




# Foam: A Python package for forward asteroseismic modelling of gravity modes

Mathias Michielsen <sup>1</sup>

<sup>1</sup> Institute of Astronomy, KU Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium

DOI: [10.xxxxxx/draft](https://doi.org/10.xxxxxx/draft)

## Software

- [Review](#) 
- [Repository](#) 
- [Archive](#) 

Editor: [Open Journals](#) 

## Reviewers:

- [@openjournals](#)

Submitted: 01 January 1970

Published: unpublished

## License

Authors of papers retain copyright  
and release the work under a  
Creative Commons Attribution 4.0  
International License ([CC BY 4.0](#))

## Summary

Asteroseismology, the study of stellar pulsations, offers insights into the internal structures and evolution of stars. Analysing the variations in a star's brightness allows the determination of fundamental properties such as mass, radius, age, and chemical composition. Asteroseismology heavily relies on computational tools, but a significant number of them are closed-source, thus inaccessible to the broader astronomic community. This manuscript presents Foam, a Python package designed to perform forward asteroseismic modelling of stars exhibiting gravity modes. It automates and streamlines a considerable fraction of the modelling process, comparing grids of theoretical stellar models and their oscillation frequencies to observed frequency sets in stars.

Foam offers the flexibility to employ diverse modelling approaches, allowing users to choose different methodologies for matching theoretically predicted oscillations to observations. It provides options to utilise various sets of observables for comparison with their theoretical counterparts, employ different merit functions for assessing goodness of fit, and to incorporate nested subgrids in a statistically rigorous manner. For applications of these methodologies in modelling observed gravity modes, refer to Michielsen et al. (2021) and Michielsen et al. (2023).

## Introduction

Stars spend approximately 90% of their evolution on their so called *main sequence*, during which they fuse hydrogen into helium in their cores. In stars with masses above about 1.2 times the mass of the sun, the stellar core in which these fusion processes take place becomes convective. Macroscopic element transport in and near the convective cores of these stars has a large influence on their life, since it transports additional hydrogen from outside of the nuclear fusion region into this region. In this way it both prolongs the main-sequence lifetime of stars and enlarges the mass of the helium core at the end of the main sequence, which significantly influences all later stages of their evolution. However, these transport processes provide the largest uncertainties in stellar structure and evolution models for stars with convective cores, due to our poor understanding of macroscopic element transport and limited number of useful observations to test the theories. (See e.g. [Anders & Pedersen, 2023](#) for a review on this topic.)

Through asteroseismology, we gain the means to unravel the interior structure of stars ([Aerts et al., 2010](#); [Aerts, 2021](#)). Gravity (g-) modes in particular have a high sensitivity to the properties of the near-core region. These modes have buoyancy as their restoring force, have dominantly horizontal displacements, and oscillate with a period of several hours to a few days. Additionally, they can only propagate in the non-convective regions in the star, which makes their propagation cavity very sensitive to the size of the convective core. We can exploit the probing power of g-modes, observed in e.g. Slowly Pulsating B-type stars ([Waelkens, 1991](#)), to

41 investigate the physics in the interior of these stars, particularly the transition region between  
42 the convective core and radiative envelope.

## 43 Statement of need

44 Some tools have been developed and made publicly available to model and determine stel-  
45 lar parameters of solar-like oscillators, such as AIMS (Rendle et al., 2019), BASTA (Aguirre  
46 Børsen-Koch et al., 2022), and pySYD (Chontos et al., 2022). However, there are several key  
47 differences between the modelling of the pressure (p-) modes observed in solar-like oscillators,  
48 and the modelling of the g-modes observed in more massive stars. First and foremost, the  
49 well-known asteroseismic scaling relations used for solar-like oscillators cannot be extrapolated  
50 to main-sequence stars with a convective core. Secondly, the effect of rotation on p-modes is  
51 often included in a perturbative way, whereas the g-mode frequencies are strongly dependent  
52 on rotation and require the inclusion of the Coriolis acceleration in a non-perturbative way.  
53 Additionally the mass regime of stars with convective cores is subject to strong correlations  
54 between several model parameters, which sometimes follow non-linear relationships. In this con-  
55 text, the Mahalanobis distance (MD) (see Aerts et al., 2018 for its application to asteroseismic  
56 modelling) provides a more appropriate merit function than the often used  $\chi^2$ , since it tackles  
57 both these non-linear correlations and includes uncertainties for the theoretical predictions.  
58 The use of a different, more appropriate merit function significantly impacts modelling results.  
59 This is demonstrated by Michielsen et al. (2021) in their comparison between the results  
60 obtained by employing the MD versus  $\chi^2$ , applied in the modelling of an observed star.

61 Foam was developed to be complimentary to the available modelling tools for solar-like oscillators.  
62 It provides a framework for the forward modelling of g-modes in main-sequence stars with  
63 convective cores, and tackles the differences in the modelling approach as compared to the  
64 case of solar-like oscillators. Foam therefore extends the efforts to provide publicly available,  
65 open-source tools for asteroseismic modelling to the g-mode domain, given that the currently  
66 available tools predominantly concern the solar-like oscillators.

## 67 Software package overview

68 Foam is designed as a customisable pipeline. It will match theoretical models to observations,  
69 computing the goodness of fit of each model based on the selected merit function. Afterwards  
70 it will determine the best model alongside the uncertainty region of this solution based on  
71 statistical criteria. On the observational side, it will take a list of frequencies as an input,  
72 optionally complemented by additional information such as a set of surface properties (effective  
73 temperature, surface gravity, luminosity, element surface abundances...). On the theoretical  
74 side Foam will use a grid of theoretical stellar models, calculated by the user to suit their  
75 specific needs. Although the current implementation is made for a grid of stellar equilibrium  
76 models computed by MESA (Jermyn et al., 2023; Paxton et al., 2011, 2013, 2015, 2018, 2019),  
77 whose pulsation frequencies are computed with GYRE (Townsend et al., 2018; Townsend &  
78 Teitler, 2013), the majority of the code is not inherently dependent on MESA. By making  
79 certain adjustments to the modelling pipeline, Foam could potentially employ grids generated  
80 by different stellar evolution codes. Some suggestions how to approach this are given in  
81 the description of the theoretical model grid in the online documentation. However, the  
82 implementation of such functionality currently remains out of the scope of the project.

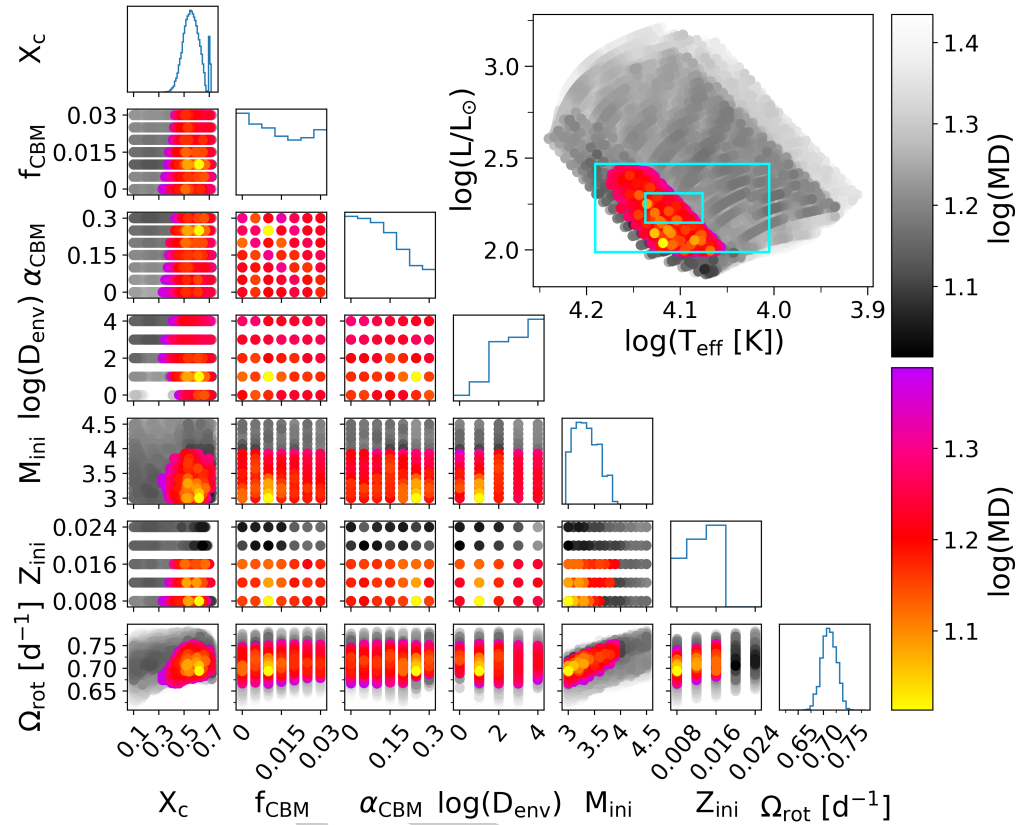
83 The script to run the pipeline can be altered in order to change the modelling approach you want  
84 to take. The various configuration options, the installation procedure, and a walkthrough of how  
85 to create your own modelling setup, are described in more detail in the online documentation.  
86 Although it relies on grids of stellar equilibrium models computed by MESA as the source of  
87 the theoretical model grid, MESA's installation itself is not required for Foam to function. The  
88 installation of GYRE is however required, specifically since Foam relies on the tar\_fit.mX.kX.h5

files included in the GYRE installation. This allows us to rescale the g-modes for various stellar rotation rates, following the traditional approximation of rotation (e.g. [Eckart, 1960](#); see [Townsend, 2020](#) for its implementation in GYRE) and assuming rigid rotation. This facilitates computing the oscillation frequencies for the grid of stellar equilibrium models only once, and subsequently rescaling them to find the optimised rotation rate (see [Michielsen et al., 2023](#)). This approach avoids repeating the oscillation computations for a variety of rotation values, which would introduce extra dimensionality in the modelling problem in the form of adding the rotation rate as an additional free parameter.

Foam's modelling procedure can be broken down into following sequential [steps of the pipeline](#):

- Extract all required parameters and quantities from the files in the theoretical MESA and GYRE grids.
- Construct the theoretical pulsation patterns for each stellar model. Thereafter select theoretical pulsation patterns matching the observational pattern whilst optimising their rotation rates. Finally combine this information with the models' surface properties.
- Calculate the likelihood of all the theoretical patterns according to the specified merit functions and observables. This list of observables consist of the pulsations, but can optionally be extended with spectroscopic or astrometric information.
- Exclude all the models that fall outside an n-sigma error box on the spectroscopic and astrometric constraints as acceptable solutions.
- Calculate the Akaike information criterion (AIC, [Claeskens & Hjort, 2008](#)) corrected for small sample size. This statistical criterion rewards goodness of fit, but penalises model complexity in the form of additional free parameters. The AIC thus allows a statistical comparison between models of different (nested) grids where the number of free parameters is not the same.
- Calculate the 2 sigma uncertainty region of the maximum likelihood solution using Bayes' theorem.
- Make corner plots for all combinations of the different modelling choices (See [Figure 1](#) for an example).
- Construct a table with the best model of the grid for each combination of different modelling choices.

Next to the tables with the best model parameters and their AIC values, the cornerplots provide a quick way to assess the output of the pipeline and visualise the modelling results. [Figure 1](#) shows an example of such a cornerplot for the modelling of KIC 4930889 performed by [Michielsen et al. \(2023\)](#). It gives a clear indication of which models are included (coloured) or excluded (greyscale) from the uncertainty region, and indicates what the best models of the grid are (yellow, see the colour bar).



**Figure 1:** Cornerplot with the parameters in the grid and the rotation. The 50% best models are shown, colour-coded according to the log of their merit function value. Models in colour fall within the 2 sigma error ellipse, while those in greyscale fall outside of it. Figures on the diagonal show binned parameter distributions of the models in the error ellipse, and the panel at the top right shows an Hertzsprung-Russell (HR) diagram with 1 and 3 sigma observational error boxes. Figure taken from Michielsen et al. (2023).

## Acknowledgements

The research leading to the development of this package has received funding from the Research Foundation Flanders (FWO) by means of a PhD scholarship to MM under project No. 11F7120N. MM is grateful to Timothy Van Reeth for his help concerning the scaling of g-modes with rotation, to Alex Kemp for his suggestions regarding the online documentation, and to the reviewers Ashley Chontos and Ankit Barik for their constructive remarks.

## References

- Aerts, C. (2021). Probing the interior physics of stars through asteroseismology. *Reviews of Modern Physics*, 93(1), 015001. <https://doi.org/10.1103/RevModPhys.93.015001>
- Aerts, C., Christensen-Dalsgaard, J., & Kurtz, D. W. (2010). *Asteroseismology*. Springer, Astronomy; Astrophysics Library. <https://doi.org/10.1007/978-1-4020-5803-5>
- Aerts, C., Molenberghs, G., Michielsen, M., Pedersen, M. G., Björklund, R., Johnston, C., Mombarg, J. S. G., Bowman, D. M., Buysschaert, B., Pápics, P. I., Sekaran, S., Sundqvist, J. O., Tkachenko, A., Truyaert, K., Van Reeth, T., & Vermeyen, E. (2018). Forward Asteroseismic Modeling of Stars with a Convective Core from Gravity-mode Oscillations: Parameter Estimation and Stellar Model Selection. *The Astrophysical Journal Supplement Series*, 237, 15. <https://doi.org/10.3847/1538-4365/aaccfb>

- 142 Aguirre Børsen-Koch, V., Rørsted, J. L., Justesen, A. B., Stokholm, A., Verma, K., Winther,  
143 M. L., Knudstrup, E., Nielsen, K. B., Sahlholdt, C., Larsen, J. R., Cassisi, S., Serenelli, A.  
144 M., Casagrande, L., Christensen-Dalsgaard, J., Davies, G. R., Ferguson, J. W., Lund, M.  
145 N., Weiss, A., & White, T. R. (2022). The BAYesian STellar algorithm (BASTA): a fitting  
146 tool for stellar studies, asteroseismology, exoplanets, and Galactic archaeology. *Monthly*  
147 *Notices of the RAS*, 509(3), 4344–4364. <https://doi.org/10.1093/mnras/stab2911>
- 148 Anders, E. H., & Pedersen, M. G. (2023). Convective Boundary Mixing in Main-Sequence  
149 Stars: Theory and Empirical Constraints. *Galaxies*, 11(2), 56. [https://doi.org/10.3390/](https://doi.org/10.3390/galaxies11020056)  
150 [galaxies11020056](https://doi.org/10.3390/galaxies11020056)
- 151 Chontos, A., Huber, D., Sayeed, M., & Yamsiri, P. (2022). pySYD: Automated measurements  
152 of global asteroseismic parameters. *The Journal of Open Source Software*, 7(79), 3331.  
153 <https://doi.org/10.21105/joss.03331>
- 154 Claeskens, G., & Hjort, N. L. (2008). *Model Selection and Model Averaging, Cambridge Series*  
155 *in Statistical and Probabilistic Mathematics*. <https://doi.org/10.1017/CBO9780511790485>
- 156 Eckart, G. (1960). Hydrodynamics of oceans and atmospheres. *Hydrodynamics of Oceans and*  
157 *Atmospheres*, Pergamon Press, Oxford. <https://doi.org/10.1002/qj.49708938224>
- 158 Jermyn, A. S., Bauer, E. B., Schwab, J., Farmer, R., Ball, W. H., Bellinger, E. P., Dotter, A.,  
159 Joyce, M., Marchant, P., Mombarg, J. S. G., Wolf, W. M., Sunny Wong, T. L., Cinquegrana,  
160 G. C., Farrell, E., Smolec, R., Thoul, A., Cantiello, M., Herwig, F., Toloza, O., ... Timmes,  
161 F. X. (2023). Modules for Experiments in Stellar Astrophysics (MESA): Time-dependent  
162 Convection, Energy Conservation, Automatic Differentiation, and Infrastructure. *The*  
163 *Astrophysical Journal Supplement Series*, 265(1), 15. [https://doi.org/10.3847/1538-4365/](https://doi.org/10.3847/1538-4365/aca8d)  
164 [aca8d](https://doi.org/10.3847/1538-4365/aca8d)
- 165 Michielsen, M., Aerts, C., & Bowman, D. M. (2021). Probing the temperature gradient in  
166 the core boundary layer of stars with gravito-inertial modes. The case of KIC 7760680.  
167 *Astronomy and Astrophysics*, 650, A175. <https://doi.org/10.1051/0004-6361/202039926>
- 168 Michielsen, M., Van Reeth, T., Tkachenko, A., & Aerts, C. (2023). Probing the physics in the  
169 core boundary layers of the double-lined B-type binary KIC 4930889 from its gravito-inertial  
170 modes. *Astronomy and Astrophysics*, 679, A6. [https://doi.org/10.1051/0004-6361/](https://doi.org/10.1051/0004-6361/202244192)  
171 [202244192](https://doi.org/10.1051/0004-6361/202244192)
- 172 Paxton, B., Bildsten, L., Dotter, A., Herwig, F., Lesaffre, P., & Timmes, F. (2011). Modules  
173 for Experiments in Stellar Astrophysics (MESA). *The Astrophysical Journal Supplement*  
174 *Series*, 192(1), 3. <https://doi.org/10.1088/0067-0049/192/1/3>
- 175 Paxton, B., Cantiello, M., Arras, P., Bildsten, L., Brown, E. F., Dotter, A., Mankovich, C.,  
176 Montgomery, M. H., Stello, D., Timmes, F. X., & Townsend, R. (2013). Modules for  
177 Experiments in Stellar Astrophysics (MESA): Planets, Oscillations, Rotation, and Massive  
178 Stars. *The Astrophysical Journal Supplement Series*, 208(1), 4. [https://doi.org/10.1088/](https://doi.org/10.1088/0067-0049/208/1/4)  
179 [0067-0049/208/1/4](https://doi.org/10.1088/0067-0049/208/1/4)
- 180 Paxton, B., Marchant, P., Schwab, J., Bauer, E. B., Bildsten, L., Cantiello, M., Dessart, L.,  
181 Farmer, R., Hu, H., Langer, N., Townsend, R. H. D., Townsley, D. M., & Timmes, F. X.  
182 (2015). Modules for Experiments in Stellar Astrophysics (MESA): Binaries, Pulsations, and  
183 Explosions. *The Astrophysical Journal Supplement Series*, 220(1), 15. [https://doi.org/10.](https://doi.org/10.1088/0067-0049/220/1/15)  
184 [1088/0067-0049/220/1/15](https://doi.org/10.1088/0067-0049/220/1/15)
- 185 Paxton, B., Schwab, J., Bauer, E. B., Bildsten, L., Blinnikov, S., Duffell, P., Farmer, R.,  
186 Goldberg, J. A., Marchant, P., Sorokina, E., Thoul, A., Townsend, R. H. D., & Timmes, F.  
187 X. (2018). Modules for Experiments in Stellar Astrophysics (MESA): Convective Boundaries,  
188 Element Diffusion, and Massive Star Explosions. *The Astrophysical Journal Supplement*  
189 *Series*, 234(2), 34. <https://doi.org/10.3847/1538-4365/aaa5a8>

- 190 Paxton, B., Smolec, R., Schwab, J., Gautschy, A., Bildsten, L., Cantiello, M., Dotter, A.,  
191 Farmer, R., Goldberg, J. A., Jermyn, A. S., Kanbur, S. M., Marchant, P., Thoul, A.,  
192 Townsend, R. H. D., Wolf, W. M., Zhang, M., & Timmes, F. X. (2019). Modules for  
193 Experiments in Stellar Astrophysics (MESA): Pulsating Variable Stars, Rotation, Convective  
194 Boundaries, and Energy Conservation. *The Astrophysical Journal Supplement Series*, 243(1),  
195 10. <https://doi.org/10.3847/1538-4365/ab2241>
- 196 Rendle, B. M., Buldgen, G., Miglio, A., Reese, D., Noels, A., Davies, G. R., Campante, T.  
197 L., Chaplin, W. J., Lund, M. N., Kuszlewicz, J. S., Scott, L. J. A., Scuflaire, R., Ball,  
198 W. H., Smetana, J., & Nsamba, B. (2019). AIMS - a new tool for stellar parameter  
199 determinations using asteroseismic constraints. *Monthly Notices of the RAS*, 484(1),  
200 771–786. <https://doi.org/10.1093/mnras/stz031>
- 201 Townsend, R. H. D. (2020). Improved asymptotic expressions for the eigenvalues of Laplace's  
202 tidal equations. *Monthly Notices of the RAS*, 497(3), 2670–2679. [https://doi.org/10.](https://doi.org/10.1093/mnras/staa2159)  
203 [1093/mnras/staa2159](https://doi.org/10.1093/mnras/staa2159)
- 204 Townsend, R. H. D., Goldstein, J., & Zweibel, E. G. (2018). Angular momentum transport  
205 by heat-driven g-modes in slowly pulsating B stars. *Monthly Notices of the RAS*, 475,  
206 879–893. <https://doi.org/10.1093/mnras/stx3142>
- 207 Townsend, R. H. D., & Teitler, S. A. (2013). GYRE: an open-source stellar oscillation code  
208 based on a new Magnus Multiple Shooting scheme. *Monthly Notices of the RAS*, 435,  
209 3406–3418. <https://doi.org/10.1093/mnras/stt1533>
- 210 Waelkens, C. (1991). Slowly pulsating B stars. *Astronomy and Astrophysics*, 246, 453.