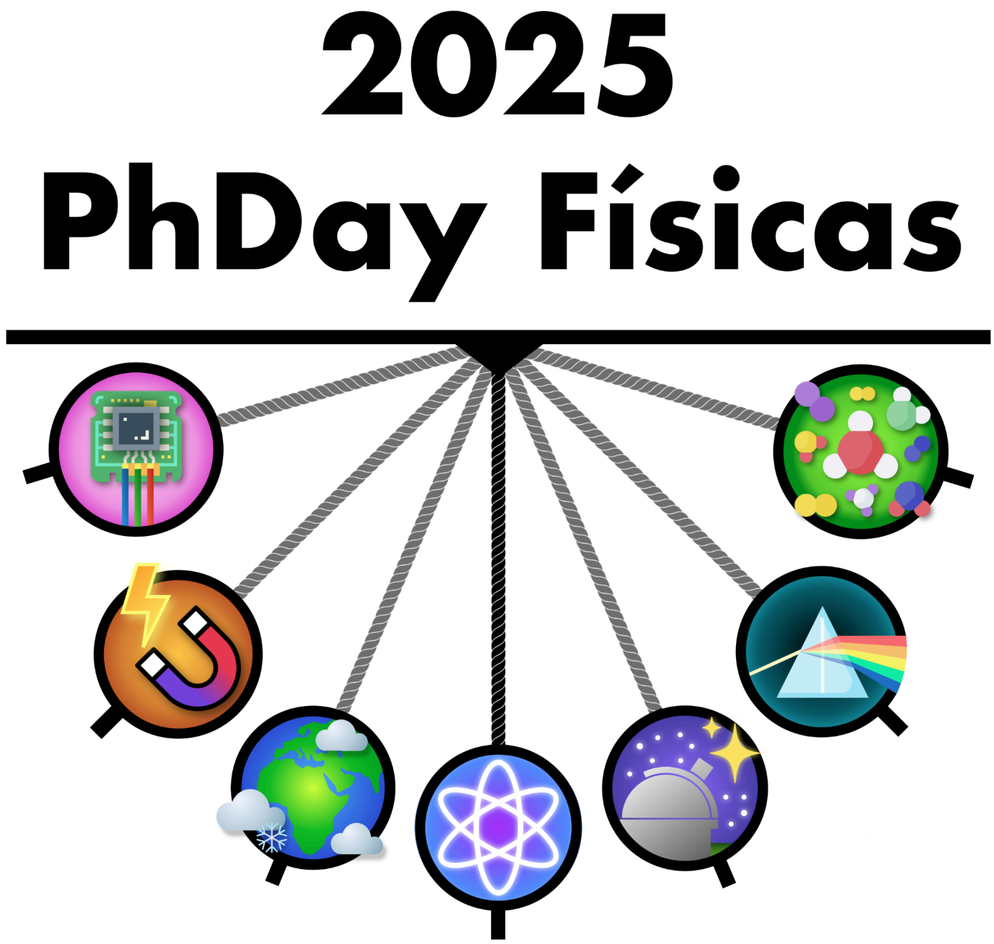
PhDay Físicas 2025

Libro de abstracts

ESCUELA DE DOCTORADO
UNIVERSIDAD COMPLUTENSE DE MADRID



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Lista de abstracts

1. Magnetic Fields in the Shapley Supercluster of Galaxies

David Alonso López

Faraday Rotation Measure (RM) Grids are a powerful tool for probing magnetised plasma across cosmic structures. In this study, we investigate the RM signal from the Shapley Supercluster Core (SSC), a dense region containing two galaxy clusters (A3558 and A3562) and two galaxy groups at redshift $z \approx 0.048$. By combining RM data from the POSSUM pilot survey with thermal Sunyaev-Zeldovich measurements from Planck, we constrain the magnetic field properties of the intra-cluster medium.

We analyze the excess RM scatter and its dependence on the distance to the nearest galaxy cluster, comparing the observations with both semi-analytic magnetic field models and cosmological magnetohydrodynamic (MHD) simulations. We detect a statistically significant excess RM scatter of 30.5 ± 4.6 rad/m^2, corresponding to magnetic field strengths of approximately 1–3 μG within the SSC structures.

Interestingly, the observed RM scatter profile is flatter than predicted by both analytic and simulated models, favoring a weak correlation between magnetic field strength and gas density. Despite this, MHD simulations that incorporate magnetic field amplification through turbulent motions in inter-cluster regions show the best agreement with the data.

These results highlight the capability of dense RM grids to resolve magnetised gas structures up to beyond the cluster's virial radii, while also exposing key tensions between observations and theoretical predictions. Our findings suggest that current models may underestimate the complexity of magnetic field distributions in large-scale cosmic environments.

2. Estudio de los precursores estratosféricos de eventos extremos en superficie a través de la modelización climática

Daniel De Maeseneire Martínez

Los eventos extremos son fenómenos climáticos con fuertes impactos socioeconómicos. Además, las proyecciones de cambio climático indican que este tipo de eventos van a ser más frecuentes en el futuro, por lo que es necesario una mejora en su predicción. Recientemente, diversos estudios sugieren la influencia de la circulación estratosférica y en concreto variabilidad asociada al vórtice polar, en la ocurrencia de este tipo de eventos extremos en superficie en latitudes medias del hemisferio norte hacia final del invierno y primavera. Estos fenómenos estratosféricos pueden ser de diferente naturaleza, puramente dinámica como los SSWs, que se caracterizan por un aumento abrupto de la temperatura de la estratosfera polar y una fuerte deceleración del vórtice polar. En esta tesis doctoral se quiere analizar la influencia de la variabilidad estratosférica en eventos extremos en superficie en el hemisferio norte, entender los mecanismos que dan lugar a esa influencia y explorar si la inclusión de variabilidad estratosférica en los modelos de predicción mejora la predicción de estos eventos extremos en superficie.

En un primer estudio, se ha analizado el impacto de los SSWs en los extremos de temperatura en superficie (olas de frío y olas de calor) en el HN. Además, se ha investigado si este impacto varía en situaciones de cambio climático. Dada la gran incertidumbre en las proyecciones futuras del vórtice polar, nuestros resultados muestran dos grupos de modelos, los que predicen un aumento en la ocurrencia de SSWs y los que muestran una disminución. Esta discrepancia va asociada a diferencias en la propagación de la señal desde la estratosfera hacia la superficie, pudiendo afectar a distintas características de las olas de frio y extremos cálidos, sobre todo en las regiones donde los SSWs tienen un mayor impacto.

3. Caracterización física y radiobiológica de irradiaciones en líneas celulares sanas y tumorales

Inés del Monte García

La radioterapia (RT) es uno de los principales tratamientos actuales contra el cáncer. Sin embargo, los fundamentos biológicos que explican su eficacia son todavía desconocidos. Además, en las últimas décadas se está viviendo un constante surgir de nuevas técnicas que tienen como objetivo aumentar la eficiencia y reducir la toxicidad del tratamiento. En este marco se encuentra nuestro proyecto, desarrollado por un equipo interdisciplinar, cuyo objetivo principal es profundizar en los mecanismos mediante los cuales las células responden a la radioterapia y determinar si y qué parámetros físicos de la RT, y sus cambios, desencadenan la activación de estos procesos.
En este contexto se encuentra mi tesis doctoral, que consiste en tender un puente entre la física y la biología que se unen en explicar los fundamentos de la RT. En primer lugar, mi formación en Física me permite entender en profundidad los parámetros físicos de la irradiación, centrándome especialmente en la tasa de dosis y en el LET de las partículas, así como la caracterización de los irradiadores y la realización de la dosimetría de los experimentos. Toda esta perspectiva física es, después, volcada en ensayos biológicos que tienen como objetivo desvelar alguno de los mecanismos radiobiológicos del tratamiento, trabajando con un modelo sano y otro tumoral. Estos ensayos van desde ensayos a largo plazo de supervivencia como ensayos a corto plazo de daño en la cadena de ADN o en el ciclo celular. La cuantificación de estos ensayos se realiza a través de imágenes, tanto de escáner como de microscopía de fluorescencia, donde vuelve a entrar en juego mi formación mediante el desarrollo de código que automatice y elimine el sesgo del observador de los resultados obtenidos. El área de sinergia de este proyecto de tesis entre la física y la biología subraya la importancia de la presencia de grupos e investigadores interdisciplinares en la investigación científica.

4. Depósito de Capas Nanométricas de AZO por Sputtering de Alta Presión: Caracterización y Aplicación en Células Solares de Alta Eficiencia.

Sebastián Duarte Cano

La pulverización catódica a alta presión (HPS) se presenta como una técnica emergente para la fabricación de óxidos conductores transparentes, como el óxido de zinc dopado con aluminio (AZO), material clave en dispositivos fotovoltaicos. Este trabajo investiga las propiedades estructurales, ópticas y eléctricas de laminas nanométricas de AZO depositadas por HPS, evaluando su potencial como alternativa a métodos convencionales. Se emplearon técnicas de caracterización como GIXRD, XPS y AFM para analizar la cristalinidad, composición química y morfología superficial. Los resultados ópticos revelan alta transparencia en el rango visible y valores de banda prohibida entre 3.35 y 3.45 eV. Las mediciones eléctricas mediante efecto Hall y método van der Pauw indican resistividades entre 10^{-2} y 10^{-3} Ω·cm, con alta concentración de portadores. Las películas obtenidas a presiones de 1.0–1.4 mbar presentan superficies homogéneas, baja rugosidad y excelente desempeño optoelectrónico. En cambio, a presiones superiores (1.4–2.2 mbar), se observa un aumento en la rugosidad y una disminución en la movilidad, aunque con mayor densidad de portadores. Estos hallazgos confirman que el AZO depositado por HPS exhibe propiedades competitivas, posicionándose como una solución escalable y eficiente para el desarrollo de células solares de próxima generación.

5. Escuchando el universo con qubits: Inferencia bayesiana cuántica para ondas gravitacionales

Gabriel Escrig Mas

En los próximos años, los detectores de ondas gravitacionales (como LIGO, Virgo y los futuros telescopios de tercera generación) captarán un torrente de señales provenientes de fusiones de agujeros negros o estrellas de neutrones. Pero cada señal lleva consigo un misterio: ¿cuáles fueron las masas, espines o la distancia del evento que la generó? Resolver esto exige algoritmos de inferencia estadística potentes y costosos.

Este trabajo presenta qBIRD, un algoritmo híbrido que mezcla lo mejor del mundo cuántico y clásico para "escuchar" esas ondas y desentrañar sus secretos. qBIRD aplica una versión cuántica del enfoque bayesiano con técnicas de renormalización y muestreo, explorando muchos parámetros en superposición y enfocándose en las regiones más prometedoras del espacio de posibilidades. Probamos qBIRD con señales simuladas y datos reales de fusiones de agujeros negros, y los resultados muestran que puede estimar parámetros con la misma precisión que los métodos clásicos establecidos, con una cantidad polinómicamente menor de pasos.

Hoy, qBIRD trabaja con modelos simplificados que involucran pocos parámetros, pero su estructura híbrida lo hace escalable hacia análisis más complejos conforme avance el hardware cuántico. En ese escenario, qBIRD podría ofrecer una vía eficiente para realizar inferencia bayesiana de alto rendimiento, complementando los métodos clásicos en la búsqueda y caracterización de ondas gravitacionales.

6. Performance of an impact-based Earthquake Early Warning System in the Alboran Sea

Lucía Escudero Palencia

Earthquakes Early Warning Systems (EEWS) are one of the most effective tools to prevent and mitigate the damage that can be caused by earthquakes. Since October 2015, the Department of Earth Physics and Astrophysics of the Complutense University of Madrid has implemented an operational EEWS throughout the Ibero–Maghrebian Region (IMR). This system is based on the PRESTo (Probabilistic and Evolutionary Early Warning SysTem) software. Currently, a new EEWS, called QuakeUp, based on the progressive temporal prediction of ground motion is being implemented in the same department. Not only does it provide an early determination of the hypocenter and magnitude, like the current EEWS, but the new method also combines Peak Ground Velocity (PGV) predictions calculated from observed P-wave amplitudes and region-specific Ground Motion Prediction Equation, while using progressively updated estimates of earthquake location and magnitude. As a result, it provides a P-wave-based shake map that is updated over time, offering a real-time, evolving map of the Potential Damage Zone defined as those zones where the Instrumental Intensity, calculated in terms of PGV, exceeds a previously defined threshold. This EEWS method has been validated using data from the 2016 Alboran Sea seismic series (Mw 5.0–6.4), which showed minimal discrepancies in origin time, hypocenter, and magnitude estimates compared to previous studies. A retrospective performance analysis for the Mw 6.4 main shock indicated lead-times of 14 to 62 s at a PGV threshold of 0.20 cm/s, with lead-times increasing with distance. At a higher threshold of 0.60 cm/s, the lead-time was 20 s for distances up to 170 km. The accuracy of impact predictions improved over time, with successful alerts rising from 72% to 90% as the final predictions were made. Despite some limitations due to focusing on moderate-magnitude earthquakes (Mw ≤ 6.4), QuakeUp has proven effective for offshore events in areas with sparse instrumentation.

7. Electron hydrodynamics in graphene devices

Jorge Estrada Álvarez

Two-dimensional materials exhibit exotic transport properties. In graphene, electron-electron collisions dominate the electronic transport and break the conventional picture of Ohm's law. Indeed, the transport is hydrodynamic, with features resembling those of a conventional fluid. The electrical response of graphene devices is highly dependent on the geometry, a key feature of hydrodynamic transport. We simulate the electron flow in graphene devices. We observe remarkable properties in symmetry-broken devices, such as the formation of whirlpools, as observed using quantum sensing microscopy, and anomalous voltage-current characteristics for applications in terahertz technology.

Another key signature of electron hydrodynamics is superballistic conduction, which enables us to mitigate electrical resistance as device size decreases. Experimental observations in a graphene antidot superlattice demonstrate a decrease in resistance with increasing temperature and the onset of hydrodynamic transport. However, they also exhibit anomalies with a conventional fluid: the absence of the Knudsen minimum constitutes a superballistic paradox, which we resolve by accounting for the details of electron collisions. Unlike conventional particles, electrons are fermions, and their quantum nature affects the resistance. Additionally, the superballistic effect and a proper choice of the geometry can be used to reduce the device's dissipation. In conclusion, an appropriate selection of device geometry enhances the hydrodynamic signatures.

8. Insights into the 100 largest European surface ozone episodes during spring–summer 2003–2022

Tahimy Fuentes Alvarez

In this study, we investigate the spatial distribution and drivers of the 100 largest ozone episodes identified in the Copernicus Atmosphere Monitoring Service global reanalysis over Europe during April–September 2003–2022. Using a semi-Lagrangian algorithm to detect large-scale ozone episodes and an atmospheric blocking and subtropical ridge identification method, we analyse the role of meteorological processes and precursor emissions in three key regions: the British Isles (BRIT) and Eastern Europe (EEU) during April–May, and Central Europe (CEU) in June–September, revealing some regional differences. The 28 days with ozone episodes in EEU are associated with anticyclonic conditions but also require elevated concentrations of precursors, often linked to wildfire activity. In contrast, episodes affecting BRIT are characterized by negative anomalies of 500 hPa geopotential height and daily maximum temperature at 2 m as well as stronger than usual winds that ventilate the region. Out of a total of 38 days with episode there, one-quarter are associated with easterly flow and changes in ozone formation sensitivity and three-quarters present varying dynamical conditions. In CEU, we identify significant north-south differences: while 36 out of a total of 60 days with episodes in northern CEU are strongly influenced by blocks and ridges, the 29 days with episodes restricted to the south are affected by weaker synoptic forcing and enhanced subsidence. These findings are relevant for future air quality assessments as they demonstrate that the occurrence of large-scale ozone episodes in Europe is driven by region-specific combinations of meteorological conditions and precursor availability.

9. Orientation-Tuned Hall Responses in Strongly Correlated Oxide Heterostructures

Rafael Fuster Rico

Ultrathin epitaxial heterostructures of correlated oxides offer unique opportunities to explore emergent quantum phenomena governed by electronic geometry and topology [1]. While most studies focus on the conventional (001) orientation, (111)-oriented heterostructures have recently emerged as promising platforms to engineer unconventional magnetotransport responses linked to the quantum metric and Berry curvature [2–4].

We investigate La0.7Sr0.3MnO3, a strongly correlated ferromagnetic quantum material, epitaxially grown along the (001) and (111) crystallographic directions. Both orientations exhibit excellent structural quality and comparable longitudinal transport properties, yet their transverse magnetotransport differs markedly. In the (111)-oriented films, the Hall coefficient RH changes sign and its temperature dependence is inverted relative to (001), while the anomalous Hall effect is strongly enhanced, illustrating how crystallographic geometry profoundly influences the electronic structure and transport phenomena governed by Berry-phase mechanisms.

These results highlight the critical role of crystallographic orientation in shaping magnetotransport properties and establish (111)-oriented correlated oxide heterostructures as ideal platforms for studying and tuning topological transport phenomena.

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[2] Lin, W. et al., Adv. Mater. 33, 2101316 (2021).
[3] Nishihaya, S. et al., Adv. Mater. e02624 (2025).
[4] Sala, G. et al., Science 389.6762, 822-825 (2025).
[5] Lesne, E. et al., Nat. Mater. 22, 576–582 (2023).

10. Quantum Simulations of QCD within a particle-based codification

Juan José Gálvez Viruet

One of the most anticipated applications of quantum information science is the simulation of complex systems. Those involving quarks and gluons are particularly compelling, as their real-time phenomenology remains elusive to computational techniques such as traditional Monte Carlo methods. Overcoming these challenges could provide unprecedented insights into the dynamics of partons.

In this context, we discuss the calculation of fragmentation functions, key to describe how quarks and gluons transform into observable hadrons. As we move along we introduce a series of strategies to face the problem using quantum computers, all grounded in a codification paradigm where particles and their internal degrees of freedom are the centralobjects.

11. Sputter-deposited Nanocolumns: Tuning Fe and Au Properties for In Vitro Biomedical Applications

María Garrido Segovia

Magnetron sputtering (MS), a highly scalable and versatile technique, is extensively employed for thin film fabrication in both industrial and academic levels. Its compatibility with glancing angle deposition (GLAD) presents a compelling approach for generating nanostructured surfaces. By taking advance of the grazing incidence angles and the inherent shadowing effect during atomic deposition, the combined MS-GLAD method enables the growth of nanocolumnar films (NCs), yielding films that exhibit significant anisotropy and porosity.
Among the materials synthesized via MS-GLAD, Fe-based NCs have gained substantial interest due to their tunable magnetic properties. These properties are intricately dependent upon the specific geometry and orientation of the columns, which are, in turn, dictated by the deposition geometry and conditions. Conversely, Au NCs have been a subject of extensive research for their exceptional optical properties. Of particular significance is the presence of localized surface plasmon resonances (LSPR), which emerge when the material is structured at the nanoscale.
In this study, a series of Au nanostructure samples were systematically fabricated by controlling the growth parameters, and concurrently, hybrid nanocolumnar systems integrating both Au and Fe were successfully synthesized using MS-GLAD. A rigorous multi-technique characterization was performed: Scanning Electron Microscopy (SEM) was employed for morphological analysis, X-ray Diffraction (XRD) for structural determination, a custom-built system for optical reflectivity measurements, and Vibrating Sample Magnetometry (VSM) for magnetic assessment (as required). Crucially, the in vitro viability of these nanostructures was evaluated, confirming their suitability for biological studies. The overall results establish the promising nature of these nanostructures for advanced applications in sensing technologies and as therapeutic agents in magnetic and photothermal cancer treatment.

12. Laser-induced sintering of Titanium niobate films from powders of TiO_2 and Nb_2O_5 for energy applications

Gonzalo Gómez Muñoz

Titanium niobates (TNOs) are a family of materials with diverse stoichiometries and crystalline structures, which turn them into a complex-system that requires highly controlled treatments in order to achieve a proper production. The most stable TNO-structure is $TiNb_2O_7$, which is an oxide that has already proven its excellent performance in emergent applications, specifically for energy storage in Li-ion batteries [1,2].

Recently, the feasibility of inducing the sintering of compact Nb_2O_5 films by fs-laser powder bed fusion while improving their electrical conductivity several orders of magnitude has been demonstrated [3]. For the case of Nb_2O_5, microstructure and anisotropy of the layers were controlled with fs-laser conditions, triggering the stabilisation of a monoclinic oxygen-deficient phase (thus, much more conductive and better for energy storage than stoichiometric niobium oxide). In this work, a similar approach has been followed in order to induce the sintering of compact TNO films starting from a mixture of TiO_2 and Nb_2O_5 powders. A characterization of the sintered films has been performed in order to understand which phases have been induced by fs-laser irradiation of the powders, leading to different scenarios depending on how do we change the laser pulse energy.

[1] Y. Zhang et al., Electrochim. Acta 330, 135299 (2020)
[2] X. Wu et al., Electrochem. Commun. 25, 39-42 (2012)
[3] B. Sotillo et al., Mater. Des. 224, 111346 (2022)

13. Stability of the Greenland Ice Sheet: from the Last Glacial Maximum to the future

Lucía Gutiérrez González

The Greenland Ice Sheet (GrIS) has undergone accelerated ice-mass loss in recent decades and it is expected to be one of the main contributors to global sea-level rise in the coming century. The GrIS is thought to be a tipping element of the Earth system due to the existence of positive feedbacks governing its mass balance. This means that with a small increase in atmospheric temperatures, if the critical threshold is exceeded, the GrIS would reach a virtually ice-free state. Furthermore, the GrIS shows hysteresis: if this ice-free state is reached, recovery to a volume similar to the present would require temperatures below present-day levels, making ice sheet recovery irreversible on human timescales.

Its stability has been studied in temperatures ranging from the present day to a global warming, showing threshold behavior in the system. However, the exact values of these critical thresholds, or tipping points, remain uncertain, and it is unknown whether hysteresis persists under colder (and therefore past) climates. Here, we address the problem from a paleoclimatic perspective and expand the range of study: from a climate representative of the Last Glacial Maximum (ca. 21,000 years ago, when temperatures in Greenland were 12°C below present-day values) to a warmer climate (+4°C above present-day values). We find that the hysteresis persists in almost the entire temperature range. We identify two tipping points: one for future warming and another for the past climate.

14. Galaxy clusters through photometric data: from membership to star formation histories

Paula Macías Pardo

Galaxy clusters provide ideal laboratories to study how environment shapes galaxy evolution. Our work approaches these systems from a photometric perspective, combining multiwavelength data and Spectral Energy Distribution (SED) fitting techniques to characterize cluster populations. As part of the ongoing efforts toward the CATARSIS survey, we are assembling deep optical and near-infrared imaging from public datasets (SDSS, LS, Euclid, WISE) and dedicated u-band and nIR observations from the Calar Alto Observatory. These data are used to derive galaxy SEDs and photometric redshifts, as part of developing a membership criterion sensitive to blue and morphologically disturbed galaxies, often missed in traditional selections, covering both core and outskirts regions. In parallel, we are extending this photometric analysis to a set of nearby clusters ($z \approx 0.015$–0.023) observed with the Hyper Suprime-Cam (HSC). The spatial resolution and depth of HSC images provide the opportunity to study morphological features and diffuse structures, including the population of ultra-diffuse galaxies (UDGs), and to relate them to the underlying stellar populations. By combining these two regimes — intermediate-redshift clusters from CATARSIS and low-redshift systems from HSC — we aim to build a consistent view of galaxy evolution in clusters, connecting the structural, photometric, and stellar population properties of galaxies across environments and epochs.

15. The physics behind Earth's latest ice ages

Sergio Pérez-Montero

The climate variability of the last 3 million years (Pleistocene) have been long studied, however, there are still uncertainties concerning the causes of certain features in the paleoclimate records. These unknowns are believed to be due to intrinsic nonlinearities in the climate system. The longer timescales involved make it infeasible to use complex climate models because of the large computational cost involved. In this context, conceptual models are built to mimic complex processes in a simpler, computationally efficient way. Here we present the Physical Adimensional Climate-Cryosphere mOdel (PACCO) which represents the coupling between northern hemisphere ice sheets and climate employing state-of-the-art knowledge about climate and ice-sheet dynamics. In this way, PACCO is able to run several glacial cycles in seconds and produces results comparable to those of paleoclimatic proxies.

16. The first galaxies of the Universe: exploring the Epoch of Reionization with JWST

Carlota Prieto Jiménez

The James Webb Space Telescope (JWST) is revolutionizing our understanding of the formation and evolution of the first galaxies in the Universe, particularly during the first billion years after the Big Bang — a period known as the Epoch of Reionization.

In this work, I present observations of two types of systems captured by JWST. The first is a star-forming galaxy, B14-65666 (Prieto-Jiménez et al. 2025), which consists of two galaxies in the process of merging. Using the Mid-Infrared Instrument (MIRI), we have obtained the first detection of the Hα emission line in this galaxy. This detection allows us to study both young and old stellar populations and gain insight into star formation in the early Universe.

The second type of sources are quasars, luminous active galactic nucleus, which are one of the most extreme objects of the Universe. We focus on two quasars, J0859 and J0224, observed with the Near Infrared Spectrograph (NIRSpec). These new observations reveal key emission lines such as [O III], Hβ, and Hα, enabling us to explore the gas properties and ionization conditions surrounding these early black holes.

Together, these results provide valuable clues about the growth of the first galaxies and black holes and their role in shaping the evolution of the young Universe.

17. Heat extremes in southern South America: from historical regional analysis to future storylines

Solange Suli Silicaro

This study investigates temperature extremes over southern South America (SSA) during the warm seasons, combining an analysis of historical (1979–2018) heat waves (HWs) and future projections (2070 – 2099) of heat extremes.
Firstly, we examine the regional characteristics of HWs using daily maximum temperature (TX) records from 131 weather stations. Based on the co-occurrence of HW days, five homogeneous regions are identified: northern, central-eastern and southern SSA, central Argentina, and central Chile. On average, around four regional HWs occur per year. Northern SSA, central-eastern SSA, and central Argentina experience longer but less intense HWs than southern SSA, while central Chile exhibits the weakest and shortest events. The associated synoptic conditions show regionally distinct circulation patterns, mainly linked to variations in subtropical high-pressure systems and northerly flow anomalies.
Secondly, based on the regionalisation derived from the historical analysis, we explore future heat extremes using a storyline approach. This methodology allows us to assess the sources of uncertainty in projected summer changes, constructing physically plausible future scenarios based on potential changes in key atmospheric and oceanic variables. Using simulations from 26 global climate models, we analyse how changes in mid-tropospheric circulation, regional soil moisture, tropical sea surface temperature, and the South Atlantic Convergence Zone shape future summer maximum temperatures (TXx). Together, these drivers explain up to 56% of the inter-model spread in future TXx projections, providing a physically consistent framework to interpret regional differences and uncertainties in future heat extremes.

18. Towards an operational early warning signal of ice-sheet collapse

Jan Swierczek-Jereczek

The melt of the Greenland and West-Antarctic Ice Sheet is bound to become the main source of sea-level rise over the coming centuries, with contributions of several meters by 2300 under intermediate and high-emission scenarios. Most importantly, this stems from crossing tipping points of the ice sheets, that is, warming levels beyond which their retreat becomes abrupt and self-sustained. Since more than a billion people live on coastlines with an elevation of less than 10 meters above global mean sea level, this poses a major challenge to human adaptation and motivates the development of early warning signals that can be reliably identified prior to an ice-sheet collapse. So far, this was done either by applying mathematical concepts to observational data, or by running ice-sheet models that rely on physical equations. While the former is incapable of predicting the timing and amplitude of the collapse, the latter can only make a very limited use of real-world data. To address this, we propose a new early warning signal that can be trained on multimodel output and subsequently used to infer a probability of ice-sheet collapse. The results obtained are coherent with glaciological insights and can be directly leveraged to develop mitigation and adaptation strategies.