Finnish Centre for Astronomy with ESO

Annual Report

2022

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FINNISH CENTRE FOR ASTRONOMY WITH ESO, ANNUAL REPORT 2022

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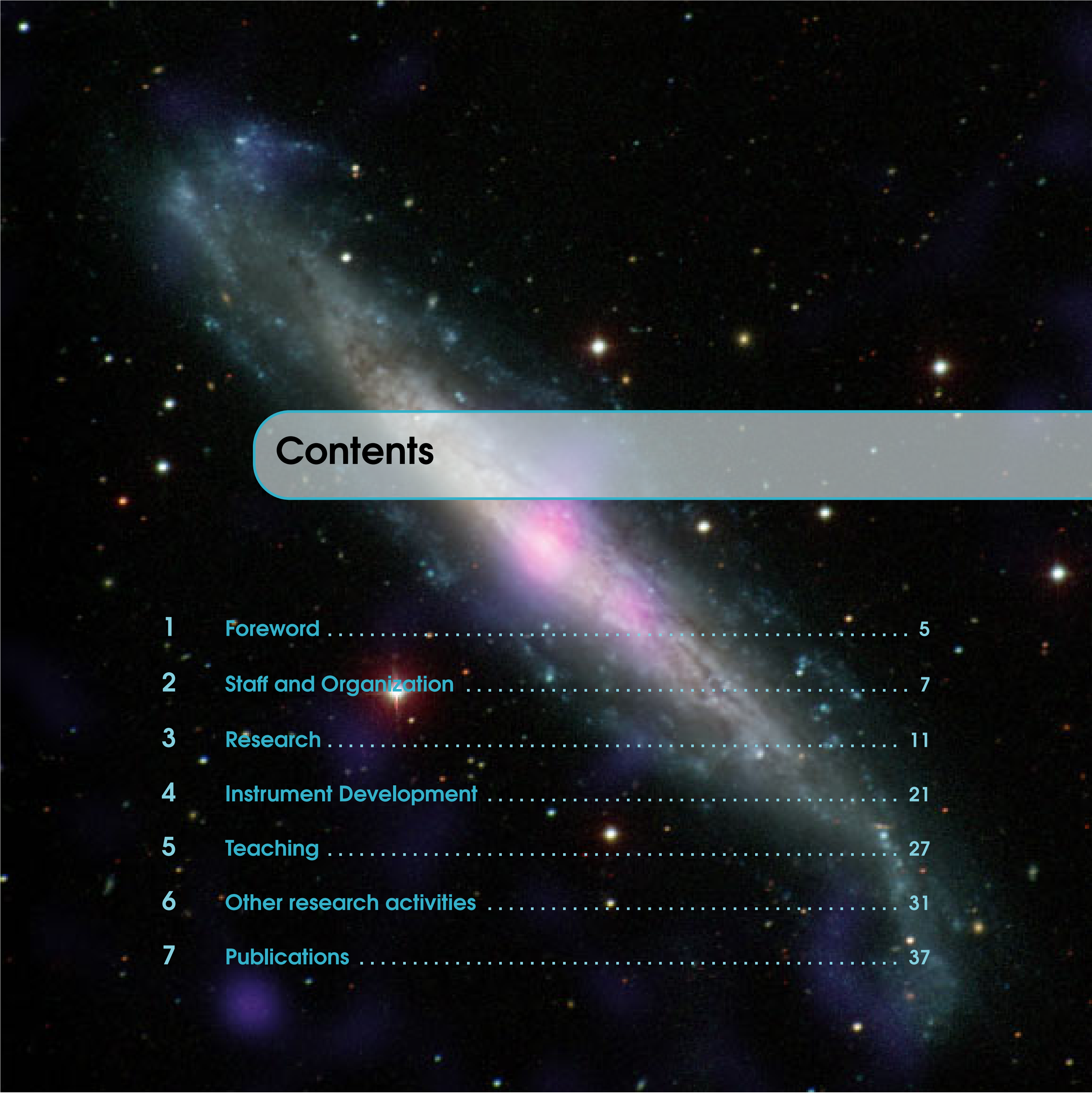
Cover: The peculiar S0 Centaurus A (courtesy: ESO)



Contents

1 Foreword 5

2 Staff and Organization 7

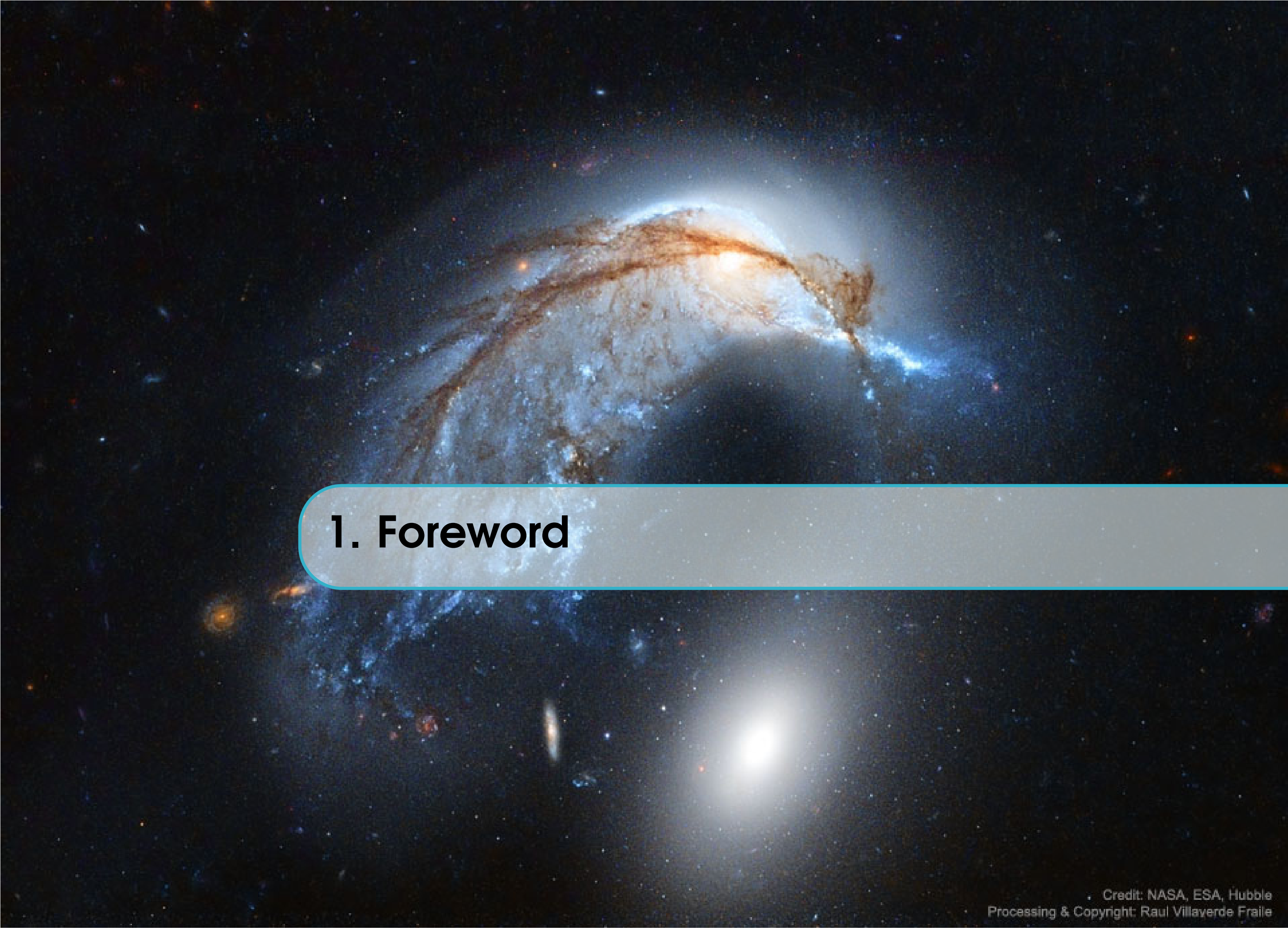
3 Research 11

4 Instrument Development 21

5 Teaching 27

6 Other research activities 31

7 Publications 37



1. Foreword

Finland is a member of the European Southern Observatory (ESO) since 2004. ESO is a world leading astronomical research and technology organization, with 16 member states, headquarters in Garching, Germany, and three world-class observatories in Chile.

Finnish Centre for Astronomy with ESO (FINCA) is a national research institute for astronomical and astrophysical research in Finland. FINCA coordinates Finnish co-operation with ESO by networking into the ESO infrastructure and projects; practices and promotes high quality research in all fields of astronomy, and ESO-related technological development work; participates in researcher training in astronomy; and fosters and implements ESO-related co-operation of all the Finnish universities engaged in astronomical research. 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 2022 marked the 13th 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 (Aalto, Helsinki, Oulu and Turku). The highest decision-making body is the Board, chaired by Vice-Rector Kalle-Antti Suominen of the University of Turku, 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), chaired by

Prof. Susanne Aalto (Chalmers University of Technology, Sweden),

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, 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 Nordic Optical Telescope (NOT), and the Atacama Large (Sub)Millimeter Array (ALMA) in the optical, near-infrared and (sub)millimeter wavelengths. Observational research is supplemented by modelling, simulations and theoretical work, that are essential in understanding the physics behind the observations. Our research is characterized by strong collaboration both within FINCA, with other astronomy departments in Finland and internationally.

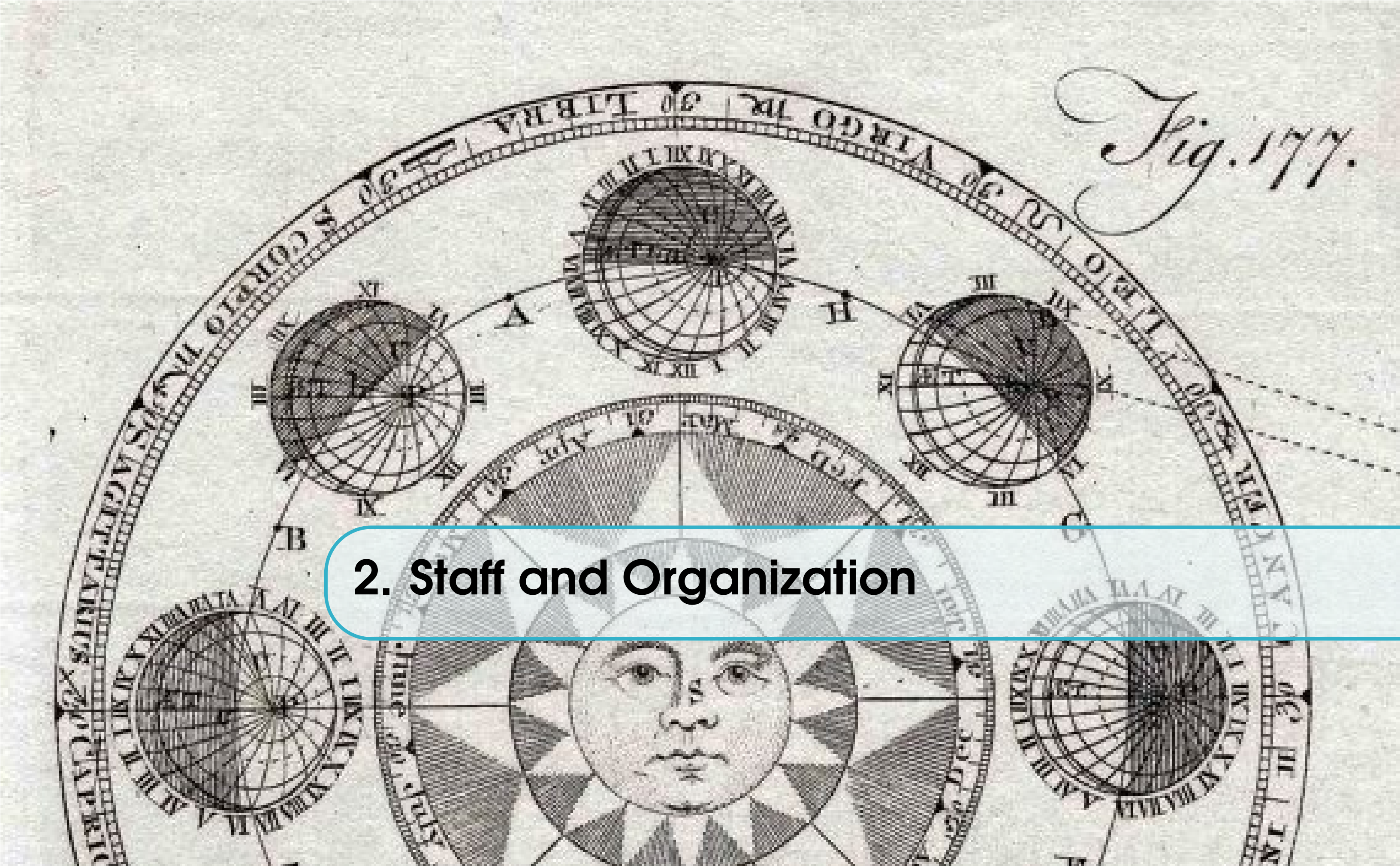
The corona situation continued to affect our research activities in 2022. International conferences were either canceled or moved on-line. Despite this, FINCA research was reported in 57 refereed scientific articles in 2022, and some of them are highlighted in this Report.

Our researcher training activities in 2022 focused on supervision of PhD and MSc students in the participating universities. Furthermore, we were able to organize 1) the annual course on remote optical/infrared observing with the NOT for MSc and PhD students and 2) the practical course for Finnish high school students on remote observations with the NOT, in hybrid mode at the Tuorla Science Center.

The construction of the ESO Extremely Large Telescope (ELT), a 39 m diameter giant for infrared and optical astronomy, is well underway, with Phase 1 instruments being constructed, Phase 2 instruments being in final design phase, all major contracts for the construction of the ELT been awarded, and construction started at Cerro Amazons. This keeps ESO on-track to remain in a world-leading position, when the ELT is expected to start operations in September 2027, only five years time from now, bringing an enormous leap forward in sensitivity and resolution.

Our acquired external funding has increased significantly in recent years. Especially, the research infrastructure (FIRI) grant from the Academy of Finland has enabled our participation in ESO instrument projects, FINCA is participating on behalf of the Finnish community in the ELT first-light instrument consortium MICADO (near-infrared adaptive optics imager), both by funding and by participating in the PSF reconstruction, in collaboration with the Department of Physics and Astronomy of the University of Turku, and the Lappeenranta University of Technology. MICADO is expected to be the only first-light instirument at ELT for some time after 2027. FINCA is also participating in a new instrument to the ESO 3.5-m New Technology Telescope (NTT), the Son Of X-Shooter (SOXS), with first light expected in 2023. Notably, the calibration unit of SOXS was built at the University of Turku, in collaboration with several local companies. FINCA will apply for more instrumentation funding from the Academy in future FIRI calls to strengthen the position of the Finnish community toward the ELT era, including participation in another ELT instrument, MOSAIC (optical and near-infrared multi-object spectrograph).

Jari Kotilainen,
FINCA Director



2. Staff and Organization

FINCA staff (Turku, unless otherwise indicated)

Director :	Jari Kotilainen
Professor emeritus :	Mauri Valtonen
University Researchers :	Roberto De Propris Pasi Hakala Kari Nilsson
Academy Research Fellows	Talvikki Hovatta (Aalto/Turku) Elina Lindfors
Postdoctoral Researchers	Claudia Gutierrez Johanna Hartke (from 1.11.2022) Jenni Jormalainen Tuomas Kangas (from 1.09.2022) Karri Koljonen (Aalto) Yannis Liodakis Derek McKay (Turku/Aalto) Venkatessh Ramakrishnan (Aalto) Quentin Salome (Aalto) Stephen Williams

FINCA board

Members

Name	University
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Mika Juvela	Helsinki
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Aku Venhola	Oulu
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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 2022, our research were reported in 57 refereed scientific articles, and some of them are highlighted below.

3.2 Research Highlights

3.2.1 Cosmology and Extragalactic Astrophysics

Polarized blazar X-rays imply particle acceleration in shocks

Some of the brightest objects in the sky are called blazars. They consist of a supermassive black hole feeding off material swirling around it in a disk, which can create two powerful jets perpendicular to the disk on each side. A blazar is especially bright because one of its jets of high-speed particles points straight at Earth. For decades, scientists have wondered: How do particles in these jets get accelerated to such high energies? In a new study published in Nature, led by FINCAns including **Yannis Liodakis** (lead author, FINCA), **Jenni Jormanainen, Elina Lindfors, Kari Nilsson**, using NASA's Imaging X-Ray Polarimetry Explorer (IXPE), astronomers find that the best explanation for the particle acceleration is a shock wave within the jet. IXPE observed Markarian 501 twice in early and late March of 2022. During these observations, many other telescopes in space and on the ground gathered information about the blazar in a wide range of wavelengths of light. These telescopes included the Nordic Optical Telescope (NOT), partly owned by the University of Turku. It was found that X-ray light is more polarized than optical, which is more polarized than radio. But the direction of the polarized light was the same for all the wavelengths of light observed and was also aligned with the jet's direction. After comparing their information with theoretical models, the paper demonstrated that the data most closely matched a scenario in which a shock wave accelerates the jet particles (Fig. refblazar). As particles travel outward away from the shock, they emit X-rays first because they are extremely energetic. Moving farther outward, through the turbulent region farther from the location of the shock,they start to lose energy, which causes them to emit less energetic light like optical and then radio waves

Evolution of the remnant of SN 1987A

Supernova (SN) 1987A is the closest SN observed in modern times and has provided the opportunity for the longest, most detailed follow-up of a SN and its transition into a SN remnant. **T. Kangas**, in collaboration with researchers in Finland and Sweden, submitted a paper on the evolution of the remnant in the near-infrared until 2017 using data from the NACO and SINFONI instruments on the VLT. The clearest feature of the remnant is the so-called equatorial ring (ER): mass lost by the progenitor star of SN 1987A some 20000 years before the explosion, illuminated by ongoing interaction with the SN ejecta. The evolution of the ER is similar in the optical and the near-infrared, but unlike in the optical, a part of the continuum emission spreads outside the ER over time. This component could be synchrotron radiation. The light curve of the ER is also similar to that in the mid-infrared, where dust emission dominates, and the possibility of hot (2000 K) dust dominating the total near-infrared luminosity is explored, but deemed unlikely. If hot dust is present in the system, its mass must be several orders of magnitude smaller than that of the warm (hundreds of K) dust that emits in the mid-infrared. The current and future evolution of the remnant is being followed up in exquisite detail with the James Webb Space Telescope.

Resolved analysis of the molecular outflowing gas in IRAS 17020+4544

IRAS 17020+4544 is a narrow-line Seyfert 1 galaxy for which a multicomponent ultra-fast outflow (UFO) was clearly identified in X-ray. Later, Longinotti et al. (2018) reported the presence of molecular outflowing gas observed as a broad blueshifted component in CO emission. Follow-up observations with NOEMA allows to resolve the CO emission and to derive the position of this outflowing gas with respect to the host galaxy. The analysis of the NOEMA data conducted by **Quentin Salomé**revealed the presence of 5 molecular outflows on both side of the AGN. Those

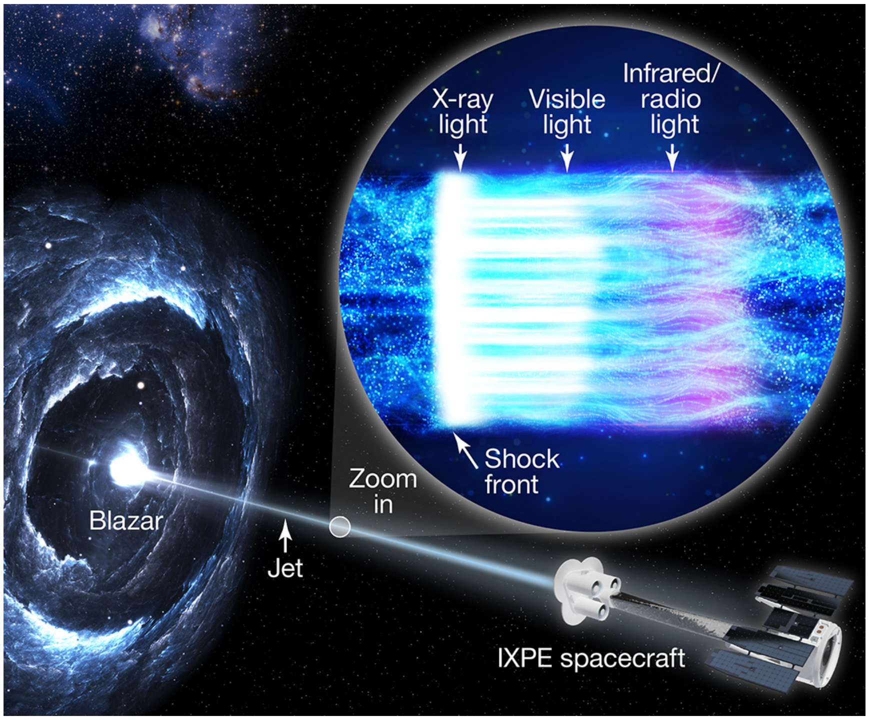


Figure 3.1: his illustration shows the IXPE spacecraft, at right, observing blazar Markarian 501, at left. A blazar is a black hole surrounded by a disk of gas and dust with a bright jet of high-energy particles pointed toward Earth. The inset illustration shows high-energy particles in the jet (blue). When the particles hit the shock wave, depicted as a white bar, the particles become energized and emit X-rays as they accelerate. Moving away from the shock, they emit lower-energy light: first visible, then infrared, and radio waves. Farther from the shock, the magnetic field lines are more chaotic, causing more turbulence in the particle stream. Image credit: Pablo Garcia (NASA/MSFC)

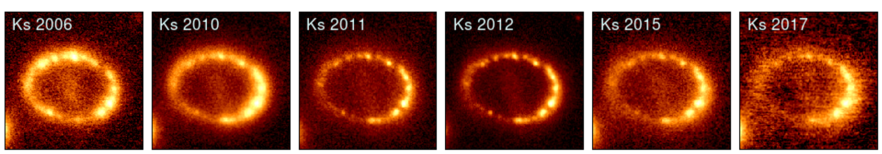


Figure 3.2: Evolution of the remnant of SN 1987A in the Ks band between 2006 and 2017, dominated by a ring of circumstellar matter ejected by the progenitor star and lit up by interaction with the ejecta. By 2010 the outer ejecta has passed the ring and it starts fading. The east side of the ring (left) fades much faster than the west side, which dominates the total brightness later on. This could indicate asymmetry in the explosion itself or in the density of the ring.

outflows have molecular gas mass of few 10^7 $M_\odot$ and velocities up to 2000 km/s (both blueshifted and redshifted). The comparison of the kinematics of the molecular and X-ray outflows confirms that this galaxy-scale outflow falls in the energy-conservation regime, suggesting that IRAS 17020+4544 is undergoing feedback processes. More details in Longinotti et al. (2023).

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

The further history of OJ287

Mauri Valtonen has coordinated a large international observing campaign of OJ287 during 2022. Besides FINCA, participants came from Tuorla observatory of University of Turku, from Metsähovi radio observatory, and 18 other institutions around the world. The observations covered the range from 37 GHz radio observations all the way to Gamma rays, seen by the Fermi Gamma-ray telescope. The reason for the campaign just at this time was that an impact of the secondary black hole on the accretion disk of the primary was expected in the OJ287 binary system. This was the best opportunity to study such an impact since 2005, when many of the participants had already taken part in the first campaign. The comparison of the results of the two campaigns confirmed much what was known about OJ287 beforehand, but new surprising facts also emerged. The first results of the campaign have just appeared in MNRAS, and many more reports are under preparation. The progress of the disk impact was expected to be revealed by a series of flares: In the interval JD2458890 to 2459030 a big and unusual flare was predicted by Sundelius et al. already in 1997. It was observed, and reported in a series of papers by Komossa et al., including many of our campaign members. In the interval JD2459160 to 2459240 a special flare called "precursor" was predicted by Pihajoki et al. 2013. It has also been observed, and the publication of results is under preparation. In the interval JD2459610 to 2459650 a very special and unique flare was expected which was predicted by our campaign members in 2021. It was seen and was well covered by multi-messenger observations which have now been published. They proved the basic parameters of the binary model correct, such as the primary mass which is now known with the accuracy of better than one percent. In addition to the verified predictions, there were two big surprises. The first one a was huge flare, rising to about 10^{46} ergs per second (if isotropic radiation) and back down to zero in just one day. Nothing like this have ever before been observed in OJ287 in the 50 years of intense monitoring, or in the overall 130 year historical data. The other surprise was a big Gamma-ray flare exactly when the secondary plunged through the accretion disk. Looking back at the orbit history and the Gamma-ray flare history, the same phenomenon was also seen by the Fermi telescope when the previous similar disk impact took place. A paper is in preparation relating to these unusual events. In the coming year a big emission line flare is expected where the lines may brighten up to an order of magnitude. Also the orientation of the radio jet is followed by VLBI observations. The jet has followed the complicated path predicted by the above mentioned binary model now for many years.

First-ever image of the shadow of the supermassive black hole in the centre of the Milky Way

In May 2022, the Event Horizon Telescope Consortium (EHTC) published the image of the supermassive black hole shadow (2022, ApJL, 930, L12-L17). This, Sagittarius A*, image holds a very important place as it allows us to test General Relativity and other space-time metrics at the best resolution. The data for SgrA* and M87* (published in 2019) were both obtained in April 2017 by a network of eight-millimetre telescopes located across the globe thus forming a continental-wide baselines. This provided an angular resolution sufficient enough to resolve the bright ring of emission with a diameter of 50 micro-arcsec. The image was cross-matched against a wide range of GRMHD simulations, which, in turn, constrained the possible accretion to be driven by a magnetic mode for a black hole of mass $\sim 4 \times 10^6$ solar masses and an inclination of ~30 degrees. **Venkatessh Ramakrishnan** is an active member of the EHTC, who was a part of the 2017 APEX observing team. He was also involved in the calibration and imaging efforts of the published results.

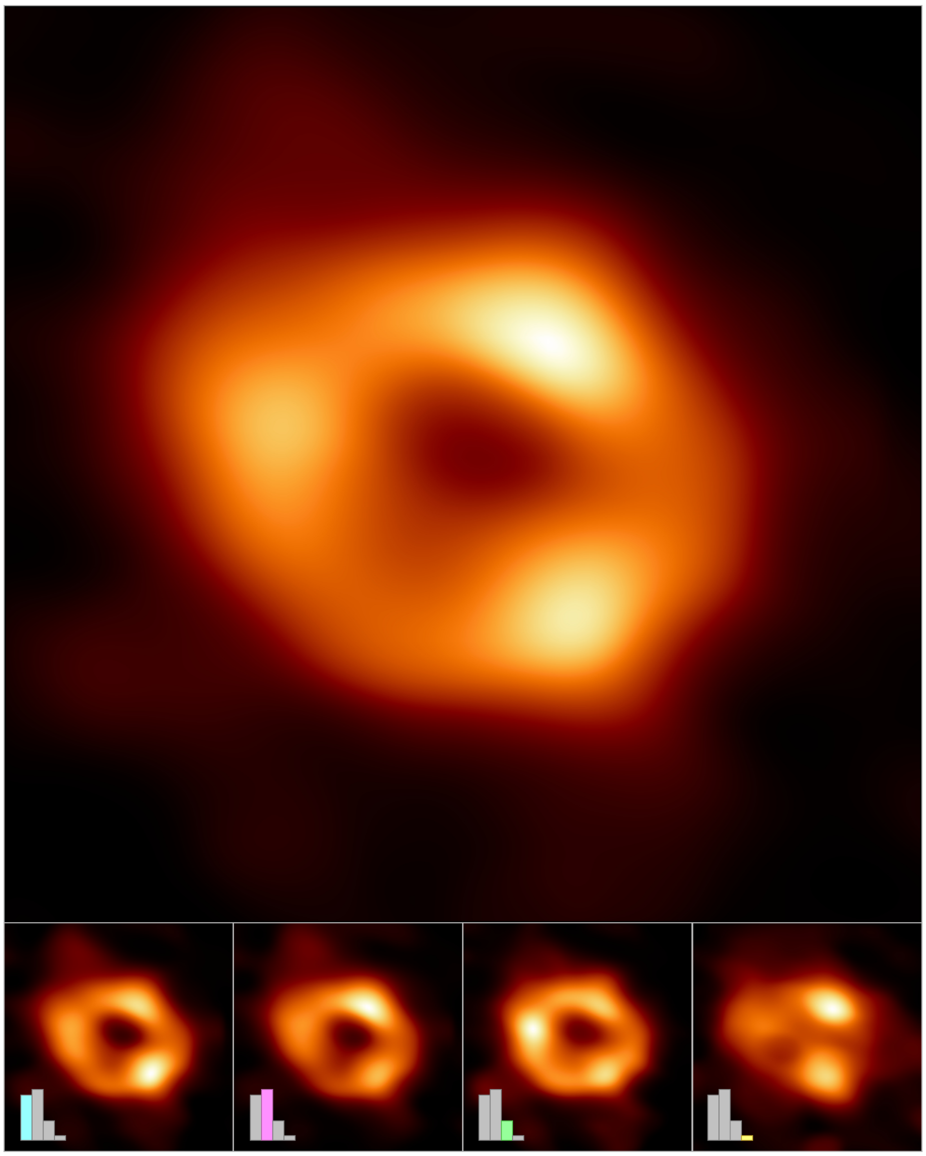


Figure 3.3: EHT image of the black hole shadow in Sagittarius A

Beyond SgrA* and M87* image of supermassive black hole shadows

After four observing campaigns (2017, 2018, 2021 and 2022), Event Horizon Telescope is now an established VLBI instrument with a superior capability of imaging regions of strong gravity. Using this as an impetus, **Venkatessh Ramakrishnan** is leading a study of imaging more such regions in the nearby Universe. He has thus curated the first set of potential targets for near-future EHT observations that were published in 2022, Galaxies, 11, 15. These images once obtained will be fundamental in establishing the space-time metric across a wide range of galaxies governed by different accretion processes. A feasibility study for detection has begun since the 2022 EHT campaign. The results from this study are foreseen in 2024 following the data correlation.

Blazars as sources of multi-messenger emission

Blazars are the most numerous sources in the extragalactic Very High Energy (VHE,E>100GeV) gamma-ray sky. FINCAns **Jenni Jormanainen, Pouya M. Kouch, Elina Lindfors, Kari Nilsson, Konstancja Satalecka** as well as **Talvikki Hovatta** and **Yannis Liodakis** continued to have an active role in the international MAGIC collaboration that operates the two Imaging Air Cherenkov Telescopes at La Palma, Canary Islands, Spain.

In 2022 we published a follow-up study of the famous "neutrino blazar" TXS0506+056, including data from radio to VHE gamma-rays. In 2017 when the breakthrough discovery of the neutrino arriving from the direction of this blazar that was then quasi-simultaneously seen flaring in gamma-rays by MAGIC. The source was in a high state throughout the whole electromagnetic spectrum. The follow-up study showed that there was also a second flaring episode in VHE gamma-rays after which the activity of the source decreased in all but radio bands.

Continuing our work on the blazar-neutrino connection, in Liodakis et al. 2022 we performed a simulation study of the prospects of discovering a high significance connection between radio flares and neutrino arrival times. We found that if the neutrinos are connected to the strongest radio flares, like tentatively suggested in our previous work (Hovatta et al. 2021), with the increasing data volume we should be able to confidently establish it. In 2022, the group has been also continued to participate in the preparatory science of the Cherenkov Telescope Array (CTA) Observatory. CTA will consist of two observatories, one at La Palma and second at ESO premises in Chile. In 2022, the redshift task force that has been organized within the CTA consortium to perform a large redshift surveys of blazars, also using ESO telescopes, published the second paper of the series (Kasai et al. 2023, including Lindfors, E.).

3.2.2 Stellar and Galactic Astrophysics

SN 2020wnt: a slow-evolving carbon-rich superluminous supernova with no O II lines and a bumpy light curve

In the paper “SN 2020wnt: a slow-evolving carbon-rich superluminous supernova with no O II lines and a bumpy light curve” (2022, MNRAS, 517, 2056), we present the analysis of one of the closest (z=0.032) hydrogen-poor superluminous supernova (SLSNe-I) discovered to date. The excellent coverage from explosion to $\sim$ 500 days allows us to characterize its properties and provides an excellent opportunity to understand the possible connection between H-poor SNe and SLSNe.

The light curves of SN 2020wnt show an early bump lasting $\sim$5 days, followed by a bright main peak. The SN reaches a peak absolute magnitude of $M_{max} \sim -20.5$ mag, with rise times between $\sim$ 61 days (in u) to 100 days from explosion (in K). This magnitude is at the lower end of the luminosity distribution of SLSNe-I, but the rise-time in r band ($\sim$ 77.5 days) is one of the longest reported to date. Unlike other SLSNe-I, the spectra of SN 2020wnt do not show O II , but strong lines of C II and Si II are detected. Spectroscopically, SN 2020wnt resembles the Type Ic SN 2007gr, but its evolution is significantly slower.

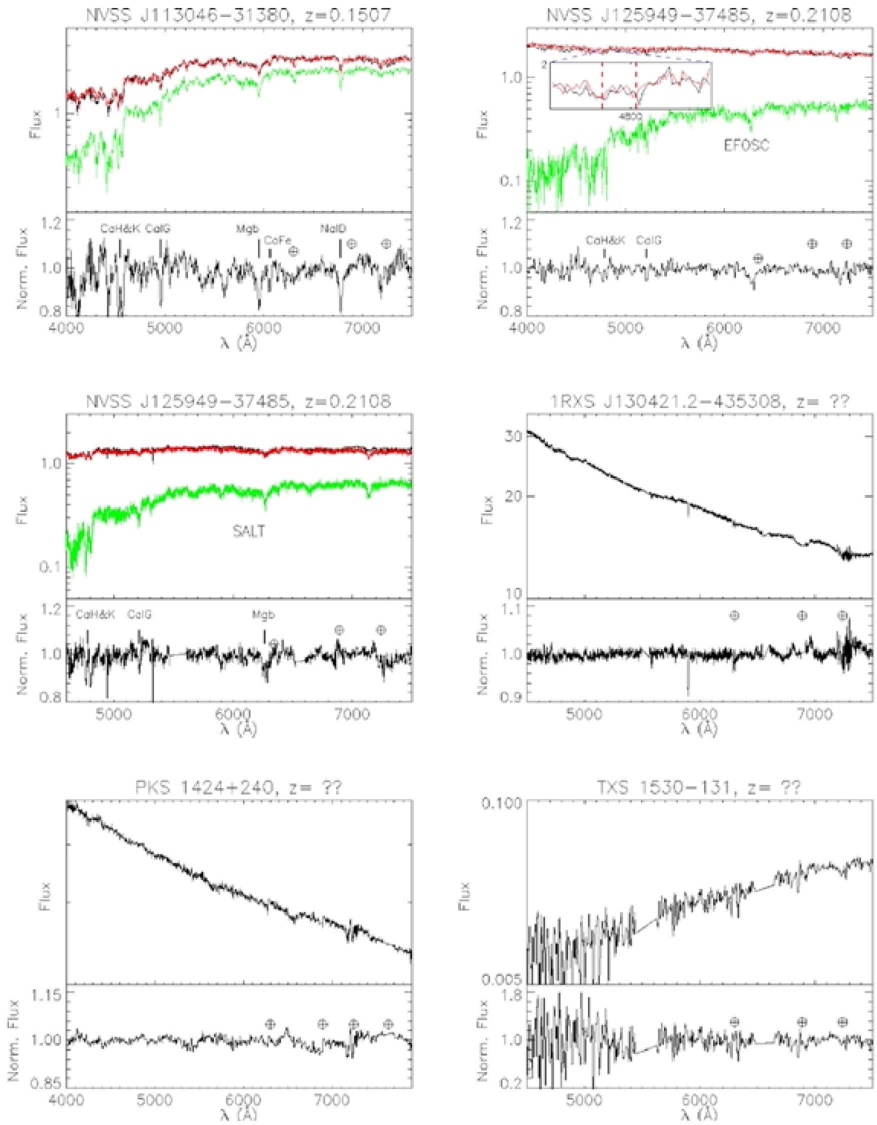


Figure 3.4: Spectra of blazar candidates

Comparing the bolometric light curve of SN 2020wnt to hydrodynamical models, we find that its luminosity can be explained by radioactive powering. The progenitor of SN 2020wnt is likely a massive and extended star with a pre-SN mass of 80 Msolar and a pre-SN radius of 15 Rsolar that experiences a very energetic explosion of 45×10^{51} erg, producing 4 $M_{\odot}$ of 56Ni. In this framework, the first peak results from a post-shock cooling phase for an extended progenitor, and the luminous main peak is due to a large nickel production. These characteristics are compatible with the pair-instability SN scenario. We note, however, that a significant contribution of interaction with circumstellar material cannot be ruled out.

Binary Stars

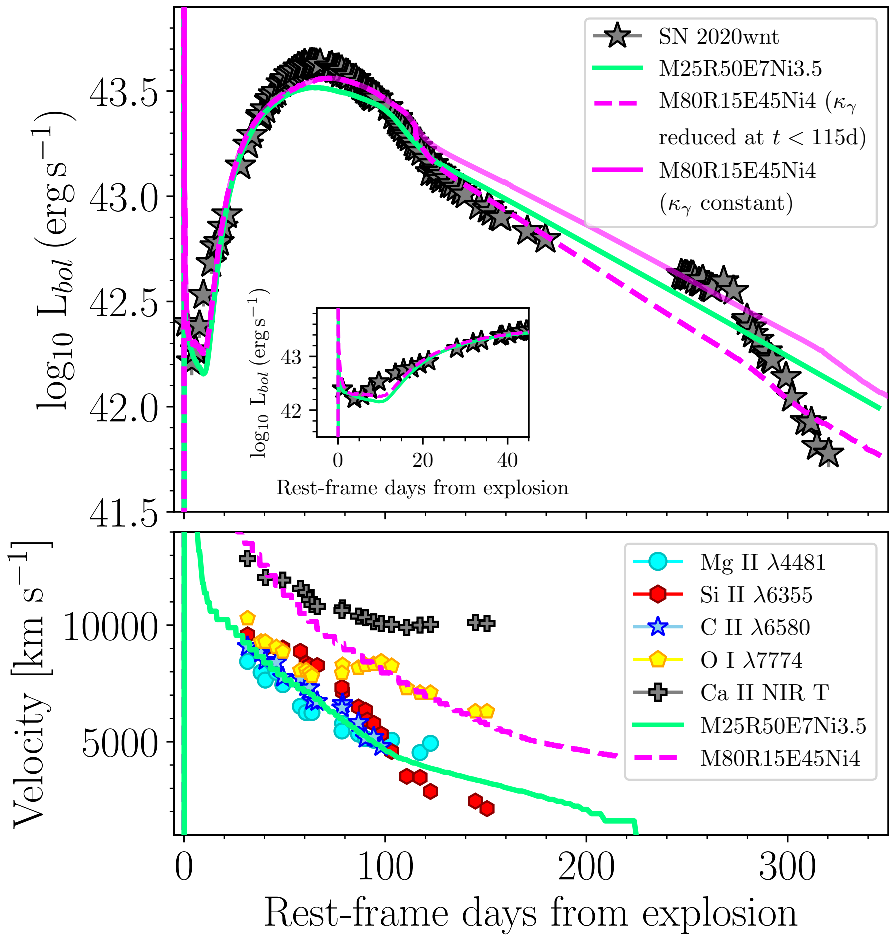


Figure 3.5: Caption: Top panel: Comparison between our best hydrodynamical models and the SN observations (grey stars). For the more massive model (magenta), we use a progenitor with a pre-SN mass of 80 $M_\odot$, $E_{exp} = 45 \times 10^{51}$ erg, a 56Ni mass of 4 $M_\odot$ and an initial radius of 15 $R_\odot$, while the less massive model (green solid line) has a pre-SN mass of 25 $M_\odot$ and $E_{exp} = 7 \times 10^{51}$ erg, a 56Ni mass of 3.5 M˘⊙ and an initial radius of 50 $R_\odot$. For the more massive model, we show the light curve with $\kappa\gamma$ constant (solid line), and a light curve with $\kappa\gamma$ reduction (dashed-line). The inset plot shows the light curves at very early phases. Bottom panel: Photospheric velocity of the models compared with the velocities of different species in SN2020wnt.

Dr Hakala has been active in various research programmes in the field of short period binary stars of various kind. Firstly, he continued collaboration with the University of Athens group studying contact binaries (W UMa systems) . He has also continued his work on magnetic white dwarfs in a variety of compact binary system. Together with colleagues from University of Warwick (UK) he started carrying out a survey for fast spinning magnetic white dwarfs in cataclysmic variables. Six nights of NTT time in ESO La Silla was allocated, and the project was extended by another 2.5 nights NTT allocation for the current ESO period. He has also published results from a NOT survey of observing the magnetic fields of white dwarfs in so called pre-cataclysmic variables, which are binary systems where a magnetic white dwarf is only accreting stellar wind from the companion star. Furthermore, he was involved in studying the accretion state changes in magnetic cataclysmic variables using NASA's TESS satellite data. This was done in collaboration with both UK and American colleagues. As a result, we now have better understanding of the process controlling accretion state variations in these systems.

Dr Hakala has also participated in TESS studies of X-ray binaries, in particular the so called high mass X-ray binaries. The TESS data have revealed previously undetected oscillations in the hot OB-stars that are the mass donor stars in these systems.

Finally , Dr Hakala has been involved in NOT and VLT-FORS2 study of fast rotating late type stars that show photometric variability, but no other signs of stellar activity like flaring. These stars are puzzling and we have used VLT-FORS2 spectropolarimetry to detect/measure magnetic fields of these stars and also spectra from the NOT to study the possible binarity of these systems. Recently further data on these systems was obtained by us in the South African Astronomical Observatory. These studies provide important clues on the origin of magnetic activity in the very lowest mass stars.

4. Instrument Development

Son of X-Shooter (SOXS) calibration unit completed

The SOXS instrument is in the construction phase. In 2021, 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.The work was led by Academy Fellow Hanindyo Kuncarayakti (Department of Physics and Astronomy, Univ. Turku). SOXS CU incorporates commercially available parts and custom-made components, some are manufactured by University of Turku's Protopaja workshop. The SOXS CU has undergone tests and final verification before being shipped to the SOXS consortium headquarter in Italy late 2021, for integration with the SOXS instrument.

MICADO: the only first-light ELT instrument for some time

Participation in the 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. It is paramount to get involved in a first-light ELT instrument, as it 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

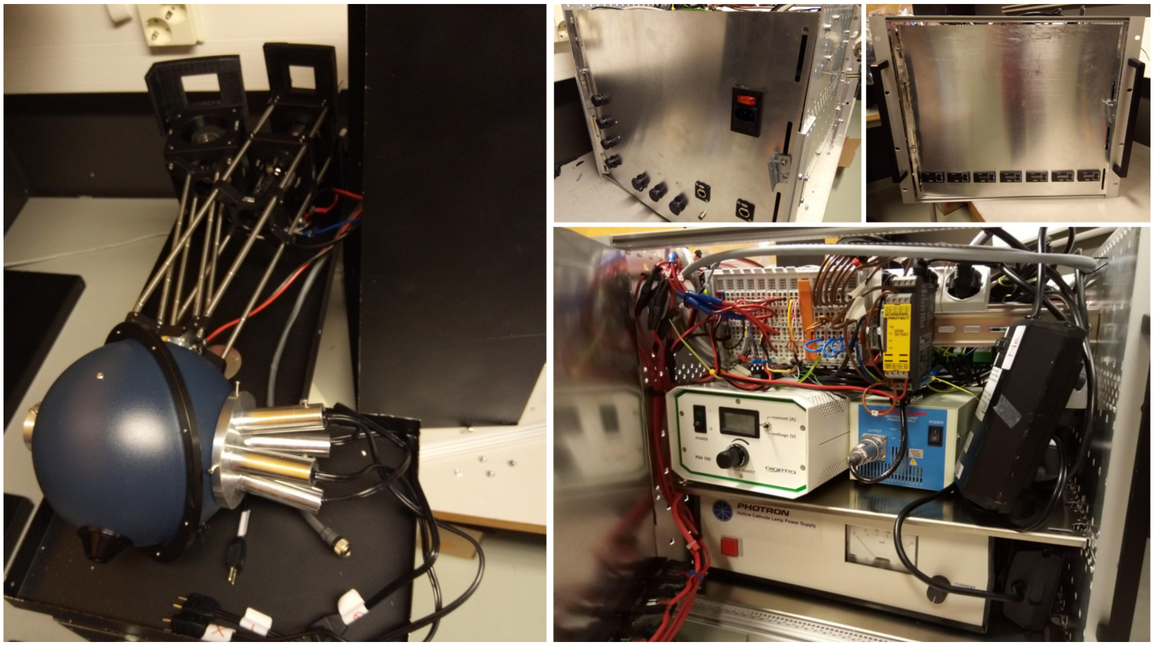


Figure 4.1: (Left) The Calibration Box with top cover removed, showing the integrating sphere and lamps. (Right) The CBX electronics subrack, outside view (top 2 panels), and inside view (bottom panel), showing the lamp power supplies and Beckhoff modules..

have used the FIRI funding to participate in the MICADO consortium, including in-kind contribution led by UTU. MICADO, the adaptive optics (AO) -assisted diffraction-limited near-infrared imager and long-slit spectrograph, is progressing successfully and will probably be the only first-light ELT instrument ready to start operations in 2027 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 excellent match with science interests in all FINCA universities.

MICADO's has already passed three of its four Final Design Reviews (FDR) with ESO, with the final FDR4 in 2022. There is going to be about 10% cost increase of MICADO, due to increased cost of material and manufacturing.

A group led by Academy Researcher Hanin Kuncarayakti (Dept. Physics and Astronomy, Univ. Turku), together with Jani Achren from Incident Angle company and FINCA postdoc Steve Williams, participate in the PSF-Reconstruction Working Group of MICADO, within the non-AO effects Work Package. Activities include simulating the MICADO optics and PSF as affected by turbulence and aberrations, and re-writing the INAF simulation code from IDL to Python.

The MICADO instrument was recently described in the article Davies et al. (2021), The Messenger, 182, 17-21. (including **J. Kotilainen** as the FINCA co-author).

Hardware at Metsähovi Radio Telescope

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

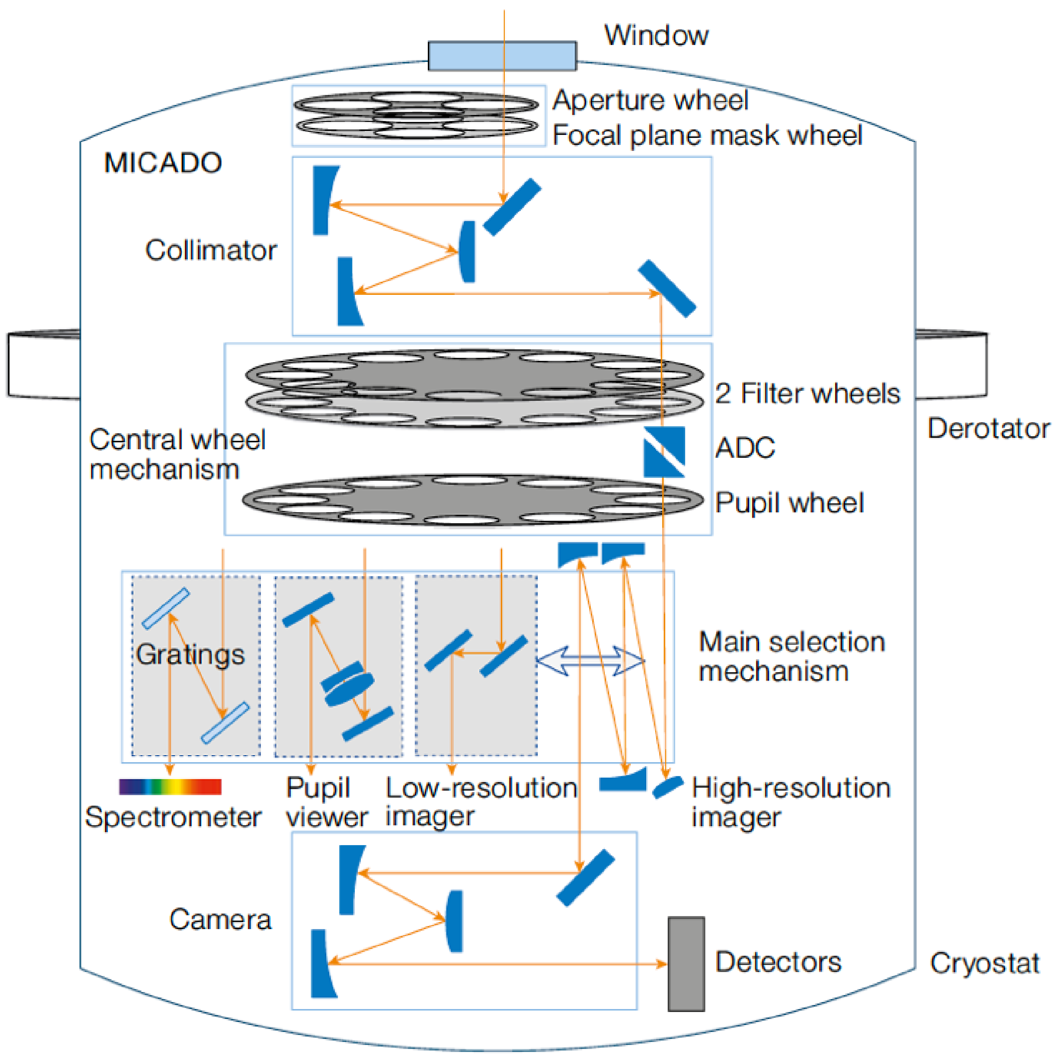


Figure 4.3: Schematic view of the MICADO design concept, illustrating how the cold optics and mechanisms are assigned to separate modules that can be tested separately and then integrated together in the cryostat.

Hardware development is also part of the Academy of Finland early career research project lead by Academy Research Fellow Talvikki Hovatta. FINCA postdoc **Derek McKay** is working on the prototyping and evaluation of components that will contribute to a new fully-digital, high-bandwidth backend for the Metsähovi Radio Telescope. The new system will record and correlate radio signals from two linear polarisations, which is imperative for advancing studies of large-scale magnetic field structure and energy dissipation in blazar jets. The hardware has now been set up at the observatory and evaluation and prototyping work is now in progress. Additionally, as part of this work, commissioning of the Metsähovi Compact Array 5-metre antenna has been carried out. This small parabolic antenna will be used for testing the new backend system.

The CTA array at ESO

In 2022 CTAO, the first VHE gamma-ray observatory, released the layouts that define the geographical position of the elements (telescopes, calibration systems and atmospheric characterization devices) that will compose the two CTAO arrays according to the approved Alpha Configuration. Obtained in a joint work between CTAO and CTAC (from FINCA Elina Lindfors was serving as Science Coordinator of CTAC in 2020-2021 and was heavily involved), the particular configuration is the result of a thorough optimization process meant to maximize the scientific performance of the two CTAO arrays: the CTAO Northern array, on the existing 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). This is a major step towards starting of the constructions of the telescopes.

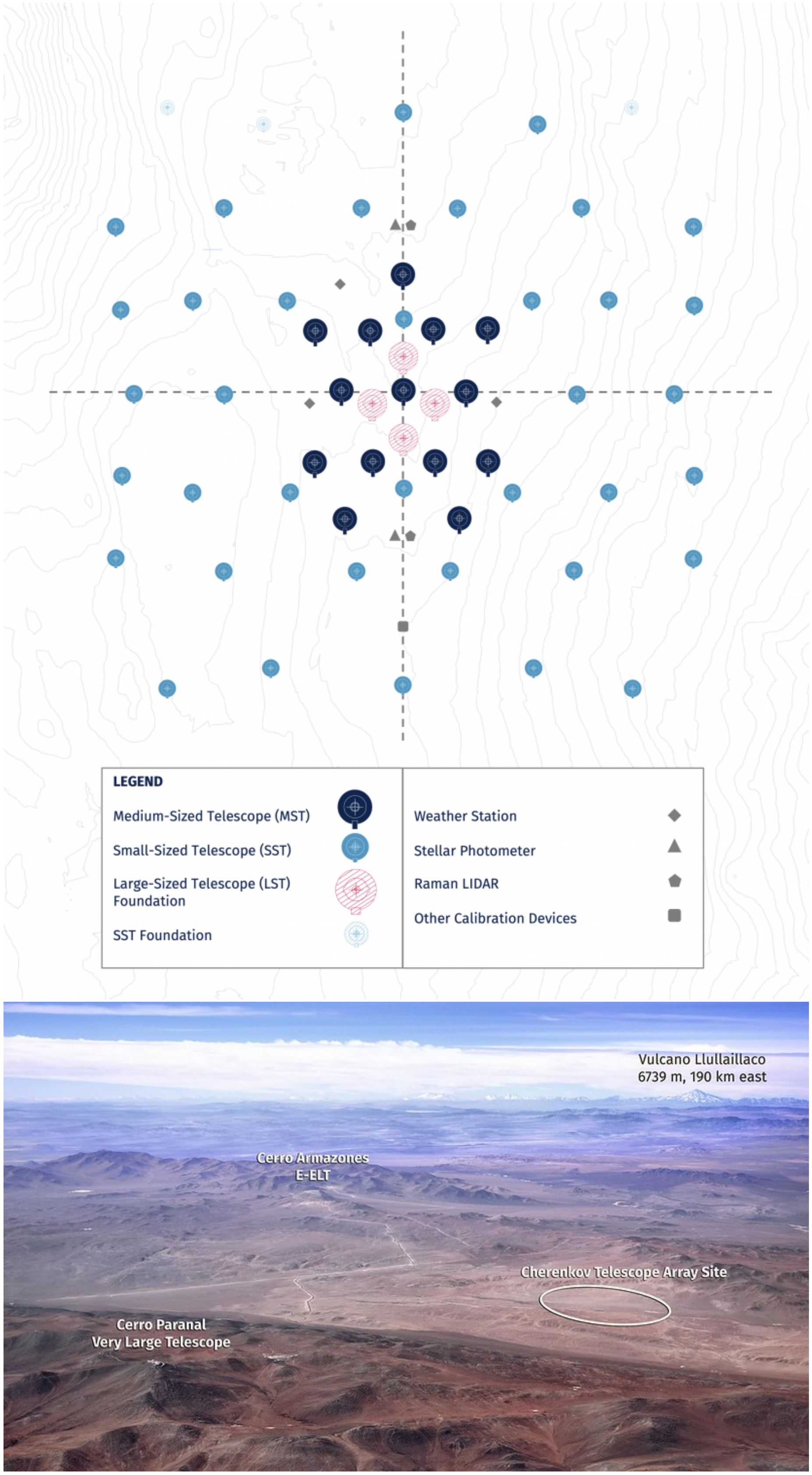
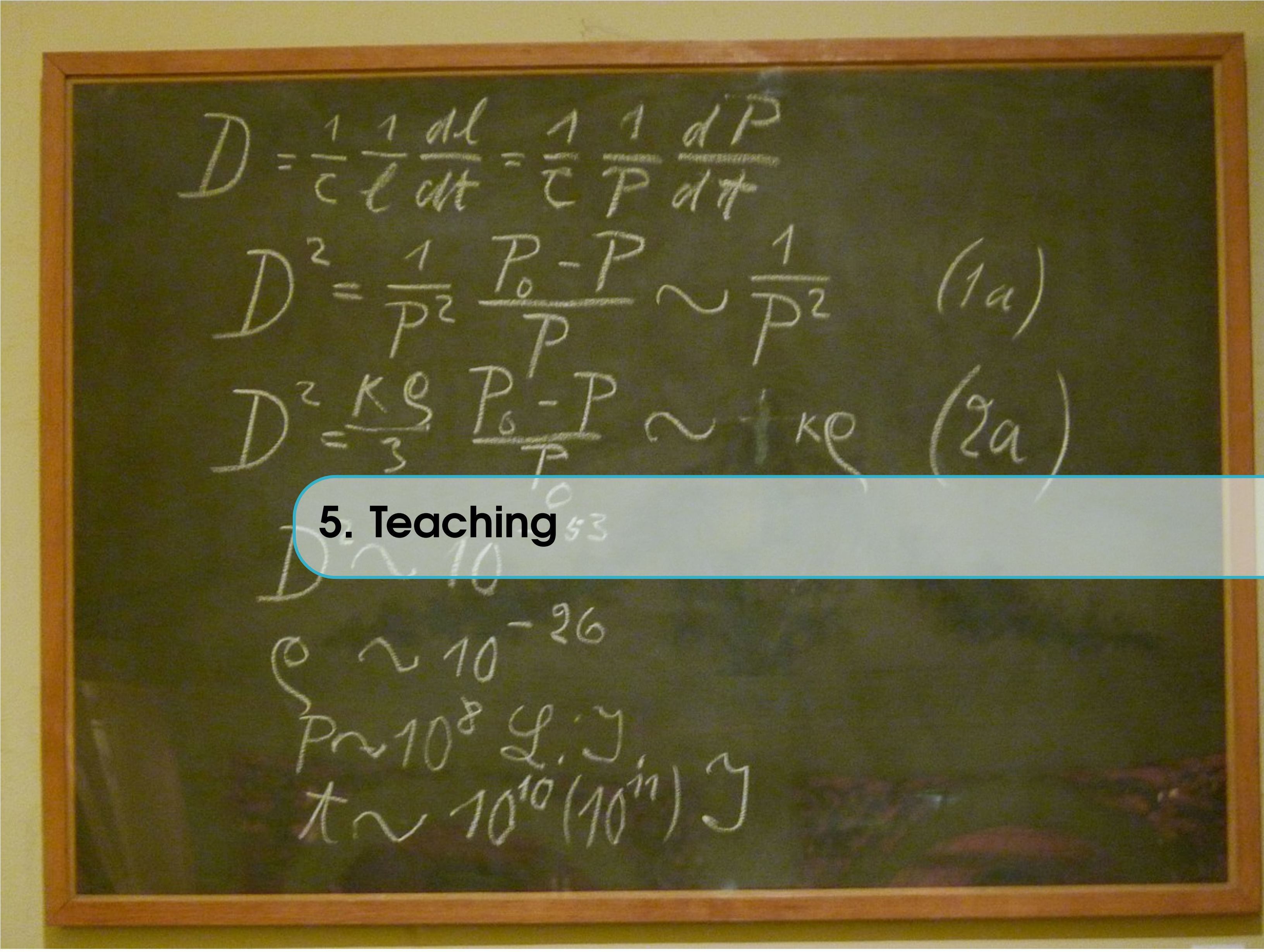


Figure 4.4: The CTAO array and location



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

Intermediate level - in Finnish or English

Advanced level - in English

Roberto De Propris (co-lecturer)	Galaxies and Cosmology	4	Turku
Claudia Gutierrez (co-lecturer)	Nordic Optical Telescope observing course 2021	NA	Turku
Talvikki Hovatta (co-lecturer)	Radio Astronomy and Interferometry	5	Turku
D. McKay	Space Debris	6	Aalto
	Radio Astronomy II	3	Aalto
Q. Salome	Radio Astronomy II	3	Aalto
	Introduction to Space	5	Aalto
Elina Lindfors (co-lecturer)	ISAPP school on Astrophysical sources of Cosmic Rays, 28th March 8th of April, 2022, Paris Saclay, France		
Elina Lindfors (tutoring the group from University of Namibia)	Observational Techniques Using the Nordic Optical Telescope		

5.2 Completed theses

MSc theses

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

C. Gutierrez	Organising Committee (LOC) of the mentorship RECA program for Colombian undergraduate students
T. Hovatta	SOC member, IAU symposium 375: The multimessenger chakra of blazar jets
D. McKay	Secretay of the Finnish Astronomical Society
	LOC Member for Astronomers' Days 2022
Y. Liodakis	Organizer, IAU symposium 375: The multimessenger chakra of blazar jets
V. Ramakrishnan	Non-horizon Science Working Group coordinator in the EHT consortium
E. Lindfors	Science coordinator of the CTA Consortium
	Member of the SOC CTAO/CTAC's webinar series "Synergies in the Exploration of the Extreme Universe"
	Member of the LOC "Finnish Astronomers Days" Jyväskylä 23-25th of May, 2022
	Member of the Consortium Board of the CTA Consortium
	Member of the Time Allocation Committee of the MAGIC Collaboration
	Member of the Collaboration Board of the MAGIC Collaboration
	Opticon and Radionet Package on "Optical and IR schools" member of the board
K. Nilsson	SOC member of the conference "NOT - a telescope for the future"
	OPTICON time allocation committee member

Conference presentations

C. Gutierrez	NOT - a telescope for the future Workshop, June 7 – 10, 2022, La Palma, Spain - “Peculiar Supernovae observed with the Nordic Optical Telescope” (oral)
	EAS 2022 Special Session 31 – Early Career Astronomers & Their Supporters, June 27 – July 1, 2022 Valencia, Spain - “RECAmentor - A virtual community mentorship program for development in Colombia” (invited)
	SuperVirtual 2022 - From Common to Exotic Transients - A virtual conference on supernovae and related transients, November 7 – 11, 2022 - “CSS161010: a luminous, fast blue optical transient with broad blueshifted lines” (online)
T. Kangas	SuperVirtual 2022 - From Common to Exotic Transients - A virtual conference on supernovae and related transients, November 7 – 11, 2022 - “Hydrogen-rich, broad-lined superluminous supernovae" (online)
Q. Salome	LYRICS Workshop, 04-22 April, Paris (France) - “Inefficient jet-induced star formation in Centaurus A: A multi-frequency analysis of the gas” (talk)
	Astronomers’ Days 2022, 22-25 May, Jyväskylä (Finland), - “Molecular outflow and AGN feedback in the NLSy1 IRAS 17020+4544” (talk)
	Multiphase AGN feeding and feedback II, 20-24 June, Sexten (Italy), - “Are AGN-driven X-ray winds quenching star formation in Narrow-Line Seyfert 1 galaxies?” (poster)
	Multiphase AGN feeding and feedback II, 27 June-01 July, Valencia (Spain), - “Are AGN-driven X- ray winds quenching star formation in Narrow-Line Seyfert 1 galaxies?” (poster)
V. Ramakrishnan	Young European Radio Astronomers Conference, August 2022, physical, oral presentation: EHT Donut Factory
	VLBI in the SKA era, February 2022, virtual, poster presentation: Sparse Image Reconstruction via Correlated Degradation Model
E. Lindfors	“Current and future observations of blazars at Very High Energies” IAU 375: The Multimessenger Chakra of Blazar Jets, December 2022, Kathmandu, Nepal (invited)
	"Association of IceCube neutrinos with radio sources observed at Owens Valley and Metsähovi Radio Observatories" Finnish Astronomers Days, May 2022, Jyväskylä
	“Shocking news - a polarizing study of a tidal disruption event" Astrophysical Polarimetry in the Time-Domain Era, August 2022, Lecco, Italy

Other talks

C. Gutierrez	“Hydrogen-rich supernovae in low-luminosity hosts”, Nicolaus Copernicus Astronomical Center, Toruń, Poland, 20 January 2022
	“Observational diversity of hydrogen-rich supernovae”, Laura Bassi Colloquium Series, Italy, 13 January 2022 (online)
	"Life as an Astrophysicist", : "Meet a female academic series", Thomas Young Centre at University College London, UK, 20 May 2022
	“RECA mentorship: The first career Astronomy mentorship program in Colombia”, ESO – ALMA talk, ESO, Santiago, Chile, 30 August 2022
J. Jormalainen	“Confronting observations of VHE gamma-ray blazar flares with reconnection models”, Astronomers’ Days, Jyväskylä, 23.-25.5.2022
	“SPACE: Ultra-fast variability in connection with constraining the emission region”, MAGIC Collaboration meeting (e-conference), 13.-17.6.2022, invited
	“Confronting observations of VHE gamma-ray blazar flares with reconnection models”, 7th Heidelberg International Symposium on High Energy Gamma Ray Astronomy, Barcelona, Spain, 4.-8.7.2022
D. McKay	"Metsähovi Compact Array Science Case", Metsähovi Observatory, 14 October 2022
V. Ramakrishnan	Roadmap for a compendium of black hole images in nearby AGNs, CSIRO, 13 December 2022
	Roadmap for a compendium of black hole images in nearby AGNs, University of Turku, 10 November 2022
	Roadmap for a compendium of black hole images in nearby AGNs, Leiden Observatory, 13 October 2022
	First-ever image of the supermassive black hole shadow of SgrA*, Tampere University, 16 May 2022
	Roadmap for a compendium of black hole images in nearby AGNs, Washington University in St Louis, 03 February 2022
	Roadmap for a compendium of black hole images in nearby AGNs, University of Arizona, 28 January 2022
K. Nilsson	“Blazar variability studies in the optical”, Tuorla-Tartu meeting, 5 May 2022
	“Blaza variabiity studies in the optical”, Astronomers’ Days, Jyväskylä, 24 May 2022

Research Visits

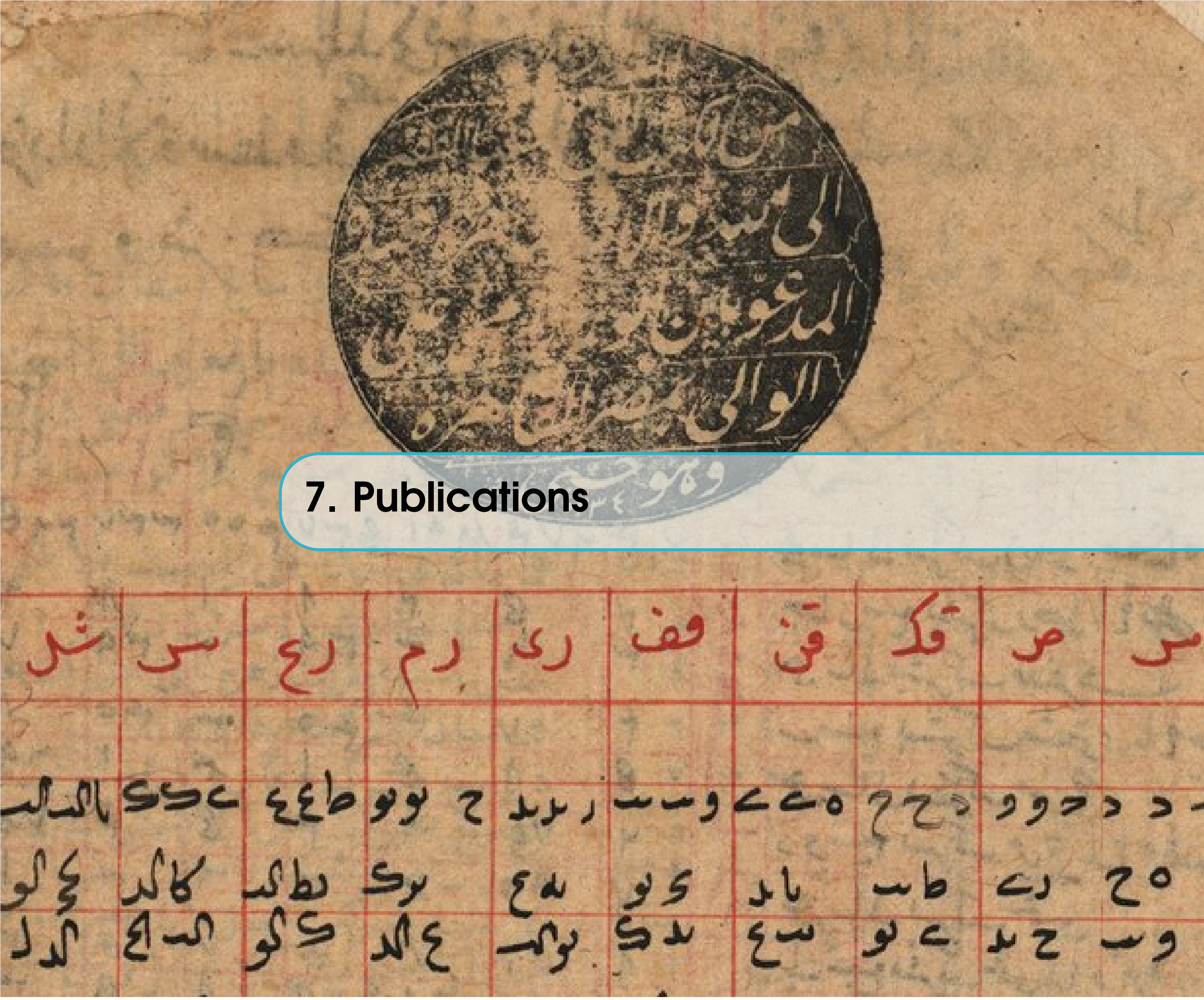
C. Gutierrez	AarhusUniversity, Denmark, 7-11 March 2022
	ePESSTO Meeting, Barcelona, Spain, 20-22 June 2022
	ESO, Santiago, Chile, 2-31 August 2022
	Institut d'astrophysique de Paris, France, 21-26 November 2022
Q. Salomé	Observatoire de Paris, France, 04-15 April 2022
	Instituto de Astronomia, UNAM, Mexico, 03-05 October
V. Ramakrishnan	December 2022, CSIRO, Perth, Australia – Host: Cormac Reynolds
	October 2022, ALMA Allegro, Leiden University, Netherlands – Host: Violette Impellizzeri
	September 2022, IPAG Grenoble, France – Host: Karine Perraut
	March 2022,ALMA JAO Santiago, Chile – Host: Edward Fomalont
	February 2022, Washington University in St Louis, USA – Host: Michael Nowak
	January 2022, University of Arizona, USA – Host: Chi-Kwan Chan

Other Activities

E. Lindfors Opponent and member of the Committee of the Doctoral Thesis by Simone Garrapa, Humboldt University, September 2022

Hosted visitors

Santiago González-Gaitán, Instituto Superior Técnico, University of Lisbon - Host: C. Gutierrez
Antonia Morales-Garoffolo, University of Cadiz, Spain - Host: C. Gutierrez
August 2022: Ed Fomalont, NRAO, USA. Host: Venkatessh Ramakrishnan
Entire July 2022: Jasmin Washington, University of Arizona, USA, Host: Venkatessh Ramakrishnan



7. Publications

Refereed publications by FINCA staff 2022:

Abdollahi. S. et al. (including **Liodakis**) *Incremental Fermi Large Area Telescope Fourth Source Catalog*, 2022, ApJS, 260. 53

Abe H. et al. (including **Fallah Ramazani, Jormalainen, Lindfors, Nilsson, Satalecka**) *Gamma-ray observations of MAXI J1820+070 during the 2018 outburst*, 2022, MNRAS, 517, 4736

Acciari, V, et al. (including **Fallah Ramazani, Jormalainen, Hovatta, Lindfors, Liodakis, Nilsson**) *Investigating the Blazar TXS 0506+056 through Sharp Multiwavelength Eyes During 2017-2019*, 2022, ApJ, 927, 197

Acciari, V, et al. (including **Fallah Ramazani, Jormalainen, Hovatta, Lindfors, Nilsson**) *Proton acceleration in thermonuclear nova explosions revealed by gamma rays*, 2022, Nature Astronomy, 6, 689

Acciari, V, et al. (including **Fallah Ramazani, Jormalainen, Hovatta, Lindfors, Nilsson**) *Combined searches for dark matter in dwarf spheroidal galaxies observed with the MAGIC telescopes, including new data from Coma Berenices and Draco*, 2022, Physics of the Dark Universe, Volume 35, 100912

Acciari, V, et al. (including **Fallah Ramazani, Jormalainen, Lindfors, Nilsson**) *Multiwavelength study of the gravitationally lensed blazar QSO B0218+357 between 2016 and 2020*, 2022, MNRAS, 510, 2344

Adams, C. B.. et al. (including **Fallah Ramazani, Jormalainen, Lindfors, Nilsson**) *Multiwavelength Observations of the Blazar VER J0521+211 during an Elevated TeV Gamma-Ray State*, 2022, ApJ, 932, 129

Ajello, M. et al. (including **Liodakis**) *The Fourth Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope: Data Release 3* , 2022, ApJS, 263, 24

Akiyama, K. et al. (including **Ramakrishnan**) *First Sagittarius A* Event Horizon Telescope Results. III. Imaging of the Galactic Center Supermassive Black Hole* , 2022, ApJ, 930, L14

Akiyama, K. et al. (including **Ramakrishnan**) *First Sagittarius A* Event Horizon Telescope Results. VI. Testing the Black Hole Metric* , 2022, ApJ, 930, L17

Brennan, S. J. et al. (including **Gutierrez**) *Progenitor, environment, and modelling of the interacting transient AT 2016jbu (Gaia16cfr)* , 2022, MNRAS, 513, 5666

Broderick, A. E. et al. (including **Ramakrishnan**) *Characterizing and Mitigating Intraday Variability: Reconstructing Source Structure in Accreting Black Holes with mm-VLBI* , 2022, ApJ, 930, L21

Cai, Y.-Z. et al. (including **Gutierrez**) *Forbidden hugs in pandemic times. III. Observations of the luminous red nova AT 2021biy in the nearby galaxy NGC 4631* , 2022, A&A, 667, 4

Castro Segura, N. et al. (including **Gutierrez**) *A persistent ultraviolet outflow from an accreting neutron star binary transient* , 2022, Nature, 603, 52

Charalampopoulos, P. et al. (including **Gutierrez**) *A detailed spectroscopic study of tidal disruption events* , 2022, A&A, 659, 34

De Propris, R. et al. *The ultraviolet upturn in field luminous red galaxies at* $0.3 < z < 0.7$, 2022, MNRAS, 512, 1400

Di Gesu, L. et al. (including **Lindfors, Liodakis**) *The X-Ray Polarization View of Mrk 421 in an Average Flux State as Observed by the Imaging X-Ray Polarimetry Explorer*, 2022, ApJ, 938,L7

Doroshenko, V. et al. (including **Liodakis**) *Determination of X-ray pulsar geometry with IXPE polarimetry*, 2022, Nature Astronomy 6, 1433

Doyle L. et al. (including **Hakala**) *The Puzzling Story of Flare Inactive Ultra Fast Rotating M dwarfs. I. Exploring their Magnetic Fields*, 2022, MNRAS, 512, 979

Driver, S. P. et al. (including **De Propris**) *Galaxy And Mass Assembly (GAMA): Data Release 4 and the z < 0.1 total and z < 0.08 morphological galaxy stellar mass functions*, 2022, MNRAS, 513, 439

Duffy, C. et al. (including **Hakala**) *Short-duration accretion states of Polars as seen in TESS and ZTF data*, 2022, MNRAS, 516. 3144

Ehlert, S. R. et al. (including **Liodakis**) *Limits on X-Ray Polarization at the Core of Centaurus A as Observed with the Imaging X-Ray Polarimetry Explorer*, 2022, ApJ, 935, 116

Fiore, A. et al. (including **Gutierrez**) *Close, bright, and boxy: the superluminous SN 2018hti*, 2022, MNRAS, 512, 4484

Georgiev, B. et al. (including **Ramakrishna**) *UA Universal Power-law Prescription for Variability from Synthetic Images of Black Hole Accretion Flows*, 2022, ApJ, 930, L20

Gibson, S. J. et al. (including **Liodakis**) *Using Multivariate Imputation by Chained Equations to Predict Redshifts of Active Galactic Nuclei*, 2022, Frontiers in Astronomy and Space Science, 9, 836215

Gomez J. L. et al. (including **Valtonen**) *Probing the Innermost Regions of AGN Jets and Their Magnetic Fields with RadioAstron. V. Space and Ground Millimeter-VLBI Imaging of OJ 287*, 2022, ApJ, 924, 122

Goyal, A. et al. (including **Fallah Ramazani, Hovatta, Lindfors**) *Multiwavelength Variability Power Spectrum Analysis of the Blazars 3C 279 and PKS 1510-089 on Multiple Timescales*, 2022, ApJ, 927, 214

Gutierrez, C. P. et al. *SN 2020wnt: a slow-evolving carbon-rich superluminous supernova with no O II lines and a bumpy light curve*, 2022, MNRAS, 517, 2056

Hakala, P. et al. *Circular polarimetry of suspect wind-accreting magnetic pre-polars*, 2022, MNRAS, 513, 3858

Irani, I.. et al. (including **Gutierrez**) *Less Than 1% of Core-collapse Supernovae in the Local Universe Occur in Elliptical Galaxies*, 2022, ApJ, 927, 10

Issaoun, S.. et al. (including **Ramakrishnan**) *Resolving the Inner Parsec of the Blazar J1924-2914 with the Event Horizon Telescope*, 2022, ApJ, 934, 145

Kim, S.-H. et al. (including **Ramakrishnan**) *Magnetic field strengths of the synchrotron self-absorption region in the jet of CTA 102 during radio flares*, 2022, MNRAS, 510, 815

Komossa, S. et al. (including **Valtonen**) *MOMO - V. Effelsberg, Swift, and Fermi study of the blazar and supermassive binary black hole candidate OJ 287 in a period of high activity*, 2022, MNRAS, 513, 3165

Kramarenko, I. G. et al. (including **Hovatta**) *A decade of joint MOJAVE-Fermi AGN monitoring: localization of the gamma-ray emission region*, 2022,MNRAS, 510, 469

Krawczynski H. et al. (including **Liodakis**) *Polarized x-rays constrain the disk-jet geometry in the black hole x-ray binary Cygnus X-1*, 2022, Science, 378, 650

Kuncarayakti, H.. et al. (including **Gutierrez**) *Late-time H/He-poor Circumstellar Interaction in the Type Ic Supernova SN 2021ocs: An Exposed Oxygen-Magnesium Layer and Extreme Stripping of the Progenitor*, 2022, ApJ, 941, 32

Liodakis, I. et al. *Polarized blazar X-rays imply particle acceleration in shocks*, 2022, Nature 611, 677

Liodakis, I. et al. (including **Hovatta, Lindfors**) *The hunt for extraterrestrial high-energy neutrino counterparts*, 2022, A&A, 666, 36

Liodakis, I. *Detecting intermediate-mass black holes in midiquasars with current and future surveys*, 2022, MNRAS, 512, L291

Liodakis, I., Binov, D., Potter, S. B., Rieger, F. M. *Constraints on magnetic field and particle content in blazar jets through optical circular polarization*, 2022, MNRAS, 509, L21

Loukaidou, G. A. et al. (including **Hakala**) *CoBiToM Project - II. Evolution of contact binary systems close to the orbital period cut-off*, 2022, MNRAS, 514, 5528

Marinucci, A. et al. (including **Liodakis**) *Polarization constraints on the X-ray corona in Seyfert Galaxies: MCG-05-23-16*, 2022, MNRAS, 516, 5907

Marshall, H. L. et al. (including **Liodakis**) *Observations of 4U 1626-67 with the Imaging X-Ray Polarimetry Explorer*, 2022, ApJ, 940, 70

Martinez L. et al. (including **Gutierrez**) *Type II supernovae from the Carnegie Supernova Project-I. III. Understanding SN II diversity through correlations between physical and observed properties*, 2022, A&A, 660, 42

Martinez L. et al. (including **Gutierrez**) *Type II supernovae from the Carnegie Supernova Project-I. I. Bolometric light curves of 74 SNe II using uBgVriYJH photometry*, 2022, A&A, 660, 40

Mason, P. A. et al. (including **Hakala**) *A Magnetic Valve at L1 Revealed in TESS Photometry of the Asynchronous Polar BY Cam*, 2022, ApJ. 938, 142

McKay, D., Grydeland, T., Gustavsson, B. *Manx arrays: Perfect non-redundant interferometric geometries*, 2022, Radio Science, 57(9), e2022RS007500

McKay, D., Vierinen, J., Kero, A., Partamies, N.*On the determination of ionospheric electron density profiles using multi-frequency riometry*, 2022, Geoscientific Instrumentation, Methods and Data Systems, 11(1), 25

Muller-Bravo, T. et al. (including **Gutierrez**) *PISCOLA: a data-driven transient light-curve fitter*, 2022, MNRAS, 512,3266

Narendra, A. et al. (including **Liodakis**) *Predicting the Redshift of Gamma-Ray Loud AGNs Using Supervised Machine Learning. II*, 2022, ApJS, 259, 55

O'Neill, S. et al. (including **Hovattta, Liodakis**) *The Unanticipated Phenomenology of the Blazar PKS 2131-021: A Unique Supermassive Black Hole Binary Candidate*, 2022, ApJ, 926, L35

Onori, F.. et al. (including **Gutierrez**) *The nuclear transient AT 2017gge: a tidal disruption event in a dusty and gas-rich environment and the awakening of a dormant SMBH*, 2022, MNRAS, 517, 76

Peirson, A. L., **Liodakis, I.**, Romani, R. W. *Testing High-energy Emission Models for Blazars with X-Ray Polarimetry*, 2022, ApJ, 931, 59

Peirson, A. L., et al. (including **Hovatta, Liodakis**) *New Tests of Milli-lensing in the Blazar PKS 1413 + 135*, 2022, ApJ, 927, 24

Pursiainen, M. et al. (including **Gutierrez**) *SN 2018bsz: A Type I superluminous supernova with aspherical circumstellar material*, 2022, A&A, 666, 30

Ramsay, G. et al. (including **Hakala**) *The puzzling story of flare inactive ultra fast rotating M dwarfs. II. Searching for radial velocity variations*, 2022, MNRAS, 511, 2755

Ramsay, G., **Hakala, P.**, Charles, P. A. *A TESS search for donor-star pulsations in high-mass X-ray binaries*, 2022, MNRAS, 516, 1219

Randriamanakoto, Z. et al. (including **Kotilainen**) *The SUNBIRD survey: the K-band luminosity functions of young massive clusters in intensely star-forming galaxies*, 2022, MNRAS, 513, 4232

Reguitti, A. et al. (including **Gutierrez**) *SN 2021foa, a transitional event between a Type IIn (SN 2009ip-like) and a Type Ibn supernova*, 2022,A&A, 662, L10

Taverna, R. et al. (including **Liodakis**) *Polarized x-rays from a magnetar*, 2022, Science, 378, 646

Tsygankov, S.. et al. (including **Liodakis**) *The X-Ray Polarimetry View of the Accreting Pulsar Cen X-3*, 2022, ApJ, 941, L14

Valerin, G. et al. (including **Gutierrez, Williams**) *Low luminosity Type II supernovae - IV. SN 2020cxd and SN 2021aai, at the edges of the sub-luminous supernovae class*, 2022, MNRAS, 513, 4983

Valtonen, M. et al. *Host galaxy magnitude of OJ 287 from its colours at minimum light*, 2022, MNRAS, 514, 3017

Vink, J. et al. (including **Liodakis**) *X-Ray Polarization Detection of Cassiopeia A with IXPE*, 2022, ApJ, 938, 40

Weilgus, M. et al. (including **Ramakrishnan**) *Millimeter Light Curves of Sagittarius A* Observed during the 2017 Event Horizon Telescope Campaign*, 2022, ApJ, 930, L19

Wethers, C.. et al. (including **De Propris, Kotilainen**) *Galaxy and Mass Assembly (GAMA): The Weak Environmental Dependence of Quasar Activity at* $0.1 < z < 0.35$, 2022, ApJ, 928, 192

Wevers, T. et al. (including **Gutierrez**) *An elliptical accretion disk following the tidal disruption event AT 2020zso*, 2022, A&A, 666, 6

Xie, F, et al. (including **Liodakis**) *Vela pulsar wind nebula X-rays are polarized to near the synchrotron limit*, 2022, Nature, 612, 658