Received: 27 June 2023 | Accepted: 28 June 2023 | Published on: 17 July 2023

DOI: 10.1002/asna.20230105

Astronomische Nachrichten

PROCEEDING

Unraveling the enigmatic soft x-ray excess: Current understanding and future perspectives

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Abstract

This article explores various theoretical models proposed to explain the soft x-ray excess phenomenon, including warm Comptonization, ionized reflection models, and ionized outflowing disc winds. The soft x-ray excess is better understood thanks to crucial observations made by ROSAT, XMM-Newton, and eROSITA. The article briefly touches upon historical discoveries in this field, specifically the initial detection of the soft x-ray excess in Narrow Line Seyfert 1 galaxies. While progress has been made in comprehending the soft x-ray excess, the article also acknowledges the challenges and limitations of the different models. We emphasize the importance of further studies to refine theoretical models by, for example, building up a large database of reverberation time lags between the disc and coronal x-ray emission to achieve a more comprehensive understanding of this intriguing phenomenon.

KEYWORDS

active galactic nuclei, soft x-ray excess, theoretical models

1 | INTRODUCTION

The soft x-ray excess observed in active galactic nuclei (AGN) has been a subject of great interest in AGN physics. This phenomenon refers to an excess emission of soft x-ray photons in the energy range of 0.1–2 keV, beyond what would be expected based on the extrapolation of the hard x-ray power-law continuum. The soft x-ray excess's origin and physical mechanisms are not fully understood.

Still, it is believed to be closely related to high accretion rates onto the central black hole in AGN and the interaction between the accretion disc and the hot corona surrounding it. The soft x-ray excess has been found to exhibit powerful emission in Narrow-Line Seyfert 1 galaxies (NLS1s). These AGN are characterized by narrow emission lines and strong Fe II multiplet emission in their optical spectra. In contrast, their x-ray spectra exhibit steep gradients in soft (0.1–2.0 keV) and hard (2–10 keV) bands and significant and rapid x-ray variability.

The ROSAT mission launched in 1990 Truemper (1982) was a pioneering mission for x-ray astronomy. ROSAT was crucial in discovering and studying the soft x-ray excess in AGN, particularly in NLS1s. ROSAT's high sensitivity and spectral resolution allowed researchers to obtain high-quality x-ray spectra of many AGNs for the first time, revealing the presence of the soft x-ray excess in a significant fraction of sources. Moreover, ROSAT's all-sky survey provided a wealth of data on the distribution and properties of AGN across the sky, leading to the identification of many new objects with soft x-ray excess emission.

In addition, ROSAT observations of AGN revealed significant variability in the soft x-ray excess on short timescales, suggesting that the emitting region is close to the central black hole and subject to strong gravitational effects. These findings have played a crucial role in shaping our physical understanding of the soft x-ray excess, the accretion process onto black holes, and the significance of these phenomena in AGN.

One possible explanation for the soft x-ray excess is ionized gas near the black hole. The ionized gas can mimic a soft x-ray excess through two main mechanisms: firstly, the gas being partially ionized makes soft x-rays more transparent below one keV, and secondly, the absorption features around one keV are imprinted. In addition to the ionized gas model, two other widely used models to explain the soft x-ray emission in AGN are the relativistic blurred reflection model and the warm Comptonization model. This paper summarizes our current knowledge and understanding of AGN's soft x-ray excess phenomenon.

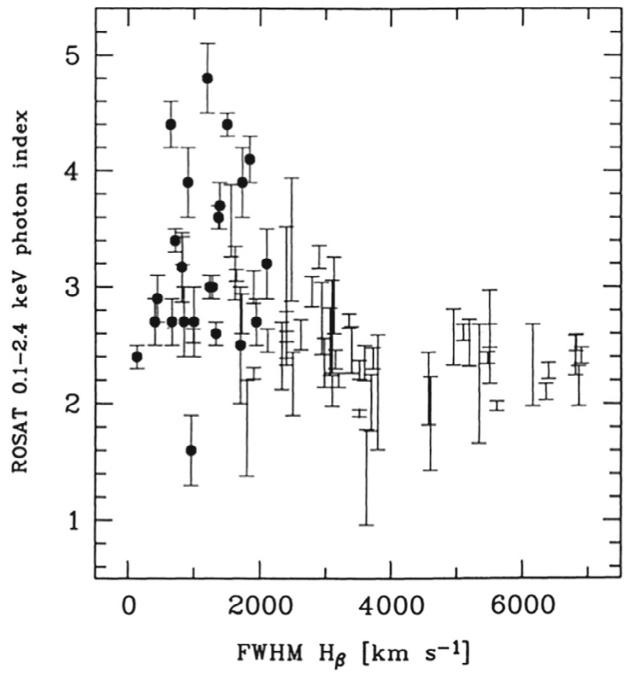

FIGURE 1 Correlation between FWHM $H\beta$ and photon index as found by Boller et al. (1996).

2 | NARROW-LINE SEYFERT 1 GALAXIES

A group of objects outstanding for their permitted lines being only slightly broader than the narrow forbidden lines, and yet unmistakably being of Seyfert type 1 due to the presence of Fe II emission lines, was first noticed by Zwicky et al. (1970), Davidson & Kinman (1978), Koski (1978), and Phillips (1978). This led to the definition of the new subclass of narrow-line Seyfert 1s by Osterbrock & Pogge (1985) and their optical criteria:

1. The permitted lines are only slightly broader than the forbidden lines.
2. The ratio of the [OIII] to Hβ line flux is less than 3.
3. Strong Fe II multiplet emission.

A line width of 2000 km/s is used as a cutoff to disentangle NLS1s from BLS1s Goodrich (1989).

The small line widths can only be explained by low masses of the central black hole Boller et al. (1996). It has been suggested that the high accretion and star-formation rates seen in NLS1s can be explained by a large amount of material available for accretion in the early phase of the AGN evolution Mathur et al. (2001). Other observational properties, including the low emissivity in [O III] from the NLR due to a larger BLR size in NLS1s compared with BLS1s caused by the intense UV emission disc from the disc, have supported this scenario. For a comprehensive summary, see (Komossa 2008; Tanaka et al. 2005).

Other characteristics of NLS1s are extreme softness, that is, soft x-ray excess, and rapid and substantial variability at x-rays. In the following section, related NLS1 research milestones are highlighted.

3 | HISTORY ON SOFT X-RAY EXCESS STUDIES

In the following, some key papers on soft x-ray excess are listed.

Puchnarewicz et al. (1992) reported on ultra-soft Einstein IPC x-ray spectra in 53 NLS1. This was the first note of an excess of soft x-ray emission compared with the power-law emission at higher energies.

Boller et al. (1996) found a relation between FWHM of Hβ and the ROSAT 0.1-2.4 keV photon index Figure 1 and interpreted this as a correlation between accretion state and black hole mass, mediated by greater disk luminosity and more significant cooling of the corona. The continuity between BLS1 and NLS1 led to the conclusion that NLS1s are type 1 Seyferts in a high/soft accretion state at the beginning of their life cycle.

Boller et al. (1997): Large and rapid amplitude variations were seen in the 30-day ROSAT monitoring light curve of IRAS 13224-3809 with a maximum factor of 57 within 1200 seconds. It was explained by the relativistic flux boosting (Lorentz 1904) of the variability caused by hot spots on the disk. Flux boosting scales with the relativistic Doppler factor to the power of $3 + \Gamma$, making this explanation plausible, as the investigated object had a steep photon index of 4.4 and was relevant for NLS1s variability.

Boller et al. (2002**)** discovered a sharp drop at around 7 keV in the XMM-Newton spectrum of 1H 0707-495, consistent with both partial covering by a neutral, Fe abundant absorber, perhaps associated with the torus, and a relativistically blurred Fe emission feature emitted from the accretion disk. This observation inspired the now-established relativistic reflection model Miniutti & Fabian (2004).

Pounds et al. (2003**)** identified blueshifted Fe K-shell absorption lines above seven keV in the XMM-Newton spectrum of PG 0844 + 349, thought to be caused by a fast ($\sim$0.2c) highly ionized outflow. This outflow is assumed to be radiation-driven and hence strong for objects accreting close to the Eddington limit. The authors suggest that ultrafast outflows (UFOs) play a significant role in such objects' mass and energy budgets.

Fabian et al. (2009**)**: A follow-up observation of the object 1H 0707-495 with XMM-Newton has revealed relativistic emission from both the Fe K and the Fe L line with an intensity ratio consistent with the line strengths expected from the line transition probabilities. A time lag between the direct power-law emission and reflected Fe line emission had been found, allowing us to estimate the height of the compact corona as only a few gravitational radii.

Boller et al. (2021**)** found extreme variability by a factor of about 100 in just one day in the eROSITA light curve of 1H 0707-495. The variability is mainly seen in the ultrasoft (0.3-1.0 keV) band, now called a new ultrasoft AGN state. The authors suggested that a combination of relativistic disk emission and partial covering caused by a clumpy and ionized x-ray outflow can explain the observations.

Parker et al. (2021**)**: The extreme variability of 1H 0707-495 was modeled by constant photoionized emission from Ne, Mg, and Fe lines at 1 keV as well as the onset of a variable obscuration of the primary x-ray emission as an enhancement to the intrinsic variability. This was in the adaption of the results reported by Kosec et al. (2018), who had already detected the presence of constant emission from an extended ionized wind moving at 8000 km/s, unaffected by a clumpy ionized absorber moving at 0.13c, in XMM-Newton data of the object and had interpreted both to be part of one outflow, cooling and slowing down at large distances to the nucleus.

The observations of NLS1s as AGN in the high accretion state provide a unique opportunity for testing and developing accretion disc models in the strong GR regime concerning AGN outflows. However, the exact nature of these processes is still under debate. Improved x-ray observations with future observations, in conjunction with advanced data analysis tools, will improve our understanding of the physical mechanisms of AGN from the gravitational radius to the kiloparsec scale.

4 | SATELLITES AND THEIR CONTRIBUTION TO THE SOFT X-RAY EXCESS

4.1 | ROSAT

The ROSAT satellite Truemper (1982) has also contributed to understanding the relationship between the soft x-ray excess and the line width of the Hbeta line in AGN. Th. Boller and colleagues used ROSAT observations to study the x-ray and optical spectra of a sample of AGNs, finding a strong correlation between the soft x-ray excess and the line width of the Hβ line Boller et al. (1996).

This correlation suggests that the soft x-ray excess may be related to the AGN's broad-line region (BLR), an ionized gas surrounding the supermassive black hole and emitting broad emission lines. The exact nature of this relationship, however, is still under investigation.

ROSAT's sensitivity in the soft x-ray band, combined with its ability to provide simultaneous optical and x-ray observations, has proven invaluable in studying the soft x-ray excess and its connection to other spectral features in AGNs.

In 1998, the ROSAT satellite monitored the AGN IRAS 13224-3809 Boller et al. (1997)—the campaign aimed to study the variability of the x-ray emission from this AGN.

The ROSAT observations revealed that IRAS 13224-3809 exhibited persistent x-ray variability over several days to weeks. In addition, the variability amplitude was much larger than what is typically seen in AGNs. This so-called "giant amplitude variability" is a rare phenomenon observed only in a few AGNs.

The variability was seen in the soft x-ray band (0.1–2.4 keV), which is consistent with a soft x-ray excess. This excess emission is thought to be related to hot spots in the accretion disk and relativistic flux boosting.

4.2 | XMM-Newton

XMM-Newton (Jansen et al. 2001) has significantly contributed to detecting and interpreting soft x-ray excess. The telescope's high sensitivity and spectral resolution have allowed for detailed observations of AGN, providing crucial data for understanding the nature of the excess emission. XMM-Newton has revealed that the soft x-ray excess is not unique to NLS1s but is present in various AGN types.

Moreover, XMM-Newton has provided evidence of a warm absorber in AGN, which may play a role in the soft x-ray excess emission. The telescope's ability to observe both the soft x-ray excess and the warm absorber simultaneously has led to new insights into the physical processes occurring in the accretion disc and the corona. Overall, XMM-Newton's contributions have significantly advanced our understanding of the soft x-ray excess and its connection to the accretion processes in AGN.

Some of the most relevant papers related to XMM-Newton's contributions to the detection and interpretation of the soft x-ray excess in AGN are given by, for example, (Jiang et al. 2022; Mundo et al. 2020; Petrucci et al. 2018; Xu et al. 2021).

4.3 | eROSITA

The extended ROentgen Survey with an Imaging Telescope Array (eROSITA) on board the Spectrum-Roentgen-Gamma (SRG) mission Merloni et al. (2012); Predehl et al. (2021) is a space-borne x-ray telescope launched in July 2019. Equipped with seven x-ray telescopes and operating in the energy range of 0.2–10 keV, eROSITA conducts an extensive and sensitive survey of the x-ray sky.

Utilizing a grazing incidence design with nested mirrors, eROSITA focuses x-ray photons onto detectors to capture high-resolution images over a wide field of view. Its primary objective is to create a comprehensive map of the x-ray universe, examining a variety of celestial phenomena, including supermassive black holes, galaxy clusters, AGN, and supernova remnants.

Over four years, eROSITA plans to complete eight full scans of the sky, providing an unprecedented dataset for further investigation. Its observations hold crucial scientific significance, contributing to the study of galaxy cluster evolution, the exploration of large-scale cosmic structures to probe dark energy, and the investigation of black hole physics and accretion processes.

The exceptional soft x-ray energy response of eROSITA enables precise measurements of the soft x-ray excess. With its advanced x-ray telescopes and sensitive detectors, eROSITA can accurately capture and analyze faint emissions in the soft x-ray range. This unprecedented capability allows for detailed investigations into the properties and origins of the soft x-ray excess, shedding light on the underlying physical processes and contributing to our understanding of astrophysical phenomena associated with this spectral feature.

Observations conducted with eROSITA during the CAL/PV phase, on the eFEDS field, and the first eROSITA all-sky survey, have already yielded significant discoveries and new perspectives on the soft x-ray excess emission. These investigations have provided valuable insights into this elusive x-ray spectral feature's nature, characteristics, and potential origins. Early discovery papers have been published by, for example, (Boller et al. 2021; Grünwald et al. 2023; Waddell et al. 2022).

Detailed eROSITA spectral studies of a few NLS1s in the South Ecliptic Pole Region (SEP) continuously observed with eROSITA will allow making progress in the understanding of the soft x-ray excess (Boller et al. 2023, in preparation) by building up a large reverberation database of time lags between the soft and hard x-ray emission to constrain models of the soft x-ray excess more physically.

5 | MODELS FOR THE SOFT X-RAY EXCESS

5.1 | Ionized disc winds

Ionized disc winds are a fundamental aspect of astrophysical systems, spanning various objects, including AGN. The intense radiation or magnetic fields in accretion discs drive these winds. These can launch and accelerate plasma to high velocities and produce complex, multiscale structures that profoundly impact their host galaxies.

The study of ionized disc winds is a rapidly evolving field. Advances in observational techniques, theoretical modeling, and numerical simulations provide new insights into the physical processes that drive these winds and their impact on their surrounding environments.

AGN are complex systems, and the physical processes that govern their behavior are still not fully understood. However, recent observations have provided significant insights into the role of ionized disc winds in these objects. These winds are believed to be launched from the accretion disc surrounding the central black hole, and they can extend over large distances, sometimes reaching up to several thousand light years away from the AGN.

Ionized disc winds in AGN can significantly impact the surrounding interstellar medium, as they can transfer energy and momentum to the gas and dust in their vicinity. This, in turn, can trigger star formation or even quench it, depending on the gas conditions and the wind's strength. Furthermore, these winds can also regulate the growth of the central black hole by removing gas from the vicinity of the accretion disc.

Observations of AGN with high-resolution instruments such as the Hubble Space Telescope and the

Chandra x-ray Observatory have revealed a complex structure of the ionized disc winds. The winds can show various physical properties, including ionization states, velocities, and temperatures. The exact physical mechanism that launches the winds is still a topic of active research, but several models have been proposed, including radiation pressure, magnetohydrodynamics, and thermal driving.

5.1.1 | Ionized disc winds as seen with XMM-Newton

X-ray observations with XMM-Newton have provided valuable insights into the properties of ionized disc winds in astrophysics. Reeves and his team analyzed x-ray spectra from several AGNs observed with XMM-Newton, searching for signatures of ionized disc winds. They found clear evidence of highly ionized iron atoms in the spectra, indicating fast-moving, dense material in the winds. By modeling the spectra, they could estimate the winds' properties, including their velocities, densities, and distances from the black hole.

These findings have important implications for our understanding of AGN and the role of ionized disc winds in their evolution. Detecting highly ionized iron atoms suggests that the winds are launched close to the black hole, where the accretion disc is the hottest and most active. The winds' estimated properties indicate that they can carry significant amounts of mass and energy away from the AGN, potentially impacting the growth of the black hole and the surrounding galaxy.

Some of the key papers on ionized disc winds detected with XMM-Newton observations are "A New Relativistic Component of the Accretion Disk Wind in PDS 456" Reeves et al. (2018); and "Resolving the Soft X-Ray Ultrafast Outflow in PDS 456" Reeves et al. (2020).

5.1.2 | Ionized disc winds as seen with eROSITA: Evidence for outflow from the gravitational radius up to the kpc-scale as seen by eROSITA

In the study of Grünwald et al. (2023), it was shown that there is evidence for ionized outflows from the gravitational radius to the kpc-scale based on correlating the photon index with the optical outflow parameters and energetics in the Narrow-Line region mainly traced by the [O III] line. The asymmetry index and the soft-x-ray photon index were analyzed for the first time to study AGN outflows based on eROSITA NLS1s DR12 detections. The superior soft-energy response of eROSITA allows us to perform unique studies of the relation between the x-ray spectral steepness in the soft-x-ray energy band and optical outflow indicators. In addition, this is the largest sample at that date of NLS1s, where the soft-x-ray photon is applied for outflow studies.

Wang et al. (2016) have suggested a connection between the accretion disc and the outflow in the NLR based on the hard 2-10 keV photon index. These authors argue that the hard-x-ray photon index is linked to accretion. In this scenario, the hard-x-ray photon index is produced by inverse Compton scattering of accretion disc photons in the hot ($\approx 10^9$ K) corona.

This article uses the soft-x-ray photon index from the eROSITA observations to study the launching mechanism driving AGN outflows. Ultrafast ionized outflows with high covering fractions can potentially cause a moderately steep power law to appear extremely steep due to blueshifted absorption features of Fe L and lighter elements, causing a depression of photons just above one keV. When simulating data using XSPEC's `zxipcf`-model, the observed photon index can reach values well above five. In general, we expect a steeper photon index with increasing optical outflow parameters as the depression of photons around one keV is due to the ionization of the nuclear gas, in addition to being a function of the covering fraction and the column density of the outflowing clumpy ionized absorber. Therefore, the eROSITA soft-x-ray photon index is a better tracer of AGN outflows at the innermost gravitational radius scale than studies based on the hard x-ray photon index, which mainly probes Comptonization effects.

The correlation between Γ and $H\beta$ asymmetry is weak but still present and is more robust for photon counts above 50. We note that the geometry and kinematics of the BLR are highly complex. The low-ionization broad line, such as Hβ, does not show any significant blueshift or redshift concerning the systemic velocity on average, which is evident from fig. 8 in Grünwald et al. (2023) as the majority of the objects have AI(Hβ)=0 values compared with the high-ionization lines, such as CIV, which are dominated by Keplerian motion.

However, a high-quality reverberation mapping study shows the presence of inflow and outflow in Hβ of a few AGNs (e.g., Grier et al. 2017). Therefore, net radial motion and/or opacity effects could produce slight Hβ asymmetry in some AGNs (Eracleous et al. 2012; Shen et al. 2016). Strong correlations have been detected between the soft-x-ray photon index and the Eddington rate, the Fe II strength, and the [O III λ5007] outflow velocity, dispersion, and the AI value.

The eROSITA studies and new asymmetry parameter calculations performed on the Rakshit et al. (2017) sample provides strong evidence for the AGN feedback processes' wind- and radiation-driven mode in NLS1s.

5.1.3 | Ionized disc winds as seen with eROSITA: going beyond standard Comptonization for extremely steep photon index objects

Grünwald et al. (2023) showed that ionized outflowing winds could explain photon indices with values above 5. Unlike a cold (neutral) absorber, a warm, absorbing material with ionized lighter elements will be transparent to soft x-rays while still opaque to higher energies. At the same time, an ionized absorber will imprint a prominent absorption feature composed of lines from moderately ionized Fe, Ne, and Mg.

This causes a loss of photons beyond the soft band, manifesting as a steeper spectrum. As the photon count statistic of the eRASS1 data is not sufficient to directly test this model on the data, we simulate the scenario using XSPEC's `fakeit` command on their `zxipcf` model.

Fig. 5 of Grünwald et al. (2023) shows the effect of an ionized absorber on a power law of $\Gamma = 4.5$ at a redshift of $z = 0.3$ (representative for the sample) with a galactic absorption of $NH = 0.04 \times 10^{22}$. The absorber is given a column density of $NH = 6 \times 10^{22}$, an ionization parameter of $\log(\xi) = 1$,[1] and a very high covering fraction of $f_{cov} = 0.99$. We note that a change in the covering fraction could lead to an observed variability of the x-ray flux.

The absorber is blueshifted toward the observer with $z = -0.2$, corresponding to an outflow velocity of ~0.4 c. Fitting the data simulated for this scenario from 0.3 to 1.5 keV with a power law while setting $NH = 0.1 \times 10^{22}$ as suggested by the best fits of the steep objects of the sample, a photon index of $\Gamma = 7.4$ is reached,[2] which further increases when assuming even higher outflow velocities.

5.2 | Relativistically blurred reflection

Soft x-ray excess and relativistically blurred reflection are two important phenomena in the study of astrophysics.

Relativistically blurred reflection, on the other hand, refers to the reflection of x-rays from the accretion disc surrounding a black hole, which is modified by the effects of strong gravity and special relativity. This results in a broadening and distortion of the reflection spectrum, which can be used to infer the properties of the accretion disc and the central compact object. Essential papers on the relativistically blurred reflection models and the relation to soft x-ray excesses are given by, for example, Dauser et al. (2013), Abdikamalov et al. (2019).

While the relativistically blurred reflection model has successfully explained many observed properties of AGN, there are some challenges in using this model to explain the soft x-ray excess.

One of the main problems with the relativistically blurred reflection model is that it typically predicts a much more significant reflection component than is observed in AGN spectra. This means that the model tends to overestimate the amount of reflection, which can lead to inaccuracies in the interpretation of the data.

Another issue with the model is that it assumes that the accretion disc is a perfect, smooth surface, which may not be the case in reality. Clumps or other structures in the disc could affect the observed spectrum and therefore impact the model's accuracy.

Additionally, the relativistically blurred reflection model relies on certain assumptions about the geometry of the accretion disc and the observer's orientation relative to the disc. The model may not accurately predict the observed spectrum if these assumptions are incorrect.

Despite these challenges, the relativistically blurred reflection model remains a valuable tool in understanding the properties of AGN and the origin of the soft x-ray excess. Ongoing research aims to improve the model and address some issues to explain the observed data better.

5.3 | Warm comptonization

Warm comptonization from UV disc photons is a physical process in specific astrophysical systems, such as accreting black holes and neutron stars. In this process, ultraviolet (UV) photons from the accretion disc surrounding the compact object are scattered by hot electrons in the surrounding corona. The scattered photons gain energy, leading to a soft x-ray excess emission observed in the x-ray spectrum of these systems.

The term "warm" in warm Comptonization refers to the fact that the scattering electrons have a temperature of a few tens to a few hundred keV, much lower than the temperatures required for thermal Comptonization. Warm Comptonization is, therefore, a nonthermal process.

The UV photons emitted by the accretion disc have energies of a few electronvolts (eV), which are too low to produce x-rays via Compton scattering directly. However,

[1] The ionization parameter ξ is defined as $\xi = \frac{L}{nr^2}$, where L is the ionization luminosity, n is the gas density, and r is the distance between the source and the absorber.

[2] When keeping the initial value for NH, the photon index is increased to $\Gamma = 6.9$, compared with the initial value of $\Gamma = 4.5$.

when these photons are scattered by the hot electrons in the corona, they gain energy through the inverse Compton effect, resulting in a soft x-ray excess emission. Relevant papers describing our understanding of warm compensation models are given by, for example, Petrucci et al. (2013), Chiang et al. (2015).

Warm Comptonization is thought to be responsible for the soft x-ray excess observed in many AGN.

While the warm Comptonization model has successfully explained some aspects of the soft x-ray excess, there are also some challenges and limitations. One issue is that the model assumes a static corona geometry, whereas, in reality, the corona is likely to be more dynamic and variable. Additionally, the model does not account for the variability observed in some AGN spectra, particularly in the soft x-ray band. There is also a debate about the origin of the seed photons for the warm Comptonization, with some studies suggesting that they may not come exclusively from the accretion disc but from other sources, such as the broad-line region or the dusty torus.

Despite these challenges, the warm Comptonization model remains one of the leading explanations for the soft x-ray excess observed in AGN.

Generally, the warm compensation layer is thought to be located in the innermost region of an accretion disc. The exact location and size of the layer can be determined by studying the energy spectra and variability of the emitted radiation, as well as through theoretical modeling.

6 | SUMMARY

This article comprehensively overviews the soft x-ray excess phenomenon observed in AGN. We have discussed the theoretical models proposed to explain this phenomenon, including warm Comptonization, ionized reflection models, and ionized outflowing disc winds. Additionally, we have described the ongoing research to refine these models and better understand the physical mechanisms involved.

We have also highlighted the key observations that have led to our current understanding of the soft x-ray excess, including those made by ROSAT, XMM-Newton, and eROSITA. Moreover, we have provided a brief history of the discoveries made in this field, including the early detection of the soft x-ray excess in the Narrow Line Seyfert 1 galaxies.

Future x-ray satellites are expected to contribute to our understanding of the soft x-ray excess in AGN. These observatories are anticipated to provide higher sensitivity, spectral resolution, and a larger field of view, allowing for more detailed studies of AGN and their soft x-ray excess emission. Such missions will provide more sensitive and higher spectral resolution observations, allowing for more detailed studies of the warm Comptonization model and other potential explanations for the soft x-ray excess. The South Ecliptic Pole Region (SEP), as observed by, for example, eROSITA, provides a unique opportunity to build up a reverberation database of time lags between the soft and the hard band to constrain models for the soft x-ray excess more physically (Boller et al., in preparation).

Overall, our discussion shows that while significant progress has been made in understanding the soft x-ray excess, many challenges and limitations remain. Further studies are needed to refine the theoretical models and provide a more comprehensive understanding of this fascinating phenomenon.

ACKNOWLEDGMENT

Open Access funding enabled and organized by Projekt DEAL.

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How to cite this article: Boller, T. 2023, *Astron.Nachr./AN*, *344*, e230105. https://doi.org/10.1002/asna.20230105