Astronomy & Physical Cosmology
speciality of the official
Master in Theoretical
Physics

Offers for
MSc Theses

2025/26

The following pages list possible projects for a MSc thesis. Please note that the topics are not restricted to be selected from this list. Students always have the option to contact any other potential supervisors and come up with a new project.

There will be two calls to present the MSc thesis: one in end June / early July and another one in early September. Each project involves an amount of work worth 12 ECTS, which translates into 300 hours (about 8 weeks) of full time dedication. Although it is expected to be primarily undertaken during (and after) the third trimester, students are encouraged to start as early as possible.

Supervisor: Savvas Nesseris (IFT UAM/CSIC)
Title: Cosmology and likelihood data analysis with machine learning

Description:
Current and forthcoming surveys are poised to rigorously test the standard cosmological constant and cold dark matter model (ΛCDM) and its underlying principles (e.g. homogeneity and isotropy), as well as possible extensions beyond general relativity (GR), offering unprecedented data quality and volume. In order to test these assumptions, one can perform specific consistency/null tests that require model-independent reconstructions of cosmological parameters and their estimation using minimal assumptions.

In this project, we focus on the Stage IV surveys (DESI, Euclid, SPHEREx) and the Baryon Acoustic Oscillations (BAO) data, coming from galaxy clustering.

The goals of this project are:

1. Understand and familiarize with the BAO data and the underlying theoretical framework.
2. Explore the Fisher forecast formalism and learn how to create realistic mock data based on survey specifications.
3. Use machine learning to place constraints on deviations from homogeneity and isotropy, and perform various consistency tests of the cosmological constant model.

Bibliography:
Euclid. I. Overview of the Euclid mission, arXiv: 2405.13491
Euclid preparation: VII. Forecast validation for Euclid cosmological probes, A&A 642 (2020) A191, arXiv: 1910.09273
Euclid: Forecast constraints on consistency tests of the ΛCDM model, A&A 660, A67 (2022), arXiv: 2110.11421

Requirements:
Programming skills: Python.
Recommended subjects: Advanced Cosmology, Advanced Mathematics

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Supervisor: Violeta González Pérez (UAM)
Title: Observational constraints on primordial non-Gaussianities

Description:
The origin of the initial conditions of the Universe are unknown. The structures that we observe today in the Universe grew from some initial perturbations set during a very short period of time in the early Universe. Inflation is the most plausible description of an early and short period of cosmic time experiencing the needed accelerated expansion. Many multi-field inflationary models predict non-Gaussian perturbations in the initial conditions of the Universe's density distribution, the Primordial Non-Gaussianities (PNG).
Studying the effect that PNG have on the distribution of observables at later times, is one of the few ways to disfavour different inflationary models. The level of local PNG can be quantified by the parameter f_NL. Cosmological surveys, such as DESI, are aiming to study the imprints of the epoch of inflation by measuring f_NL. These surveys are making accurate maps through cosmic history using cosmological tracers: galaxies, gas and QSOs (supermassive black holes actively accreting gas and stars).
With this project we will explore how the particular geometry of DESI can affect the measurement of f_NL. This will contribute to one of the critical tasks from the DESI topical group exploring PNG. In particular, we will study the implementation of the angular and radial integral constrain, and the wide angle expansion for the power spectrum window function. The student will make use of 1000 model catalogues available at NERSC for the DESI collaboration.
This project will require to code and to deal with large quantities of data in different formats ("data mining"). The project will also require learning to work in remote environments.

Bibliography:
DESI DR2: https://arxiv.org/abs/2503.14738
f_NL estimations from DESI data:
https://arxiv.org/pdf/2411.17623 N-body simulations with PNG:
https://arxiv.org/pdf/2312.12405

Requirements:
Programming skills: at least one programming course completed
Recommended subjects: Advanced Cosmology, Computational astrophysics

Contact information: violeta.gonzalez@uam, Mod 8, despacho 314 (UAM).
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Supervisor: Miguel Icaza and Violeta González Pérez (UAM)
Title: Machine Learning to produce catalogues of model galaxies

Description:
Cosmological surveys are producing 3D maps of the Universe to gain insights into how matter is distributed and shaped by cosmic evolution (e.g. DESI DR2). To interpret such data, cosmologists often use catalogues of model galaxies generated from large dark matter simulations (e.g. VGP+2020). Observations are covering such large volumes that is computationally prohibitive to use complex models for galaxies. Nowadays, for cosmological studies, galaxies are typically added to dark matter simulations using fast approximations like Halo Occupation Distribution (HOD) models (e.g. Reyes-Peraza+2024).
HOD models populate dark matter halos with galaxies based on simple prescriptions tied to halo properties. While they can reproduce key statistical properties, they may introduce biases because galaxies are assigned to halos using simplified statistical rules rather than physically motivated formation histories. This lack of realism could affect the inferred galaxy–halo connection and potentially distort the interpretation of survey data (e.g. Avila,VGP+2020).
In this project, the student will test several HOD models of varying complexity by comparing them to a mock catalogue generated using a physically motivated neural network (Icaza-Lizaola+2024). The student will generate catalogues of model galaxies using existing HOD codes designed at UAM (https://github.com/computationalAstroUAM/hod_madrid_py). They will fit their parameters to match the reference catalogue, and evaluate potential biases. A neural-network surrogate could also be developed to accelerate the fitting process, offering an accessible introduction to machine learning. This project will require to code and to deal with large quantities of data in different formats ("data mining"). The project will also require learning to work in remote machines and machine learning techniques.

Bibliography:
DESI DR2: https://arxiv.org/abs/2503.14738
VGP+2020: https://arxiv.org/abs/2001.06560
Reyes-Peraza+2024:
https://arxiv.org/abs/2312.13199
Avila,VGP+2020: https://arxiv.org/abs/2007.09012
Icaza-Lizaola+2024:
https://arxiv.org/abs/2311.10823

Requirements:
Programming skills: at least one programming course completed
Recommended subjects: Advanced Cosmology, Computational astrophysics

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Supervisors: Yago Ascasibar (UAM), Pablo Corcho Caballero (RUG)
Title: Star formation in galaxies

Description:
Identifying the main physical mechanism(s) that regulate the conversion of gas into stars is one of the main open problems in extragalactic astrophysics. From a theoretical point of view, different processes (internal to the galaxy, as well as arising from the interaction with nearby objects) acting on different time scales (from millions to billions of years) are predicted to leave distinctive imprints on the star formation and chemical evolution history. From an observer's perspective, this information is encoded in the spectral energy distribution, and different statistical techniques may be applied in order to reconstruct a galaxy's past from the available measurements.

In this work, we will combine multi-wavelength observations for a sample of galaxies with different mass, star formation activity, environment, and dynamical state. Depending on the interests of the student, we will focus on the reduction and/or analysis of these data, the recovery of physical properties (in particular, the star formation rate on different time scales), the identification of systematic trends and scaling relations between local and global properties, or the development of self-consistent chemical evolution models.

Bibliography:
https://arxiv.org/abs/2503.15315
https://arxiv.org/abs/2212.03981
https://github.com/paranoya/population-synthesis-tool
kit

Requirements:
Programming skills: Basic/intermediate Python and data analysis, depending on the project focus.
Recommended subjects: Formation & Evolution of Galaxies

Contact information: yago.ascaribar@uam.es
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Supervisors: Yago Ascasibar (UAM), M. Rocamora (U. Innsbruck), M. Wechakama (U. Kasetsart)
Title: The origin of cosmic rays

Description:
Cosmic rays are relativistic particles that propagate through the interstellar and intergalactic medium. While hadrons (protons, antiprotons, and light nuclei) are relatively well understood, the origin of leptons (in particular positrons, both at the central regions of the Milky Way and the Solar neighbourhood) is still a mystery. The favoured candidates are supernova remnants, pulsars, and potentially the annihilation or decay of dark matter particles.

After being introduced to the fundamentals of astroparticle physics, the students will use different numerical codes to model the production and propagation of cosmic rays throughout the Galaxy, as well as the predicted emission at different frequencies. By comparing the results with state-of-the-art observations in the radio, microwave, and/or gamma-ray regime, we will attempt to constrain the main sources of cosmic rays and the relevant propagation parameters (e.g. gas density, radiation and magnetic fields).

Bibliography:
https://arxiv.org/abs/2403.03303
https://github.com/cosmicrays/DRAGON2-Beta_versi
on https://github.com/cosmicrays/hermes

Requirements:
Programming skills: Install and run DRAGON and HERMES, basic data analysis.
Recommended subjects: Astroparticle Physics

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Supervisor: Yago Ascasibar (UAM)
Title: Cosmic Microwave Background in a finite universe

Description:
As the precision of different tracers of cosmic expansion -most notably, the Cosmic Microwave Background (CMB) radiation, the scale of the Baryon Acoustic Oscillations (BAO), and the Hubble-Lemaître diagram of Type Ia supernovae- has improved beyond a few per cent, several tensions have emerged between the low- and high-redshift probes under the assumption of a spatially flat LCDM cosmology. If all the observational tracers turned out to be correctly calibrated, their results would imply that the so-called standard cosmological model may not be the ultimate description of our universe.

Here we will consider an alternative scenario where three-dimensional space is a finite hypersphere of radius R(t). Our previous results show that this geometry is perfectly compatible with all the available measurements. After acquiring a minimum theoretical background and learning about the main probes of the composition and expansion history of the universe, the student will focus on the evolution of matter and energy in the proposed cosmology and study the main properties of the CMB to test its viability.

Bibliography:
https://arxiv.org/abs/1911.02087
https://wiki.cosmos.esa.int/planck-legacy-archive/index.php/Cosmological_Parameters

Requirements:
Programming skills: Python
Recommended subjects: Advanced Cosmology

Contact information: yago.ascaribar@uam.es
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Supervisor: Daniel Ceverino (UAM)
Title: Proto-clusters of galaxies in the early Universe

Description:

Galaxy clusters with hundreds or thousands of galaxies are the biggest objects of the Universe. Its formation is one of the key challenges in modern cosmology. Cosmological simulations of galaxies can help to clarify this puzzle. This work uses the database of the "The Three Hundred" project to identify and characterize proto-clusters and its constituent galaxies. The student will use algorithms of data mining to extract scientifically useful information for developing a model of formation and evolution of protoclusters.

Bibliography:
https://www.nottingham.ac.uk/astronomy/The300/index.php
https://arxiv.org/pdf/2202.14038

Requirements:
Programming skills: Python, C or fortran
Recommended subjects: Formation and Evolution of Galaxies

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Supervisor: Daniel Ceverino (UAM)
Title: Synthetic images from cosmological simulations of first galaxies

Description:

The new James Webb Space Telescope (JWST), the successor of the Hubble Space Telescope, is revolutionizing our understanding of the first galaxies that formed in the early Universe. This is one of the main objectives of this telescope.
The goal of this project is the understanding of the role of dust attenuation in synthetic images of first galaxies that can be compared directly with JWST observations. From a large set of existing images from the FirstLight database, the student will compare images with and without attenuation and study its effect in the galaxy morphology.
Tentative observations suggest that dust attenuation is less severe in small, faint galaxies and it increases in more massive galaxies with higher gas (and dust) column densities. Due to the large sample of galaxies with different masses, the student will be able to test different models of dust attenuation and address the importance of dust as a function of galaxy mass and redshift.
The student will use the FirstLight database, a large number of cosmological simulations of first galaxies (N-body + hydro).

Bibliography:
https://jwst.nasa.gov/content/science/firstLight.html
http://odin.ft.uam.es/FirstLight/index.html

Requirements:
Programming skills: Python, C or fortran
Recommended subjects: Formation and Evolution of Galaxies

Contact information: daniel.ceverino@uam.es
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Supervisor: Weiguang Cui (UAM)
Title: co-rotation between baryons and dark matter -- a theoretical study

Description:

Galaxies, especially disk galaxies, are rotating/spinning, and so are the dark matter halos and the diffuse halo gas, in which they are living. As galaxies are currently the most reliable objects for peculiar velocity measurement, investigating and understanding these questions is critical for us to know our largely invisible Universe:

1. Which baryon property is the best tracer of the halo rotation?
2. Where is the boundary of halo rotation if there is a boundary? And does that correlate with other radii, such as r200c, r200m or backsplash radius?
3. What is the connection between halo rotation and the filaments?
   The student will receive training on how to use the available hydrodynamic simulations, write scripts for analysing the data, and how to scientifically answer these questions.

Bibliography:
https://www.nottingham.ac.uk/astronomy/The300/index.php
https://arxiv.org/pdf/2202.14038 and more reference papers can be found at: https://www.zotero.org/groups/5374752/halo_rotation

Requirements:
Programming skills: Python, C or C++
Recommended subjects: Formation and Evolution of Galaxies

Contact information: weiguang.cui@uam.es, Office: Module 8, sala 315.

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Supervisor: Pedro de la Torre and Miguel A. Sánchez Conde (UAM and IFT UAM-CSIC)
Title: The role of heavy elements in the production of gamma-rays and neutrinos in the Galaxy

Description:
While NASA's Fermi-LAT experiment has enabled precise characterization of the diffuse gamma-ray sky at GeV energies, these emissions remain poorly understood at TeV–PeV energies. Recent observations from the Chinese LHAASO experiment have, for the first time, provided accurate measurements of diffuse Galactic gamma-ray emission in this higher energy range, revealing fluxes significantly higher than previously expected. Similarly, IceCube has achieved the first measurement of neutrino emission along the Galactic plane, again detecting fluxes that exceed earlier predictions.

As a result, precise evaluations of diffuse neutrino and gamma-ray emissions are now a key focus. These emissions arise from interactions between cosmic rays and interstellar gas, but the composition, spatial distribution, and energy spectrum of the cosmic rays involved remain highly uncertain.

Here, we aim to improve the modeling of neutrino and gamma-ray production by cosmic rays, with a particular focus on quantifying the contribution of heavy nuclei. We will use the latest measurements of cosmic ray spectra to model their flux across different regions of the Galaxy. Using these inputs, we will compute the resulting neutrino and gamma-ray emissions and assess the associated uncertainties by comparing several state-of-the-art interaction cross-section models.

This TFM will be carried out within the boundaries of the DArk Matter, AStroparticles and COsmology (DAMASCO) group at the UAM Theoretical Physics Department and the Institute for Theoretical Physics (IFT UAM-CSIC). DAMASCO's current main research interests include the indirect search for dark matter, with special care to gamma rays; the analysis of numerical cosmological simulations, mainly to shed light on the smallest scales; high-energy neutrino astrophysics; cosmic-ray astrophysics; multi-messenger astronomy. DAMASCO belongs to the Fermi-LAT, CTAO and DESI international collaborations. The group has also a numerous and excellent network of collaborations with (local, national, international) experts in astroparticle physics and cosmology. Further info about the team and research activities: https://projects.ift.uam-csic.es/damasco/

Bibliography:
LHAASO collab. Physical Review Letters 134, 081002 (2025). ArXiv:2411.16021
IceCube Collab. Science 380, 6652, 1338-1343 (2023). ArXiv:2307.04427
De la Torre Luque et al (2025), ArXiv:2502.18268
LHAASO collab. (2025), ArXiv:2505.14447

Requirements (recommendations):
Programming skills: Basic/intermediate level, preferably Python or C++.
Recommended subjects: Astroparticles, Cosmology.

Contact information: pedro.delatorre@uam.es

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Supervisor: Gwendolyn Meeus (UAM, gwendolyn.meeus@uam.es)
Title: Properties of exoplanet hosts

Description: To date, more than 6000 planets have been detected around mainly main sequence stars. But the first detections around young, pre-main sequence stars have recently been made. With such a huge amount of detections, it is now possible to study the properties of the exoplanets, and their relation with the properties of their host stars. Do they form more often around more massive or less massive stars? What is the influence of a companion on the formation of a planet? In order to be able to answer such questions, we will also look into the properties of protoplanetary discs around young stars, in which planets are expected to be formed. We will compare the properties of these discs with what we see in main sequence stars where exoplanets have been detected.

This TFM will make use of observational data, found in the literature or databases, and basic Python scripts to analyse the data.

Requirements (recommendations):
Programming skills: Basic Python.
Recommended subjects:Técnicas Observacionales de Astrofísica.
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Supervisor: Gwendolyn Meeus (UAM, gwendolyn.meeus@uam.es)
Title: Exocomets in young stars: link with disc properties?

Description:

A circumstellar disc around a star is a natural byproduct of the star-forming process. It is in this disc, made out of interstellar gas and dust, that planets will eventually form. By studying the evolution of those protoplanetary discs (PPD), a lot can be learned about the planet-forming process. In this TFM, we will study the PPD around young intermediate mass stars (2-8 solar masses), the Herbigs and the IMTTS. We will look into their disc geometry and search for clues indicating the presence of a planet. In particular, we will look into red-shifted variable absorption features in their spectra, indicative of infalling material, attributed to exocomets. We will relate the presence/absence of exocomets with other properties of the star and/or disc, such as stellar temperature, metallicity, accretion rate and location of the inner rim. This TFM will make use of observational data, found in the literature or databases, and basic Python scripts to analyse the data.

Requirements (recommendations):
Programming skills: Basic Python.
Recommended subjects:Técnicas Observacionales de Astrofísica.
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Supervisor: Gwendolyn Meeus (UAM, gwendolyn.meeus@uam.es)
Title: The properties and environments of massive young Herbig Be stars

Description: Stars form from a cloud of dust and gas, and are initially still surrounded by that material. They also often form in a cluster, and often have a gravitationally-bound companion. Herbig Be stars are intermediate-mass stars of spectral type B, that are often still very young (less than 1 Myr), and therefore still are surrounded by the maternal cloud. In this TFM, we will study their properties at a range of wavelengths, based on data available from archives, and also look for the presence of a companion, based on new high spatial resolution data. Once the companions have been identified, we will look for correlations with other stellar properties, in order to better understand the formation process of these rather massive stars. This TFM will make use of observational data, or material found in the literature or databases, as well as basic Python scripts to analyse the data.

Requirements (recommendations):
Programming skills: Basic Python.
Recommended subjects:Técnicas Observacionales de Astrofísica.
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Supervisor: Francisco Najarro, Lee Patrick (Centro de Astrobiología; CAB)
Title: Variability of the most massive stars in the Centre of the Galaxy

Description:
Massive stars shape their surrounding environments via intense stellar winds throughout their lives and as they explode as supernovae at the end of their lives, which provides chemical and energetic feedback for future generations of stars. Luminous blue variable (LBV) stars represent a transitional phase in the life cycle of massive stars, which experience large eruptions from their atmospheres expelling large amounts of material in short bursts, and are thought to be progenitors to some of the most energetic supernova explosions known. LBVs are so rare that only a handful are known in the Milky Way and despite their importance, much remains unknown about their evolution. Using observational data from the K-band Multi-Object Spectrograph on Very Large Telescope (KMOS/VLT), Chile, the student will study the three LBVs in massive star clusters and assess how the spectroscopic appearance of LBVs vary over time. The binary nature of the LBVs will be investigated and the consequences of the variability of lack thereof will be put into context in the overall evolutionary cycle of massive stars.

This project will be conducted within the Massive star group at the
CAB https://auditore.cab.inta-csic.es/masivas-torrejon/

Bibliography:
Clark et al. 2023 https://arxiv.org/abs/2302.04008
Clark et al. 2018 https://arxiv.org/abs/1805.10139
Najarro et al. 2012 https://link.springer.com/chapter/10.1007/978-1-4614-2275-4_4

Press release on LBVs and Yellow Hypergiants:
https://universemagazine.com/en/rho-cassiopeiae-and-its-relatives-mystery-of-yellow-hypergiant-o u tbursts/

Requirements:
Programming skills: Good communication skills, Basic python and data
analysis Recommended subjects: Something to do with stars

Contact information: najarro@cab.inta-csic.es lrpatrick@cab.inta-csic.es
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Supervisor: Lee Patrick (Centro de Astrobiología; CAB)
Title: Multiplicity properties of the BAF-type supergiant stars from BLOeM

Description:
Massive stars shape their surrounding environments via intense stellar winds throughout their lives and as they explode as supernovae at the end of their lives, which provides chemical and energetic feedback for future generations of stars. Blue and yellow supergiants are some of the brightest and most luminous stars in any given star-forming galaxy but their origins and evolution are not understood. Central to the confusion over their histories is that in Local Group galaxies, the observed number of these stars far exceeds the predicted number by theory. We now know that the majority of massive stars are born within binary or higher-order multiple systems and how these stars interact with their companions is key to determining how they end their lives. Therefore, the multiplicity properties hold vital clues to better understand their origin and evolution. As part of The Binarity at LOw Metallicity (BLOeM) campaign in the Small Magellanic Cloud, this project will use the latest data release to study 128 B5--F5 supergiant stars in the Small Magellanic Cloud. The BLOeM observing campaign on the Very Large Telescope, Chile is near completion. This project will build upon earlier results, using a much smaller observing time, to assess the variability and multiplicity properties of this vitally important population.

This project will be conducted within the Massive star group at the CAB (https://auditore.cab.inta-csic.es/masivas-torrejon/)

Bibliography:
Patrick et al. 2025, https://arxiv.org/abs/2502.02644
Shenar et al. 2024, https://arxiv.org/abs/2407.14593
Sana et al. 2025 https://www.nature.com/articles/s41550-025-02610-x
Press release from Sana et al.:
https://phys.org/news/2025-09-massive-stars-metal-poor-environment.html

Requirements:
Programming skills: Good communication skills, Basic python and data analysis Recommended subjects: Something to do with stars

Contact information: lrpatrick@cab.inta-csic.es
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Supervisor: Lee Patrick, Jesús Maíz Apellániz (Centro de Astrobiología)
Title: Photometric variability of red supergiant stars in the Magellanic Clouds

Description:
Red supergiant stars (RSGs) are the final evolutionary stage of the majority of massive stars before a supernova explosion. When a massive star stops burning hydrogen into helium in its core, the star drastically expands its outer envelope and appears as an RSG. Despite their importance for understanding the diversity of observed supernovae, the physics of the atmospheres of RSGs is incomplete, which has implications for our understanding of how much mass massive stars lose throughout their lives and ultimately what the final supernova explosion looks like. Studies of the physics of RSGs have previously focused on individual systems and a complete picture of how variable the atmospheres of RSGs is lacking.

New results from the latest Gaia data release (DR3; June 2022) allows the study of stellar variability in different evolutionary phases for entire populations of stars in the Magellanic Clouds: two of our nearest neighbour galaxies. In this project the student will study the variability of RSGs in the Magellanic Clouds using a new catalogue of variability based on Gaia DR3. Global trends will be studied and a relationship between evolutionary phase and variability will be developed. The student will analyse this large dataset and use this to place in context the recently observed Great Dimming of Betelgeuse.

Bibliography:
Maíz Apellániz et al. 2023 https://arxiv.org/abs/2304.14249
Chiavassa et al. 2011 https://arxiv.org/abs/1109.3619
c. f. The great dimming of Betelgeuse e.g. :
https://science.nasa.gov/missions/hubble/hubble-sees-red-supergiant-star-betelgeuse-slowly-r e cov ering-after-blowing-its-top/

Movies on RSG atmospheres:
https://www.oca.eu/en/andrea-chiavassa/1525-andrea-chiavassa-research

Requirements:
Programming skills: Good communication skills, Basic python and data analysis Recommended subjects: Something to do with stars

Contact information: lrpatrick@cab.inta-csic.es jmaiz@cab.inta-csic.es

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Supervisor: Lee Patrick, Miriam Garcia (Centro de Astrobiología; CAB)
Title: Bi-modal metallicity distribution of the IC 1613 galaxy

Description:
IC 1613 is a low-metallicity dwarf irregular galaxy with a controversial metal abundance. Recent studies using Blue Supergiant stars suggest that this galaxy contains an intriguing, bimodal metallicity distribution. By determining metallicities of ~40 Red Supergiant Stars (RSGs), using the well tested J-band analysis technique, the student will independently estimate the metallicity distribution of IC 1613 and examine the hypothesis of bimodality.
Spectroscopic observations using the K-band Multi-Object spectrograph on the Very Large Telescope have been obtained. The student will reduce and analyse these data, using a well defined reduction recipe. Using a grid of stellar models the student will determine the effective temperature, metallicity and surface gravity of each star and study the metallicity distribution of IC1613.

This project will be conducted within the Massive star group at the CAB (https://auditore.cab.inta-csic.es/masivas-torrejon/)

Bibliography:
Berger at al. 2018 https://arxiv.org/abs/1805.07352 Patrick et al. 2017 https://arxiv.org/abs/1702.06966 Garcia et al. 2009 https://arxiv.org/abs/0904.4455

Requirements:
Programming skills: Good communication skills, Basic python and data analysis Recommended subjects: Something to do with stars

Contact information: lrpatrick@cab.inta-csic.es mgg@cab.inta-csic.es
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Supervisor: Hough, Tomás (UAM)

Title: Galaxy formation and evolution: study of feedback mechanisms and environmental effects with simulations of different resolutions.

Description

Galaxy formation and evolution models rely on free parameters that regulate the impact of astrophysical processes on galaxy properties. In high density environments, external effects like ram-pressure stripping and tidal interactions often regulate star-formation activity. However, internal processes or even the merger history that a galaxy experiences can also play a role on the properties of galaxies located inside galaxy clusters.

In this project, the student will calibrate the free parameters of a semi-analytic model of galaxy formation, and investigate the properties of the galaxy populations using different resolutions.

The student will learn how to calibrate a semi-analytic model, understand how astrophysical processes (ram-pressure stripping, supernova feedback, galaxy mergers) are modeled, and analyze the outputs. The project also allows flexibility: the student may choose which galaxy properties to focus on, and which analysis techniques will be applied (from usual data analysis to machine learning techniques).

Bibliography:

Hough et al. (2023) https://ui.adsabs.harvard.edu/abs/2023MNRAS.518.2398H/abstract

Gomez et al. (2025) https://ui.adsabs.harvard.edu/abs/2025A%26A...697A.171G/abstract

Programming skills: python.

Recommended courses: Galaxy formation and evolution and Cosmology.

Contact information: tomashough@gmail.com

Supervisor: Frank Tramper, Lee Patrick (Centro de

Astrobiología; CAB)

Title: The physical properties of extremely low-metallicity red supergiants

Description:
Massive stars have played a key role in galaxy evolution throughout cosmological time, and understanding the evolution of the early generations of massive stars is therefore key in mapping the evolution of the Universe. While it is impossible to study individual stars in high-redshift galaxies, nearby low-metallicity dwarf galaxies provide environments with conditions that are similar to those in the early Universe, and have resolved stellar populations. This allows for the testing of stellar evolution models for the early generations of massive stars. In this project, the student will study the properties of red supergiant stars (RSGs) in the extremely low-metallicity galaxy Sextans A, using integral field spectroscopy obtained with the MUSE instrument on the Very Large Telescope in Chile. RSGs are key indicators of stellar metal content, particularly in low-metallicity environments, and are the direct progenitors of the most common type of core-collapse supernova.. The main aim is to determine the luminosity and temperature of these stars (i.e. to place them in the Hertzsprung-Russell diagram), and compare these to the theoretical predictions. Additionally, abundances of iron and other elements will be determined.

This project will be conducted within the Massive star group at the
CAB https://auditore.cab.inta-csic.es/masivas-torrejon/

Bibliography:
Britavskiy et al. 2019
https://arxiv.org/abs/1909.13378 Bonanos et al.
2024 https://arxiv.org/abs/2312.04626

Requirements:
Programming skills: basic python and data analysis
Recommended subjects: stellar physics/evolution

Contact information: ftramper@cab.inta-csic.es, lrpatrick@cab.inta-csic.es

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Supervisor: Asunción Fuente (CAB)

Title: Search for complex organics in massive disks

Description: Amino acids, compounds essential for life, have been detected in meteorites such as Murchison, but their study in space has been limited due to the difficulty of detecting them in their solid phase and the extreme conditions necessary for their release into the gas phase. Recently, the Hayabusa2 and OSIRIS-REx space missions have brought refractory material directly from space, revealing a complex chemical composition with the presence of all the amino acids essential for life, as well as compounds with refractory elements such as sulphur (S) and phosphorus (P), key elements in biochemistry. The objective of this project is to search for organic species containing O, N, and S in protoplanetary discs using ALMA data already obtained by the research group. The detailed work plan is as follows:

1.-The student will acquire knowledge of interferometry and image synthesis using specialised codes for the visualisation and analysis of interferometric data, CARTA and CASA. Using the group's data, they will extract the spectra in the sample discs.

2.- The student will learn to use molecular line catalogues (CDMS, JPL) and the XCLASS code, which allows them to simulate spectra based on specific physical conditions and abundances. These tools will be used to identify the lines in the spectra obtained in point (1) to search for complex molecules with O, N, and S.

3.- Maps of the identified lines will be made and artificial intelligence tools (chemical emulators) will be used to explore the formation and destruction processes of the detected molecules.

Programming skills: python.

Contact information: afuente@cab.inta-csic.es

Supervisor: Miguel A. Sánchez Conde (UAM and IFT UAM-CSIC)
Title: The search of WIMP dark matter with gamma rays

Description:
The nature of the dark matter (DM) in the Universe is one of the greatest mysteries of our time, and its quest of utmost relevance for the whole scientific community. This DM has not been directly detected, yet its gravitational effects have been observed at all astrophysical scales. Among the preferred DM candidates, the so-called weakly interacting massive particles (WIMPs) are, undoubtedly, the ones most intensely searched for. Different yet complementary approaches for their detection are possible. Among them, indirect detection techniques aim at detecting WIMP annihilation/decay products, such as gamma rays, neutrinos or antimatter [1,2].

In this TFM, the student will first model the DM distribution within a promising, DM-dominated astrophysical target (e.g., dwarf galaxy, galaxy cluster…) adopting results from numerical cosmological simulations (and observations whenever possible). This DM modelling will be used to compute predicted WIMP-induced gamma-ray signals at Earth with the CLUMPY software [3]. Then, an analysis of actual gamma-ray data collected by the NASA Fermi satellite will be performed to look for such signatures. Alternatively, simulation data from the Science Data Challenge of the upcoming Cherenkov Telescope Array Observatory (CTAO) may also be analyzed with this same goal. Should no signals be found, the student will set limits on the properties of the WIMP [4,5].

This TFM will be carried out within the boundaries of the DArk Matter, AStroparticles and COsmology (DAMASCO) group at the UAM Theoretical Physics Department and the Institute for Theoretical Physics (IFT UAM-CSIC). DAMASCO's current main research interests include the indirect search for dark matter, with special care to gamma rays; the analysis of numerical cosmological simulations, mainly to shed light on the smallest scales; high-energy neutrino astrophysics; cosmic-ray astrophysics; multi-messenger astronomy. DAMASCO belongs to the Fermi-LAT, CTAO and DESI international collaborations. The group has also a numerous and excellent network of collaborations with (local, national, international) experts in astroparticle physics and cosmology. Further info about the team and research activities: https://projects.ift.uam-csic.es/damasco/

Bibliography:
1. G. Bertone, D. Hooper & J. Silk, Physics Reports 405 (2005) 279–390 [arXiv:0404175]
2. G. Bertone, D. Hooper, Reviews Modern Physics 90 (2018) 045002 [arXiv:1605.04909]
3. M. Hütten et al., CPC 235 (2019) 336 [arXiv:1806.08639]
4. E. Charles, M. Sánchez-Conde, et al., Physics Reports, 636 (2016) 1[arXiv:1605.02016]
5. M. Doro, M. Sánchez-Conde, et al, Adv. in VHE Astrophysics (2022) [arXiv:2111.01198]

Requirements (recommendations):
Programming skills: Basic/intermediate level, preferably Python.
Recommended subjects: Astroparticles, Cosmology.

Contact
information: miguel.sanchezconde@uam.es

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Supervisor: Miguel A. Sánchez Conde (UAM and IFT UAM-CSIC)

Title: The impact of DESI on the search of dark matter-induced signals in dwarf galaxies

Description:
The nature of the dark matter (DM) in the Universe is one of the greatest mysteries of our time, and its quest of utmost relevance for the whole scientific community. This DM has not been directly detected, yet its gravitational effects have been observed at all astrophysical scales. Among the preferred DM candidates, the so-called weakly interacting massive particles (WIMPs) are, undoubtedly, the ones most intensely searched for. Different yet complementary approaches for their detection are possible. Among them, indirect detection techniques aim at detecting WIMP annihilation/decay products, such as gamma rays, neutrinos or antimatter [1,2].

In this TFM, the student will investigate the capabilities of the Dark Energy Spectroscopic Instrument (DESI) [3] to improve our knowledge of the DM distribution in Milky Way satellite dwarf galaxies and, in turn, its impact for current and future gamma-ray DM searches (dwarf galaxies are considered to be the best DM targets [4,5]). Specifically, the student will study how different possible configurations of both the number and distribution of stars about to be observed by DESI in such objects, impacts the inference of the underlying DM potential and, thus, of the induced gamma-ray flux. The result –an optimized DESI observing strategy for these objects in the context of DM searches— will be then used to set more competitive and robust constraints on WIMP DM. For the latter, predicted gamma-ray DM signals for the studied dwarfs will be computed with the CLUMPY software [6].

This TFM will be carried out within the boundaries of the DArk Matter, AStroparticles and COsmology (DAMASCO) group at the UAM Theoretical Physics Department and the Institute for Theoretical Physics (IFT UAM-CSIC). DAMASCO's current main research interests include the indirect search for dark matter, with special care to gamma rays; the analysis of numerical cosmological simulations, mainly to shed light on the smallest scales; high-energy neutrino astrophysics; cosmic-ray astrophysics; multi-messenger astronomy. DAMASCO belongs to the Fermi-LAT, CTAO and DESI international collaborations. The group has also a numerous and excellent network of collaborations with (local, national, international) experts in astroparticle physics and cosmology. Further info about the team and research activities: https://projects.ift.uam-csic.es/damasco/

Bibliography:

1. G. Bertone, D. Hooper & J. Silk, Physics Reports 405 (2005) 279–390 [arXiv:0404175]
2. G. Bertone, D. Hooper, Reviews Modern Physics 90 (2018) 045002 [arXiv:1605.04909]
3. A. Aghamousa et al., (2016) [arXiv:1611.00036]
4. E. Charles, M. Sánchez-Conde, et al., Physics Reports, 636 (2016) 1[arXiv:1605.02016]
5. M. Doro, M. Sánchez-Conde, et al, Adv. in VHE Astrophysics (2022) [arXiv:2111.01198]
6. M. Hütten et al., CPC 235 (2019) 336 [arXiv:1806.08639]

Requirements (recommendations):
Programming skills: Basic/intermediate level, preferably Python.
Recommended subjects: Astroparticles, Cosmology.

Contact
information: miguel.sanchezconde@uam.es

Supervisor: ~~Miguel A. Sánchez-Conde (UAM and IFT-UAM-CSIC) and Sergio Hernández-~~Cadena (SJTU, China)
Title: The contribution of Dark Matter to the diffuse emission induced by electrons in galaxy clusters

Description:

Galaxy clusters represent the larger gravitationally bounded objects in the Universe with almost 85% of their content in the form of Dark Matter (DM) [1]. Observations in radio and X-rays also point to the existence of a relics and halos as result of the acceleration and propagation of electrons in the Intra Cluster Medium (ICM) [2]. However, the size of the observed emission should require additional injection sources to overcome the short cooling times of electrons. While DM has been extensively searched trough gamma-ray signals induced by annihilation or decay [3], other channels can lead to the production of electrons and positrons and constitute an additional source of electrons injected in the ICM.

In this TFM, the student will investigate the role and contribution of DM as a source of electrons and positrons in galaxy clusters, and estimate the resultant emission after propagation and diffusion of such electrons in the ICM. To that end, the student will investigate about the large-scale properties of galaxy clusters such as magnetic field, temperature, numerical density of particles in the ICM, and DM and total mass distributions [4]. Then, using state-of-the-art results from numerical tables [5], the rate of electrons injected into the ICM through the annihilation and decay of DM particles will be estimated. CRPropa [6] will be used to estimate the induced emission by the propagation and diffusion of electrons in the ICM, and obtain the expected surface brightness maps of a sample of nearby galaxy clusters to compare with current observations.

This TFM will be carried out within the boundaries of the DArk Matter, AStroparticles and COsmology (DAMASCO) group at the UAM Theoretical Physics Department and the Institute for Theoretical Physics (IFT UAM-CSIC). DAMASCO's current main research interests include the indirect search for dark matter, with special care to gamma rays; the analysis of numerical cosmological simulations, mainly to shed light on the smallest scales; high-energy neutrino astrophysics; cosmic-ray astrophysics; multi-messenger astronomy. DAMASCO belongs to the Fermi-LAT, CTAO and DESI international collaborations. The group has also a numerous and excellent network of collaborations with (local, national, international) experts in astroparticle physics and cosmology. Further info about the team and research activities: https://projects.ift.uam-csic.es/damasco/

Bibliography:

[1] The Planck Collaboration; A&A 594, A13 (2016). [https://doi.org/10.1051/0004-6361/201525830]
[2] R. J. Van Weeren et al; Space Sci Rev 215, 16 (2019).
[3] J. L. Feng., Annual Reviews, Vol 48 (2010).
[4] F. Governato et al; MNRAS, 307, 949
[5] C. Arina et al, CosmiXs: [https://arxiv.org/abs/2312.01153]
[6] R. A. Batista et al;; JCAP09 (2022) 035.

Requirements (recommendations):
Programming skills: Basic/intermediate level, preferably Python.
Recommended subjects: Astroparticles.

Contact information: miguel.sanchezconde@uam.es

Supervisor: Isabel Rebollido Vázquez (ESA, Madrid), María Luiza Linhares Dantas (U. Católica, Chile)

Title: The properties of free floating planets

Description:

The definition of planets is linked to their gravitational bound to a star (or several), but recent discoveries have found a number of substellar objects compatible with planetary mass free-floating in the interstellar medium. These "free-floating planets" (FFP) or "isolated planetary mass objects" (IPMO) are expected to be ejected from their birth place through gravitational interactions, but to still originate in protoplanetary disks. Current studies are extremely preliminary due to the lack of data. These objects are faint and hard to disentangle from background sources, but recent innovative techniques and facilities have been able to identify hundreds of candidates yet to be confirmed.

We propose here a master project to gather the current known information about both candidates and confirmed FFP, perform an exploratory analysis of their properties with the available data and prepare a program to explore future Roman Space Telescope results on this field.

Bibliography:

- Zapatero Osorio, M. R. (6 October 2000). "Discovery of Young, Isolated Planetary Mass Objects in the σ Orionis Star Cluster". *Science*. **290** (5489): 103–7
- Pearson, Samuel G.; McCaughrean, Mark J. (2 October 2023). "Jupiter Mass Binary Objects in the Trapezium Cluster". p. 24. arXiv:2310.01231

Requirements (recommendations):

Programming skills: Basic/intermediate level, preferably Python. High proficiency in reading/writing english

Recommended subjects: Exoplanets, planet formation.

Contact information: Isabel.rebollidovazquez@esa.int

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Supervisors: Markus Kissler-Patig (ESA/ESAC & LMU Munich), Siyi Xu (NOIRLab, Tucson); Amy Bonsor (University of Cambridge)

Title: Searching for Exotic Transits around Planet-Hosting Stars

Description:

Planet formation is a dynamic and often violent process. In our own solar system, the giant impact that formed the Moon generated a cloud of dust that persisted for about a hundred years. Similar spectacular collisions have also been detected in extrasolar systems — for example, the event around ASASSN-21qj, which is likely caused by the collision of two ice giants. However, such spectacular events are rare and not yet well studied - your task will be to systematically search for more events in relevant state-of-the-art databases.

This project will use time-series photometric data from the Zwicky Transient Facility (ZTF), the Asteroid Terrestrial-impact Last Alert System (ATLAS), and the All-Sky Automated Survey for Supernovae (ASAS-SN) to carry out a systematic search for exotic transits around planet-hosting stars. The results will provide new insights into one of the most dramatic phases of planet formation.

The TFM is offered at the European Space Astronomy Centre (ESAC) of the European Space Agency (ESA) in Villafranca del Castillo. You are expected to spend about a day per week at ESAC, giving you the unique opportunity opportunity to interact with international Master and PhD students as well as postdocs and to peak into ESA's activities on its science missions.

Bibliography:

A planetary collision afterglow and transit of the resultant debris cloud: https://www.nature.com/articles/s41586-023-06573-9

Oxygen isotope identity of the Earth and Moon with implications for the formation of the Moon and source of volatiles: https://www.pnas.org/doi/10.1073/pnas.2321070121

Requirements:

Programming skills: Intermediate level, preferably Python.
Recommended subjects: Observational Techniques in Astrophysics (TOA), Stellar Structure and Evolution (EEE)
High proficiency in reading/writing english
Availability to come to ESAC (Villafranca del Castillo) a day per week (or every two weeks)

Contact information: Markus Kissler-Patig, mkissler@esa.int

Supervisor: Amélie Godard Palluet (Centro de Astrobiologia, CAB)

Project title: Collisional excitation of the $HCCS^+$ ion by H_2 for astrophysical applications

Description:

Astrochemistry investigates the chemical composition and processes occurring in astrophysical media. To date, over 330 molecules have been detected in space [1]. A central question in this field is how these molecules form. The $HCCS^+$ ion is thought to play an important role in sulfur chemistry, which remains poorly understood in the interstellar medium (ISM) [2].

To study the chemistry of such molecules, their accurate abundances should be determined. These are typically derived from the analysis of molecular spectra obtained by telescopes. However, this analysis often relies on the Local Thermodynamic Equilibrium (LTE) approximation, which is known to be inaccurate for most astrophysical environments, including TMC-1, where $HCCS^+$ was recently detected for the first time [3].

To overcome this approximation and accurately derive $HCCS^+$ abundances, the collisional rate coefficients of $HCCS^+$ with H_2 (the most abundant species in the ISM) must be calculated. This is done by (1) computing the electronic interaction between $HCCS^+$ and H_2 using quantum chemistry methods, and (2) performing scattering calculations using quantum methods to simulate the collision between the two species. Once obtained, these data will enable the first accurate determination of $HCCS^+$ abundance in the ISM, advancing our understanding of sulfur chemistry and its evolution in space.

The main task of the hired student will be to perform scattering calculations to determine $HCCS^+$-H_2 collisional rate coefficients. The results obtained during this work will be published in a peer-reviewed journal. He/she will participate in weekly meetings within the Chemical complexity in the ISM and star formation group at CAB [4], and will have the opportunity for daily interactions with theoretical chemists, astronomers and software engineers.

[1] https://www.astrochymist.org/
[2] Ruffle et al., MNRAS 306, 691 (1999)
[3] Cabezas et al. A&A 657 L4 (2022).
[4] https://sites.google.com/view/cab-ccismsf-group/home

Requirements (recommendation):

Programming skills: Intermediate level, preferably in Fortran
Language: English

Recommended subjects: Observational Techniques in Astrophysics (TOA), Stellar Structure and Evolution (EEE)

Contact information: amelie.godard@cab.inta-csic.es