3rd AstroFIt2 Annual Meeting
Rome 15/10/2019

COnstrain STellar physics using all-sky AsteRoseismology

Enrico Corsaro

Marie Sklodowska-Curie Fellow AstroFIt2

INAF - Osservatorio Astrofisico di Catania

Final report

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement Nº 664931.

Fellowship on stellar physics

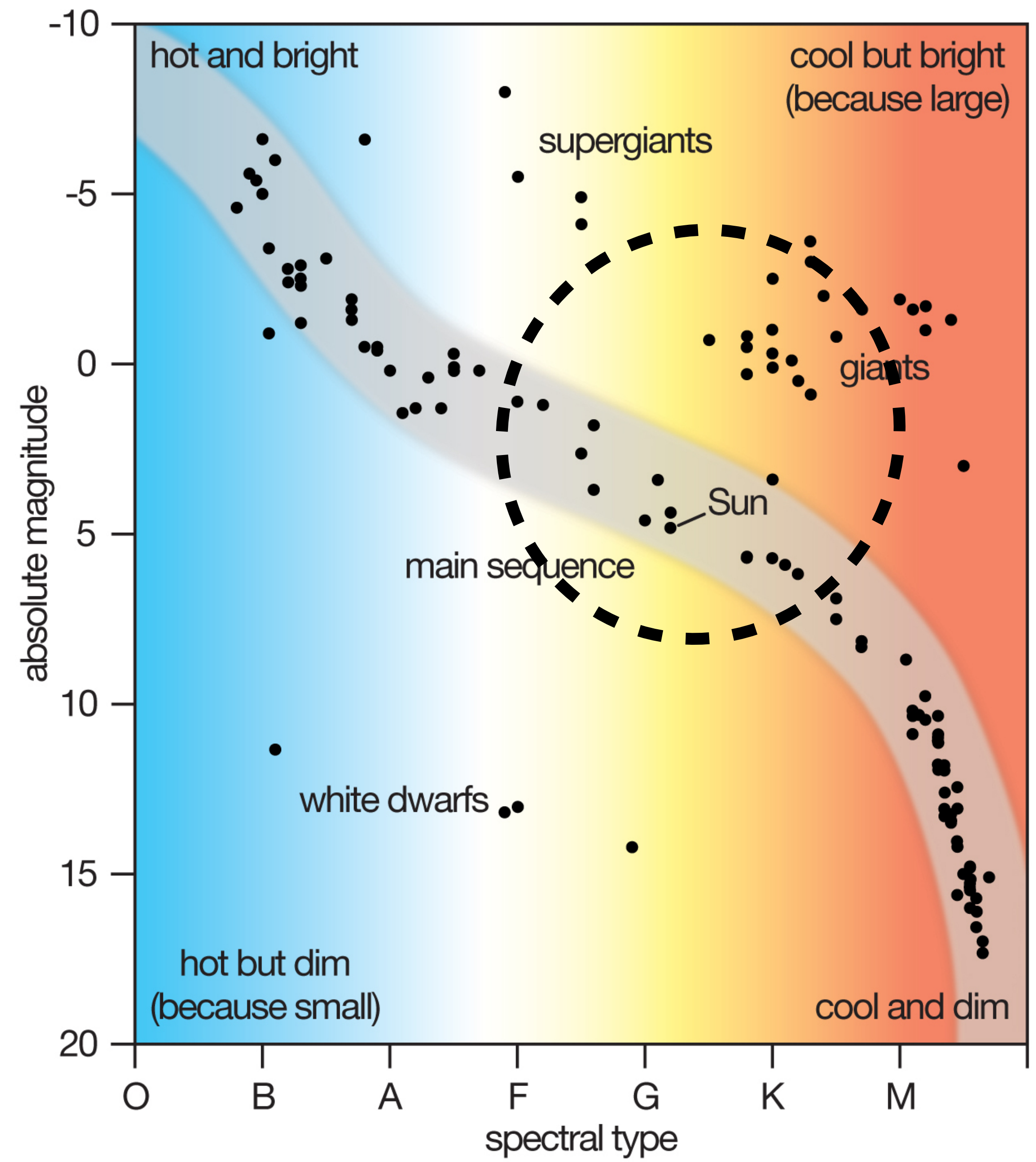
- I was working at CEA Saclay (Paris) when I applied for AstroFIt2
- Applied for 1st call
- Fellowship conducted between October 2016 and September 2019
- I started my contract right after the end of my postdoc at CEA
- Excellent opportunity to come back to my home institution and conduct my research with optimal resources

Scientific Objectives

- Use asteroseismology for a large number of stars (order 10^3) from past and ongoing space missions to improve our understanding of:
  - stellar rotation and angular momentum evolution
  - stellar convection
- Couple results with spectroscopic measurements of stellar atmospheric parameters

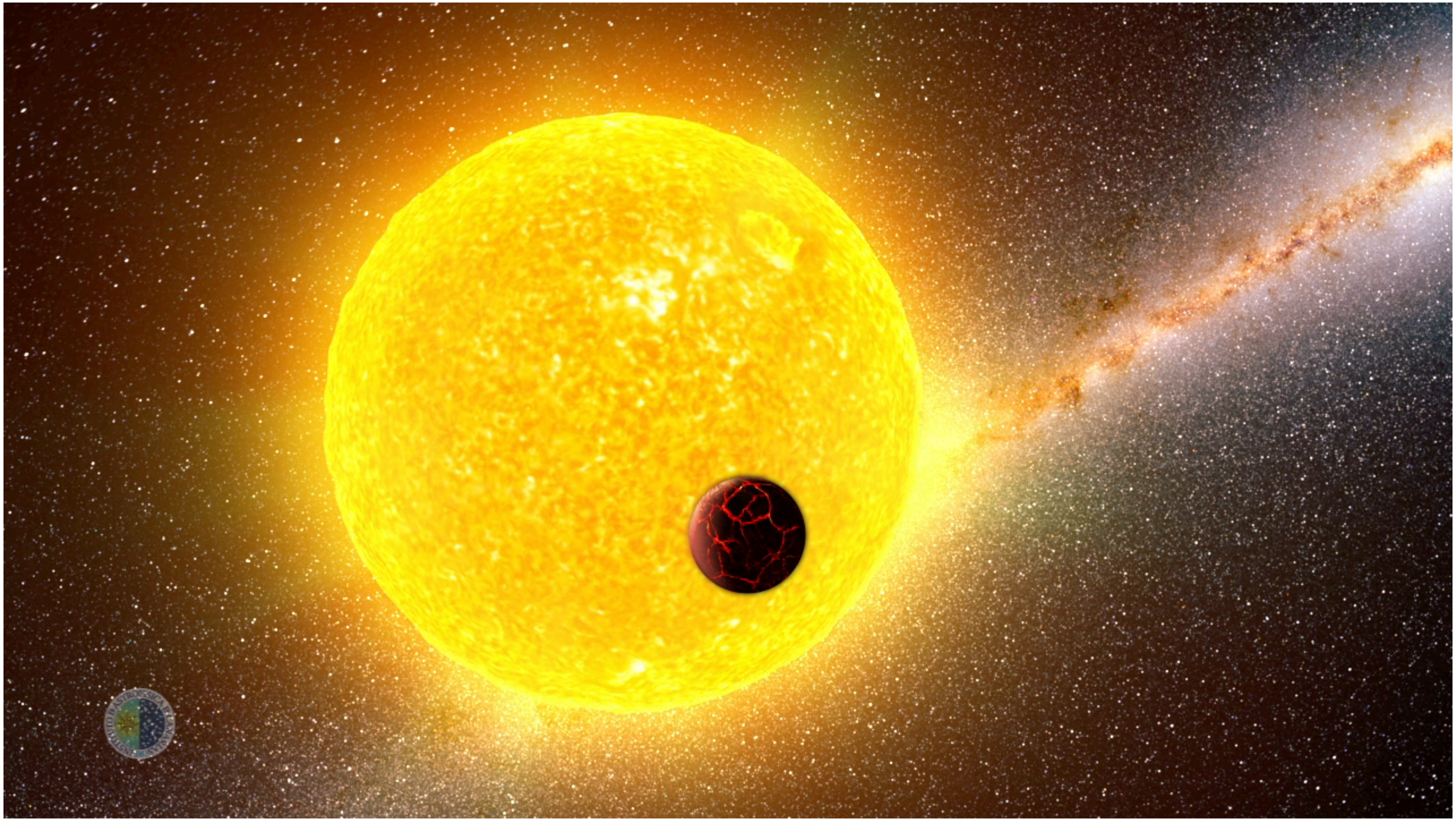
Asteroseismology

- Most stars with M ~ 1-3 M_{Sun} oscillate like the Sun
- Oscillations are caused by surface convective motions
- ~100 K stars known today
- Space missions MOST, CoRoT, NASA *Kepler,* K2, TESS, BRITE
- More to follow: ESA CHEOPS (2020), PLATO (2026) space missions



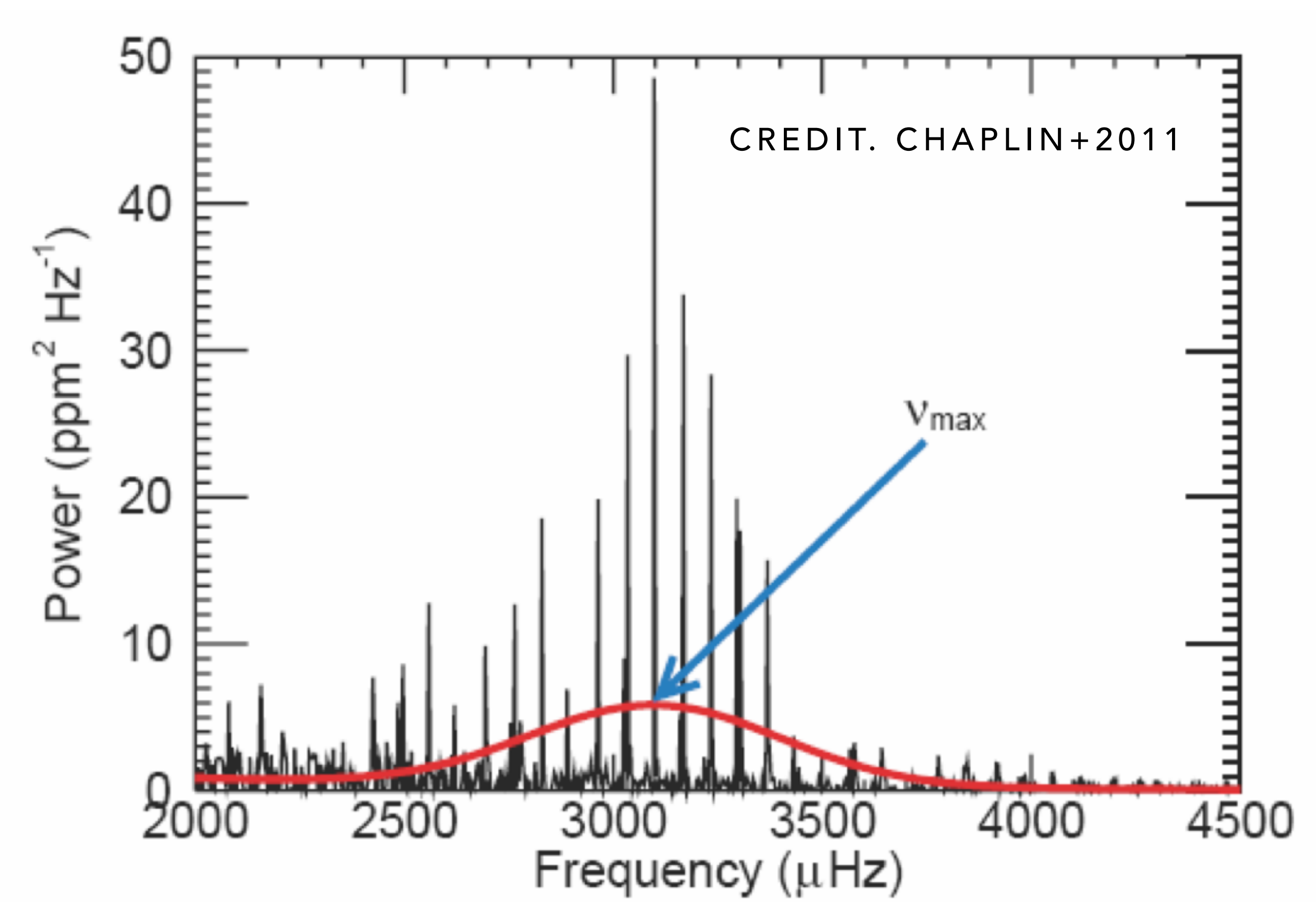
Asteroseismology

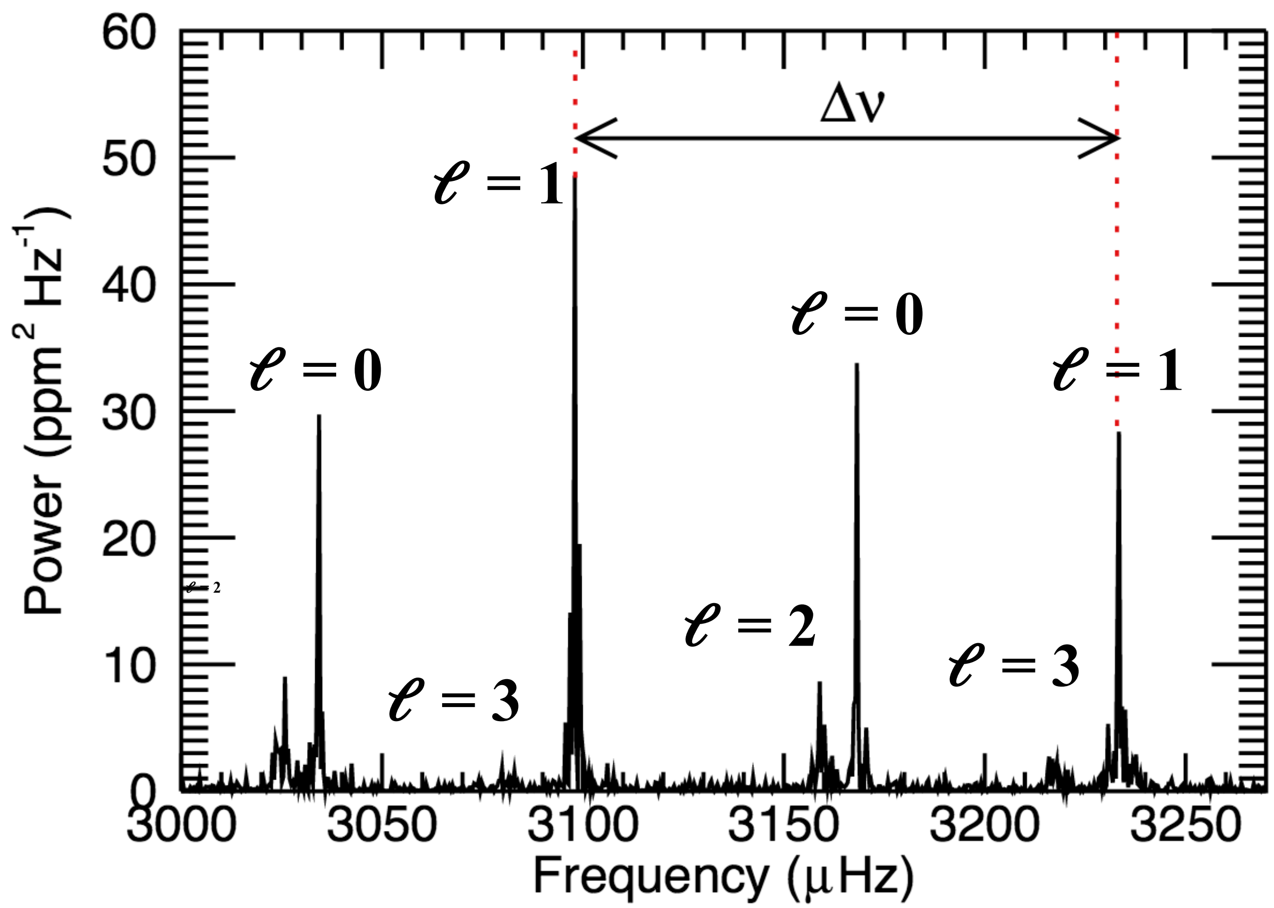
- Acoustic modes (***p modes***) excited by surface convection



Asteroseismology

- Luminosity and RV variations can be measured over time. FFT produces PSD

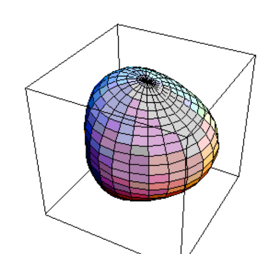


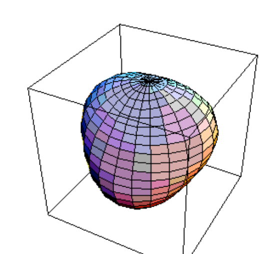


- Global asteroseismic parameters yield stellar mass and radius

$$\nu_{\rm max} \propto g/\sqrt{T_{\rm eff}}$$

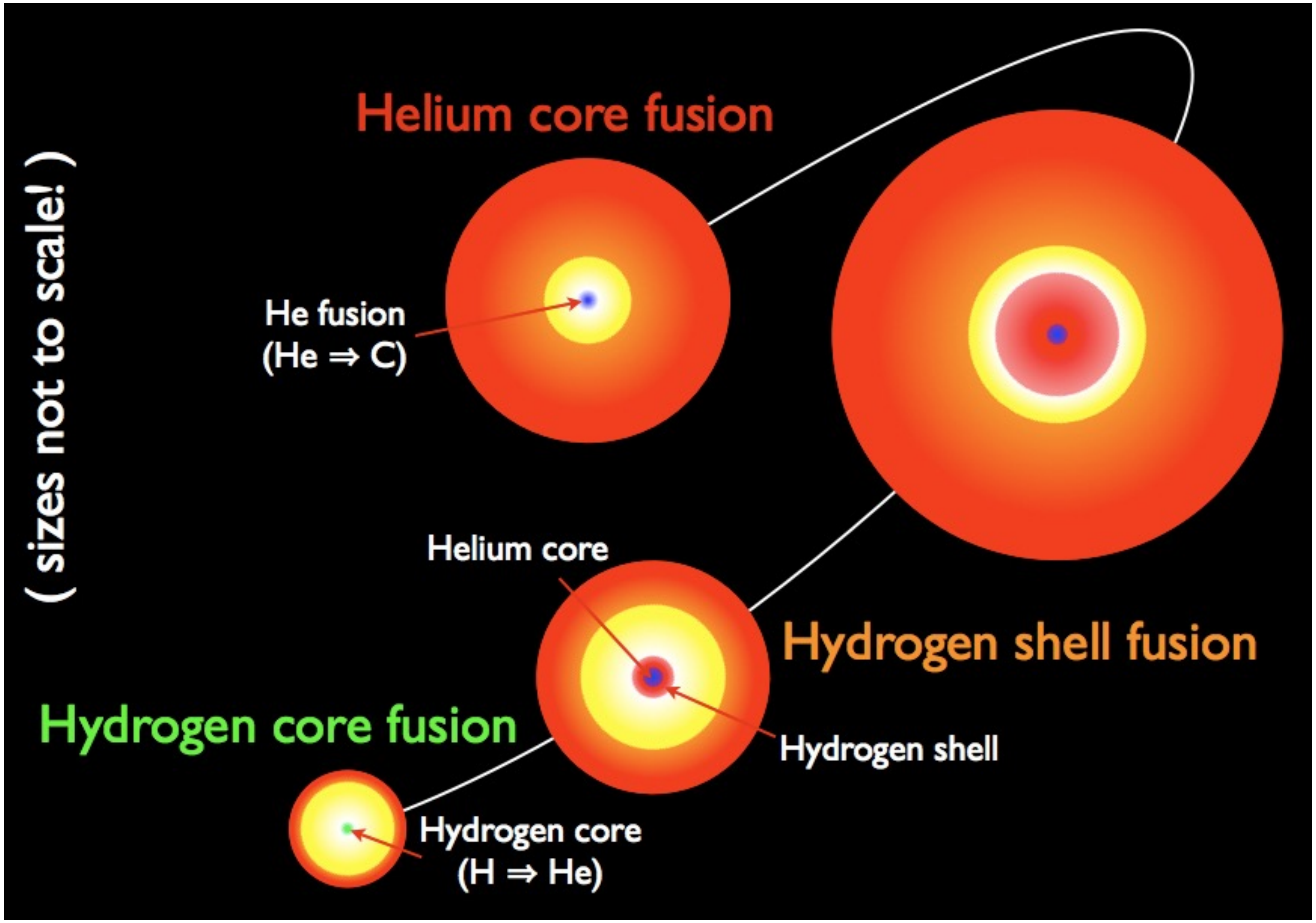
$$\Delta\nu \propto \sqrt{\bar{\rho}}$$





Asteroseismology

- Distinguish between RGB and RC stars (core thermonuclear conditions)



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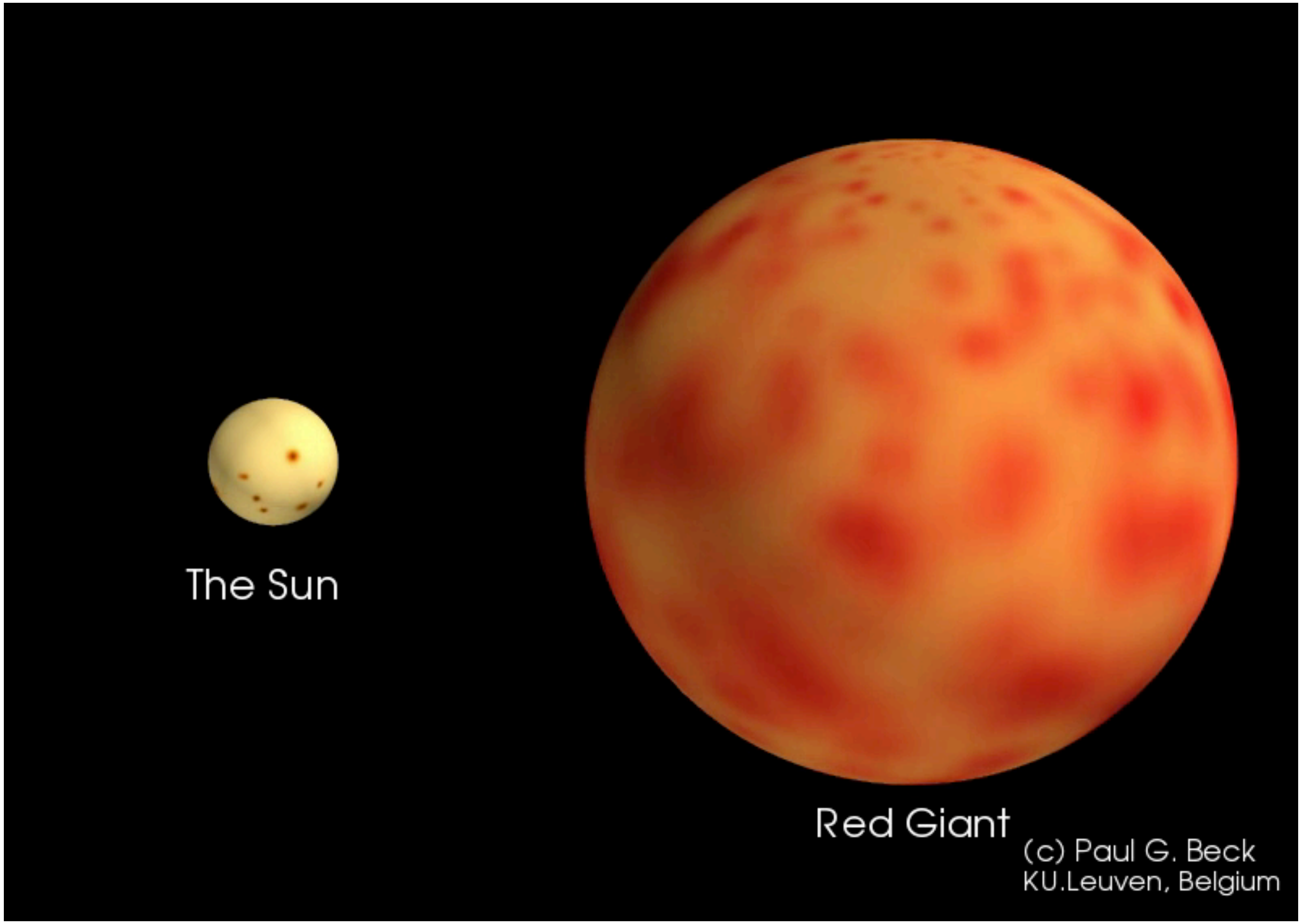
BEDDING ET AL. 2011 NATURE

Asteroseismology

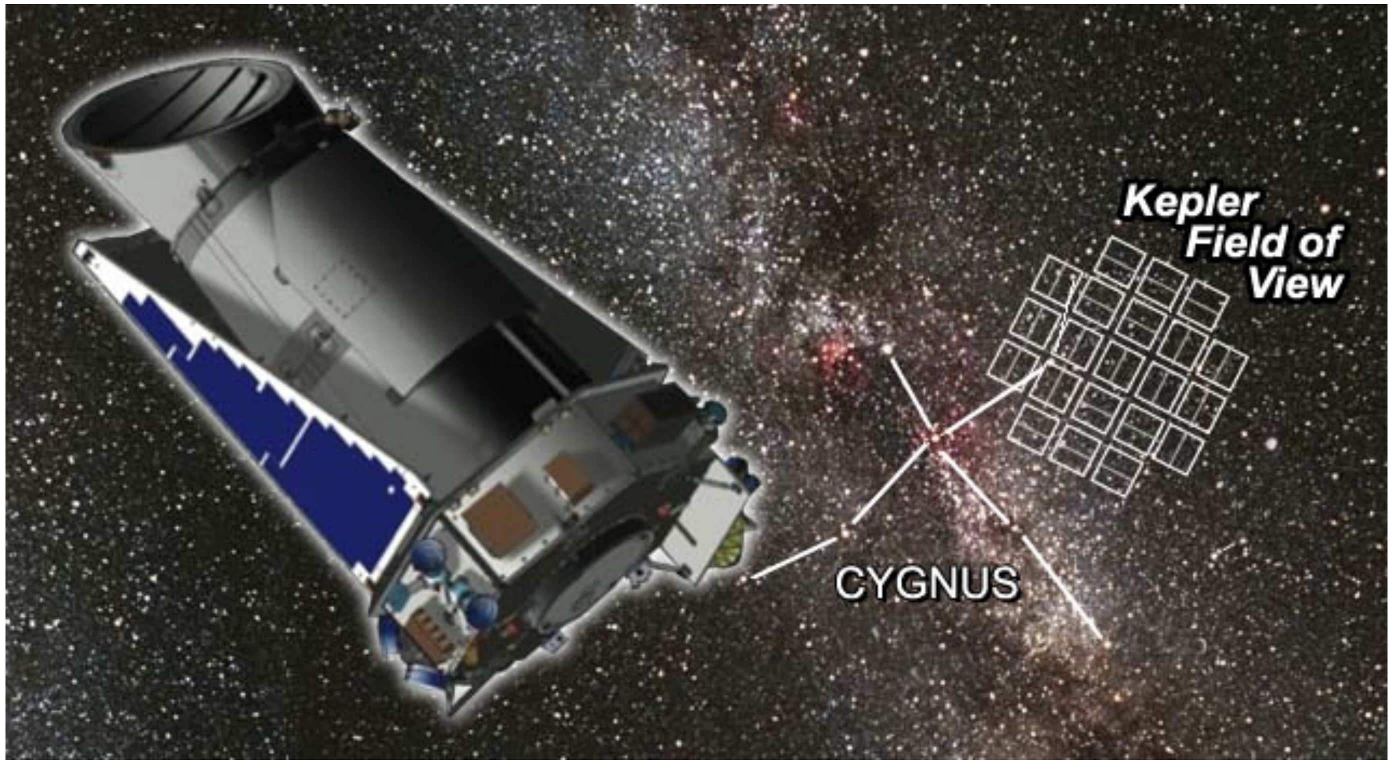
- Measure core-to-envelope internal rotation in stars



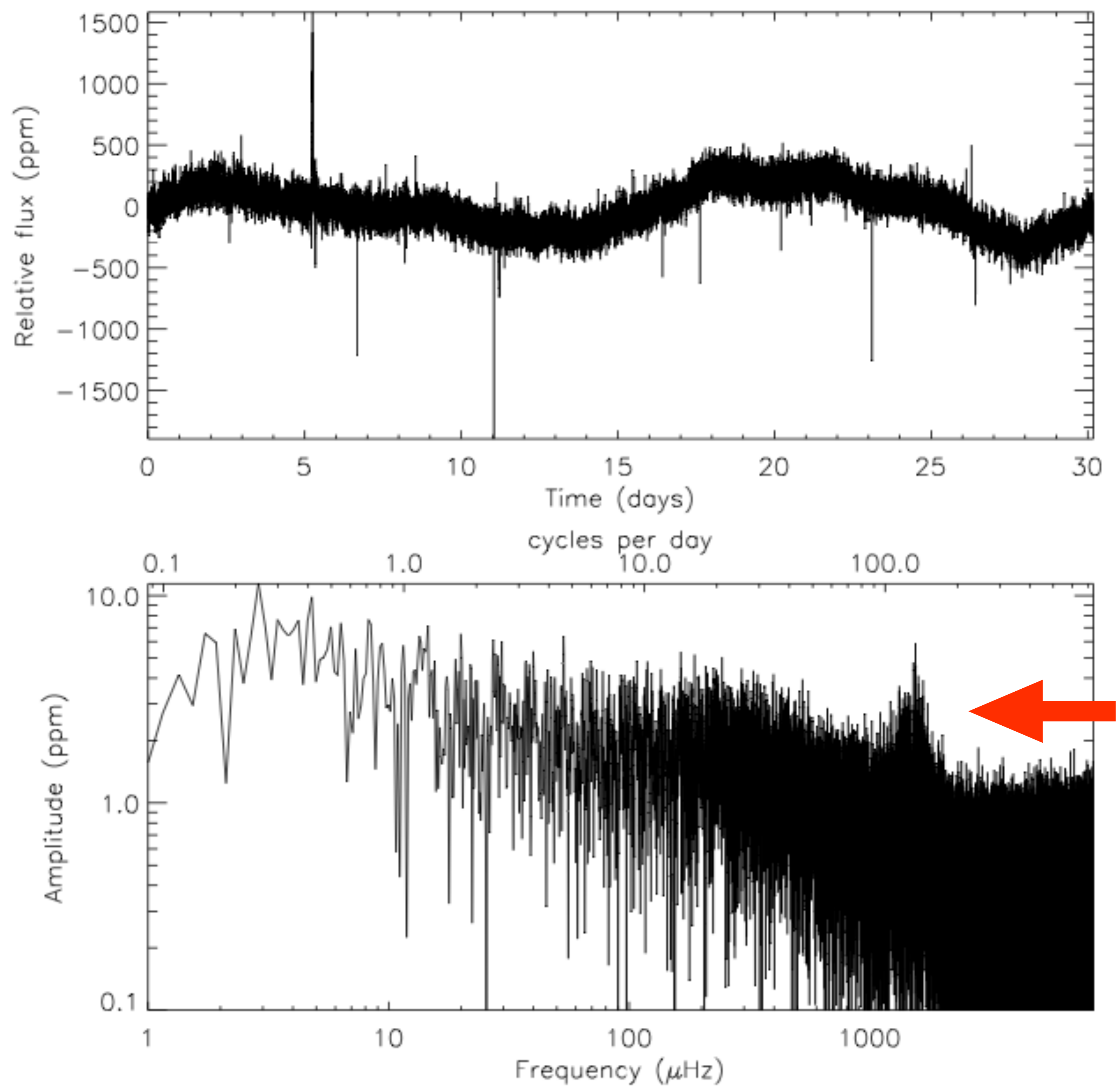
BECK ET AL. 2012 NATURE

NASA Kepler mission

- Launched 2009 - End nominal mission in 2013
- Mission devoted to exoplanets discovery
- 150,000 stars observed in the Cygnus - Lyra constellations
- Kepler photometric band:
  430-890 nm



Photometric observations



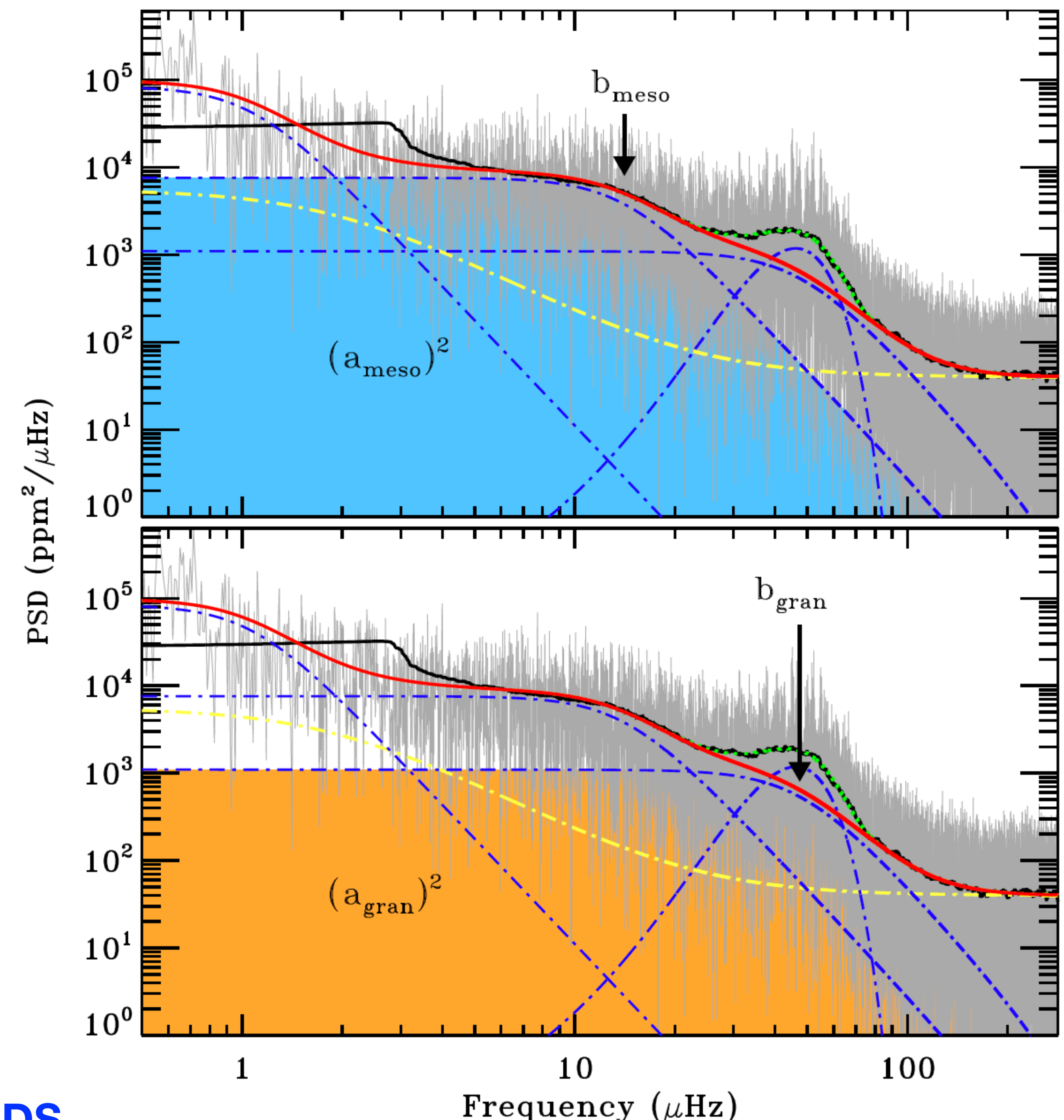
Data analysis (1)

- Measuring the oscillation properties requires that the non-seismic signal is properly estimated
- Non-seismic signal requires a complex fit to the stellar PSD
- Model incorporates granulation and meso-granulation variability

DIAMONDS™

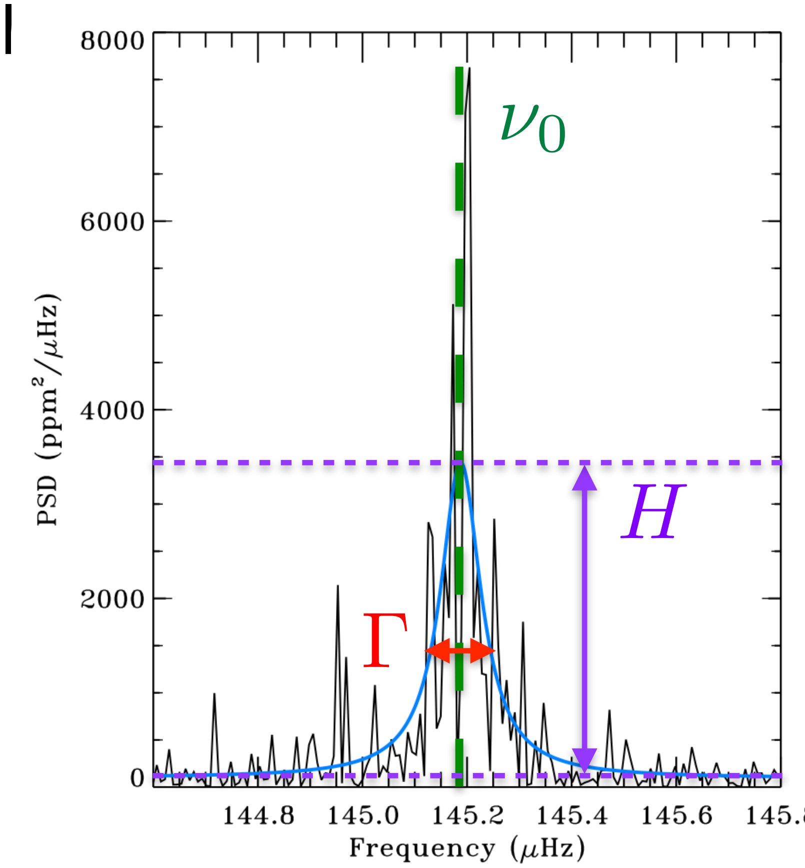
https://github.com/EnricoCorsaro/DIAMONDS

CORSARO ET AL. 2017, A&A



Data analysis (2)

- Then extracting oscillation properties from individual modes is very complicated
- Requires adoption of sophisticated numerical approaches
- Fitting models may contain more than 100 free parameters
- Apply my Bayesian inference code DIAMONDS
- DIAMONDS performs efficient fitting of high-dimensional problems and allows Bayesian model comparison for model selection



https://github.com/EnricoCorsaro/DIAMONDS

DIAMONDS™

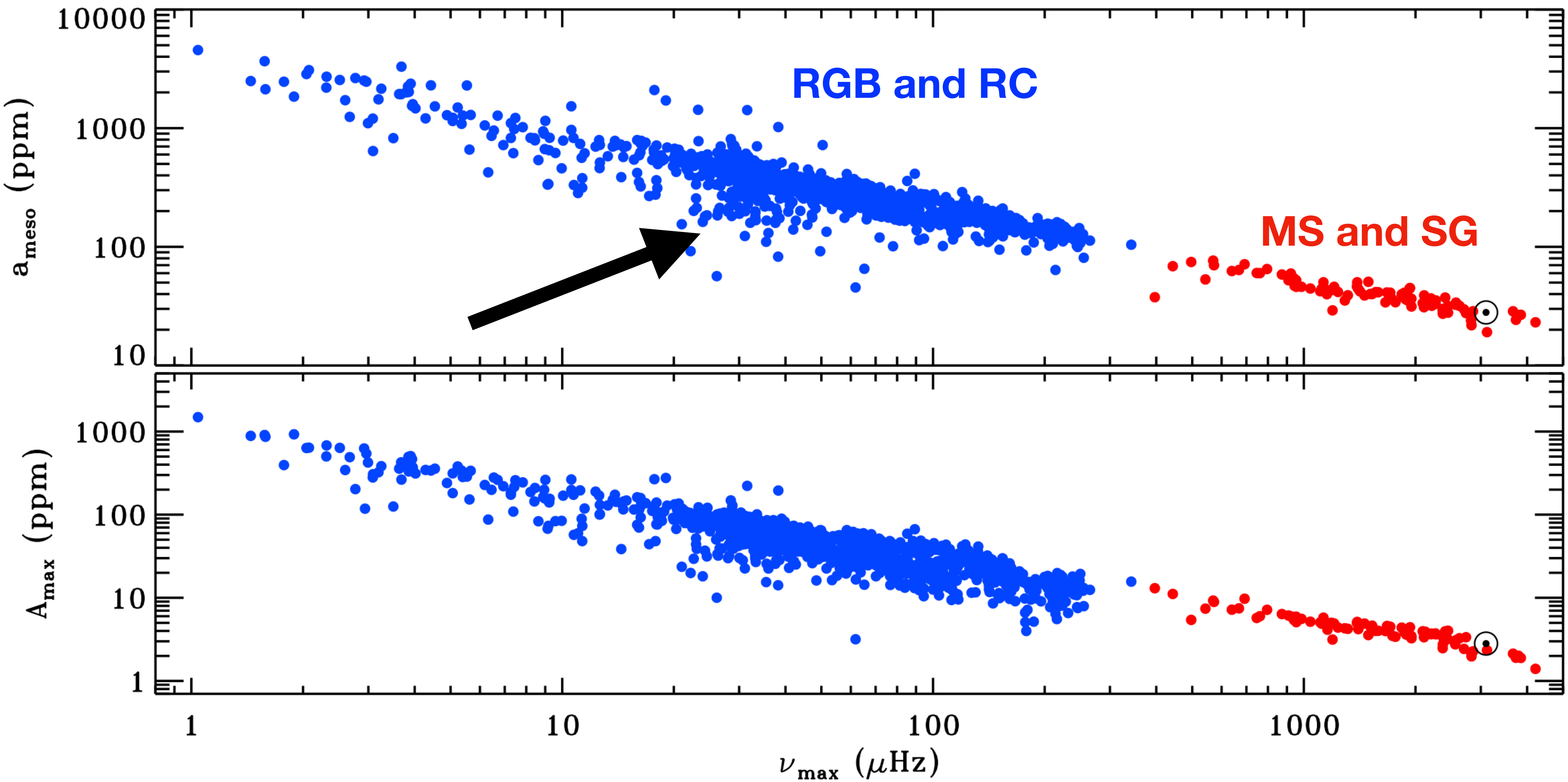
Some statistics (1)

- Published a total of **22** papers in main refereed journals, of which:
    - **4** as a 1st author
    - **7** as a 2nd or 3rd author
- I have **6** more papers in preparation (2 as 1st author and 4 as co-author), and **1** paper under review in *Nature* (co-author, already at 2nd iteration)
- Participated in **9** international conferences, with **2** invited and **4** contributed talks, and 2 poster presentations
- Presented **8** invited and **1** contributed seminars during international collaboration visits
- Invited as lecturer to organize and plan a workshop in Nice, France, on Bayesian inference approaches for astrophysics using DIAMONDS: 24 researchers attending from Observatoire Cote d'Azur

Some statistics (2)

- Co-I-ship for INAF Main Stream Project on stellar evolution and asteroseismology with PLATO
- PI-ship for **2** INAF-CHIPP proposals, for HPC facilities to carry out the proposed asteroseismic analysis
- PI-ship for **3** SONG observing proposals, targeting magnetically active red giant stars
- Co-I-ship for **3** SONG observing proposals, focused on the study of metal-poor halo red giant stars
- Co-I-ship for **2** TESS Guest Investigator proposals, for the study of angular momentum evolution in subgiant stars

Stellar sample investigated



About 1500 stars from NASA *Kepler*

Computational resources

- Exploited INAF-CHIPP computing facilities for parallel computing
- About 15 000 multi-dimensional fits performed with DIAMONDS (about 500K core/hours)
- Project selected for an experimental test using new parallel computing Google Cloud and Compute Engine systems for HTC developed at INAF
- Test was successful

Major achievements

1. **Angular momentum evolution**:
   Discovery of imprint of angular momentum evolution from formation epoch on the spin orientation of stars in old open clusters

2. **Convection**:
   Discovery of metallicity effect on the stellar granulation from stars in open clusters

3. **Data analysis techniques**:
   Development of a new cutting edge methodology for the detailed asteroseismology of stars: currently the best approach available!

1- Angular momentum evolution

- Theory (3D MHD simulations) predicts that star and cluster formation process is dominated by turbulent motions

- Molecular cloud's angular momentum during gravitational collapse scrambled by turbulence

- Stars in open clusters are excellent candidates to test this: they share a common origin!

- Past observations did not find evidence of any imprint in cluster stars

1- Angular momentum evolution

nature astronomy

LETTERS

PUBLISHED: 13 MARCH 2017 | VOLUME: 1 | ARTICLE NUMBER: 0064

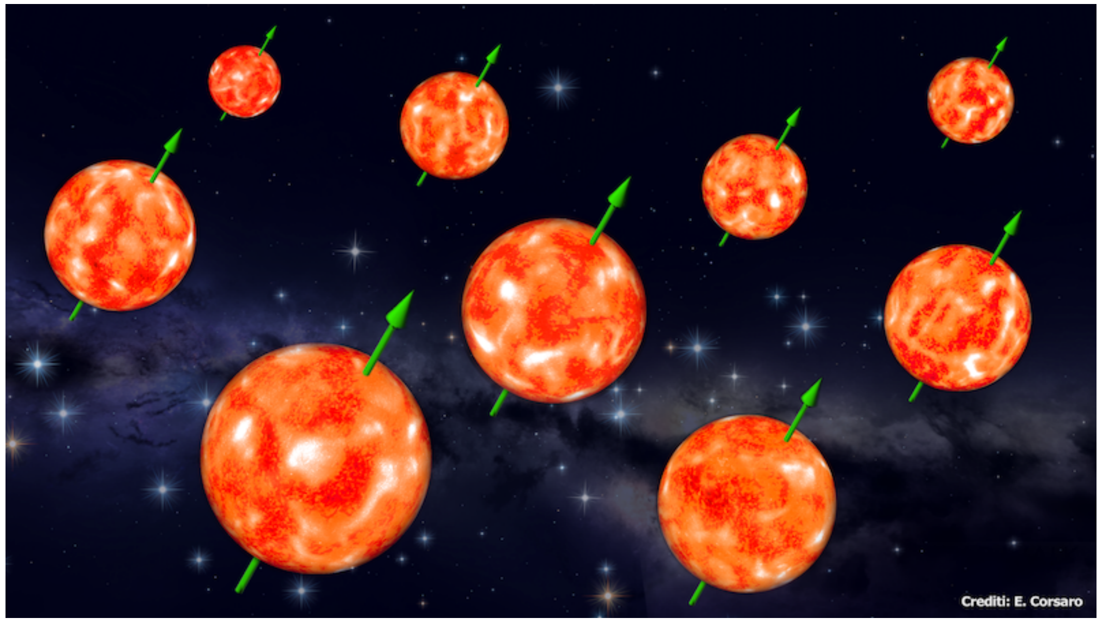
Spin alignment of stars in old open clusters

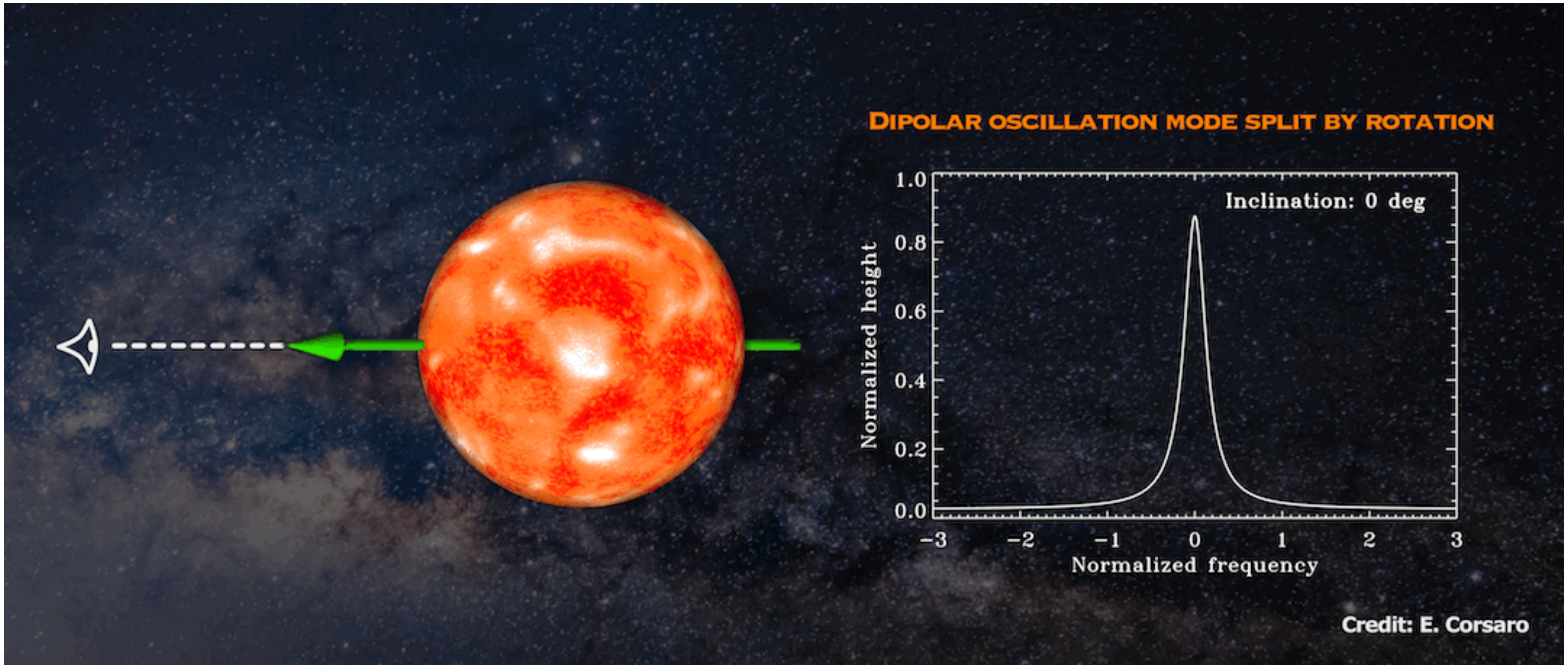
Enrico Corsaro[1,2,3,4*], Yueh-Ning Lee[1], Rafael A. García[1], Patrick Hennebelle[1], Savita Mathur[5], Paul G. Beck[1], Stephane Mathis[1], Dennis Stello[6,7] and Jérôme Bouvier[8,9]

Nature Astronomy Journal Cover March 2017

- Applied asteroseismology on cluster red giant stars (about 100 targets)
- Discovery of a strong effect of stellar spin axis alignment
- Must be imprint from the formation epoch
- Angular momentum from the cloud was inherited by stars forming inside. Imprint has lasted for several Gyr!
- New link between asteroseismology and star formation

1- Angular momentum evolution





1- Angular momentum evolution

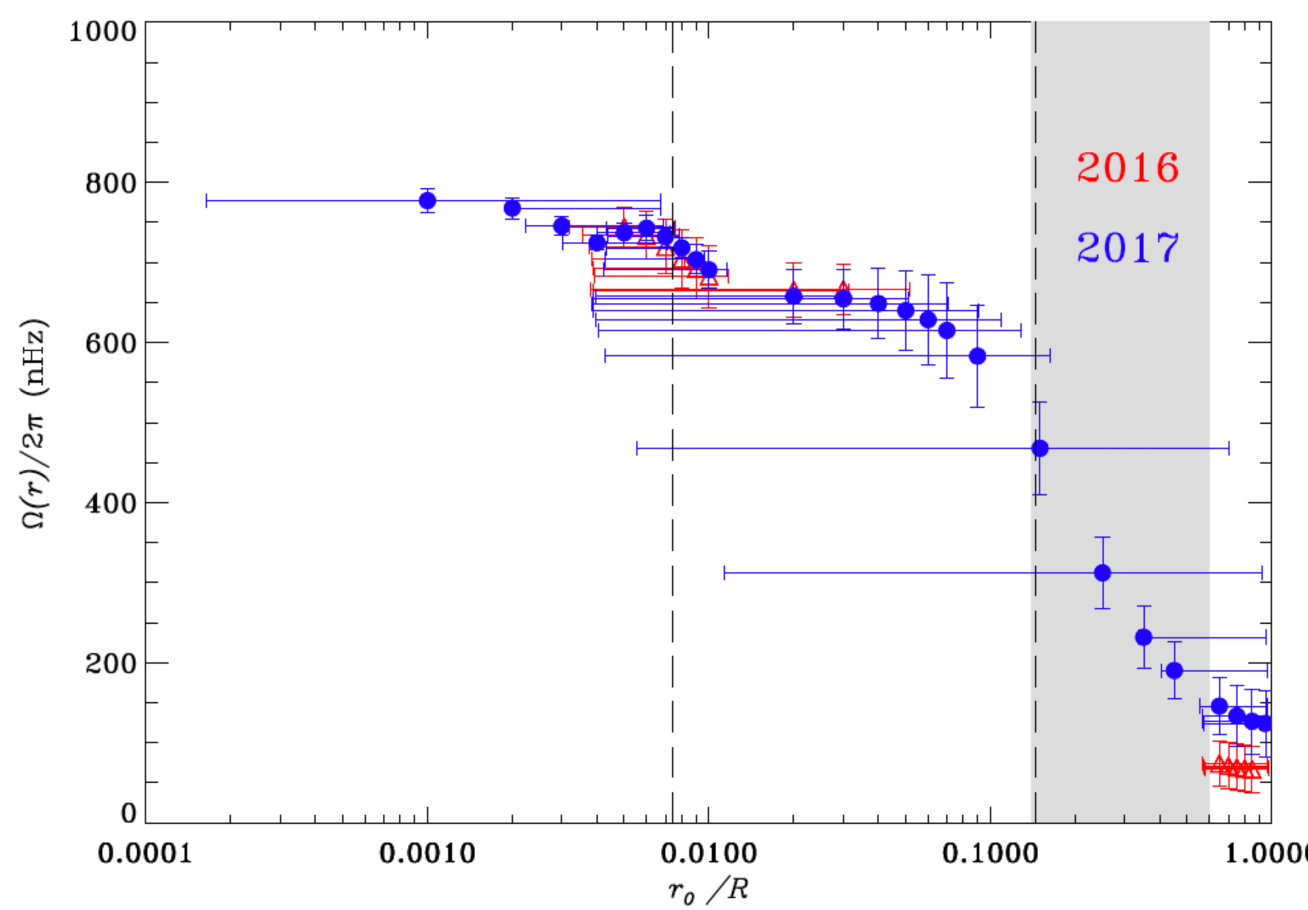
THE ASTROPHYSICAL JOURNAL, 862:9 (10pp), 2018 July 20 https://doi.org/10.3847/1538-4357/aac7c4

CrossMark

The Rotational Shear Layer inside the Early Red-giant Star KIC 4448777

Maria Pia Di Mauro[1], Rita Ventura[2], Enrico Corsaro[2], and Bruno Lustosa De Moura[3,4]

- Applied my Bayesian techniques for asteroseismology to obtain most detailed study of internal rotation profile to date for a red giant star
- New constraints on the rotation of the H-burning shell!
- Core is rotating nearly uniformly, about 6 times faster than convective envelope



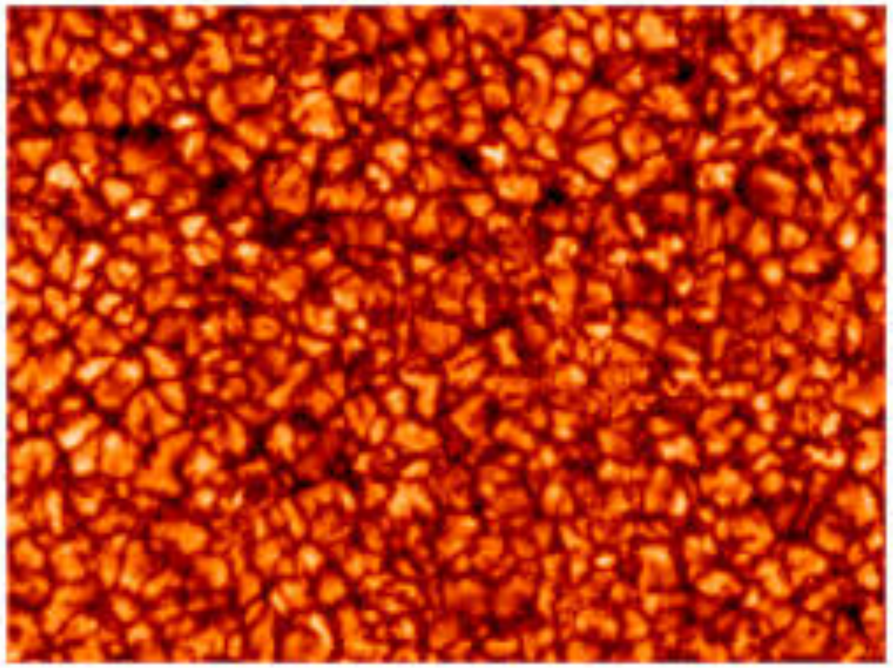
2 - Convection

- Stellar granulation is a surface manifestation of convection

- Theory (3D MHD simulations) predicts that metallicity influences the size of the granules, meaning that the granulation variability is affected

- No evidence found before in the literature

- Effect is difficult to detect because coupled with other dependencies on surface gravity, mass, and temperature



2 - Convection

A&A 605, A3 (2017)
DOI: 10.1051/0004-6361/201731094

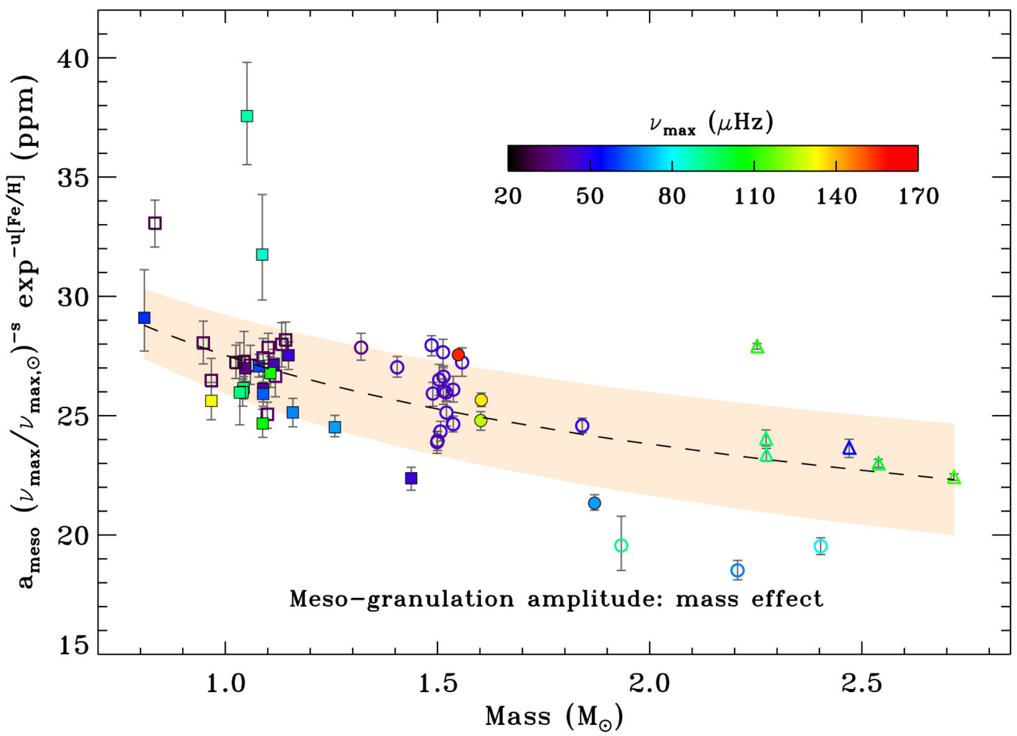
Astronomy & Astrophysics

Metallicity effect on stellar granulation detected from oscillating red giants in open clusters

E. Corsaro[1,2,3,4], S. Mathur[5], R. A. García[4], P. Gaulme[6,7,8], M. Pinsonneault[9], K. Stassun[10], D. Stello[11,12,13], J. Tayar[9], R. Trampedach[5,13], C. Jiang[14], C. Nitschelm[15], and D. Salabert[4]

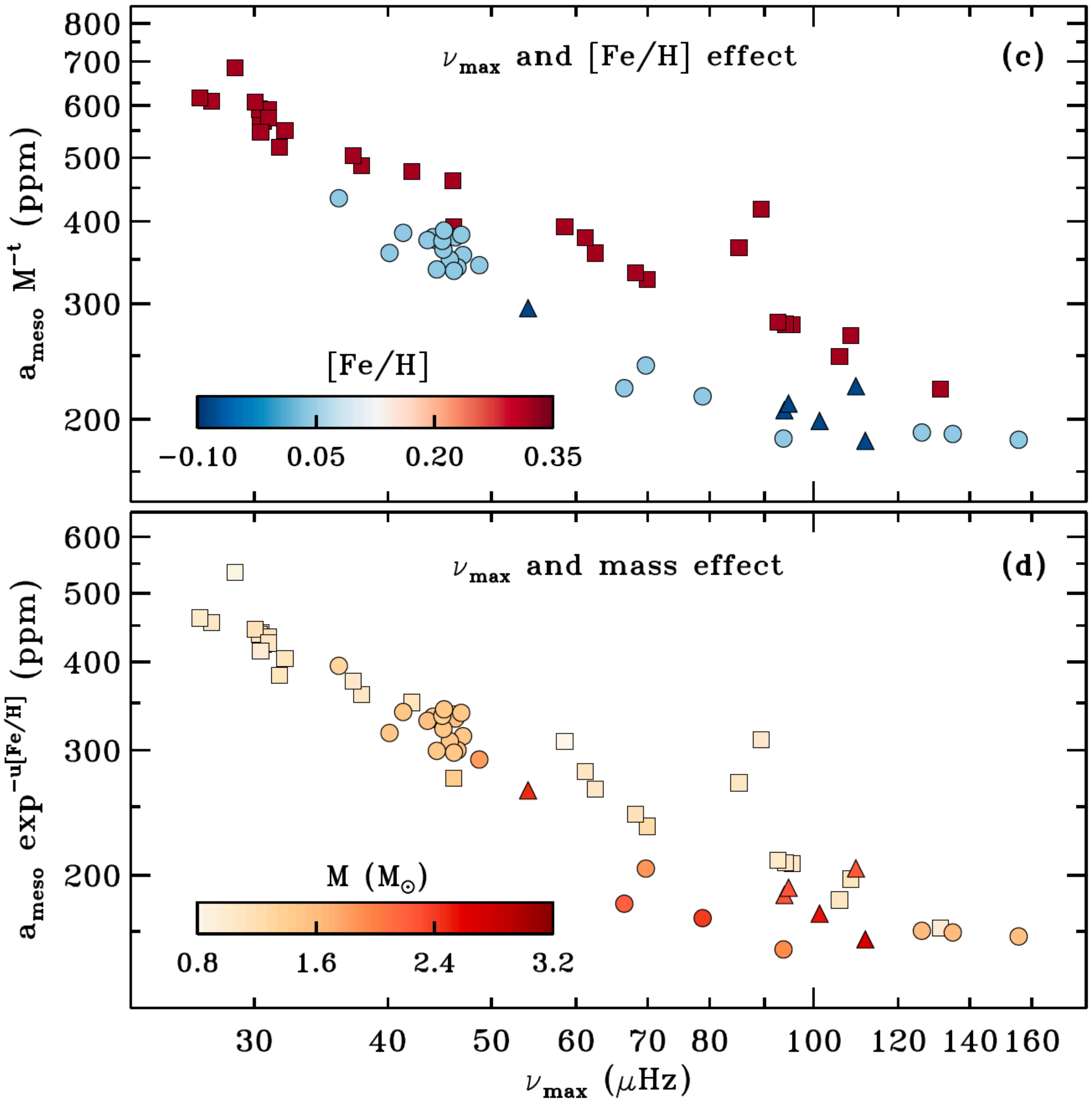
- Applied asteroseismology to cluster red giants and combined with spectroscopy from APOGEE to obtain precise masses and radii
- Detected clear metallicity effect in agreement with theoretical predictions!
- Calibrated new relations to predict metallicity from granulation and oscillation properties

Astronomy & Astrophysics Journal Cover September 2017



Metallicity and mass effects on stellar granulation
(Corsaro, E., et al., 2017, A&A, 605, A3)

2 - Convection



2 - Convection

THE ASTRONOMICAL JOURNAL, 155:22 (12pp), 2018 January
https://doi.org/10.3847/1538-3881/aa998a

Empirical Accurate Masses and Radii of Single Stars with *TESS* and *Gaia*

Keivan G. Stassun[1,2], Enrico Corsaro[3], Joshua A. Pepper[4], and B. Scott Gaudi[5]

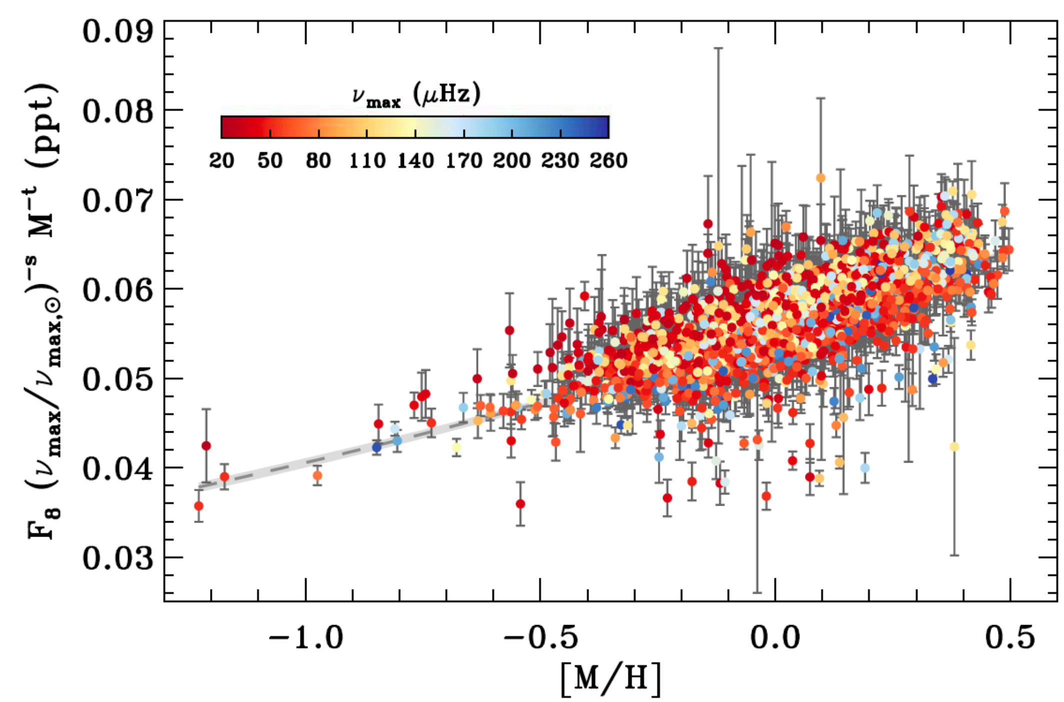
THE ASTROPHYSICAL JOURNAL, 883:195 (12pp), 2019 October 1
https://doi.org/10.3847/1538-4357/ab3db1

Predicting Granulation "Flicker" and Radial Velocity "Jitter" from Spectroscopic Observables

Jamie Tayar[1,2,6], Keivan G. Stassun[3,4], and Enrico Corsaro[5]

- Applied my scaling relations to obtain accurate masses and predict granulation flicker for stars (helpful for discovery of planets)

- Results obtained for a sample of 2500 field stars observed by NASA *Kepler* and TESS, from MS to RGs

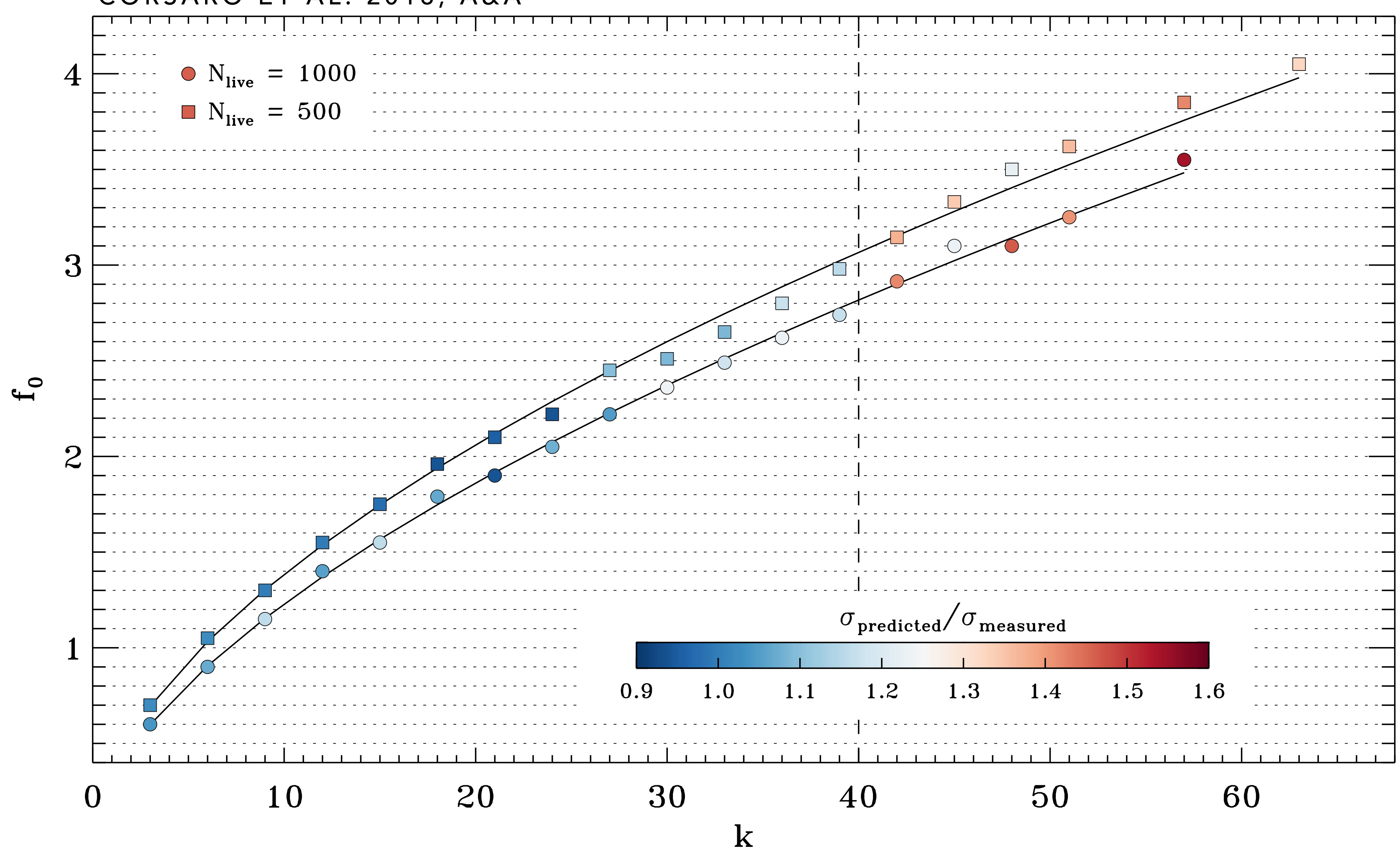


3 - Data analysis techniques

- Improved code performances and with new calibration law

DIAMONDS™

CORSARO ET AL. 2018, A&A

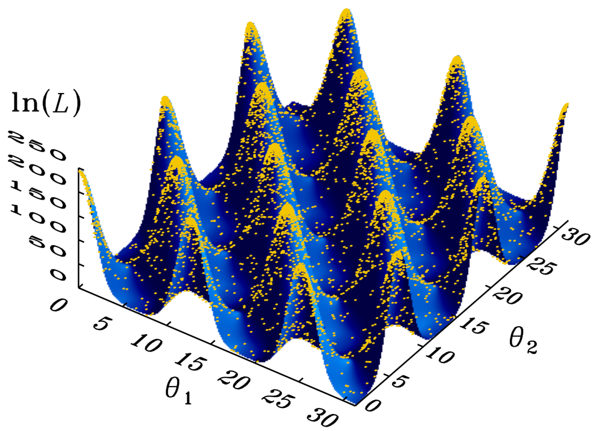


3 - Data analysis techniques

frontiers
in Astronomy and Space Sciences

PERSPECTIVE
published: 09 April 2019
doi: 10.3389/fspas.2019.00021

Check for updates



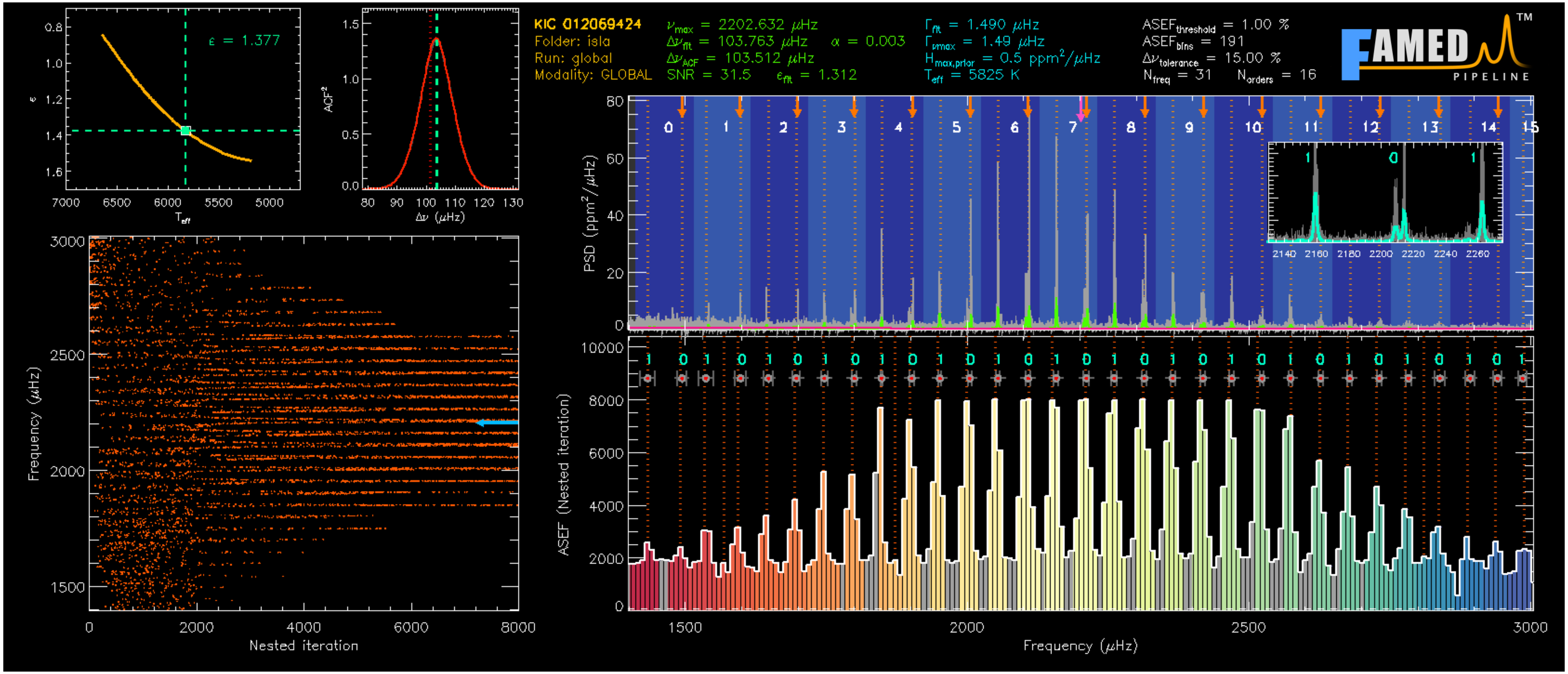
Fast and Automated Oscillation Frequency Extraction Using Bayesian Multi-Modality

*Enrico Corsaro**

FAMED PIPELINE ™

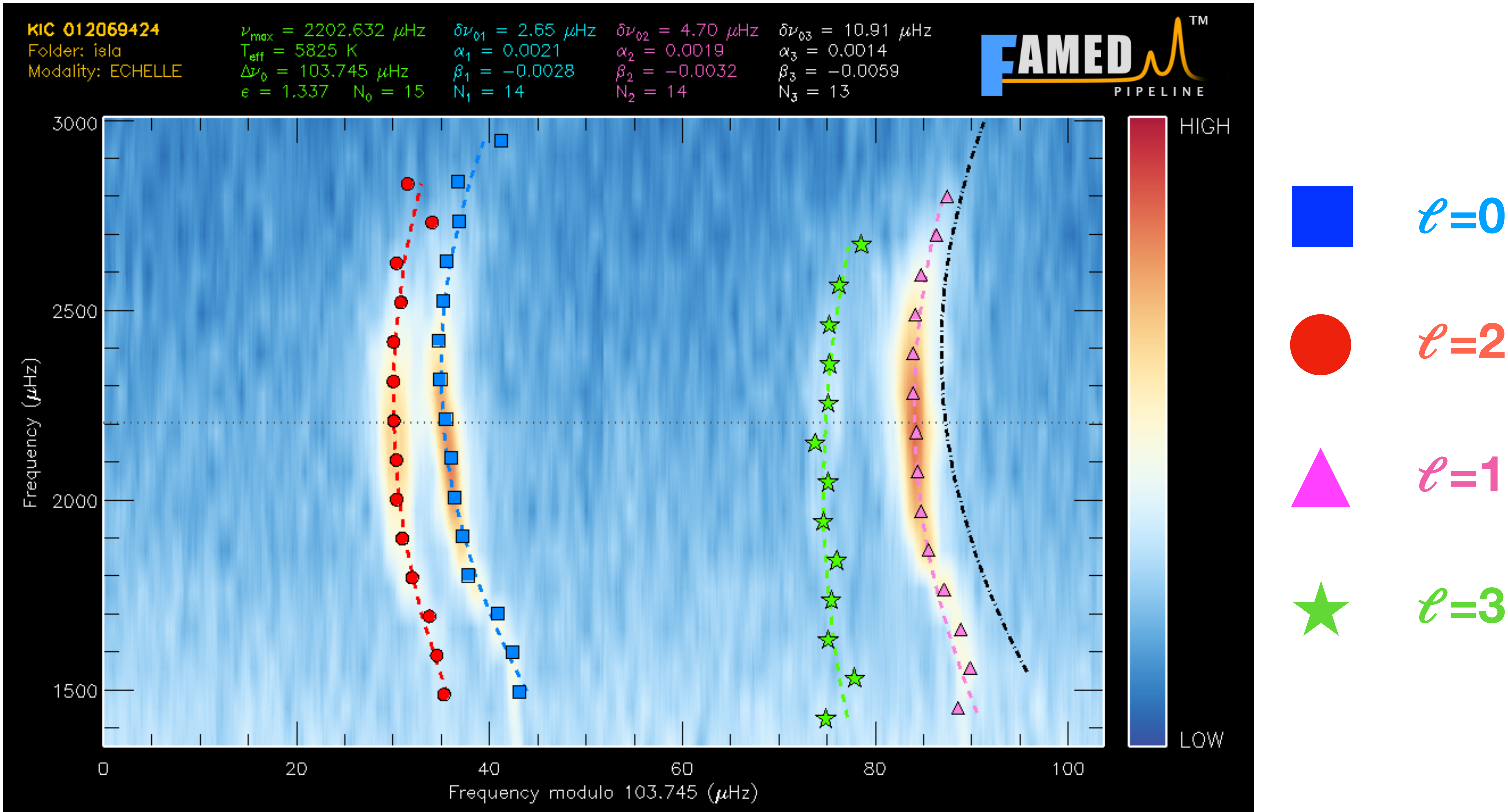
- Invited perspective contribution to Frontiers journal for the topic: "*The future of Asteroseismology*"
- Developed new pipeline termed **FAMED** (Fast and AutoMated pEak bagging with DIAMONDS)
- Pipeline presented in last yearly conference of TESS and *Kepler* asteroseismic consortia at MIT, Cambridge, July 2019

3 - Data analysis techniques



- Most performant pipeline available for detailed asteroseismology today
- Can process stars from MS to RGs in less than 1 minute!
- Fully automated (first pipeline of this kind) (1 paper in preparation)

3 - Data analysis techniques



Additional studies

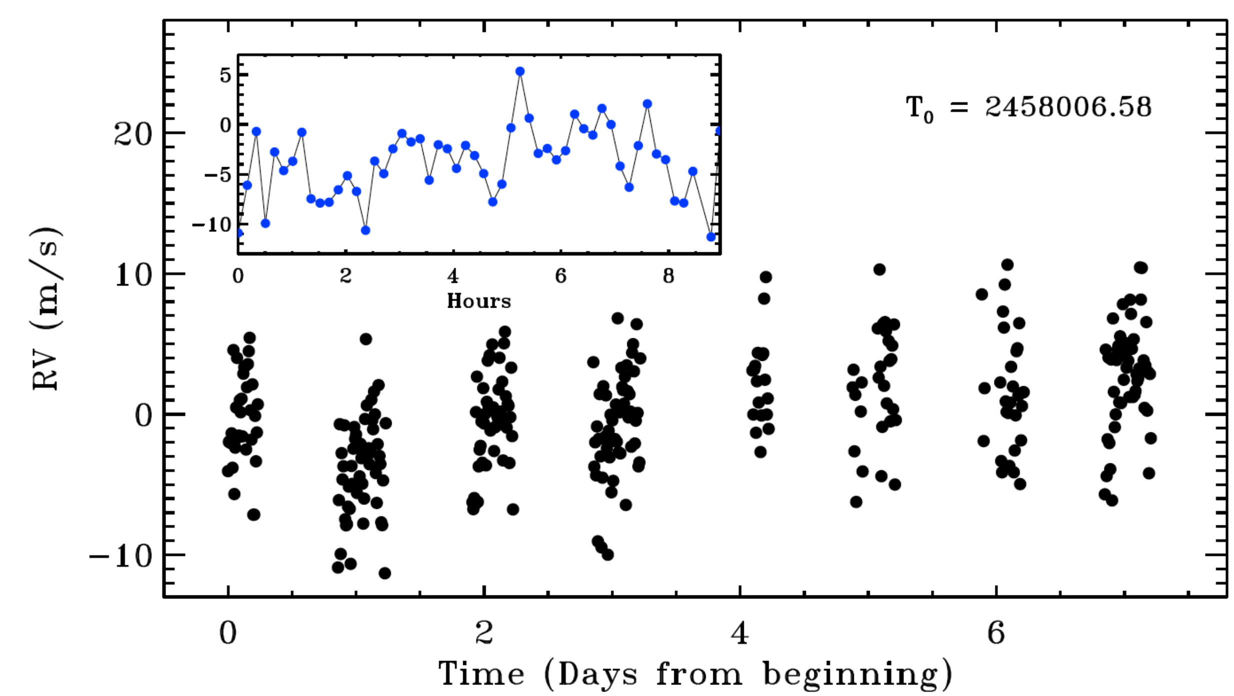
4. **Magnetic fields**:
   Investigate the impact of magnetic fields on stellar evolution by observing evolved stars with the spectroscopic instrument SONG

5. **Exoplanetary systems**:
   Exploit detailed asteroseismology on planet-host stars to measure planet densities to test the evolution of the planetary system

6. **Oscillations in pre-MS stars**:
   Using my DIAMONDS code for the search of solar-like oscillations in very young stars. Supervision of master student project.

4 - Magnetic fields

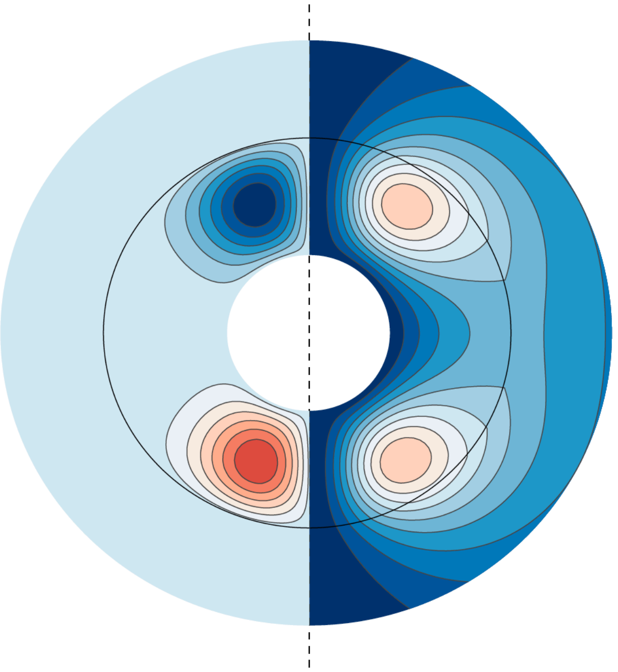
- Stellar Observations Network Group
- I am an associate member
- RV observations of oscillating stars
- Less sensitive to granulation signal
- Better suited to study magnetic activity in stars from its impact on oscillation amplitudes
- PI-ship of 3 SONG proposals for the study of magnetic activity in red giant stars
- Pursuit collaboration with Prof. Pallé, spanish Co-I of SONG



4 - Magnetic fields

A&A 628, A106 (2019)
https://doi.org/10.1051/0004-6361/201935834

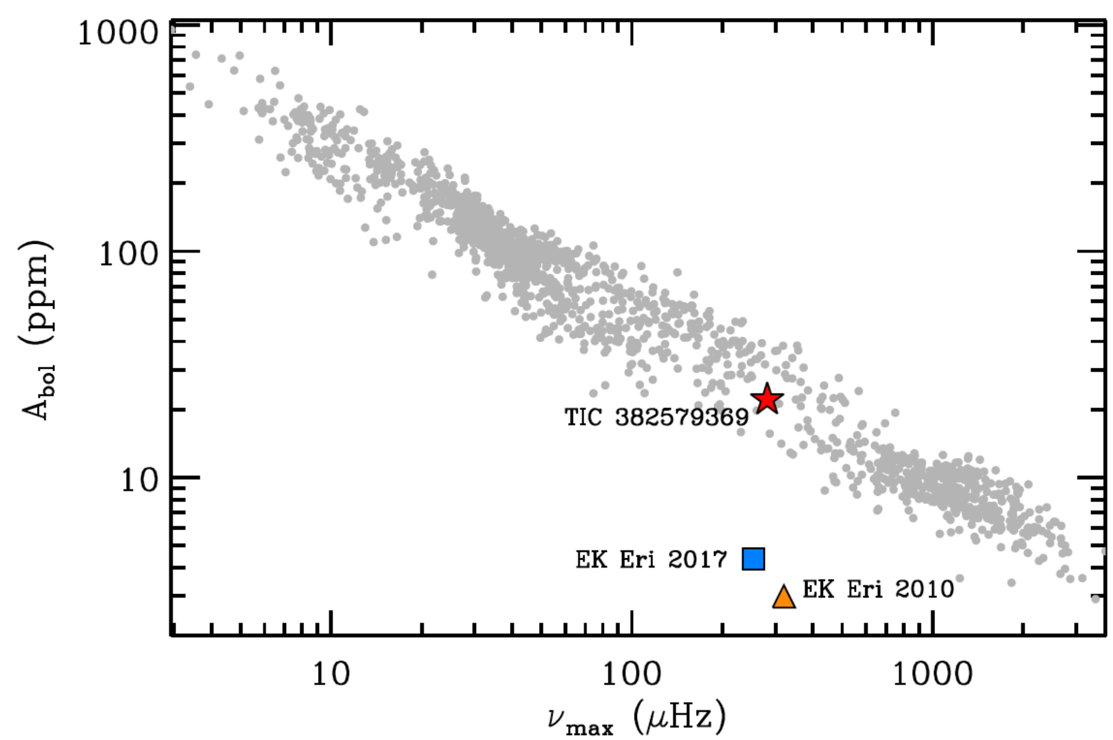
Astronomy & Astrophysic



Acoustic oscillations and dynamo action in the G8 sub-giant EK Eridani★,★★

A. Bonanno[1], E. Corsaro[1], F. Del Sordo[2,3], P. L. Pallé[4], D. Stello[5], and M. Hon[5]

- Testing the origin of strong magnetic fields observed in red giants
- Exploiting my PI-ship for 3 SONG observing proposals
- Found that a dynamo explanation can exist to sustain strong magnetic fields in stars evolved off the MS



5 - Exoplanetary Systems

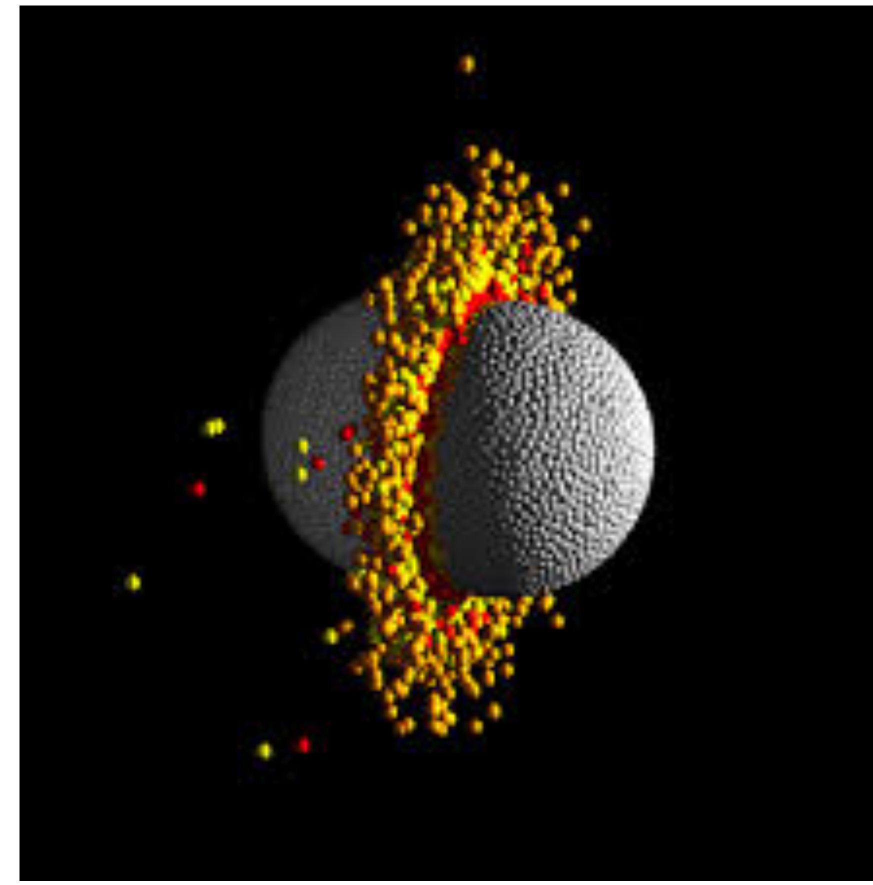
nature astronomy

LETTERS

https://doi.org/10.1038/s41550-018-0684-9

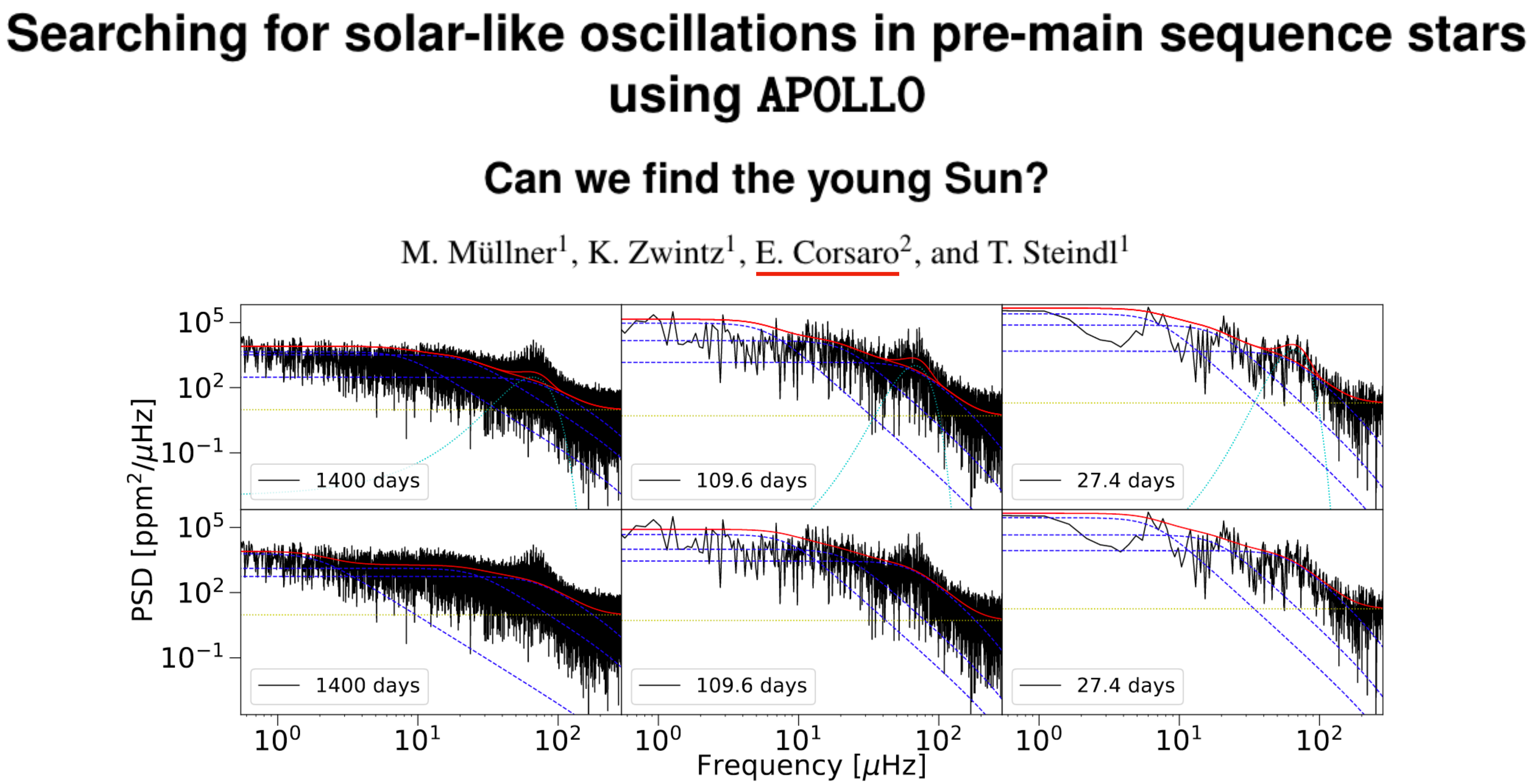
A giant impact as the likely origin of different twins in the Kepler-107 exoplanet system

Aldo S. Bonomo[1*], Li Zeng[2], Mario Damasso[1], Zoë M. Leinhardt[3], Anders B. Justesen[4], Eric Lopez[5], Mikkel N. Lund[4], Luca Malavolta[6,7], Victor Silva Aguirre[4], Lars A. Buchhave[8], Enrico Corsaro[9], Thomas Denman[3], Mercedes Lopez-Morales[10], Sean M. Mills[11], Annelies Mortier[12], Ken Rice[13], Alessandro Sozzetti[1], Andrew Vanderburg[10,14], Laura Affer[15], Torben Arentoft[4], Mansour Benbakoura[16,17], François Bouchy[18], Jørgen Christensen-Dalsgaard[4], Andrew Collier Cameron[12], Rosario Cosentino[19], Courtney D. Dressing[20], Xavier Dumusque[18], Pedro Figueira[21,22], Aldo F. M. Fiorenzano[19], Rafael A. García[16,17], Rasmus Handberg[4], Avet Harutyunyan[19], John A. Johnson[10], Hans Kjeldsen[4], David W. Latham[10], Christophe Lovis[18], Mia S. Lundkvist[4,23], Savita Mathur[24,25], Michel Mayor[18], Giusi Micela[15], Emilio Molinari[26], Fatemeh Motalebi[18], Valerio Nascimbeni[6,7], Chantanelle Nava[10], Francesco Pepe[18], David F. Phillips[10], Giampaolo Piotto[6,7], Ennio Poretti[19,27], Dimitar Sasselov[10], Damien Ségransan[18], Stéphane Udry[18] and Chris Watson[28]



- Using detailed asteroseismology to constrain stellar radius, mass, hence planet density
- Found that two inner planets exist, having same radius but different density: proposed giant impact scenario - First evidence found!

6 - Oscillations in pre-MS stars



- A new pipeline based on DIAMONDS developed by my student to search for the oscillations in pre-MS stars (1 paper to be submitted soon)
- DIAMONDS Bayesian model comparison allows to reliably detect the oscillation envelope

Training received

by Dr. Alfio Bonanno

- Use of stellar evolution code CT-GARSTEC at INAF-OACT
- Use of stellar pulsation code GYRE at INAF-OACT
- Exploited INAF-CHIPP computing facilities to compute grids of hundreds of solar models
- Investigated the impact of axion-energy emission on solar oscillation frequencies by applying a Bayesian inference and model comparison approach (1 paper in preparation)

Extras

ESA PLATO

- Participated in ESA PLATO preparation activities for development of a pipeline for automated fitting of stellar oscillations from MS to SG
- Important participation to be in the consolidating community devoted ESA PLATO
- I applied my first development of the new fitting methodology, which set the basis to the subsequent development of FAMED
- Test performed on about 40 simulated datasets, with 90% accuracy reached

NASA TESS

- Participated in several projects conducted in the framework of NASA TESS asteroseismology: targeting both exoplanet host stars and red giants
- I have already 2 papers published using my Bayesian techniques for NASA TESS exoplanet hosts

Ongoing & future plans

- Winner of INAF 2019 young researchers competition: will start a new position as **permanent staff researcher** at INAF-OACT on 4/11/2019
- Already submitted **ERC-STG-2020** proposal (deadline October 16 2019) focusing on stellar physics
- Work plans:
  - finalize the FAMED pipeline
  - apply FAMED to the stars investigated during the fellowship
  - apply FAMED to ESA PLATO simulated data for new analysis
  - extend study of stellar internal rotation to thousands of stars
  - analysis on a sample of 100 SG observed in TESS GI proposal Cycle 1 (observations ended up recently) to study internal angular momentum evolution

Thank you!

Enrico Corsaro