Looking inside the rotating red giant star KIC 006144777 by means of asteroseismology with Kepler

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ABSTRACT: We have analysed oscillations of the red giants star KIC 6144777 observed by NASA *Kepler* satellite. The data consists of the first eleven quarters of science operations of *Kepler* which cover about 27 months. The high signal-to-noise ratio (S/N) and continuous data sets allow us to accurately extract the oscillation parameters from the power spectrum. We have found that the mean large frequency separation, $\Delta\nu$, and the frequency of the maximum oscillation power, ν_{max}, are around 10.9 and 128 μHz, respectively. We use the scaling relations of and to estimate the preliminary asteroseismic mass, which will be compared with results of detailed stellar modeling. Stellar models are calculated with CESAM2k stellar evolution code. We have calculated the oscillation frequencies of p mode of degree *l* up to *3* and the frequencies of a large number of models along the evolutionary tracks using LNAWENR linear, non-radial, non-adiabatic oscillation code. We have chosen the KIC values to constrain the effective temperature, metallicity and surface gravity of the best fitting model of KIC 6144777. We have measured the observed rotational splittings in the nonradial dipole mixed modes and we have found the maximum value of the rotational splitting in the g-m mixed modes as 0.237 μHz. The link between observed rotational splittings and the rotating core is investigated. By fitting a model of internal rotation profile to observed splittings we have estimated the size of rigid rotating core as about 0.004 of stellar radius. Also, we have found differential rotation in the convective envelope as a signature of angular momentum transport from core to envelope. The mean observational period spacing for the l=1 mixed modes of about 61 s suggests that this red giant branch star is in the shell hydrogen-burning phase.

Global oscillation analysis

The signal due to granulation is modelled by a modified Lorentzian-like function, first introduced by Karoff (2008). The contribution of the other surface phenomena (such as stellar activity, faculae, etc.) to background signal is included in a white noise component. The power excess hump from stellar oscillations is approximately Gaussian, so the complete spectrum is modelled by:

$$P(\nu) = P_n + \frac{4\sigma^2\tau}{1+(2\pi\nu\tau)^2+(2\pi\nu\tau)^4} + P_g \exp\left(\frac{-(\nu_{max}-\nu)^2}{2\sigma_g^2}\right)$$

For the fitting of the power density spectrum of KIC 006144777 with the model given by that equation we used Maximum Likelihood Estimator (Appourchaux 2003). The fit returned the maximum amplitude of excess power P_{max}=867.406 ± 23.079 ppm^{2}μHz^{-1}. The corresponding frequency is ν_{max}=128.803 ± 2.598 μHz (see Fig. 2).

The analysis of the power spectrum was performed by adopting the peak-bagging method based on the fit of Lorentzian profiles to the power density spectrum using Maximum Likelihood Estimators (MLE) (Appourchaux et al. 1998). The power spectrum was smoothed with a Gaussian and the frequencies of the peaks above a threshold that was set at 0.99 confidence were used as initial starting values for the fitting with Lorentzians. We first computed a guess value for the large frequency separation using power spectrum auto-correlation method in the region of p-mode power excess. Then, we have identified the l=0 peaks (and, immediately, the l=2 peaks) in the power spectrum. The mean large frequency separation is found to be $\Delta\nu$=10.905 ± 0.013 μHz.

The power spectrum in the region of p-mode excess power was modelled as a background noise component similar with that used in Expression (1) and a sum of Lorentzian profiles. Thus, the total power from the stellar oscillations is described as:

$$P(\nu) = P_n + \frac{4\sigma^2\tau}{1+(2\pi\nu\tau)^2+(2\pi\nu\tau)^4} + \sum_{i=1}^{n} L(\tau_i, H_i, \nu_i)$$

The Lorentzian profile is defined as

$$P_{Lorentzian}(\nu) = L(\tau_i, H_i, \nu_i) = \frac{H_i}{1+(2\pi\cdot(\nu-\nu_i)\cdot\tau_i)^2}$$

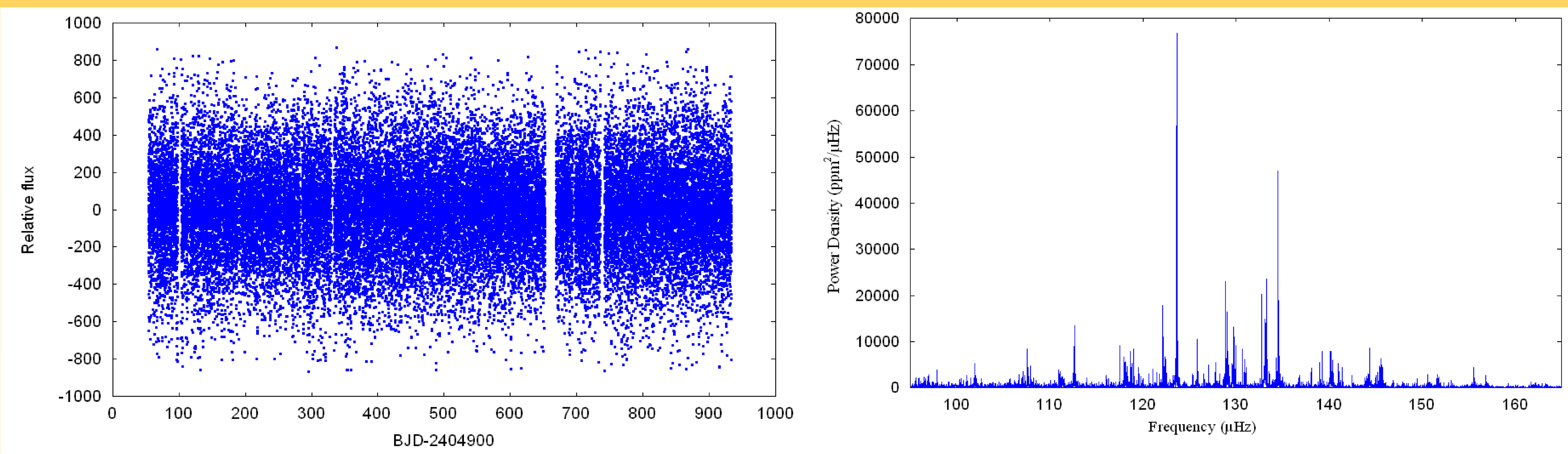


Fig. 1 **Left panel: Light curve corrected for slopes and discontinuities, cleaned for obvious outliers and normalized to the mean value. Right panel: Power Spectrum Density in the region of p mode excess hump.**

Fig. 2 **Power density spectrum of KIC 6144777. Light grey: power density spectrum, thick solid red line: global fit according to the model described in the text; dotted line: semi-Lorentzian plus the white noise component, thick solid blue and dashed lines: the semi-Loretzian and the white noise component of the global fit, respectively.**

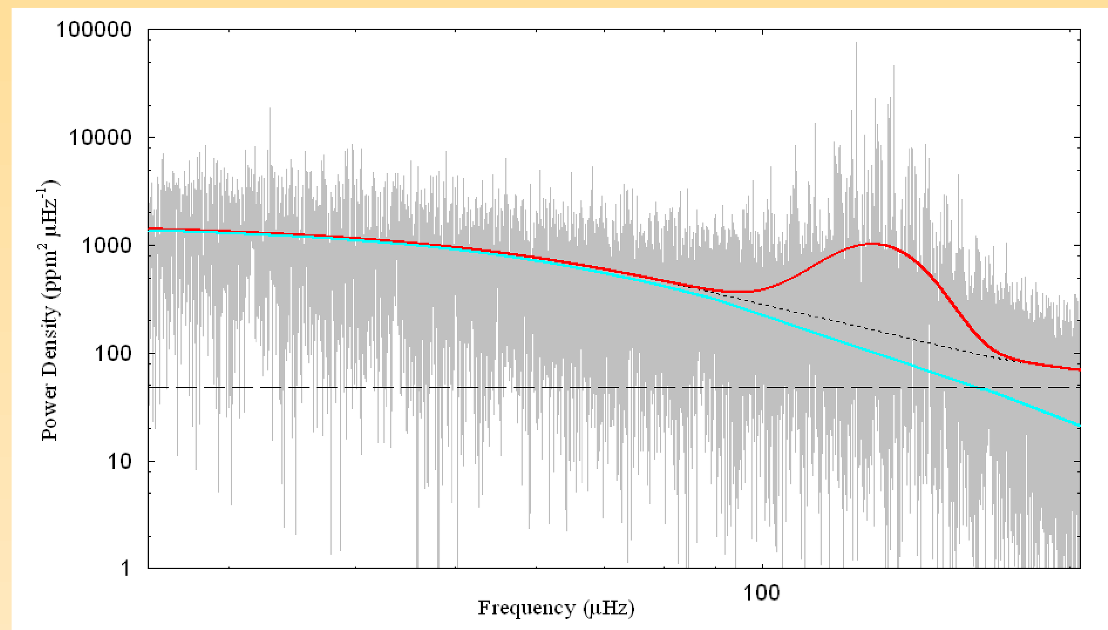
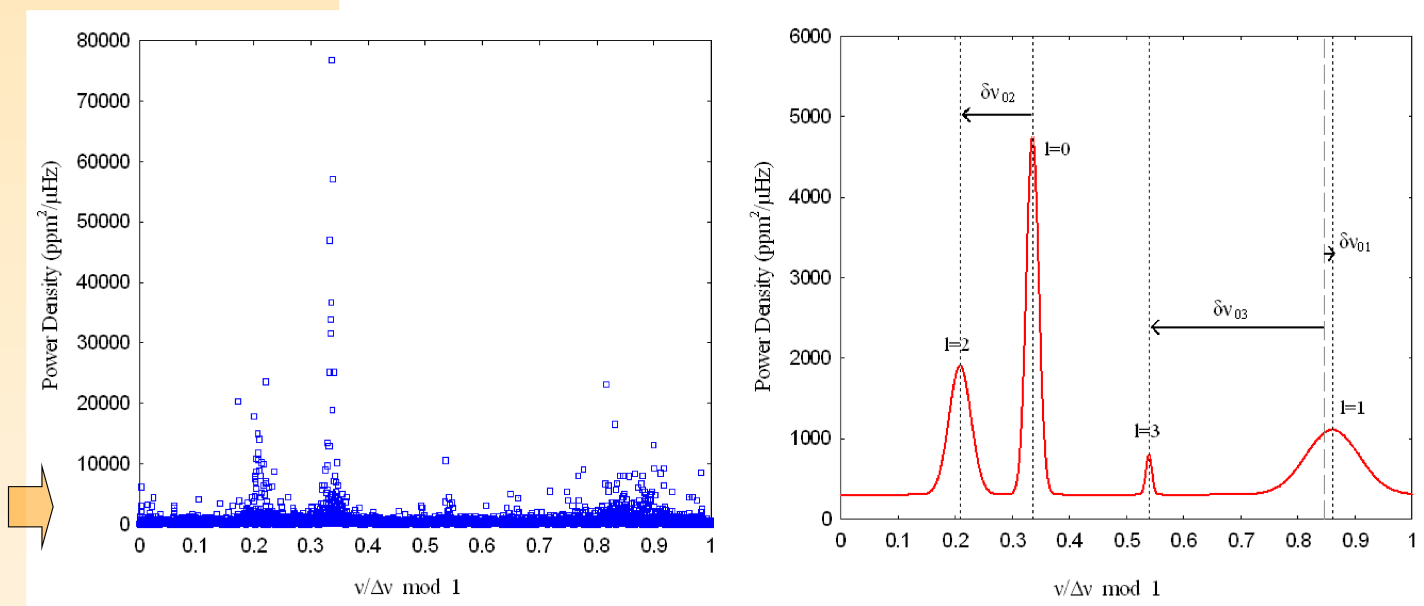


Fig. 3 **Collapsed PSD and ridge identification and definition of small separations used in this paper. The dotted lines mark the centres of l=0, 1, 2, 3 ridge. The dashed line correspond to midpoint of adjacent l=0 modes.**

$\delta\nu_{01} = -0.014 + 0.219/-0.914\,\mu Hz$

$\delta\nu_{02} = 0.127 + 0.063/-0.061\,\mu Hz$

$\delta\nu_{03} = 0.307 + 0.198/-0.893\,\mu Hz$



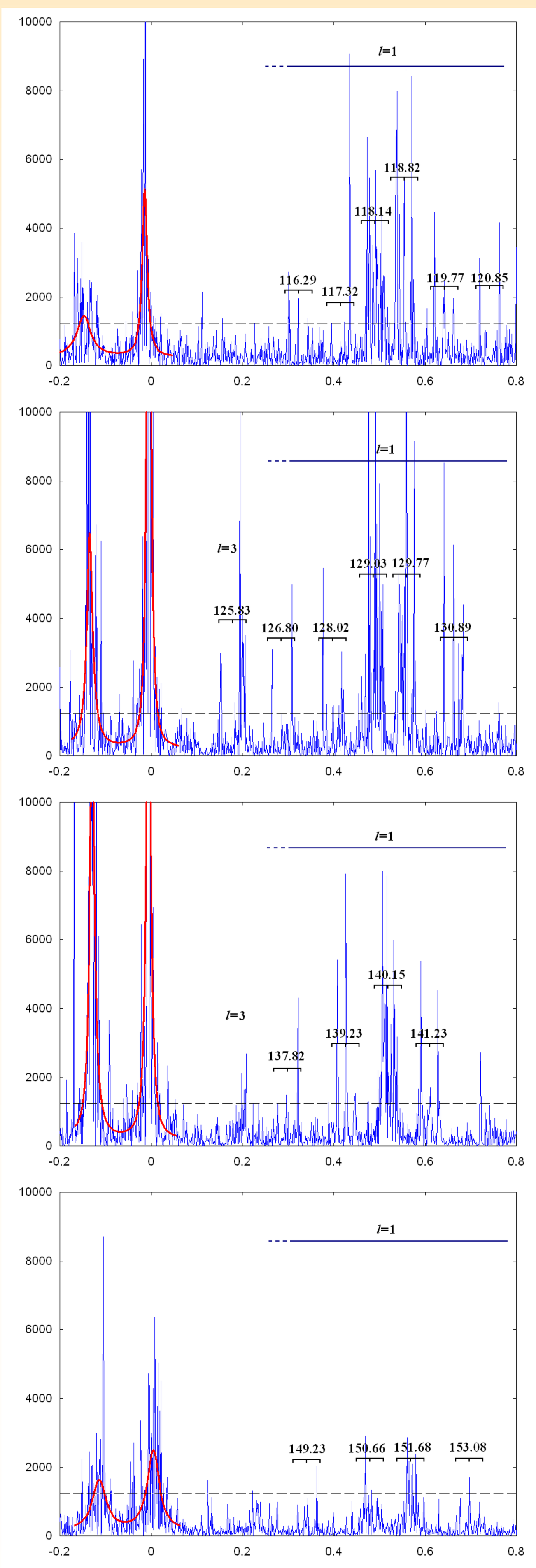


Fig. 4 ROTATIONAL SPLITTING

The échelle diagram as a function of the reduced frequency $\nu/\Delta\nu-(n_p+\varepsilon)$
The radial order is (from top to down) 9, 10, 11 and 12.

Table 1 **Mosser et al (2012) proposed a model for describing the rotational splittings of dipole mixed modes:** $\delta\nu_{split} = \nu_{n,1,m} - \nu_{n,1} = mR_n(\nu)\delta\nu_{rot}$

$$R_{n_p}(\nu) = 1 - \frac{\lambda}{1+\left(\frac{\nu-\nu_{n_p,1}}{\beta\Delta\nu}\right)^2}$$

The calculated values of the rotational splittings, $\delta\nu_i^{calc}$ using the model proposed by Mosser et al. (2012) that match best the measured rotational splittings, $\delta\nu_i^{obs}$. All the values are in μHz.

$\nu_{l=1,m=0}$	$\delta\nu_i^{obs}$	$\delta\nu_i^{calc}$
116.29	0.225	0.230
117.32	0.221	0.213
118.14	0.155	0.166
118.82	0.175	0.166
119.77	0.227	0.217
120.85	0.235	0.232
126.80	0.237	0.233
128.02	0.218	0.218
129.03	0.149	0.164
129.77	0.171	0.172
130.89	0.216	0.223
137.82	0.237	0.232
139.23	0.211	0.210
140.15	0.158	0.154
141.23	0.200	0.205
149.42	0.228	0.229
150.66	0.192	0.188
151.68	0.176	0.169
153.08	0.228	0.226

Stellar modelling

We computed radial and nonradial eigenfrequencies with mode degree *l* up to 3 for models of intermediate-mass stars from 1.00 to 1.20M☉ in steps of 0.01M☉. The initial metal mass fraction Z=0.004 to 0.01 and initial hydrogen Y = 0.21 to 0.28. The mixing length parameter is free between 1.3 and 2.0. For the effective temperature, surface gravity and metallicity we considered the KIC values: 4657 K, 2.887 and -0.062. We selected as the best fit model for KIC 006144777 the model that fit best the observed radial frequencies and is situated in the error box of effective temperature and surface gravity. The model parameters are: M=1.11M☉ , log g=2.929 dex, R=5.22R☉, L=9.78L☉, X=0.716, Y=0.28, Z=0.004 (or [Fe/H]=-0.43), Age=2.7Gyr.

Fig. 5 LINKING THE ROTATION SPLITTING TO THE CORE ROTATION

The normalized integrated rotational kernels (blue)

$$\int_0^{x_c} K_{n,l}(x)dx \Big/ \int_0^1 K_{n,l}(x)dx$$

for the l=1 modes in the frequency range [118.27, 150.2], having minima mode inertia in the best fitting stellar model for KIC006144777. The values of these kernels at the core boundary are proportional with the mode inertia. Dashed line marks the base of the convective envelope, located at r/R=0.142. The red line represents the thermonuclear energy generation rate ε.
We see that the kernels in the g-m modes are dominated by the core, since the normalized integrated kernels reach a value larger than 0.75 at the core boundary.

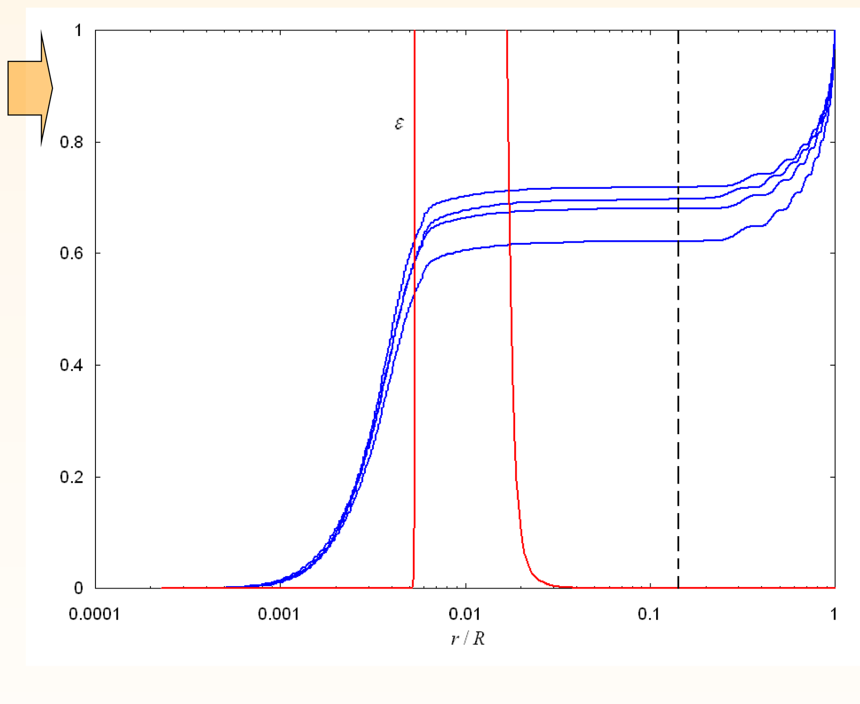
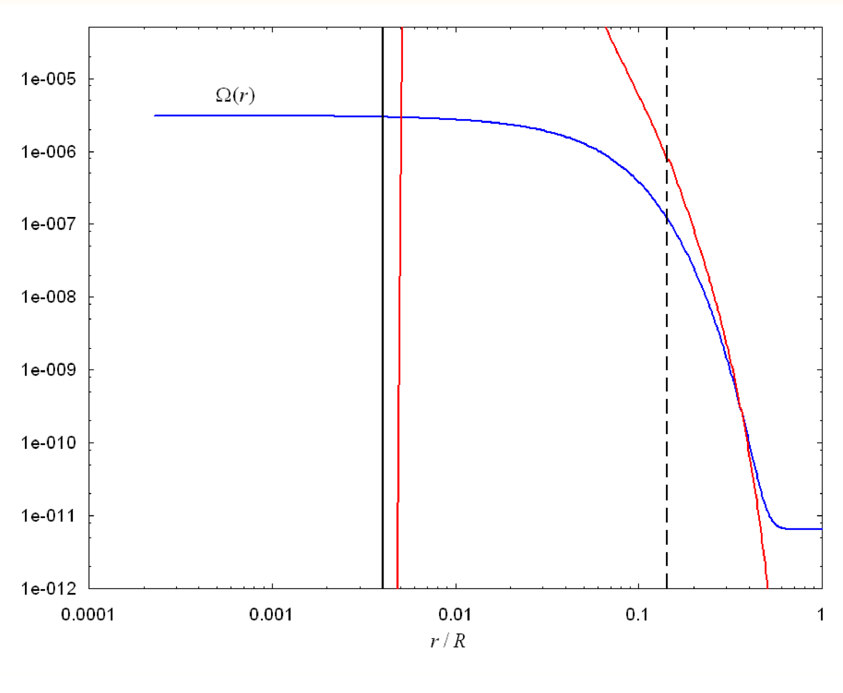


Fig. 6 **Internal differential rotation profile (blue). We adopted the following expression to describe the internal stellar rotation (Lee & Saio, 1993):**

$$\Omega(x) = \Omega_s\left[1+\frac{b-1}{1+e^{a(x-x_c)}}\right]$$

where *a*, *b* are real, *b>1*. We have found the internal rotation profile that match best the calculated and the observed splitting of the l=1 modes of our stellar model with the frequencies between 116 μHz and 152 μHz.
Logarithmic scale was used on both axes. The vertical black line marks the boundary, of the rigid rotating core. The red line and the dashed line represent the thermonuclear energy generation rate ε and the base of the convective envelope, respectively.



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