Space UV spectroscopy with miniaturized cross-dispersed echelle spectrographs

Advisors: Manuel Abreu (DF/FCUL & IA U.Lisboa), Alexandre Cabral(DF/FCUL & IA U.Lisboa)

Abstract: High resolution (HR) ultraviolet (UV) spectroscopy has a fundamental contribution for exoplanet characterization. Observing in this region of the electromagnetic spectrum can lead to the detection of biosignatures that might suggest the presence of life in an alien world.

Due to Earth's low atmospheric transmittance in the UV and deep blue domains, it is necessary a space-based solution to explore this band. However, these are high cost missions presenting a challenge for UV exploration.

Nowadays, disruptive advancements in technologies for small satellites (SmallSat), open an opportunity for UV science to "piggy-back" in other spectral range missions. Due to its reduced weight they can be launched as secondary payloads, dramatically lowering the mission costs.

Currently, cross disperse echelle spectrographs are the vanguard of ultra HR spectroscopy, however they are bulky, power demanding and heavy instruments. For a SmallSat application, trading with the level of spectral resolution, it is necessary to go against the trend and study possible miniaturized versions of this type of instruments to match this satellite standard specifications.

The scope of this PhD work is to study the trade-offs of miniaturizing a cross-dispersed echelle spectrograph operating in the UV with the Size Weight and Power requirements for a SmallSat solution.

University: Lisboa

New insights into stellar physics from the NASA-TESS survey on A-type stars

Advisors: Margarida Cunha (IA U.Porto), Daniel Holdsworth (U. Central Lancashire, UK)

Abstract: The study of stellar pulsations – or Asteroseismology - provides the only mean to probe directly the interior of a star and constrain its physical and dynamical properties. Among the different types of stars exhibiting stellar pulsations, the Ap stars are unique for their strong magnetic fields and for their chemical peculiarity, properties that make them laboratories for studying the physical processes taking place inside stars that are currently most challenging to our understanding, such as macroscopic mixing, microscopic diffusion, and magnetic fields.

The main goal of this project is to take advantage of the data that is being acquired by the NASA TESS satellite to take the modelling of Ap stars to a new standard. It is expected that the project will contribute decisively to the understanding of the interplay between magnetic fields and pulsations in Ap stars and potentially provide unprecedented constrains to the evolution of stellar magnetic fields, mixing, and diffusion processes.

The project will be organized in three steps, namely: (1) The analysis of TESS data on Ap stars in search for new stellar pulsators with well characterized pulsation frequencies; (2) The confrontation of these pulsation frequencies with those derived from theoretical models, with different magnetic field strengths and physical properties; (3) The ensemble analysis of the results from step (2) aimed at

characterizing the magnetic field properties and the efficiency of diffusion and mixing of a large sample of pulsating Ap stars, as function of the stars' global properties (radius, mass, and age). The project will be supervised by the IA researcher Margarida Cunha, Co-chair of the Working Group on A-F stellar pulsators for the TESS Asteroseismic Science Consortium (TASC), expert in theoretical asteroseismology, and co-supervised by Daniel Holdsworth, from the University of Central Lancashire, UK, expert on asteroseismic data analysis.

University: Porto

Toward a new generation of stellar models: impact of physical ingredients on the accuracy of stellar parameter inferences

Advisors: Diego Bossini (IA U.Porto), Morgan Deal (IA U.Porto)

Abstract: Main-sequence stars are the most numerous and fundamental bricks of our Galaxy. Unraveling the physics behind them is essential for their correct characterization, whether our intent is to study planet-host systems, stellar population, or the history of the Milky Way. However, accurate modellization is still nowadays a challenge in stellar astrophysics. In this context, the recent developments of asteroseismic techniques is largely helping to constrain various aspects of their internal processes. A key-role is played by their chemical element abundance, for which changes can affect the entire evolution of a star. This project is dedicated to understand and quantify the dependency of the stellar properties from the chemical composition and related physical processes (e.g. helium enrichment law, core-overshooting, equation of state), in order to improve stellar models and to prepare the next generation of optimization codes to receive the data that ESA's Mission PLATO will soon provide. In practice, the goal will be accomplished by pursuit a series of objectives: to quantify precisely the impact of several aspects of stellar modelling, to develop an optimization code (PARAM) for calculating global stellar properties, and to apply the tool to study the main sequence stars in the solar vicinity, observed by Kepler and TESS, giving an overview of the chemical evolution of the solar neighborhood.

University: Porto

The magnetic environment of Young Stellar Objects

Advisors: Jorge Filipe Gameiro (IA, U. Porto), João Lima (IA, U. Porto)

Abstract: It has been demonstrated in the last decade that magnetic fieds play a central role throughout the star formation. In the Pre-Main-Sequence (PMS) phase the stellar magnetic fields have a larger impact on the stellar evolution and likely control accretion processes and trigger outflows/jets. The Young PMS star hosts a large-scale magnetic field that disrupt the inner circumstellar disk and the accretion proceeds from the inner disk rim to the stellar surface through the magnetic funnels (star/disk magnetospheric interaction). The production of high energy photons are responsible for heating and ionizing the disk and likely originate disk winds. However, the star/disk interaction and its connection to the outflow is still an open question. Also, understanding the disk dispersal is important to constrain the star and planet formation.

SPIRou is a near Infrared (nIR) spectropolarimeter instrument mostly aimed at detecting and characterizing Earth-like planets and at investigating how magnetic fields impact star/planet formation.

The stronger polarimetric sensitivity of the instrument will be important to improve our knowledge of magnetic field topology in PMS Object, which are far less obscured in the nIR than in the optical.
This PhD project will be done under the SPIRou Legacy Survey in which we are participating. The main goal is to undertake a intensive survey of magnetic fields in PMS stars and inner accretion disks. The project aims to understand how the young star magnetically interacts with the circumstellar disk, in order to obtain a more quantitative description on the star and planet formation. The modeling of the large-scale stellar magnetic fields can be later used to constrain the numerical simulations we are currently working on and understand the connection between accretion and outflows.

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University: Porto

Density amplification at filament junctions and massive star formation

Advisor: Nanda Kumar (IA U. Porto)

Abstract: Gravitational collapse of cold, dense gas in the interstellar clouds lead to star formation. How does this collapse produce low mass stars is fairly well understood. A prototypical star forming region such as the Orion Nebula or Rosette Nebula will display a spectrum of objects from 0.1 to 100Msun. How does the same cloud produce this spectrum of objects, especially those stars that are 50-100 Msun is the main puzzle that is yet to be understood.

We have recently shown that all known massive star formation take place in pockets of highly amplified densities and mass, that occur at junctions of filaments. There is much evidence that these density amplified pockets are capable of driving longitudinal flows of gas, allowing gravity to dominate over turbulence. Magnetic fields are expected to further aid and modify the physical conditions within these pockets.

The goal of this thesis project is to investigate the properties of the density amplified regions, to understand its physics and how it impacts the formation of the most massive monstrous stars of our Galaxy. Using a variety of observational tools and methods, we want to understand the density and kinematic structure, role of magnetic field and turbulence, and the mass function of objects that such regions produce.

The candidate student should demonstrate a solid understanding of undergraduate level physics, chemistry and mathematics, a flair to study star formation, a willingness to undertake scientific adventures behind computer displays and on top of the worlds high-rise mountain observatories. During the PhD, the student will specialize in reduction and analysis of sub-millimeter and infrared data, both from single telescopes and interferometer arrays.

University: Porto

The role of feedback of massive stars on star formation

Advisors: Pedro Palmeirim (IA U. Porto), Nanda Kumar (IA U. Porto)

Abstract: Star formation is a fundamental process for the enrichment of the InterStellar Medium (ISM). This ongoing recycling process that continuously enriches the ISM is mainly regulated by the feedback from massive stars that enable star formation in a self-consistent manner. Upon formation, the energy from UV radiation and stellar winds from massive stars develop an HII region that ionizes and expands against the cold dense surrounding environment, triggering the formation of a new generation of stars. Several observational studies have detected thousands of HII regions throughout the Galactic Plane and shown that a large significant fraction (25%-50%) of the ongoing star formation in the Milky Way is occurring in these environments.

This PhD project aims to understand how the impact of feedback from massive stars can enhance or disrupt star formation by performing a detailed study of the star formation rate and efficiency in HII regions and compare with other known regions absent from feedback effects. For this purpose, nearby (<3kpc) HII regions will be selected from the large sample studied by the Advisor. The PhD student will conduct a variety of observations: Sub-millimetre continuum observations (Herschel) to probe the cold gas compressed in the shell and how it fragments into cores and protostars; IR observations (Spitzer, 2MASS and the upcoming JWST) to analyse the more evolved YSO population; single-dish millimetre observations to analyse the velocity dispersions in the dense part of the shell structure and constrain the level of infall motions onto the dense cores.

The PhD candidate is expected to specialise in data reduction and analysis, while building strong skills in understanding and describing the physics of (high-mass) star-formation and their role in the enrichment of the ISM. Follow-up high-resolution interferometric observations with ALMA, SMA or IRAM PdB based on the selection of massive dense cores in HII regions are foreseen.

University: Porto

ESPRESSO's look at fine structures of stellar surfaces using exoplanet transits.

Advisors: Vardan Adibekyan (IA U. Porto), Nuno C. Santos (IA U. Porto)

Abstract: Stellar surfaces are full of inhomogeneities (due to the presence of stellar granulation, magnetic spots, etc.) which cause different types of difficulties for exoplanet related studies (e.g. exoplanet detection, bulk and atmospheric characterization etc.). Ironically, exoplanet transits can provide enormous information about the nature of these inhomogeneities, and stellar surfaces, in general.

Transiting planets consecutively block the light coming from different segments of the stellar disk. High-resolution differential spectroscopy will provide the spectra of these small surface segments temporarily covered by the transiting planet. Studying center-to-limb variations of asymmetric profiles and wavelength shifts of spectral lines with different properties (different strengths, excitation potential, ionization level), and comparing them with the predictions of the 3D models of stellar atmospheres will unable to characterize the fine structures of these atmospheres. Understanding and characterizing the 3-dimensional and time-dependent properties of stellar atmospheres is crucial for accurate determinations of stellar properties and for the properties of planets orbiting them.

The detection of very subtle changes in line profiles and wavelength shifts requires ultra high signal-to-noise (S/N) ratio. This will be only possible by averaging many spectral lines of similar properties and taken from very high-resolution and high-S/N spectra. The new ESPRESSO spectrograph, installed at the VLT, perfectly fits the aforementioned requirements and provides a unique possibility to perform such an unprecedented study.
Note: It is important to note that both Advisors: are science team members of the ESPRESSO consortia (N. Santos is the Co-PI of the instrument) and have access to 270 nights of GTO observations. All the observations needed to conduct this project are or will soon be available.

University: Porto

Observational constraints on magnetic properties of solar-type stars

Advisors: Ângela Santos (University of Warwick, UK), Margarida Cunha (IA U.Porto), Tiago Campante (IA U.Porto)

Abstract: In this project, we propose to determine properties of surface rotation and magnetic activity of solar-type stars (spectral types from mid-F to M) observed by the NASA Kepler satellite.

We will obtain constraints on surface differential rotation, which has been revealed as a non-trivial measurement to be made from spot modulation of stellar light curves. Differential rotation is, however, key for the generation of magnetic fields and magnetic cycles. Therefore, such constraints will be important to inform magnetic-generation models and better understand stellar magnetism.

Attempts have been made to detect and characterize activity cycles in solar-type stars observed by Kepler. However, activity cycles have been unambiguously detected only for a small number of stars. In this project, we will use the long-term brightness variations due to dark magnetic spots to search for activity-cycle candidates and constrain properties related to stellar dynamo processes.

At least three scientific papers are expected from this project: 1) testing and validation of the technique to determine differential rotation; 2) measurements of the amplitude and signal of differential rotation of solar-type stars observed by Kepler and how these properties depend on other stellar properties; and 3) validation of the technique, detection of activity cycles in solar-type stars, and determination of the dependence of cycle period and strength on other stellar properties.

University: Porto

The star-planet compositional link with SWEET-Cat

Advisors: Vardan Adibekyan (IA U. Porto), Elisa Delgado Mena (IA U. Porto), Sergio Sousa (IA U. Porto)

Abstract: The Nobel Prize-winning discovery of 51 Pegasi b - the first extrasolar planet orbiting a solar-type star - marks the start of observational exoplanetology. Exoplanet research experienced huge progress since then. Nowadays, several thousand of exoplanets are discovered, dozens of them being located in the so called habitable zone.

Today, the main effort in exoplanet research is moving towards the precise characterization of the detected planets. Interestingly, the precise characterization of exoplanets cannot be dissociated from the study of their host stars. Knowing that stars and planets are formed out of the same molecular clouds, they are indeed expected to share some of their chemical properties and composition. Furthermore, in order to precisely assess planetary physical properties, the derivation of the chemical abundances of planet host stars has recently been shown to be of extreme importance. As a matter of fact, it has been shown that individual abundances of heavy elements and specific elemental ratios end up controlling the structure and composition of the planets.

Our team is hosting the largest homogeneous catalog of stars hosting planets called SWEET-Cat. The catalog currently provides precise stellar parameters (temperature, surface gravity, and overall composition) for most of the exoplanet hosts, and soon will be updated with the detailed chemical compositions of individual elements. The main objectives of this project are twofold: i) use the unique SWEET-Cat data to study the chemical link between stars and planets of different masses, ii) use the host star composition to precisely characterize terrestrial planets with an ultimate goal of identifying the most Earth-like ones. The results of this work may actually have an important impact on our understanding of the number of habitable planets in our Galaxy.

University: Porto

Discovery and characterization of temperate Earth-like worlds with ESPRESSO

Advisors: Sergio Sousa (IA U.Porto), Pedro Viana (IA U.Porto), Nuno Santos (IA U.Porto)

Abstract: Finding and characterizing other Earths, rocky planets with the physical conditions to hold liquid water on their surface is one of the boldest objectives of present-day astrophysics. The recent discovery that rocky planets are actually very common around solar-type stars (e.g. Mayor et al. 2014, Hsu et al. 2019), has made this goal more achievable and motivated the development of a whole new generation of ground and space-based instruments and missions by the main international agencies (e.g. ESA, ESO, NASA).

When a star is orbited by a planet, the gravitational pull from the orbiting companion makes the former move about the center of mass of the star-planet system. This motion can be observed as a variation in the radial-velocity (RV, the velocity in the direction of the line-of-sight) of the star as a function of time, holding information about the orbital parameters and mass of the planet. However, the RV amplitude induced by the presence of an Earth-like planet orbiting a solar-type star is only of the order of 10 cm/s. Fortunately, the development of new state-of-the-art spectrographs like ESPRESSO (at ESO's VLT) is now making this kind of measurements possible. ESPRESSO, on which our team has a leading participation, is the first instrument able to measure the mass of planets like Earth orbiting other stars.

Traditionally, the associated RV induced wavelength shifts have been estimated with respect to absorption lines identified in very high signal-to-noise spectra obtained for a few reference stars (e.g. Baranne et al. 1996, Pepe et al. 2002), or imprinted on the spectrum of each observed star by making its light go through a gas cell placed at the entrance of the spectrograph (e.g. Butler et al. 2016, Gao et al. 2016). More recently, it has been explored the possibility of estimating the (relative) RV induced wavelength shifts without the use of an external set of reference absorption lines, relying instead on internal self-calibration (e.g. Anglada-Escud´e et al. 2012, Czekala et al. 2017, Sablowski et al. 2017, Dumusque 2018, Zechmeister et al. 2018). Despite the enormous success of the existing approaches, the derivation of precise RVs can however be further improved.

The main objective of this project is to develop software that implements a new data processing and analysis algorithm for the precise estimation of stellar radial velocities from high-resolution stellar spectra. This software should infer the stellar spectrum and telluric lines, as well as estimate the stellar radial velocity, at each observed epoch. This software will then be applied to real data, in particular, data from the ESPRESSO and NIRPS (ESO-3.6m) spectrographs, where our team has a leading participation. The ultimate goal is to allow for the accurate and precise recovery of the radial-velocity signals induced by the orbital motion of exoplanets, particularly in the presence of higher-amplitude stellar noise, thus enabling the detection and characterization of temperate Earth-like worlds.

University: Porto

Detecting the atmosphere of exoplanets using high resolution ESPRESSO spectra

Advisors: Olivier Demangeon (IA U. Porto), Nuno Santos (IA U.Porto)

Abstract: In 1995, the discovery of a planet around a solar star (Mayor and Queloz, 1995) marked a huge milestone in the Astrophysical Sciences. Since then it was developed and improved a number of detection techniques with increasing precision and stability, pushing constantly the boundaries of the regime of masses and systems we can identify. In particular, radial velocities, from the ground, and transit photometry both ground and space based have contributed for the bulk of planet detections.

Light measurements from planetary reflection and thermal self-emission are minute when compared with the contribution from the host star. The reflection magnitude depends on the planet-star distance, radius and albedo of the planet. The signal will peak typically at the same wavelength as the star in the visible (Schneider, 2002), faded by the distance from the star and reflective properties of the planet. For the emission, the strongest sources are hot planets due to their proximity to their parent star or their young age.

Measurements of transmitted light is a fundamental resource if we hope to characterize a broad class of exoplanets and has been so far the most successful in the detection of spectral features in alien worlds (e.g. Tinetti et al. (2007); Berta-Thompson (2016); Cubillos et al. (2020)). In particular narrow-band transmission spectroscopy has been proven as a tool to detect molecules (Snellen et al., 2010) and atomic species (Wyttenbach et al., 2015) both in optical and NIR wavelengths.

In this proposal, we will focus on the use of high resolution spectroscopy as a mean to probe exoplanet atmospheres. The tools being developed will be utilized to analyse data from ESPRESSO's (Pepe et al., 2013) GTO list as a first step and later adapted to NIRPS (Wildi et al., 2017) data in the NIR. At high spectral resolution, the detectability of the minute signal from exoplanet atmospheres can be improved by comparing the observed spectra with a template which combine several spectral lines. This ensures that it is possible to achieve an optimal signal-to-noise ratio.

To explore the retrieval of spectral signatures using methods based on the construction of the cross-correlation function (CCF):

– A first application of the CCF based methods will be done with chromatic Rossiter-McLaughlin analysis (Di Gloria et al., 2015);

– The observed spectra collected during transits in the visible (ESPRESSO) will be processed through a routine to be developed in order to try to detect chemical signatures. In short, a spectra containing both stellar and planetary signal would be cross-correlated with a model of the atoms/molecules absorption spectrum.

– The same implementation would be adapted, if time allows, to search for signatures in the NIR (e.g. Snellen et al., 2010) using NIRPS data.

University: Porto

Probing the architecture of multi-planetary systems

Advisors: Susana Barros (IA U. Porto), Olivier Demangeon (IA U. Porto)

Abstract: The Kepler satellite has revealed that a large percentage of the known transiting exoplanets are in multi-planetary systems (∼40%). Multi-planetary systems are great laboratories to test theories of formation and migration of planetary systems. Many interesting systems found by Kepler and others recently found by the K2 mission are still awaiting detailed modelling due to the extra-complexity that the gravitational interaction between the different planets of the system introduce. This project aims at the study of the architecture of multi-planetary systems using detailed state of the art n-body simulations coupled with a Bayesian modelling.

The project is built on a photodynamic transit and radial velocity (RV) fitting tool developed by our group to study interesting known Kepler multi-planetary systems and/or new multi-planetary systems discovered by the K2 and TESS new surveys. A photodynamical analysis, accounting for the dynamical interactions between the planets of the system at the earliest stage of the data analysis, achieves a better precision and accuracy on the determination of the system parameters than usual methods. It is also more sensitive to the low masse planets. The goal of this project is to focus on the lowest mass planets (super-Earths and mini-Neptunes), for which it is not possible to determine masses with current RV instruments alone and will probe this fascinating population of planets.

Our group has developed a pipeline to reduce K2 data and compute high precision light curves combined with a transit search algorithm to search for planetary transits. Hence we have a competitive advantage to discover knew interesting systems from K2 or even TESS data. We are also involved in a collaboration to obtain precise radial velocities with the HARPS spectrograph to confirm and characterise these candidates. The student will study the most promising know systems and is also expected to be involved in the search and characterisation of these new multi-planetary systems.

University: Porto

SOAP+: modelling stellar activity using solar data

Advisors: Nuno C. Santos (IA U. Porto), Mahmoud Oshagh (IAC, Spain)

Abstract: SOAP is a numerical tool developed by our team that allows to simulate the effects of stellar activity in both high resolution spectroscopy and photometry. This tool has been developed to understand the stellar noise in exoplanet research data.

The goal of this project is to further develop SOAP in the context of high precision spectroscopy. In particular, we propose to include real data of active regions in the Sun as observed using instruments such as the LARS spectrograph. The results may be used to simulate the expected effects of stellar activity in both ultra-high precision radial velocity measurements as well as in transmission spectroscopy to study exoplanet atmospheres.

The code will then be applied to ESPRESSO data, both to test the code and to inform about the best approach to correct the spurious activity induced signals. It will then be applied in exoplanet research, to derive the masses or known transiting planets (detected by space missions such as TESS), and to search for Earth-mass planets in the habitable zones of solar-type stars.

University: Porto

How rare is the Earth and the Solar System architecture?

Advisors: Pedro Viana (IA U. Porto), Olivier Demangeon (IA U. Porto)

Abstract: The estimation of how rare Earth-like planets are, as well as planetary systems similar to our own, requires the joint statistical characterisation of the full population of exoplanets and their systems. This can also be used to indirectly infer exoplanet or exoplanetary system properties, given direct knowledge about others. And it leads to a better understanding of the physical processes that were most important during planetary formation and evolution. However, if these aims are to be achieved, the selection effects associated with the sampling of the exoplanet population, have to be taken properly into account.

The student will use advanced statistical and machine learning techniques, namely Hierarchical Bayesian Modelling, Approximate Bayesian Computation, Importance Sampling and Gaussian Processes, to characterise the population of exoplanets considering the full impact of sample selection effects. The objective is to obtain robust and unbiased estimates of: planetary occurrence rates as a joint function of exoplanet mass, radius, insolation and orbital parameters, as well as stellar characteristics; the population of exoplanetary systems, through the occurrence rate of distances in the space of exoplanet properties, as a function of stellar characteristics. This work will be based on exoplanet catalogues assembled by searching for planetary transits in front of the stars observed with the NASA missions Kepler and TESS, for which the selection effects are well understood. And take into account spectroscopic data obtained with ground-based telescopes, namely at the European Southern Observatory (ESO), which holds essential information about exoplanet mass and stellar characteristics. For this data to be properly considered, it will be jointly analysed with the transit data using always the same methodology, based on Bayesian joint modelling of planetary and stellar activity. Its accuracy and precision will be characterised through simulations.

University: Porto

Possible Climate of Exo-VEnus with a GCM

Advisors: Gabriella Gilli (IA U. Lisboa), Thomas Navarro (McGill, Canada)

Abstract: The study of extra-solar planet atmospheres is widely seen as the new frontier in Astrophysics, a necessary step to elucidate the wide diversity of planetary environments existing outside our Solar System, and crucial for the future detection of life signatures in other worlds. Given the variety of Planetary Atmospheres in our Solar System, and the number of exo-planet observed so far, we can expect a vast diversity among exoplanet climates. Predicting the actual climate regime on a specific planet remains very challenging. Our experience on modelling the atmosphere of the Earth, as well as Mars, Venus and Titan is crucial to start building numerical simulators of “virtual” planets. This may be achieved by sophisticated 3D models, already implemented to study specific cases of Earth-like exoplanets.

Some previous works on known terrestrial ESP used a new Generic version of the General Circulation Model (G-GCM) specifically developed at the Laboratoire de Meteorologie Dynamique (LMD) (hereinafter LMD G-GCM) for exoplanets and paleoclimate studies. For instance, successful applications of the LMD G-GCM are those done to address studies of the cold super-earth Gliese 581d, a tidally locked ESP like Gliese 581c/HD85512b (Wordsworth et al. 2011, ApJ, 733 L48), or Proxima b (Turbet et al. 2016), the closest potentially habitable ESP discovered so far. The LMD model uses a 3D dynamical core, common to all the terrestrial planets, and a physical core adaptable to each specific planet. In the perspective of detecting more and more close-in-orbit hot terrestrial ESP in the near future, with mass and radius similar to the Earth, but with a completely different climate, a Venus-like atmosphere may be one of the most relevant cases to address observational prospects

We propose here to use the LMD G-GCM currently installed and operational on IA clusters to study hot-terrestrial exoplanets on a short period orbit around a M dwarf (best targets for transmission spectroscopy studies). The LMD G-GCM was recently adapted to represent the characteristics of a Venus-like planet (e.g. similar composition, state-of-the-art cloud model, atmosphere in super-rotation, etc) as done Gilli et al. 2019.

Methodology:

The student will run the LMD G-GCM adapted to Venus-like exoplanets, and he/she will perform sensitivity tests with the goals of:

- exploring the period of superrotation varying key parameters (e.g. solid body rotation, clouds thickness)
- evaluating the effect of the distance from the host-star, star irradiation, atmosphere in superrotation, etc. to the observable (e.g. transition spectra, phase curve)
- providing case studies to characterize future observation of the atmosphere of close-in-orbit terrestrial exoplanets

University: Lisboa

Atmospheric Gravity Waves: a key process in Mars and Venus atmospheres

Advisors: Pedro Machado (IA U. Lisboa), Gabriella Gilli (IA U. Lisboa), Javier Peralta (JAXA, Japan)

Abstract: Recent observations by Venus Express (VEx) spacecraft [Svedhem+2007,Drossart+2007] and ground-based campaigns, allowed to carry out an unprecedented characterization of winds [Machado+2014, 2017,Peralta+2017a] and atmospheric temperatures of Venus [Limaye+2017]. Those new measurements significantly improved our comprehension of Venus atmospheric circulation and achieved new valuable constraints in atmospheric dynamics of planets with superrotation. At the same time, they put in evidence the high variability of the Venus atmosphere, and they opened new scientific questions such as: what processes control the transition region (70-120 km) between the retrograde superrotating zonal flow and day-to-night circulation? How does the interplay of planetary and small-scale waves control the circulation features? We propose a systematic characterization and

classification of the waves apparent on Venus using remote sensing images from VEx and Akatsuki (Nakamura+2007) cameras.
This systematic characterization of atmospheric waves is of critical importance to constrain current sophisticated 3D models of terrestrial planet atmospheres [Gilli+2017].
Objectives: This PhD proposal will be devoted to reach the following goals:
1 - Studying the wind variability and the presence of atmospheric planetary waves on Venus using all dataset from two instruments on board VEx (VMC and VIRTIS), following previous studies also leaded by the Advisors: [Machado+2014, +2017; Peralta+2014].
2 - Systematic characterization and classification of the waves apparent on Venus using remote sensing images from Venus Express (VMC and VIRTIS-M) [Svedhem+2007] and Akatsuki cameras (UVI, IR1, IR2 and LIR) [Nakamura+2007]. In the case of remote sensing images, the wave amplitudes can be derived by means of devoted Radiative Transfer models. Of critical importance for the 3D models is the systematic characterization and classification of atmospheric waves on Venus, what will allow to provide accurate estimations of the energy
transport in these atmospheres.
3 - Perform data-models and model-model inter-comparison to disentangle the processes going on in the complex and highly unexplored transition region (70-120 km) of Venus atmosphere, and to help interpreting the large observed variability, transport of energy from the lower to the upper layers, and small-scale waves.
4 - Estimate the impact of small scale waves on the energy budget of the middle atmosphere of Venus and Mars by performing detailed sensitivity studies, following previous works leaded by co-Advisor [Gilli+2017, Gilli+2019].
5 - Perform for the first time an intercomparison between two reference 3D models of Venus atmosphere, the LMDVGCM [Gilli+2017] and VTGCM [Brecht+2012], comparing simulations from 90 to 150 km altitude, to validate them and/or identify possible missing processes.
This PhD project intends to combine space and ground-based observations with model simulations synergistically to improve the understanding of physical and dynamical processes in the atmosphere of terrestrial planets.

University: Lisboa

Study of chemical minor compounds of Solar System planetary atmospheres

Advisors: Pedro Machado (IA U. Lisboa), Santiago Pèrez-Hoyos (UPV, Spain)

Abstract: Chemical detection and abundance retrieval of important species to study atmospheric composition and evolution of giant planets of the Solar System, using high-resolution spectra and NEMESIS code. High-resolution spectra will be used to investigate some important open questions on atmospheric chemistry:
- In the case of the giant planets Jupiter and Saturn the deuterium abundance D/H will be investigated from hydrogen and methane bands in the visible and near infrared.
- For Uranus and Neptune, the CH_4 abundance as a function of latitude will be monitored. This will help understanding the origin and the structure of the localized wave propagating from the troposphere.
- NEMESIS suite will be used combined with high-resolution spectroscopy in order to study and quantify the presence of minor chemical species in planetary atmospheres.
- Titan Doppler winds will be retrieved as a side work of this PhD project.
Objectives: The main goals of this study are to investigate certain aspects of the chemical behaviour of the atmosphere of the giant planets of our Solar System, mainly Jupiter and Saturn but also Uranus, Neptune, and Titan, which are still open questions. In order to achieve the objectives listed in the

following the applicant will use ground-based observations taken with VLT-ESPRESSO, VLT-UVES, CAHA-CARMENES, TNG-HARPS and IRTF-iSHELL and TEXES data. Most of the described observations were already taken by our team, or are granted for the next period of observations. The observations that will be proposed and carried out by the applicant, although relevant in the framework of the present project, will not imply a high risk for reaching the core objectives of this project since the already existing data cover most of the issues that will be addressed by this program.
At a glance the applicant main goals are:
- Measure deuterium abundance D/H from hydrogen and methane absorptions in the visible and near infrared on Jupiter and Saturn.
- Monitor the CH_4 abundance as a function of latitude in the visible or near-IR range on Neptune and Uranus.
- Detection and abundance retrieval of various chemical species, e.g. C_3 on Titan, in order to constrain their photochemical networks. In order to perform those retrievals the applicant will use NEMESIS suite, a particularly useful tool in the visible and near-infrared spectral regions, where sunlight reflected by clouds and hazes can be observed, and in the thermal-infrared, where thermal emission spectra constrain temperatures, gas and aerosol abundances.
- To better understand the nature of the processes governing Titan's overall atmospheric dynamics, the applicant will provide Doppler wind measurements using visible Fraunhofer lines scattered by Titan's atmosphere.
Work Description: Throughout the past decades, the interest on Jupiter and Saturn atmospheres has grown amongst the astrophysics scientific community. Yet, the last in situ measurements were taken from the Cassini probe, and there are still several open questions.

University: Lisboa

Atmospheric Dynamics' studies of telluric planets using Space and ground based observations

Advisor: Pedro Machado (IA U. Lisboa), Alejandro Cardesín-Moinelo (ESA-INTA, Spain), Javier Peralta (JAXA, Japan)

Abstract: On Mars and Venus, temporal and spatial variability of winds, the role of waves and the mechanisms that allow topography to influence the upper cloud motions need to be addressed. In order to accomplish the goals proposed in this PhD project the applicant will take advantage of:
- The use of high-resolution Doppler capabilities in order to explore the correlation between topographic features and wind variability on Venus mesosphere, study the impact of solar tides on wind variability, analyse Doppler winds at different altitudes in order to constrain the vertical wind shear.
- Will adapt our Doppler velocimetry method, based on high-resolution spectra, to the infra-red wavelength range, using ground-based high-resolution spectra from CAHA/CARMENES and IRTF/iSHELL (already in our possession).
- Characterization of atmospheric gravity waves on Mars using Mars Express OMEGA data (access already granted).
- Detection and characterization of atmospheric waves on Venus using VEx/VMC dataset.
At a glance the applicant main goals are:
- Our group optimized and fine-tuned a Doppler technique tool in order to retrieve winds at Venus cloud top region in the visible. This method will consist in the stepping stone to adapt it to the infrared. The scientific objective related with this technical achievement is to study Venus' nightside dynamics based on carbon dioxide emission lines' Doppler shifts, oxygen airglow nightside emission lines. This tool will be used also to explore the dynamical transition across Venus' terminator.

- Detect and characterize Venus' atmospheric gravity waves and stationary waves using Venus Express VMC data, Akatsuki data and infrared Doppler technique developed under this proposal. The student will quantify the impact of waves in atmospheric superrotation.
- This project aims to use all the available dataset of the hyperspectral camera OMEGA (Bibring et al., 2004) onboard Mars Express, building a catalogue of gravity waves present in the dayside images, especially in seasons when the atmosphere is optically thicker due to atmospheric clouds and aerosols (water ice, CO2 ice and dust). Doing a visual inspection of the images in search of wave patterns at different wavelength ranges, resulting in a catalogue of wave observable features such as geographical position, wavelength, wave packet length and width, orientation and phase speed.
- With an evolved tool of cloud tracking based on phase correlation between images that will allow to explore Venus' atmosphere dynamics based on coordinated space and ground observations (Akatsuki, TNG/HARPS, VLT/UVES, VLT/ESPRESSO, BepiColombo at Venus' flyby, THEMIS, Venus Express (archive)), we note that this datasets are already in our possession or the related observations are already granted.

The main objectives of this project are three-fold: contribute to the Venus' atmospheric dynamics characterization using Doppler velocimetry techniques in the infrared. Use cloud tracking methods in order to address the yet not explained superrotation state of the Venus' atmosphere. And detect and characterize atmospheric planetary waves on both Mars and Venus atmospheres.

University: Lisboa

Changing times - a window to planetary systems

Advisor: Susana Barros (IA U. Porto)

Abstract: Recent years have seen a revolution in our knowledge of exoplanetary systems including many surprising discoveries. In contrast, several expected results have not yet been observed or confirmed. Among these is the existence of moons and rings, as well as of tidal decay of the exoplanets that orbit very close to their parent star. This project aims at detecting these extreme systems taking advantage of the unprecedented precision of the ongoing and future transit missions like TESS, CHEOPS and PLATO in which our team is deeply involved.

This project will take advantage of the extreme precision of CHEOPS to measure the changing transit times of known exoplanets, which can give us a wealth of information about planetary systems. A single planet orbiting a star will have perfect periodic transits. However, the existence of other planets, rings, moons or the tidal interaction between the planet and the host star will result in a variation in the transit times. Therefore, we will use the change of the transit times to probe the planetary systems in a unique way.

We propose to use the change of transit times combined with shape variations to probe the existence of moons and rings in exoplanets and detect the first exo-ring or exomoon. For planets that are very close to the parent star we propose to measure the variation of transit times that would be due to the tidal interaction with the host star. Furthermore, for multi-planetary systems in resonant configurations we propose to use the variations of the transit times to constrain the planetary masses. This method to measure masses called TTV-masses can obtain planetary masses independently from other methods and has allowed measuring the smaller exoplanet masses known to date due to its high sensitivity.

Our team has privileged access to CHEOPS data and hence the student will be able to access this unique dataset. Furthermore, the tools developed during this project may also be used for other datasets: NASA KEPLER, K2 and TESS missions. The results of this project will increase the scientific exploitation of these state of the art missions and the future ESA mission, PLATO and will lead to a better understanding of planetary systems.

University: Porto

Exoplanetary atmosphere: the 3D revolution

Advisor: Olivier Demangeon (IA U. Porto)

Abstract: The 2019 Nobel prize awarded to Michel Mayor and Didier Queloz symbolizes the exponential growth of exoplanetology. Since the discovery of 51 Peg b, the first exoplanet found around a Sun-like star in 1995, we have witnessed a succession of revolutions: the ubiquity of exoplanets in the galaxy, a new paradigm of planetary formation and migration, the detection of molecules in exoplanetary atmospheres and a new revolution is on the way.

Transmission spectroscopy has been and will likely be for the next decades, the main window into exoplanet atmospheres with the NASA JWST and the ESA ARIEL telescopes. The models used to interpret these transmission spectra are, for the vast majority, 1D models. Their validity relies on an assumption: The fraction of the planetary atmosphere probed during the transit of an exoplanet can be reduced to a homogeneous and narrow annulus around the planet.The emergence of a new generation of instruments, ESPRESSO, SPIROU and soon NIRPS and JWST and their unprecedented precision are now challenging this assumption. In a recent study, Ehrenreich et al. 2020 Nature. 580:597–601, we have shown that the composition and temperature-pressure conditions at the limb of the exoplanet WASP 76 b are not at all homogeneous. In order to fully exploit these data and the ones to come, 3D models are required to properly reproduce this heterogeneity.

For this PhD, the successful applicant will make use of open-source codes as described in Caldas et al. 2019 A&A 623:A161 or Mendonça et al. 2016 APJ 829(2):115 to interpret transmission spectra. Thanks to the involvement of our team in the ESPRESSO, SPirou and NIRPS spectrographs, the applicant will have the opportunity to analyze state of the art datasets like the one of WASP-76 b. This work will also contribute to the scientific preparation of ARIEL and proposal for observations with JWST.

University: Porto

3D modelling of “transitional planets”: the pathway towards other Earths

Advisors: Gabriella Gilli (IA U. Lisboa), Olivier Demangeon (IA U. Porto)

Abstract: The 2019 Nobel prize awarded to Mayor and Queloz symbolises the impact of the discovery of the first exoplanet found around a Sun-like star. Since 1995, we have witnessed tremendous progress in the field of exoplanets: from characterization as function of their radius/mass, host star and orbit, to the detection of molecular compounds in their atmosphere. Even within the limits of our current observational capabilities, studies of exoplanets are providing a unique contribution to improving our understanding of planet formation and the conditions that may make them habitable. But what is the

place that Solar System (SS) and the Earth occupies in the galactic context? How unique life is on Earth?

New discoveries of planets with radii between those of the Earth and Neptune (1.0-3.9 R_E) indicated that this new class of “transitional planets” are by far the most common (e.g. in the sample identified by the NASA Kepler mission), while our Solar System has no example of these intermediate planets. They may either have a rocky core enveloped in a H2-He gaseous envelope or contain a significant amount of H2O-dominated fluids, being a potential habitable water world. Detecting the composition of their atmosphere would be essential to constrain current atmospheric models and help building up a more realistic scenario.

The main window into exoplanet atmosphere is nowadays transmission spectroscopy. This technique will be used in future space mission (JWST and ARIEL) to shed a light on the atmospheric properties of exoplanets (Tinetti et al. 2018 Exp. Astronomy, Vol.46, Issue1). Models used to interpret these spectra are for the vast majority 1D, which rely on the assumption that the limb of the planet, probed by transmission spectroscopy, is a horizontally homogeneous narrow annulus in of the planetary atmosphere. The rise of a new generation instruments for which the team has a privileged access (ESPRESSO, SPIROU) is contesting this hypothesis (Ehrenreich et al. 2020 Nature. Vol.580): to properly interpret unprecedented precision data, 3D models are required.

The PhD candidate will make use of a 3D model inherited from terrestrial planets and adapted to exoplanets, like the LMDZ generic GCM (Charnay et al. 2015, ApJ Letters, Vol. 813, Issue I, Turbet et al. 2019, A&A, 28) to 1) investigate possible climate scenarios for “transitional” planets 2) identify the solutions that match the transmission spectra to the best 3) contribute to preparation of future ARIEL and JWST observations.

University: Porto/Lisboa

Fundamental cosmology from precision spectroscopy: from ESPRESSO to the ELT

Advisors: Carlos Martins (IA U. Porto), P. Molaro (INAF – Trieste)

Abstract: ESPRESSO is a latest-generation spectrograph, combining the efficiency of a modern Echelle spectrograph with extreme radial velocity and spectroscopic precision, and including improved stability thanks to a vacuum vessel and wavelength calibration done with a Laser Frequency Comb. It is installed in the Combined Coudé Laboratory of the VLT and linked to the four Unit Telescopes (UT) through optical Coudé trains, allowing operations either with a single UT or with up to four UTs. A key science driver of ESPRESSO is to perform improved tests of the universality of physical laws, and in particular to confirm or rule out the recent indications of dipole-like variations of the fine-structure constant. In this thesis the student will be directly involved in the analysis and scientific exploration of the ESPRESSO fundamental physics GTO, and in the preparation of any follow-up observations. Apart from its direct impact on cosmology and fundamental physics, the ESPRESSO data is also important as a reliable precursor of analogous high-resolution spectrographs for the next generation of Extremely Large Telescopes, and in particular of ELT-HIRES (in whose Phase B the student will also be involved). A second goal of the thesis is to use the ESPRESSO data for detailed and realistic simulations to assess the cosmology and fundamental physics impact of ELT-HIRES, including tests beyond the sensitivity of ESPRESSO, such as the Sandage test. The student, who should have a genuine interest and previous experience in experimental spectroscopy and astrophysical data analysis, will be working within the general framework of the ESPRESSO science team, and will also join the FCT-funded CosmoESPRESSO project.

University: Porto

New Maps of the Dark Side: Euclid and beyond

Advisors: Carlos Martins (IA U. Porto), coAdvisor within Euclid consortium

Abstract: The growing amount of observational evidence for the recent acceleration of the universe unambiguously demonstrates that canonical theories of cosmology and particle physics are incomplete (if not incorrect) and that new physics is out there, waiting to be discovered. The most pressing task for the next generation of astrophysical facilities is to search for, identify and ultimately characterise this new physics. The acceleration is seemingly due to a dark component whose low-redshift gravitational behaviour is very similar to that of a cosmological constant. However, currently available data provides very little information about the high-redshift behaviour of this dark sector or its interactions with the rest of the degrees of freedom in the model. It is becoming increasing clear that tackling the dark energy enigma will entail significantly extending the redshift range where its behaviour can be accurately mapped. A new generation of ESA and ESO facilities, such as Euclid, the ELT, and the SKA have dark energy characterization as a key science driver, and in addition to significantly increasing the range and sensitivity of current observational probes will allow for entirely new tests. The goal of this thesis will be to carry out a systematic exploration of the landscape of physically viable dark energy paradigms and provide optimal discriminating observational tests. The work will initially focus on Euclid (whose launch is fast approaching) and will gradually broaden to explore synergies and probe combination with the SKA and ELT-HIRES. The work will be done in the framework of the Euclid TWG (who have already endorsed the project, and will provide a co-Advisor in due course). Thus the student will be a member of Euclid, as well as joining the FCT-funded CosmoESPRESSO project.

University: Porto

Coding the Cosmos: Simulating Superstrings

Advisors: Carlos Martins (IA U. Porto), P. Peter (IAP), E.P.S. Shellard (Cambridge)

Abstract: Cosmic strings arise naturally in many proposed theories of new physics beyond the standard model unifying the electroweak and strong interactions, as well as in many superstring inspired inflation models. In the latter case, fundamental superstrings produced in the very early universe may have stretched to macroscopic scales, in which case they are known as cosmic superstrings. If observed, these objects provide a unique window into the early universe and possibly string theory. Recent progress in CMB polarization and gravitational wave detection highlights how some of these scenarios could be constrained by high-resolution data. However, they also show that the current bottleneck is the lack of accurate high-resolution simulations of defect networks that can be used as templates for robust statistical analysis, implying that current constraints are not reliable. This will be an even bigger problem for next-generation facilities such as CORE and LISA. While most numerical simulations so far have been performed for the simplest Abelian-Higgs (or Nambu-Goto) model, realistic cosmic strings will have non-trivial internal structure, including charges and currents. Suitable analytic models are being developed, but numerical studies of these internal structures and their evolution are still lacking. The scientific goal of the thesis is to fill this gap, continuing the development of a new generation of high-scalability defect evolution codes that will match the

sensitivity of ongoing and forthcoming observational searches. It will use both CAUP computational resources (including a GPU donated by NVIDIA) and world-leading HPC facilites accessed through PRACE. The student should have an interest and relevant previous experience in computational physics, data analysis and visualisation. Experience of parallel and/or GPU programming would also be highly beneficial. The student will join the FCT-funded CosmoESPRESSO project and will also be a member of a recently approved Paris-Porto-Cambridge exchange grant.

University: Porto

Coupled tachyonic dark energy: a test in the Euclid era

Advisors: Alberto Rozas-Fernández (IA U. Lisboa) and Francesco Pace (University of Bologna)

Abstract: The main goal of ESA's Euclid space mission, to be launched in 2022, is to understand the origin of the observed late-time accelerated expansion of the Universe. One tantalising theoretical possibility is to describe the acceleration and the formation of structure in models in which dark energy interacts directly with dark matter. The goals of the proposed thesis are to study the background expansion and the evolution of cosmological structure in the coupled tachyonic scenario, forecasting Euclid's ability in testing this hypothesis. For this purpose, we shall consider conformally coupled, disformally coupled, together with models which simultaneously make use of both couplings. The different models will be tested first at the linear level against the most recent observational data. Afterwards, we shall explore the mildly non-linear regime by studying structure formation in the spherical collapse approach. Those preliminary results will then inform the study of the full non-linear regime, testing the models with non-linear data both from current and future developments.

University: Lisboa

Shapes of Galaxy Clusters as a probe of gravity

Advisors: Claudio Llinares (IA U. Lisboa), Ismael Tereno (IA U. Lisboa)

Abstract: Galaxy clusters are the largest gravitationally bound structures in the Universe. According to the standard cosmological model they consist of a dark matter halo that encloses the hot gas and the cluster galaxies. Their density profiles, and shape properties such as ellipticity and flexion, are determined by gravity and dark matter properties. This means that these observable quantities can help us to discriminate between different extensions to Einstein's theory for gravity or different dark matter models. The relation between different components of the clusters (galaxies, dark matter and gas) are also sensitive to the underlying models and may help us to rule out alternative theories or even the standard paradigm. This is crucial given the existing discrepancies between observations and predictions for the standard cosmological model.

In this project, the student will derive analytical and numerical predictions for the shapes of clusters in the framework of different models and assumptions. The numerical calculations will be done by analyzing data from state-of-the-art cosmological simulations that were performed with standard gravity and several extended models. The student will also have access to observational data to test the predictions. The data will come from two very different astrophysical surveys: in the X-rays (detecting the hot gas of the cluster) and in the optics (detecting galaxies positions and shapes). In particular, the student will work with simulations and data provided by the ESA mission Euclid, of which the institute has a leading role. Euclid, to be launched in 2022, will deliver an unprecedented catalogue of around

20,000 galaxies in massive clusters (~1000 are observed today), greatly improving the statistics on cluster properties.

University: Lisboa

Origin of the arrow of time of the Universe

Advisors: Marina Cortês (IA U. Lisbon/Perimeter Institute), Andrew R. Liddle (IA) and Lee Smolin (Perimeter Institute for Theoretical Physics - Canada)

Abstract:
"Time always moves in the same direction, it always increases and never decreases: we always remember the past and never the future. This asymmetry of time is universal, from scales on Earth up to cosmological scales. We receive light that galaxies emitted long ago in the past and never receive light they emitted in the future.

This time asymmetry is not reflected in the majority of physics laws which are time symmetric, they work in the same way if time is increasing or decreasing. In fundamental physics time is symmetric, and we attribute the cosmological arrow of time to very unusual initial conditions in the beginning of the universe. These conditions are so special that their probability is of order 1 in 10^90. Why the universe started in such an unlikely state is a question we have no answer for in cosmology.

In this work we investigate whether the time asymmetry may already be present in the fundamental laws, which would avoid having to attribute it to very special initial conditions at the Big Bang.
We construct models that simulate such a time asymmetry and the student will run simulations with these models from existing code. The code for the simulations is already in place, so the student can directly start working on it. The goal is to infer from the results of the simulations what are the properties of physics if its are fundamentally time asymmetric. This project is co-supervised by Prof. Andrew R. Liddle of I.A, and by Prof. Lee Smolin of the Perimeter Institute for Theoretical Physics in Canada."

University: Lisboa

Biocosmology: Rethinking our place in the Universe

Advisors: Andrew Liddle (IA U.Lisboa) and Marina Cortês (IA U.Lisbon)

Abstract: This project lies within an ongoing research programme that seeks to challenge the widely-held perception that biology and cosmology have little to teach each other. Cosmological modelling follows traditional physics approaches, which however appear incapable of providing complete explanations of biological systems. We seek to investigate the long-term arc of biological systems in a cosmological context, and investigate how new ideas in theoretical biology could impact cosmological understanding. Goals include an enhanced understanding of the development of cosmic entropy and the naturalness of cosmic initial conditions, modelling of possible emergent behaviours and available states, and a study of radically non-ergodic phenomena in the Universe. The student will play a key role in developing numerical models and algorithms to place these ideas in suitable mathematical frameworks.

The project will receive additional supervision from physicist Prof Lee Smolin of the Perimeter Institute in Canada and biologist Prof Stuart Kauffman of Seattle in the USA, and potentially could include an extended research visit to Perimeter.

University: Lisboa

Simulating the Universe beyond general relativity

Advisors: Noemi Frusciante (IA, U Lisboa), Claudio Llinares (IA, U Lisboa),

Abstract: The observed late-time acceleration of the Universe is one of the greatest mysteries in modern cosmology. Although by now several observations have confirmed the presence of such phenomenon, a clear theoretical explanation is still lacking. The simplest model relies on the addition of the so-called cosmological constant Λ, as a source for cosmic acceleration, into the equations of General Relativity (GR). The resulting model is dubbed cosmological standard model or Λ-cold-dark-matter (ΛCDM). In this scenario Λ has shown several shortcomings (e.g. its theoretical expected value differs by 60 orders of magnitude from the observed one). Furthermore, mild observational tensions also arise among different data sets. These reinforced the idea that we need to look for alternative models beyond GR. In particular, some of these models have shown to be very promising in resolving such cosmic tensions and in some cases they offer a better fit to data than ΛCDM.

However, these models have been explored only on the largest linear scales. Extending these calculations towards smaller scales is crucial if we want to maximize the amount of information that can be extracted from a given set of observations. This increment in resolution is not trivial and requires the use of sophisticated simulation techniques. The development of these simulations is timely given the increasing wealth of high-quality data of near future astronomical surveys.

The student will apply theoretical modeling and numerical methods to develope simulation codes for different extensions to Einstein's theory of relativity. The analysis tools that will also be developed by the student are expected to be used in the upcoming ESA Euclid mission in which the host institution has a leading role. In order to ensure a successful PhD, the project contains coding and numerical elements. Strong physical intuition will also be necessary to interpret the simulation data.

University: Lisboa

New machine learning approaches to the modeling of clusters and voids in N-body simulations

Advisors: António da Silva, Nelson Nunes

Abstract: Galaxy clusters and cosmic voids are peaks and valleys in the large-scale density distribution of the Universe. They offer a unique way to study the formation and evolution of cosmological structures and to test alternative cosmological models such as those that include dynamical dark energy, modified gravity, dark matter and primordial non-Gaussian models. Some of the main issues of using clusters and voids as cosmological probes are: i) the way their observed properties relate to the underlying cosmology is still unknown for a variety of models that can be tested with upcoming high quality data from galaxy surveys such as that by the ESA/Euclid Space mission; ii) these properties are often only poorly modelled with approximate fitting functions that fail to fully capture the complex nature of cluster and void populations in numerical N-body simulations; iii) Cosmological inference using clusters and voids, applies these approximations and relies on standard Markov-Chain-Monte-

Carlo methods, that require time-consuming computations of likelihood functions. All these issues require new statistical learning approaches and powerful N-body simulation techniques to efficiently compare model predictions with observations.
The main objective of this project is to develop new approaches to the modeling of galaxy cluster and voids, by combining new machine learning (ML) approaches and state-of-the-art N-body simulations featuring dynamical dark energy models. The work involves the modification of existing N-body codes to generate new cluster and void data and the development of artificial intelligence algorithms that learn the details of these objects in simulations. These algorithms can then be used to provide realistic estimates of cluster and void properties, such as mass functions and observable scaling relations, to study cosmological model signatures and degeneracies over a wide range of masses/radii and redshift. A possible extension of this work involves the use of these algorithms with new ML cosmological inference techniques, that avoid the explicit computation of likelihoods, to forecast and/or impose constraints on dynamical dark energy models using forthcoming and/or existing observations.

University: Lisboa

Cosmological tests of gravity theory beyond General Relativity

Advisors: Francisco Lobo (IA U.Lisboa), Noemi Frusciante (IA U.Lisboa)

Abstract: An outstanding problem faced by modern cosmology concerns cosmic acceleration, i.e. the phase of accelerated expansion recently entered by the Universe, for which we still lack a satisfactory theoretical explanation. Within the context of General Relativity, an accelerated expansion can be achieved adding an extra ingredient in the energy budget of the Universe, commonly referred to as dark energy. A different approach is to modify the law of gravity describing the Universe at large scales. A plethora of modified gravity models addressing the phenomenon of cosmic acceleration have been proposed and analyzed. The astronomical community has embarked on an intense observational effort to help exploring the real nature of the cosmic acceleration. Up and coming missions will deliver highly accurate data, offering an unprecedented insight into gravity on cosmological scales. This observational effort is not yet balanced by an equally focused effort at theoretical modeling. The ability to constrain various properties of cosmological models using observational data, such as the anisotropies of the cosmic microwave background, the large scale structure of the galaxy distribution, the expansion and acceleration rate of the universe and other such quantities, has become an essential part of modern cosmology.

The goal of the PhD project will be to unveil the real nature of the theory of gravity. To achieve this, the student will apply theoretical modeling and numerical methods to the best data available and perform forecasts for future next generation surveys.

Development of this project is required for several reasons 1) new theoretical models need to be built; 2) new numerical patches need to be developed which serve to test models against cosmological observations. The analysis tools developed by the student are expected to be used in the upcoming ESA Euclid mission in which the host institution has a leading role. In order to ensure a successful PhD, this project contains theoretical and numerical elements that are flexible such that they can fit with the student’s skills and expertise.

University: Lisboa

Galaxy evolution on the MOONS

Advisor: Cirino Pappalardo (IA U.Lisbon)

Abstract: In Astrophysics the topic of galaxy evolution has undergone a tremendous improvement in recent years, because of the substantial advancement that occurred in different scientific and technical areas. However, despite this huge improvement, we are still lacking a fundamental understanding of specific topics that prevent us from reaching a more comprehensive theory.
One such topic is the transformation of the galaxy population between the epoch of the universe where most of the stars were formed (~10 billion years ago; when the Universe had only 25% of its current age) and the more local Universe we see today.

This connection will be addressed in the next few years by the observations of thousands of galaxies using the new generation spectrograph of the European Southern Observatory (ESO) - MOONS (the Multi-object Optical and Near-IR spectrograph). This topic is of particular relevance for the Institute of Astrophysics and Space Sciences (IA) and for this reason, it participates in the development and construction of MOONS through its researchers and engineers.
MOONS is a multi-object spectrograph that will be mounted in one of the 8 meters telescopes of the VLT, in the desertic region of Atacama, at 2.600 meters of altitude in the North of Chile. MOONS will cover ~500 arcminutes square of sky, collecting simultaneously high-resolution spectra in the optical and near-infrared wavelengths range.

After years of development, the project is now at a crucial stage, where all the particulars of its design need to be fixed before the assembly of the instrument and its delivery to the VLT. The project proposed here will allow the student to participate in the validation of different methods proposed for the analysis of the MOONS spectra granting them a unique opportunity to participate in the development of a scientific instrument. Furthermore, they will also get significant insight into the physical information contained in the spectra of different populations of galaxies and witness their change with cosmic time.

University: Lisboa

Investigating Structure Formation around Massive Galaxies through a Radio-Infrared Synergy

Advisors: José Afonso (DF/FCUL & IA U.Lisbon), Hugo Messias (Joint ALMA Observatory)

Abstract: One of the greatest challenges facing observational cosmology is understanding the formation of large scale structure in the Universe. Hierarchical models for structure formation developed over the last few years, achieving the high degree of predictive success that they do, are however still unconstrained, in particular in helping to understand how the light (galaxies) traces the underlying (dark) matter and how this relation evolves over time. We will address this problem by performing a systematic study of the evolution of the densest regions of the Universe, as traced by the most massive galaxies and their environments, improving our understanding of how the most massive regions of the Universe form and evolve. This will only be possible by using data from a deep mid-infrared wide-field survey, the extended Spitzer Extragalactic Representative Volume Survey (SERVS), now including over 2700 hours of deep mid-infrared observations and capable of finally overcoming long-standing observational limitations.

University: Lisboa

The First Radio Galaxies in the Universe

Advisors: **José Afonso** (DF/FCUL & IA U.Lisbon), **Israel Matute** (IA U.Lisbon), Hugo Messias (Joint ALMA Observatory)

Abstract: Recent observations of the highest redshift quasars and radio galaxies pinpoint the early growth of supermassive black holes (SMBH) that trigger the formation of active galactic nuclei (AGNs) at redshifts greater than 7. It is anticipated that radio emission can be detected from such early AGN, although its characteristics are still quite indeterminate. The importance of such detection, however, is extremely high. It will: (a) provide us with a lighthouse that reveals the physics of the first accretion episodes to the first SMBHs in the Universe; (b) allow the direct study of the neutral gas throughout the Epoch of Reionisation itself with the next generation of radio telescopes, through the observation and study of the HI 21cm forest against such early AGN; (c) allow us to trace the early growth of Large Scale Structure in the Universe. After decades of laborious work, trying to understand the deepest radio observations, the conditions are now finally right to develop a project that can make us understand where are the "first radio galaxies" and how to find them with upcoming radio telescopes.

University: Lisboa

Type: This topic may correspond to a mixed fellowship with up to 1 year abroad.

The build-up of metals within galaxies with cosmic time

Advisors: **Jarle Brinchmann** (IA U.Porto)

Abstract: With the MUSE instrument on the VLT we are producing the deepest spectroscopic observations of the Universe with an unprecedented sensitivity and spatial resolution. In this project the student will develop a method to combine the data from MUSE with spectra from HST and in the future the Euclid satellite. With this in hand he/she will carry out the largest survey of how metals are distributed in galaxies as a function of cosmic time – constraining the physics of galaxy formation.

University: Porto

Self-consistent spectral modeling of quasars and its implication to the mass assembly history galaxies

Advisors: **Jean Michel Gomes** (IA U.Porto), Luis Vega Neme (IATE – OAC, Córdoba)

Abstract: Quasars are thought to be hosted by a supermassive black hole (SMBH) capable of producing an energy release due to matter accretion that easily outshines the whole host galaxy, leading to this featureless *quasi-stellar object* appearance the most massive and luminous galaxies in the early Universe. Over the past few years, it was discovered several quasars even at early times (redshift ~7). We propose a new spectral fitting code for fitting the UV-optical range in a self-consistent manner to be applied to quasars. This code will include a standard accretion disk model (Shakura & Sunyaev 1973) and a more realistic UV-optical model from, e.g., Kubota & Done (2018). We will tie these prescriptions together in order to energetically reproduce both the observed continuum plus emission-

lines in quasars considering internal attenuation. This new fitting code will be publicly available and additionally applied to ~500 000 quasars from the SDSS DR15. We will produce a full database catalog for the astronomical community. This is a preparatory work for the MOONS spectrograph in which IA co- leads also it will add value when the modules for fitting quasars are incorporated in the population synthesis code FADO (Gomes & Papaderos 2017).

This project provides an excellent combination of astrophysical theory with observations, and it will lead to valuable expertise on the field of spectral synthesis and AGN phenomenon. Several publications will support the future career of the student. Preferable computing languages are Fortran, Python or IDL.

University: Porto

Dark matter and metal poor stars in Ultra Faint Dwarfs

Advisors: **Jarle Brinchmann** (IA U.Porto)

Abstract: Ultra-faint dwarfs are the most dark matter dominated objects we know – in some there is 1000 times more dark matter than baryonic. They are also the faintest and lowest mass galaxies we know with the entire galaxy less bright than a single star. These facts combine to make these systems excellent places to look for dark matter and to explore the effect of stellar feedback on galaxy evolution in low mass dark matter halos. To that end I am carrying out a survey of 100hrs with MUSE on the VLT to study the make-up of these ultra-faint satellites and constrain their metal enrichment history and dark matter content. The student will be involved in both of these aspects, with a particular focus on the metal enrichment history and stellar make-up of the ultra-faint dwarfs.

University: Porto

Studying extended gas associated with distant AGN using MUSE observations of extended Lyman-alpha emission

Advisors: **Andrew Humphrey** (IA U.Porto)

Abstract: This project will use VLT MUSE observations of extended Lyman-alpha emitting gas to study the co-evolution between the interstellar medium, star formation activity and the outputs of the active nucleus itself, thereby obtaining new pieces of the jigsaw puzzle that is our understanding of the formation and evolution of galaxies. The student will process and analyze archival VLT MUSE integral field spectroscopy observations of high-redshift radio galaxies and/or quasars, and study in detail the morphological, kinematic, ionization and chemical enrichment properties of extended (>10 kpc) Lyman-alpha emitting gas halos associated with the active galaxies. Observational information will be compared with models from the literature, and the ionization and chemical enrichment properties will be modeled using state of the art ionization modeling codes. Important new information on cluster (or protocluster) environment will also be obtained.

University: Porto

Uncovering the mass assembly history of late-type galaxies in different environments with IFS data

Advisors: **Jean Michel Gomes** (IA U.Porto), **Catarina Lobo** (DFA/FCUP & IA U.Porto), Tom Scott (IA U.Porto)

Abstract: Galaxy clusters and groups are gravitationally bound structures that contain hundreds to thousands of galaxies bonded by gravity and embedded in a dense medium. They are excellent laboratories for studying the impact of the environment on the mass assembly history of their member galaxies. As such, there is abundant literature on how several processes such as ram pressure stripping, strangulation, tidal effects and merging can lead to significant changes in the secular evolution of galaxies. A combination of these mechanisms is expected to explain some of the morphological transformations of galaxies and the quenching of their star formation activity. Pinning down the dominant mechanism responsible for these evolutionary trends is one of the key-questions in extragalactic astronomy, that is likely linked to the process of in fall of galaxies into clusters occurring within the framework of the hierarchical growth of large scale structure. The cold gas medium of galaxies is expected to be tightly connected with their capacity to keep forming stars and is extremely sensitive, in small timescales, to the mechanisms mentioned above. It should thus provide indications of the relevant processes acting on galaxies located at different cluster centric radii and in the field. Recent studies that show abnormally strong and frequent cold gas interstellar medium interactions signatures in the late-type galaxies in merging clusters seem to indicate that this phase of the galactic content carries the signatures of the physical processes occurring in different environments.

This project proposes a systematic study of 2D integral field spectroscopy (IFS) from the MaNGA (Mapping Nearby Galaxies at APO) survey combined with HI and molecular gas ancillary data for a large sample of galaxies inhabiting different environments. In order to reconstruct the spatially resolved star-formation and chemical enrichment history of galaxies in distinct environments, the student will make use of the FADO population synthesis code and Porto3D post-processing IFS analysis pipeline.

This project provides an excellent combination of astrophysical theory with observations, and it will lead to valuable expertise in the field of spectral synthesis and environment of galaxies, i.e. cluster as compared to field galaxies. Several publications will support the future career of the student. Previous knowledge on one of the following computing languages is desirable: ESO-MIDAS script language, Fortran 77/2008+, C, C++, IDL or Python.

University: Porto

Citizen Science: public engagement in astronomy research and astronomy communication

Advisors: Carla Morais (UEC/FCUP), Mário João Monteiro (DFA/FCUP & IA U.Porto)

Abstract: The high scientific production in astronomy compel us to find new ways to carry out the dissemination of content, but also, of processes to approach non-specialized audiences. Thus, in addition to promoting attitudes, knowledge and public involvement with science, decision-making based on scientific criteria is favoured. In this context the citizen science project “CoAstro: @n Astronomy Condo” arose. It directly connected five astronomers, nine elementary school teachers, four science communicators and one mediator. In CoAstro, that lasted an academic year, scientific content and processes were appropriated and integrated by teachers, in initiatives involving school communities, the Porto Planetarium – Ciência Viva Center (PP-CCV) and the Instituto de Astrofísica e Ciências do Espaço (IA), directly reaching 980 people. Such astronomy communication emerged from one CoAstro´s work package where teachers were actively engaged in astronomy research, through two subprojects: “Stars” and the “Planets”. In the first, teachers analysed standard stellar spectra that allow the qualitative and quantitative composition determination of 57000 stars. Besides, they determined star luminosity using “Data Release 2” from the European Space Agency – ESA – GAIA Mission. In the “Planets project”, the team started with the production of a planetary transit video through “Python” program. Then, teachers analysed light curves to signal potential exoplanets. Framed in a qualitative research methodology, data for our study were collected through questionnaires, interviews, document analysis, and observations. Results showed gains in teachers’ substantive and procedural knowledge; a positive change in epistemological attitudes and beliefs towards astronomy; as well as the increasing of the quality of teachers’ scientific dissemination practices. For astronomers and communicators, it was found that they agree that CoAstro impacted research and astronomy dissemination and the way of structuring them. On the other hand, CoAstro also reinforced their perception about the importance and purposes of these communication practices, promoting new personal communication skills. In an overall look, CoAstro allowed us to understand how a citizen science project can contribute to a reciprocal opening between school and the surrounding community and between public and astronomy research.

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(Portuguese version in next page)

Ciência Cidadã: envolvimento do público na investigação e divulgação em astronomia
Orientadores: Carla Morais (UEC/FCUP), Mário João Monteiro (DFA/FCUP & IA U.Porto)
Resumo:
A elevada produção científica em astronomia desafia-nos a encontrar novas formas de realizar a divulgação de conteúdos, mas, também, de processos junto de audiências não especializadas. Assim, para além de se poderem promover atitudes, conhecimento e envolvimento do público com a ciência, poderá favorecer-se a tomada de decisões alicerçadas em critérios científicos. É neste contexto que surge o projeto de ciência cidadã "CoAstro: um Condomínio de Astronomi@", que colocou em interação direta cinco astrónomos, nove professores do 1.º Ciclo do Ensino Básico, quatro divulgadores e um mediador. No CoAstro e ao longo de um ano letivo, conteúdos e processos científicos foram apropriados e integrados pelos professores em iniciativas envolvendo as comunidades escolares, o Planetário do Porto – Centro Ciência Viva (PP-CCV) e o Instituto de Astrofísica e Ciências do Espaço (IA), alcançando diretamente 980 pessoas. Tal divulgação da astronomia emergiu a partir da etapa de implementação do CoAstro em que os professores foram envolvidos ativamente em práticas de investigação em astronomia, através de dois subprojetos: o "Projeto estrelas" e o "Projeto planetas". No primeiro, os professores analisaram espetros de estrelas-padrão visando determinar a composição qualitativa e quantitativa de 57000 estrelas. Para além disso, determinaram a luminosidade de estrelas usando dados do Data Release 2 da Agência Espacial Europeia – missão GAIA. No "Projeto planetas" e partindo da produção um vídeo de um trânsito planetário através do programa "Python", os professores analisaram curvas de luz, para sinalizar a existência de potenciais exoplanetas. Enquadrado numa metodologia de investigação qualitativa, no presente estudo recolheram-se dados através de questionários, entrevistas, análise documental e observações. Os resultados demonstraram ganhos de conhecimento substantivo e processual dos professores; alteração positiva de atitudes e crenças epistemológicas em relação à astronomia; bem como, incremento da qualidade das suas práticas de divulgação científica. Do lado dos astrónomos e divulgadores verificou-se que consideraram que o CoAstro teve impactos na investigação e divulgação da astronomia e na forma de as estruturar. Por outro lado, reforçou a sua perceção quanto à importância e finalidades dessas práticas de divulgação, concorrendo para o desenvolvimento pessoal de novas competências comunicacionais. De uma forma global o CoAstro permitiu, pois, perceber como um projeto de ciência cidadã pode contribuir para uma abertura recíproca entre a escola e a comunidade e entre o público e a investigação.

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Citizen science: from an investigative technique to a method of equity in access to astronomy communication and education

Advisors: (to be defined)

Abstract: The citizen science (CS) concept is now summarized in a simple common idea: the public engagement in different stages of scientific processes. If the view of CS as a scientific technique is very consensual, its use as a science communication and education (SCE) method is not. However, accomplishing science communication goals is one of the most common purposes of CS, highlighted by both scientists and CS project managers alike. Indeed, the advantages of associating science communication and science education have long been known, namely through CS projects, helping to bridge the gap between scientific research and science education. Thus, engaging teachers in CS processes is a natural path, enhanced by the "school effect" and the "teacher effect" in students, but also in the effect these have in student's families and the surrounding school community. This "multiplier effect" of influences which schools provide is unique and highly positive.

On the other hand, one of SCE's main challenges is to promote participation in science initiatives by citizens who don’t spontaneously seek to be involved. In astronomy, this is decisively related to the lack of knowledge about scientific contents and processes. In Portuguese schools, this type of public is well identified by the initiative “CVnE – Clubes Ciência Viva nas Escolas”. Among those who have to teach astronomy within those schools, primary teachers are the ones which have the biggest conceptual and procedural gaps in astronomy. Because of these gaps, in this exploratory scientific research (PeX) we will focus on key astronomy concepts and on attitudes and beliefs towards science.

It is, therefore, supported by data of our previous research and in a synergistic context between science education, science communication to non-interested audiences and scientific research in astronomy, that “CoAstro: @n Astronomy Condo” PeX emerges. In it we have as objectives: i) to structure, implement and evaluate the effects of a co-designed CS project by primary teachers (from regions with low spontaneous involvement with science), astronomers and science communicators; ii) to evaluate knowledge, attitudes and beliefs towards science, of teachers and its changes, as a result of participation in CoAstro; iii) perceive the impact of CoAstro on the dissemination of astronomy among school communities; iv) to improve a CS design for a public with low interest in astronomy and in regions far away from science centres.

As described in the previous study, although our core participants group had a maximum of 10 elements (primary teachers), it can be seen, by the above mentioned multiplier effect of influences, that participants can easily reach a number in the order of a thousand. Due to CoAstro sample size, also related to the nature of this PeX, we choose to implement a qualitative study, more specifically a case study. It will allow us to follow a small group of participants for one school year, in face-to-face and remote dynamics. To do so, we will use various data collection techniques – interview survey, questionnaire, document analysis and observations. Consequently, we will use various instruments – interview guides, field notes, questionnaires and documents produced by the participants.

The innovation of this PeX comes from:

i) attention to the impact of CS on knowledge, attitudes and beliefs of their participants;

ii) high bilateral relational interactions, due to CoAstro´s purpose of assess the possibility engaging citizens from Portuguese official language developing countries (and therefore with expected technological limitations);

iii) a CS with astronomers and non-specialist public, but also with science communicators;

iv) a mediated CS by someone close and knowledgeable about all the participants' professional contexts;

v) co-design between its participants, according to their (scientific, educational…) needs;

vi) a CS with scientific, educational and dissemination outputs.

According to our previous study we expect to find that schools are suitable environments, with efficiency and agility, to flow scientific results and also processes. So, we may prove that schools are means to reach audiences with low astronomy awareness and accomplish long-lasting astronomy dissemination effects. We also expect, for all participants, an increase in the quality of scientific education and communication practices. For teachers, changing in attitudes and beliefs towards astronomy and gains in substantive and procedural knowledge.