Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | Roma Tre

Radio-Quiet Active Galactic Nuclei

LINEE

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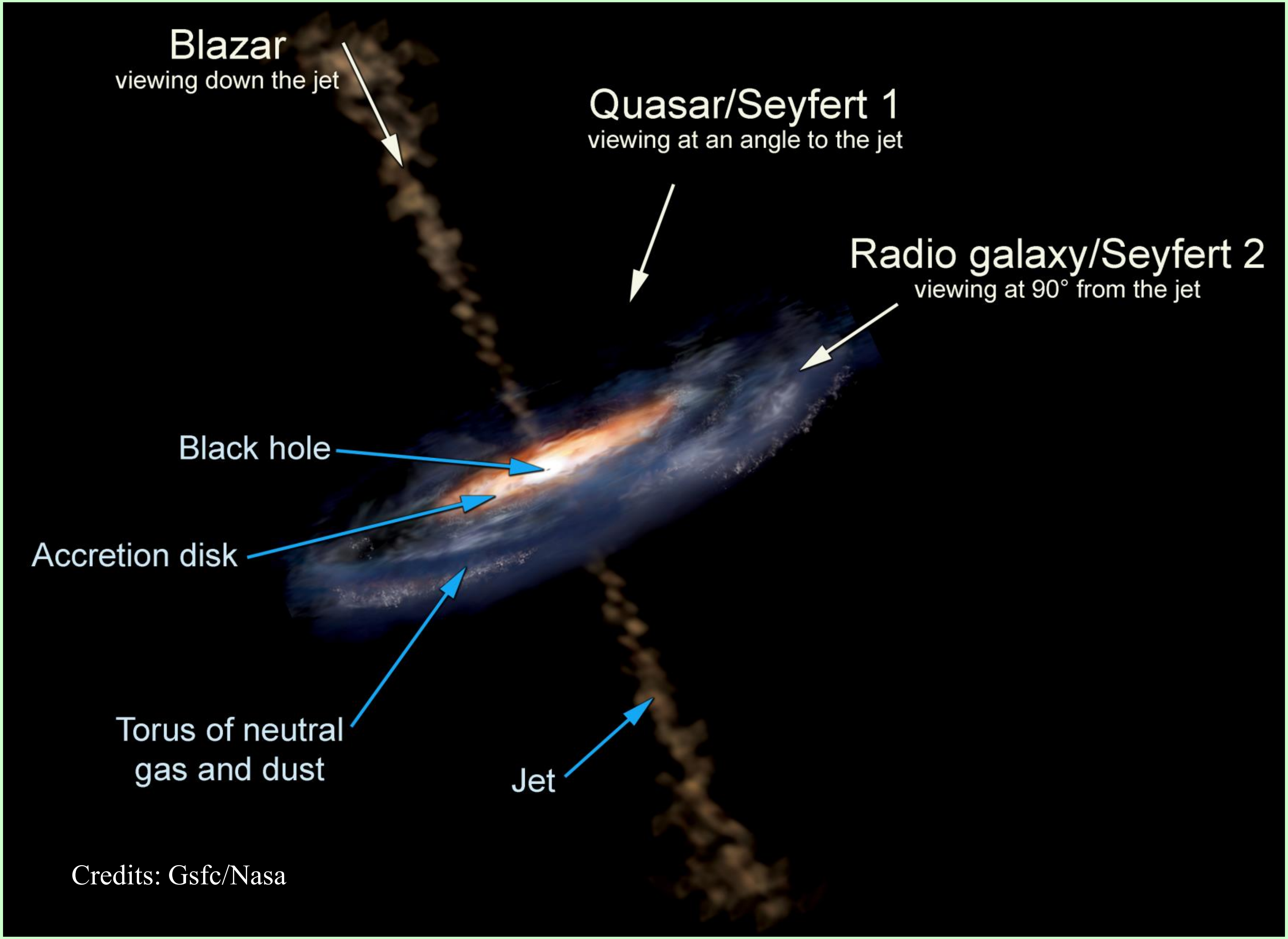
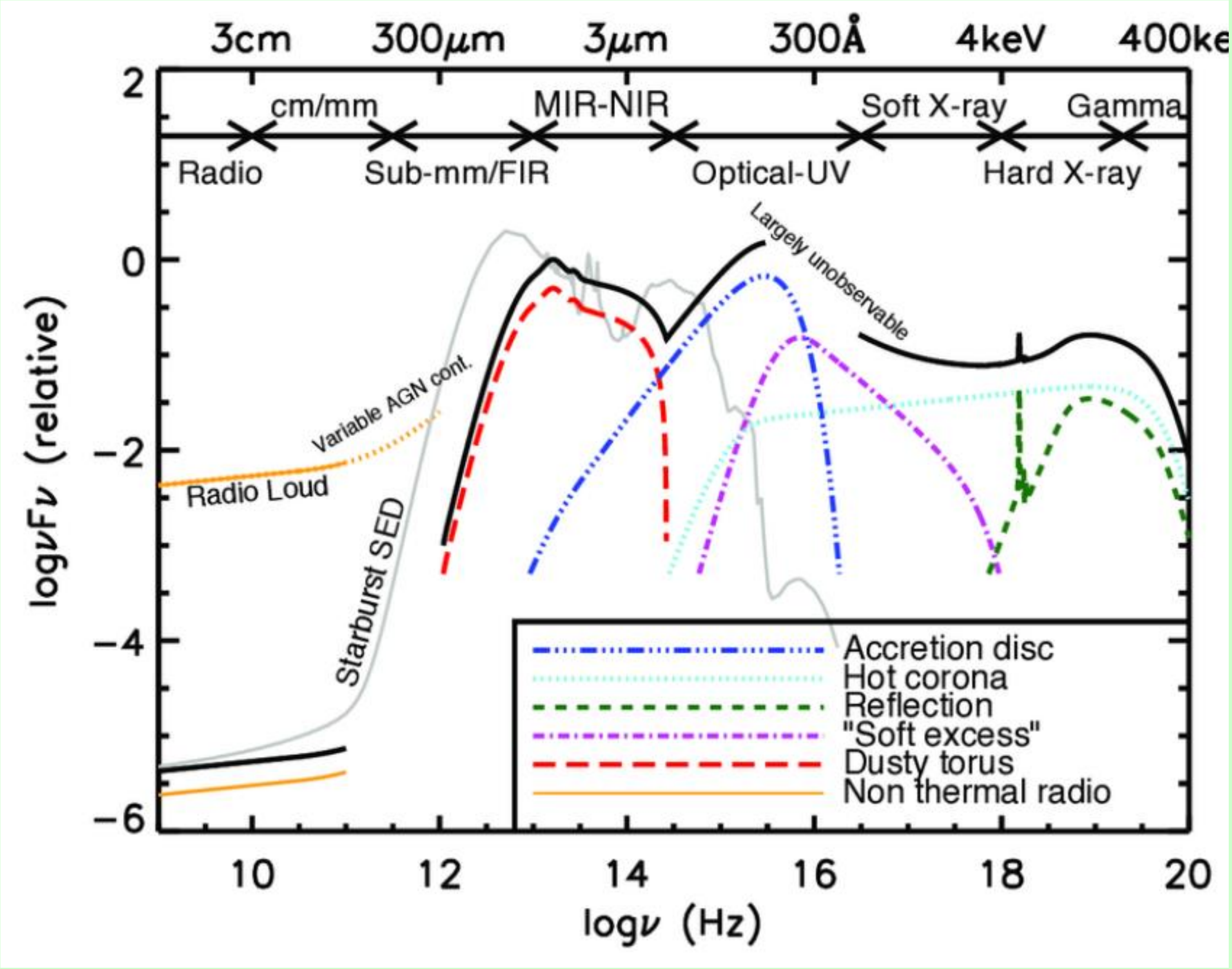
Many thanks to F. Ursini, A. Marinucci and the RQ AGN IXPE Topical Working Group

Active Galactic Nuclei

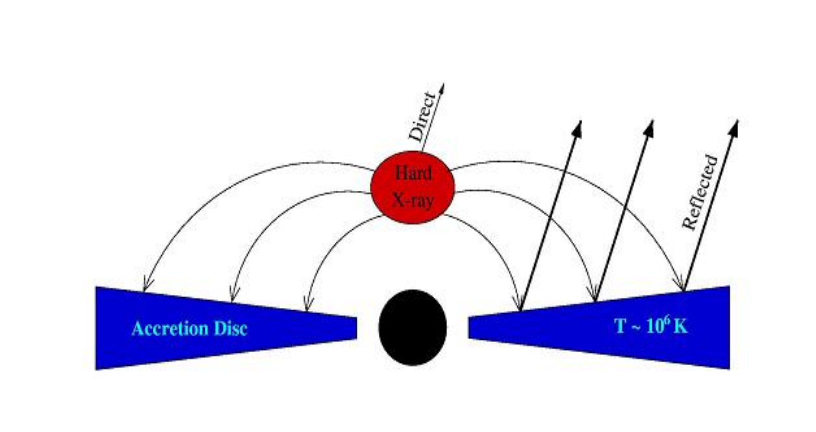


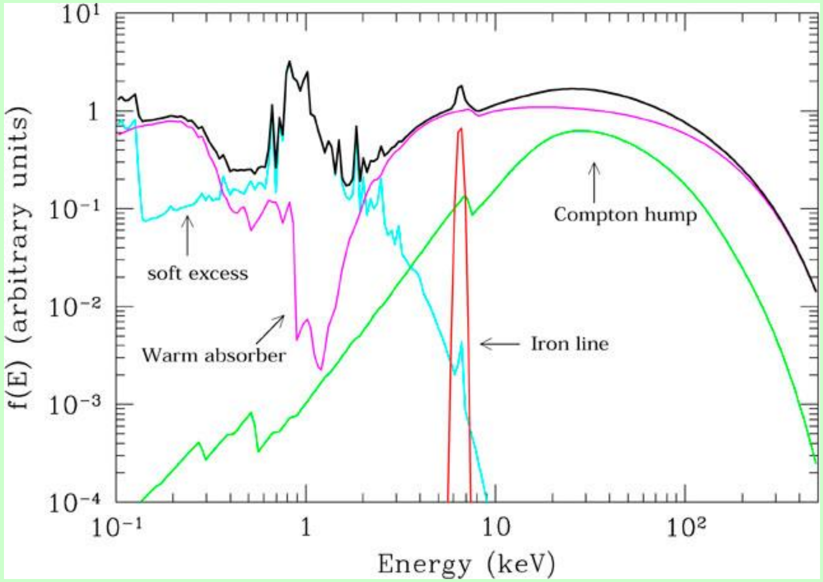
Active Galactic Nuclei

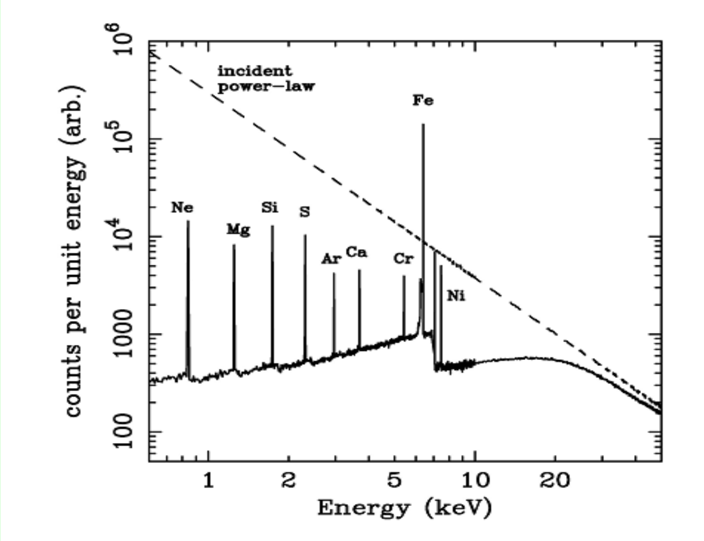


Active Galactic Nuclei in X-rays

In AGN the primary X-ray emission is due to Inverse Compton by electrons in a hot corona of the UV/soft X-ray disc photons. It is likely to be polarized (e.g. Haardt & Matt 1993, Poutanen & Vilhu 1993).







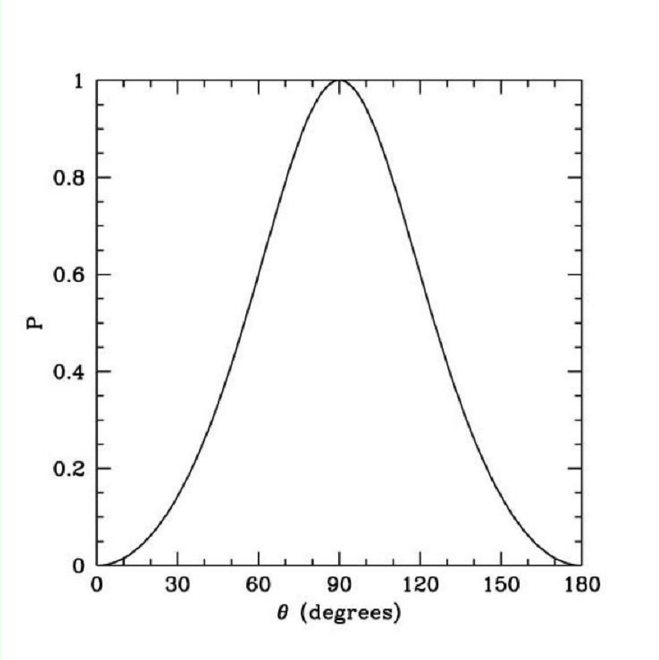
Part of the primary emission illuminates the disc and/or the torus and is reflected (and polarized) via Compton Scattering

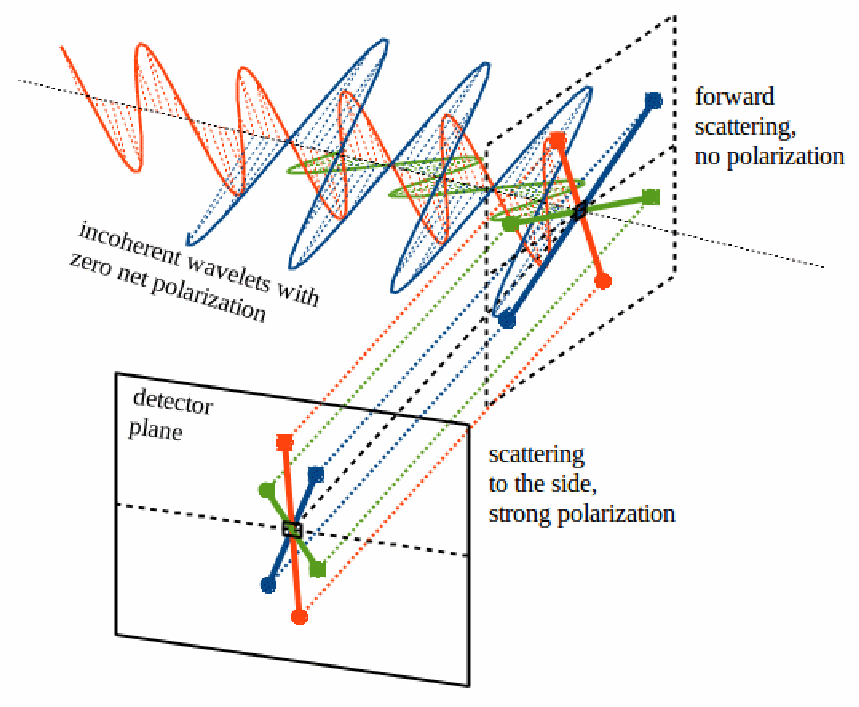
Thomson Scattering

The scattered radiation is polarized. A 100% polarized incident beam gives rise to a 100% polarized scattered beam, independently of the scattering angle.

If the incident beam is unpolarized, the polarization of the scattered radiation is:

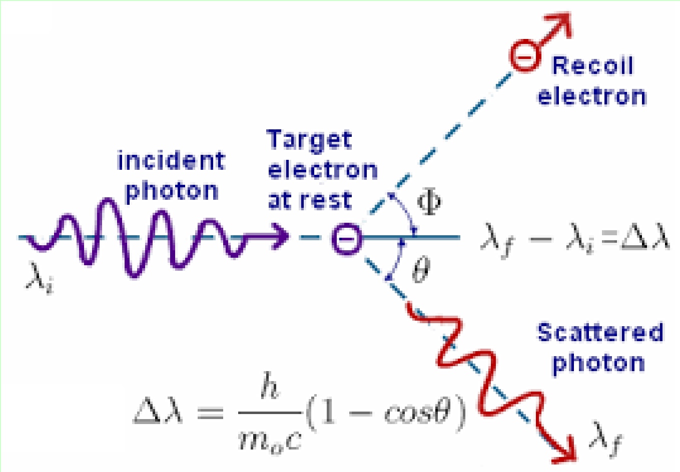
$$P = \frac{1-\cos^2\theta}{1+\cos^2\theta}$$



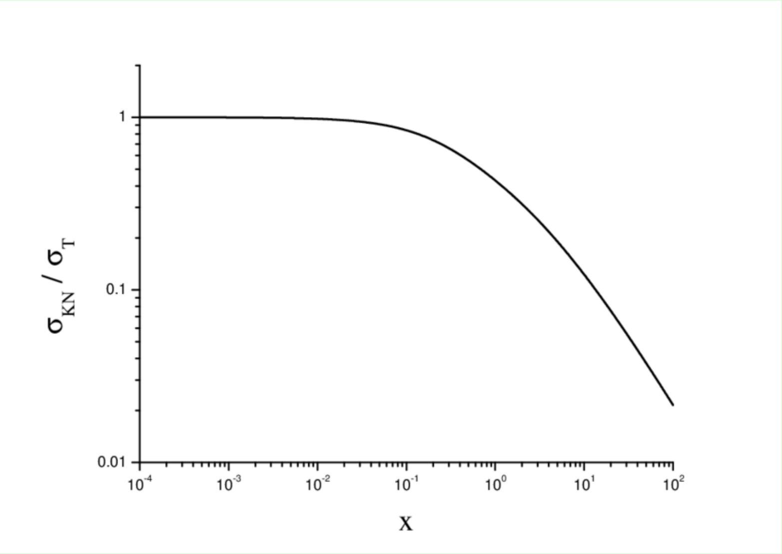


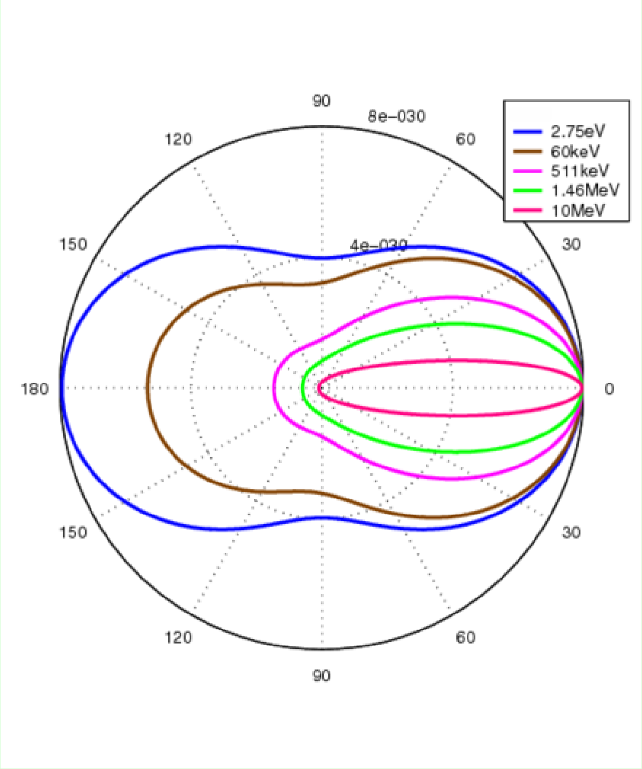
The net polarization vector is perpendicular to the scattering plane.

Compton Scattering



When *hv* is no longer « *mc*^{2} the scattering is inelastic. The Klein-Nishin cross section decreases with energy, and the emission pattern is more complex.





Compton Scattering

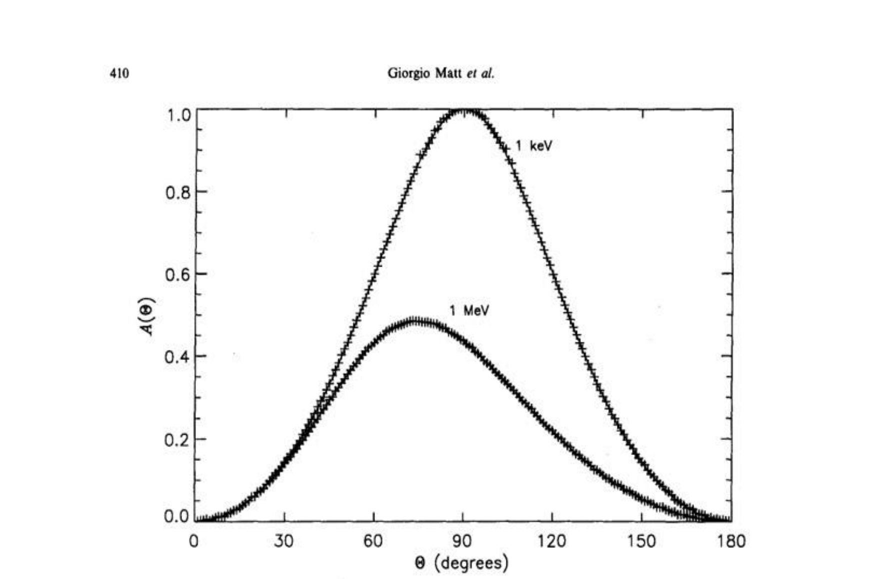
Compton scattering radiation is polarized, but less than Thomson scattering. Polarization degree decreases with $h\nu/mc^2$ in the reference frame of the electron

A 100% polarized beam gives rise to <100% polarized scattered radiation, depending on the scattering angle.

For an unpolarized beam, maximum polarization is less than 100%.

$\beta = E/E_0$
Θ=polar scatt. angle
Φ=azimuthal scatt. angle

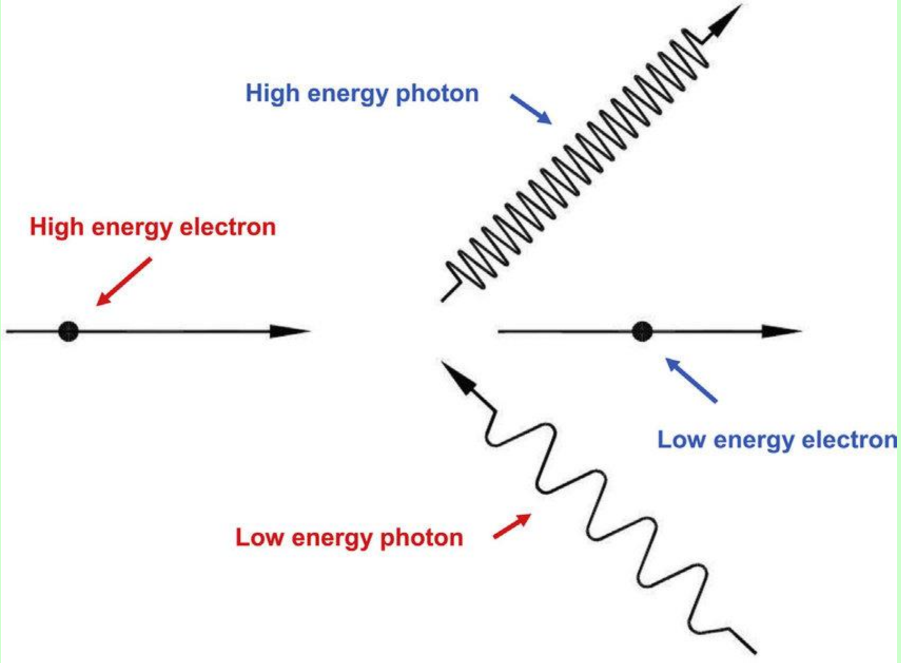
$$\Pi_P = 2\frac{1-\sin^2\Theta\cos^2\Phi}{\beta+\beta^{-1}-2\sin^2\Theta\cos^2\Phi}.$$



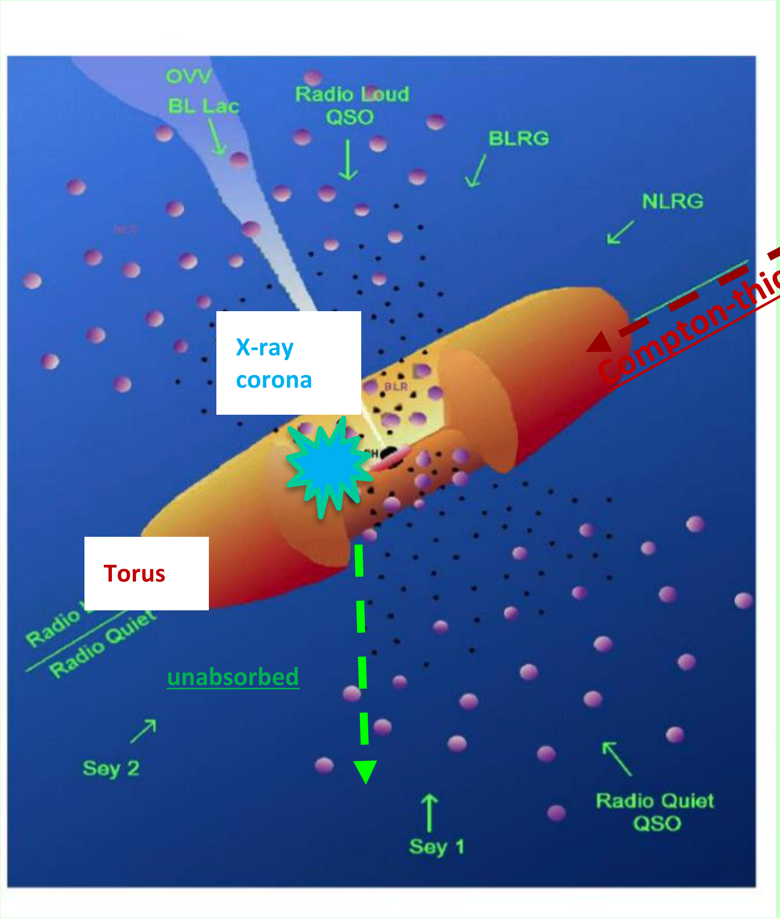
$$\Pi_U = \frac{1-\cos^2\Theta}{1+\cos^2\Theta+\beta+\beta^{-1}-2}.$$

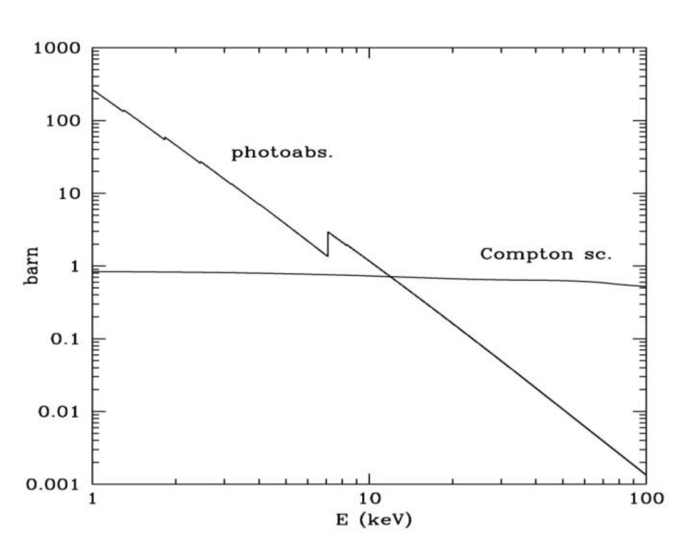
Inverse Compton Scattering

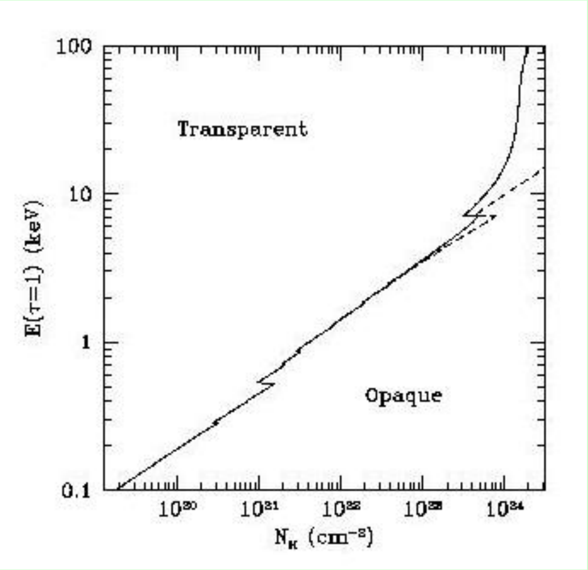
In the observer reference frame, the electron may be moving, and it is also possible that the kinetic energy of the electron is larger than the energy of the photon. In this frame, it is the photon which gains energy (i.e. frequency). The polarization properties are calculated by going to the electron frame, calculating the polarization in the appropriate (Thomson or Compton) regime, and transforming back into the observer frame.



Active Galactic Nuclei in X-rays



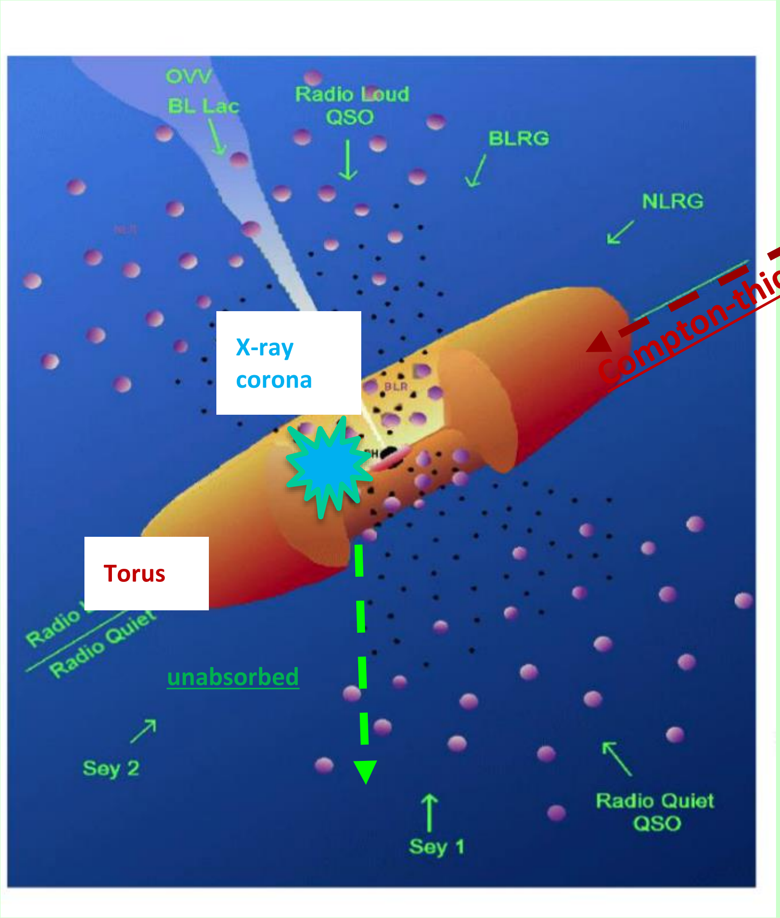


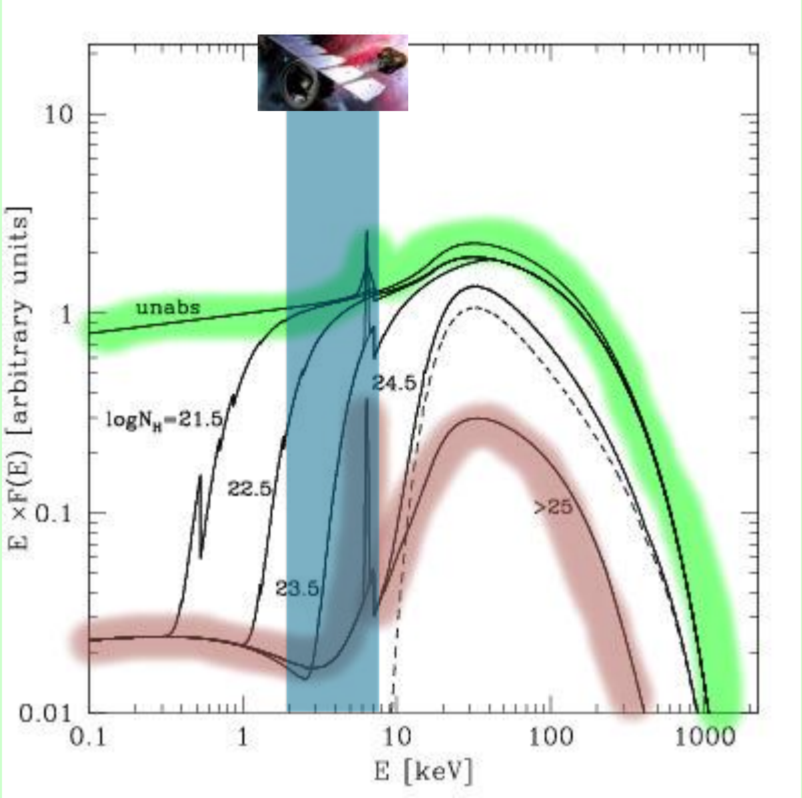


$$\tau(E)=\sigma(E)N_H$$

$N_H/A(V) \sim (1.8\text{-}2.2) \times 10^{21}$ atoms cm^{-2} mag^{-1}

Active Galactic Nuclei in X-rays





Plan of the talk

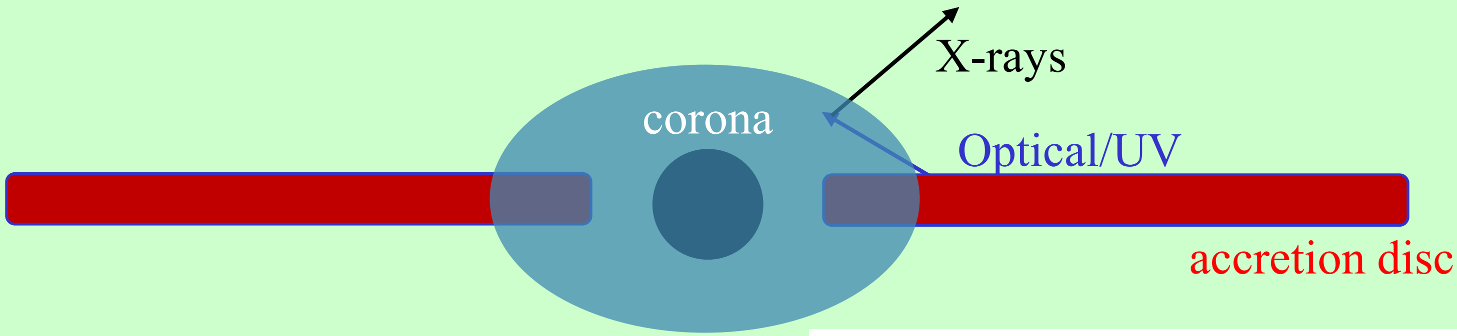
The geometry of the hot corona (Seyfert 1)

The geometry of the ``torus'' (Seyfert 2)

Plan of the talk

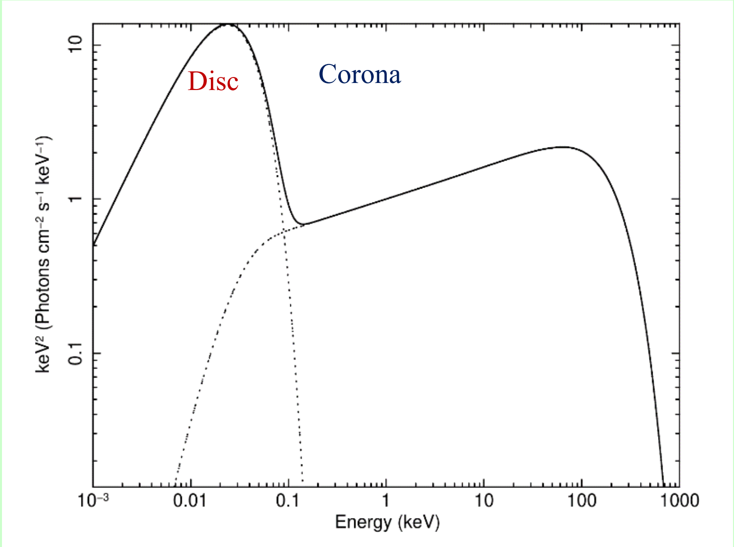
The geometry of the hot corona (Seyfert 1)

In AGN the primary X-ray emission is due to Comptonization by electrons in a hot corona of the UV/soft X-ray disc photons (Shapiro et al. 1976; Sunyaev & Titarchuk 1980; Haardt & Maraschi 1991)



Cutoff power law $F_E \sim E^{-\Gamma} \exp(-Ec/kT)$
$\Gamma = \Gamma(kT,\tau)$, while Ec depends on kT

Temperature kT ~ 10-100 keV
Thomson optical depth ~ 1



Broad-band X-ray spectroscopy can constrain the physical parameters of the corona (e.g. temperature and optical depth.

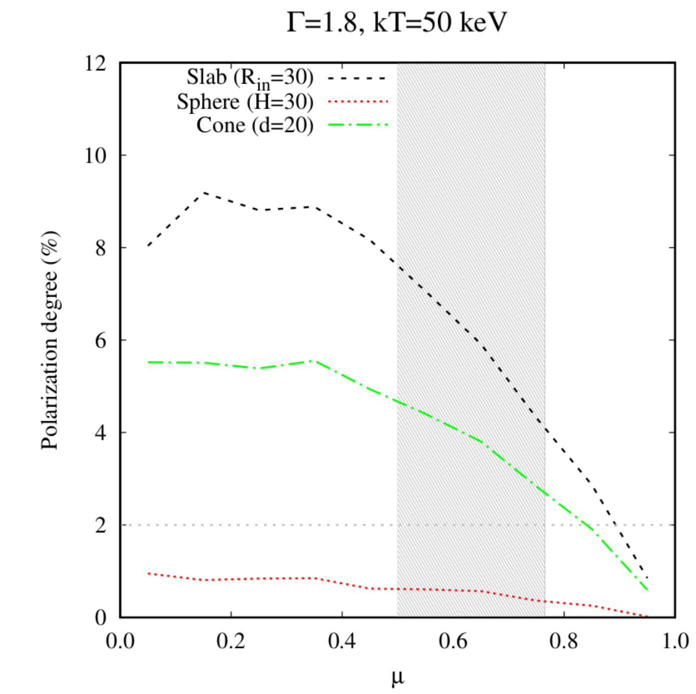
However, it is almost insensitive to its shape and location.

Polarimetry, on the contrary, is very sensitive to the geometry of the corona, and can measure deviations from a spherical symmetry.

The coronal geometry is related to its physical origin.

Comptonized continuum model: compPS		
Assumed corona geometry: slab		
χ^2	1159	690
R	0.65 ± 0.05	0.83 ± 0.09
kT_e (keV)	26 ± 2	26 ± 3
τ_e	2.2 ± 0.1	2.2 ± 0.2
Assumed corona geometry: sphere		
χ^2	1161	691
R	0.69 ± 0.04	0.89 ± 0.08
kT_e (keV)	25 ± 2	25 ± 3
τ_e	3.2 ± 0.2	3.3 ± 0.3

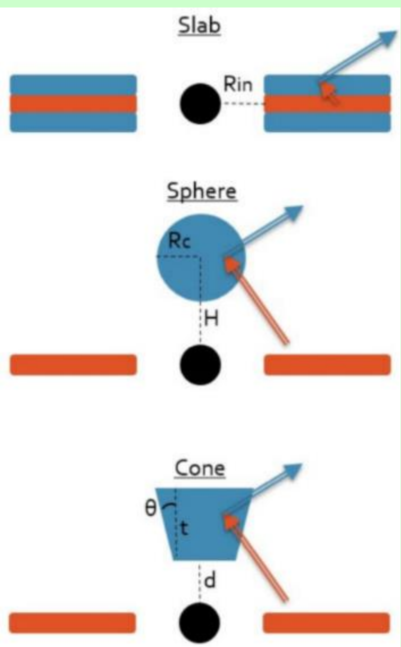
MCG -5-23-16
(Balokovic et al 2015)



Polarization from slab and wedge geometries higher than for spherical lamppost geometries.

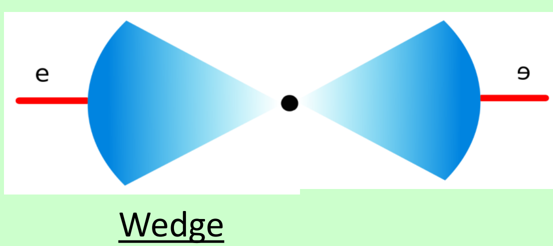
Intermediate values for the conical geometry

Polarization either parallel (sphere, cone) or perpendicular (slab, wedge) to the accretion disc



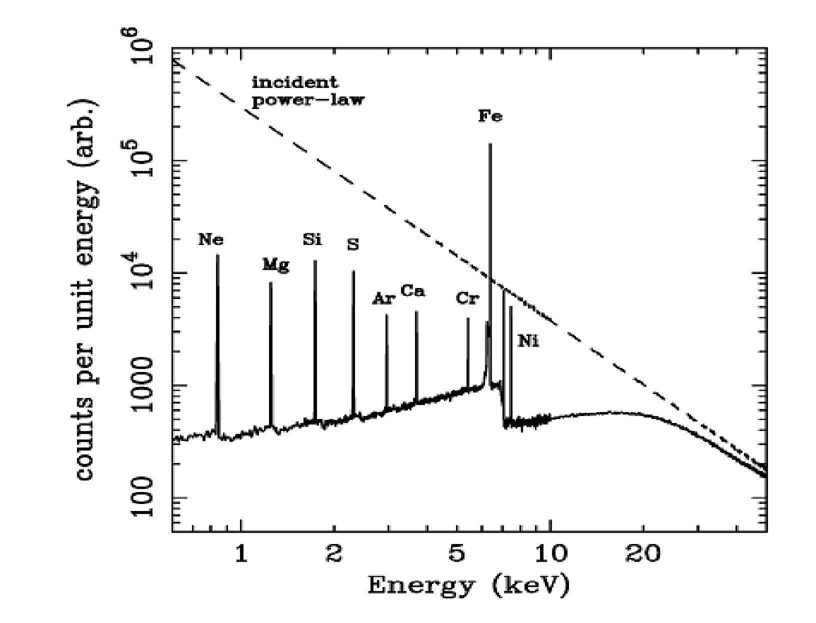
MCG-5-23-16

The exact values depends on the temperature and optical depth → need for broad band spectroscopic simultaneous observations (NICER or XMM + NuSTAR)

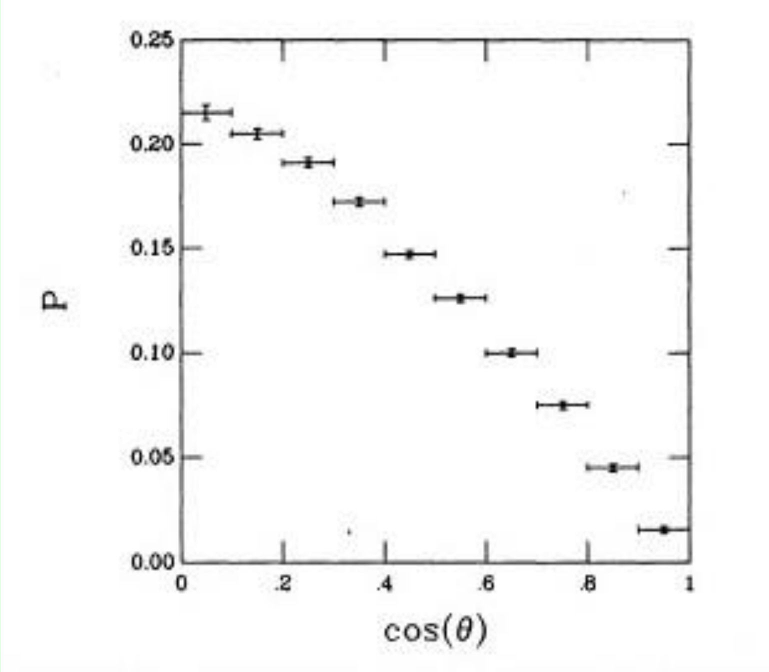


Results depend on the (usually unknown) inclination angle

Polarization of reflected flux



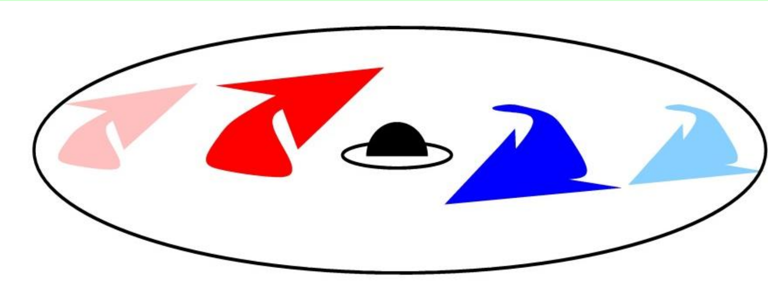
Polarization of reflected (continuum) radiation is large, up to 20% (Matt et al. 1989) assuming isotropic illumination, a plane-parallel reflecting slab and unpolarized illuminating radiation.



The exact values depend on the actual geometry of the system, on the ionization of the matter and on the polarization degree of the primary radiation (e.g. Podgorny et al. 2023)

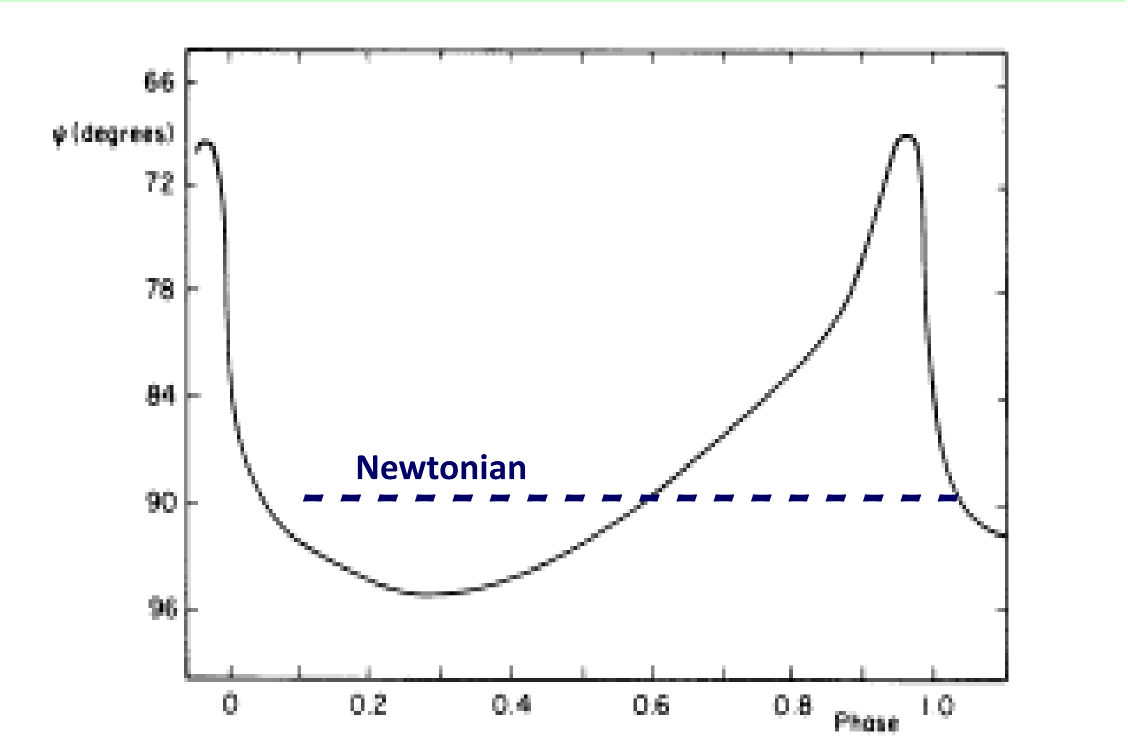
Probing strong gravity effects

General and Special Relativity effects around a compact object ("strong gravity effects") significantly modifies the polarization properties of the radiation. In particular, the Polarization Angle (PA) as seen at infinity is rotated due to aberration (SR) and light bending (GR) effects (e.g. Connors & Stark 1977; Pineault 1977).
The rotation is larger for smaller radii and higher inclination angles.



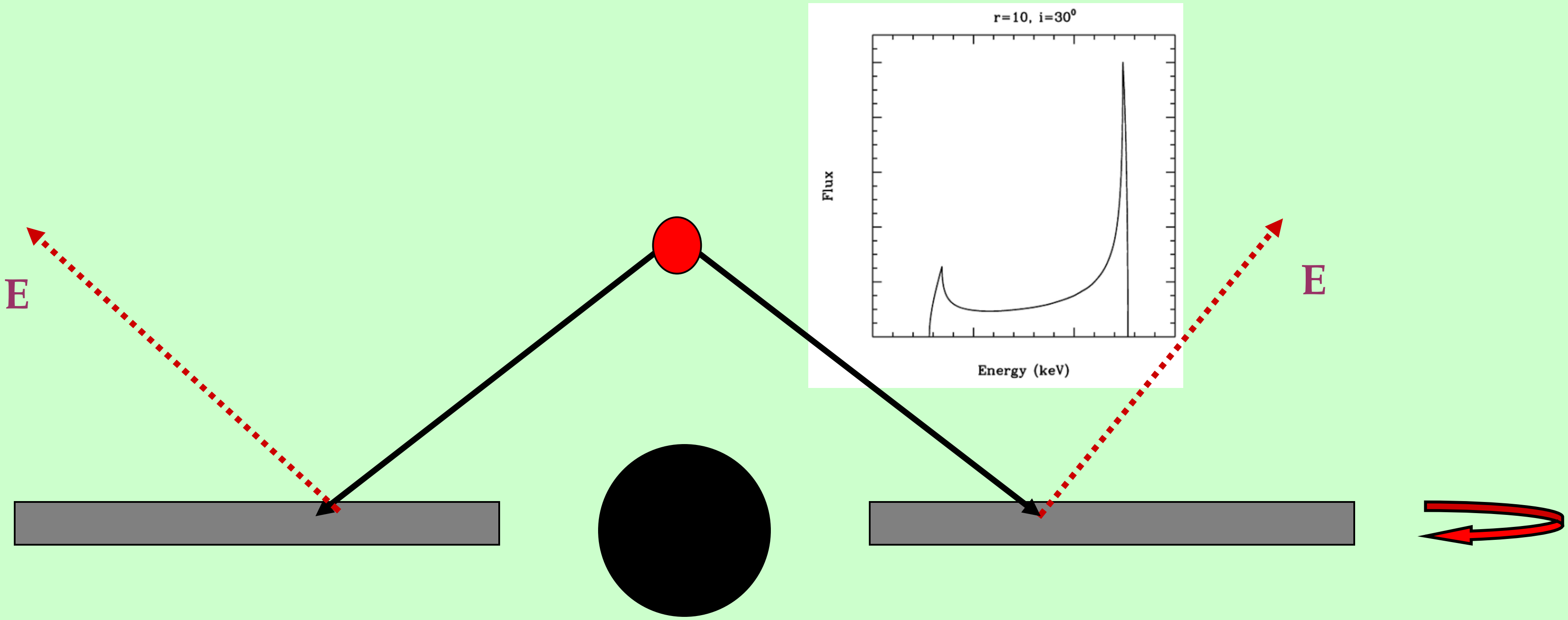
Orbiting spot with:
a=0.998; R=11.1 Rg
i=75.5 deg

(Phase=0 when the spot is behind the BH).



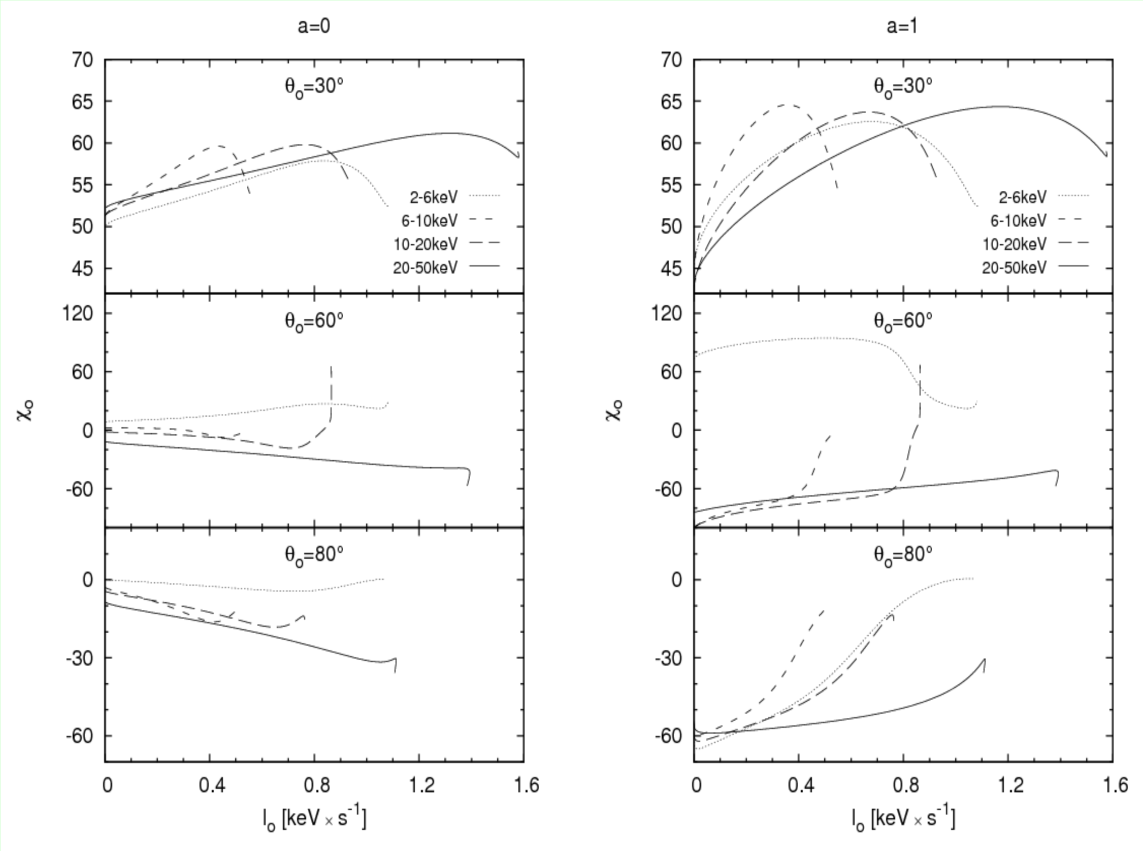
The PA of the net
(i.e. phase-averaged)
radiation is also rotated!

Reflection in Relativistic discs



Breaking of the symmetry due to SR (Doppler boosting) also causes a rotation of the PA with respect to the Newtonian case. Changes in the illumination properties (e.g. in the height of the lamp-post) will cause changes in the total PA, which is therefore likely to be time- (and flux-) dependent. Variations of the height have been claimed in several AGN (e.g. Miniutti et al. 2003, Parker et al. 2014).

Reflection in Relativistic discs

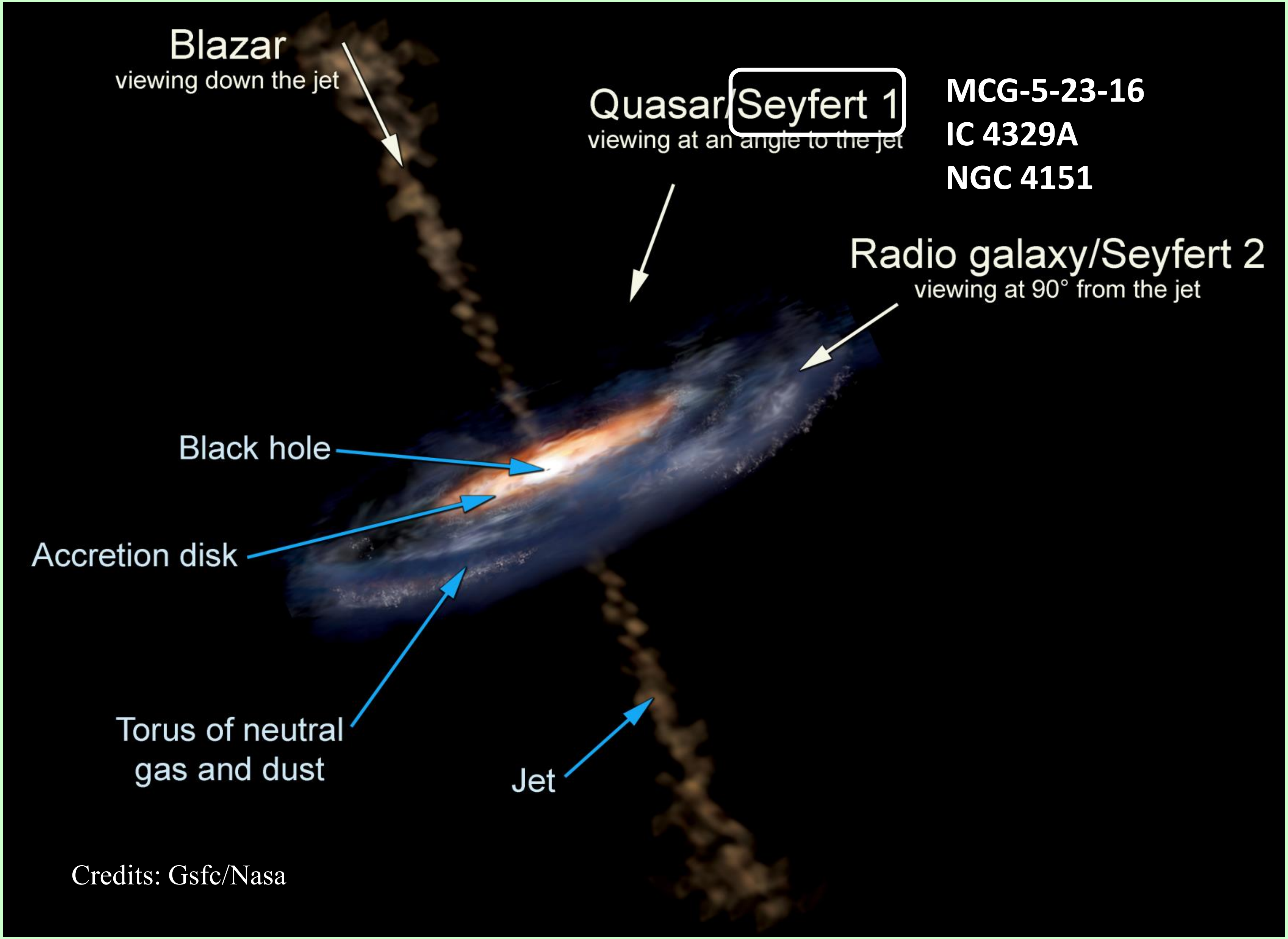


Variation of h with time implies a time and flux variation of the degree and angle of polarization.

The effect depends also on the BH spin.

Dovciak et al. (2011)

IXPE observations (baseline phase)



Credits: Gsfc/Nasa

IXPE Observations (baseline phase)

To study the geometry of the hot corona in AGN three bright Compton-thin Seyfert galaxies have been observed by IXPE

MCG-05-23-16 May+November 2022 (Marinucci et al. 2022, Tagliacozzo et al. 2023) $M_{BH}=2x10^7\ M_{sun}$ (Ponti et al. 2012)

IXPE: 486 ks+642 ks

XMM-Newton: 58 ks/none -- NuSTAR: 83 ks/85ks

NGC 4151 December 2022 (Gianolli et al. 2023)

$M_{BH}=4.6x10^7\ M_{sun}$ (Bentz et al. 2006)

IXPE: 632 ks

XMM-Newton: 33 ks -- NuSTAR: 97 ks

IC 4329A January 2023 (Ingram et al. 2023)

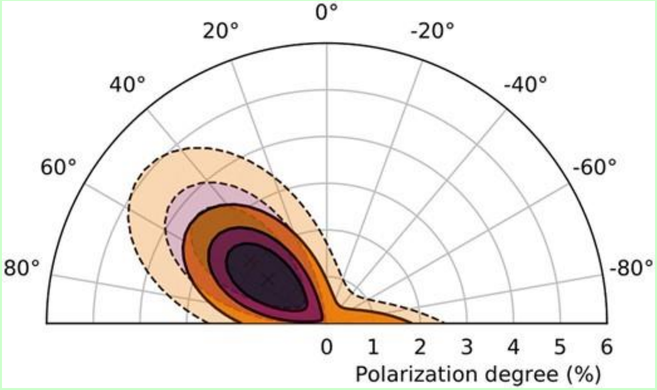
$M_{BH}=7x10^7\ M_{sun}$ (Bentz et al. 2023)

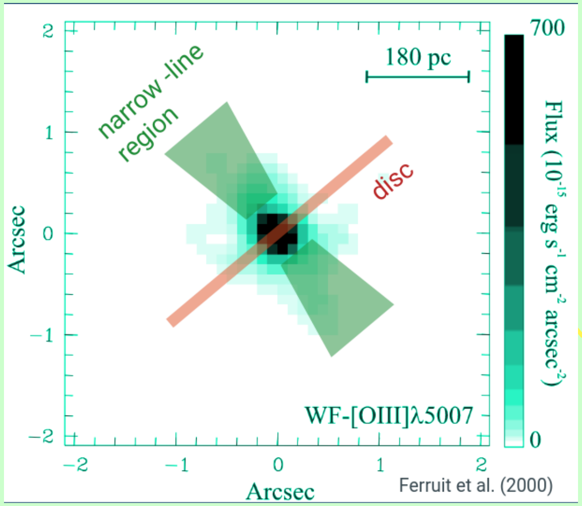
IXPE: 458 ks

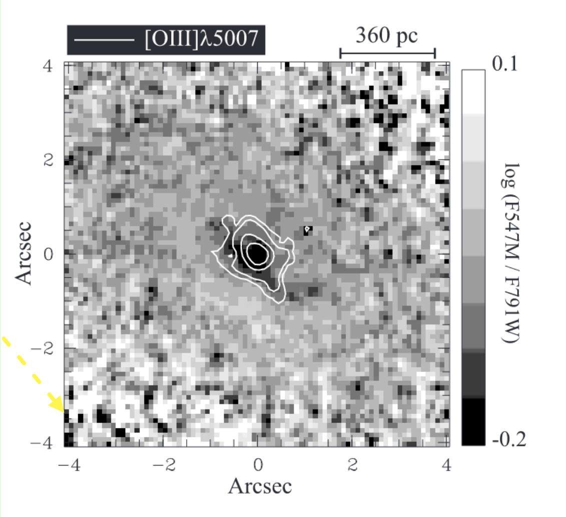
XMM-Newton: 62 ks -- NuSTAR: 82 ks

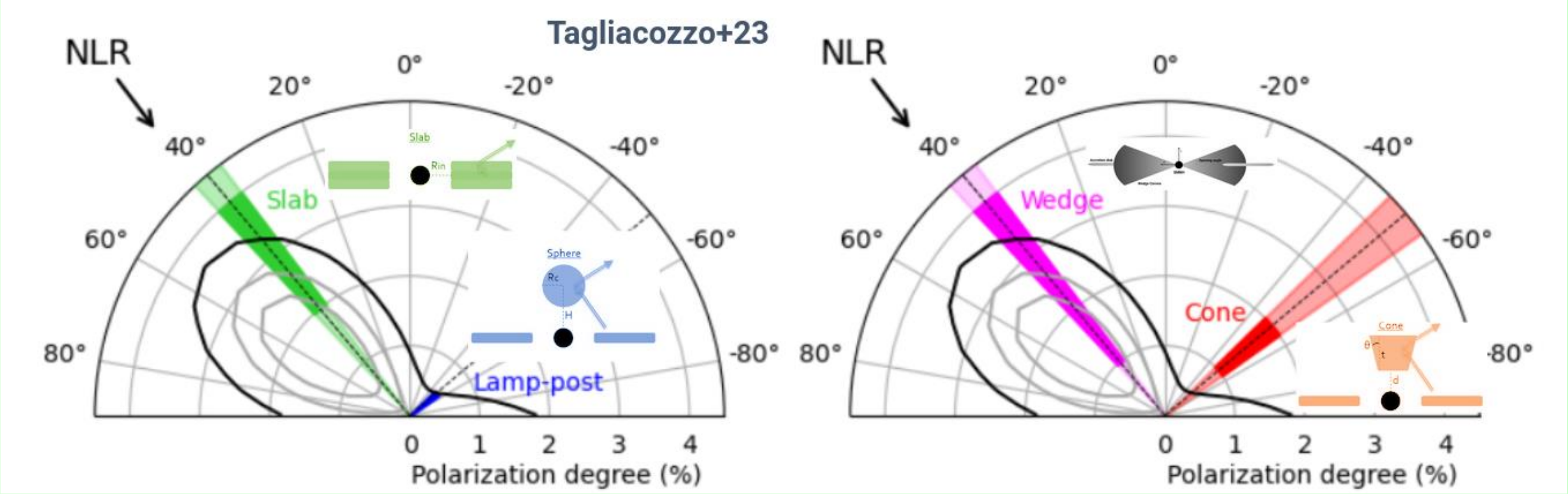
MCG-5-23-16

P < 3.2%









Tagliacozzo et al. 2023

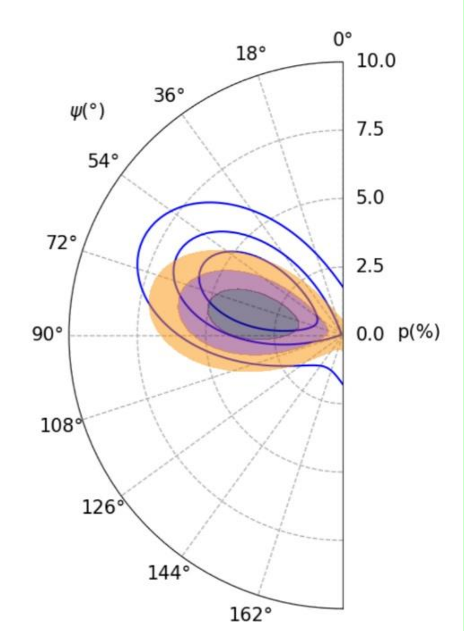
IC 4329A

Strictly speaking, an upper limit.

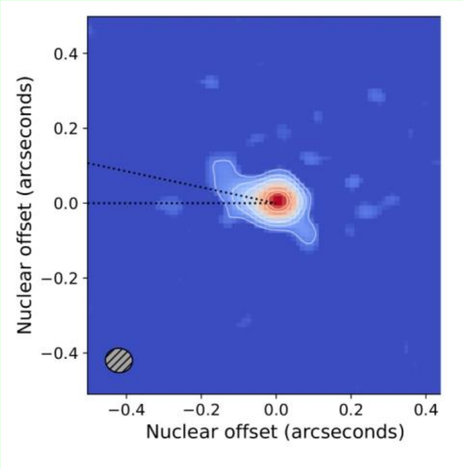
However, a 2.97σ result with P=3.3%

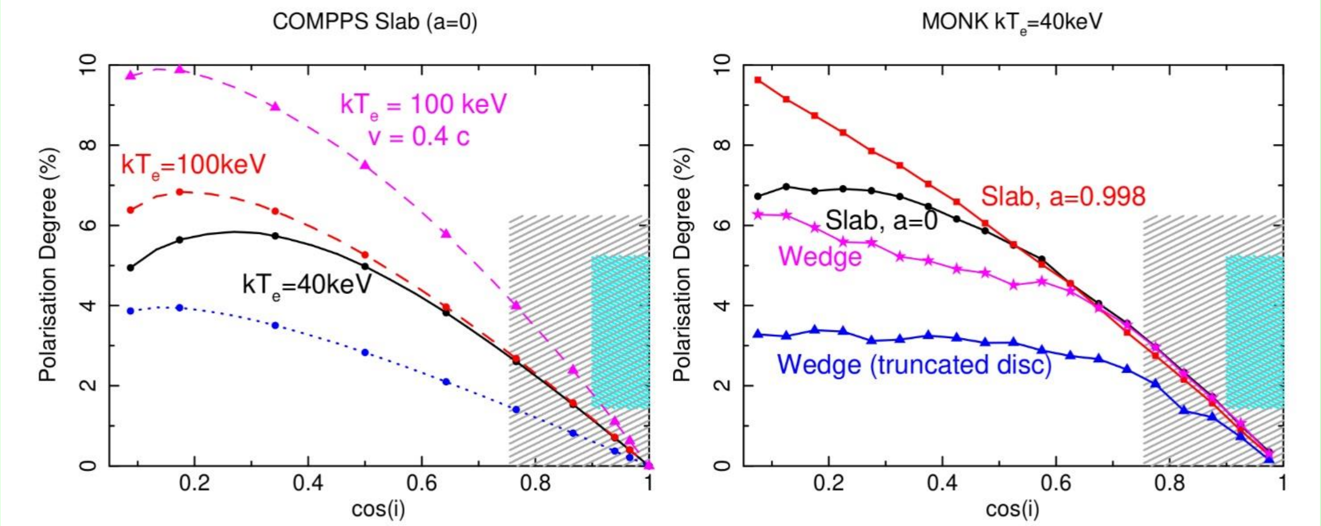
Slab or wedge favoured

Ingram et al. 2023

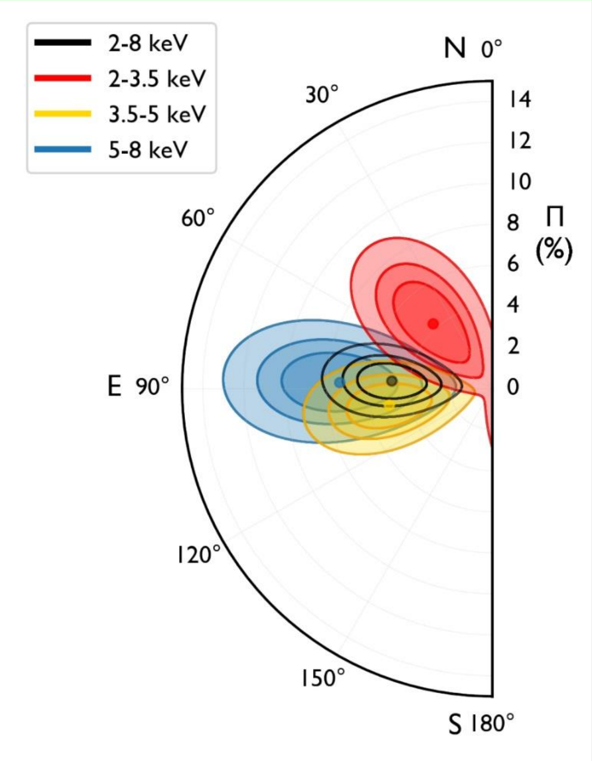


ALMA image at 100 GHz

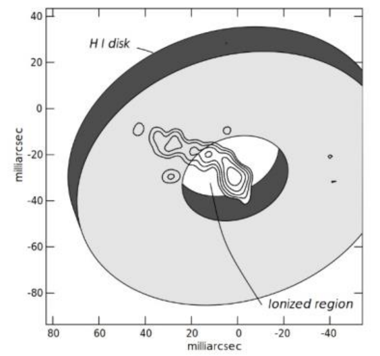




NGC 4151



P=4.9±1.1% in the 2-8 keV range



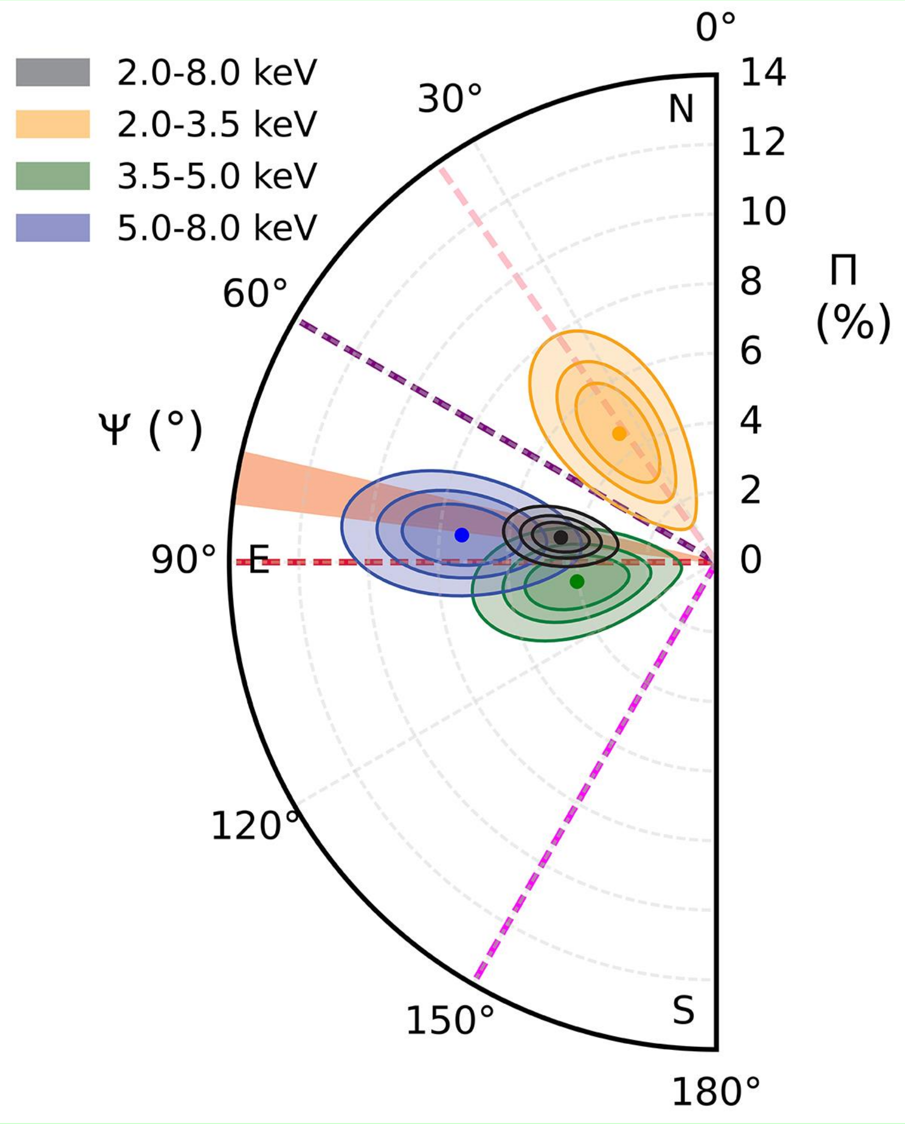
Ulvestad et al. 1998

The measured Ψ is in the direction of the radio emission (P.A.~83°: Wilson & Ulvestad 1982, Harrison et al. 1986, Pedlar et al. 1993)

Gianolli et al. (2023)

The polarization degree and angle disfavours the lamppost geometry for the hot corona.

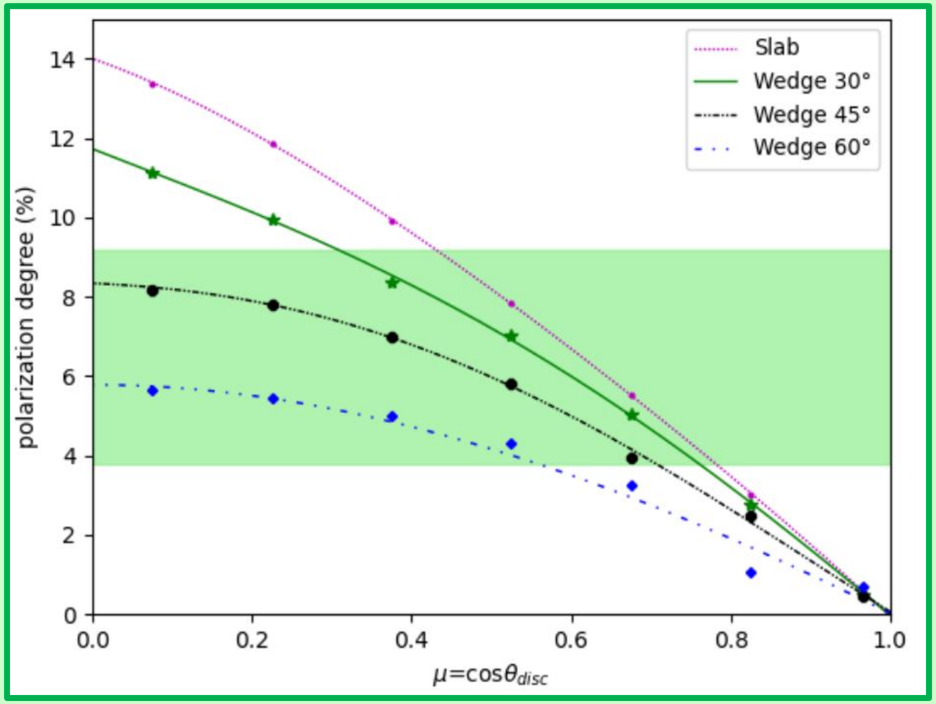
NGC 4151

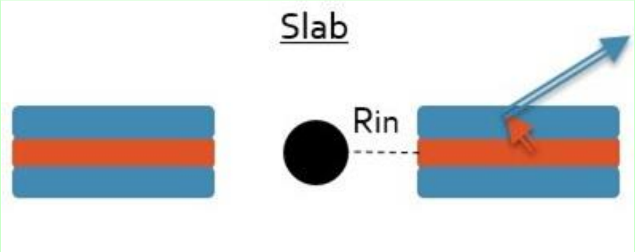


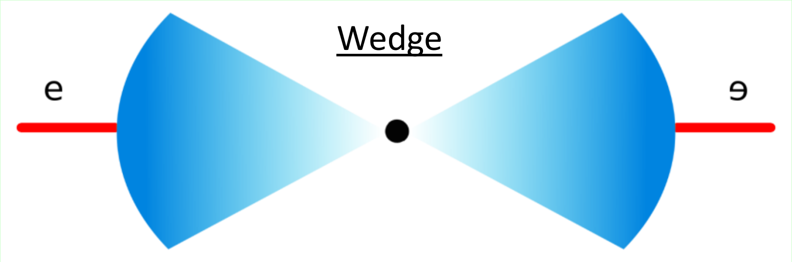
Re-observed in GO1, similar results (Gianolli et al. 2024)

NGC 4151

After subtracting the other components, the PD of the coronal emission is in the 4-9% range

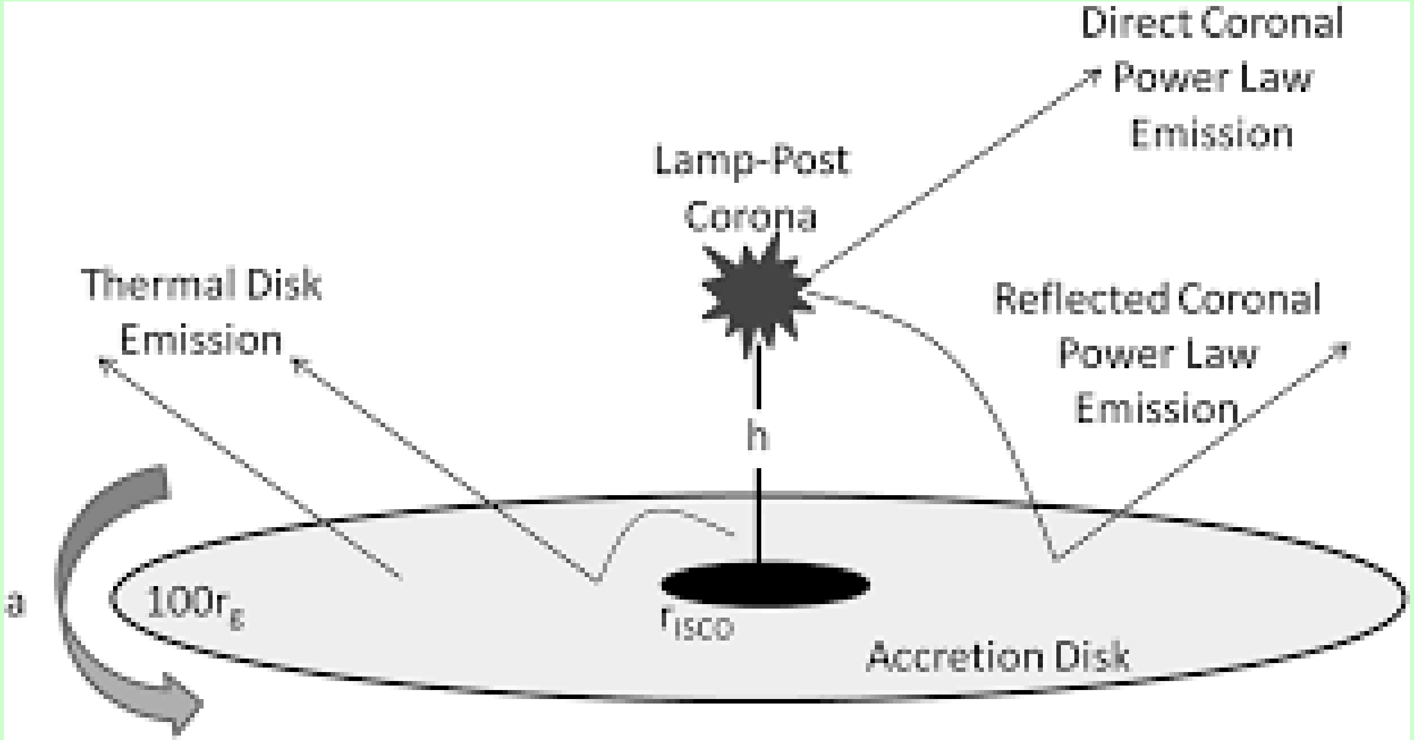






Radially extended geometries are favoured.

NGC 4151



Reflection from a spherical lamppost still possible, but rather extreme conditions required (Kammoun, Dovciak, private communications).

Summary on Seyfert 1s

- One robust detection (NGC 4151), one marginal detection (IC4329A), one upper limit (MCG-5-23-16)

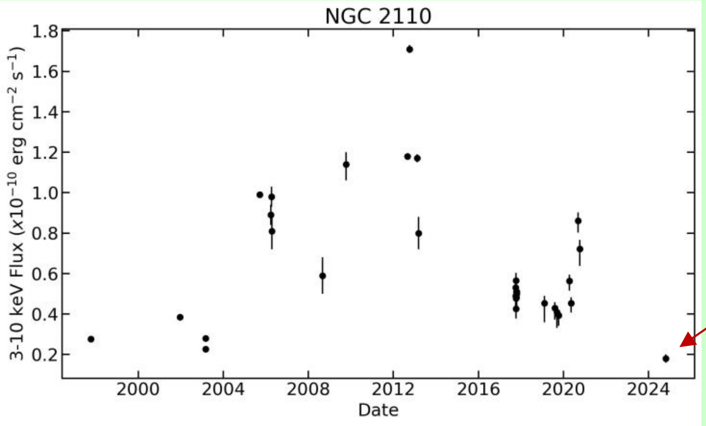
- Polarization angle parallel to the symmetry axis (like in Galactic Black Hole systems!)

- Radially extended coronae are favoured !!

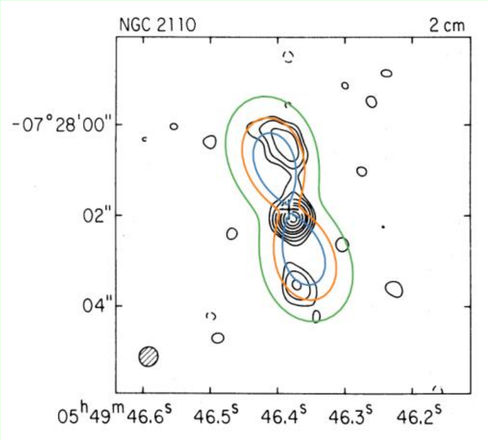
GO1: NGC 2110

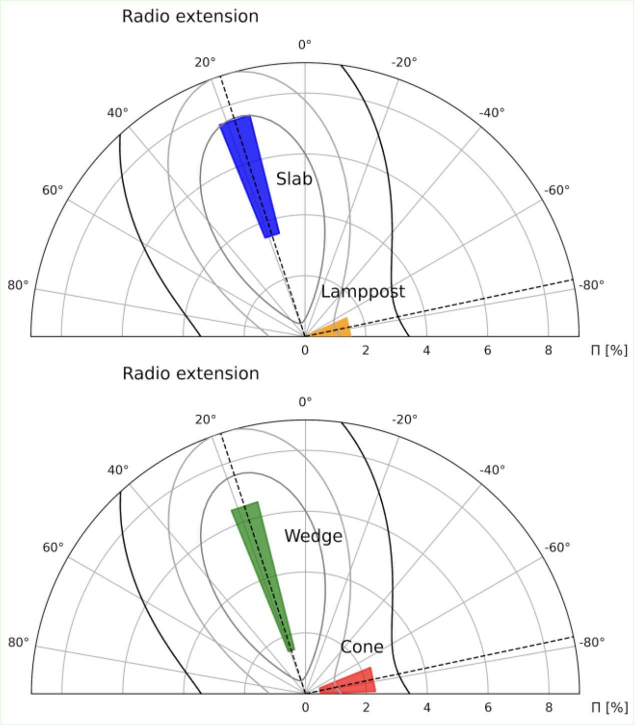
Observed in GO1 for 550 ks (Chakraborty et al. 2025, Pal et al. 2025).

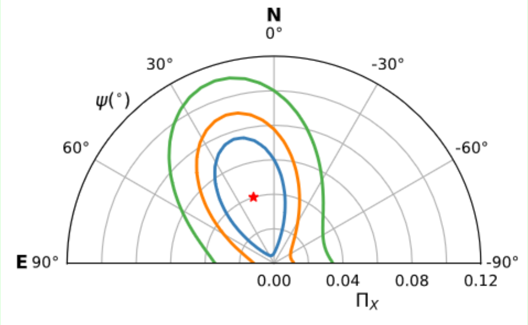
Somewhat underexposed because found at a low flux level, so only an unconstraining upper limit could be found

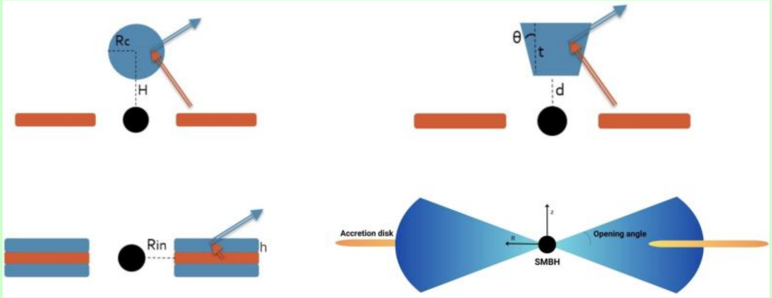


IXPE









GO2

MCG-5-23-16 (A) – A detection, at last?

NGC 5506 (A) – A bright source

NGC 3227 (C) - LLAGN

Fairall 51 (C) – A polar scattered source

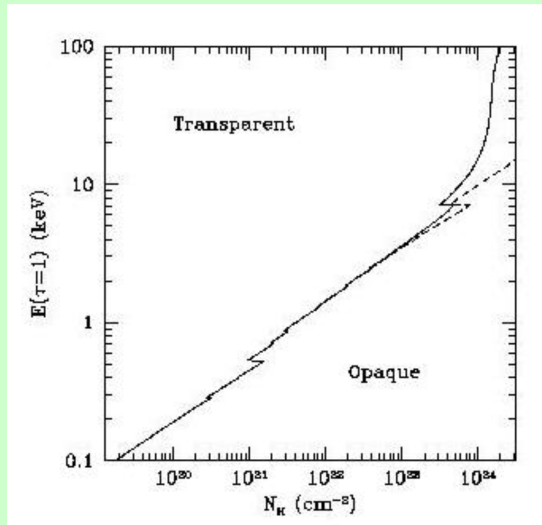
1ES 1927+654 (C) – A newly formed X-ray corona

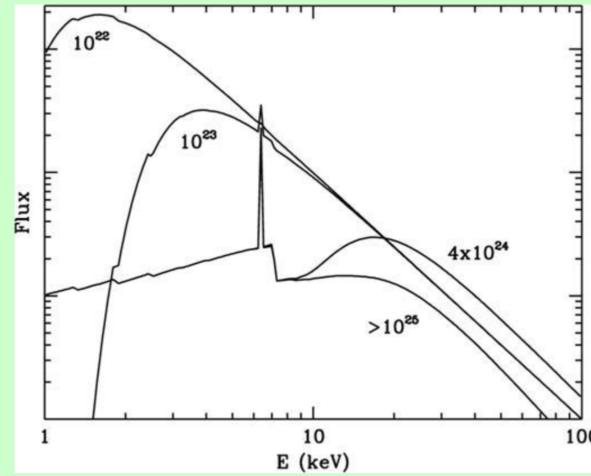
Plan of the talk

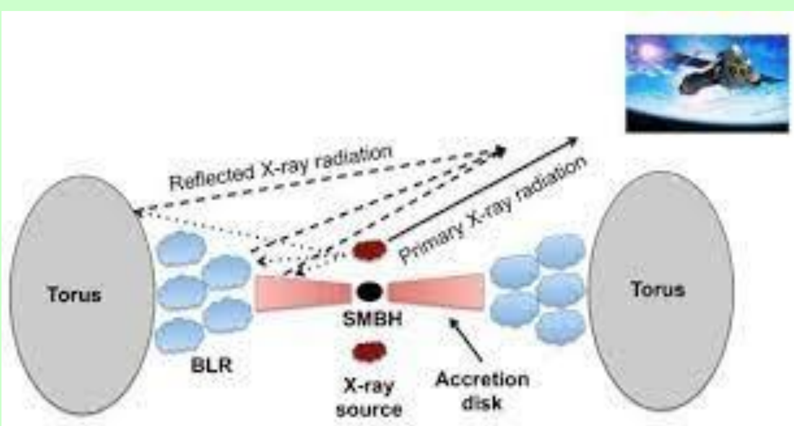
The geometry of the ``torus'' (Seyfert 2)

RQ AGN: Compton-thick sources

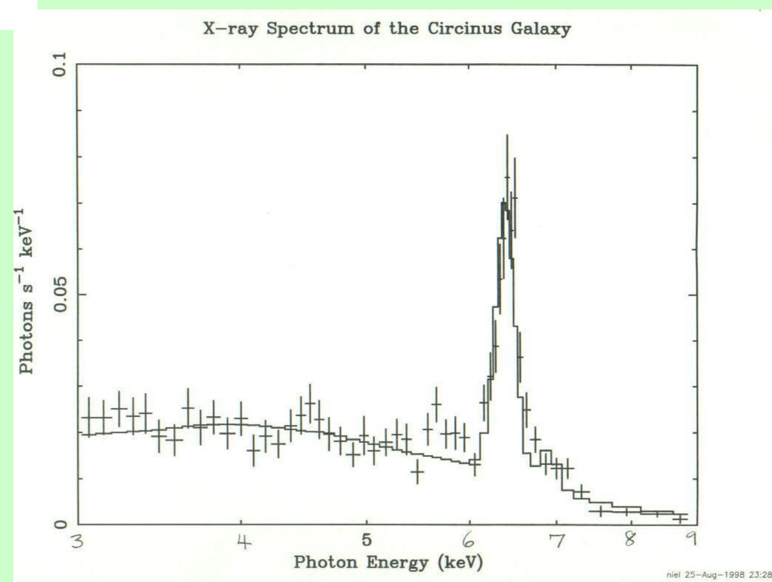
Compton-thick AGN (i.e. obscured by matter with NH≥1.5×10^{24} cm^{-2}) are the ideal sources to study the torus, because the primary (diluting) emission is blocked by this matter.



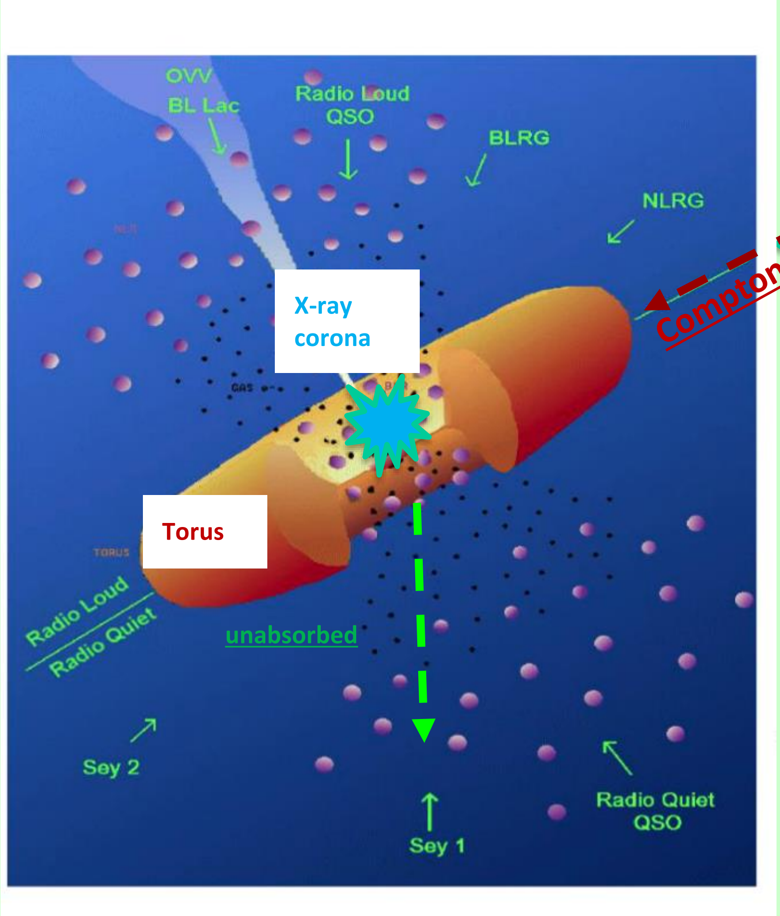


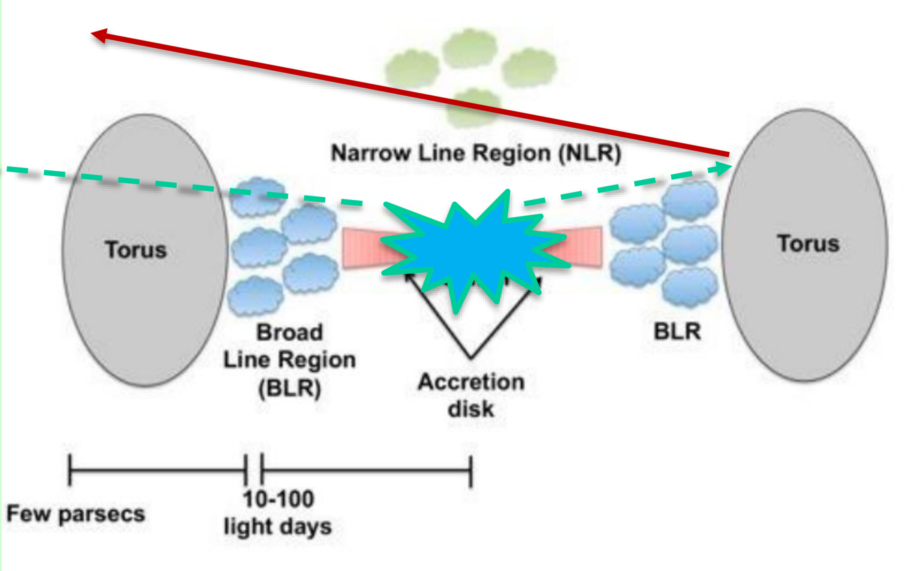


Circinus Galaxy (Matt et al. 1996)



RQ AGN: Compton-thick sources



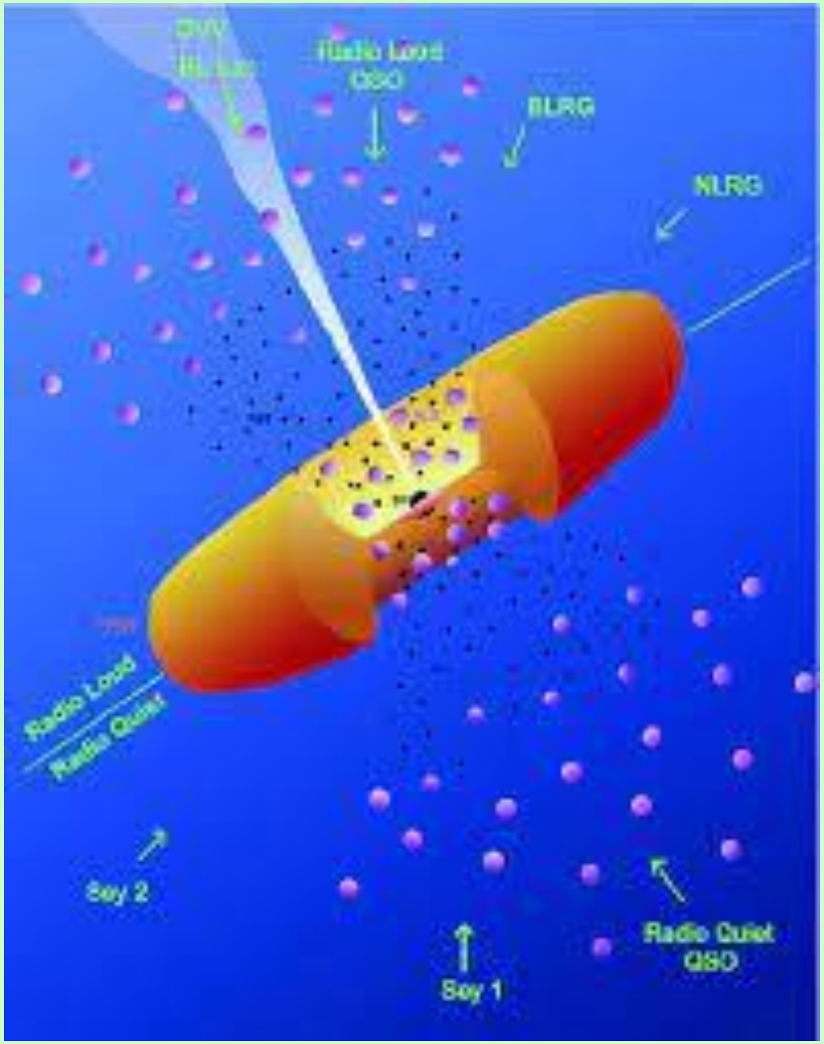


RQ AGN: Compton-thick sources

X-ray emission is dominated by reflection, so it should be highly polarized.

Polarization degree from the torus depends on the geometry of the system (inclination angle, torus opening angle)

The polarization vector is expected to be in most cases orthogonal to the torus axis.



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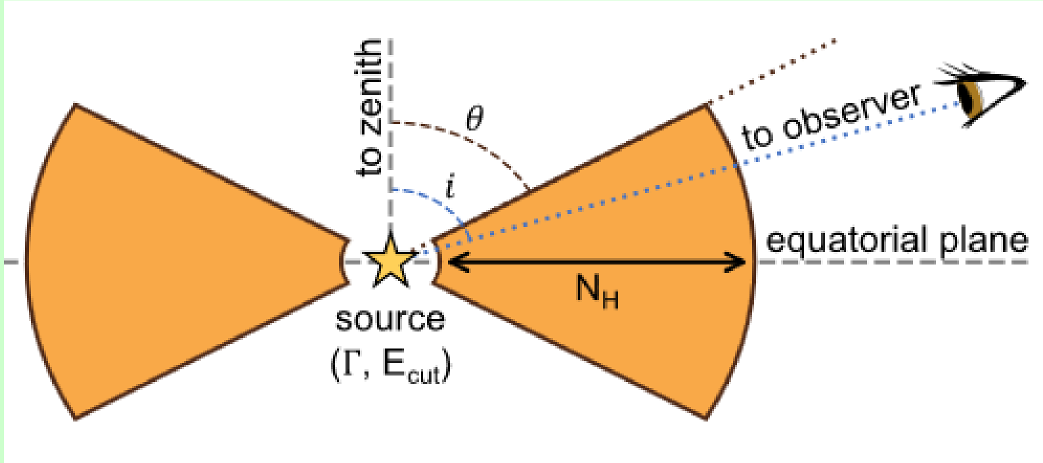
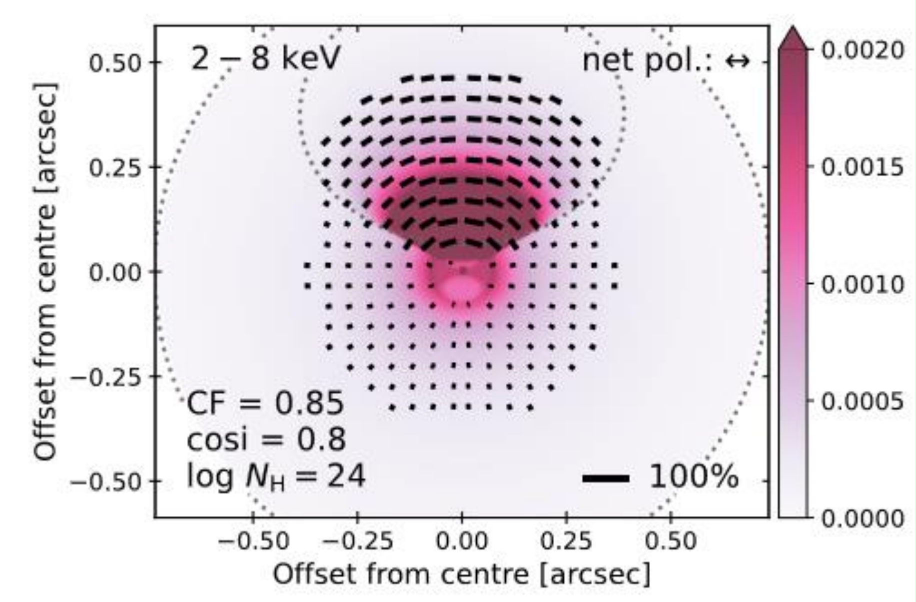




SKIRT code (Van der Meulen et al. 2024)

RQ AGN: Compton-thick sources

The ionization cone/NLR may also reflect (and polarize) the primary emission.

The matter is optically thin, and for a simple, conical geometry the polarization properties can be analytically calculated

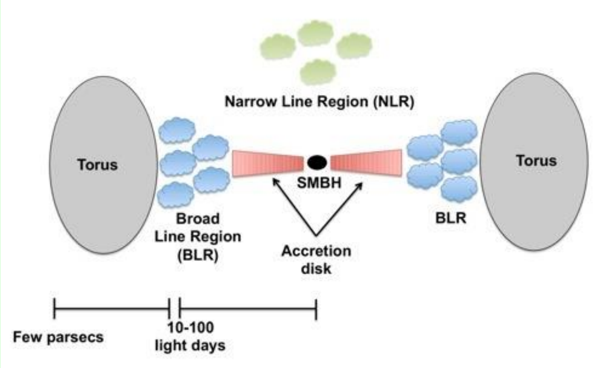
Brown & McLean 1977

$$P = P(\gamma, i) = \frac{\sin^2 i}{2\alpha + \sin^2 i}$$

$$\alpha = \frac{1+\gamma}{1-3\gamma}$$

$$\gamma = \frac{\int_{r=0}^{\infty} \int_{\mu=-1}^{1} n(r,\mu)\mu^2 dr d\mu}{\int_{r=0}^{\infty} \int_{\mu=-1}^{1} n(r,\mu) dr d\mu}$$

$$\mu = \cos\theta$$



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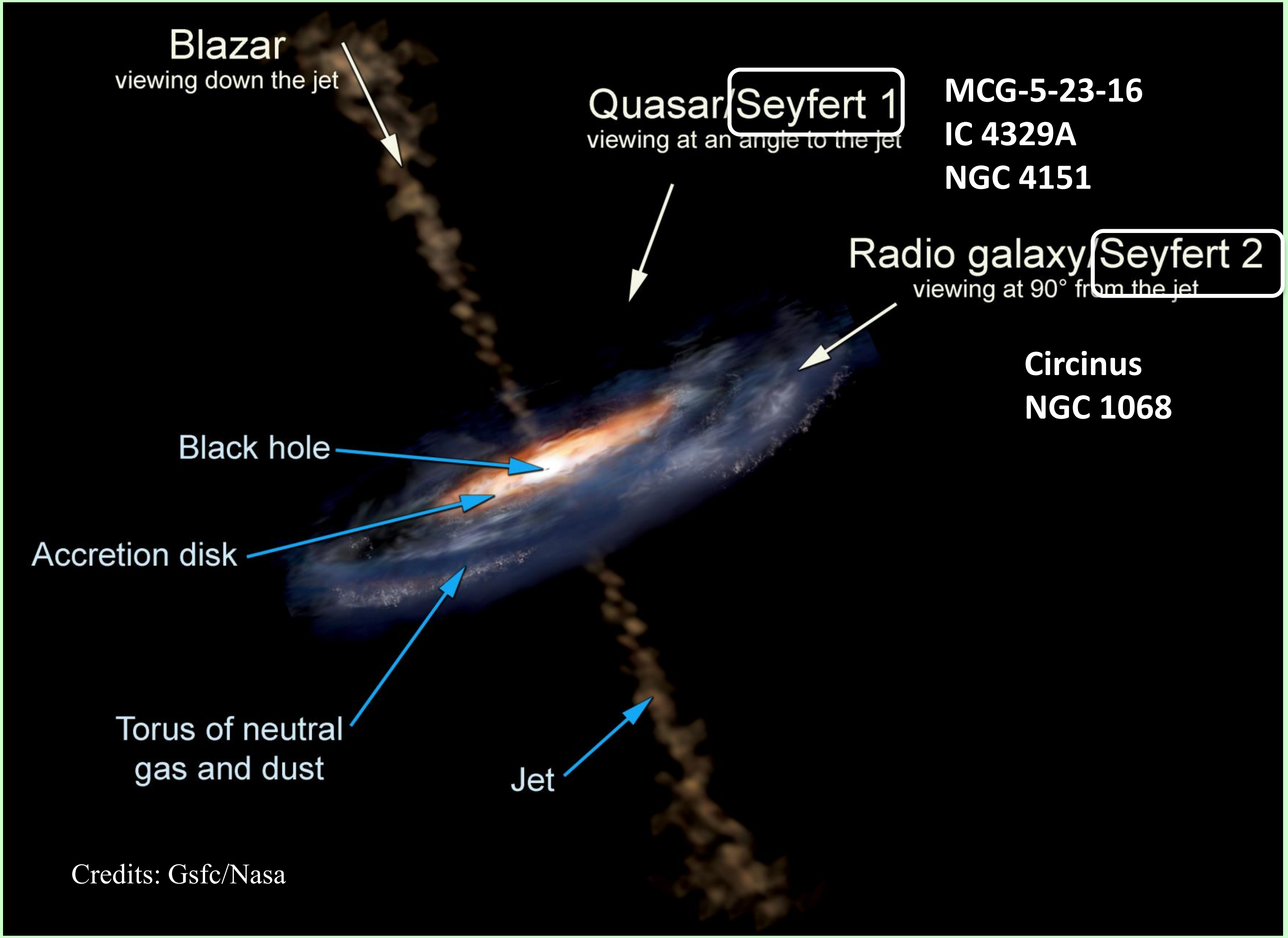
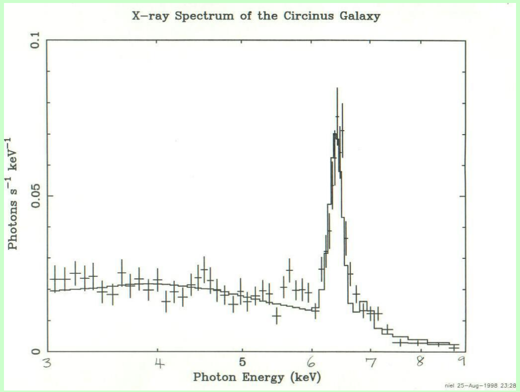
IXPE observations



Circinus Galaxy

The **Circinus Galaxy** is one of the closest AGN (4.2 Mpc), and the X-ray brightest **Compton-thick** AGN.

Neutral reflection dominates the X-ray spectrum in the IXPE band.

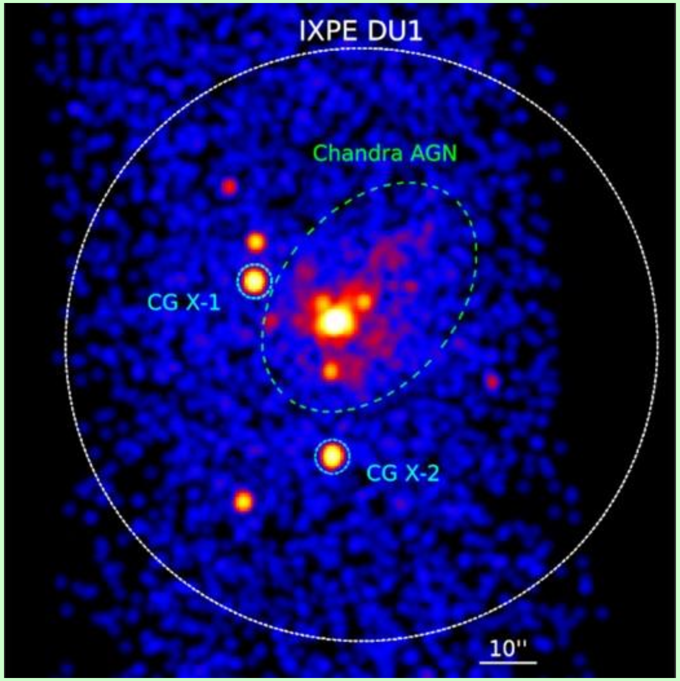


→ large polarization expected!

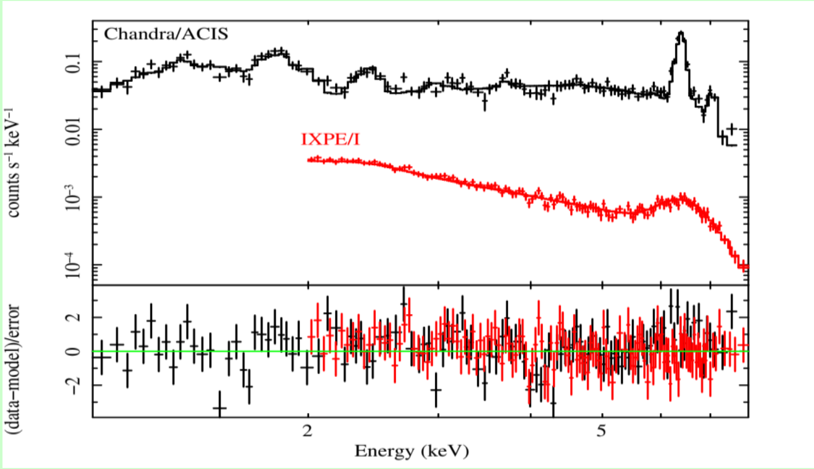
Circinus Galaxy

IXPE observed the Circinus Galaxy for about 800 ks, along with two Chandra snapshots to monitor the ULXs in Circinus.

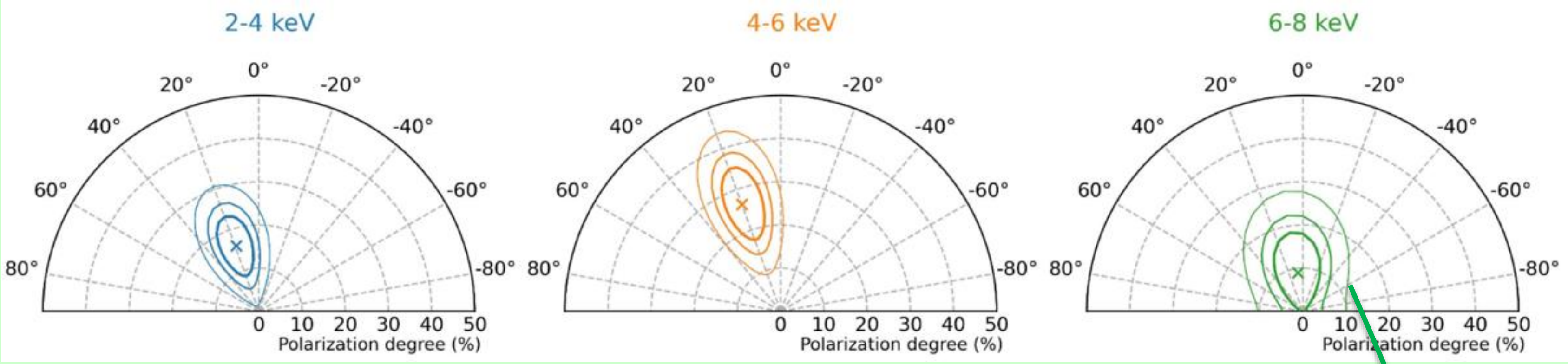
A high polarization degree (about 18%) is found, perpendicular to the radio jet (and the ionization cone)



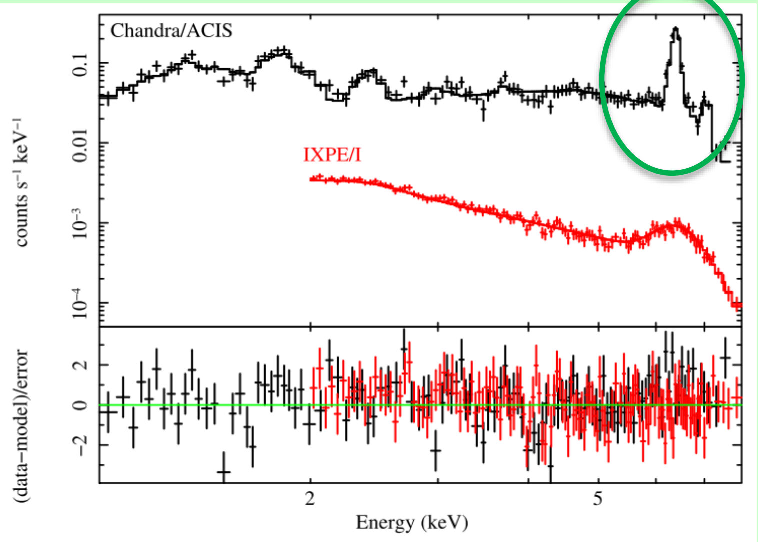
Ursini et al. 2023



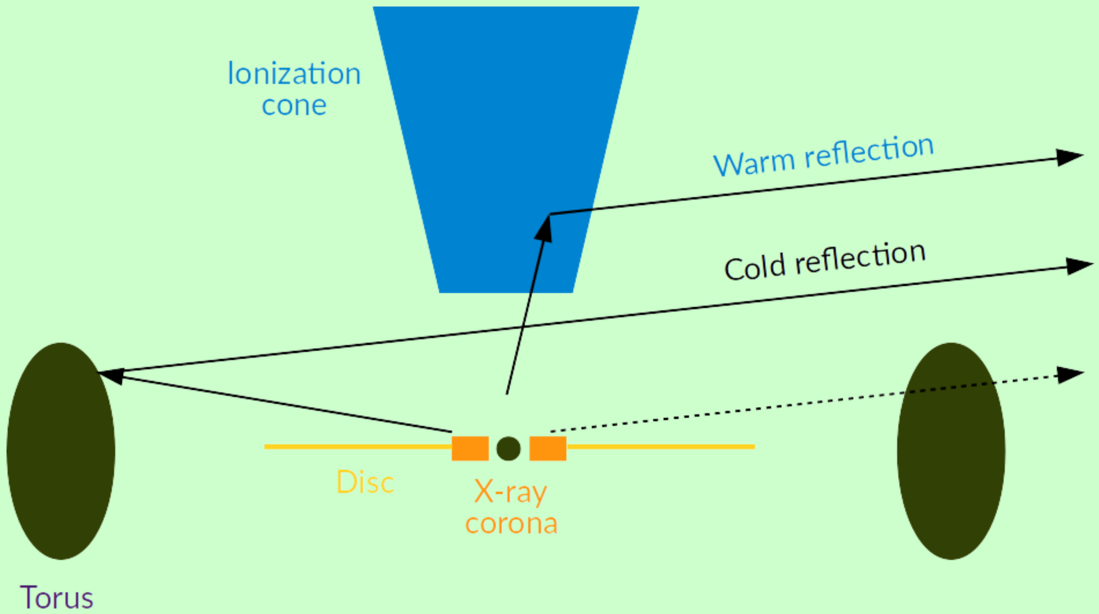
Circinus Galaxy

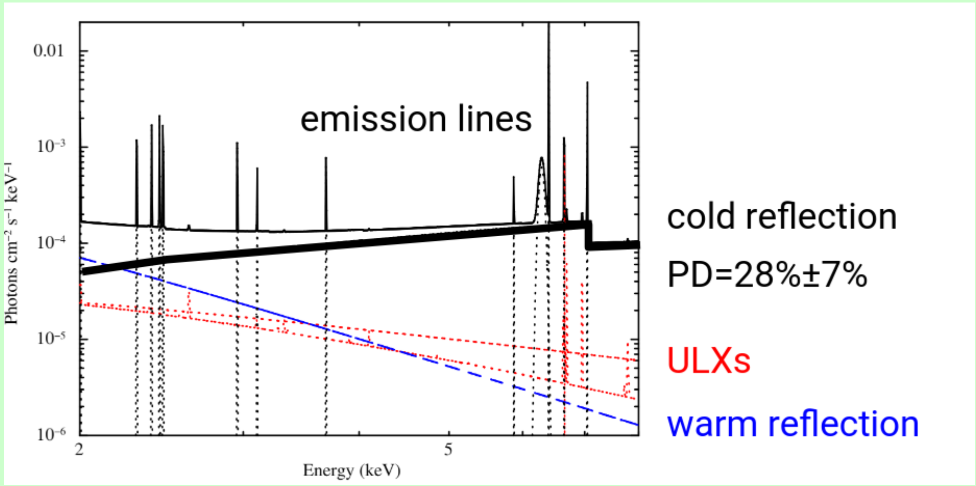


Energy	P.D. (%)	P.A. (deg)
2–8 keV	17.6 ± 3.2	16.9 ± 5.3
2–4 keV	16.0 ± 4.9	19.1 ± 8.9
4–6 keV	26.3 ± 5.7	20.2 ± 7.5
2–6 keV	20.0 ± 3.8	19.1 ± 5.5
6–8 keV	< 24.5	-



Circinus Galaxy

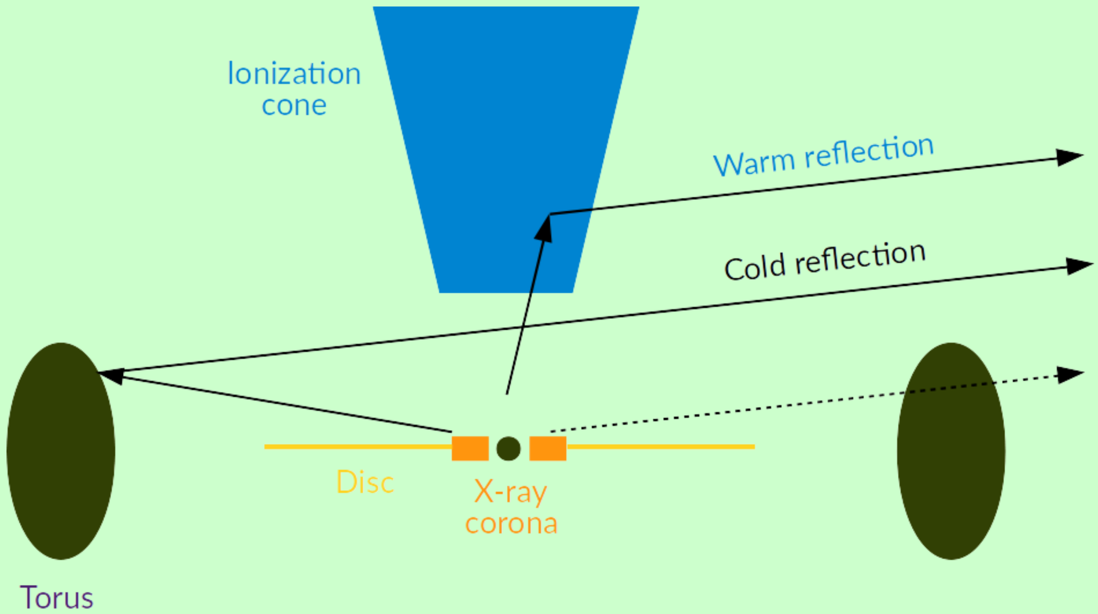


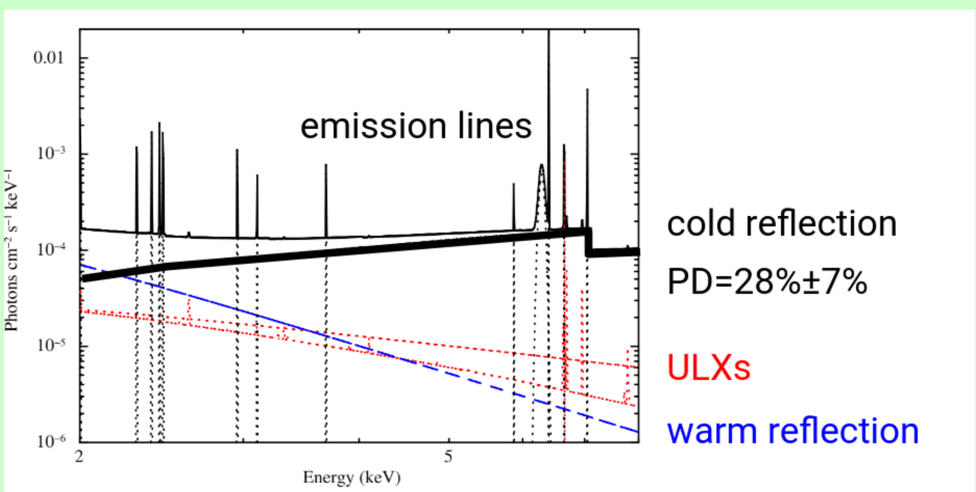


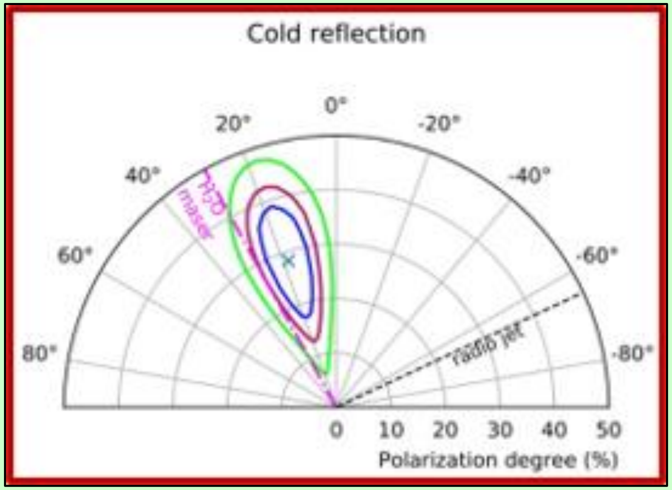
From the spectro-polarimetric analysis a PD=28% of the reflection component is found.

For all the other components the PD is unconstrained.

Circinus Galaxy

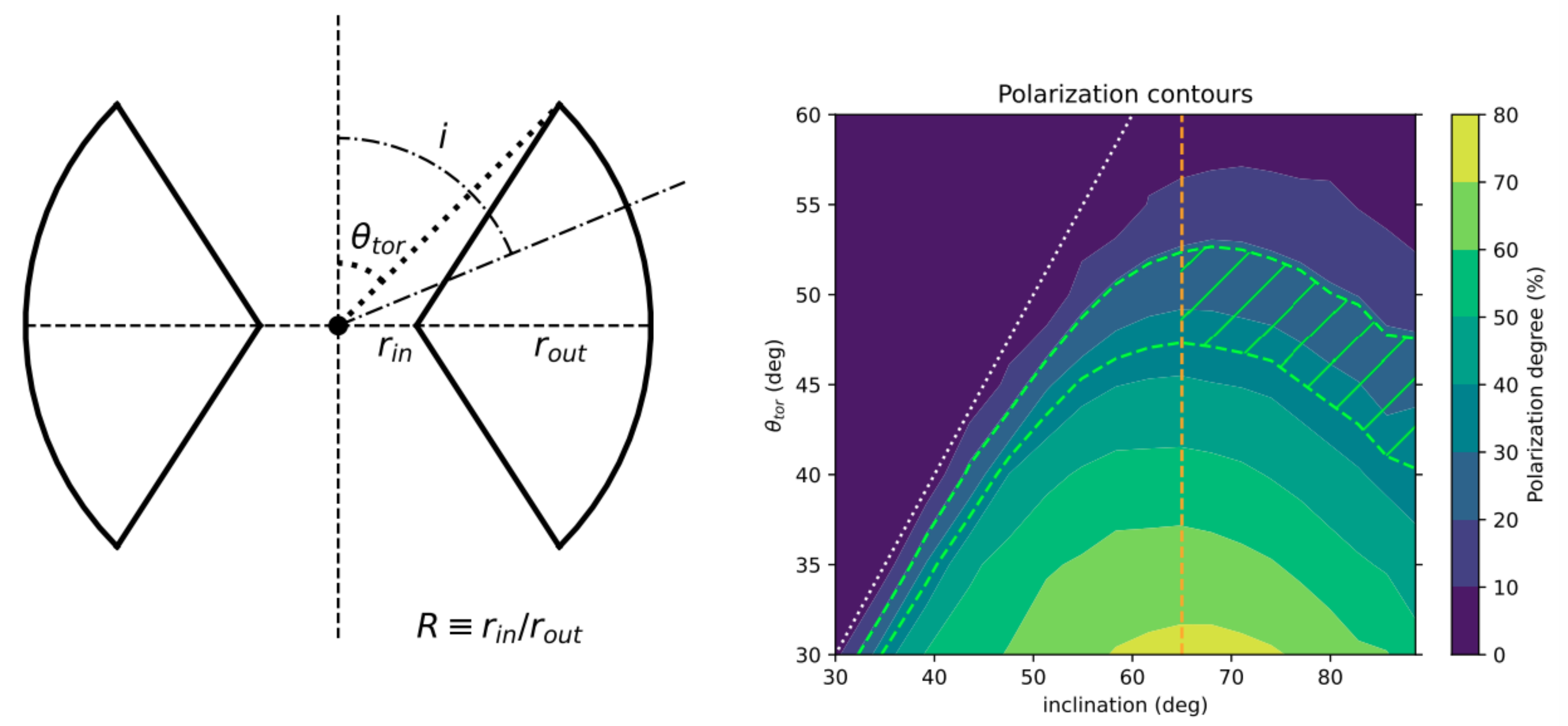






Circinus Galaxy

Numerical simulations with the code of Ghisellini et al. (1994)



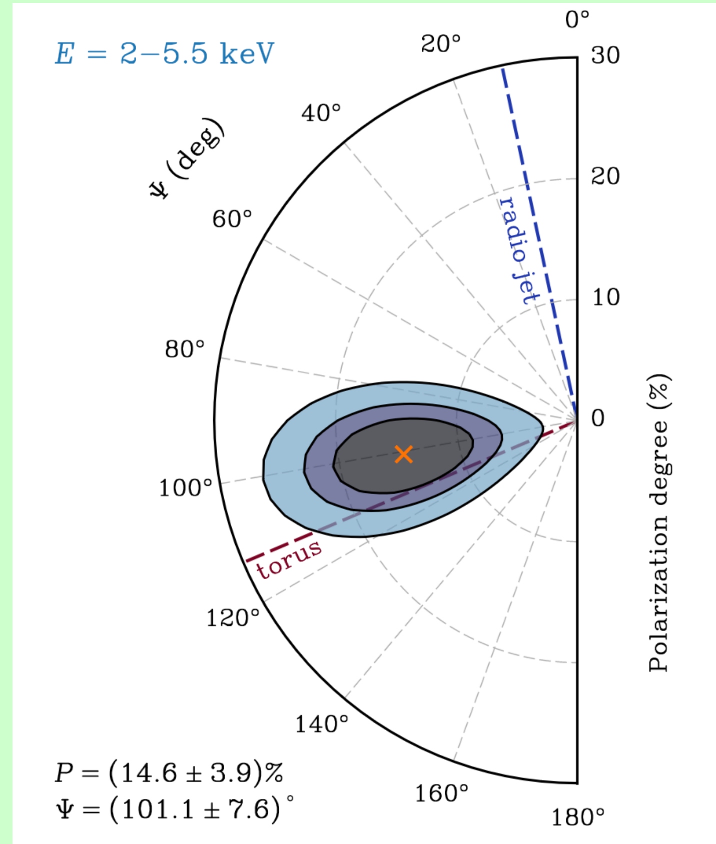
Torus opening angle ~40-50 degrees, fully consistent with Unification Model

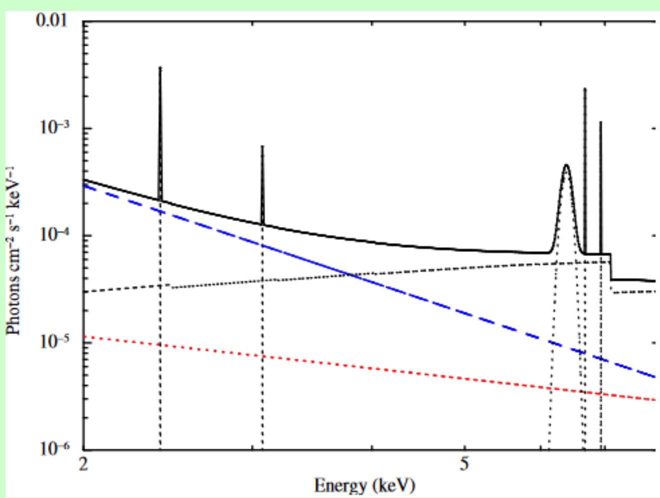
NGC 1068

IXPE observed NGC 1068 for about 1200 ks, along with two Chandra snapshots to monitor the ULXs.

A polarization degree of about 15% is found in the 2-5.5 keV range, again perpendicular to the radio jet.

Torus is less dominant in the IXPE band than in Circinus



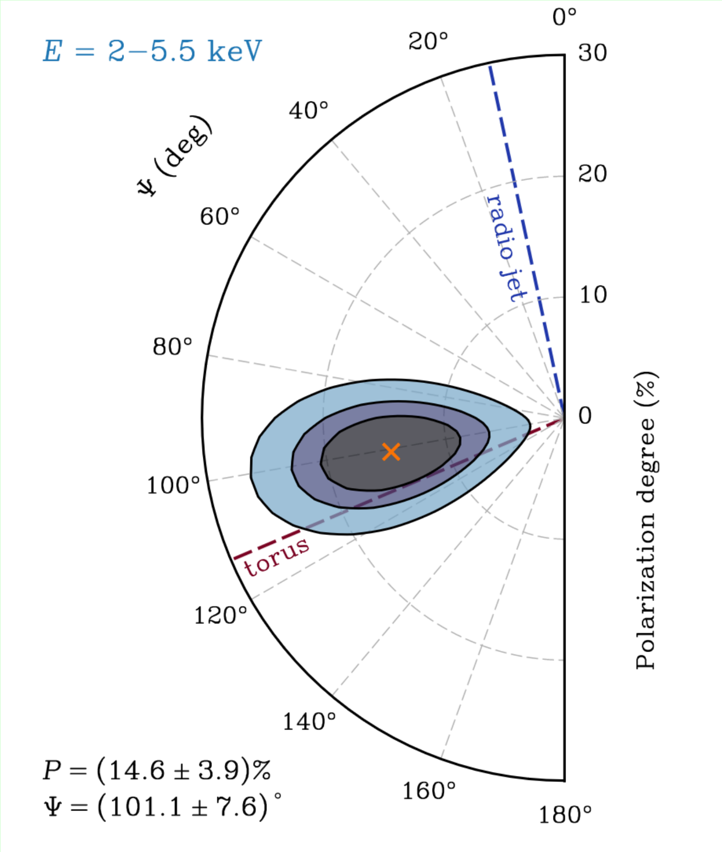


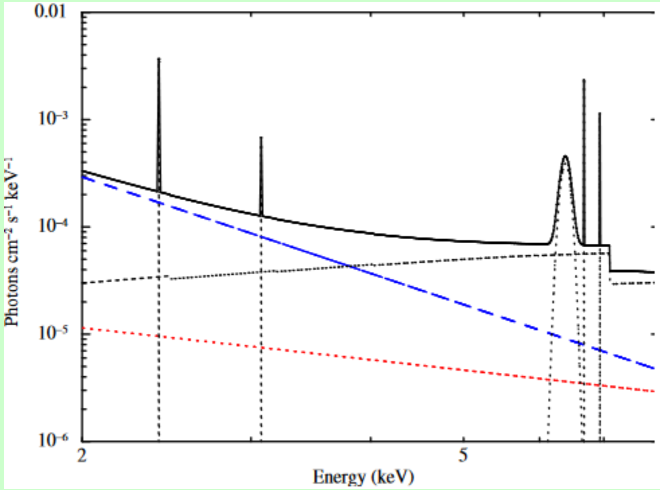
Marin et al. 2024

NGC 1068

The spectropolarimetric analysis indicates a torus polarization degree of about 20%

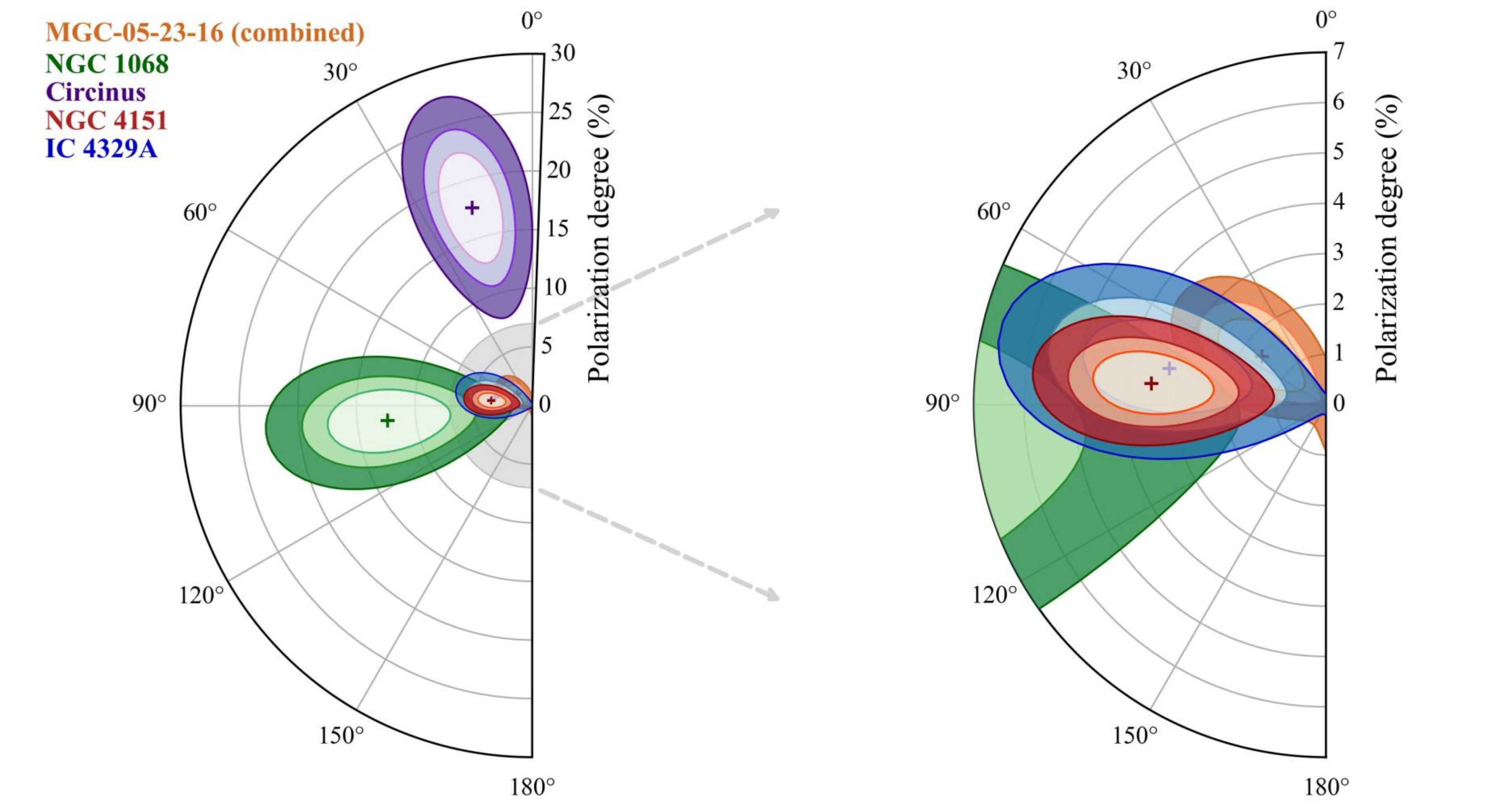
Numerical simulations suggest a half opening angle of 50-55 deg





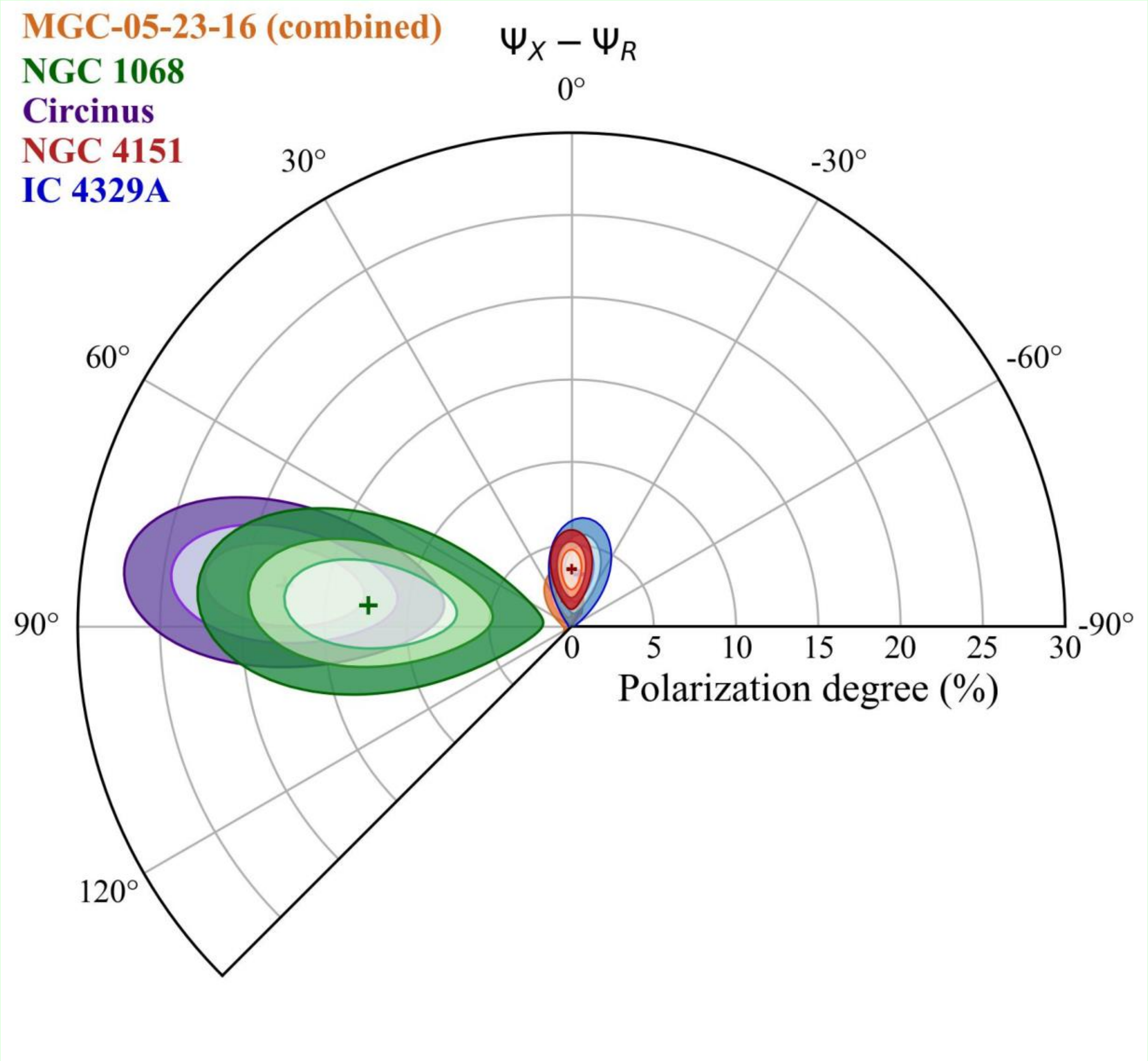
Marin et al. 2024

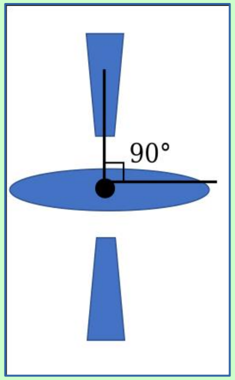
Summary



Marin et al. 2024b

Summary





Courtesy of
Andrea Marinucci

Future perspectives (beyond IXPE)

eXTP: Chinese mission, due to be launched around 2030. Same polarimeter as IXPE, but with larger effective area
→ Population studies

Broad band missions with sensitive polarimeters above 10 keV: just a concept at the moment
→ Reflection component