Finnish Centre for Astronomy with ESO

Annual Report

2023

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FINNISH CENTRE FOR ASTRONOMY WITH ESO, ANNUAL REPORT 2023

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Based on a template by Andrea Hidalgo.

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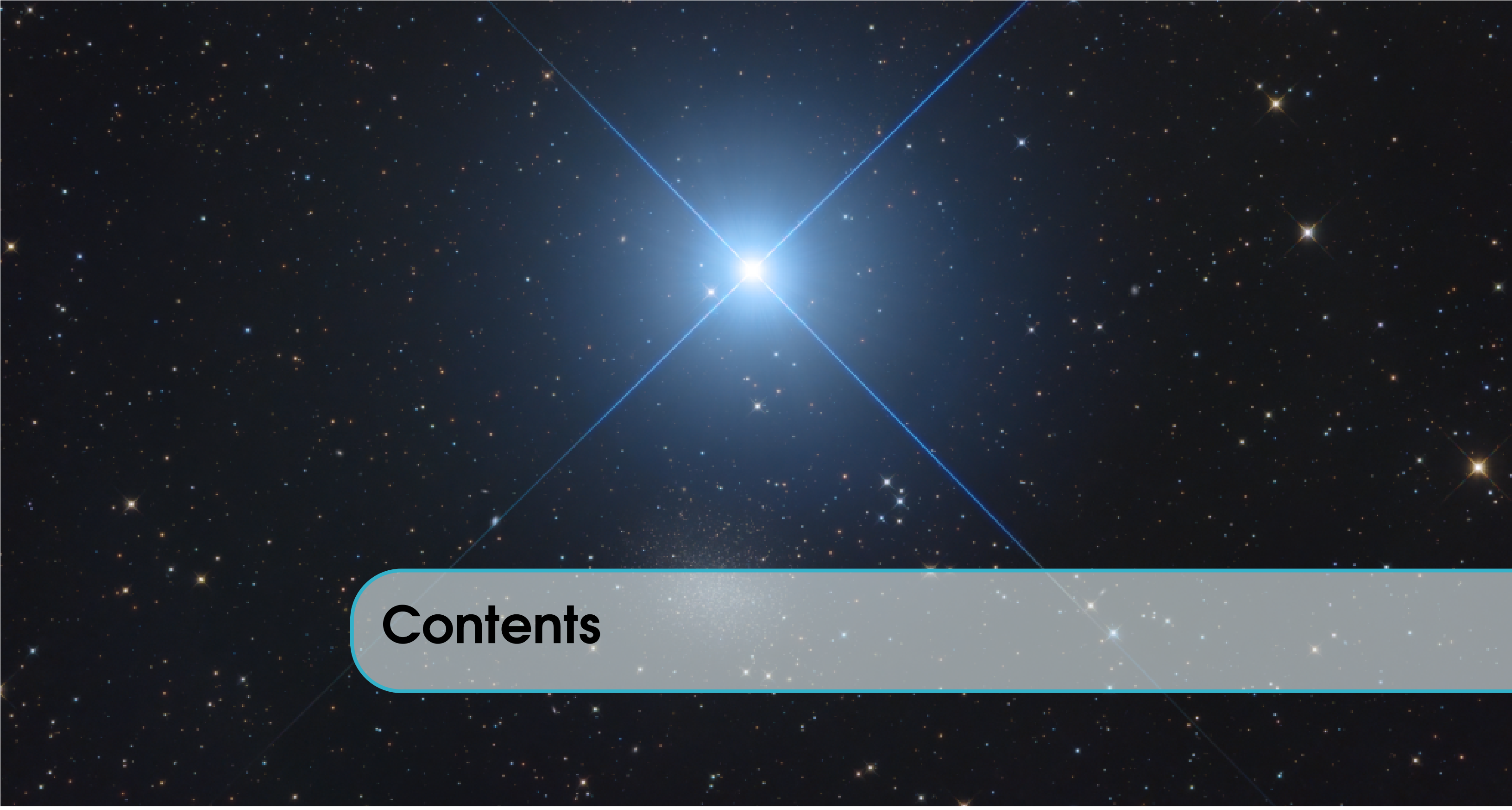
Cover: the Atacama Pathfinder Experiment (APEX) telescope. (courtesy: ESO)



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1. Foreword

The European Southern Observatory (ESO) is the world's leading science and technology organisation in ground-based astronomy, and the most productive astronomical observatory in the world. Its headquarters are in Garching, Germany, and it operates three state-of-the-art observatories in Chile. ESO also carries out an ambitious program driving new technologies, including building the revolutionary €1.5 billion Extremely Large Telescope (ELT) with a main mirror of 39-m diameter. ESO is a government-level treaty organisation, with 16 member states currently, including Finland, which joined in 2004.

Being an integral part of ESO is essential for the Finnish astronomical community to remain at the forefront of high-quality research in the field. To ensure this, a national astronomy research institute, the Finnish Centre for Astronomy with ESO (FINCA) was founded in 2010 to promote high-quality national research in the field by utilising ESO infrastructure and technological projects, and to lead co-operation between all the Finnish universities, Aalto (AU), Helsinki (UH), Oulu (UO), Turku (UT), that are engaged in astronomical research. In addition to ESO-based science, FINCA promotes and coordinates Finnish participation in ESO-related infrastructure and technological development projects. Furthermore, realising that best science is usually done collaboratively, and across multiple wavelengths, FINCA supports high-level observational astronomy more broadly as well. Nationally, FINCA participates in researcher training in astronomy at the universities, and is also taking a coordination role with activities and training related to the Nordic Optical Telescope (NOT) with UT. The ultimate goal of FINCA is to improve the scientific and industrial benefit of Finland's membership in ESO, and Finland's international competitiveness in astronomical research.

The year being reported on, 2023, marked the 14^{th} year of operation for FINCA, administratively a Special Unit of the University of Turku, and funded by the Ministry of Education and Culture, and by the participating universities. The highest decision-making body is the Board, chaired by Vice-Rector **Kalle-Antti Suominen** of UT, and comprising of two members from each participating university, and one member from FINCA staff. The scientific activities of FINCA are overseen by an international Scientific Advisory Board (SAB).

The research at FINCA covers a large range in contemporary astronomy, from cosmology, active galaxies, and galaxy formation and evolution, through properties of nearby galaxies, to supernovae and their progenitor stars, stellar activity and star formation in our own Galaxy. In our research, highlights of which are presented in this Annual Report, we use radio to gamma-rays multi-wavelength observational data from large ground-based and space telescopes, especially from the four 8m ESO Very Large Telescopes (VLT), the NOT, and the Atacama Large (Sub)Millimetre Array (ALMA), in the optical, near-infrared and (sub)millimetre wavelengths. Observational research is supplemented by modelling, simulations and theoretical work, that are essential in understanding the physics behind the observations. Our research is characterised by strong collaboration within FINCA, with other astronomy departments in Finland, and internationally. FINCA scientists published **115** officially recognized refereed Journal papers during the course of 2023, which are listed at the end of this Report.

Researcher training activities in 2023 focused on supervision of PhD and MSc students in the participating universities. Furthermore, as before, FINCA funded the annual national course on remote optical/infrared observing with the NOT for MSc and PhD students organized by the UT Department of Physics and Astronomy, and the extremely popular hands-on course for Finnish high school students utilizing remote observations with the NOT, and run by the LUMA Centre South West. FINCA researchers and students also tutored participating groups in these schools.

Regarding ESO-developments, the construction of the ESO's ELT, the 39m diameter giant for infrared and optical astronomy, is well underway, with Phase 1 instruments being constructed, and the construction of the telescope already started at Cerro Armazones. ESO is thus on-track to remain in a world-leading position when the ELT is expected to start operations in 2028 or soon after. It will revolutionise our perception of the Universe by pursuing many prominent questions: When and how did the first galaxies assemble? What is the star formation history of the Universe? How do supermassive black holes grow and what is their role in the formation of galaxies? How do planetary systems form and evolve, and are there habitable planets, or even life, elsewhere? The ELT instrumentation brings an enormous leap forward in sensitivity and resolution for the global astronomy community, and, FINCA is proud to be involved in some of these instrumentation projects (see below).

FINCA's external funding has increased in recent years. In addition to FINCA researchers having been awarded competitive external grants, a research infrastructure (FIRI) grant in 2017 from the Research Council of Finland enabled the start of our participation in ESO instrument projects. Hence, FINCA is participating, on behalf of the Finnish community, in the ELT first-light instrument consortium MICADO (near-infrared adaptive optics imager) in the form of both direct funding, and by participating in the PSF reconstruction work package. The latter is led by UT in collaboration also with the Lappeenranta University of Technology. MICADO is expected to be the first-light instrument at ELT giving Finnish astronomers an unprecedented front-row seat when this new window into the universe opens. FINCA is participating in another ELT instrument as well, MOSAIC (optical and near-infrared multi-object spectrograph), a 2nd phase instrument projected to see light in the 2030's. Furthermore, we are involved in a new instrument being built for the ESO 3.5-m New Technology Telescope (NTT), the Son Of X-Shooter (SOXS). Notably, the calibration unit of SOXS was built at UT, in collaboration with local companies. Finally, FINCA, together with UT and UH, is participating in a new instrument being built at the Niels Bohr Institute in Copenhagen, the NOT Transient Explorer (NTE), an imaging spectrograph to be shipped to La Palma likely in 2025.

After 14 years as the FINCA Director, **Jari Kotilainen** returned to the Department of Physics and Astronomy of UT in 2023, and passed on the FINCA baton. I formally started as the new FINCA director in August 2023, first in a part-time capacity, while the vice-director **Kari Nilsson** took care of day-to-day activities until my move to Finland, and Turku, from Cape Town, South Africa, in March 2024. I wish to warmly thank Jari for his time and efforts over the many successful years, and very much look forward to working together with FINCAns, and the whole Finnish astronomical community, to continue developing and strengthening the field amidst the exciting developments happening at ESO and elsewhere.

Petri Väisänen,

FINCA Director (from 1.8.2023)

2. Staff and Organization

FINCA staff 2023

Director :	Jari Kotilainen (until 31.7.2023)	Turku
	Petri Väisänen (from 1.8.2023)	Turku
Professor emeritus :	Mauri Valtonen	Turku
University Researchers :	Roberto De Propris (on leave)	Turku
	Pasi Hakala	Turku
	Kari Nilsson	Turku
Academy Research Fellows	Talvikki Hovatta	Aalto/Turku
	Elina Lindfors (until 31.8.2023)	Turku
Postdoctoral Researchers	Grigori Fedorets (from 1.9.2023)	Helsinki
	Claudia Gutierrez (until 30.4.2023)	Turku
	Johanna Hartke	Turku
	Tuomas Kangas	Turku
	Jyri lehtinen	Helsinki
	Yannis Liodakis (until 31.8.2023)	Turku
	Derek McKay (until 28.5.2023)	Aalto
	Venkatessh Ramakrishnan	Aalto
	Quentin Salome	Aalto
PhD Students	Jenni Jormanainen	Aalto/Turku
	Pouya Mahmoudi Kouch (until 16.10.2023)	Aalto/Turku
	Maria Stone	Turku
Visiting researcher	Bela Dixit (from 11.9.2023)	Aalto

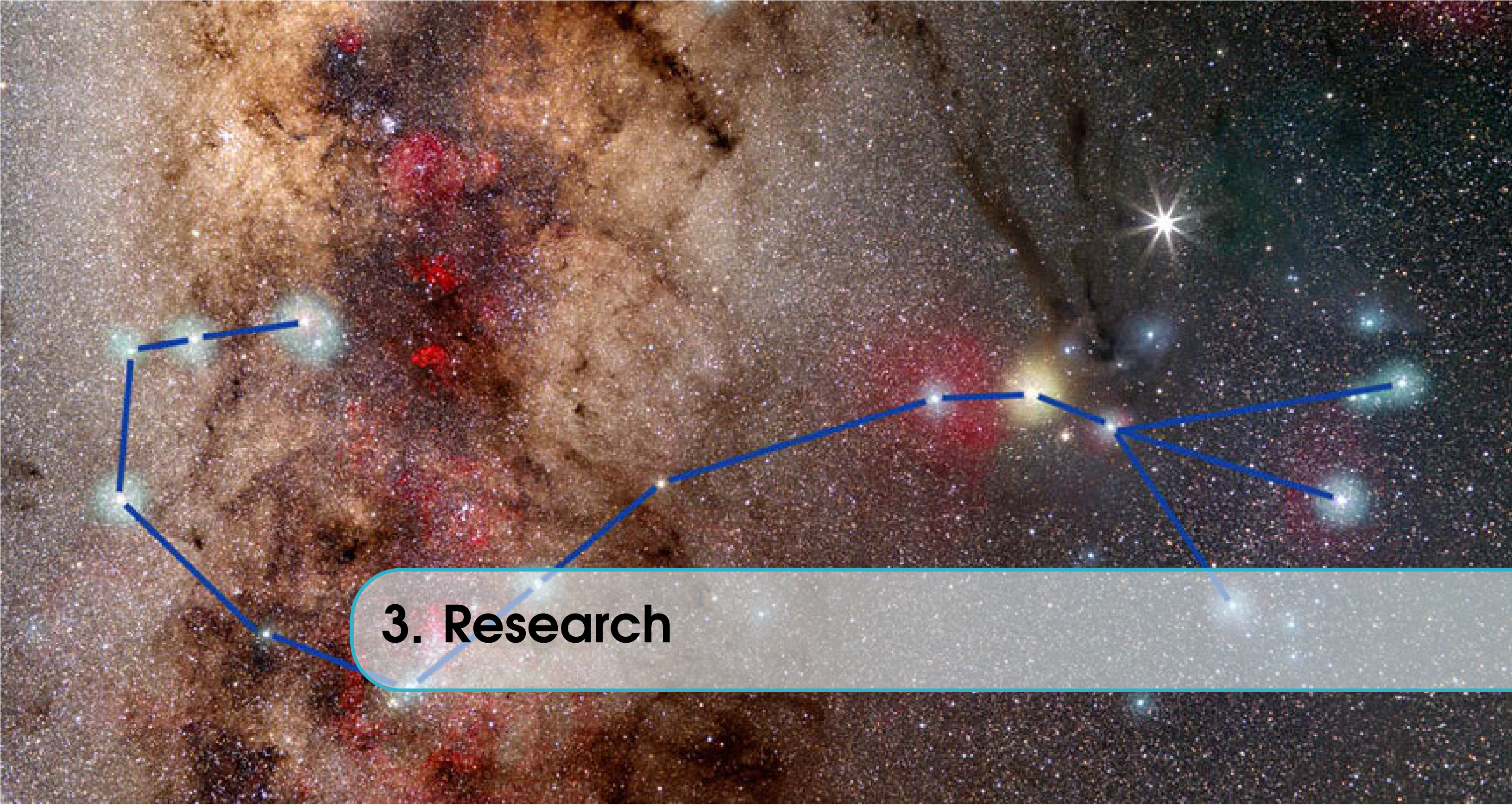
FINCA board

Members

Anne Lähteenmäki	Aalto
Merja Tornikoski	Aalto
Simo Huotari	Helsinki
Alexis Finoguenov	Helsinki
Heikki Salo	Oulu
Vitaly Neustroev	Oulu
Kalle-Antti Suominen (Chair)	Turku
Seppo Mattila	Turku
Talvikki Hovatta (staff representative)	Turku

Deputy members

Joni Tammi	Aalto
Tuomas Savolainen	Aalto
Karri Muinonen	Helsinki
Mika Juvela	Helsinki
Jurgen Schmidt	Oulu
Aku Venhola	Oulu
Mikael Granvik	Helsinki
Juri Poutanen	Turku
Kari Nilsson (staff representative)	Turku



3. Research

3.1 Main research areas

The research at FINCA concentrates on observational astronomy carried out using radio to γ-rays, multi-wavelength data from large ground-based and space telescopes. Especially, we make use of ESO's large ground-based facilities in the optical and infrared (the four 8m ESO Very Large Telescopes; VLT) and in (sub)millimetre (Atacama Large Millimeter Array; ALMA), together with the Nordic Optical Telescope (NOT) on La Palma, in the northern hemisphere. Our observational research is supplemented by modelling, computer simulations and theoretical work, that are essential in understanding the physics behind the observations. The present science topics at FINCA cover a large range in contemporary astronomy from observational cosmology, distant active galaxies, and galaxy formation and evolution, through properties of nearby galaxies, to supernovae and their progenitor stars, stellar activity and star formation in our own Galaxy. In 2023, our research were reported in 115 refereed scientific articles, and some of them are highlighted below.

3.2 Research Highlights

3.2.1 Cosmology and Extragalactic Astrophysics

The case of UDG 32 in the Hydra Cluster

Ultra-diffuse galaxies (UDGs) are extremely low-surface brightness galaxies with a size of several kpc, i.e. comparable to that of the Milky Way, but with at least 100 times smaller stellar masses. The LEWIS project (Looking into the faintEst WIth muSe, PI: Iodice, co-I **Johanna Hartke**), is an ongoing ESO large programme with the MUSE integral field spectrograph at the Very Large Telescope (VLT), targeting a complete sample of 32 UDG candidates (La Marca et al., 2022) in the 50 Mpc-distant Hydra I cluster.

One of the UDGs in the sample, UDG 32, has been found to be co-spatial with the stellar filaments of the spiral galaxy NGC 3314a, and is one of the faintest and most diffuse UDGs in the sample (Iodice et al., 2021; Fig. 3.1). Based on imaging data alone, it is impossible to establish whether this object is just seen in projection on top of the filaments or whether we are indeed witnessing the formation of UDG 32 from the material stripped from NGC 3314a. Thanks to the MUSE data acquired through the LEWIS large programme we could spectroscopically confirm the association of UDG 32 with the filaments of NGC 3314a. UDG 32 may be the first case where we are witnessing the formation of a UDG from RPS gas clumps.

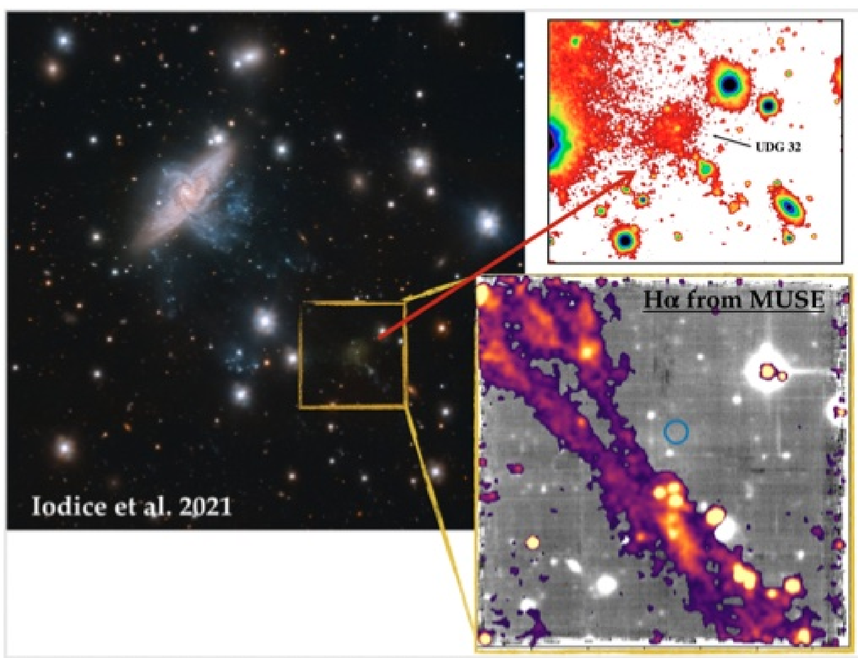


Figure 3.1: UDG 32 (top-right panel), discovered in the stellar filaments of NGC 3314a/b (left panel) from deep optical images with the VLT Survey Telescope (Iodice et al., 2021). The lower right panel shows the MUSE data from the LEWIS large programme, where we discovered the H-alpha emission from ionised gas in the stellar filaments of NGC 3314a. The blue empty circle marks the region where we extracted the spectrum of the UDG to confirm its redshift and association with the filaments.

Evolution of the mass-metallicity relation for quiescent galaxies

Roberto De Propris investigated the evolution of the age-mass-metallicity relation for quiescent galaxies in the VANDELS survey confirmed to have early-type morphologies from HST imaging (Fig. 3.2). The stellar metallicity and age of VANDELS passive galaxies at $z \sim 1.2$ are positively correlated with their stellar mass, as for galaxies in the local Universe: higher mass galaxies host stars formed earlier and are more metal rich than most of the lower mass galaxies. We do not detect any cosmic evolution of the metallicity-mass relation, either in the slope or in the normalization down to $z \sim 0$, as confirmed by the comparison with the relation derived from LEGA-C passive galaxies at $z \sim 0.65$ and with the local relations from the literature.

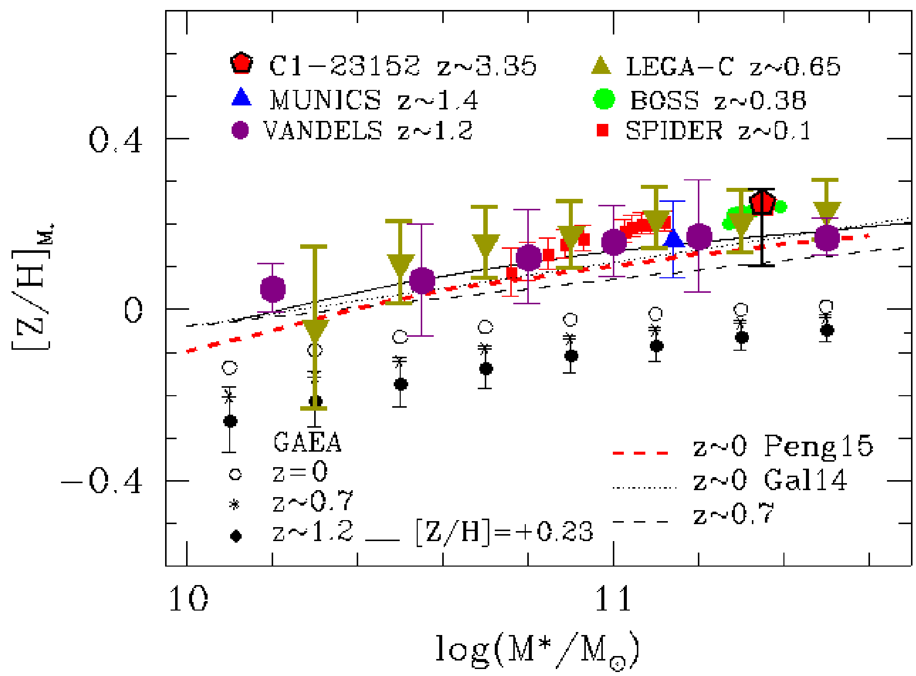


Figure 3.2: Mass-weighted metallicity derived through non-parametric full-spectrum fitting (npFSF) to stacked spectra of quiescent galaxies at different redshifts as a function of mass. The fitting was performed with STARLIGHT code and EMILES models over the same wavelength range ([3350-4350] Å) for all the spectra. Purple circles are VANDELS stacked spectra, military triangles are LEGA-C stacked spectra at 0.6<z<0.7; green filled circles are stacked BOSS spectra of massive ETGs at $z \sim 0.38$ from Salvador-Rusinol et al. (2020); red squares are stacked SPIDER spectra of massive ETGs at $z \sim 0.05$ (La Barbera et al. 2013); blue triangle is the median value of the 5 massive ETGs at $z \sim 1.4$ from Gargiulo et al. (2016); red diamond is the massive ETG C1-23152 at $z \sim 3.35$ studied by Saracco et al. (2020b). Superimposed to the data are also predictions from GAEA models (Fontanot et al. 2021, black open and filled symbols) for different redshifts as in the legend. The black thin curve is the GAEA prediction at $z \sim 1.2$ rescaled up by +0.23 in [Z/H] to match the median value of VANDELS data. The mass-metallicity relations by Gallazzi et al. (2014, black dotted and dashed lines) and Peng et al. (2015, red dashed curve) are also shown.

Massive galaxies ($\log(M_*/M_\odot) > 11.0$) host old stellar populations ($t_{form} < 2$ Gyr) characterized by supersolar metallicity ([Z/H>0.05). These stars have been formed in short time ($\Delta_{t50} < 1$ Gyr) implying high star formation rates ($SFR > 100 M_\odot$/yr) originating in high mass density regions, $\log(\Sigma_{1kpc}) > 10 M_\odot/kpc^2$. This sharp picture tends to blur with decreasing mass: galaxies with intermediate mass, e.g., $\log(M_*/M_\odot) \sim 10.6$ can host either stars with sub-solar metallicity as old as those in massive galaxies, or younger stars with supersolar metallicity, depending on the duration of the star formation, shorter or longer respectively in agreement with other studies at intermediate redshift.

Physical conditions of the gas in Centaurus A's northern filaments

Evidence of recent star formation is observed in the halo of few radio galaxies, where the radio jet encounters a gas reservoir. This suggests that star formation is triggered by the interaction (jet-induced star formation). The northern filaments of Centaurus A are a testbed to study the influence of the radio jet on gas in the halo. Located at about 15 kpc from the galaxy, where the jet encounters a large HI shell, the filaments host a large reservoir of molecular gas. Surprisingly, star formation is really inefficient. **Quentin Salomé** is leading a multi-wavelength spectroscopic campaign to study the physical conditions of the gas in the filaments and the energetic budget (heating vs cooling). The aim is to understand the inefficiency of the jet-induced star formation. ALMA and the VLT instruments enable to trace the different phases of the gas at the scale of giant molecular clouds and provide observational diagnostics to constrain theoretical models.

AGN feedback in narrow-line Seyfert 1 galaxies

Quentin Salomé and collaborators studied the star formation efficiency in a sample of narrow-line Seyfert 1 galaxies for which nuclear X-ray fast winds are well established. The comparison of the CO emission with global properties of the host galaxies suggest that the star formation is very efficient and the AGN activity only plays a minor role in the regulation of star formation.

Blazars seen in the highest of energies and as multimessenger counterparts

During the 20th anniversary year of the international MAGIC Collaboration, FINCAns **Pouya M. Kouch**, **Jenni Jormanainen**, **Elina Lindfors**, **Kari Nilsson**, **Talvikki Hovatta** and **Yannis Liodakis** were involved in many blazar studies in utilising the very-high-energy (VHE, E > 100 GeV) gamma-ray data. The MAGIC Collaboration operates two Imaging Air Cherenkov Telescopes at La Palma, Canary Islands, Spain. To maximize the science output, the FINCA team also continues to perform quasi-simultaneous optical observations of the sources observed by MAGIC using the Nordic Optical Telescope and Joan Oró Telescope.

Blazars are known to be extremely variable sources in all wavelengths, and in 2023, we published a study (Jormanainen et al. 2023) regarding the fastest variability observed in the VHE gamma rays and magnetic reconnection as its possible driving mechanism. Magnetic reconnection has been suggested as an explanation of hour-to-minute time scale VHE gamma-ray variability of blazars in the past, but only now with simulated light curves generated using the results of 2D particle-in-cell simulations and radiative transfer calculations, a fully statistical comparison was possible (Fig. 3.3) The study was performed using the light curves of a famous and bright blazar Mrk 421, which were compared with the simulated light curves, giving more tight constraints to some of the source parameters, such as the magnetic field strength and the jet viewing angle.

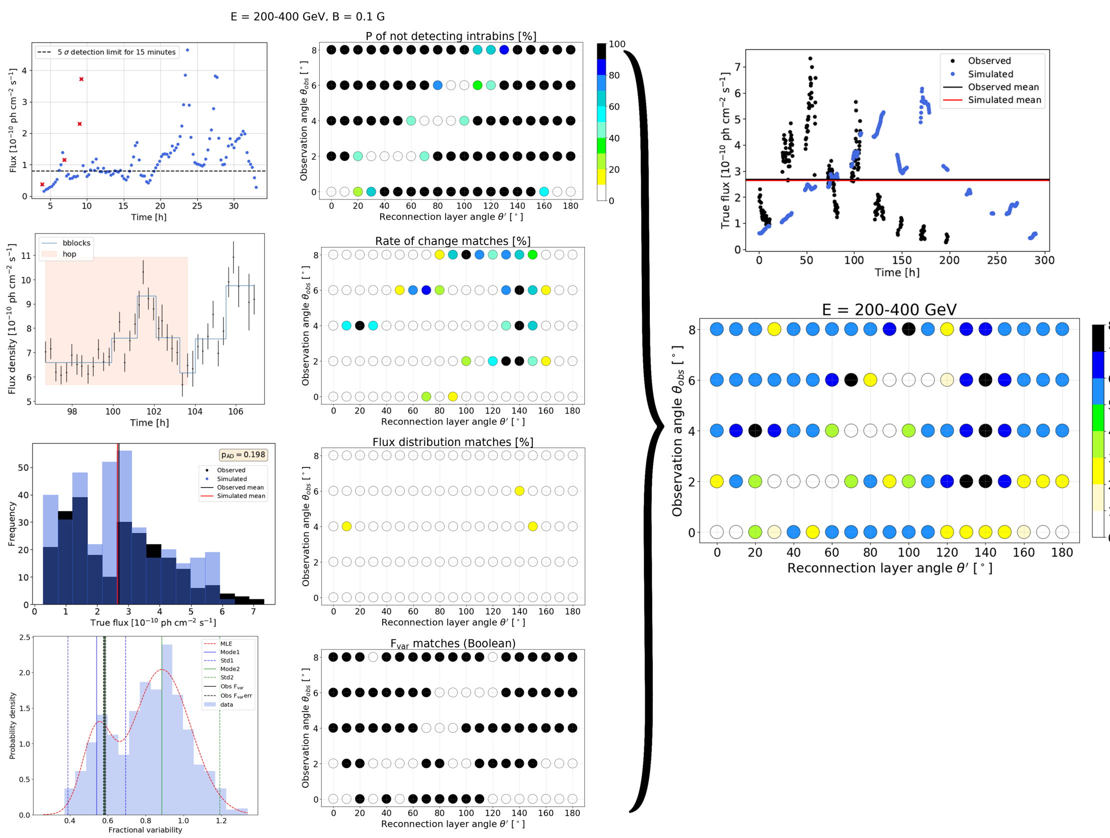


Figure 3.3: Statistical methods developed to compare the observed VHE gamma-ray light curves with magnetic reconnection simulations, along with the respective result acquired with each method and their combined results.

We also continued our research on the mystery of the blazar-neutrino connection. Ever since the high significance spatio-temporal correlation of a HE neutrino event and the flaring blazar TXS0506+056, researchers have been trying to establish a systematic correlation between blazars and HE neutrinos. So far the results have remained rather suggestive, but ultimately inconclusive.

In 2023, we submitted Kouch et al. (2024), following up on our previous studies (Hovatta et al., 2021; Liodakis et al., 2022). We performed a spatio-temporal correlation study on the blazars of the CGRaBS sample and the high-energy neutrino events of the IceCat-1 catalog, in the radio and optical bands, while introducing a novel analysis method. We found that while not all flaring blazars are emitting neutrinos, some may be ($> 2\sigma$ chance probability) — under the assumption that the IceCube neutrino event error regions are underestimated due to unknown systematic errors. As such, the main conclusion of our study is that unravelling the blazar-neutrino mystery heavily depends on the reliability of the reconstruction of the neutrino events; the upcoming next-generation neutrino detectors are expected to help in this regard.

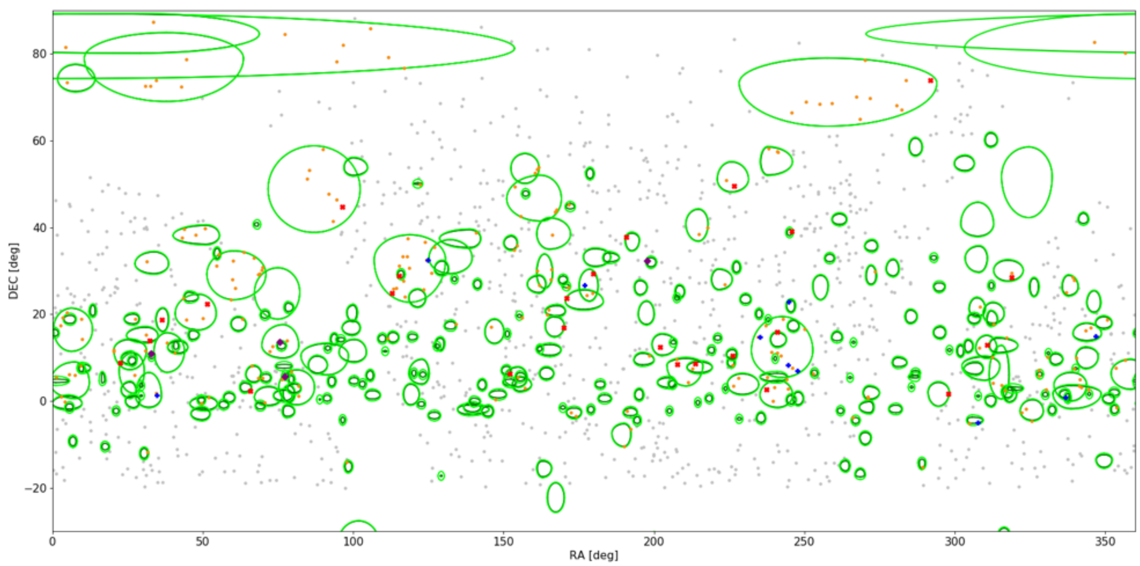


Figure 3.4: Colored dots are flaring blazars coinciding with the arrival time of spatially-associated IceCube neutrino events (whose error region are shown as green ellipses).

In 2023 we also finished our multiyear, multiwavelength study of the blazar PG 1553+113 (z $\sim$ 0.5). This blazar was reported to exhibit periodic variations in the Fermi gamma-ray bands E $>$ 100 Mev and E $>$ 1 Gev with P = 2.18 $\pm$ 0.08 years over 3.5 cycles (Ackermann et al. 2015, ApJ 813, L41). Correlated variations in the optical were also detected with a similar period over 4.5 cycles. Through a multiyear campaign (Fig. 3.5) we extended the optical and gamma-ray coverage and expanded the study to radio, x-ray, UV and Very High Energy (VHE) bands. Our main result was that the x-ray and VHE gamma-ray bands show no evidence of periodic variations over a time window covering more than 3 cycles. The periodograms of radio, optical and UV light curves show a peak corresponding to the 2-year period, but with low significance. The only significant periodicity was found in the Fermi gamma-ray band. Our results indicate that in addition to possible periodic modulation of the jet emission in PG 1553+113, ther must be another, partly uncorrelated emission component contributing to the total emission.

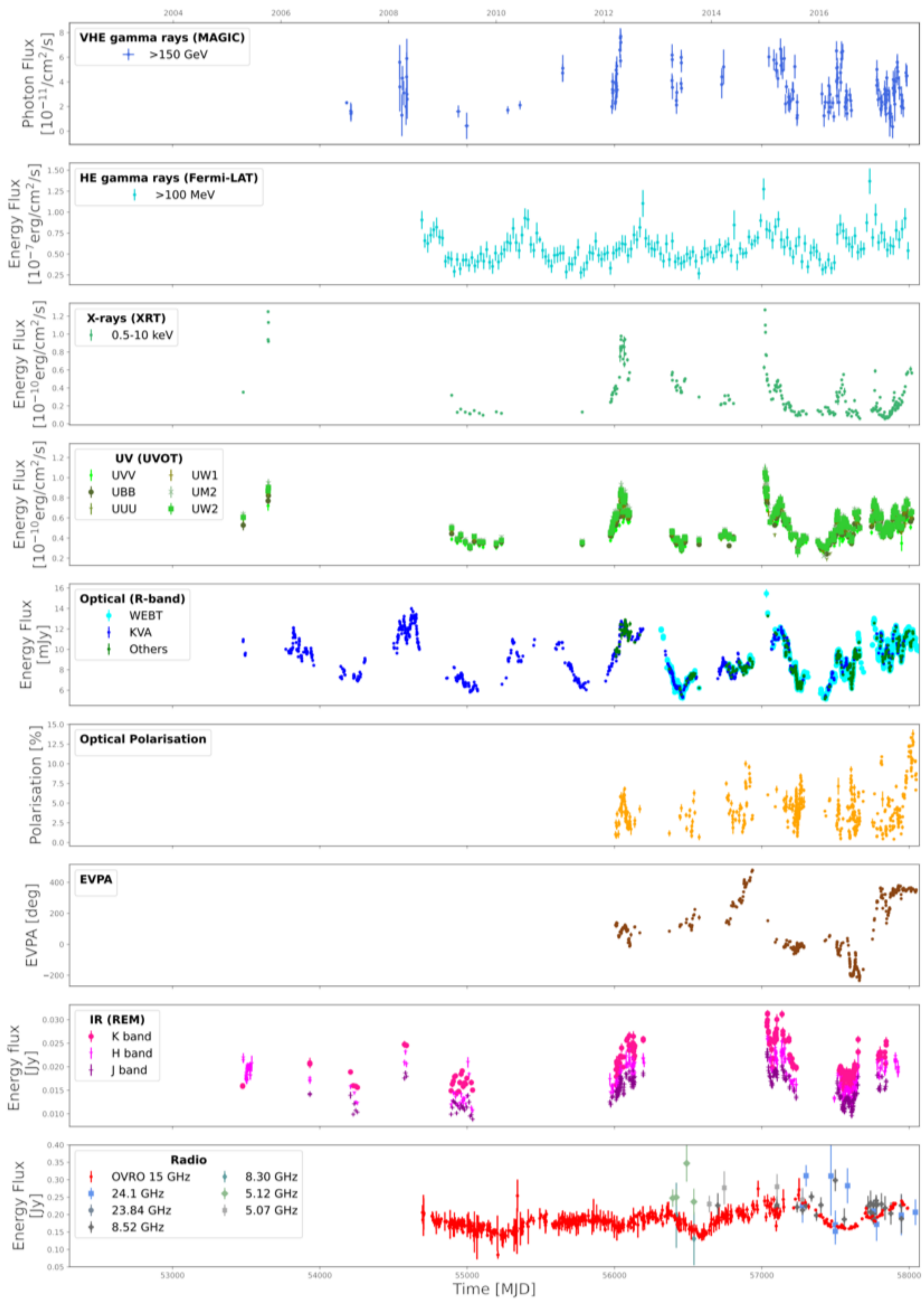


Figure 3.5: Multiwavelength long-term light curves of PG 1553+113).

3.2.2 Stellar and Galactic Astrophysics

An unprecedented double-peaked transient challenges supernova models

Tuomas Kangas led the follow-up and analysis of an enigmatic transient event, dubbed SN 2023aew. This initially seemingly uninteresting "stripped-envelope" supernova (SESN), i.e. a supernova (SN) with little or no hydrogen left in its progenitor star, exhibited a plateau in brightness, followed by a sudden rebrightening that led to a more luminous second peak, both longer and brighter than most other SESNe (Fig. 3.7). While other double-peaked SESNe do exist, the time delay between peaks is nearly always shorter and the second peak less abrupt. The second peak is due to a sudden increase in temperature while the photosphere radius nearly monotonically shrinks, indicating an internal heating mechanism powering the rebrightening.

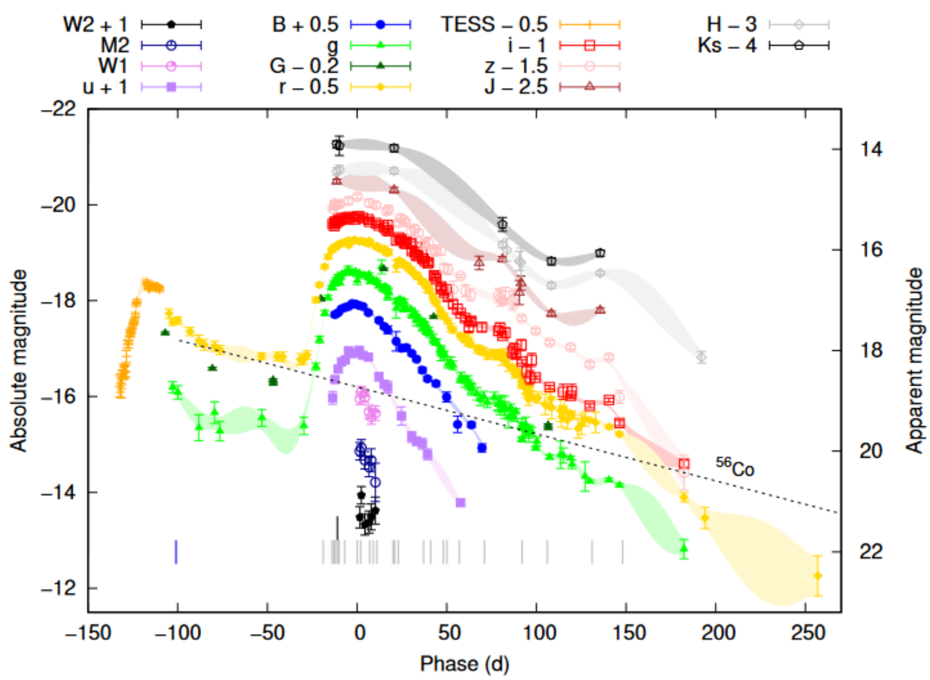


Figure 3.6: Light curve of the double-peaked SN 2023aew from the ultraviolet to the near-infrared. The delay between peaks is extremely long, and the second peak is more luminous than the SN (first peak) itself. The vertical lines indicate spectroscopic follow-up, while the dashed line denotes the decline rate from the usual power source of SESNe, the decay of cobalt-56, clearly inconsistent with both the early and late light curve. The light curve after the second peak is bumpy and the evolution of the object is very slow for a SN, possibly powered by accretion onto a newborn black hole.

The possibility of two SESNe on approximately the same line of sight was explored but excluded, as was a scenario where the first peak is merely a (powerful) pre-SN eruption. The first peak is almost certainly a real SN, followed by an unprecedented delayed input from some internal power source. Interaction between the ejecta and circumstellar material is disfavored as the dominant power source, although it can contribute in a smaller way. A central engine generated by a magnetar (a highly magnetized fast-spinning neutron star) born in the explosion is unlikely given the 100 d delay before its onset, but it is possible that the SN only represented a partial ejection of the progenitor star's envelope, followed by accretion of the fallback material onto a newborn black hole in the following months. This scenario does require some fine-tuning, but is tentatively supported by peculiarities in the spectra and light curves of both peaks. A paper on this object led by T. Kangas has been submitted.

Interacting Binary Stars

Pasi Hakala continued his various research programmes involving studies of interacting binary stars. These include several programmes using NASA's TESS data in order to study the causes of long term mass transfer changes in magnetic cataclysmic variables. In particular, he has used unsupervised neural networks (SOM) to classify different mass transfer modes of these systems, based on TESS light curves. Based on these classifications, he has also modelled the underlying cyclotron emission changes by mapping the cyclotron emission on the magnetic white dwarfs using the differential evolution algorithm (Mason , Hakala et al. 2024). He has also been involved in a photopolarimetric study of exotic hot subdwarf binaries, setting limits on accretion disc emission. Dr Hakala has also been leading three different ESO observing projects as PI, two of which include VLT data and one NTT data. These observations were carried out during summer 2023 and the data is mostly till under analysis. These projects involve co-Is from Oxford, Cambridge, Southampton, Warwick, IAC (Spain), Athens and Dartmouth. In particular, an extensive VLT/Xshooter monitoring programme of V Sge, an enigmatic, highly luminous, galactic interacting binary has produced exquisite data, that is opening new windows into the highest mass transfer rate regime ever observed onto a white dwarf. The high signal-to-noise XShooter spectra enable us to study the fine details of the accretion process like never before.

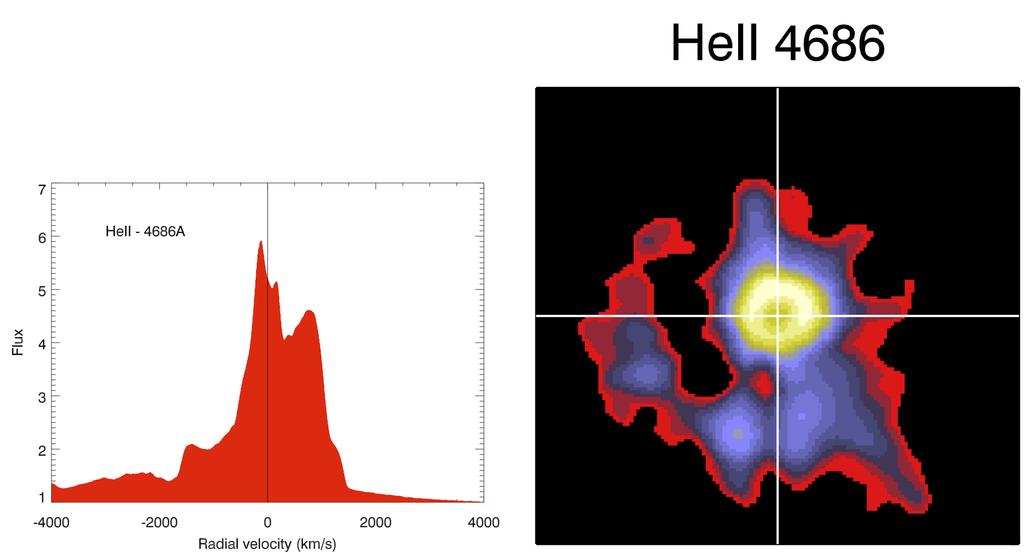


Figure 3.7: Example emission line profile (HeII 4686), together with a resulting Doppler tomogram (an image of accreting matter, constructed by inversion methods), produced from 50 individual spectra taken at different binary rotation angles, revealing previously unseen details.

Small Solar System bodies

Grigori Fedorets has commenced his FINCA postdoctoral fellowship in the Planetary Science Research group at the University of Helsinki in September 2023. Currently, his main scientific interest lies in observational studies of very small asteroids, which are the small building blocks of the Solar System. Physically characterising a statistically significant sample will eventually permit to pose additional constraints to the formation of the Solar System. Moreover, G. Fedorets has continued his duties as the maintainer of the software for orbit determination of the short-term processing (i.e. new discoveries) of ESAs Gaia mission.

Additionally, as a part of an international team lead by scientists from Queen's University Belfast, Fedorets has carried out research on developing a synoptic small Solar System body survey simulator for the upcoming LSST survey of the Vera C. Rubin Observatory. Upon its completion, and with the commencement of the LSST survey (anticipated in 2025), the ongoing project will, among other things, enable the debiased modelling of various small Solar System populations. Of particular interest to the researchers in the University of Helsinki Planetary Research group is the modelling of discoverability of the elusive population of minimoons – asteroids that are temporarily captured Earth's satellites.

4. Instrument Development

Son of X-Shooter (SOXS) nearing completion

The SOXS instrument is in the construction phase. The construction of the calibration unit (CU) of SOXS, Finland's contribution funded through FINCA FIRI grant, was completed in the SOXS lab at Quantum building, University of Turku, in 2021. The work was led by Academy Fellow **Hanindyo Kuncarayakti** (Department of Physics and Astronomy, Univ. Turku), a former FINCA post-doc. SOXS CU incorporates commercially available parts and custom-made components, some are manufactured by University of Turku's Protopaja workshop. The SOXS CU was shipped to the integration hall in INAF Padova, Italy, and integrated with the rest of the SOXS instrument. The other SOXS subsystems, such as the UV-VIS and NIR spectrographs (Fig. 4.1), the common path, and the acquisition camera, are also finished and are being integrated in Padova – SOXS as a whole is thus nearing completion, expected in 2024. The Finnish contribution to the project subsequently enters a new phase, where we cover the instrument troubleshooting, and spare parts procurement, with no in-house hardware work ongoing or foreseen.

MICADO: the first-light instrument for the ELT

Participation in much larger scale ELT instrument projects is necessary for the Finnish community to strengthen its position in front-line astronomical research. These instruments are being built by international consortia between institutes in ESO member states. Being involved in a first-light ELT instrument represents a unique opportunity for the Finnish community to get access to ELT data from the start. For this purpose, we are full members in, and have used the FIRI funding, to participate in the MICADO consortium, including in-kind contributions led by UTU.

MICADO, the adaptive optics (AO)-assisted diffraction-limited near-infrared imager and long-slit spectrograph, is progressing successfully and is poised to be the first-light ELT instrument ready to start operations in 2028 when the ELT will be completed. MICADO has much better sensitivity and spatial resolution than any current facility, and addresses key science topics, such as the dynamics of dense stellar systems, black holes in galaxies, the star formation history of galaxies through resolved stellar populations, the formation and evolution of galaxies in the early universe, planets and planet formation, and the solar system. The primary science cases for MICADO are an

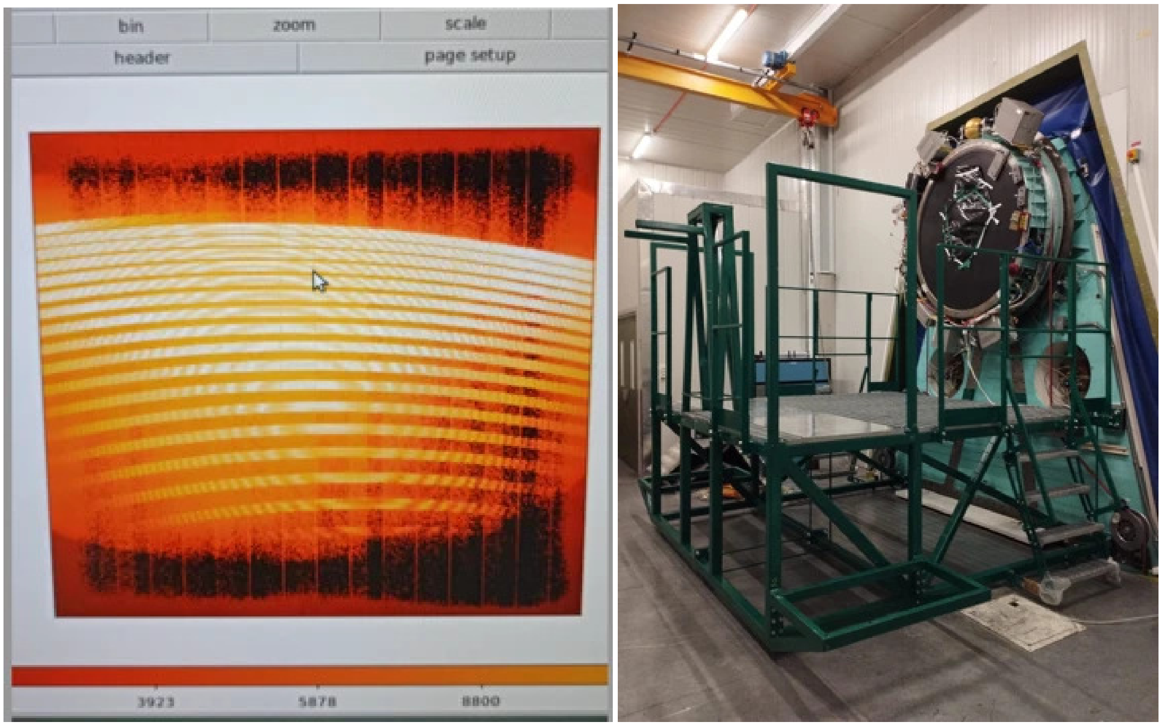


Figure 4.1: SOXS progress in 2023. *Left*: First light image of the SOXS NIR array. *Right*: SOXS platform installed at the NTT telescope at La Silla.

Figure 4.2: The logos of the participating institutes of the MICADO consortium

excellent match with science interests in all FINCA affiliated universities.

MICADO is undergoing the final phases of the Final Design Review (FDR), which is expected for completion in 2024. Following the FDR, the hardware work will proceed fully in order to construct the instrument and have it ready on time. A group led by Academy Researcher **Hanindyo Kuncarayakti** (Dept. Physics and Astronomy, Univ. Turku), together with Jani Achren from Incident Angle, a local optical design company, FINCA postdoc **Johanna Hartke**, and **Seppo Mattila** (University of Turku) participate in the PSF-Reconstruction Working Group of MICADO, within the non-AO effects Work Package. Activities include simulating the MICADO optical train and the resultant point spread function (PSF) as affected by turbulence and aberrations, and defining the MICADO calibration procedures with the ELT.

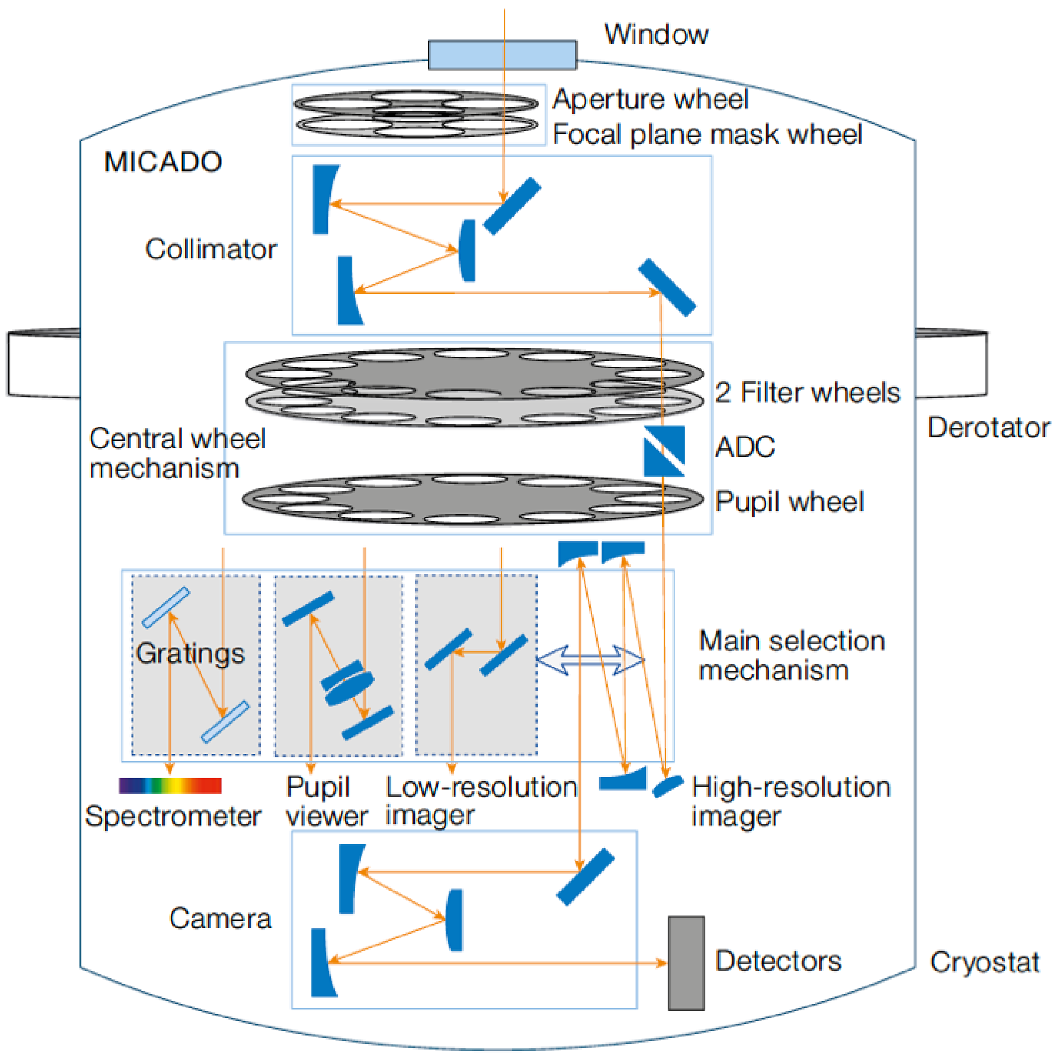


Figure 4.3: Schematic view of the MICADO design concept, illustrating how the cold optics and mechanisms are assigned to separate modules that can be tested separately and then integrated together in the cryostat.

Hardware at Metsähovi Radio Telescope

Backend development for the new ultra wideband triple band receiver for Metsähovi Radio Observatory is part of the Academy of Finland early career research project lead by Academy Research Fellow **Talvikki Hovatta**. In 2023, the former FINCA postdoc **Derek McKay** started as the operations engineer at Metsähovi and **Kaj Wiik** and **Bela Dixit** started working on the backend development. The initial FPGA (Field Programmable Gate Array) design of the backend was finished and verified that it fits to the selected FPGA and that it passes the timing constraints. A modular system was selected as the basis of the backend: the timing critical high speed RFSoC subsystem will be purchased as a module and a carrier board containing e.g. the analog downconverters will be designed in-house. Support for the KnowledgeResources RFSoC module was added to the CASPER design toolflow. Testing of the interleaving and sideband separation algorithms continued successfully.

The CTA array at ESO

CTAO, the first VHE gamma-ray observatory will consist of two telescope arrays: the CTAO Northern array, on Instituto de Astrofísica de Canarias' (IAC's) Roque de los Muchachos Observatory on the Canary island of La Palma (Spain), and the CTAO Southern array, at the European Southern Observatory's (ESO's) Paranal Observatory in the Atacama Desert (Chile, Fig. 4.4). In 2023, the construction of the three more LST telescopes of the Northern array started. Also the preparation for the science data challenge continued in collaboration between CTAO and CTA Consortium. **Elina Lindfors** from FINCA was serving as Science Coordinator of CTAC in 2020-2021 and remains involved in the preparation of the science data challenge.

African Millimetre Telescope

qIn 2023, a major European Research Council Synergy Grant, where FINCAns **Talvikki Hovatta** and **Elina Lindfors** are co-Is, was granted that secured building of the African Millimetre Telescope. African Millimetre Telescope will be built in Namibia and it will be part of the Event Horizon Telescope, where also ALMA participates. AMT will also perform single dish flux monitoring, which will have important science synergies with CTAO.

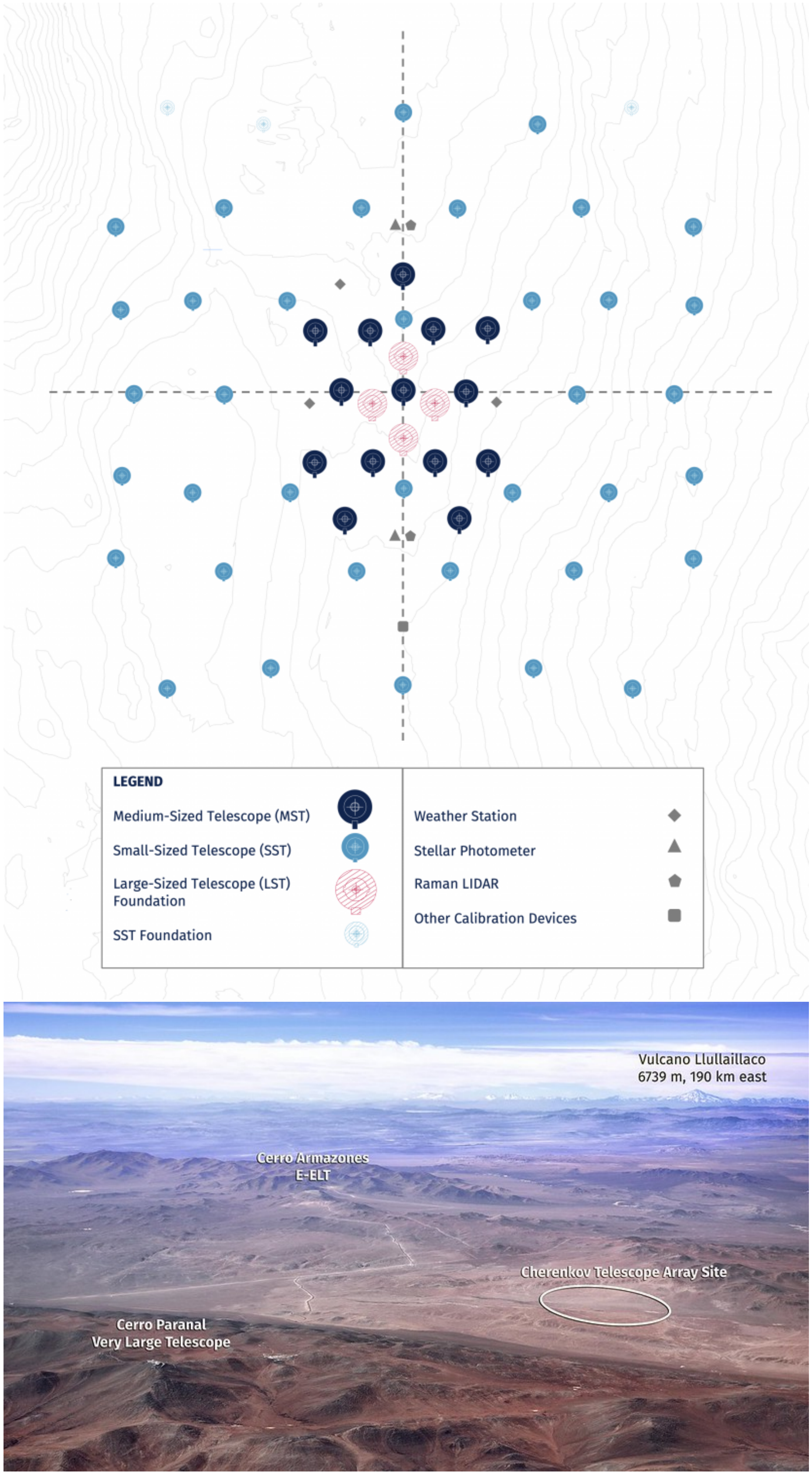
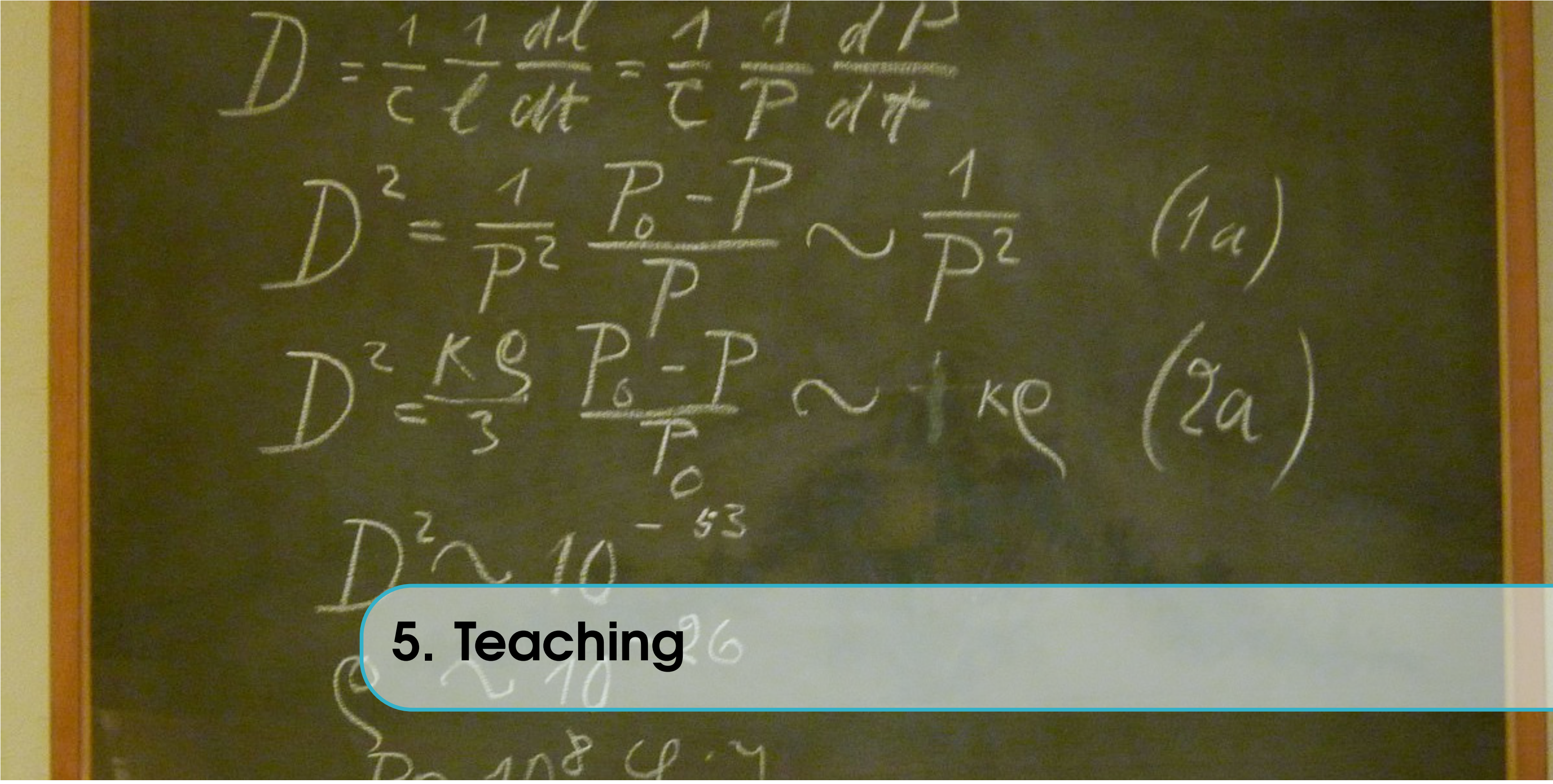


Figure 4.4: The CTAO array and location.



5. Teaching

5.1 Lectured courses (in whole or in part)

Basic level - in Finnish

Teacher	Course	Credits	Location
Jenni Jormanainen (assistant)	The Big Bang for the Studies	4	Turku
	NOT-school for high schoolers	NA	Turku
Talvikki Hovatta (co-lecturer)	Introductory Astronomy (Radio)	5	Turku
Elina Lindfors (co-lecturer)	Maailmankaikkeuden ja maapallon luonnon kehitys alkuräjähdyksestä nykyhetkeen	5	Turku

Advanced level - in English

Teacher	Course	Credits	Location
Roberto De Propris (co-lecturer)	Galaxies and Cosmology	4	Turku
Tuomas Kangas (co-lecturer)	Observational Techniques Using the Nordic Optical Telescope	7	Turku
	Spectroscopic Diagnostics in Astrophysics	8	Turku
Talvikki Hovatta (co-lecturer)	Radio Astronomy and Interferometry	5	Turku
Q. Salomé	Introduction to Space	5	Aalto
	Radio Astronomy I	5	Aalto
Grigori Fedorets (course assistant)	Small Bodies in the Solar System		Helsinki
Grigori Fedorets (course assistant)	Advanced Course in Observational Astronomy I		FINCA

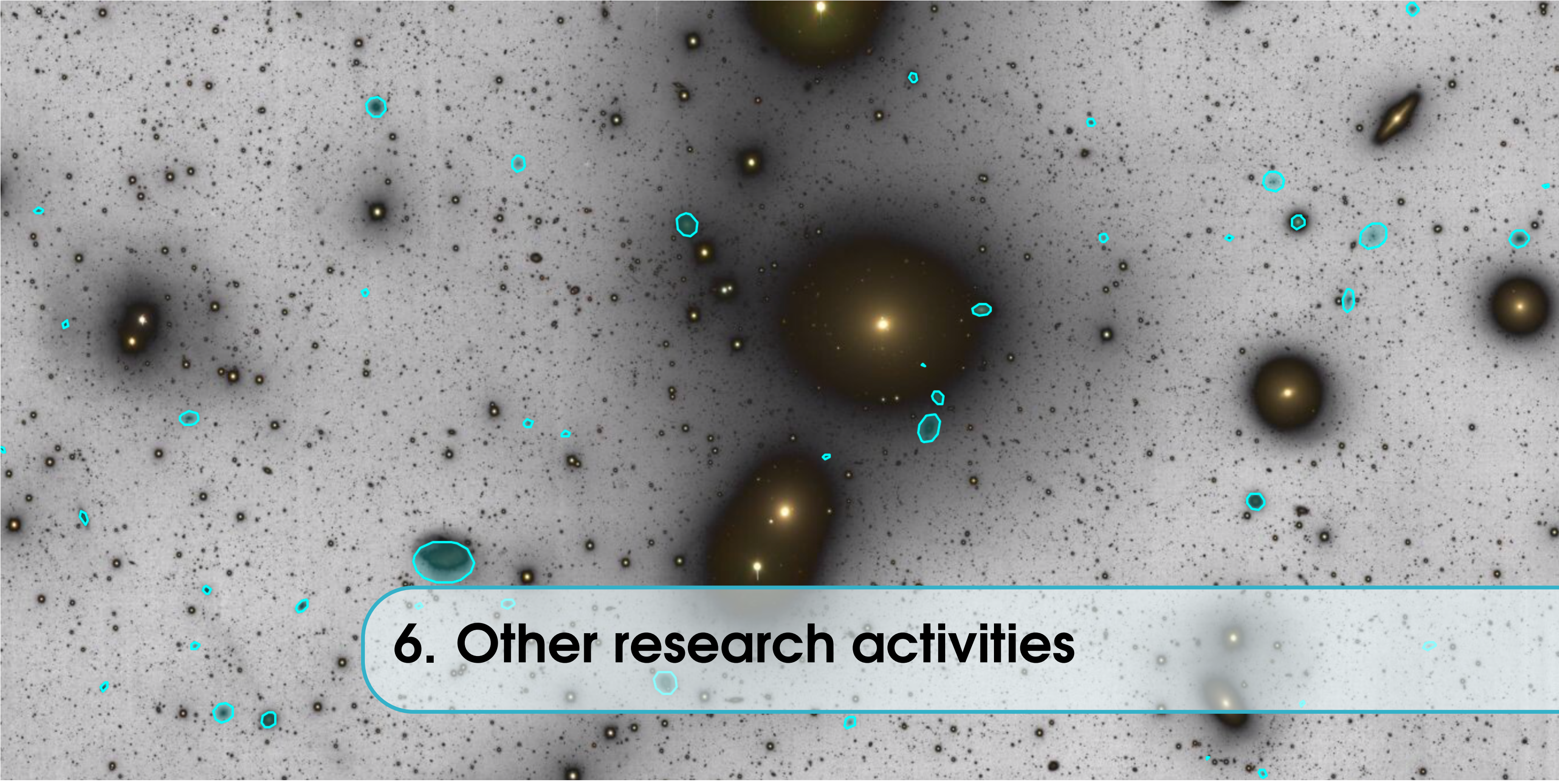
5.2 Completed theses

MSc theses

Jan Aaltonen, University of Turku, *Investigating the connection between optical and very high energy gamma-ray emission of BL Lac objects*, supervisor: Elina Lindfors

PhD theses

Matthew Grayling, University of Southampton, UK *Core-collapse Supernovae in the Dark Energy Survey*, co-supervisor: Claudia Gutierrez



6. Other research activities

Memberships in conference SOC/LOC and other committees

T. Hovatta	Finnish representative in the ESO Scientific Technical Committee
	Member of the European Science Advisory Committee for ALMA
J. Hartke	Member of the ESO ELT PSF-R working group
E. Lindfors	Member of the National Committee of Education and Outreach
K. Nilsson	Member of the OPTICON-Radionet pilot programme time allocation committee
Q. Salomé	Board Member of the Finnish Astronomical Society
	Loc Member for Astronomers' Days

Conference presentations

E. Lindfors	“Observations of AGN variability with CTA", CTA consortium meeting, Granada, Spain, April 2023
	”Association of IceCube neutrinos with major blazar flares” International Cosmic Ray Conference, Nagoya, Japan, August 2023
	"Target of Opportunity and Flat Spectrum Radio Quasar observations with MAGIC" MAGIC 20 years science symposium, La Palma, Spain, October 2023
T. Hovatta	“Resolving supermassive black hole jets with VLTI-GRAVITY”, ESO day 2023, June 2023, Helsinki (invited)
J. Hartke	”Mapping the outskirts of galaxies with discrete tracers”, 14 July 2023, invited talk EAS SS10, Krakow, Poland
	“Planetary nebulae populations in the haloes of nearby massive early-type galaxies” 4 September 2023, invited talk IAU Symposium 384, Krakow, Poland
Q. Salomé	“Inefficient jet-induced star formation in Centaurus A: Can shocks regulate star formation in the northern filaments?” (talk) AGN on the beach, 10-15 September, Tropea (Italy)
T. Kangas	"The ZTF phase I sample of hydrogen-rich superluminous supernovae without strong narrow emission lines", EAS 2023, Krakow, Poland, July 2023

Other talks

E. Lindfors	"Multimessenger emission of relativistic jets launched by supermassive black holes", Botswana International University of Science and Technology, May 2023
	"Shocking news - a polarizing study of a tidal disruption event", University of Namibia, May 2023
J. Hartke	“Integral-field spectroscopy with VLT-MUSE”, 7 February 2023, FINCA retreat, Teijo, Finand
	“Tracing halo and intra-cluster light assembly with planetary nebulae”, 17 March 2023, Helsinki Astrophysics Seminar, Helsinki, Finland
	“The case of UDG32”, 4 April 2023, LEWIS collaboration meeting, INAF Naples, Italy
	“The MUSE-faint survey”, 2 June 2023, Galaxy Journal Club, University of Oxford, UK
	“A multi-tracer view on the assembly of galaxy halos and intra-group light in nearby groups and clusters”, 11 October 2023, INAF colloquium, Naples, Italy

Research Visits

T. Hovatta	California Institute of Technology, USA, 10-30 November 2023
J. Hartke	MICADO consortium meeting and visit to INAF Padova (hosted by Dr A. Zanella), 28 March — 31 March 2023, Padova, Italy
	LEWIS collaboration meeting and visit to INAF Naples (hosted by Dr M. Spavone and Dr E. Iodice), 3 April — 5 April 2023, Naples, Italy
	Research visit to Sub-department of Astrophysics (hosted by Dr C. Spiniello and Prof. Dr M. Bureau), University of Oxford, 31 May — 7 June 2023, Oxford, UK
	FINCA mobility visit to INAF Naples (hosted by Dr E. Iodice), 29 September 2023 — 12 October 2023, Naples, Italy
	JWST Data Masterclass, 12 — 14 December 2023, ESA Madrid, Spain

Other Activities

E. Lindfors	PhD thesis opponent and pre-examiner: Anna Luahvili "Study of the origin of rapid variability observed in two classes of Active Galactic Nuclei: peculiar gamma-ray emitting NLS1 galaxies and powerful TeV-detected blazars", PSL University Paris, France
E. Lindfors	PhD thesis opponent and pre-examiner: Hector Rueda "Period Search and Forecasting Techniques in Gamma-ray Active Galactic Nuclei with a Time-Domain Formalism", Universite Paris-Saclay, France
E. Lindfors	PhD thesis opponent and pre-examiner: Jorge Oetro Santos "Disentangling the contributions to the optical emission of gamma-ray bright blazars through variability studies", University of La Laguna, Spain

Hosted visitors

Visitor	Time	Host(s)
Heidi Korhonen (ESO) and Preeti Kharb (NCRA)	March 2023	E. Lindfors & T. Hovatta
Simone Garrapa (Humbholdt University, Germany)	May 2023	E. Lindfors
Jorge Otero Santos, IAA Granada, Spain	July 2023	E. Lindfors
Karri Koljonen, NTNU, Norway	August 2023	E. Lindfors
Ana I. Ennis (University of Waterloo and Perimeter Institute, Waterloo, Canada)	3-7 July 2023	J. Hartke

7. Publications

Refereed publications by FINCA staff 2023:

1. Abdollahi, S. et al. (**Liodakis**) 2023, The Fermi-LAT Lightcurve Repository, ApJS, 265, 31
2. Abe, H. et al. (**Fallah Ramazani, Jormanainen, Hovatta, Lindfors, Nilsson, Satalecka**) 2023, Multimessenger Characterization of Markarian 501 during Historically Low X-Ray and γ-Ray Activity, ApJS, 266, 37
3. Abe, H. et al. (**Fallah Ramazani, Jormanainen, Lindfors, Nilsson, Satalecka**) 2023, Search for Gamma-Ray Spectral Lines from Dark Matter Annihilation up to 100 TeV toward the Galactic Center with MAGIC, Physical Review Letters, 130, 6, article id.061002
4. Abe, H. et al. (**Fallah Ramazani, Jormanainen, Lindfors, Nilsson, Satalecka**) 2023, MAGIC observations provide compelling evidence of hadronic multi-TeV emission from the putative PeVatron SNR G106.3+2.7, A&A, 671, 12
5. Abe, H. et al. (**Jormanainen, Kouch, Lindfors, Nilsson, Satalecka, Suurinen**) 2023, Performance of the joint LST-1 and MAGIC observations evaluated with Crab Nebula data, A&A, 680, A66
6. Acciari, V. A. et al. (**Fallah Ramazani, Jormanainen, Hovatta, Lindfors, Liodakis, Nilsson, Satalecka**) 2023, Long-term multi-wavelength study of 1ES 0647+250, A&A, 670, 49
7. Acciari, V. A. et al. (**Fallah Ramazani, Lindfors, Nilsson,**) 2023, Study of the GeV to TeV morphology of the γ Cygni SNR (G 78.2+2.1) with MAGIC and Fermi-LAT. Evidence for cosmic ray escape, A&A, 670, 8
8. Acciari, V. A. et al. (**Fallah Ramazani, Jormanainen, Lindfors, Liodakis, Nilsson,**) 2023, A lower bound on intergalactic magnetic fields from time variability of 1ES 0229+200 from MAGIC and Fermi/LAT observations, A&A, 670, 145
9. Acero, F. et al. (**Lindfors, Liodakis Satalecka**,) 2023,Astroparticle Physics, Volume 150, article id. 102850.
10. Acharyya, A. et al. (**Hovatta, Lähteenmäki,Liodakis**, 2023, VERITAS Discovery of Very High Energy Gamma-Ray Emission from S3 1227+25 and Multiwavelength Observations, ApJ, 950, 152
11. Acharyya, A. et al. (**Lindfors**, 2023, Sensitivity of the Cherenkov Telescope Array to TeV photon emission from the Large Magellanic Cloud, MNRAS, 525, 5353

12. Akiyama, K., et al. (**Ramakrishnan**, 2023, First M87 Event Horizon Telescope Results. IX. Detection of Near-horizon Circular Polarization, ApJ, 957, L20
13. Ali, S. S. & **De Propris** 2023, Unveiling UV-bright stellar populations in red and dead galaxies with CUBES, Experimental Astronomy, 55, 199
14. Alvarez-Hernandez, A. et al. **Hakala** 2023, Dynamical mass of the white dwarf in XY Ari: a test for intermediate polar X-ray spectral models, MNRAS, 524, 3314
15. Arendt, R. G. et al. **Kangas** 2023, JWST NIRCam Observations of SN 1987A: Spitzer Comparison and Spectral Decomposition, ApJ, 959, 95
16. Bettoni, D. et al. (**Kotilainen** 2023, Low-redshift quasars in the SDSS Stripe 82 - III. MOS observations, MNRAS, 519, 2929
17. Bevacqua, D. et al. (**De Propris, R.**) 2023, The elemental abundance of quiescent galaxies in the LEGA-C survey: the (non-)evolution of [α/Fe] from z = 0.75 to z = 0, MNRAS, 525, 4219
18. Blinov, D. et al. (**Hovatta, Jormanainen, Liodakis** 2023, The RoboPol sample of optical polarimetric standards, A&A, 677, 144
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33. Di Gesu, L. et al. (**Kouch, Lindfors, Liodakis**) 2023, Discovery of X-ray polarization angle rotation in the jet from blazar Mrk 421, Nature Astronomy, 7, 1245
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63. **Liodakis, I.** et al. (**Berton,Hovatta, Koljonen, Jormanainen,Lindfors, Nilsson** 2023, Optical polarization from colliding stellar stream shocks in a tidal disruption event, Science, 380, 656
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