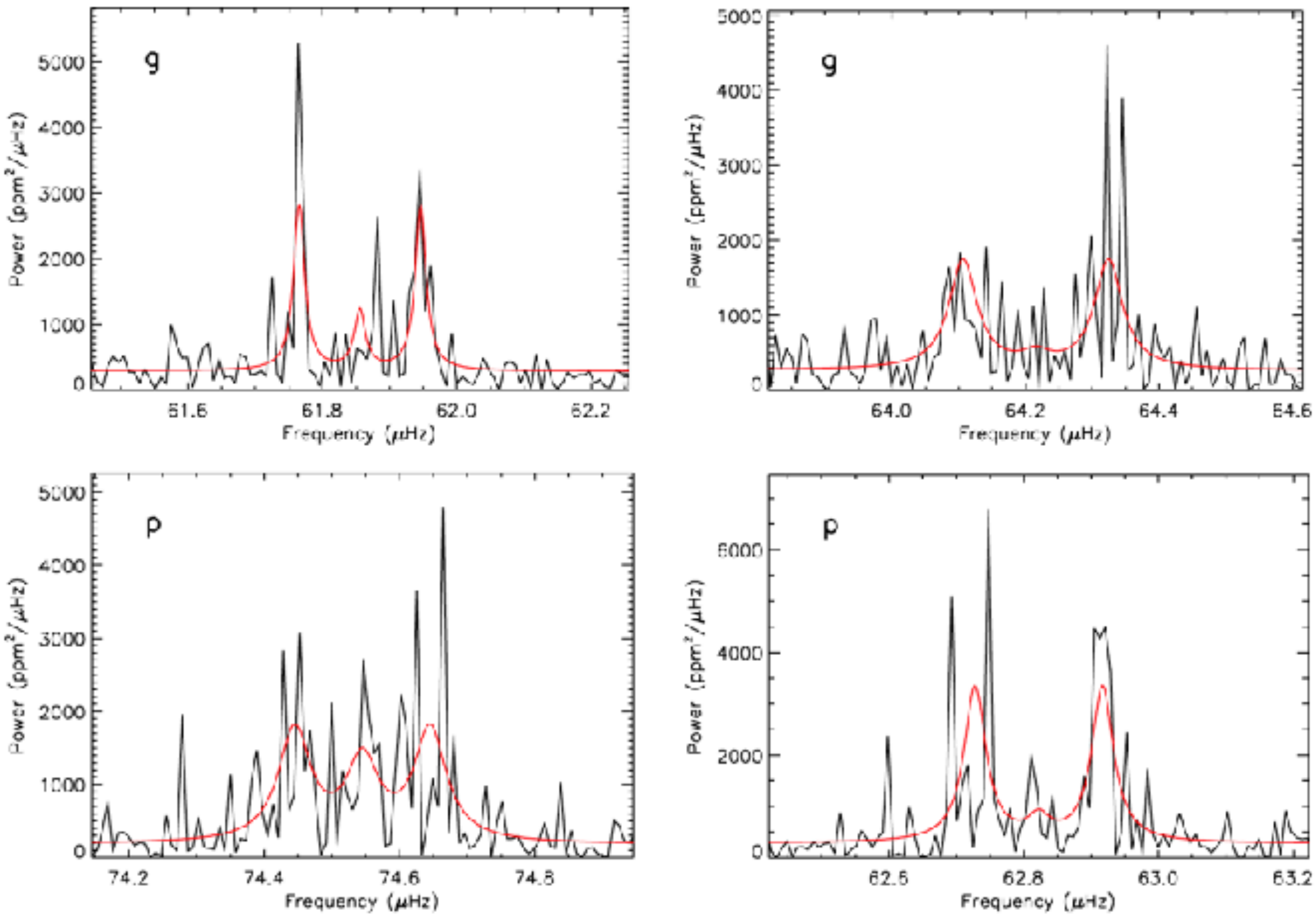
L'épopée des géantes rouges



Deheuvels et al 2012

Fréquences observées et fréquences déduites du modèle

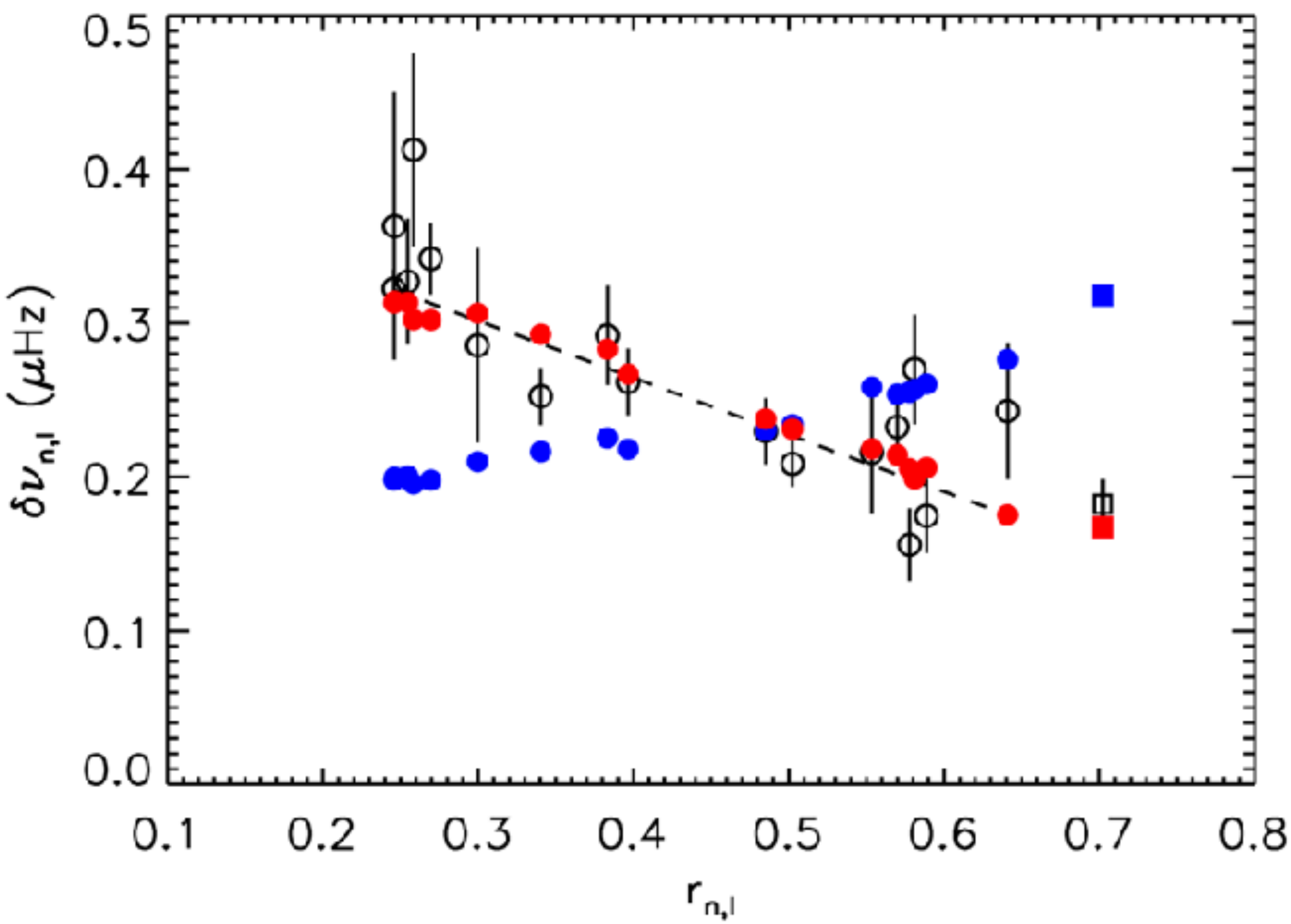
L'épopée des géantes rouges



Mesure du décalage rotationnel pour des modes mixtes

Deheuvels et al 2015

L'épopée des géantes rouges



Deheuvels et al 2012

Rotation observée, rotation à 2 zones, rotation rigide

=> coeur en rotation 5x plus rapide que la surface

L'épopée des géantes rouges

Deheuvels et al 2012: coeur en rotation **5x** plus rapide que la surface (1 étoile RGB)

Goupil et al 2013: coeur en rotation **20x** plus rapide que la surface (1 étoile RGB)

Deheuvels et al 2015: coeur en rotation (**1.8**±0.3)x à (**3.2**±1.0)x plus rapide que la surface pour 6 étoiles (Red Clump 2), 1 compatible rotation rigide (aussi RC2)

L'épopée des géantes rouges: archéologie galactique

$$\frac{M}{\mathrm{M}_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)^3 \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4} \left(\frac{T_{\mathrm{eff}}}{T_{\mathrm{eff},\odot}}\right)^{3/2}$$

$$\frac{R}{\mathrm{R}_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\mathrm{eff}}}{T_{\mathrm{eff},\odot}}\right)^{1/2} .$$

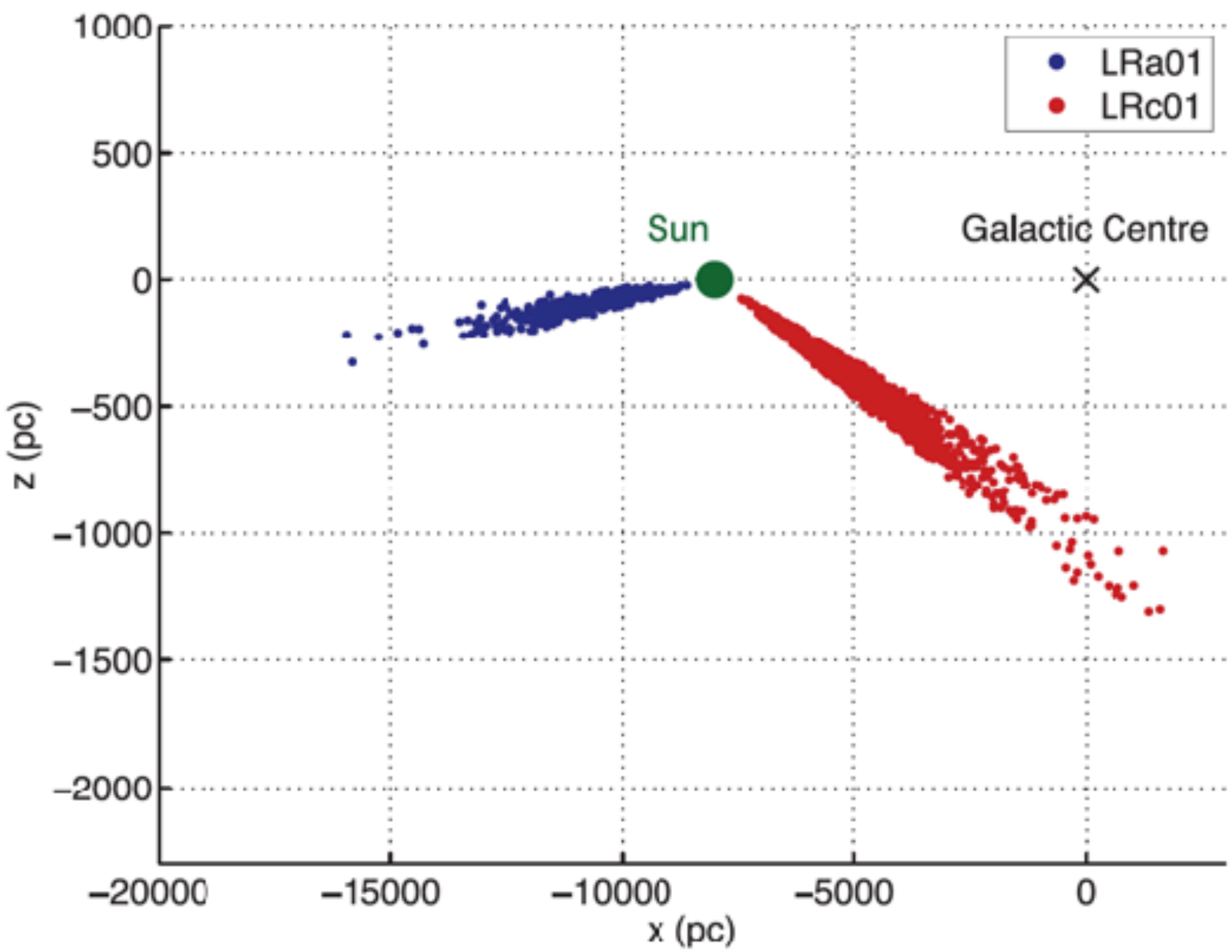
ν_{max} + $\Delta\nu$ + T_{eff} => masse, rayon

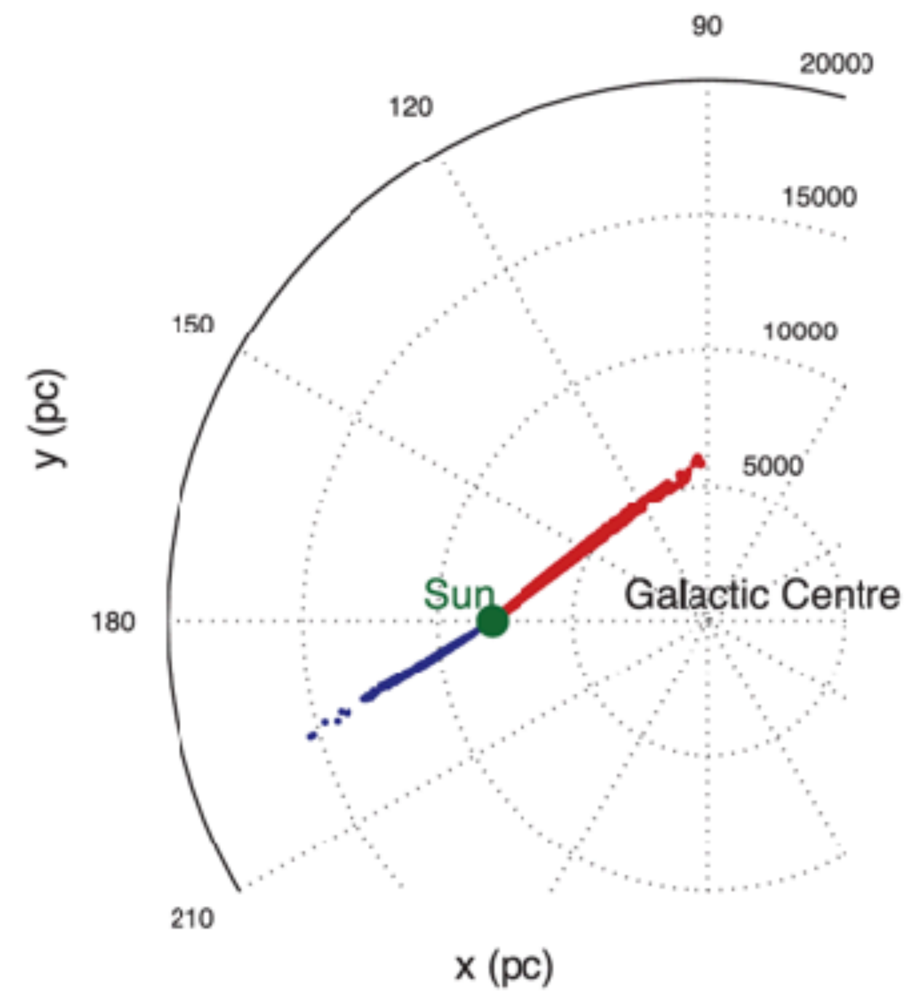
rayon + T_{eff} + magnitude => distance

masse + géante rouge => âge

Miglio et al 2013

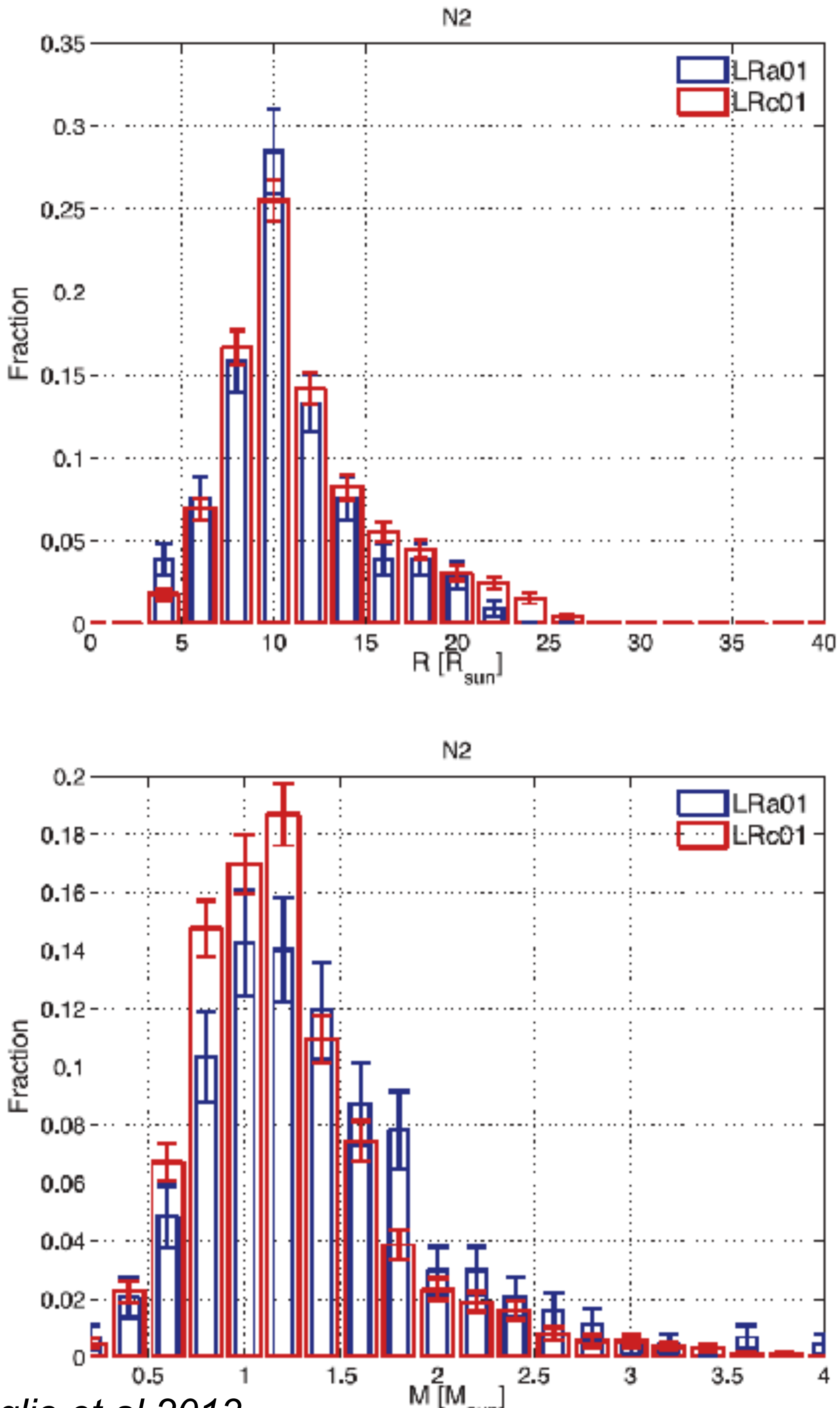
L'épopée des géantes rouges: archéologie galactique





avec 2 runs CoRoT

Miglio et al 2013



Miglio et al 2013

Archéologie galactique

avec 2 runs CoRoT

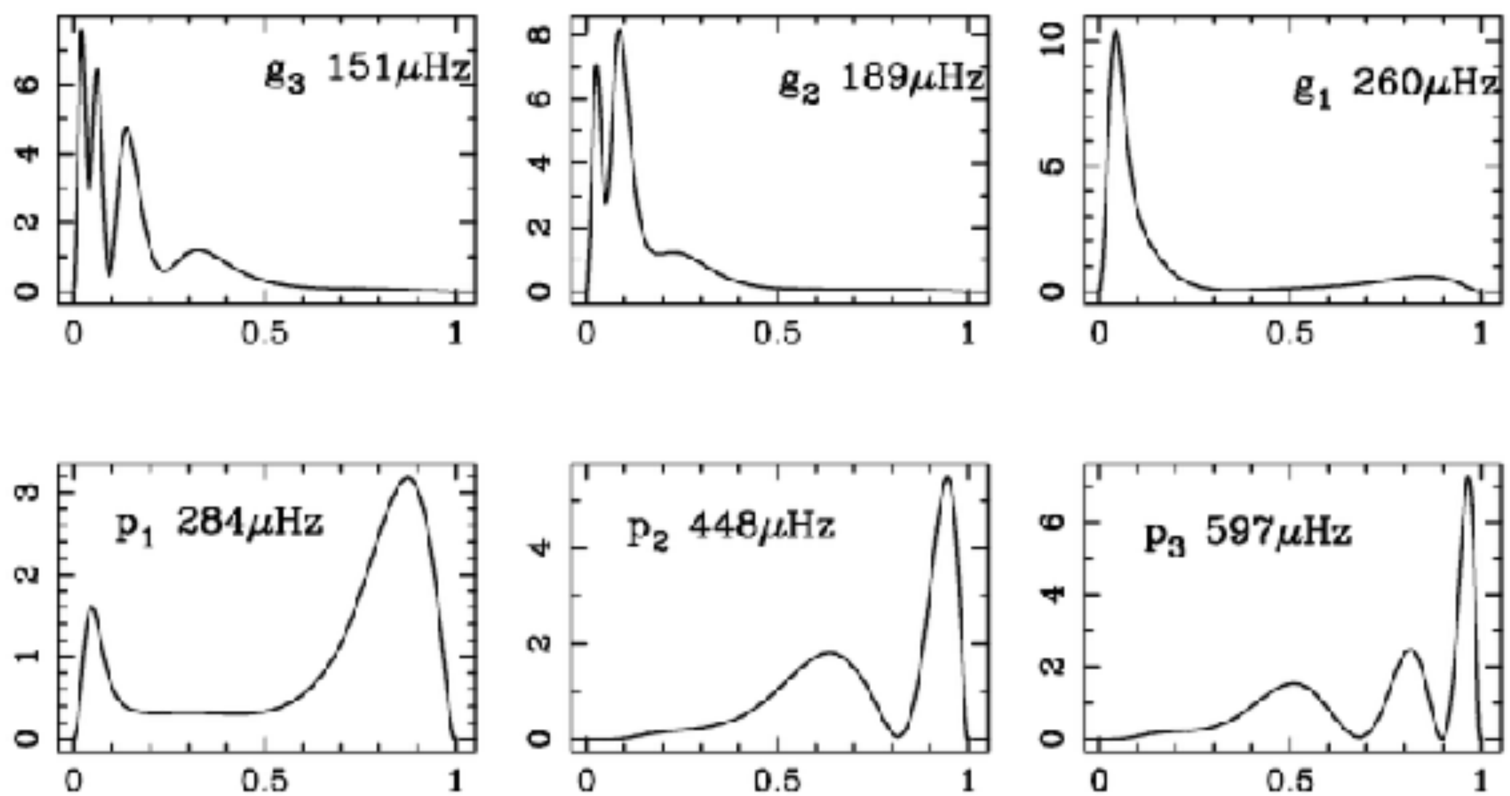
Différence en masse
=> différence en âge
(étoiles âgées plus dispersées)

(voir aussi Anders et al 2017)

La saga des modes g (solaires)

Pourquoi?

=> sonder le cœur (structure, rotation)



Provost et al 2000

Amplitude?

=> 10^{-4} à 1 cm/s

[modes p ~10 cm/s]

Asymptotique, équidistant en période

La saga des modes g (solaires)

Nature Vol. 259 January 15 1976 87

articles

Observations of solar pulsations

A. B. Severny, V. A. Kotov & T. T. Tsap

Crimean Astrophysical Observatory, p/o Nauchny, Crimea, 334413 USSR

We have modified our solar magnetograph to measure velocities at the solar surface, rather than magnetic fields. Using this apparatus, we have observed fluctuations of period 2 h 40 min, which are remarkably stable. The interpretation of this phenomenon seems to cause much theoretical difficulty.

WE have reported previously[1,2] on the successful measurement of the Sun's magnetic field using a solar magnetograph and the Crimean Solar Tower Telescope. The magnetograph consists of an electro-optical modulator to pick out the circularly polarised Zeeman components of magnetically sensitive lines, a grating and photomultipliers set on the wings of the lines. We thus achieve sensitivity, but, with the aid of an automatic Doppler compensator, avoid the perturbations of varying relative velocities between the Earth and Sun, turbulence in the atmosphere and apparatus noise. By the use of some additional apparatus

calibration signal $\delta_{\parallel}(O)$, with the aid of glass plate of the velocity compensator (calibrations, and 'on' for recording $\Delta\lambda_c$), an the intensity at the central part of the solar ir rim, $\beta = I_r/I_c \approx \frac{1}{2}$ in our case (intensities m multipliers). The calibration is made for a sta ± 0.031 Å of the 5,123.7 Å line, which corre of $\simeq 1{,}815$ m s^{-1}, so that $\delta_{\parallel}$ equals $\delta_{\parallel}$ (O) w $\Delta\lambda_c$—for a speed of 4,238 m s^{-1}.

Accuracy of experiment

The accuracy of the method is limited by spectrograph and electronic noise, and can b the accuracy of magnetic field measureme field strengths of 1 gauss were measured, corre m s^{-1}. By increasing the data accumulatio we can achieve $\simeq 1.0$ m s^{-1}, correspondi shift $\Delta\lambda_v \sim 10^{-5}$ Å.

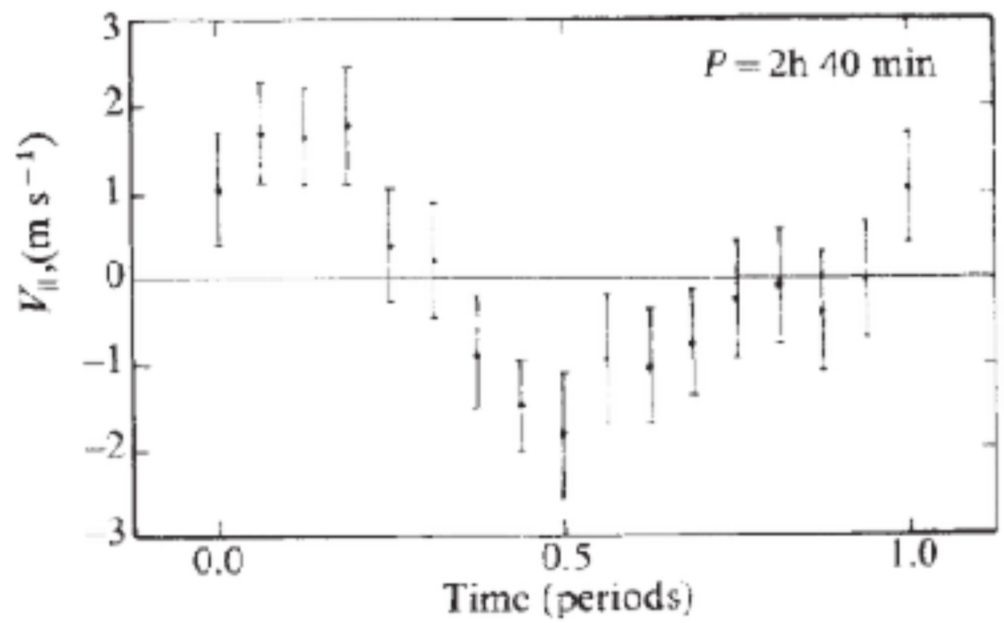


Fig. 3 Result of the superposed epoch analysis with 2 h 40 min period. Error bars represent r.m.s. deviations of individual measurements for each 10-min block of the data.

by Eddington[11] and Rosseland[12], where the best agreement with observations can be reached for almost homogeneous spheres at $\gamma = 5/3$. We agree with Rosseland's conclusion that 'a thorough discussion of the problem on a new basis seems to be called for.'

We thank Dr D. Gough for helpful discussion of the paper before publication.

Note added in proof: Preliminary results of observations for 16 d in 1975 show the same periodicity in the mean magnetic field of the Sun, with an amplitude of 0.01 gauss.

Received June 2; accepted October 23, 1975.

Severny et al 2000

Les fameuses 160 mn…

La saga des modes g (solaires)

Confirmant une théorie d'Einstein quatre chercheurs européens ont décelé des ondes qui font vibrer le Soleil

LE MONDE | 12.10.1983 à 00h00 • Mis à jour le 12.10.1983 à 00h00

MAURICE ARVONNY

Une découverte majeure vient d'être faite par quatre chercheurs européens : la première mise en évidence d'ondes gravitationnelles, donnant ainsi l'explication d'une mystérieuse vibration du Soleil, qui se traduit par des mouvements de sa surface. Les Français Philippe Delache (observatoire de Nice) et Jacques Paul (Centre d'études nucléaires de Saclay), le Britannique George Isaak (université de Birmingham) et l'Italien Giovanni Bignami (université, de Milan), ont montré que cette vibration est engendrée par les ondes gravitationnelles qu'émet Geminga, un astre effondré - trou noir ou étoile à neutrons - relativement proche du système solaire (le Monde du 24 août 1983).

Le Monde

1983

Le presque aussi fameux "Geminga"...

La saga des modes g (solaires)

THE ASTROPHYSICAL JOURNAL, 338:557–562, 1989 March 1

Elsworth et al 1989

THE 160 MINUTE SOLAR OSCILLATION: AN ARTIFACT?

Y. P. ELSWORTH,[1] S. M. JEFFERIES,[2] C. P. MCLEOD,[1] R. NEW,[1] P. L. PALLÉ,[3]
H. B. VAN DER RAAY,[1] C. RÉGULO,[3] AND T. ROCA CORTÉS[3]
Received 1987 December 16; accepted 1988 August 11

ABSTRACT

Analysis of data obtained at Izana over the years 1980–1985 are analyzed to show that the period of the 160 minute signal is indeed 160.00 minutes. It is further demonstrated that this signal may be simulated by a slightly distorted diurnal sine wave such as that occasioned by differential atmospheric extinction.

Subject headings: Sun: oscillations

I. INTRODUCTION

The birth of helioseismology was her[...] neous publication in *Nature* (Brookes, Isa[...] 1976; Severny, Kotov, and Tsap 1976) of [...] mingham University and Crimean Astro[...] groups announcing the discovery of a 1[...] lation of amplitude ~2 ms⁻¹. Howeve[...] Leighton, Noyes, and Simon (1962), Ulri[...] cher and Stein (1971) should not be overl[...] that the authenticity of this signal was i[...] minutes is exactly one-ninth of a day. I[...] obtained over the period 1974–1976 (Bro[...] cated that the experimental evidence f[...] stable, phase-coherent 160 minute sola[...] from conclusive. Although the signal w[...] amplitude appeared variable and Le [...] reported.

The reaffirmation of the 160 minute [...] from an analysis of the combined data of [...] over a long period of time. Using a sup[...] nique, it was found that the phase of th[...]

Analysis of these simulated data mimic the spectrum, frequency, and phase of the actual recorded data. Hence it may be concluded that, for the Izana observations, the observed 160.00 minute "solar" oscillation is an artifact produced by a simple distortion of the diurnal signal due primarily to differential atmospheric extinction interacting with a rotating Sun.

An independent analysis of the same data presented at the IAU Symposium 123 (Pallé and Roca Cortés 1986), although misinterpreted at the time, confirms the phase constancy of the 160.00 minute signal. In this analysis a signal of frequency 104.160 μHz (160.01 minutes) was fitted to the data and the phase was found to increase at the rate of ~32 minutes per

La saga des modes g (solaires)

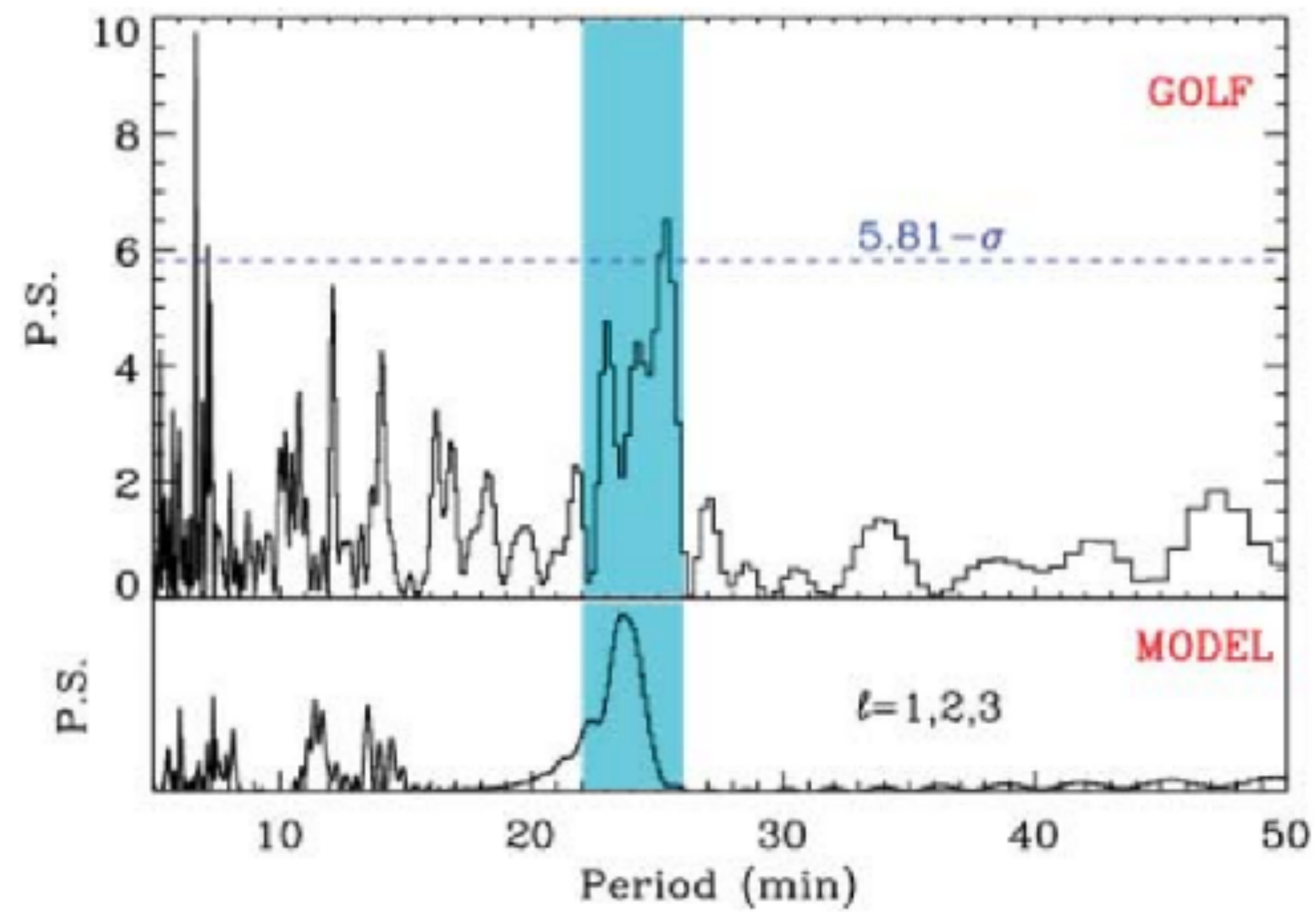
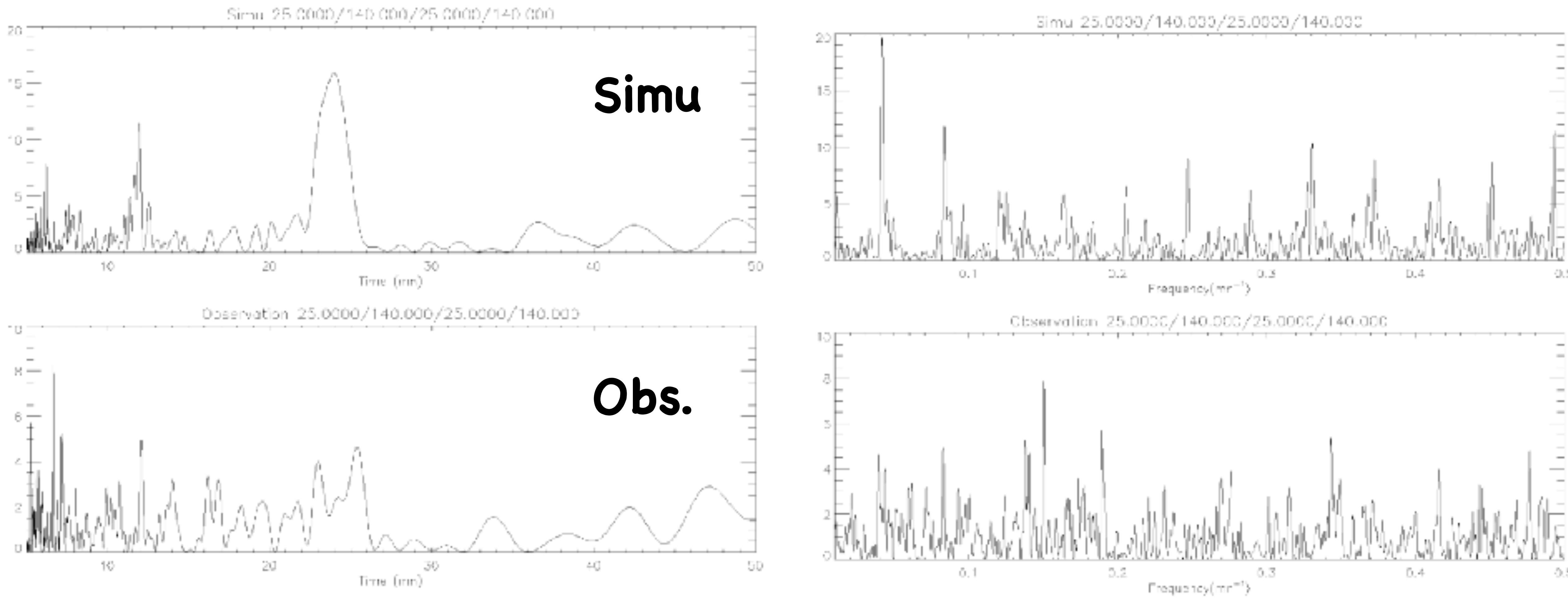


Fig. 3. Power spectrum of the PSD, normalized to the standard deviation, for the real GOLF data (top) and a numerical simulation (bottom) of $\ell = 1$, 2, and 3 gravity modes computed using the seismic model, for a core rotating at 433 nHz and without noise. The shaded region corresponds to the zone where the ΔP_1 peak is expected. This pattern changes slightly (with maxima at ~7.3σ or 6σ) when shorter frequency ranges in the PSD are used (fig. S2). The horizontal dashed line at 5.81σ corresponds to 99.7% confidence level for individual peaks (equivalent to 3σ level of a normal distribution). A full interpretation of the other highest peaks at low period is given in (*22*).

Garcia et al 2007

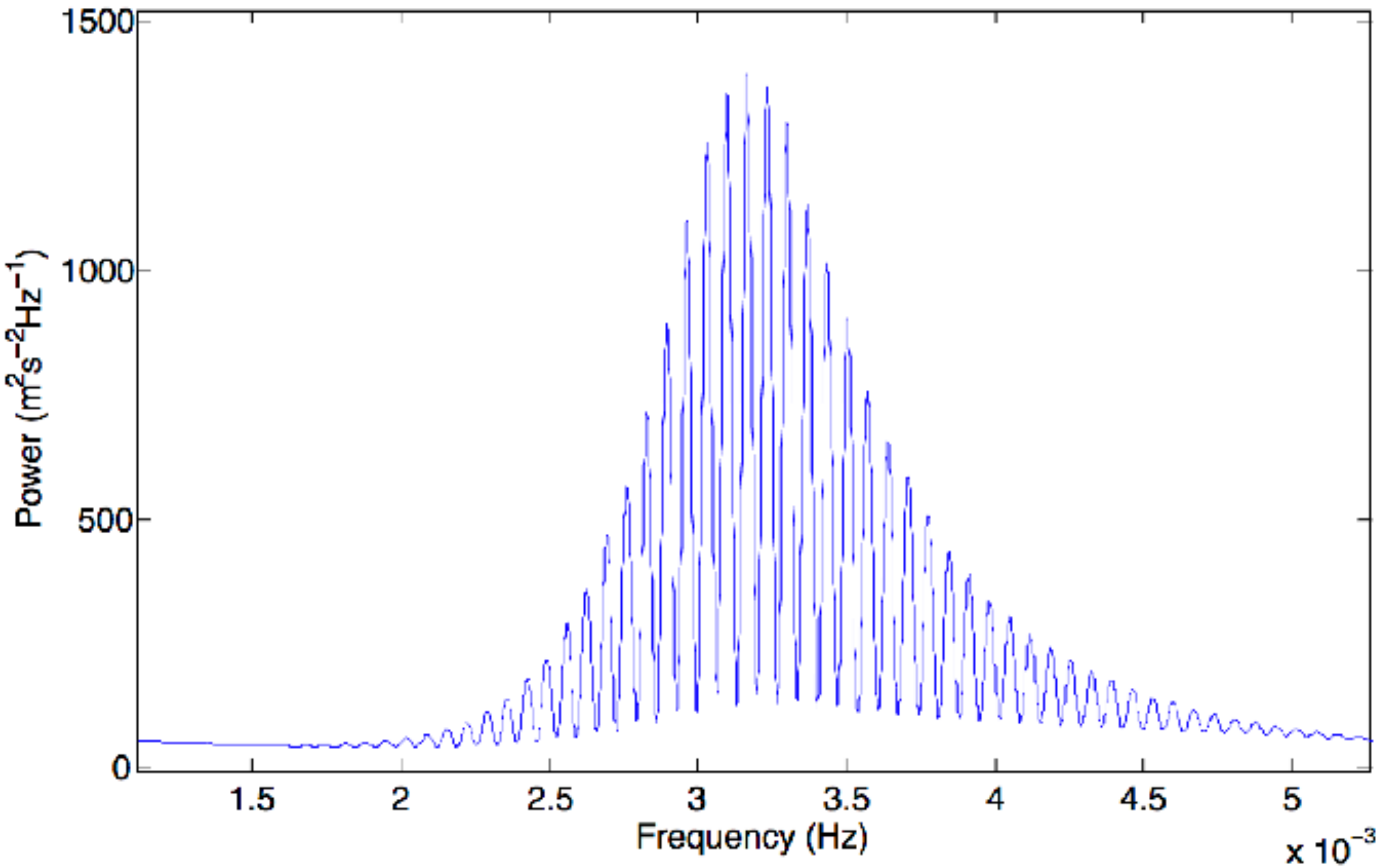
La saga des modes g (solaires)



Spectres en période **Spectres en fréquence**

Elsworth et al 2006

La saga des modes g (solaires)

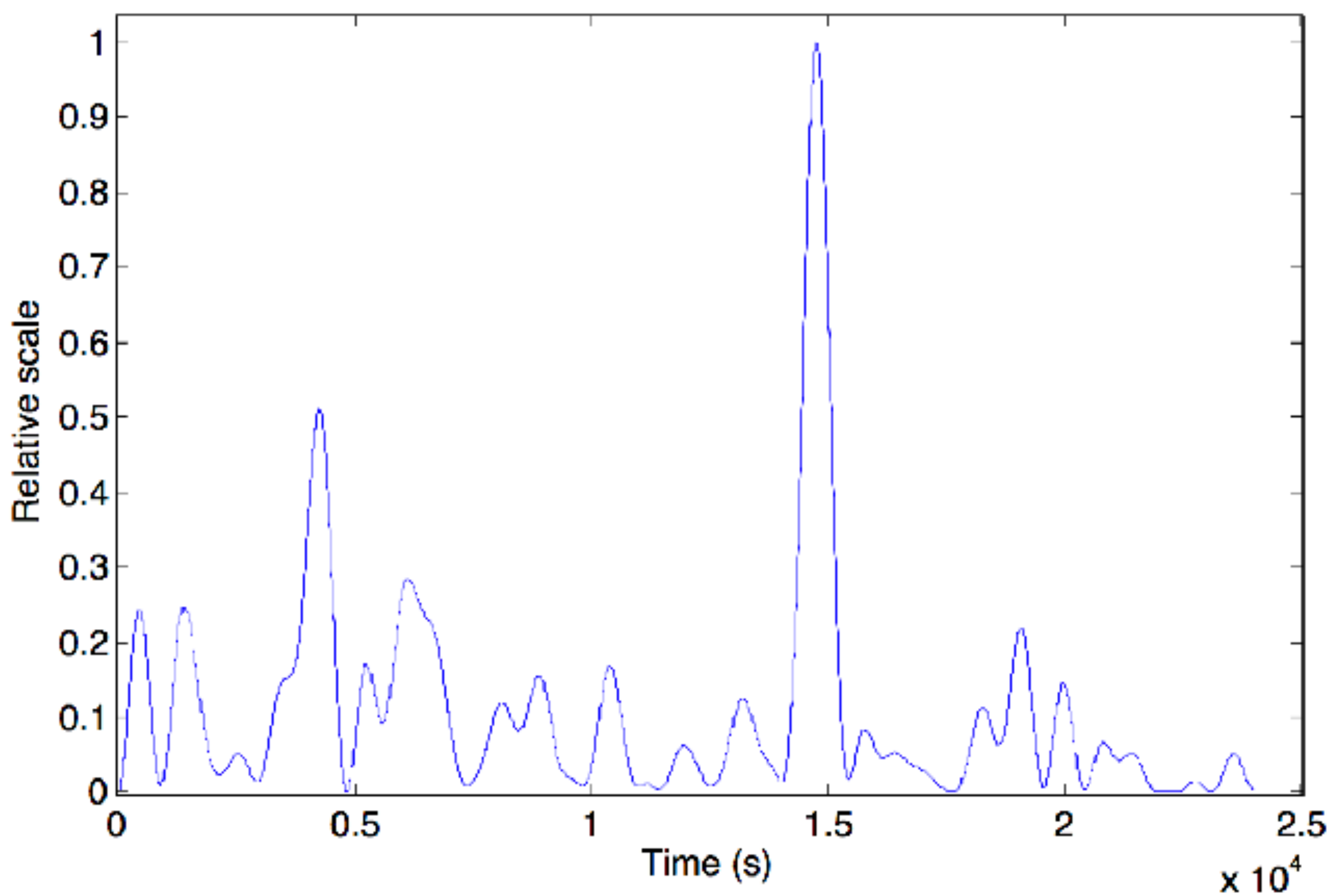


Fossat et al 2017

Derniers épisodes en date

(une méthode encore plus compliquée...)

La saga des modes g (solaires)



Etape 1: spectre du spectre

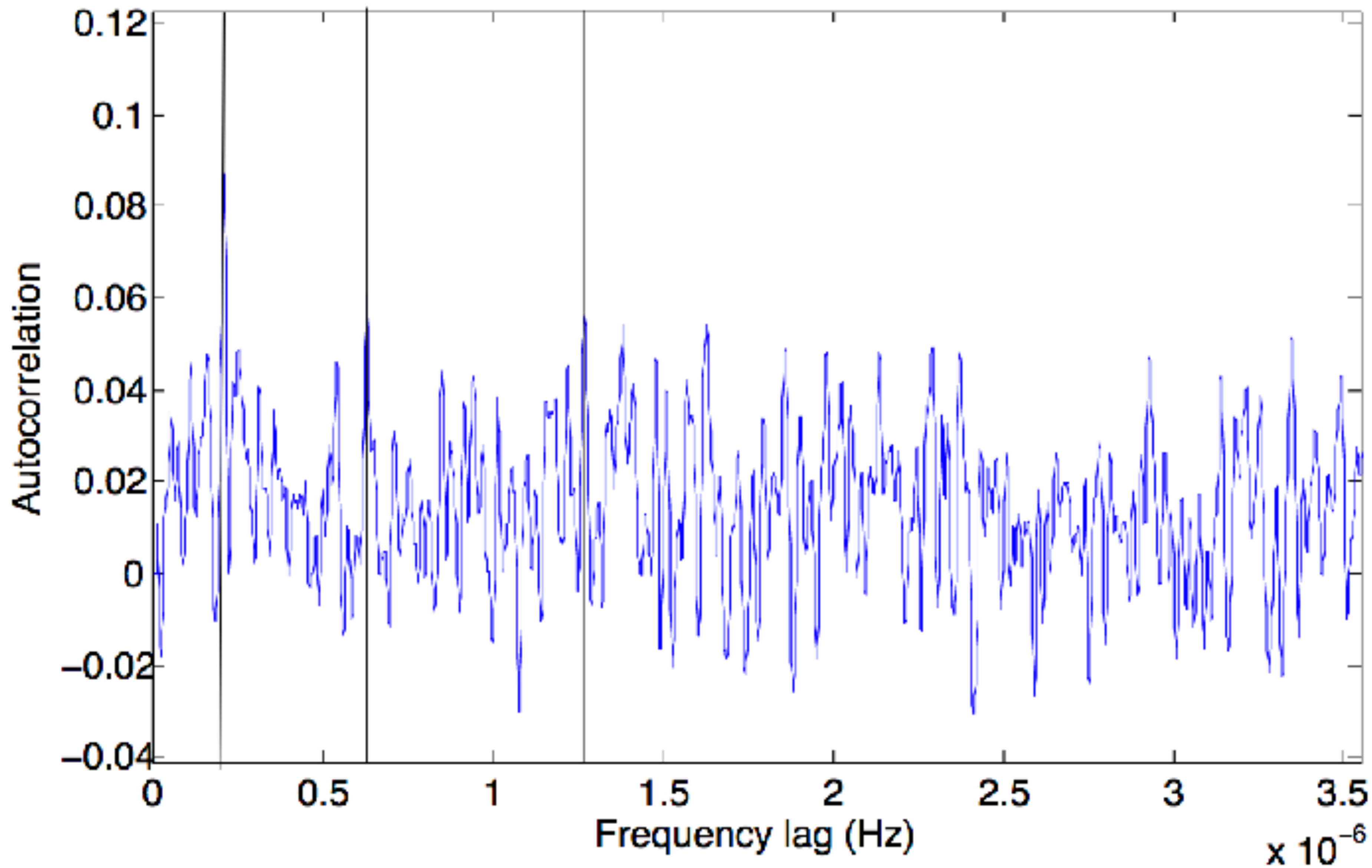
Fossat et al 2017

=> périodicité du spectre

(variations de la grande séparation avec le temps

=> nouvelle série temporelle)

La saga des modes g (solaires)

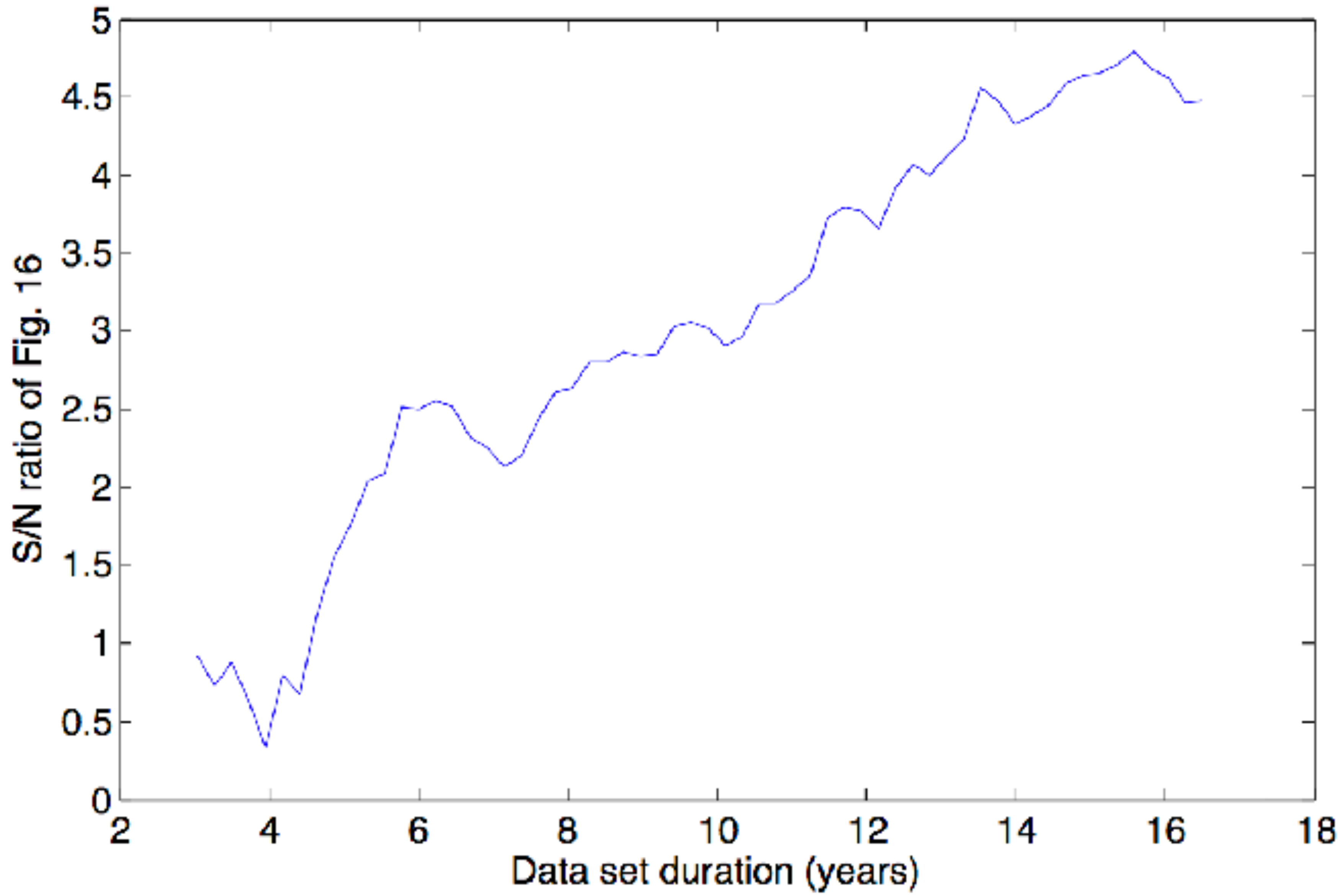


Fossat et al 2017

Etape 2: autocorrélation du spectre de $\Delta\nu(t)$

=> décalage rotationnel

La saga des modes g (solaires)



Fossat et al 2017

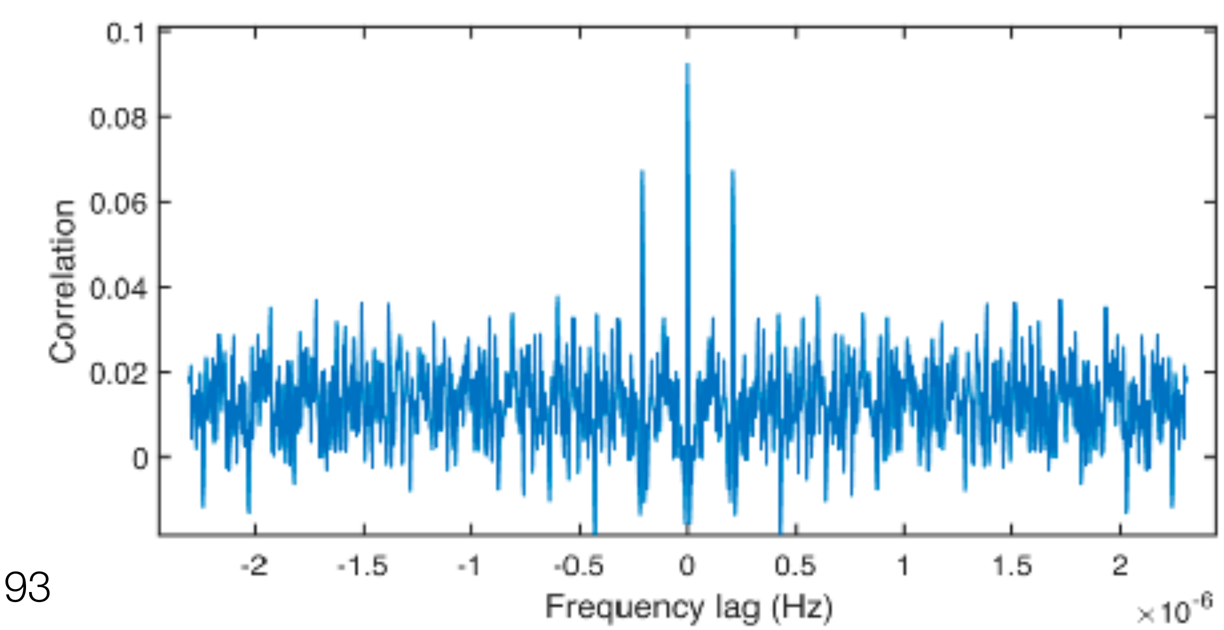
Vérification: le S/B augmente avec la durée de la série temporelle

La saga des modes g (solaires)

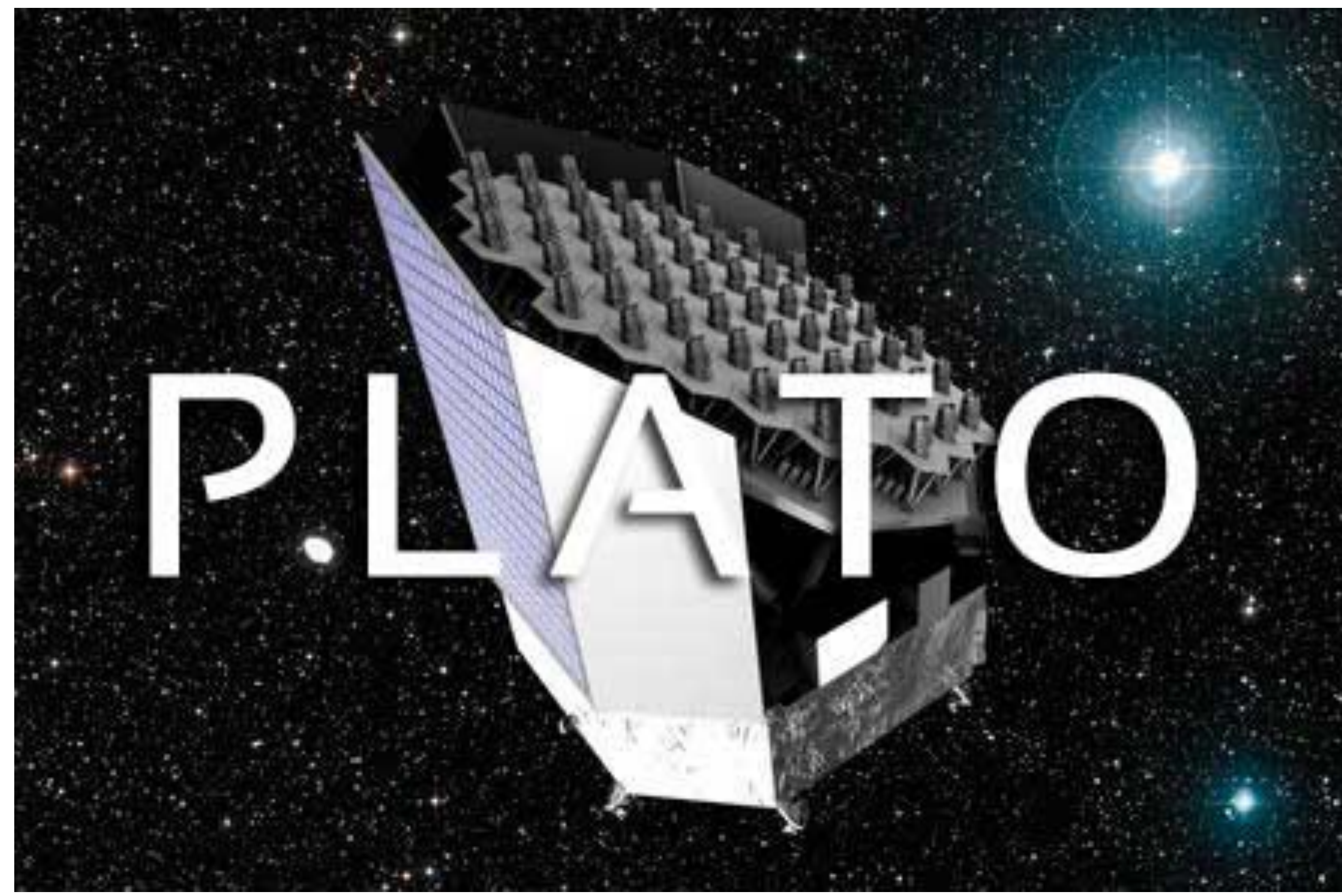
Garcia et al, Jimenez et al:
rotation du coeur 3-5x rotation de surface

Fossat et al:
rotation du coeur (3.8±0.1)x rotation de surface

Prochain épisode?!?
(en attendant: Fossat & Schmider 2018 confirment de leur côté)



Perspectives



Que de données...

Perspectives

=> lien avec les exo-planètes (R, M, âge)

=> rotation stellaire (et solaire!)
    => magnétisme
        => dynamo/structure interne

=> micro-physique
    => évolution
        => âge (exoplanètes, archéologie galactique)

Ouf...