Astronomy & Physical Cosmology

speciality of the official Master in Theoretical Physics

Universidad Autónoma de Madrid

Offers for MSc Theses 2026/27

(05/10/2026 UPDATE)

Rich protoclusters at (sub-)mm wavelengths through cosmic time

Supervisor(s): Itziar Aretxaga (CAB, CSIC_INTA, ESAC Campus) & Gustavo Yepes (UAM) gustavo.yepes@uam.es

Abstract: Galaxy clusters are massive ($M \gtrsim 10^{14}\ M_\odot$), rare, gravitationally bound systems and represent the most massive virialized structures in the present day Universe. Proto-clusters trace the early stages of cluster assembly and provide key insight into how massive structures form. They have been identified up to redshifts z ~ 6–8 (e.g. Hashimoto et al. 2023) and often show enhanced star formation activity compared to the field (Overzier 2016). Studying proto-clusters is therefore essential to understand how galaxy clusters assemble their mass and how galaxy populations evolve in dense environments. Their evolution can be traced in N-body simulations, while finding these structures observationally is still a challenge.

We will expand on the 100 square degree GARDENS-Wise mock redshift survey methodology (Nava-Moreno et al. 2024, 2026) to trace the protocluster evolution of the most massive clusters (Cui et al. 2018) contained in the MultiDark-Planck 2 dark-matter halo simulation (Kyplin et al. 2016). We will analyze the contribution of the optically-selected star-forming and dust-obscured star-forming galaxies (DSFGs) to the protocluster structures and their Large-Scale Structure morphologies from z=10 to 0. We will derive predictions for the foreseen observational surveys with current and future single-dish facilities such as the existing TolTEC camera on the 50m Large Millimeter Telescope and the ESO Expanding Horizons proposed 50m AtLAST.

References:

1. Cui W, Knebe A., Yepes G. et al. 2018, MNRAS, 480, 2898
2. Hashimoto T., et al., 2023, ApJL, 955, L2
3. Klypin A., Yepes G., Gottlöber S., et al. 2016, MNRAS, 457, 4340
4. Nava-Moreno N. A., Montaña A., Aretxaga I. et al. 2024, MNRAS, 531, 4900
5. Nava-Moreno N.A., Montaña A., Aretxaga I. et al. 2026, MNRAS, submitted
6. Overzier R. A., 2016, A&ARv, 24, 14

Recommended subjects:

Advanced Cosmology, Computational Astrophysics

Robust cosmology from Machine Learning the Universe

Supervisor(s): Supervisors: Santiago Ávila (CIEMAT), Violeta González Pérez (UAM) violeta.gonzalez@uam.es

Abstract:
Cosmology is living a golden era thanks to galaxy surveys such as Euclid or DESI. The Large-Scale Structure of the Universe (LSS) contains a wealth of information capable of pinning down the correct cosmological model with high precision. However, standard methods only rely on 2-point statistics (distances among pairs of galaxies), leaving out the majority of information.
The SimBIG collaboration uses artificial intelligence to learn the full likelihood of the whole distribution of galaxies in the Universe and infer the cosmological model. However, it relies on certain assumptions of galaxy formation and its relation to the dark matter distribution. The goal of this project is to test the reliability of the SimBIG approach when more complicated (and realistic) galaxy formation scenarios are in place. The student will run the SimBIG cosmological inference on simulated galaxy catalogues from the UNITsim project (led by UAM, http://www.unitsims.org/), based on semi-analytical models of galaxy formation. The student will have the chance to work with the international networks of UNITsim and SimBIG.
References:
SimBIG collaboration: https://arxiv.org/abs/arXiv:2310.15246
Recommended subjects:
Advance cosmology, Computational Astrophysics, Galaxy formation and Evolution

Machine Learning catalogues of model galaxies for the Euclid satellite

Supervisor(s): Miguel Icaza y Violeta González Pérez (UAM) violeta.gonzalez@uam.es

Abstract:
Euclid is a ESA mission taking millions of spectra of galaxies. This will allow the survey to produce a very detailed 3D map of the Universe to learn about its components and evolution.

Euclid is targeting galaxies with strong spectral emission lines. In this project we will study how to produce galaxy catalogues for Euclid, based on machine learning algorithms (Icaza-Lizaola+2024). We will train these algorithms on catalogues of model galaxies produced with different complexities (VGP+2020).

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. The student will get involved with the Euclid international collaboration.

References:
Euclid: https://arxiv.org/abs/2405.13495
VGP+2020: https://arxiv.org/abs/2001.06560
Icaza-Lizaola+2024: https://arxiv.org/abs/2311.10823

Recommended subjects:
Advance cosmology, Computational Astrophysics, Galaxy formation

Evolution of galaxies with strong spectral emission lines as cosmological tracers.

Supervisor(s): Violeta González Pérez (UAM) violeta.gonzalez@uam.es and Ginevra Favole (IAC)

Abstract:

Galaxies with strong spectral emission lines are being traget by cosmological surveys such as Euclid and DESI, to study the nature of dark energy.

At UAM we have developed a code to model spectral emission lines ((https://github.com/galform/get_nebular_emission)). In this project we aim to include evolution to the properties of the ionising regions, responsible of producing emission lines.

This new model for spectral lines will be applied to the Multidark catalogues of galaxies to explore the sptial distribution of emission-line galaxies. In particular, we will start by focusing on the clustering, bias and halo occupation distribution of the SDSS Main DR7 emission-line galaxies at redshift 0.02<z<0.2, as a function of their luminosity for the Halpha spectral line. Using the SDSS MPA-JHU DR7 spectral information, we build five volume-limited samples in the full sample. We will compare observational data to models of galaxy formation and evolution, Multidark, run together with an spectral line model.

This project will require to code and to deal with large quantities of data in different formats ("data mining"). The second part of this project will also require learning to work in remote machines.

References:

ELGs in SDSS: https://doi.org/10.1051/0004-6361/202346443
Multidark: https://ui.adsabs.harvard.edu/abs/2018MNRAS.474.5206K/abstract

Recommended subjects:

Advance cosmology, Computational Astrophysics, Galaxy formation

Understanding QSOs in a cosmological context

Supervisor(s): Violeta González Pérez violeta.gonzalez@uam.es y Miguel Icaza-Lizaola(UAM)

Abstract:

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). QSOs are one of the objects being observed by spectrocopical cosmological surveys. These are very bright objects, visible when the Universe had half its current age and beyond. QSOs are super-massive black holes actively accreting mass.

To interpret 3D maps of the Universe, 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. 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 fit several HOD models to catalogues of model galaxies produced with with complex galaxy models (Shark and Galform) using a code developed at UAM (https://github.com/computationalAstroUAM/HODfit2sim). The student will also 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.

With machine learning algorithms (Icaza-Lizaola+2024) we will also explore how relevant for the production of catalogues of model QSOs is "baryonification" (Contreras+2026). This term is usually used to refer to the changes induced in dark matter haloes by the presence of gas, stars and black holes within them.

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.

References:

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
Contreras+2026: https://arxiv.org/abs/2604.24837

Recommended subjects:

Advance cosmology, Computational Astrophysics, Galaxy Formation

Rotating Black Hole in the Galactic Center

Supervisor: Ivan De Martino (Universidad de Salamanca), Riccardo Della Monica (CENTRA, Lisboa)

Abstract: The Galactic Center (GC) of the Milky Way, thanks to its proximity, allows for performing astronomical observations that investigate physical phenomena at the edge of astrophysics and fundamental physics. As such, it offers a unique laboratory to probe gravity, where one can not only test the basic predictions of general relativity (GR), but is also able to falsify theories that, over time, have been proposed to modify or extend GR; to test different paradigms of dark matter; and to place constraints on putative models that have been formulated as alternatives to the standard black hole paradigm in GR.

In recent years, we developed a new computational tool, PyGRO, with the aim of numerically integrating the geodesic equations for the trajectories of massive and massless test particles in any analytic four-dimensional space-time. The result of our work is a fast, modern, highly customizable, and user-friendly open-source Python package that can perform numerical integration of the geodesic equations. Combining symbolic and numerical calculations, PyGRO offers a variety of methods to obtain fully relativistic orbits with minimal intervention by the user, and it is able to work in full generality with any user-given symbolic expression of the space-time metric tensor.

The project aims to extend and apply PyGRO to the future observations of the orbital motion of S-Stars in the Galactic centre to forecast the precision down to which a Kerr-like Black Hole can be constrained by the data.

References:

W. Schmidt, Class. Quant. Grav. 19 (2002), 2743
M. van de Meent and A. G. Shah, Phys. Rev. D 92 (2015) no.6, 064025
Della Monica, R., 2025. Astronomy and Astrophysics 698. doi:10.1051/0004-6361/202554300
de Mora Losada, V., Della Monica, R., de Martino, I., et al.\ 2025, \aap, 694, A280. doi:10.1051/0004-6361/202452814
Della Monica, R. \& de Martino, I.\ 2025, arXiv:2501.03912. doi:10.48550/arXiv.2501.03912
De Martino, I., Della Monica, R., \& Rubiera-Garcia, D.\ 2024, \prd, 109, 2, 024016. doi:10.1103/PhysRevD.109.024016
De Martino, I., Della Monica, R., \& Rubiera-Garcia, D.\ 2023, \prd, 108, 12, 124054. doi:10.1103/PhysRevD.108.124054
Della Monica, R. \& de Martino, I.\ 2023, \prd, 108, 10, L101303. doi:10.1103/PhysRevD.108.L101303
De Laurentis, M., de Martino, I., \& Della Monica, R \ 2023, Reports on Progress in Physics, 86, 10, 104901. doi:10.1088/1361-6633/ace91b
Della Monica, R., De Martino, I., \& De Laurentis, M.\ 2023, \mnras, 524, 3, 3782. doi:10.1093/mnras/stad2125
Fern{\'a}ndez Fern{\'a}ndez, R., Della Monica, R., \& de Martino, I.\ 2023, \jcap 2023, 8, 039. doi:10.1088/1475-7516/2023/08/039

Comparing synthetic images from simulations of first galaxies with observations from the James Webb Space Telescope.

Supervisor(s): Daniel Ceverino (UAM).

Abstract: The launch of the James Webb Space Telescope (JWST) in 2023 started a new golden era in extragalactic astrophysics and we can now witness the formation of the first galaxies in the early Universe. This is one of the main objectives of this telescope.

The goal of this project is the use of synthetic images from the FirstLight simulations to compare directly with JWST observations. From a large set of existing images from the FirstLight database, the student will study the effect of the dust attenuation, inclination effects and other interesting questions.
The FirstLight database is a large number of cosmological simulations of first galaxies (N-body + hydro).

Requirements: Good programming skills in any of the following languages: Fortran, C, Python

References:

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

Recommended subjects:

1. Formation and evolution of galaxies

Synchrotron emission to unveil the origin of the Galactic Center Excess

Supervisor(s): Pedro de la Torre (pedro.delatorre@uam.es) and Jordan Koechler

Abstract:

The nature of dark matter (DM) remains one of the biggest mysteries in physics today. One of the most intriguing possible signatures of DM is the excess of GeV gamma rays observed toward the Galactic Center by the Fermi-LAT experiment. The origin of this so-called Galactic Center Excess (GCE) is still intensely debated within the astroparticle community. While DM annihilation provides an appealing explanation, an alternative possibility is that the excess originates from a population of unresolved millisecond pulsars (MSPs).

The objective of this project is to investigate whether radio observations can help distinguish between these two scenarios. Both DM annihilation and MSPs can produce energetic electrons and positrons in the Galactic Center, which subsequently generate synchrotron emission through their interaction with the Galactic magnetic field.

The student will model the electron and positron populations expected in the two scenarios and calculate the resulting synchrotron emission in the Galactic Center. The project will investigate whether the spatial and spectral properties of the predicted synchrotron signal are sufficiently different to distinguish between the DM and MSP interpretations, taking into account uncertainties in the Galactic magnetic-field configuration and astrophysical backgrounds. If time allows, the project can be extended to polarized synchrotron emission, investigating whether the polarization properties provide an additional way to distinguish between the two scenarios.

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/

Recommended subjects:

- Mandatory courses for the specialty "Elementary Particles and Cosmology" (PEC)
- Astroparticle Physics
- Computational Astrophysics
- Open Problems of the Standard Model

References:

- Koechler, De la Torre Luque & Di Mauro (2026), arXiv:2605.26220
- Murgia (2020), arXiv:2001.08516
- Manconi, Calore & Donato (2024), arXiv:2402.04733
- Amerio, Hooper & Linden (2025), arXiv:2412.05220
- Di Mauro (2026), arXiv:2605.22913

The impact of DESI on the search of dark matter-induced signals in dwarf galaxies
Supervisor: Miguel A. Sánchez Conde (UAM and IFT UAM-CSIC)

Description:
The nature of the dark matter (DM) in the Universe is one of the greatest mysteries of our time, and thus its quest of utmost relevance. 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 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

The role of dark matter halo substructure in gamma-ray dark matter searches

Supervisor: Miguel A. Sánchez Conde (UAM and IFT UAM-CSIC) & Alejandra Aguirre-Santaella (Instituto de Astrofísica de Canarias)

Description:

Dark matter (DM) halo substructure represents a natural expectation of the way structure formation works within the standard CDM cosmological model: small structures or *halos* collapse and form first and then, by accretion and merging, larger structures come to existence. In this bottom-up formation scenario, halo substructures, or *subhalos*, are predicted to be largely abundant within larger halos, for instance galaxies like ours. It is nowadays evident that this halo substructure is called to play a critical role for DM searches, namely those that look for gamma-ray photons generated from the decay or annihilation of DM particles such as WIMPs [1,2].

In this TFM, the student will make use of recent results from the Auriga hydrodynamical cosmological simulations [3] to quantify the so-called *subhalo boost factor* [4], i.e., enhancement of DM-induced gamma-ray signals due to the existence of halo substructure, with a focus on Milky-Way sized galaxies. Not only an accumulated subhalo boost will be computed, but also its radial and redshift dependence will be characterized in detail. This work is expected to have a very significant impact on current and future strategies aimed at discovering DM signals in gamma-ray, neutrino and cosmic-ray observatories [5,6].

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. S. Porras et al., PDU 52 (2026) 102262 [arXiv:2601.11452]
4. A. Moliné et al., MNRAS 466 (2017) 4974 [arXiv:1603.04057]
5. E. Charles, M. Sánchez-Conde, et al., Physics Reports, 636 (2016) 1[arXiv:1605.02016]
6. 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

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

Description:
The nature of the dark matter (DM) in the Universe is one of the greatest mysteries of our time, and thus its quest of utmost relevance. 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 get familiarized with the group analysis pipeline used to search for DM-induced signatures in actual gamma-ray data collected by the NASA Fermi satellite. Then, an optimized analysis will be performed for a promising, DM-dominated astrophysical target (e.g., dwarf galaxy, galaxy cluster…) to be identified during the completion of the work. The DM modelling will adopt results from numerical cosmological simulations (and observations whenever possible). Alternatively, if time permits and subject to the student's own interests, the DM modelling needed to compute predicted WIMP-induced gamma-ray signals at Earth could be done more accurately with the CLUMPY software [3]. Finally, 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. E. Charles, M. Sánchez-Conde, et al., Physics Reports, 636 (2016) 1[arXiv:1605.02016]
4. M. Doro, M. Sánchez-Conde, et al, Adv. in VHE Astrophysics (2022) [arXiv:2111.01198]
5. 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

Properties of exoplanet hosts

Supervisor(s): Gwendolyn Meeus (gwendolyn.meeus@uam.es)

Abstract: To date, more than 7000 planets have been detected around mainly main sequence stars. With such a huge amount of detections, it is now possible to study various properties of the exoplanets, and their relation with the presence of a stellar companion on the formation of a planet. But around young, pre-main sequence stars, only recently the first 2 detections have been made. In order to be able to answer questions about planetary formations, we will also look into the properties of protoplanetary discs around young stars, discs in which planets are expected to be formed. We will compare the properties of these discs with what observations of main sequence stars where exoplanets have been detected.

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

Requirements: Programming skills: Basic Python.

References: https://exoplanet.eu/catalog/

Recommended subjects: Formation of stars and planets

Exoplanets around Lambda Boo stars

Supervisor(s): Gwendolyn Meeus (gwendolyn.meeus@uam.es)

Abstract: To date, more than 7000 planets have been detected around mainly main sequence stars, while around young, pre-main sequence stars, so far only 2 detections have been made, even though they host the protoplanetary discs, in which planets are expected to form. However, there are indirect indications that these young stars have a planet in their protoplanetary disc (for instance, a gap in their disc). Often, such stars with a gap in the disc have accreted metal-poor material, as witnessed by the composition of their stellar atmosphere. On the other hand, there are Main Sequence stars that show a similar metal underabundance, the lambda Bootis stars. Is it possible that these are the succursors of the protoplanetary gapped discs, and hence, are stars where exoplanets can be found more easily?

In order to be able to answer such questions, we will first look into the properties of the metal-poor lambda Boo stars, to see if they still have a remnant disc or other distinguishing features through a study of archival data. Next, we will look into the properties of protoplanetary discs around young stars, with indirect signatures of forming planets. 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 archival databases, and Python scripts to analyse the data.

Requirements: Programming skills: Basic Python.

References: Banzatti et al. 2018, A&A 609, L2; Murphy et al. 2020 MNRAS 449, 2701

Recommended subjects: Formation of stars and planets

Using backsplash galaxies to infer cluster sizes with machine-learning techniques.

Supervisors: Tomás Hough (UAM), Roan Haggar (Waterloo University, Canada)

Abstract: Backsplash galaxies — objects that have already passed through a cluster's core and are now moving back outward — trace the same dynamical transition that defines the splashback radius. This radius is a more physically motivated alternative to the conventional R200c or R200m boundaries, since it marks the true separation between virialized and infalling material, and it is observable through galaxies rather than dark matter alone. In this project, the student will use simulated galaxy clusters from *The Three Hundred* Collaboration to reconstruct the orbital histories of member and former-member of massive galaxy clusters. The student will train and apply machine-learning classifiers to identify backsplash galaxies from observationally accessible properties, such as projected clustercentric distance, line-of-sight velocity, stellar mass and other baryonic properties. Finally, this classified population will be used to derive a "backsplash radius," compared against R200c, R200m and existing particle-based splashback-radius measurements, to obtain a more physically grounded characterization of cluster size, mass, and the distribution of visible and dark matter.

References:

- Diemer, B., & Kravtsov, A. V. 2014, ApJ, 789, 1
- Cui, W., et al. 2018, MNRAS, 480, 2898 (The Three Hundred project overview)
- Haggar, R., Gray, M. E., Pearce, F. R., Knebe, A., Cui, W., Mostoghiu, R., & Yepes, G. 2020, MNRAS, 492, 6074

Requirements: python programming

Recommended subjects: Cosmology, Galaxy formation and evolution.

Contact: tomas.hough@uam.es // tomashough@gmail.com

Tracking the runners: Red supergiant runaway stars with Gaia DR4

Supervisor(s): Lee R. Patrick (Centro de Astrobiología (CAB), Torrejón de Ardoz)

Abstract:

Runaway stars are stars with a complex history that have been kicked-out of a binary system after a supernova explosion or kicked out of a cluster after interacting with other stars. Red supergiant stars are massive stars right at the end of their lives. These stars explode in core-collapse supernovae that redistributes the material that they have processed throughout their lives to pollute their surrounding environment and trigger the next generation of star formation. Because of their importance to the subsequent generations of star formation, understanding where massive stars die and where they came from are vital statistics for galaxy evolution models and galaxy energy budgets and as red supergiant stars are at the end of their lives, they are the perfect tracers of runaway statistics.

This project will study the recently discovered population of red supergiant runaway stars in the Large Magellanic Cloud (LMC) galaxy. The LMC is one of the nearest neighbour galaxies to our own Milky Way and acts as an excellent laboratory to study both galactic dynamics and massive stars. Using Gaia DR4 this project will either focus on (depending on your preference):

- Tracing the red supergiant runaway stars to their birth sites and explosion sites via detailed dynamical forward and backward modelling
- Determining the runaway fractions of evolved and unevolved massive stars to enable an accurate quantitative comparison between evolutionary stages on a galaxy-wide sample

The candidate will assess the impact of runaway stars on the shaping and heating of the interstellar medium of the LMC and the wider inter-galactic medium.

This research project will be conducted within the Massive Star research group at the Centro de Astrobiologia de Madrid and within the wider international collaboration our group has established on runaway stars.

References:

1. Carretero-Castrillo et al. 2026, *“An observational study of rotation and binarity of Galactic O-type runaway stars”*, A&A, 705, A215
2. Stoop et al. 2024 *“Two waves of massive stars running away from the young cluster R136”*, *Nature*, 634, 8035, 809
3. Portegies Zwart et al. 2025 “Origin of the Most Recently Ejected OB Runaway Star from the R136 Cluster”, *Physical Review Letters*, vol. 135, no. 2

Recommended subjects:

Formation of stars and planets

Search for refractory species and organics in massive disks

Supervisor(s): Asunción Fuente (Centro de Astrobiología) and Álvaro Sánchez-Monge (Instituto de Ciencias del Espacio)

Abstract: Amino acids, compounds essential for life, have been detected in meteorites such as Murchison, but research into them in space has been limited du their release into the gaseous phase. Recently, the Hayabusa2 and OSIRIS-REx space missions have made it possible to bring refractory material directly from space, revealing a complex chemical composition that includes all the amino acids essential for life, as well as compounds containing sulphur (S) and phosphorus (P), key elements in biochemistry. Although the detection of these compounds in the interstellar medium remains a challenge, the high angular resolution of the ALMA interferometer has enabled the identification of refractory molecules such as NaCl and KCl in nine protoplanetary discs around young massive stellar objects (‘salty discs’) [1] [2]. One of our group’s key projects aims to search for new refractory species and complex organic molecules of prebiotic interest in these discs. As part of this project, we have detected CaS for the first time, and tentatively detected KS, KSH and FeS in the G351-mm1 and Orion Src I discs [3] [4]. The aim of this Master’s thesis is to extend the search to new refractory and organic species, as well as to determine the spatial distribution of the detected molecules.

References:

[1] Ginsburg, A., McGuire, B., Plambeck, R., Bally, J., Goddi, C., and Wright, M., “*Orion SrcI’s Disk Is Salty*”, 2019, ApJ, 872, 54

[2] Ginsburg, A., A., McGuire, B. A., Sanhueza, P., et al. “*Salt-bearing Disk Candidates around High-mass Young Stellar Objects*”, 2023, ApJ, 942, 66

[3] Tasa-Chaveli, A., Sánchez-Monge, Á., Fuente, A., et al. “*A Quest for Sulfur-bearing Refractory Species: Identification of CaS in the Interstellar Medium*”, 2025, ApJL, 2025, 993, no. 2, L42

[4] Tasa-Chaveli, A., Sánchez-Monge, Á., Fuente, A., et al. “*Tentative Detection of FeS toward Orion SrcI*”, 2026, ApJ, in press.

Recommended subjects:

Star formation

Contact: afuente@cab.inta-csic.es

Star formation in galaxies

Supervisor(s): Yago Ascasibar (UAM), Pablo Corcho-Caballero (RUG).

Abstract:

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), statistical analysis of large galaxy samples, or the development of self-consistent chemical evolution models.

References:

1. https://arxiv.org/abs/2503.15315
2. https://arxiv.org/abs/2503.15314
3. https://arxiv.org/abs/2212.03981
4. https://arxiv.org/abs/2604.05532
5. https://github.com/paranoya/population-synthesis-toolkit

Recommended subjects:

1. Formation and Evolution of Galaxies

Contact: yago.ascasibar@uam.es

The internal dynamics of open clusters: clues in the longevity of the oldest systems

Supervisor: Ricardo Carrera(UAM/INAF-OAPd)

Abstract:

Open clusters (OCs) are fundamental building blocks of the Galactic disc, comprising from hundreds to tens of thousands of gravitationally bound stars. Because their stars share the same age, distance, and initial chemical composition, OCs have traditionally been key laboratories for understanding stellar structure and nucleosynthesis. However, they are also powerful probes of "near-field cosmology" and Galactic archaeology. As they orbit the Milky Way, OCs are subjected to the Galactic tidal field, interacting with giant molecular clouds, spiral arms, and potentially dark matter subhalos.

While most OCs dissolve relatively quickly, this disruption is far from being merely the end of their lifecycle; it is suspected to be a fundamental mechanism driving the formation and growth of stellar populations in the discs of late-type galaxies. The exact extent to which cluster dissolution contributes to the continuous assembly of the Galactic disc remains a major open question in galaxy evolution. On the other hand, a fraction of these systems manages to survive for billions of years, defying their expected fate.

By studying a large sample of clusters across a wide range of ages and evolutionary stages, this project investigates the intricate balance between internal stellar dynamics and external Galactic forces. We will characterize the detailed dynamical state of these clusters by combining the unprecedented astrometry of the *Gaia* mission with precise radial velocities from major next-generation spectroscopic surveys (e.g., GES, WEAVE, 4MOST, APOGEE).

Using advanced machine learning tools and statistical data analysis, we will map their internal kinematics to isolate the primary stabilizing and disruptive factors. Crucially, we will explore the role of their initial mass, density, and the retention of stellar-mass black hole populations—an aspect of high relevance for gravitational wave astrophysics. Ultimately, this project connects the birth and dissolution of stellar clusters to the macroscopic growth of galaxies, using them as luminous tracers of the Milky Way's gravitational potential and evolutionary history.

References:

- Alvarez-Baena *et al.* 2024 “The longevity of the oldest open clusters. Structural parameters of NGC 188, NGC 2420, NGC 2425, NGC 2682, NGC 6791, and NGC 6819” A&A, 687, A101
- Carrera et al. 2019 “Extended halo of NGC 2682 (M67) from Gaia DR2” A&A, 627, A 119

Recommended subjects:

Stellar Structure and Evolution

Contact: ricardo.carrera@uam.es

Understanding massive stars at previous cosmic times

Supervisor(s): Miriam García (Centro de Astrobiología -CAB-, sede Torrejón), Frank Tramper (CAB), Jesús Gómez Mantecón (CAB)

Abstract:

The first stars of the Universe, formed from metal-free gas, could have been extremely massive. Their radiation field and SN explosion would fundamentally impact the primitive intergalactic medium, hence setting the conditions for the formation and early-evolution of the first galaxies. The initial mass function and physical properties of the metal-free first stars is an open field in Astrophysics, tackled from different fronts that range from simulations to looking for signatures of their SN explosion in ancient Milky Way stars.

Our team's approach to this problem is studying massive stars in nearby galaxies with 1/7-1/20 Zsun, constrain their physical properties, understand their behaviour as metallicity decreases, and ultimately re-construct the physics of the first stars.

In this TFM we will focus on the Local Group galaxy IC1613, interesting because current 8-10m telescopes could constrain CNO abundances and yield insight on the evolution of their interiors for the first time.

The student will reduce and analyse recent deep spectroscopic observations in this galaxy, taken with GTC-OSIRIS-MOS in 2026. Then, she/he will then progress into the study of these objects as much as time permits, with possible venues of work including spectral classification with tools developed by the our, analysis with advanced model atmosphere codes to constrain basic stellar parameters, abundances, and study of the stars in the context of the models of stellar evolution. Ideally, this work will be published in a scientific journal.

References:

Garcia et al. 2014, ApJ, 788, 64
Garcia et al. 2019, BAAS, 51, 545
Garcia et al. 2019, MNRAS, 484, 422
Lorenzo et al. 2022, MNRAS, 516416

About the team:

Contact: mgg at cab.inta-csic.es
https://auditore.cab.inta-csic.es/masivas-torrejon/

Recommended subjects:

Stellar Astrophysics
Fluent programming in any language

Linking the ice and gas chemistry in massive young stellar objects

Supervisor(s): Asunción Fuente (Centro de Astrobiología, CSIC-INTA, Torrejón de Ardoz, Spain) and Ángele Taillard (Univ Toulouse, CNES, CNRS, IRAP, Toulouse, France)

Abstract:

Sulfur is one of the most abundant elements in the Universe and plays a fundamental role in biological systems, where it is an essential component of amino acids and proteins. However, the observed gas-phase abundances in star-forming regions account for only a small fraction of its cosmic abundance. Comparisons with sulfur abundances measured in comets suggest that a substantial fraction of sulfur may be locked in the solid phase, within interstellar ices.

It was hoped that the launch of JWST would help solve the mystery of the missing sulfur; however, observations to date have only detected OCS and placed upper limits on other major sulfur-bearing species, such as SO2 and H2S, and only in a handful of regions. We have obtained deep radio observations with the 40 m Yebes telescope towards two massive young stellar objects that have also been observed in the near-infrared. These infrared observations provide detailed constraints on the composition of their icy mantles, offering a unique opportunity to directly compare the sulfur inventory in the solid and gas phases.

Our goal is to investigate the interplay between the solid and gas phases to eventually understand the formation of S-bearins species and large organics. As a first step, we should identify the gaseous species detected in our ultra-sensitive Yebes 40m surveys, compare their abundances with those measured in the ices, and use astrochemical modelling to determine which physical conditions and chemical mechanisms control the formation of molecules in the ice and their release to the gas phase. The Yebes 40 m surveys provide access to a rich inventory of complex organic molecules and carbon-chain species, enabling us to investigate the broader chemical connection between sulfur chemistry and molecular complexity in massive star-forming regions.

References:

1. McClure, M. K., “An Ice Age JWST inventory of dense molecular cloud ices”, Nature Astronomy, vol. 7, pp. 431–443, 2023. doi:10.1038/s41550-022-01875-w.
2. Taillard, A., “Predicting the detectability of sulphur-bearing molecules in the solid phase with simulated spectra of JWST instruments”, Astronomy and Astrophysics vol. 694, Art. no. A263, EDP, 2025. doi:10.1051/0004-6361/202452900.
3. Navarro-Almaida, D., Taillard, A., Fuente, A., Caselli, P., Martín-Doménech, R., and Miranzo-Pastor, J. J., “Fine-tuning the complex organic molecule formation: Sulfur and CO ice as regulators of surface chemistry”, Astronomy and Astrophysics vol. 701, Art. no. A131, EDP, 2025. doi:10.1051/0004-6361/202554678.
4. Moral-Almansa, L., “Chemical study of two starless cores in the B213/L1495 filament”, Astronomy and Astrophysics, vol. 706, Art. no. A272, EDP, 2026. doi:10.1051/0004-6361/202556867.

Recommended subjects:

Star formation

Contact: afuente@cab.inta-csic.es

Variability of the most massive stars in the Centre of the Galaxy

Supervisor: Francisco Najarro (Centro de Astrobiología; CAB), Lee Patrick (CAB)

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/

Requirements:
Programming skills: Good communication skills, Basic python and data analysis
Recommended subjects: Stellar structure and evolution

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

Resolving the physical properties of high-redshift galaxies with JWST

Supervisors: Mahmoud Hamed (CAB) & Javier Álvarez-Márquez (CAB)

Description:
JWST allows us to resolve the internal structure of galaxies at z > 4, on scales where individual star-forming regions, clumps, bulges and discs can be distinguished. Mapping how stellar mass, star formation rate, age, dust and metallicity vary within a galaxy shows where and when it built up its stars and how it is evolving. This requires modelling the spectral energy distribution (SED) with stellar population synthesis models, an approach limited by degeneracies between age, dust and metallicity, and, in integrated fits, by outshining, where young, bright regions hide older stellar populations.

In this project, the student will study the resolved properties of one or a few galaxies at z > 4 with deep JWST observations (NIRCam and, depending on the target, MIRI imaging). The student will build spatially resolved maps of stellar mass, star formation rate, age and dust attenuation by fitting the SED, and compare them with the integrated properties. Depending on the student's interests, the project can be extended to reconstruct resolved star formation histories under different modelling assumptions.

The MSc thesis will be carried out within the Extragalactic group at the Centro de Astrobiología (CAB, CSIC-INTA), where the student will gain hands-on experience with state-of-the-art JWST data and analysis tools. The scientific focus and target can be adapted to the student's interests.

Requirements:

- Programming skills in Python, familiarity with a Unix/Linux environment (command line, bash) and basic data analysis
- Good level of English
- Recommended subjects: galaxy formation and evolution

Bibliography:

- Álvarez-Márquez et al. 2024, arXiv:2412.12826
- Boquien et al. 2019, arXiv:1811.03094
- Carnall et al. 2019, arXiv:1811.03635
- Hamed et al. 2026, arXiv:2606.31312
- Pacifici et al. 2023, arXiv:2212.01915

Contact: mhamed@cab.inta-csic.es

Axion cooling of neutron stars

Supervisors: Marina Cermeno (UPM) marina.cermeno@upm.es y David Cerdeño davidg.cerdeno@gmail.com (IFT CSIC)

Description: Neutron stars (NSs) are among the most compact objects in the Universe, making them excellent laboratories for studying matter at densities unattainable on Earth. Following the supernova explosion that gives birth to a neutron star, the star cools primarily through neutrino emission from its interior. Neutrinos are produced through processes such as Direct Urca and Modified Urca reactions, as well as nucleon-nucleon bremsstrahlung. At later times, typically beyond $\sim 10^5$ years, photon emission from the stellar surface becomes the dominant cooling mechanism. Axions are hypothetical elementary particles that were originally introduced to solve the strong CP problem in QCD, but they may also play a significant role in cosmology and stellar physics. Axions and axion-like particles (ALPs) might be produced in stellar interiors and provide an additional channel for energy loss. In this project, we investigate how axions may modify the cooling of neutron stars.