An asteroseismic and spectrosopic pipeline for the analysis of structures and rotation profiles of rapidly-rotating main sequence stars.

UNIVERSITY OF SURREY
Science & Technology Facilities Council

Giovanni M. Mirouh, University of Surrey (UK) with Daniel R. Reese, Grégory Faure, Yunpeng Li, et al.

The problem with rotation

Massive stars ($M > 2M_\odot$) are usually fast rotators → structure distorted by centrifugal forces, gravity darkening making $T_{\rm eff}, \log g$ dependent on inclination, Coriolis force impact mode propagation

→ need for 2D models and 2D complete mode calculations → ESTER and TOP codes.

Machine learning for rotating-star seismology

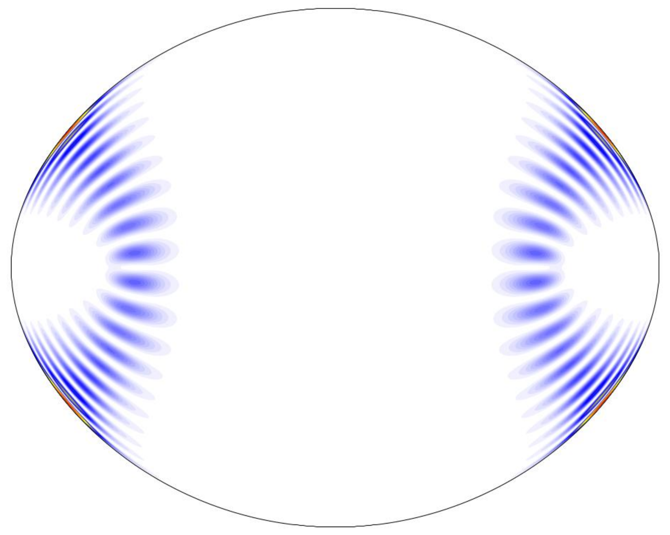
Separating subsets of modes and identifying regular patterns

Oscillation modes in solar-like stars are known to follow regular patterns → in massive, fast-rotating stars, modes can be split in subsets that exhibit such patterns.
Mirouh et al. (2019) used a **convolutional neural network** to separate modes into subsets based on their geometry.
Among those, **island modes** are the most visible, and follow the scaling relation $\langle\rho\rangle \propto \Delta\nu^2$

Reaching a complete description of the island-mode spectrum

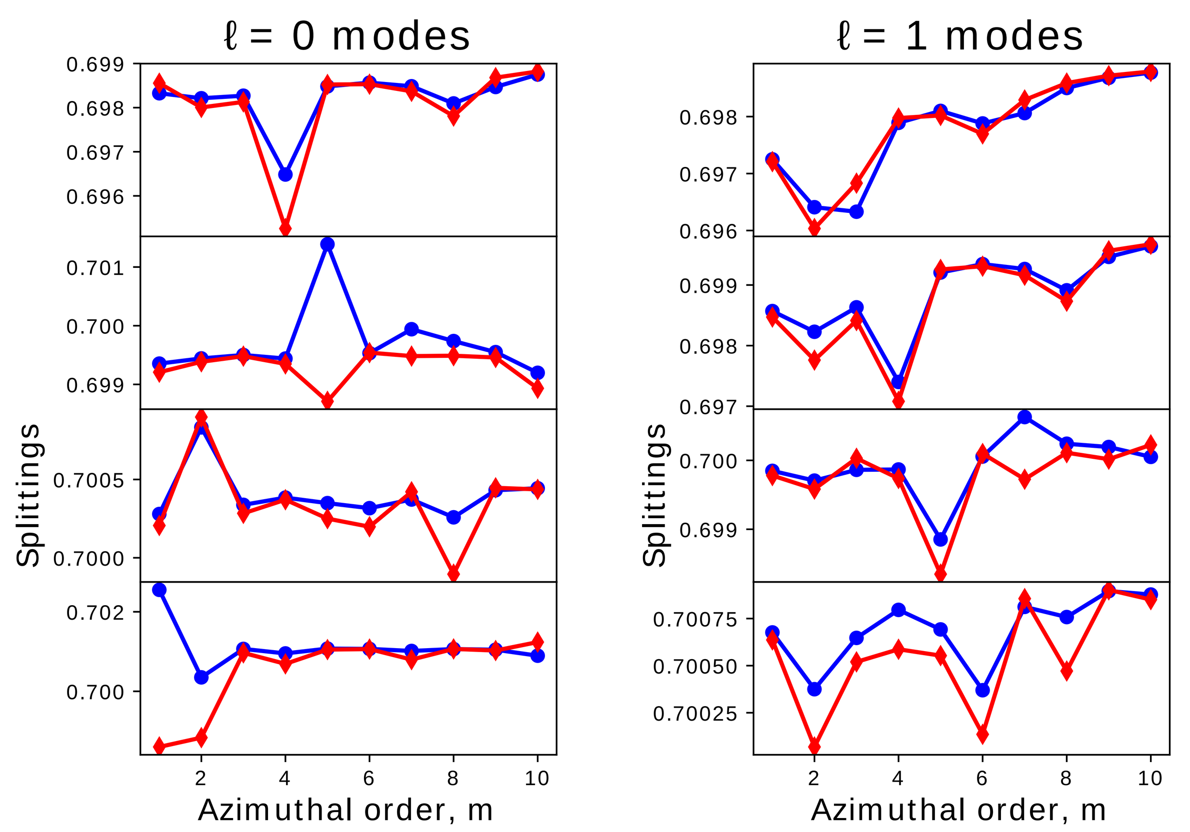
(Reese, Mirouh et al. submitted to A&A)

Rotational splittings = degeneracy lift for modes at $m \neq 0$, can be predicted



$3.0\mathrm{M}_\odot$ Ω=$0.7\Omega_\mathrm{K}$
687.7μHz m=1

Considering a doublet at $+m$ and $-m$ → models give us frequencies
We compute integrals over the propagation domain → **integration kernels** ▶
→ we need a theoretical link with internal rotation



Theoretical prediction from the **variational principle**
→ effective rotation probed $\Omega_\pm^{\rm eff}$ for modes at $\pm m$

$$\frac{\nu_+ - \nu_-}{2|m|} \approx \frac{\Omega_+^{\rm eff} - \Omega_-^{\rm eff}}{4\pi} + \frac{-C_+ + C_-}{4\pi|m|}$$

$$\text{with} \quad \Omega_\pm^{\rm eff} = \frac{\int_V \Omega\rho_0||\xi_\pm||^2 dV}{\int_V \rho_0||\xi_\pm||^2 dV}$$

$$\text{and} \quad C_\pm = \frac{\int_V \rho_0\Omega \cdot (\xi_\pm^\star \times \xi_\pm)\, dV}{\int_V \rho_0||\xi_\pm||^2 dV}$$

◀ Good match between model and theory, usually
→ discrepancies can be attributed to **avoided crossings**

Asteroseismology : summary

Island modes are the key to the seismology of fast-rotating stars
→ the convolutional neural network allows us to **identify modes**
→ separation-density scaling relation and workable rotational splittings

Future development = extension to **other subsets of modes** → non-island pressure, gravity, and inertial modes

Spectroscopy of fast-rotating stars

Two-dimensional models to fit observations

We want to find the best $(M, X_{\rm core}, \Omega, i)$ combination for a given set of observables $(T_{\rm eff}, \log g, v\sin i, L, \Delta\nu)$.
From a grid of two-dimensional models for various masses, ages, rotation rates and inclinations
→ 1D atmospheres computed at each point + limb-darkening + flux-weighted average on the visible surface
→ estimate of **surface properties** to compare with observations.

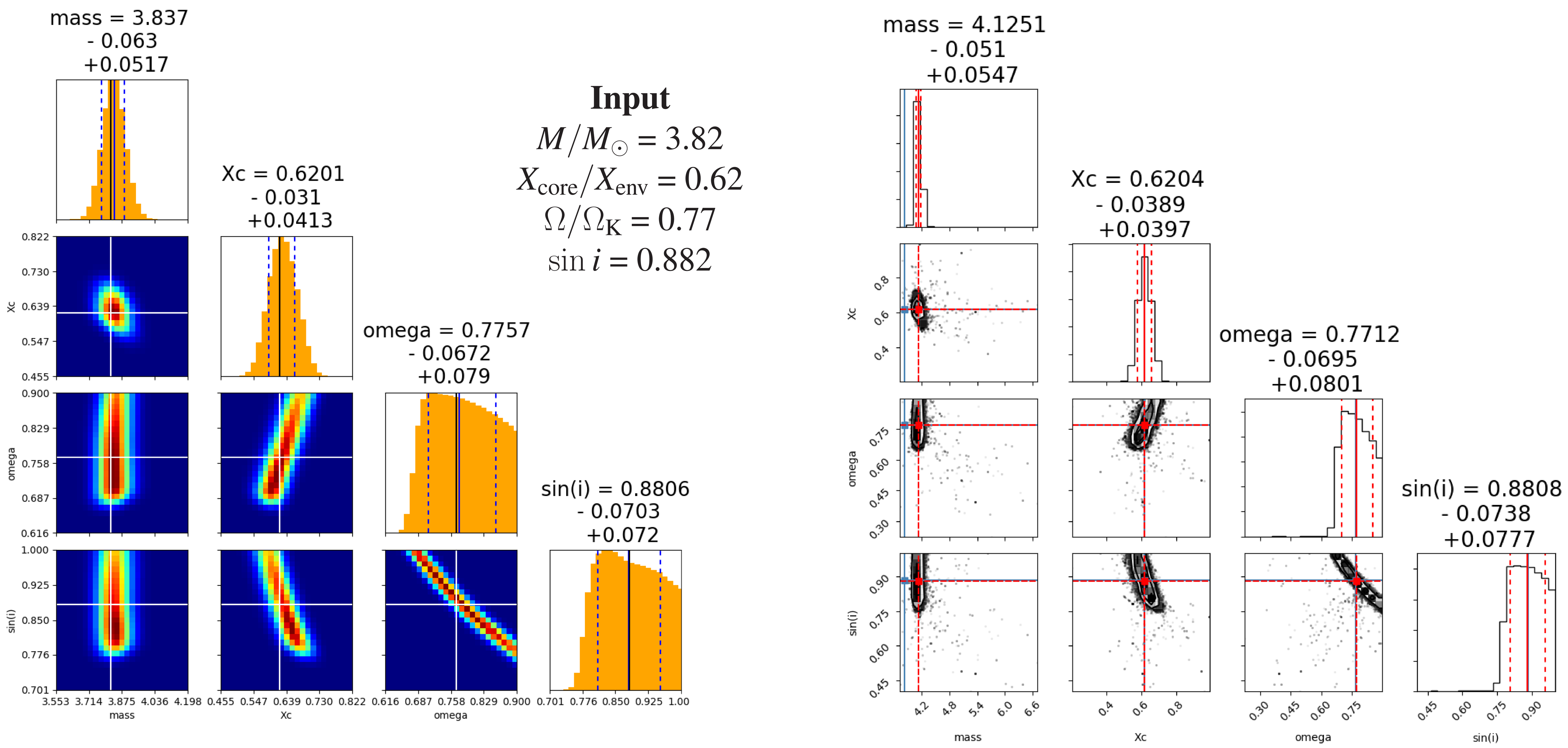
Finding the best-fit models

We use both a full 4D Bayesian analysis and a Monte-Carlo Markov Chain (MCMC) algorithm to find the best-fit model quickly and reliably. These methods allow to include observational errorbars and provide uncertainties on the model.
The likelihood of a model is computed as $L = \exp\left(-\frac{\chi^2}{2}\right)$ with $\chi^2 = \frac{(L_{\rm model} - L_{\rm obs})^2}{\sigma_L^2} + \ldots$

Hare-and-hounds exercise to test the method

Create a random 2D model → compute their surface properties $(T_{\rm eff}, \log g, v\sin i, L)$ → feed those values in the pipeline and retrieve the original model.

Including seismic diagnosis such as $\Delta\nu$ reduces the degeneracy of the problem
→ low uncertainties for fast rotators, both full Bayesian and MCMC show **very promising results** ▼



Spectroscopy : summary

Combining seismology and spectroscopy → automatically constrain fast-rotating stars and **determine their inclination** → builds on available observations, avoids expensive interferometry
Both **theoretical developments work on test cases** and must now be applied to actual observations.

Future development = spectral energy distributions → chemical constraints, use on actual data