M2FINDERS and Beyond: Magnetic Fields around Black Holes

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Book of Abstracts

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The M2FINDERS project

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The recent successes presented by the LIGO/VIRGO, GRAVITY, and EHT collaboration in probing physical conditions near the event horizon scale of massive cosmic object have established arguably the best evidence for existence of cosmic black holes. However, what is as yet still largely missing to fully confirm their existence and to accurately determine their physical properties, is precision information about the magnetic field near the event horizon, where it reflects the fundamental black hole physics and governs the formation of the relativistic jets. Such measurements pose tremendous challenges and cannot be realised merely from forthcoming improvements of the EHT imaging capabilities. The M2FINDERS sets off to accomplish this ambitious goal by combining multi-frequency polarimetric VLBI imaging and opacity measurements with novel methods for image analysis and modeling of relativistic flows. Leveraging the recent major advances in VLBI instrumentation, M2FINDERS aims to undertake an observational program that will result in the most stringent constraints on the strength and three-dimensional structure of the magnetic field near the event horizon. With this program, we should be in an excellent position for providing crucial evidence, independent and complementary to EHT imaging, for the existence of black holes and their event horizons, as well as delivering the most stringent constraints on their physical properties.

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Magnetic fields around black holes and their exotic cousins

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The most compelling present evidence for existence of cosmic black holes enshrouded by their event horizons is arguably provided by the LIGO/VIRGO detection of gravitational waves, the GRAVITY tracking of relativistic stellar and accretion disk motions in the Galactic Centre, and the EHT imaging of the strong gravitational lensing on scales down to several gravitational radii in M87 and Sgr A*. However, while successfully ruling out most of potential alternatives, these observations can still be reconciled with a range of putative horizonless entities such as wormholes, gravastars, and naked singularities. This poses a problem of identifying the most efficient means and ways for discerning between all these possibilities. It can be argued that, for the broad class of horizonless objects, the total strength and three-dimensional structure of magnetic field on scales below about ten thousand of gravitational radii may be used for that purpose. Exploration of this possibility is the prime focus of investigation in the M2FINDERS project aimed at making robust and reliable magnetic field measurements as close as possible to the event horizon scale in a number of radio loud AGN. To illustrate the foundations of this approach, basic properties of magnetic fields near the event horizon scales in black holes and selected classes of horizonless objects will be briefly discussed.

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Measuring magnetic fields near the event horizon

Prof. ROS, Eduardo[None]

The core observational task of M2FINDERS is to carry out systematic measurements of the strength and three dimensional structure of magnetic field in powerful radio loud AGN in which linear scales smaller than about ten thousand of gravitational radii can be probed. The main approaches adopted for dealing with this task rely on multiband polarisation observations made at frequencies 15, 22, 43, 86, and 230 GHz using the facilities provided by the VLBA, GMVA, and EHT. From these multiband data, images of total and polarised intensity are reconstructed and used as a basis for making a range of measurements probing the magnetic field. The maximum strength of the magnetic field and its evolution along the jet are estimated from imsges of the synchrotron turnover frequency and flux density and from measurements of the frequency dependence of the apparent position of the jet base (core shift). The respective piciture-plane and line-of-sight components of the field are estimated using measurements of fractional linear polarisation and Faraday rotation obtained from multiband images of lineraly polarised emission. The combination of all measurements should then yield a robust way to reconstruct the overall strength and morphology of the magnetic field. Details of these procedures and measurements will be discussed in this presentation.

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Spatial and Temporal Evolution of Rotation Measure in AGN jets

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Extremely luminous active galactic nuclei (AGN) residing in the centres of many galaxies are a unique testbed to study the evolution of extreme magneto-ionic environments; they are emitters of polarised relativistic synchrotron radiation and can be highly spatially and temporally variable. The MOJAVE program has performed 15, 23, and 43 GHz observations of 25 AGN using the Very Long Baseline Array (VLBA). These observations span across 23 monthly epochs between August 2019 to June 2021. This survey is the largest of its kind, in the number of sources surveyed, the length of time covered, and the cadence of observations.
From these observations, we derive Faraday rotation, intrinsic electric vector position angles, intrinsic polarization, and the amount of depolarization, while tracking the evolution of these quantities over time. These quantities allow us to track the spatial and temporal evolution of the 3D magnetic fields, gaining a better understanding of the underlying mechanisms affecting the magneto-ionic environments of AGN.

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Jet formation and expansion studied with multi-frequency VLBI

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How jets in Active Galactic Nuclei (AGN) are formed and accelerated remains one of the central open questions even after decades of astronomical studies. The high resolution obtained with VLBI is a key method to probe the region of formation and collimation of AGN jets by resolving these from their foot point out towards several parsecs from the central engine. In this talk I will introduce our Python based software project VCAT which allows the user to derive physical parameters such as magnetic field strength, continuum spectral shape, and jet collimation profiles from multi-frequency VLBI observations. Based on recent single-source studies out of the M2FINDERS sample I will present the different use cases of VCAT. This includes

multi-frequency VLBI observations of the LINER in NGC 1052 down to mm wavelengths, which reveal a complicated inner collimation structure of its double sided jet and high magnetic fields.

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Investigating jet launching in 3C84

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AGN-launched jets are a crucial element in the study of super-massive black holes (SMBH) and their closest surroundings. The formation of such jets, whether they are launched by magnetic field lines anchored to the accretion disk (Blandford & Payne 1982) or directly connected to the black hole's (BH) ergosphere (Blandford & Znajek 1977), is the subject of ongoing, extensive research.
3C 84, the compact radio source in the central galaxy NGC 275 of the Perseus super-cluster, is a prime laboratory for testing such jet launching scenarios, as well as studying the innermost, sub-parsec AGN structure and jet origin. Very long baseline interferometry (VLBI) offers a unique view into the physical processes in action, in the immediate vicinity of BHs, unparalleled by other observational techniques. With VLBI at short (millimetre) wavelengths particular high angular resolutions are obtained.
Utilising such mm-VLBI observations of 3C 84, we study the magnetic field strength and associated accretion flow around the SMBH of 3C 84. This is possible, as mm- VLBI measurements are capable of peering through the dusty torus surrounding the central engine of 3C 84, which is known to block the line of sight to the sub-parsec counter-jet via free-free absorption. We furthermore study the magnetic field's signa- ture in the core region, as manifested in polarised light. As part of this analysis we compare our observations to relativistic magneto-hydrodynamic simulations. In this talk I will present our most recent results, as well as some new, preliminary results, and offer a comprehensive summary of jet launching in 3C 84.

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Magnetic fields and the radio-gamma connection in 3C345

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Following increased gamma ray activity in 2009, a multi-wavelength VLBI follow-up observation of the quasar 3C345 has provided new insights into the post-flare jet and magnetic field structure. With the motivation of recent, even more extreme gamma activity, we have analyzed recent 43 GHz VLBI data to confirm previous findings regarding the origin of the gamma ray emission. Specifically, we examine the role of stationary features within 0.2 milliarcseconds of the VLBI core and their interaction with newly ejected jet components.

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Polarimetric studies of magnetic fields in AGN at high frequencies

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Magnetic fields play an important role in the production and propagation of relativistic jets in Active Galactic Nuclei (AGN). Non-thermal emission may be produced in these jets, especially

at radio wavelengths, with a polarization directly related to the strength and geometry of these magnetic fields, coupled to the magneto-ionic conditions in the AGN's immediate neighborhood. In this talk, we will discuss about polarization observations of AGN jets, from cm to mm-submm wavelenghts, and covering spatial scales from kpc to a few gravitational radii around their central supermassive black holes. Resolving the polarized brightness distributions, together with their frequency dependence, allows us to constrain the physical mechanisms related to the birth and propagation of the AGN jets.

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Imaging the central engine in M87

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Due to its proximity and large black hole mass, the nearby radio galaxy M87 is a prime target for high-resolution imaging studies of an AGN central engine. In this talk, we report on the first Very Long Baseline Interferometry (VLBI) results of M87 obtained with the Global Millimeter VLBI Array (GMVA) in conjunction with the phased ALMA and the Greenland Telescope (GLT) at 3.5 mm. The addition of the phased ALMA and the GLT to the GMVA greatly improved the imaging capabilities and revealed a ring-like structure located at the apex of the M87 jet. The diameter of this ring-like structure at 3.5 mm is about 50% larger than that of the ring observed with the Event Horizon Telescope at 1.3 mm. We show that this larger ring-like structure is dominated by the accretion flow around the black hole and how it is connected to the jet on event-horizon scales.

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Multifrequency VLBI study of M87

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We present the results of a multi-frequency study of Kelvin-Helmholtz instability developing in the jet in M87. For observations VLBA at 8 and 15 GHz and RadioAstron at 1.7 and 5 GHz. All Stokes I images show multiple filamentary pattern with up to three regular threads developing and propagating inside the jet on scales up to 400 mas. Thus, radio images show a spiral-like jet structure. The pattern observed in the spectral index map between 8 and 15 GHz is also consistent with observed threads. In addition, the global jet bending is observed at a core separation of ∼100 mas that also can be induced by the instability. We quantify the observed structural patterns by measuring transverse intensity profiles along the jet and modelling them with multiple Gaussian components. This analysis shows evidence for growing oscillatory patterns which are consistent with the helical and elliptical surface and body modes of Kelvin-Helmholtz instability developing on scales from 5 to 400 milliarcseconds.

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VLBI Observations with Frequency Phase Transfer and Source-Frequency Phase-Referencing

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VLBI observations at millimetre wavelengths are usually challenging due to the short coherence time imposed by the turbulent atmosphere. Recent developments in multi-band receivers (or fast frequency switching) have enabled transferring phase solutions in the frequency domain. By calibrating the non-dispersive propagation effects with frequency phase transfer (FPT), the coherence time of the residual phases can be extended by up to two orders of magnitudes. The increased coherence could lead to improved detection sensitivity and image dynamic ranges.
The residual phases after FPT are also mildly varying with the line of sight, making it possible to calibrate the residual propagation effects by referencing a nearby source and, at the same time, achieve relative astrometry, which provides essential geometric information about the emission region (e.g., vicinity of SMBHs, massive star-forming region, transient sources, binary SMBHs, etc.)
Previous observation results by the Korean VLBI network have demonstrated the power of this new observing mode. The number of VLBI facilities capable and the frequencies available for FPT have been growing recently. For instance, The planned development in task 6 of M2FINDERS is expected to provide core-shift measurements of AGN jets with μas-scale accuracy. The large collecting area of the Effelsberg telescope will also significantly improve the sensitivity of the current array capable of doing FPT observations.
In this talk, we will review the current achievements, ongoing developments, and future aspects of applying FPT for mm-VLBI observations.

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The next generation of VLBI imaging algorithms

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Radio-interferometric data have been successfully imaged by the rather straightforward CLEAN-algorithm for decades. However, CLEAN is challenged by the needs of the current and upcoming generation of high-precision radio astronomy instruments. A wide variety of modern machine learning techniques have been developed in recent years, particularly for VLBI, and have been demonstrated to significantly outperform CLEAN with respect to accuracy, dynamic range and resolution. In this talk I will review the state of the art in VLBI imaging. I will discuss the features that are still missing from the analysis (multimodality, multiobjectivity) and possible solutions by wavelet-based multiscalar and genetic evolutionary approaches. Finally, I will conclude with a short outlook on the future of VLBI imaging and the application of deep learning to VLBI.

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Bayesian self-calibration and imaging in Very Long Baseline Interferometry

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Self-calibration methods with the CLEAN algorithm have been widely employed in Very Long Baseline Interferometry (VLBI) data processing in order to correct amplitude and phase corruptions presented in the data. However, the modification of the data during the conventional self-calibration imposes human biases, which might produce artifacts in the image. In this work, self-calibration and image reconstruction are combined in a Bayesian inference framework. Amplitude and phase gains for each antenna and polarization mode are corrected by inferring the temporal correlation of the gain solution. The data is calibrated with the rPICARD CASA-based pipeline, and VLBA M87 Stokes I image at 43GHz with antenna-based gain calibration is reconstructed by the Bayesian imaging algorithm RESOLVE. Antenna-based gain and image uncertainties are estimated by the Variational Inference method. As a result, robust M87 Stokes I

image with high resolution is obtained by Bayesian self-calibration. Uncertainty estimation of image and antenna-based gains allows us to quantify the reliability of our result. These results show that the automated data reduction process in VLBI can reduce human biases, and reproducible robust images are reconstructed by incorporating self-calibration into image reconstruction.

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Probing the black hole environment on the event horizon scale

Dr. WIELGUS, Maciej[1]

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I will review the general aspects of probing the physical conditions in the compact environment near the event horizon of supermassive black holes. These consist of diagnostics for the plasma density and temperature, as well as the magnetic field strength and geometry and the accretion structure configuration. I will illustrate the presentation with practical examples from recent publications interpreting high angular resolution VLBI observations.

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Modeling black hole magnetospheres

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Magnetic fields surrounding black holes are responsible for a variety of astrophysical phenomena related to accretion processes and relativistic jets. Depending on the source, the strength and configuration of the field lines may differ significantly, which can, in turn, affect the trajectories of charged particles and the corresponding observables. Usually, the magnetic fields around black holes are modeled within a single source or current generating the field. However, magnetic field can have more than a single origin, being a combination of different fields, such as, e.g., that of an accretion disk and external large-scale or Galactic ones. In this talk, I will review some most known solutions to electromagnetic fields around black holes and introduce the new analytic solutions, which can be effectively used for modeling relativistic jets and matter accretion. I will also present some effects of electromagnetic interaction on the dynamics of matter (flares) surrounding the astrophysical black holes, including Sgr A*.

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Imaging ultracompact objects with radiative inefficient accretion flows

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Recent Event Horizon Telescope observations of the M87* and Milky-way galactic center at sub-mm wavelength furthers the argument for the existence of a central supermassive compact object which could be a black hole of about four million solar masses. Although, we have a best-bet model (black hole) the true nature of the central compact object still remains a mystery. In this talk, I will present the results utilizing the semi-analytic Radiatively Inefficient Accretion Flows (RIAF) model to investigate the images of ultracompact objects such as the Joshi-Malafarina-Narayan (JMN-1) naked singularity, dilaton black hole and Schwarzschild BH to find their distinguishing signatures and probe them as the central compact object.

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Blazar Multiwavelength Variability and the VLBI Connection

Dr. PATIÑO ÁLVAREZ, Víctor M.[1]

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I present some of the results obtained during the last few years by myself and the INAOE AGN Group, including the work of the Master and PhD students. Regarding the multiwavelength variability studies. We find that sources like 3C 279 and 3C 454.3 have activity periods in which the gamma-rays can be dominated by either synchrotron self-Compton (which was previously though not possible for this type of blazars), or external inverse Compton. In the sources 3C 279, 3C 454.3, CTA 102, and B2 1633+382 we discovered the location of at least one gamma-ray emission region within the jet, at 42 pc, 9 pc, 25 pc and 41 pc, respectively, from the central engine. For 3C 279 and 3C 454.3 we find evidence of there being multiple gamma-ray emission regions, and in the case of the former, we can even pinpoint one of them to a moving VLBI component. We also found evidence of the existence of broad line emitting material that is being ionized by the jet in the sources 3C 454.3 and CTA 102; this has important implications on the calculation of black hole masses. Also, preliminary results from our research show that over half of the blazar population presents this additional broad line region.

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Is everybody MAD?

Dr. SAVOLAINEN, Tuomas[1]

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One of the major open questions related to the production of jets by accreting black holes is: why sources with similar accretion powers produce so vastly different jet powers? What are the conditions that are required to produce a powerful jet? If jets are powered by the Blandford-Zjanek mechanism, there are two obvious parameters controlling the jet power besides the black hole mass - black hole spin and the magnetic flux threading it. Since there appears to exist highly spinning black holes without jets, it seems possible that the jet production efficiency depends on whether the black hole has been able to accrete high enough magnetic flux or not. The highest efficiency jets in this picture are launched from magnetically arrested disks (MAD). In this talk, I will discuss a method to test this hypothesis using VLBI core-shift measurements to estimate the magnetic flux, present results obtained so far, and note some common mistakes that appear in the literature regarding the magnetic flux estimates.

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Unveiling the Nature of Magnetic Fields on Compact Scales: Insights from the Nearby Radio Galaxy NGC 315

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Relativistic jets since their discovery have always fascinated astronomers. Over the last decades, thanks to the possibilities offered by the Very Long Baseline Interferometry observations, crucial steps forward in unveiling their nature have been made. Relativistic jets are expected to initially propagate as magnetic-dominated outflows and to progressively reach the equipartition state on sub-parsec and parsec scales. Over the same distances, they collimate reaching opening angles of

a few degrees, and accelerate up to high relativistic velocities. Such processes are intrinsically intertwined with the properties of the jet magnetic fields, for which a comprehensive understanding is still nowadays elusive.
In this presentation, the topic is addressed by focusing on the nearby giant radio galaxy NGC 315. Thanks to its vicinity and high black hole mass, NGC 315 offers a unique opportunity to unveil its magnetic field properties from parsec scales up to the jet injection point. Independent analyses involving the spatial evolution of the turnover frequency and the jet brightness temperature along the jet indicate a quasi-linear increase in magnetic field strength on the involved scales, providing valuable insights into magnetic field morphologies. This behavior, coupled with measured strengths of 0.1 G on parsec scales, suggests magnetic field strengths of approximately 100-1000 G in the core region. The magnetic field values are extrapolated from the core-shift measurements employing a new formalism that is valid for a collimating and accelerating jet.
Finally, the extrapolated properties of the magnetic fields are used to gain insights into the jet formation and propagation processes, such as the nature of the accretion disk and the jet acceleration.

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VLBI study of a flaring blazar from the early Universe

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TXS 1508+572 is a high-redshift (z=4.3) blazar that exhibited a significant (approx. 5σ) gamma-ray flare in February 2022. Since then, it has been a subject to an extensive multi-wavelength monitoring campaign (PI:A. Gokus) covering all wavebands from the radio to gamma-rays. As part of the follow-up, we have requested observations with the Very Long Baseline Array (VLBA) at 15, 22 and 43 GHz (80, 117 and 228 GHz in the rest frame of the blazar) which were carried out in 4 epochs distributed between 2022 March and 2023 January. In this talk I will discuss the preliminary results from our VLBI monitoring, including the changes in source morphology, kinematic and spectral analysis, and coreshift measurement.

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Current status and prospects of the VLBI blazar - neutrino saga

Dr. KOVALEV, Yuri[1]

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We present results from a joint analysis of VLBI observations of a complete sample of active galactic nuclei and neutrino data from IceCube supplemented by interesting selected single source cases from ANTARES and Baikal-GVD. We have found a 4sigma-significant observational evidence that high energy neutrinos are generated in radio-bright blazars and arrive preferentially during their flares. VLBI effectively selects active galaxies with jets whose electromagnetic and neutrino emission is relativistically boosted towards us. Recent results involving deep X-ray survey data will also be presented. We will also discuss other possible sources of high-energy neutrinos. We summarize new opportunities for multi-messenger studies to explore the nature of blazars nuclei as powerful proton accelerators for the current and new planned facilities.

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Sgr A* in the JWST era

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The Galactic Centre harbours a supermassive black hole known as Sgr A, providing a unique opportunity to study the extreme astrophysical phenomena associated with these enigmatic cosmic entities. The James Webb Space Telescope (JWST), an advanced observatory launched in 2021, assures pioneering Mid Infrared (MIR) observations due to its improved sensitivity and enhanced infrared capabilities. Despite its exceptional sensitivity, observing the emission from Sgr A at the Galactic Centre is difficult due to several challenges. The centre is enveloped in warm (˜100K) dust emission, which in the mid-infrared regime radiates at flux densities of several tens Jys, surpassing Sgr A* by several hundred factors. Moreover, the Galactic Centre displays a complex extinction structure known to vary sustainably on small scales. At MIR wavelengths, there is a lack of high-precision measurements of extinction. The ISO/SWS mission in the mid-90s provides the only available measurements. However, the MIRI instrument on JWST covers a spectral range from 5 to 25 microns, which is unprecedented. This wavelength range connects the better-understood radio emission to the NIR infra-red flares and is particularly enticing. In this presentation, I shall specify the challenges and exhibit the outlook for our forthcoming mid-sized JWST/MIRI observations.

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Global linear polarization parameters of AGNs with NOEMA

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NOEMA (and its predecessor the PdBI array) use AGN as phase and amplitude calibrators. Observations lasting above six hours, usually cover a wide range of paralactic angles that global linear polarization parameters (polarization fraction and angle) can be obtained to these calibrators by means of the Earth rotation polarimetry (ERP) technique. This is possible because the strength (>0.3 Jy) and the point-like structure (for NOEMA observations) of these AGNs. I will present ERP results obtained to 240 AGNs observed since 2009. The results may help to select adequate polarization calibrators (e.g., to future full stokes polarization observation with NOEMA) and to study emission processes in AGNs.

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Behind the scenes of staging an EHT campaign at APEX

Dr. ROY, Alan[1]

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I tell the story of the APEX VLBI hardware and team preparations for the latest EHT campaign, EHT2023. A particular focus this time was developing the components required for the night at 345 GHz, the first array observation at this frequency.

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Tentative association of a Baikal neutrino-cascade triplet with the Galactic high-energy sources.

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Baikal Gigaton Volume Detector (Baikal-GVD) recently reported results of the four years of high-energy cascade-like neutrino event observations. New astrophysical neutrino events were studied from the perspective of identifying their sources. Apart from the VLBI-bright blazar associations, an evidence has emerged regarding Galactic origin of some high energy cascade neutrino events.

In the GVD sample, directions of three neutrinos are found to be close to microqusar LS I +61 303 and Ultraluminous X-Ray Pulsar Swift J0243.6+6124. We report an analysis of their X-ray and gamma activity, contemporary to the GVD triplet. While the data has not revealed pronounced activity, the intersection and the computed p-value of 0.024 is a suggestive indicator, pointing towards this region near the Galactic plane as being a promising site of high energy Galactic neutrinos. For publication, see Allakhverdyan et al. 2023 (arXiv:2307.07327).

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Adding NOEMA to the GMVA: resolving the jet of BL Lac

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We analyze a single-epoch Global mm-VLBI Array (GMVA) observation of the blazar BL Lacertae (BL Lac) from April 2021. This particular GMVA dataset is special owing to the first participation of the phased Northern Extended Millimetre Array (NOEMA) in a VLBI observation and the coincidence with a historically huge gamma-ray flare in BL Lac. We aim to explore the nature of the inner subparsec jet of BL Lac and the impact of the NOEMA participation in the observation. For the data reduction, we employ two advanced automatic pipelines: rPICARD for the flux density calibration and model-agnostic signal stabilization and GPCAL for polarization calibration. The conventional hybrid imaging (CLEAN plus amplitude/phase self-calibration) is applied to the calibrated visibilities to generate a final image of the jet. We perform a ridge-line analysis and Gaussian model-fits on the final jet image to derive various physical parameters of the jet. In our data, the presence of NOEMA improves the image sensitivity by a factor of 2.5. The jet shows a clear wiggling structure within 0.4 mas from the core. Using the jet ridge lines, we find an indication of a helical jet structure (i.e., a sinusoidal pattern). Six circular Gaussian components are fitted to the inner jet region. We estimate the apparent brightness temperature of ˜3 x 10ˆ12 K from the two innermost components. We find four significant polarized knots in the jet. Interestingly, two of them are located in the core region. We suggest a number of physical scenarios to interpret our results.

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Jets at all scales

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Accretion in our own Galaxy

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AI applications for radio astronomical imaging from a remote sensing perspective

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Concluding remarks

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