

This work was written as part of one of the author's official duties as an Employee of the United States Government and is therefore a work of the United States Government. In accordance with 17 U.S.C. 105, no copyright protection is available for such works under U.S. Law.

Public Domain Mark 1.0

<https://creativecommons.org/publicdomain/mark/1.0/>

Access to this work was provided by the University of Maryland, Baltimore County (UMBC) ScholarWorks@UMBC digital repository on the Maryland Shared Open Access (MD-SOAR) platform.

Please provide feedback

Please support the ScholarWorks@UMBC repository by emailing scholarworks-group@umbc.edu and telling us what having access to this work means to you and why it's important to you. Thank you.

X-ray polarization measurement of the gold standard of radio-quiet active galactic nuclei : NGC 1068

F. Marin^{1*}, A. Marinucci², M. Laurenti^{3,4,17}, D. E. Kim^{5,6,3}, T. Barnouin¹, A. Di Marco⁵, F. Ursini⁷, S. Bianchi⁷, S. Ravi⁸, H.L. Marshall⁸, G. Matt⁷, C.-T. Chen⁹, V. E. Gianolli^{10,7}, A. Ingram¹¹, W. P. Maksym¹², C. Panagiotou⁸, J. Podgorny¹³, S. Puccetti⁴, A. Ratheesh⁵, F. Tombesi^{3,14,15}, I. Agudo¹⁶, L. A. Antonelli^{4,17}, M. Bachetti¹⁸, L. Baldini^{19,20}, W. Baumgartner²¹, R. Bellazzini¹⁹, S. Bongiorno²¹, R. Bonino^{22,23}, A. Brez¹⁹, N. Bucciantini^{24,25,26}, F. Capitanio⁵, S. Castellano¹⁹, E. Cavazzuti², S. Ciprini^{4,14}, E. Costa⁵, A. De Rosa⁵, E. Del Monte⁵, L. Di Gesu², N. Di Lalla²⁷, I. Donnarumma², V. Doroshenko²⁸, M. Dovčiak¹³, S. Ehlert²¹, T. Enoto²⁹, Y. Evangelista⁵, S. Fabiani⁵, R. Ferrazzoli⁵, J. Garcia³⁰, S. Gunji³¹, J. Heyl³², W. Iwakiri³³, S. Jorstad^{34,35}, P. Kaaret²¹, V. Karas¹³, F. Kislak³⁶, T. Kitaguchi²⁹, J. Kolodziejczak²¹, H. Krawczynski³⁷, F. La Monaca^{5,3,6}, L. Latronico²², I. Liodakis³⁸, G. Madejski³⁹, S. Maldera²², A. Manfreda¹⁹, A. Marscher³⁴, F. Massaro^{22,23}, I. Mitsuishi⁴⁰, T. Mizuno⁴¹, F. Mulieri⁵, M. Negro^{42,43,44}, S. Ng⁴⁵, S. O'Dell²¹, N. Omodei³⁹, C. Oppedisano²², A. Papitto¹⁷, G. Pavlov⁴⁶, M. Perri^{4,17}, M. Pesce-Rollins¹⁹, P.-O. Petrucci¹⁰, M. Pilia¹⁸, A. Possenti¹⁸, J. Poutanen⁴⁷, B. Ramsey²¹, J. Rankin⁵, O. Roberts⁹, R. Romani³⁹, C. Sgrò¹⁹, P. Slane¹², P. Soffitta⁵, G. Spandre¹⁹, D. Swartz⁹, T. Tamagawa²⁹, F. Tavecchio⁴⁸, R. Taverna⁴⁹, Y. Tawara⁴⁰, A. Tennant²¹, N. Thomas²¹, A. Trois¹⁸, S. Tsygankov⁴⁷, R. Turolla^{50,51}, J. Vink⁵², M. Weisskopf²¹, K. Wu⁵¹, F. Xie^{53,5}, and S. Zane⁵¹

(Affiliations can be found after the references)

Received February X, 2024; accepted Month Day, 2024

ABSTRACT

Context. NGC 1068 is the radio-quiet active galactic nucleus (AGN) which has been the most observed in photo-, spectro-, imaging and timing polarimetry. It led to the unified scheme of AGNs in the 90's, a global, zeroth-order picture of AGNs that is still widely used.

Aims. However, high energy polarimetry has never been probed before due to the lack of dedicated polarimeters. This is critical because X-rays allow us to probe the orientation and geometric arrangement of (sub)parsec-scale matter without being polluted by the host emission.

Methods. We used the Imaging X-ray Polarimetry Explorer (*IXPE*) satellite to measure, for the first time, the 2–8 keV polarization of NGC 1068. We pointed *IXPE* for a net exposure time of 1.15 Ms on the target, in addition to two ~ 10 ks each *Chandra* snapshots in order to account for the potential impact of several ultraluminous X-ray source (ULXs) within *IXPE*'s field-of-view.

Results. We measured a 2 – 8 keV polarization degree of $12.4\% \pm 3.6\%$ and an electric vector polarization angle of $101^\circ \pm 8^\circ$ at 68% confidence level. If we exclude the spectral region containing the bright Fe K lines and other soft X-ray lines where depolarization occurs, the polarization fraction rises up to $21.3\% \pm 6.7\%$ in the 3.5 – 6.0 keV band, with a similar polarization angle. The observed polarization angle is found to be perpendicular to the parsec scale radio jet. Using a combined *Chandra* and *IXPE* analysis plus multi-wavelength constraints, we estimated that the circumnuclear "torus" may sustain a half-opening angle of $50 - 55^\circ$ (from the vertical axis of the system).

Conclusions. Thanks to *IXPE*, we have measured the X-ray polarization of NGC 1068 and found comparable results, both in terms of polarization angle orientation with respect to the radio-jet and torus half-opening angle, to the X-ray polarimetric measurement achieved for the other archetypal Compton-thick AGN : the Circinus galaxy. Probing the geometric arrangement of parsec-scale matter in extragalactic object is now feasible thanks to X-ray polarimetry.

Key words. polarization – X-rays: galaxies – X-rays: individuals: NGC 1068 – galaxies: active – galaxies: Seyfert

1. Introduction

NGC 1068, also known as Messier 77 (M77), is an optically bright ($V = 11.8$ mag in a $4.9''$ aperture, Sandage 1973) type-2 active galactic nuclei (AGN), located in the nearby Universe ($z = 0.00379$). Because of its proximity and brightness, it is among the AGNs that have been the most studied over the past century. In particular, it is the source that is at the origin of the Unified Scheme of AGNs such as established by Antonucci (1993) and Urry & Padovani (1995). In this zeroth-order model, all AGNs are similar in morphology, but their apparent observational properties can differ depending on the inclination of the AGN core

with respect to the observer. This is mainly due to the fact that, along the equatorial plane of the AGN, lies an optically-thick circumnuclear reservoir of gas and dust that creates a strong geometric asymmetry in emission and absorption. The model has evolved since then, encompassing evolution and accretion to explain several observational differences that orientation cannot explicate alone (Dopita 1997), but determining the real inclination and morphology of AGNs remains a challenge.

In the case of NGC 1068, there seems to be a consensus about its nucleus inclination. Studies based on the modelling of the spectral energy distribution usually find a (torus) inclination of the order of $70 - 90^\circ$ (Hönig et al. 2007; Hönig, Prieto, & Beckert 2008; Lopez-Rodriguez et al. 2018). Observations and

* E-mail: frederic.marin@astro.unistra.fr

modeling of the polar outflows kinematics bring more extreme inclination values, $\sim 85^\circ$, under the assumption of biconical outflow models (Das et al. 2006; Fischer et al. 2013; Miyauchi & Kishimoto 2020). Interestingly, Fig. 8b in Miyauchi & Kishimoto (2020) shows the $0.1''$ (~ 7 pc) scale distribution of the gas clouds in NGC 1068 that has been essentially confirmed by the VLTI/MATISSE reconstructed image obtained by Gámez Rosas et al. (2022), who also estimate that the circumnuclear, optically thick, dusty region is seen nearly edge-on. Finally, the presence of water masers coexisting with the central engine in NGC 1068 can be used to trace the structure and velocity field of the torus, provided that the dusty molecular torus is indeed responsible for the maser emission (Greenhill et al. 1996). VLA observations and Effelsberg 100m monitoring allowed to estimate that the maser disk is rather thin and inclined by $80 - 90^\circ$ (Gallimore et al. 2001). VLBI observations of the same water maser also allowed to estimate the central black hole mass ($\sim 10^7 M_\odot$, Greenhill et al. 1996).

Because polarization is sensitive to the morphology of a source, it can be used as an independent tool to determine the orientation of AGNs. Using three dimensional models of the system, Packham et al. (1997) and Kishimoto (1999) attempted to reproduce their near-infrared and near-ultraviolet polarization maps of NGC 1068, respectively. Both found that the northern outflowing region is inclined towards the observer, while the southern wind is directed away, but could not determine the AGN inclination nor the torus geometry. The main problem with this approach is that the ultraviolet, optical and infrared bands are heavily polluted by unpolarized starlight emission from the host and/or dust reemission by the torus. To get around this problem, it is necessary to go to higher energies, where there is neither stellar emission nor re-emission by hot dust. Thanks to the very low contribution of polluting X-ray sources, and therefore to a rather clean observational window, X-ray polarimetry offers a powerful probe to narrow down the uncertainties in determining the AGN inclination, together with its torus half-opening angle and density (Goosmann & Matt 2011; Marin et al. 2018).

It is now possible to measure the X-ray polarization of extragalactic objects thanks to the Imaging X-ray Polarimetry Explorer (*IXPE*), NASA's first mission to study the polarization of astronomical X-rays that was launched in December 2021 (Weiskopf et al. 2022). *IXPE* is capable of measuring the linear polarization of electromagnetic waves from 2 to 8 keV, and it was already pointed towards several radio-quiet AGNs: NGC 4151 (Gianolli et al. 2023), MCG-05-23-16 (Marinucci et al. 2022; Tagliacozzo et al. 2023), IC 4329A (Ingram et al. 2023) and the Circinus galaxy (Ursini et al. 2023). The later observation revealed that the neutral reflector in Circinus produces a polarization degree of $28\% \pm 7\%$ at 68% confidence level, with a polarization angle roughly perpendicular to the radio jet. According to Monte Carlo simulations, the half-opening angle of the torus was determined to be of the order of $50^\circ \pm 5^\circ$ (Ursini et al. 2023). In the hopes to achieve similar results, we hereby report the first pointing of NGC 1068 by *IXPE*, together with two *Chandra* snapshots, to enable a spatially resolved spectropolarimetric study. For the remainder of this paper, a Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ is adopted. Also, unless specified otherwise, errors are given at 68% confidence level for one parameter of interest and upper limits are given at 99% confidence level.

2. Observations and data reduction

2.1. *IXPE*

IXPE observed NGC 1068 (02h42m40.711s, -00d00m47.81s in J2000.0 equatorial coordinates) from January 3 to January 29, 2024 (ObsID 02008001), for a net exposure time of 1.15 Ms. Cleaned level 2 event files were firstly treated with the background rejection procedure described in Di Marco et al. (2023)¹. Then they were produced and calibrated using standard filtering criteria with the dedicated FTOOLS tasks and the latest calibration files available in the *IXPE* calibration data base (CALDB 20230526).

I, Q, and U spectra were extracted according to the weighted analysis method described in Di Marco et al. (2022) by setting the parameter `stokes=neff` in XSELECT. The background spectra were extracted from source-free circular regions with a radius of $78''$. Extraction radii for the I Stokes spectra of the source were computed via an iterative process which leads to the maximization of the signal-to-noise ratio (SNR) in the 2 – 8 keV energy band (similarly to Piconcelli et al. 2004), which led to radii of $47''$, $52''$ and $47''$ for the Detector Units (DUs) 1, 2 and 3, respectively. The same circular regions (centered on the source) were used for all three DUs for I, Q and U. This results in a 2–5.5 keV background of 10.4%, 14.9% and 13.9% for the total DU1, DU2, and DU3 I spectra. These values rise to 23.7%, 28.4% and 25.7% in the 5.5 – 8 keV band. We used a constant energy binning of 0.2 keV for Q and U Stokes spectra and required an SNR higher than 3 in the intensity spectra. The choice of dividing the full energy band into two bins below and above 5.5 keV is driven by the need to explore the influence of the iron line complex that dominates the emission above 5.5 keV.

2.2. *Chandra*

Similarly to the Circinus case (Ursini et al. 2023), there are several ultraluminous X-ray (ULX) sources around NGC 1068 (Smith & Wilson 2003; Matt et al. 2004; Zaino et al. 2020). To monitor the flux levels of the off-nuclear point like sources, two *Chandra* observations were performed at the beginning and at the end of the *IXPE* pointings, on 2024, January 4 (ObsID 29071) and on January 28 (ObsID 29072), with the Advanced CCD Imaging Spectrometer (ACIS, Garmire et al. 2003). To reduce pileup effects, the frame time was set to 0.5 s and custom CCD subarrays were used. Data were reduced with the *Chandra* Interactive Analysis of Observations (CIAO, Fruscione et al. 2006) 4.14 and the *Chandra* Calibration Data Base 4.11.0, adopting standard procedures. We generated event files for the two observations with the CIAO tool `chandra_repro` and, after cleaning for background flaring, we got net exposure times of 10.3 ks and 9.3 ks for the first and for the second observation, respectively.

We used a circular extraction region with a $15''$ radius for the AGN and background spectra were extracted from source-free circular regions with a radius of $10''$. Spectra from the two observations were added and then binned in order to oversample the instrumental resolution by a factor of 3 and to have no less than 30 counts in each background-subtracted spectral channel. This allows the applicability of the χ^2 statistic. We ignored channels between 8 and 10 keV due to pileup, which was calculated via the CIAO tool `pileup_map`. We estimated an average pileup

¹ The adopted script is available on <https://github.com/aledimarco/IXPE-background>

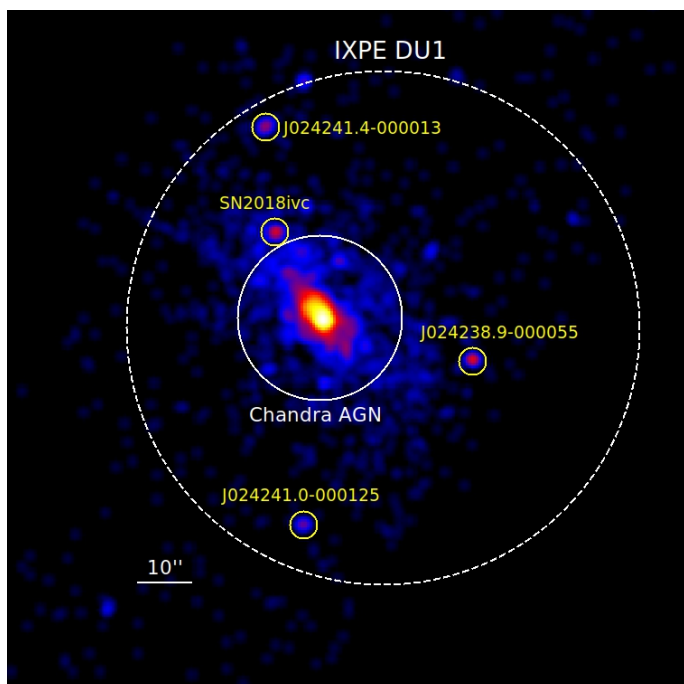


Fig. 1. The $2' \times 2'$ central region of NGC 1068 is shown in the 0.3–7.0 keV band (*Chandra* ObsID 29071). The dashed white circle corresponds to the *IXPE* DU1 source extraction region. A Gaussian smoothing kernel of 3×3 pixels has been applied for the sake of visual clarity.

fraction of 7.5% in the central 3×3 pixels region, ranging from 5% to 10% (in the central pixel) for both observations.

Spectra from other point-like sources within the field of view were extracted from circular regions with $2.5''$ radii. In the 2–8 keV band, the brightest ones are: SN 2018ivc (Bostroem et al. 2020; Maeda et al. 2023), CXOU J024241.4-000013, CXOU J024238.9-000055 and CXOU J024241.0-000125 (Smith & Wilson 2003). Spectral fit of the other point-like sources showed 2–8 keV fluxes lower than $\sim 2.5 \times 10^{-14}$ erg cm $^{-2}$ s $^{-1}$, which is approximately 0.5% of the total flux of the AGN. These sources were not considered in the spectro-polarimetric fit, since their overall contribution is negligible. Spectra were then binned requesting at least 5 counts in each spectral bin and the Cash statistics (Cash 1979) was used for the data analysis.

3. Measures of NGC 1068’s X-ray polarization

3.1. *IXPE* polarization cubes

We estimated the X-ray polarization properties using event-based Stokes parameter analysis methods, as implemented in Kislat et al. (2015). The model-independent analysis was performed using the unweighted method employing the PCUBE algorithm in *ixpeobssim*, as detailed in Baldini et al. (2022). The polarization degree and angle were derived from normalized q and u Stokes parameters, calculated as $P = \sqrt{(q)^2 + (u)^2}$ and $\Psi = 1/2 \tan^{-1}(u/q)$ (measured from North to East), with the background polarization subtracted. Consequently, we estimated the time-averaged X-ray polarization properties of the source within the 2 – 8 keV range as $P = 9\% \pm 5\%$ and $\Psi = 113^\circ \pm 16^\circ$. As justified in Sect. 2.1, we divided the nominal energy band into two bins and measured $P = 14\% \pm 4\%$ and $\Psi = 105^\circ \pm 8^\circ$ (99.7% confidence level) for the energy range 2 – 5.5 keV. The

remaining *IXPE* band, 5.5 – 8 keV, only shows an upper limit with $P < 20\%$.

Furthermore, to explore the variability of polarization over time and energy, we segmented the entire observation into subsets based on time and energy, as described in Kim et al. (2024). Specifically, we divided the q and u data into identical time spans, depending on the selected number of bins (e.g., 2 bins with 100 ks gives 50 ks/bin) from 2 to 15 bins. In all cases, the probability of the hypothesis that the data are constant was greater than 28%, implying no significant evidence of time variability. Energy-resolved analysis was performed in a similar manner. In this case, we divided the 2–8 keV range into 2, 3, 4, 6, 8, and 12 bins (e.g., 2 bins = 2 – 5 keV, 5 – 8 keV). The polarization is consistent with being constant with energy, with a probability greater than 24% in all cases.

3.2. *IXPE* spectropolarimetry

The X-ray spectropolarimetric analysis was carried out with XSPEC v12.13.1e (Arnaud 1996). The Galactic absorption along the line of sight amounts to $N_{\text{H,Gal}} = 2.59 \times 10^{20}$ cm $^{-2}$ (HI4PI Collaboration et al. 2016) and is accounted for by using the TBABS model with the ISM abundances from Wilms, Allen, & McCray (2000). We fit the I, Q, and U spectra simultaneously while including a cross-calibration constant (CONST) between the three different DUs. For what concerns the sole *IXPE* data, we focus on a phenomenological modeling while a more physical approach is described in the following section. In this case, the X-ray continuum is modeled as a simple power law (POWERLAW) throughout the whole feasible 2 – 8 keV energy interval.

In order to probe the polarization properties of NGC 1068 we adopted the POLCONST model, that assumes an energy-independent polarization and has two free parameters: P and Ψ . Thus, we first start with a model that can be written as $\text{CONST} \times \text{TBABS} \times \text{POLCONST} \times \text{POWERLAW}$ in XSPEC. The spectral fit is clearly unsatisfactory ($\chi^2/\text{dof} = 931/476$), since we observe large positive residuals at energies larger than 6 keV, likely owing to the broad iron line complex. We thus add a Gaussian emission line (ZGAUSS) to account for this component, and this leads to a significant fit improvement ($\chi^2/\text{dof} = 537/473$), implying $\Delta\chi^2 = 394$ for three degrees of freedom. We fixed the line width to the value of $\sigma = 500$ eV returned by the best-fit, since the centroid energy cannot be constrained otherwise. Such a broad emission feature is the result of the blend of several emission lines from both neutral and ionized gas (Matt et al. 2004), that we cannot individually resolve with *IXPE*. The emission line is centered at $E = 6.58^{+0.05}_{-0.04}$ keV. We find a rather soft X-ray continuum, with the photon index having a value of $\Gamma = 2.35^{+0.05}_{-0.04}$.

Nonetheless, we still observe some residuals at softer energies which we try to account for by including an additional power-law component. This leads to a further improvement of the spectral fit ($\chi^2/\text{dof} = 474/472$). Thus, our best-fit phenomenological model consists of:

$$\text{CONST} \times \text{TBABS} \times \text{POLCONST} \times (\text{POWERLAW}_1 + \text{POWERLAW}_2 + \text{ZGAUSS})$$

The line centroid shifts towards $E = 6.67 \pm 0.06$ keV and the two power-law photon indices are $\Gamma_1 = 0.9 \pm 0.4$ and $\Gamma_2 = 4.3^{+0.8}_{-0.6}$. The best-fit values of the 2 – 8 keV polarization degree and angle are $P = 12.4\% \pm 3.6\%$ and $\Psi = 100.7^\circ \pm 8.3^\circ$, respectively.

Finally, we divided the broad energy band into smaller intervals to probe the polarization properties of NGC 1068. The 2 – 5.5 keV band shows the highest significance in terms of polarization detection. Fig. 2 shows the contour plot of the polarization angle versus the polarization degree in such interval. At

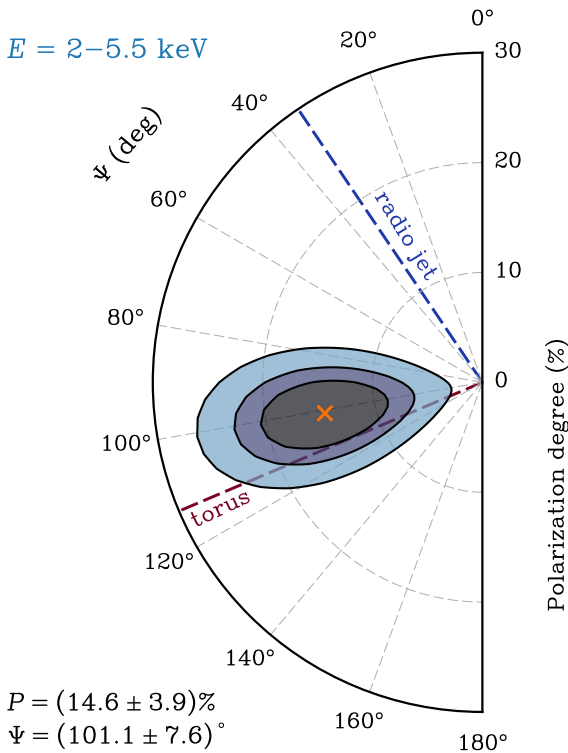


Fig. 2. Contour plot of the polarization angle vs polarization degree accounting for the 68%, 90% and 99% confidence levels, computed by taking into account the *IXPE* I, Q and U spectra in the 2–5.5 keV band (the energy band with the highest significance in terms of polarization detection). The orange cross indicates the best-fit values of P and Ψ , that are also reported in the lower left corner. The dashed blue line describes the direction of the parsec-scale radio jet (Wilson & Ulvestad 1983). The dashed brown line indicates the orientation of the molecular torus derived by García-Burillo et al. (2019) with *ALMA*, see Sect. 4.1.

energies higher than 5.5 keV, there is a clear rise of background contribution in addition to the emission lines from the iron K complex that are blended and widened due to the modest *IXPE* spectral resolution. The results are listed in Tab. 1 and are generally in good agreement with the values reported from the PCUBE model-independent analysis described in the previous section.

3.3. *IXPE*+*Chandra* fitting

Thanks to the *Chandra* data, we are able to take into account the contribution of the ULXs in the spectral analysis (Bauer et al. 2015). We co-add the *Chandra* spectra of extranuclear point sources that are significantly detected above 2 keV, and we model this combined ULX emission with a power law having a fixed slope of 1. We obtain a 2–8 keV flux of 2.2×10^{-13} erg cm $^{-2}$ s $^{-1}$ for the ULX power law. The AGN, on the other hand, has a 2–8 keV flux of 4.3×10^{-12} erg cm $^{-2}$ s $^{-1}$.

The 2–8 keV continuum is well described by two components: a warm reflector, mostly contributing below 4 keV, and a cold reflector, dominating above 5 keV (see also Matt et al. 2004). In both cases, the reflected continuum is expected to be significantly polarized, while the associated emission lines are expected to be unpolarized. We fit jointly the *Chandra* and *IXPE* I, Q, U Stokes spectra with a phenomenological model consisting of: a power law to describe the warm reflector continuum, a PEXRAV (Magdziarz & Zdziarski 1995) component for the cold

reflector continuum, and six Gaussian emission lines². The photon indices of the warm and cold reflection components are not well constrained by the *Chandra* + *IXPE* fit, therefore we adopt values consistent with those reported by Matt et al. (2004), Marinucci et al. (2016) and Zaino et al. (2020). We fix the photon index of PEXRAV at 2, and that of the warm reflector at 3. To fit the *IXPE* spectra, we also include the power law describing the ULX emission as derived from *Chandra*, fixing both the photon index and the flux. Finally, we multiply the different components by the POLCONST model. We assume the emission lines and the ULXs to be unpolarized³. The XSPEC model is as follows:

$$\begin{aligned} & \text{c_CAL} \times \text{TBABS} \times [\text{POLCONST}^{(0)} \times (\sum \text{ZGAUSS}^{(i)} \quad \text{lines} \\ & \quad + \text{POWERLAW}) \quad \text{ULXs} \\ & \quad + \text{POLCONST}^{(w)} \times \text{POWERLAW} \quad \text{warm refl.} \\ & \quad + \text{POLCONST}^{(c)} \times \text{PEXRAV}] \quad \text{cold refl.} \end{aligned}$$

where c_CAL is the cross-calibration constant. We fix the polarization degree of POLCONST⁽⁰⁾ at zero, which corresponds to an unpolarized component in XSPEC. The data and best-fitting model are shown in Figs. 3 and 4.

We find significant degeneracy among the polarization parameters of the warm and cold reflectors. The contour plot (not shown here) between the polarization degrees of the two components indicates that even at 1-sigma, P_{cold} is barely above zero and P_{warm} has only an upper limit of 28%. To reduce such degeneracy, we need to make some assumptions. We thus fix the polarization parameters of the warm component using the far-UV polarimetric measurements by Antonucci, Hurt, & Miller (1994), see also Sect. 4.3. Those authors have shown that, within the first arcseconds, electron scattering in the winds is mainly responsible for the far-UV polarization. We postulate that the X-ray counterpart should be similar. We thus fix the polarization degree and angle of the warm reflector at 16% and 97°, respectively. With this assumption, we obtain a good fit with $\chi^2/\text{dof} = 534/527$: the cold reflector has a polarization degree of $20\% \pm 10\%$ (non-zero at merely two sigma) and a polarization angle of $102^\circ \pm 15^\circ$. The best-fitting parameters are reported in Table 3.3. Finally, we note that the warm reflection component is expected to be still significantly contaminated by unresolved emission lines, in which case the polarization degree could be much lower than our initial assumption. In the extreme hypothesis of null polarization of the warm reflector, we obtain a statistically equivalent fit, and a polarization degree of the cold reflector of $36\% \pm 10\%$.

4. Analysis

4.1. The geometrical distribution of scatterers

The observed X-ray polarization angle can be compared to the position angle PA of the parsec-scale radio-jet seen in NGC 1068 to determine whether scattering occurs along the equatorial plane ($\Psi - \text{PA} \approx 0^\circ$) or in the polar direction ($\Psi - \text{PA} \approx 90^\circ$). The resolved parsec-scale jet on the 4.9 GHz map of Wilson & Ulvestad (1983) sustains a PA $\sim 34^\circ$ (see also Mutie et al. 2024 for

² We use PEXRAV plus emission lines instead of models which self-consistently include both the continuum and the lines because the polarization of the reflected continuum and of the emission lines is expected to be different, see also Ursini et al. (2023).

³ ULXs are likely polarized, with P depending on their true nature, orientation and geometry (Veledina et al. 2023). However, the ULXs around NGC 1068 contribute so weakly to the total flux that assuming no polarization is a reasonable hypothesis.

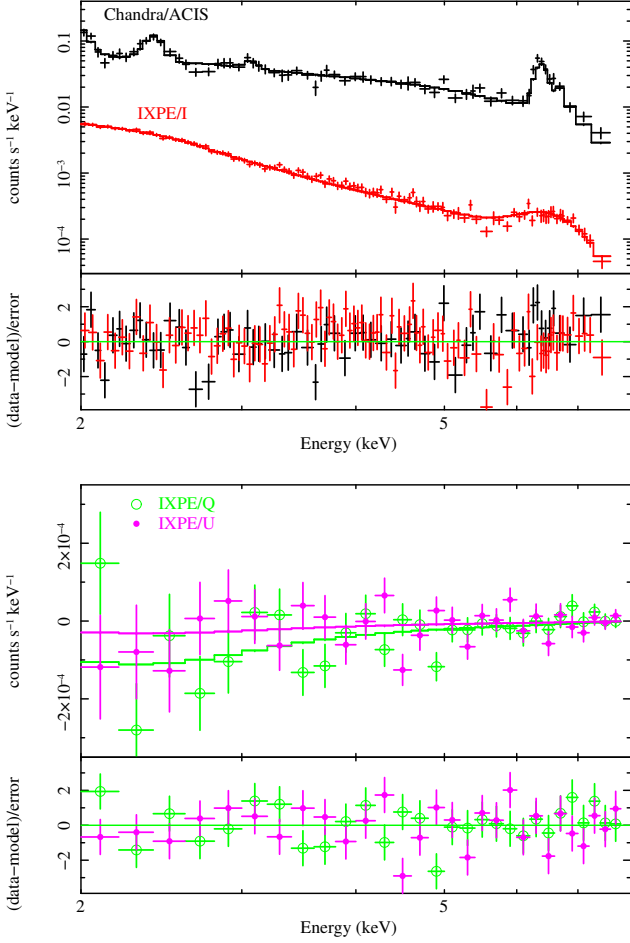


Fig. 3. Top panel: *Chandra*/ACIS and *IXPE* I spectra with best-fitting model and residuals. Bottom panel: *IXPE* Q and U Stokes spectra with best-fitting model and residuals.

a very precise cartography of the radio emission in NGC 1068). We find that the observed X-ray polarization angle of NGC 1068 is perpendicular to the radio structure axis, implying that the ob-

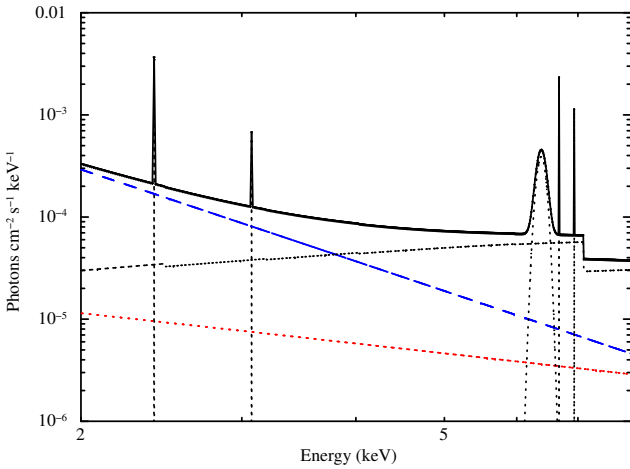


Fig. 4. Best-fitting total model (black solid line) for the *Chandra*+*IXPE* data. The plot shows the different components, i.e. cold reflection (black dotted line), warm reflection (blue dashed line), ULXs (red dotted line).

| Energy (keV) | P (%) | Ψ (°) |
|--------------|----------------|------------------|
| 2.0 – 8.0 | 12.4 ± 3.6 | 100.7 ± 8.3 |
| 2.0 – 3.5 | 9.8 ± 4.9 | 104.2 ± 14.9 |
| 3.5 – 6.0 | 21.3 ± 6.7 | 102.2 ± 9.2 |
| 6.0 – 8.0 | < 38.5 | – |
| 2.0 – 5.5 | 14.6 ± 3.9 | 101.1 ± 7.6 |
| 5.5 – 8.0 | < 26.8 | – |

Table 1. XSPEC measured polarization degree P and angle Ψ for various energy bands. Errors are given at 68% confidence level for one parameter of interest. Upper limits are given at 99% confidence level.

| Parameter | Value |
|-----------------------------|---------------------------------------|
| Lines (ZGAUSS) | |
| E_1 (keV) | 1.96 ± 0.02 |
| N_1 | $5.6 \pm 0.8 \times 10^{-5}$ |
| E_2 (keV) | 2.42 ± 0.07 |
| N_2 | $3.5 \pm 0.3 \times 10^{-5}$ |
| E_3 (keV) | $3.09^{+0.02}_{-0.04}$ |
| N_3 | $0.55^{+0.19}_{-0.17} \times 10^{-5}$ |
| E_4 (keV) | $6.41^{+0.01}_{-0.02}$ |
| σ_4 (eV) | 76 ± 12 |
| N_4 | $7.4^{+0.5}_{-0.6} \times 10^{-5}$ |
| E_5 (keV) | $6.7(f)$ |
| N_5 | $2.3 \pm 0.4 \times 10^{-5}$ |
| E_6 (keV) | $6.966(f)$ |
| N_6 | $1.1 \pm 0.5 \times 10^{-5}$ |
| ULXs (POWERLAW) | |
| Γ | $1(f)$ |
| N | $2.3 \times 10^{-5}(f)$ |
| Cold reflector (PEXRAV) | |
| Γ | $2(f)$ |
| N | $(1.97 \pm 0.08) \times 10^{-2}$ |
| P.D. (%) | 20 ± 10 |
| P.A. (deg) | 102 ± 15 |
| Warm reflector (POWERLAW) | |
| Γ | $3(f)$ |
| N | $2.36^{+0.06}_{-0.12} \times 10^{-3}$ |
| P.D. (%) | $16(f)$ |
| P.A. (deg) | $97(f)$ |
| Cross-calibration constants | |
| $C_{DU1-ACIS}$ | 0.68 ± 0.01 |
| $C_{DU2-ACIS}$ | 0.64 ± 0.01 |
| $C_{DU3-ACIS}$ | 0.60 ± 0.01 |
| Observed flux | |
| $F_{2-8\text{keV}}$ | $(4.32 \pm 0.15) \times 10^{-12}$ |
| $\chi^2/\text{d.o.f.}$ | $534/527$ |

Table 2. Best-fitting parameters (68 per cent confidence level for one parameter of interest) of the joint *Chandra* and *IXPE* fit. Normalizations are in units of photons $\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$, while the flux is in unit of $\text{erg cm}^{-2} \text{s}^{-1}$. (f) denotes a fixed parameter. The energies of the two lines E_5 and E_6 are fixed at the values of the Fe XXV and Fe XXVI $K\alpha$ lines. The width of all lines is fixed at zero, with the only exception of the neutral Fe $K\alpha$ line.

served X-ray polarization arises from scattering onto material that is preferentially situated well above the equatorial plane.

Two components of the AGN can be responsible for this: the outflows or the torus. Our measurements reported in Tab. 1 show that Ψ is similar in the 2 – 3.5 keV band (where the warm component dominates the X-ray spectrum, see Sect. 3.3) and in the 3.5 – 6 KeV band, where the cold component takes prece-

dence. Both components are thus likely sharing the polarization position angle. While producing perpendicular polarization in a polar wind is trivial (Goosmann & Gaskell 2007), obtaining a similar polarization angle from an equatorial torus implies that scattering must occur inside the funnel and/or on the uppermost (outer) edges of this Compton-thick region. Such finding is strongly supported by the Atacama Large Millimeter Array (ALMA) observation of an extended patch of linear polarization arising from a spatially resolved elongated nuclear disk of dust of $\sim 50 - 60$ pc in diameter and oriented along an averaged PA of $\sim 113^\circ$ (García-Burillo et al. 2019).

The *Chandra* map at $0.5''$ resolution of the X-ray emission in NGC 1068 presented by Ogle et al. (2003) also supports our conclusion that the X-ray polarization we measured with *IXPE* mainly originates from the torus. The authors have shown (see their Figs. 3 and 4) that the peak of the 6 – 8 keV (Fe K) emission is coincident with the nucleus, as expected if produced in the inner wall of the molecular torus. Surrounding the X-ray peak in the nuclear region, 3 – 6 keV extended emission is detected, which is attributed to X-rays that have scattered on the outer edge of the torus. The emission from the warm reflector (the ionization cones) is seen in their *Chandra* 1.3 – 3 keV map and is dominated by emission from highly ionized Mg, Si, and S. The warm component is also appearing in their 3 – 6 keV emission map but it is mostly scattered continuum. Using *XSPEC* to measure the associated X-ray polarization in those three energy bands (see Tab. 1) gives only an upper limit to the 6 – 8 keV emission, resulting from the combination of higher background levels and strong, little-to-no polarized emission from the iron K complex. In the 3.5 – 6 keV band, where scattering off the torus is prevalent, P rises up to $\sim 21\%$. In the softest X-ray band (2 – 3.5 keV), the observed polarization degree is much lower ($\sim 10\%$), mostly due to the forest of narrow emission lines that depolarise the signal. Many of those lines are significantly enhanced by photo-excitation, so they might be polarized, albeit at a lower level from the hard continuum.

4.2. Estimating the AGN inclination and torus geometry

Even if nothing definitive can be said about the intrinsic polarization degree and angle originating from the torus, we can try to evaluate the geometry of this region thanks to Monte Carlo radiative transfer simulation of optically thick tori. We used the radiative transfer Monte Carlo code *STOKES* (Goosmann & Gaskell 2007; Marin et al. 2012; Marin, Goosmann, & Gaskell 2015; Marin 2018; Rojas Lobos et al. 2018) to simulate a central, isotropical, continuum source with a power law index $\Gamma \sim 2.04$ (Matt et al. 2004, Pounds & Vaughan 2006 and Sect. 3.3). The source emits a 2% parallel polarized primary continuum, since it has been shown in NGC 4151 that the X-ray continuum is parallelly polarized by a few percents (Gianolli et al. 2023). Around the central source, we modeled a uniform-density torus using a circular cross-section. The inner wall of the torus is set at a fixed distance of $r_{in} = 0.25$ pc (Lopez-Rodriguez et al. 2018; Vermot et al. 2021) and the radius a of the torus is set by the region's half-opening angle Θ such as $a = r_{in} \cos \Theta / (1 - \cos \Theta)$. The neutral hydrogen density N_H is set to 10^{25} atom cm^{-2} along the equatorial plane (Matt et al. 2004). The half-opening angle of the torus and the system inclination i are free parameters, both measured from the vertical symmetry axis of the system. Type-2 AGNs are thus found for $i > \Theta$. Such models have been examined in details in Podgorný, Marin, & Dovčiak (2023) and we refer the reader to this publication for in-depth details.

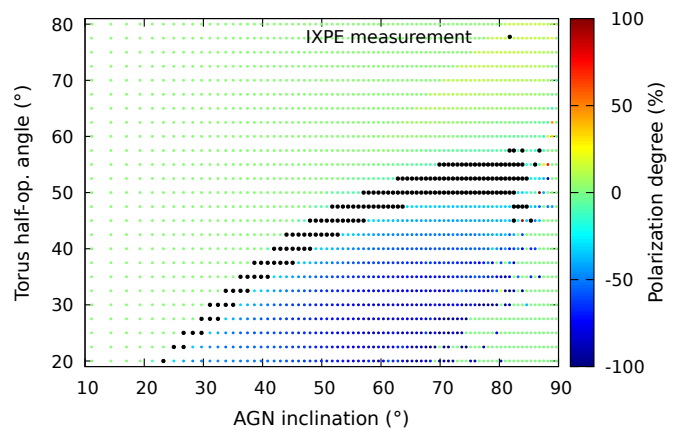


Fig. 5. STOKES simulations of a circular-shaped torus with various half-opening angles Θ seen at several observer inclinations i . The color-coded polarization degree is integrated from 3.5 to 6.0 keV to avoid contribution from intense emission lines. A positive polarization degree indicates that the photon electric field vector is parallel to the axis of symmetry of the system. Thus, negative polarization stands for perpendicularly polarized photons. Each colored dot represents a (Θ, i) simulation. If the polarization degree and angle of a dot is consistent with the X-ray polarization of the torus as measured by *IXPE*, the dot is shown in black.

We present in Fig. 5 the results of the simulations for a wide variety of Θ and i angles. The polarization is integrated between 3.5 and 6 keV to avoid as much contamination as possible from the fluorescent and recombination lines (see Fig. 4). Superimposing the estimated neutral reflector X-ray polarization ($20\% \pm 10\%$) to the models allows us to put strong constraints on the geometrical configuration of the system. Excluding a) all torus half-opening angles smaller than that of the ionized polar winds seen in NGC 1068, that sustain a half-opening angle of 40° as traced by [O III] emission (Macchetto et al. 1994), b) all results for $i < \Theta$ and c) all non-perpendicular polarization angles (an assumption compatible with *IXPE* data), we find that the range of permitted AGN inclinations is $42^\circ - 87^\circ$ and the range of torus half-opening angles is $40^\circ - 57.5^\circ$ (as illustrated by the black dots on Fig. 5). Further observation with better statistics could narrow down the parameter space but, if we rely on the range of inclinations i estimated from the literature ($70^\circ - 90^\circ$, see Sect. 1), the permitted range of Θ becomes $45^\circ - 57.5^\circ$, with a much higher probability to be in the range $50^\circ - 55^\circ$. Interestingly, this is comparable to the range of Θ found in the case of the Circinus galaxy ($45^\circ - 55^\circ$), the only other type-2 AGN probed by *IXPE* (Ursini et al. 2023).

For the sake of completeness, we also tested the line dominated warm reflector scenario ($P = 0\%$), that would lead to a neutral reflector polarization of $36\% \pm 10\%$ (see Sect. 3.3). By doing so, the torus half-opening angle estimated from Monte Carlo radiative transfer simulations becomes $40^\circ - 50^\circ$, with a much higher statistical probability to be between 45° and 50° . This is also comparable to the range of Θ found in the case of the Circinus galaxy.

4.3. Comparison with optical data

The broadband polarization of NGC 1068 has been thoroughly examined from the ultraviolet to the infrared band (see Marin 2018 and reference therein for a review). Yet, due to strong starlight dilution by the host, the true (intrinsic) polarization levels of the AGN cannot be measured. The addition of the

X-ray polarization measurement achieved by *IXPE* brings another piece to the puzzle, since it is essentially free from diluting sources (albeit the almost negligible ULX signal). A comparison between X and optical data can thus lead to better constraints on the global geometry of the AGN.

To do so, $0.35 - 1.1 \mu\text{m}$ linear spectropolarimetry was obtained on December 1 – 6th, 2023, with the FOcal Reducer/low dispersion Spectrograph 2 (FOR2S2) instrument mounted on the Very Large Telescope (VLT), quasi-simultaneously to the *IXPE* observation. The observation, under program ID 112.26WL.001, will be analyzed and published later on (Marin et al., in prep.), but the reduced optical data confirm that the linear polarization from NGC 1068 remained stable since the last decades, especially in the continuum. The polarization degree rises from $\sim 1.5\%$ in the red up to $\sim 12\%$ in the blue band. The polarization position angle is almost constant with wavelength, slowly rotating from $\sim 100^\circ$ in the red to $\sim 90^\circ$ in the blue. The rise of P continues in the ultraviolet band up to 16% at a position angle of 97° shortward of 2700 \AA (Antonucci, Hurt, & Miller 1994). The polarization degree then plateaus, as the host starlight contribution becomes negligible, indicating that electron scattering dominates in the winds.

The matching of the polarization angle between the near-infrared, optical, ultraviolet and X-rays clearly indicates that the polarization results, in all cases, from scattering by material well above the equatorial plane. But they are not due to the same AGN component. X-ray spectropolarimetry tends to favor light reflection off atoms and molecules from the cold component (the torus), while optical imaging and spectropolarimetry advocates for electron (or dust) scattering inside the polar outflows (Antonucci & Miller 1985; Antonucci, Hurt, & Miller 1994). In the spectral region where emission from the ionized winds dominates the X-ray signal ($2 - 3.5 \text{ keV}$, see Fig. 4), we measured $P = 9.8\% \pm 4.9\%$ at $104.2^\circ \pm 14.9^\circ$. Although diluted by the emission lines, the polarized X-ray continuum probably comes from the optically thin region that scatters the optical and ultraviolet photons (Antonucci & Miller 1985).

As things currently stand and with the statistics offered by our observation, we note that the optical/ultraviolet and X-ray measurements are different in P (but not in Ψ), so we caution using ultraviolet polarization measurements of Seyfert-2 galaxies as a basic proxy to predict the polarization level of a source in the X-rays.

5. Conclusions

We have measured the $2 - 8 \text{ keV}$ polarization of the archetypal Seyfert-2 AGN NGC 1068 with *IXPE*. We found a linear polarization degree of $12.4\% \pm 3.6\%$ at $100.7^\circ \pm 8.3^\circ$ (68% confidence level). The polarization is perpendicular to the position angle of the parsec-scale radio structure, similarly to what is observed for all Seyfert-2s in the optical band. A combined *Chandra* and *IXPE* analysis indicated a significant degeneracy among the polarization parameters of the warm and cold reflectors but, from multi-wavelength constraints, we estimated that the cold reflector has a polarization degree of $20\% \pm 10\%$ and polarization angle of $102^\circ \pm 15^\circ$. By taking the result at the face value, numerical simulations allowed us to derive a probable torus half-opening angle of $50 - 55^\circ$ (from the vertical axis of the system). This morphological constraint is quite similar to the torus half-opening angle derived for the Circinus galaxy thanks to X-ray polarimetry, the only other type-2 AGN probed by *IXPE* so far. By doing so, X-ray polarimetry has shown its powerful and

unique capabilities of constraining the geometrical arrangement of matter around supermassive black holes.

Acknowledgments. The Imaging X-ray Polarimetry Explorer (*IXPE*) is a joint US and Italian mission. The US contribution is supported by the National Aeronautics and Space Administration (NASA) and led and managed by its Marshall Space Flight Center (MSFC), with industry partner Ball Aerospace (contract NNM15AA18C). The Italian contribution is supported by the Italian Space Agency (Agenzia Spaziale Italiana, ASI) through contract ASI-OHBI-2022-13-L.O, agreements ASI-INAf-2022-19-HH.0 and ASI-INFN-2017.13-H.0, and its Space Science Data Center (SSDC) with agreements ASI-INAf-2022-14-HH.0 and ASI-INFN 2021-43-HH.0, and by the Istituto Nazionale di Astrofisica (INAF) and the Istituto Nazionale di Fisica Nucleare (INFN) in Italy. This research used data products provided by the *IXPE* Team (MSFC, SSDC, INAF, and INFN) and distributed with additional software tools by the High-Energy Astrophysics Science Archive Research Center (HEASARC), at NASA Goddard Space Flight Center (GSFC). A.D.M., E.Co., R.F., S.F., F.L.M., F. Mu. P.So. are partially supported by MAECI with grant CN24GR08 “GRBAXP: Guangxi-Rome Bilateral Agreement for X-ray Polarimetry in Astrophysics”. F.T. acknowledges funding from the European Union - Next Generation EU, PRIN/MUR 2022 (2022K9N5B4). M.D., J.P., and V.K. thank GACR project 21-06825X for the support and institutional support from RVO:67985815. I.L. was supported by the NASA Postdoctoral Program at the Marshall Space Flight Center, administered by Oak Ridge Associated Universities under contract with NASA. The work of RTa and RTu is partially supported by grant PRIN-2022LWPEXW of the Italian MUR. The French contribution (F.M., T.B., V.E.G., P.-O.P.) is partly supported by the French Space Agency (Centre National d’Etude Spatiale, CNES) and by the High Energy National Programme (PNHE) of the Centre National de la Recherche Scientifique (CNRS).

References

- Antonucci R. R. J., Miller J. S., 1985, *ApJ*, 297, 621. doi:10.1086/163559
- Antonucci R., Hurt T., Miller J., 1994, *ApJ*, 430, 210. doi:10.1086/174395
- Antonucci R., 1993, *ARA&A*, 31, 473. doi:10.1146/annurev.aa.31.090193.002353
- Arnaud K. A., 1996, *ASPC*, 101, 17
- Baldini L., Bucciantini N., Lalla N. D., Ehlert S., Manfreda A., Negro M., Omodei N., et al., 2022, *ascl.soft. ascl:2210.020*
- Bauer, F. E., Arévalo, P., Walton, D. J., et al. 2015, *ApJ*, 812, 116. doi:10.1088/0004-637X/812/2/116
- Bostroem K. A., et al., 2020, *ApJ*, 895, 31B
- Cash, W. 1979, *ApJ*, 228, 939. doi:10.1088/0004-637X/812/2/116
- Das V., Crenshaw D. M., Kraemer S. B., Deo R. P., 2006, *AJ*, 132, 620. doi:10.1086/504899
- Di Marco A., Costa E., Muleri F., Soffitta P., Fabiani S., La Monaca F., Rankin J., et al., 2022, *AJ*, 163, 170. doi:10.3847/1538-3881/ac51c9
- Di Marco A., Soffitta P., Costa E., Ferrazzoli R., La Monaca F., Rankin J., Ratheesh A., et al., 2023, *AJ*, 165, 143. doi:10.3847/1538-3881/acba0f
- Dopita M. A., 1997, *PASA*, 14, 230. doi:10.1071/AS97230
- Fischer T. C., Crenshaw D. M., Kraemer S. B., Schmitt H. R., 2013, *ApJS*, 209, 1. doi:10.1088/0067-0049/209/1/1
- Fruscione A., et al., 2006, in Silva D. R., E. D. R., eds, *SPIE Conf. Ser. Vol. 6270, Observatory Operations: Strategies, Processes, and Systems*.
- Gómez Rosas V., Isbell J. W., Jaffe W., Petrov R. G., Leftley J. H., Hofmann K.-H., Millour F., et al., 2022, *Natur*, 602, 403. doi:10.1038/s41586-021-04311-7
- Gallimore J. F., Henkel C., Baum S. A., Glass I. S., Claussen M. J., Prieto M. A., Von Kap-herr A., 2001, *ApJ*, 556, 694. doi:10.1086/321616
- García-Burillo S., Combes F., Ramos Almeida C., Usero A., Alonso-Herrero A., Hunt L. K., Rouan D., et al., 2019, *A&A*, 632, A61. doi:10.1051/0004-6361/201936606
- Garmire G. P., Bautz M. W., Ford P. G., Nousek J. A., Ricker G. R., 2003, in Truemper J. E., D. T. H., eds, *SPIE Conf. Ser. Vol. 4851, X-Ray and Gamma-Ray Telescopes and Instruments for Astronomy*. pp 28–44

- Gianolli V. E., Kim D. E., Bianchi S., Agís-González B., Madejski G., Marin F., Marinucci A., et al., 2023, MNRAS, 523, 4468. doi:10.1093/mnras/stad1697
- Goosmann R. W., Gaskell C. M., 2007, A&A, 465, 129. doi:10.1051/0004-6361:20053555
- Goosmann R. W., Matt G., 2011, MNRAS, 415, 3119. doi:10.1111/j.1365-2966.2011.18923.x
- Greenhill L. J., Gwinn C. R., Antonucci R., Barvainis R., 1996, ApJL, 472, L21. doi:10.1086/310346
- Hönig S. F., Beckert T., Ohnaka K., Weigelt G., 2007, ASPC, 373, 487. doi:10.48550/arXiv.astro-ph/0611946
- Hönig S. F., Prieto M. A., Beckert T., 2008, A&A, 485, 33. doi:10.1051/0004-6361:200809606
- HI4PI Collaboration, Ben Bekhti N., Flöer L., Keller R., Kerp J., Lenz D., Winkel B., et al., 2016, A&A, 594, A116. doi:10.1051/0004-6361/201629178
- Ingram A., Ewing M., Marinucci A., Tagliacozzo D., Rosario D. J., Veleđina A., Kim D. E., et al., 2023, MNRAS, 525, 5437. doi:10.1093/mnras/stad2625
- Kim D. E., Di Gesu L., Liodakis I., Marscher A. P., Jorstad S. G., Middei R., Marshall H. L., et al., 2024, A&A, 681, A12. doi:10.1051/0004-6361/202347408
- Kishimoto M., 1999, ApJ, 518, 676. doi:10.1086/307290
- Kislat F., Clark B., Beilicke M., Krawczynski H., 2015, APH, 68, 45. doi:10.1016/j.astropartphys.2015.02.007
- Lopez-Rodriguez E., Fuller L., Alonso-Herrero A., Efsthathiou A., Ichikawa K., Levenson N. A., Packham C., et al., 2018, ApJ, 859, 99. doi:10.3847/1538-4357/aab7b
- Macchetto F., Capetti A., Sparks W. B., Axon D. J., Boksenberg A., 1994, ApJL, 435, L15. doi:10.1086/187583
- Maeda K., et al., 2023, ApJ, 942, 17M
- Magdziarz P., Zdziarski A. A., 1995, MNRAS, 273, 837. doi:10.1093/mnras/273.3.837
- Marin F., Goosmann R. W., Gaskell C. M., Porquet D., Dovčiak M., 2012, A&A, 548, A121. doi:10.1051/0004-6361/201219751
- Marin F., Dovčiak M., Muleri F., Kislat F. F., Krawczynski H. S., 2018, MNRAS, 473, 1286. doi:10.1093/mnras/stx2382
- Marin F., Goosmann R. W., Gaskell C. M., 2015, A&A, 577, A66. doi:10.1051/0004-6361/201525628
- Marin F., 2018, MNRAS, 479, 3142. doi:10.1093/mnras/sty1566
- Marin F., 2018, A&A, 615, A171. doi:10.1051/0004-6361/201833225
- Marinucci A., Bianchi S., Matt G., et al. 2016, MNRAS, 456, L94. doi:10.1093/mnras/lsv178
- Marinucci A., Muleri F., Dovčiak M., Bianchi S., Marin F., Matt G., Ursini F., et al., 2022, MNRAS, 516, 5907. doi:10.1093/mnras/stac2634
- Matt G., Bianchi S., Guainazzi M., Molendi S., 2004, A&A, 414, 155. doi:10.1051/0004-6361:20031635
- Miyauchi R., Kishimoto M., 2020, ApJ, 904, 149. doi:10.3847/1538-4357/abc264
- Mutic I. M., Williams-Baldwin D., Beswick R. J., Bempong-Manful E. K., Baki P. O., Muxlow T. W. B., Gallimore J. F., et al., 2024, MNRAS, 527, 11756. doi:10.1093/mnras/stad3864
- Ogle P. M., Brookings T., Canizares C. R., Lee J. C., Marshall H. L., 2003, A&A, 402, 849. doi:10.1051/0004-6361:20021647
- Oliva E., Marconi A., Cimatti A., di Serego Alighieri S., 1998, A&A, 329, L21. doi:10.48550/arXiv.astro-ph/9711054
- Packham C., Young S., Hough J. H., Axon D. J., Bailey J. A., 1997, MNRAS, 288, 375. doi:10.1093/mnras/288.2.375
- Piconcelli E., Jimenez-Bailón E., Guainazzi M., Schartel N., Rodríguez-Pascual P. M., Santos-Lleó M., 2004, MNRAS, 351, 161. doi:10.1111/j.1365-2966.2004.07764.x
- Podgorný J., Marin F., Dovčiak M., 2023, MNRAS, 526, 4929. doi:10.1093/mnras/stad3085
- Pounds K., Vaughan S., 2006, MNRAS, 368, 707. doi:10.1111/j.1365-2966.2006.10139.x
- Rojas Lobos P. A., Goosmann R. W., Marin F., Savić D., 2018, A&A, 611, A39. doi:10.1051/0004-6361/201731331
- Sandage A., 1973, ApJ, 183, 711. doi:10.1086/152261
- Smith D. A., Wilson A. S., 2003, ApJ, 591, 138. doi:10.1086/375291
- Tagliacozzo D., Marinucci A., Ursini F., Matt G., Bianchi S., Baldini L., Barnouin T., et al., 2023, MNRAS, 525, 4735. doi:10.1093/mnras/stad2627
- Urry C. M., Padovani P., 1995, PASP, 107, 803. doi:10.1086/133630
- Ursini F., Marinucci A., Matt G., Bianchi S., Marin F., Marshall H. L., Middei R., et al., 2023, MNRAS, 519, 50. doi:10.1093/mnras/stac3189
- Veleđina A., Muleri F., Poutanen J., Podgorný J., Dovčiak M., Capitanio F., Churazov E., et al., 2023, arXiv, arXiv:2303.01174. doi:10.48550/arXiv.2303.01174
- Vermot P., Clénet Y., Gratadour D., Rouan D., Grosset L., Perrin G., Kervella P., et al., 2021, A&A, 652, A65. doi:10.1051/0004-6361/202141349
- Weisskopf M. C., Soffitta P., Baldini L., Ramsey B. D., O'Dell S. L., Romani R. W., Matt G., et al., 2022, JATIS, 8, 026002. doi:10.1117/1.JATIS.8.2.026002
- Wilms J., Allen A., McCray R., 2000, ApJ, 542, 914. doi:10.1086/317016
- Wilson A. S., Ulvestad J. S., 1983, ApJ, 275, 8. doi:10.1086/161507
- Zaino A., Bianchi S., Marinucci A., Matt G., Bauer F. E., Brandt W. N., Gandhi P., et al., 2020, MNRAS, 492, 3872. doi:10.1093/mnras/staa107

- ¹ Université de Strasbourg, CNRS, Observatoire Astronomique de Strasbourg, UMR 7550, 67000 Strasbourg, France
- ² ASI - Agenzia Spaziale Italiana, Via del Politecnico snc, 00133 Roma, Italy
- ³ Dipartimento di Fisica, Università di Roma “Tor Vergata”, Via della Ricerca Scientifica 1, 00133 Roma, Italy
- ⁴ Space Science Data Center, SSDC, ASI, Via del Politecnico snc, 00133 Roma, Italy
- ⁵ INAF Istituto di Astrofisica e Planetologia Spaziali, Via del Fosso del Cavaliere 100, I-00133 Roma, Italy
- ⁶ Dipartimento di Fisica, Università degli Studi di Roma “La Sapienza”, Piazzale Aldo Moro 5, I-00185 Roma, Italy
- ⁷ Dipartimento di Matematica e Fisica, Università degli Studi Roma Tre, via della Vasca Navale 84, 00146 Roma, Italy
- ⁸ MIT Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA
- ⁹ Science and Technology Institute, Universities Space Research Association, Huntsville, AL 35805, USA
- ¹⁰ Université Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France
- ¹¹ School of Mathematics, Statistics, and Physics, Newcastle University, Newcastle upon Tyne NE1 7RU, UK
- ¹² Center for Astrophysics, Harvard & Smithsonian, 60 Garden St., Cambridge, MA 02138, USA
- ¹³ Astronomical Institute of the Czech Academy of Sciences, Boční II 1401/1, 14100 Praha 4, Czech Republic
- ¹⁴ Istituto Nazionale di Fisica Nucleare, Sezione di Roma “Tor Vergata”, Via della Ricerca Scientifica 1, 00133 Roma, Italy
- ¹⁵ Department of Astronomy, University of Maryland, College Park, Maryland 20742, USA
- ¹⁶ Instituto de Astrofísica de Andalucía—CSIC, Glorieta de la Astronomía s/n, 18008 Granada, Spain
- ¹⁷ INAF Osservatorio Astronomico di Roma, Via Frascati 33, 00078 Monte Porzio Catone (RM), Italy
- ¹⁸ INAF Osservatorio Astronomico di Cagliari, Via della Scienza 5, 09047 Selargius (CA), Italy
- ¹⁹ Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy
- ²⁰ Dipartimento di Fisica, Università di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy
- ²¹ NASA Marshall Space Flight Center, Huntsville, AL 35812, USA
- ²² Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Via Pietro Giuria 1, 10125 Torino, Italy
- ²³ Dipartimento di Fisica, Università degli Studi di Torino, Via Pietro Giuria 1, 10125 Torino, Italy
- ²⁴ INAF Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, 50125 Firenze, Italy
- ²⁵ Dipartimento di Fisica e Astronomia, Università degli Studi di Firenze, Via Sansone 1, 50019 Sesto Fiorentino (FI), Italy
- ²⁶ Istituto Nazionale di Fisica Nucleare, Sezione di Firenze, Via Sansone 1, 50019 Sesto Fiorentino (FI), Italy
- ²⁷ Department of Physics and Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, California 94305, USA
- ²⁸ Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, 72076 Tübingen, Germany
- ²⁹ RIKEN Cluster for Pioneering Research, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
- ³⁰ California Institute of Technology, Pasadena, CA 91125, USA
- ³¹ Yamagata University, 1-4-12 Kojirakawamachi, Yamagatashi 990-8560, Japan
- ³² University of British Columbia, Vancouver, BC V6T 1Z4, Canada
- ³³ International Center for Hadron Astrophysics, Chiba University, Chiba 263-8522, Japan

- ³⁴ Institute for Astrophysical Research, Boston University, 725 Commonwealth Avenue, Boston, MA 02215, USA
- ³⁵ Department of Astrophysics, St. Petersburg State University, Universitetskyy pr. 28, Petrodvoretz, 198504 St. Petersburg, Russia
- ³⁶ Department of Physics and Astronomy and Space Science Center, University of New Hampshire, Durham, NH 03824, USA
- ³⁷ Physics Department and McDonnell Center for the Space Sciences, Washington University in St. Louis, St. Louis, MO 63130, USA
- ³⁸ Finnish Centre for Astronomy with ESO, 20014 University of Turku, Finland
- ³⁹ Department of Physics and Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, California 94305, USA
- ⁴⁰ Graduate School of Science, Division of Particle and Astrophysical Science, Nagoya University, Furocho, Chikusaku, Nagoya, Aichi 464-8602, Japan
- ⁴¹ Hiroshima Astrophysical Science Center, Hiroshima University, 1-3-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8526, Japan
- ⁴² University of Maryland, Baltimore County, Baltimore, MD 21250, USA
- ⁴³ NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
- ⁴⁴ Center for Research and Exploration in Space Science and Technology, NASA/GSFC, Greenbelt, MD 20771, USA
- ⁴⁵ Department of Physics, The University of Hong Kong, Pokfulam, Hong Kong
- ⁴⁶ Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
- ⁴⁷ Department of Physics and Astronomy, 20014 University of Turku, Finland
- ⁴⁸ INAF Osservatorio Astronomico di Brera, Via E. Bianchi 46, 23807 Merate (LC), Italy
- ⁴⁹ Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, Via Marzolo 8, 35131 Padova, Italy
- ⁵⁰ Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, Via Marzolo 8, 35131 Padova, Italy
- ⁵¹ Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT, UK
- ⁵² Anton Pannekoek Institute for Astronomy & GRAPPA, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands
- ⁵³ Guangxi Key Laboratory for Relativistic Astrophysics, School of Physical Science and Technology, Guangxi University, Nanning 530004, China