Introduction to Black Hole Astrophysics

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CENTRO DE ASTROBIOLOGÍA

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STRONGGRAVITY
EU FP7-SPACE research project 312789 2013 - 2017
SEVENTH FRAMEWORK PROGRAMME

Outline of the 3 lectures-course

Lecture 1

- The different flavors of astrophysical BHs
- Observational evidence for astrophysical BHs:
  - BHs in binary systems
  - The Milky Way super-massive BH (SMBH): the case of Sgr A*
  - SMBHs in other galaxies

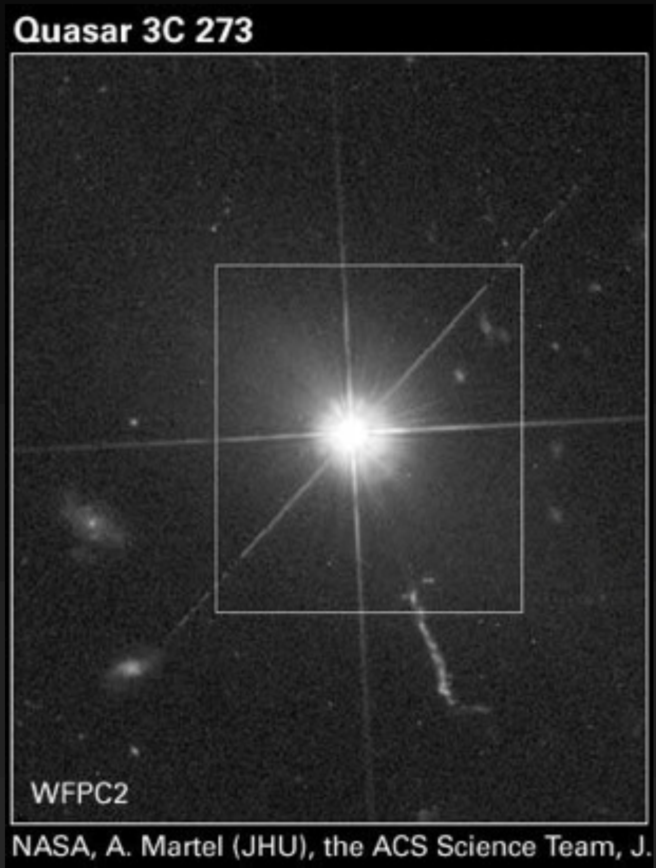
Lecture 2

- BH accretion, energy release, efficiency, Eddington limit, BB emission and IC
- BH transients (X-ray binaries): states. BH spin from thermal BB disc
- IMBHs: the special case of HLX-1 in ESO 243-49

Lecture 3

- Intro to Active Galactic Nuclei (AGN)
- The importance of AGN in the wide context: feedback and galaxy evolution
- X-ray properties of AGN (some)

Intro to Active Galactic Nuclei



In the 60s sources which looked like stars (i.e. unresolved sources) where discovered

Optical spectra revealed significant redshift (thus distance) which led to the first L estimates

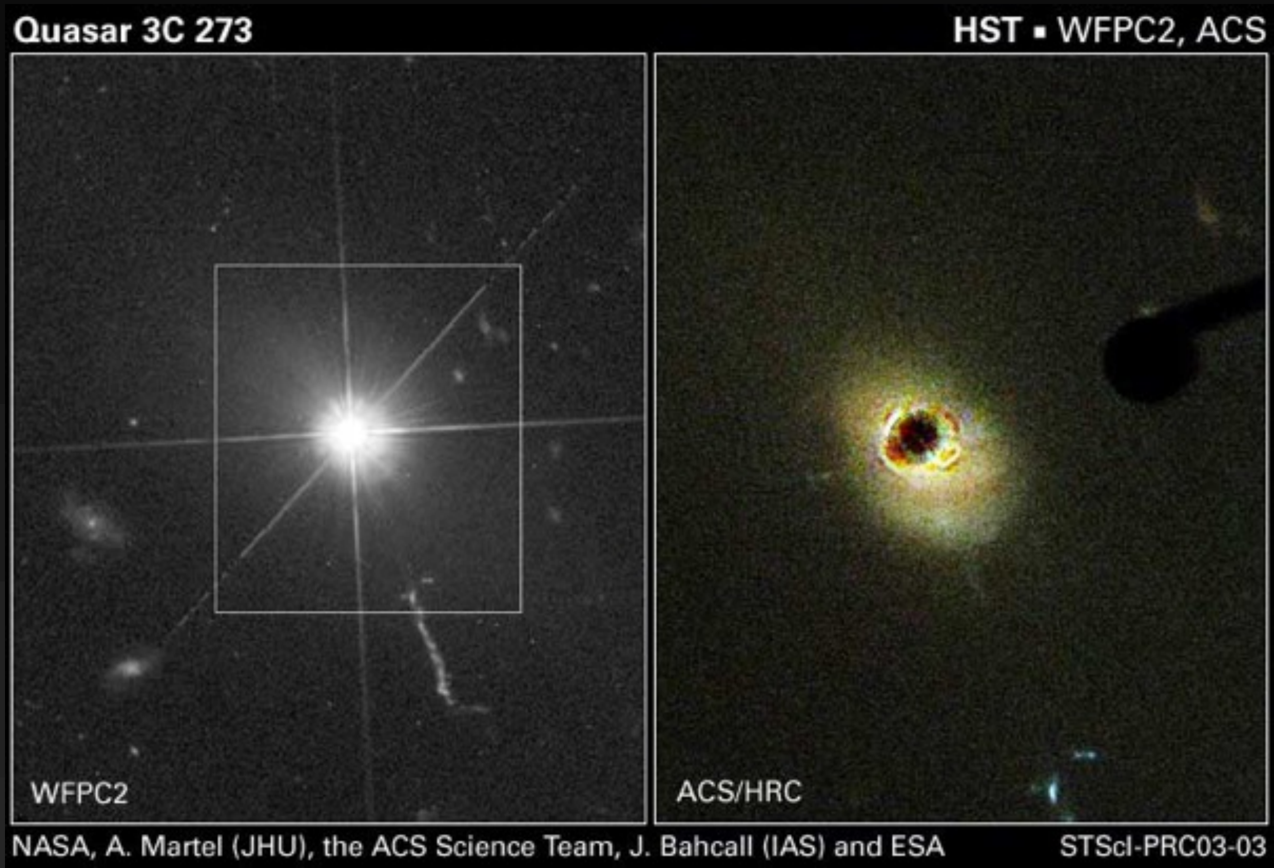
This objects could reach $L \sim 10^{46}$-10^{47} erg/s

Remember that $L_{sun} \sim 4x10^{33}$ erg/s and that a typical galaxy comprises ~ 10^{11} stars …

The most luminous quasars (QSOs=quasi-stellar-objects) outshine their host galaxy completely

so the idea that they were powered by accretion onto SMBHs was put forward
[remember that $L_{edd} \sim 1.3x10^{38}$ (M/M_{Sun}) erg/s]

Intro to Active Galactic Nuclei



In many cases, the host galaxy can only be revealed with deep exposures and removing the emission from the central region

Intro to Active Galactic Nuclei

The host galaxies of QSOs are often disturbed/interacting which helps channeling large amount of gas into their central regions (fuel for accretion and luminosity)

Intro to Active Galactic Nuclei

The phenomenology is very rich and led to a rather complex taxonomy and classification scheme

However, after many years of research a unification model has emerged, in which all types of AGN can be classified basically according to luminosity, radio properties (whether they have relativistic jets or not) and orientation

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From an optical spectroscopy viewpoint, the major dicothomy is between

type I AGN which exhibit both broad and narrow emission lines
type II AGN which exhibit narrow emission lines only

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Broad optical/UV emission lines (with typical FWHMs of a few thousands km/s) are the signature that the emission comes from material in fast motion, from a region located relatively close to the central SMBH and under its gravitational influence

Narrow emission lines (100s of km/s) are instead interpreted as due to gas far from the BH (extended gas illuminated by the central engine)

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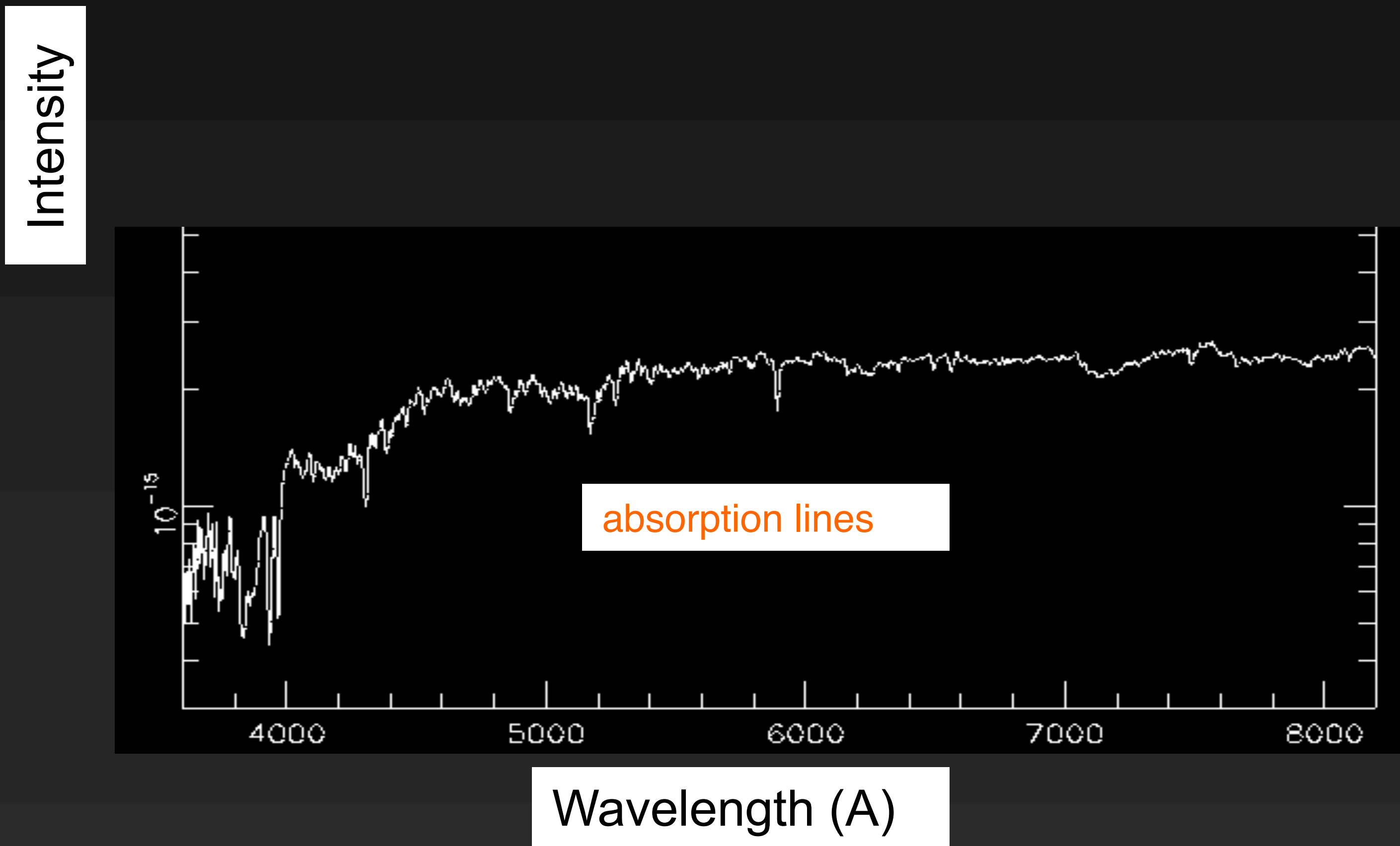

Typical normal galaxy spectrum:

integrated light of stars

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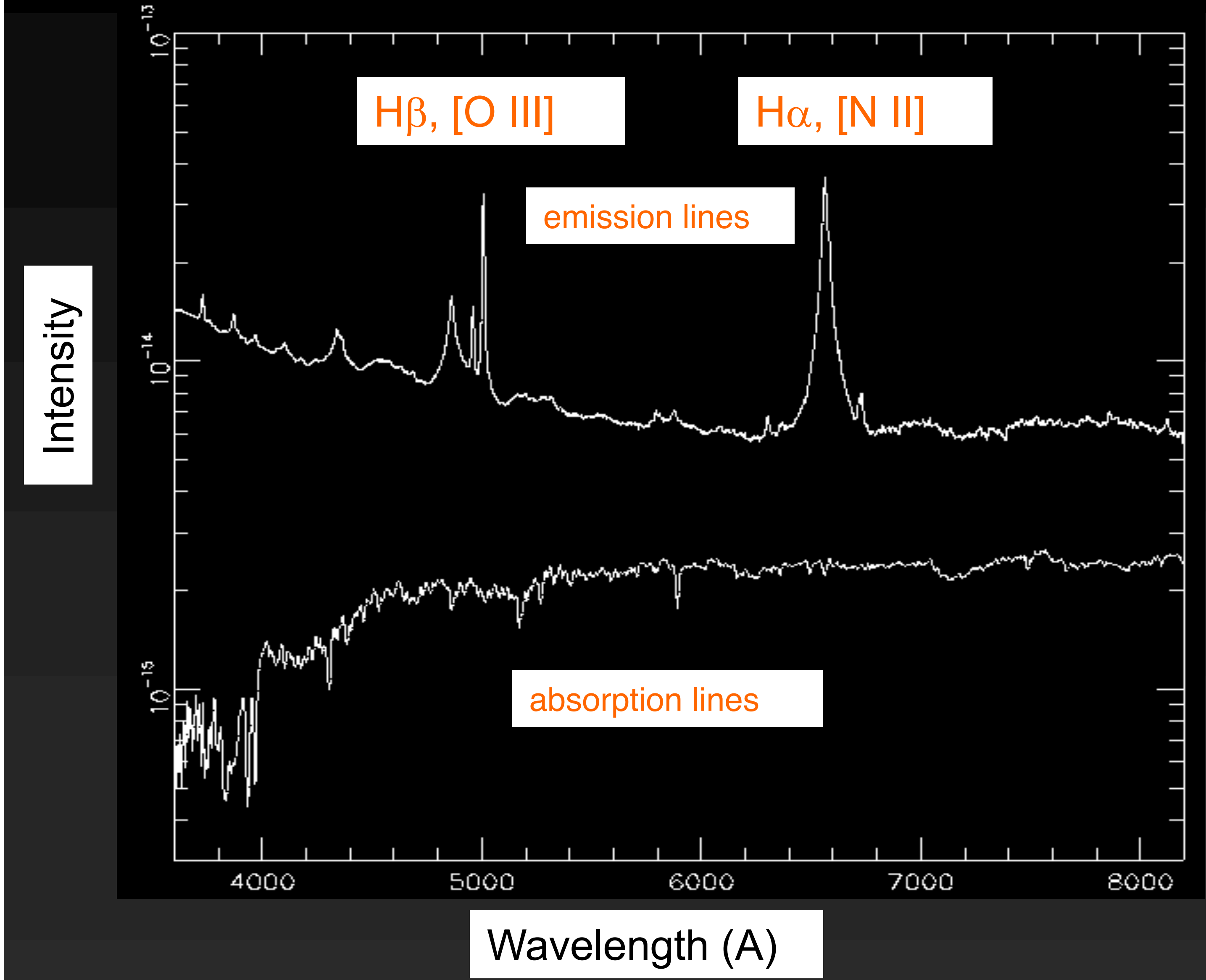

Typical AGN optical spectrum

photo-ionized lines

Typical normal galaxy spectrum:

integrated light of stars

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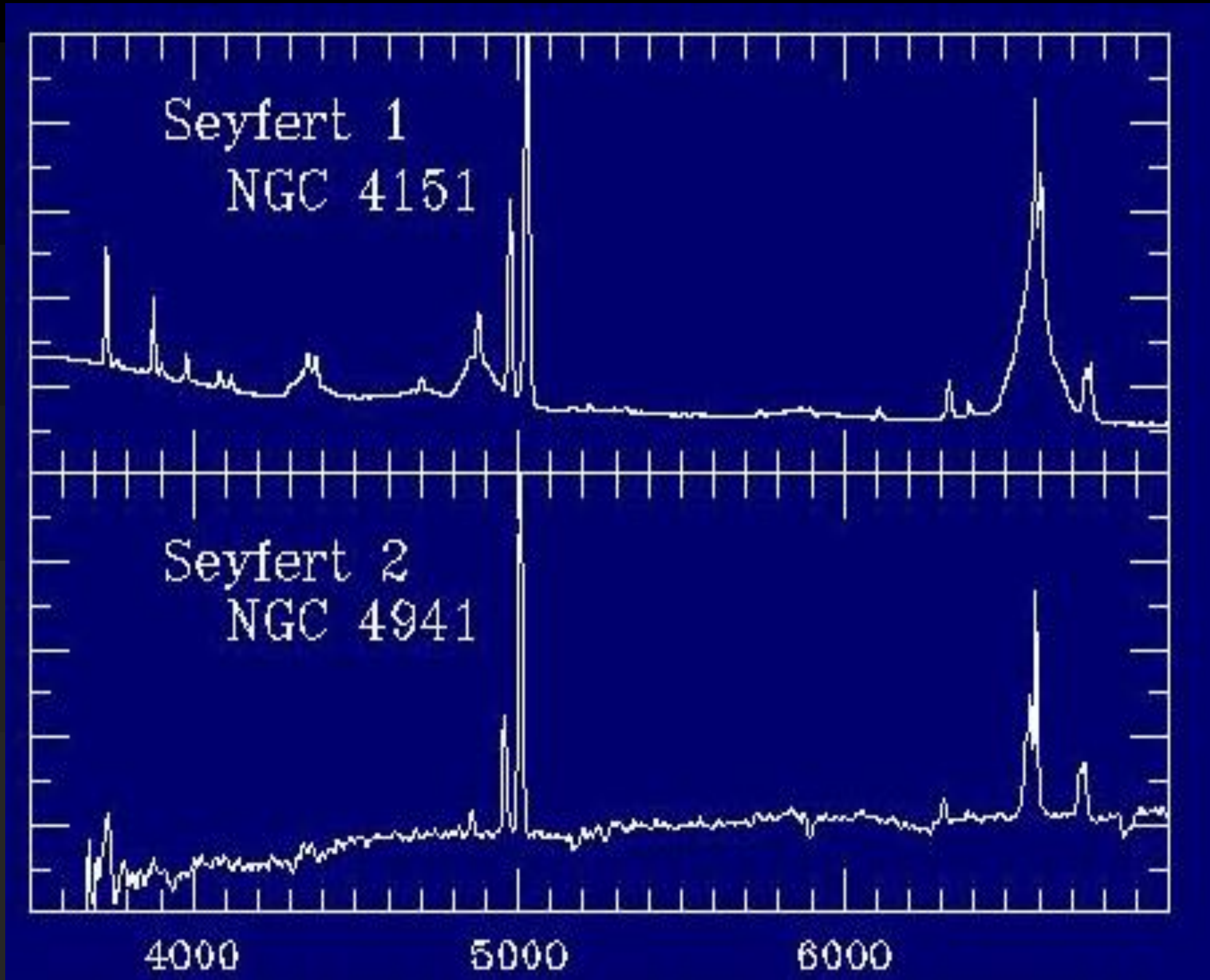

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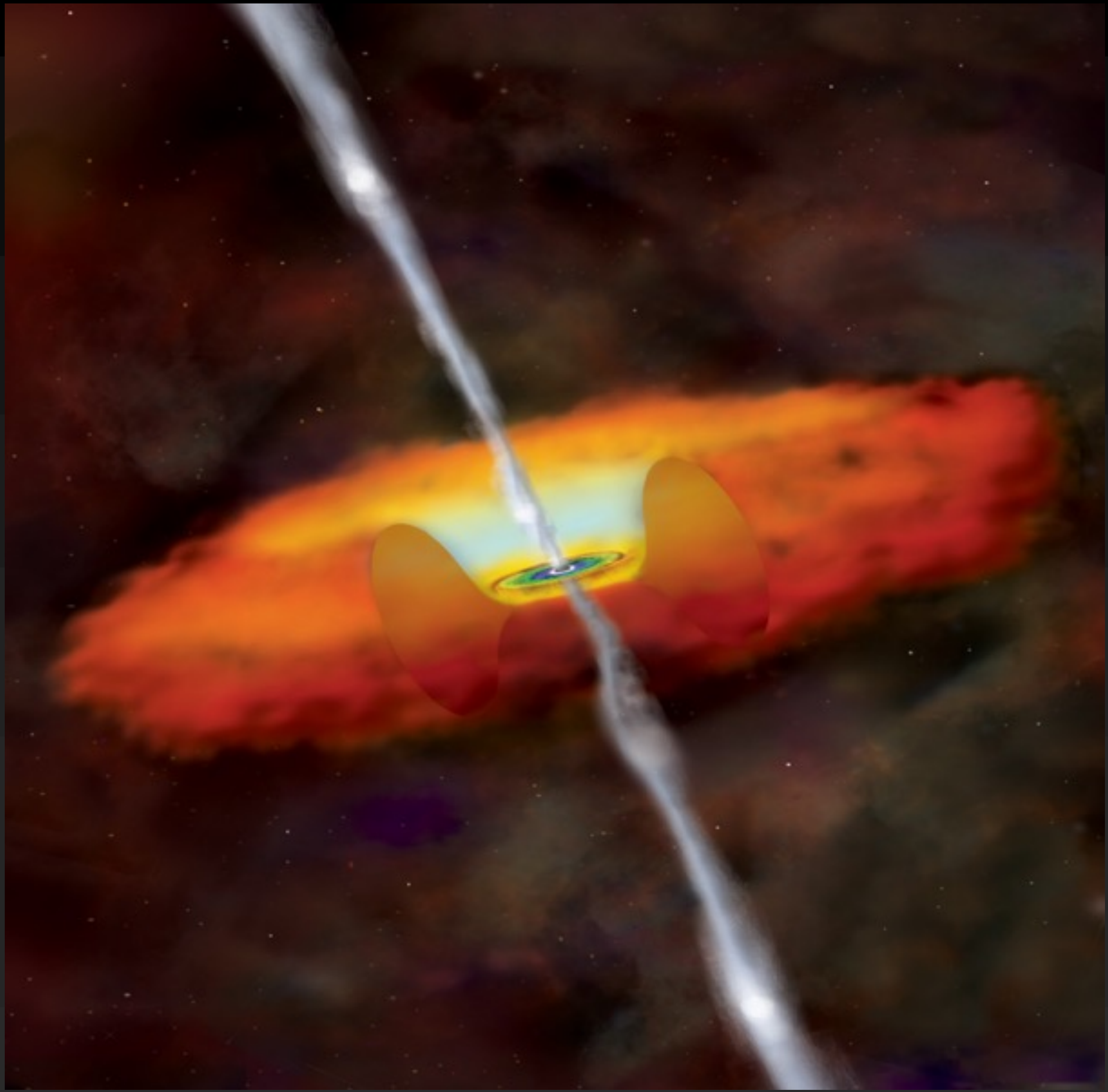

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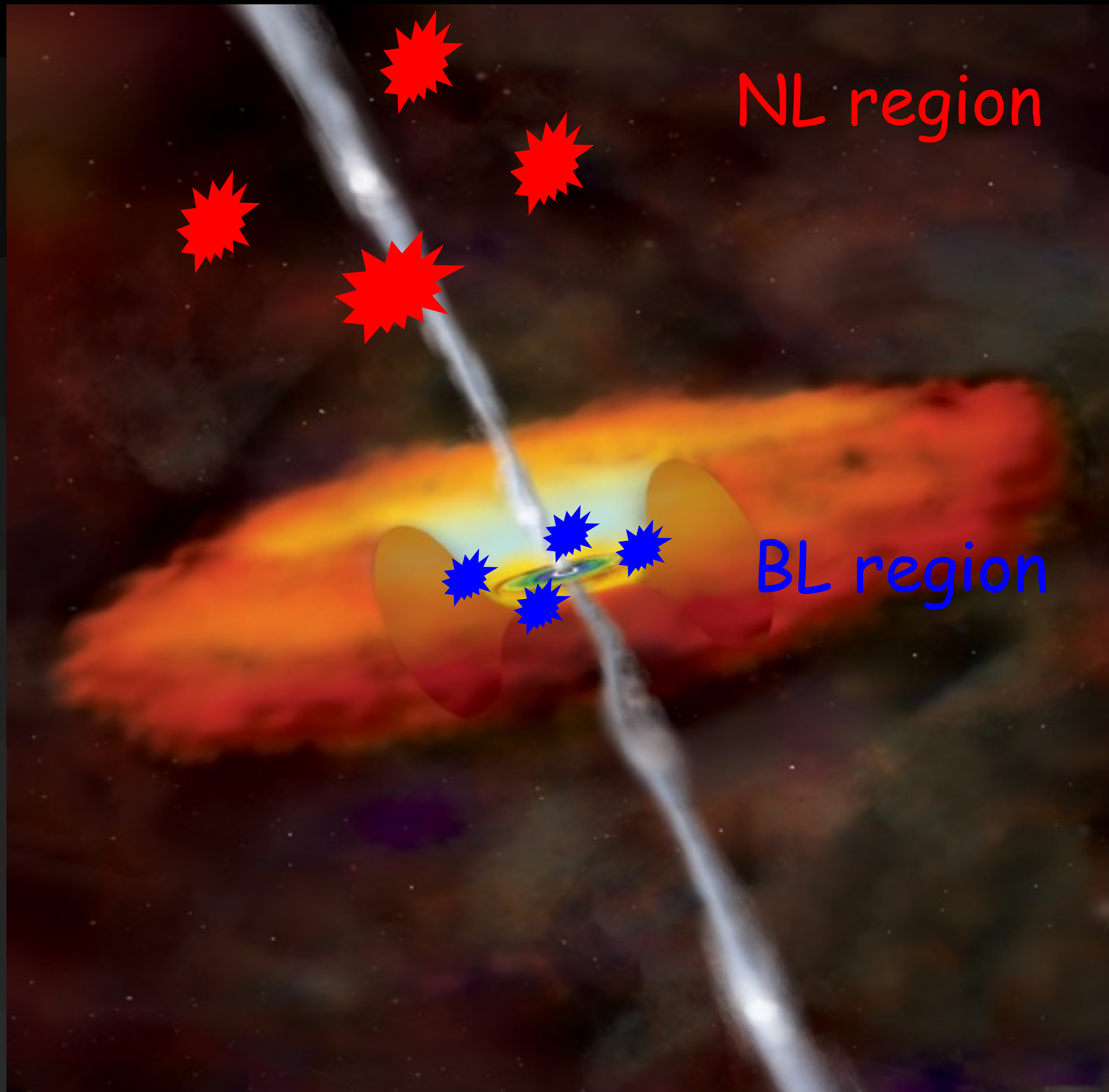

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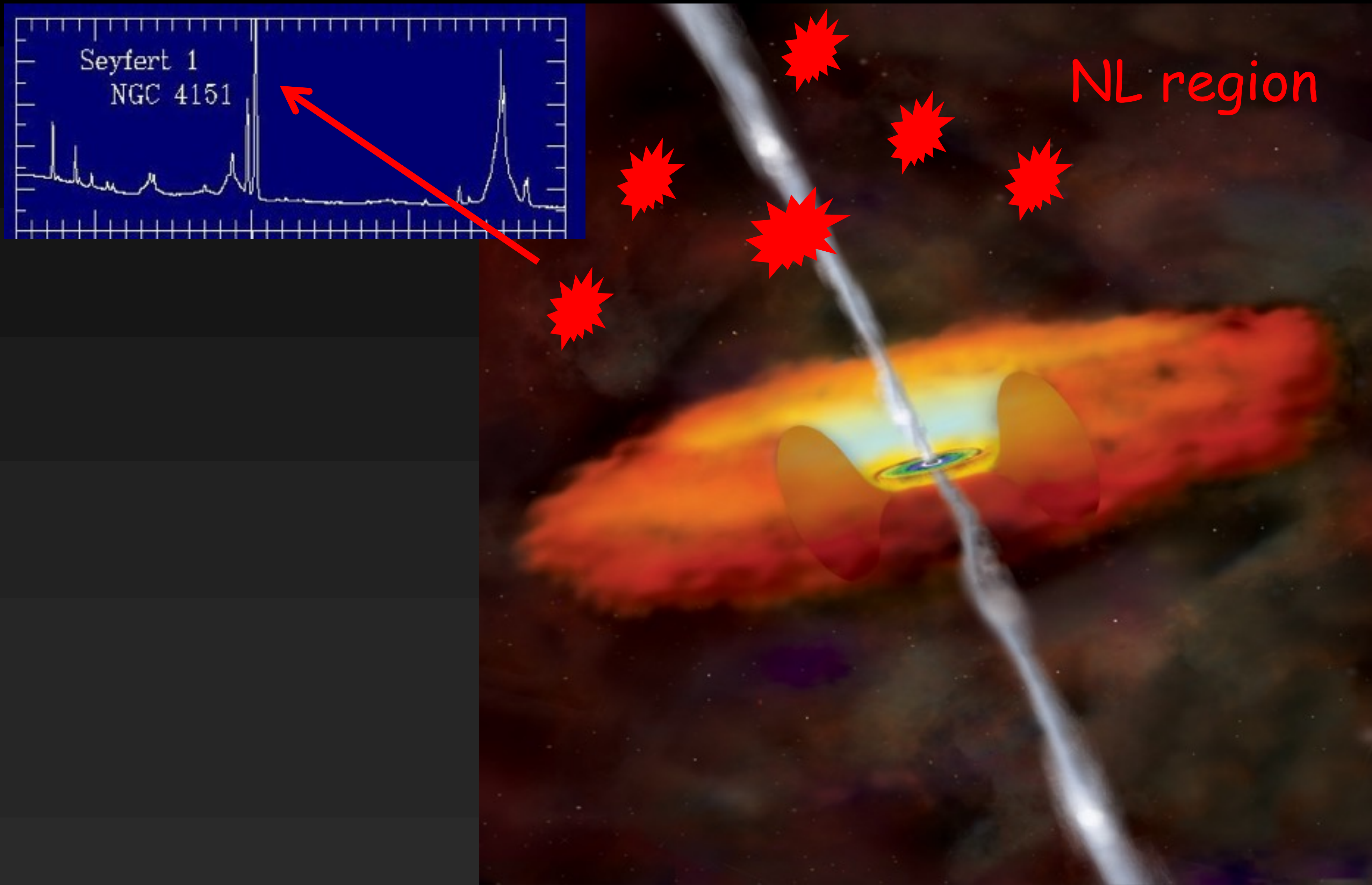

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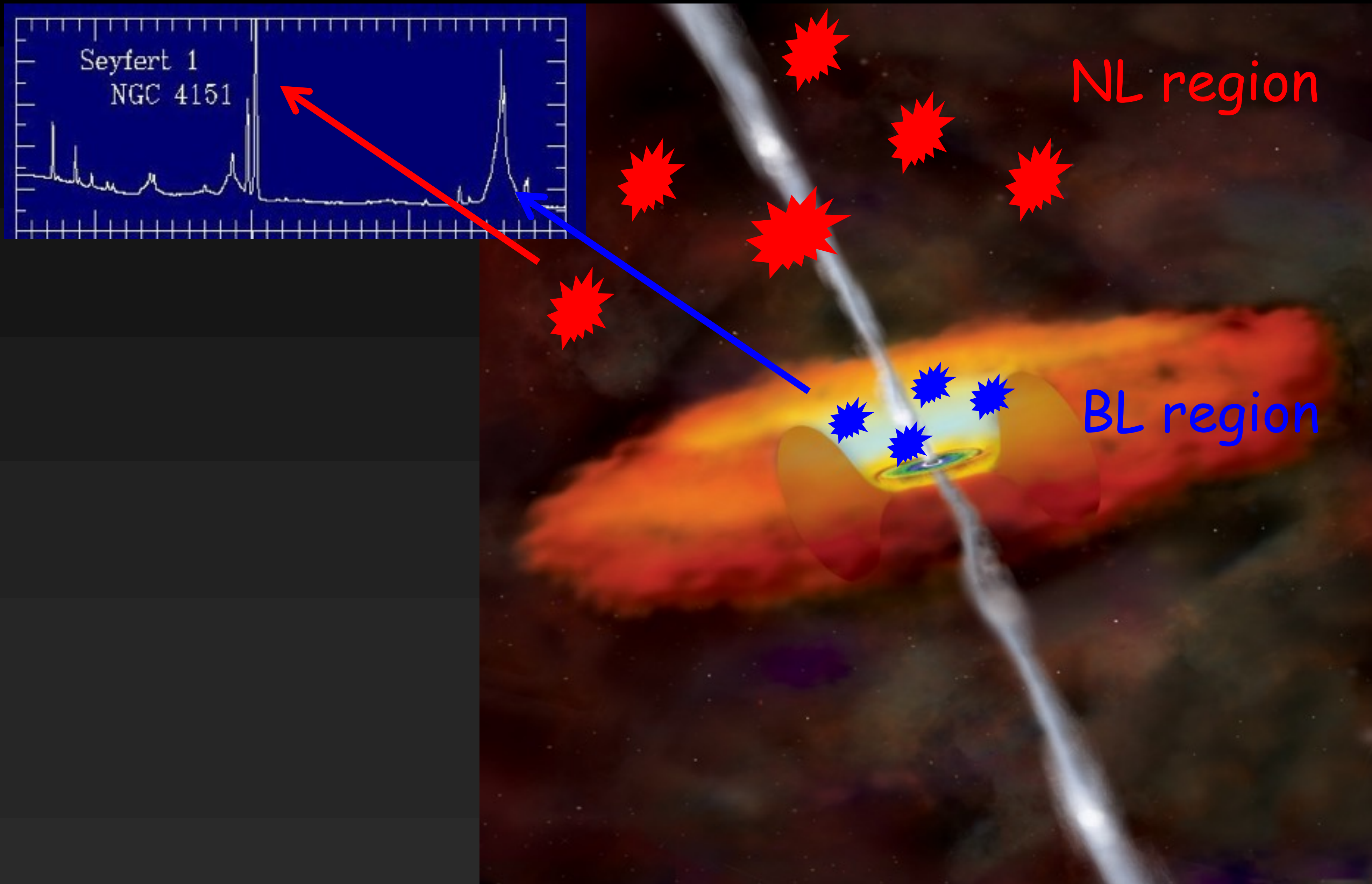

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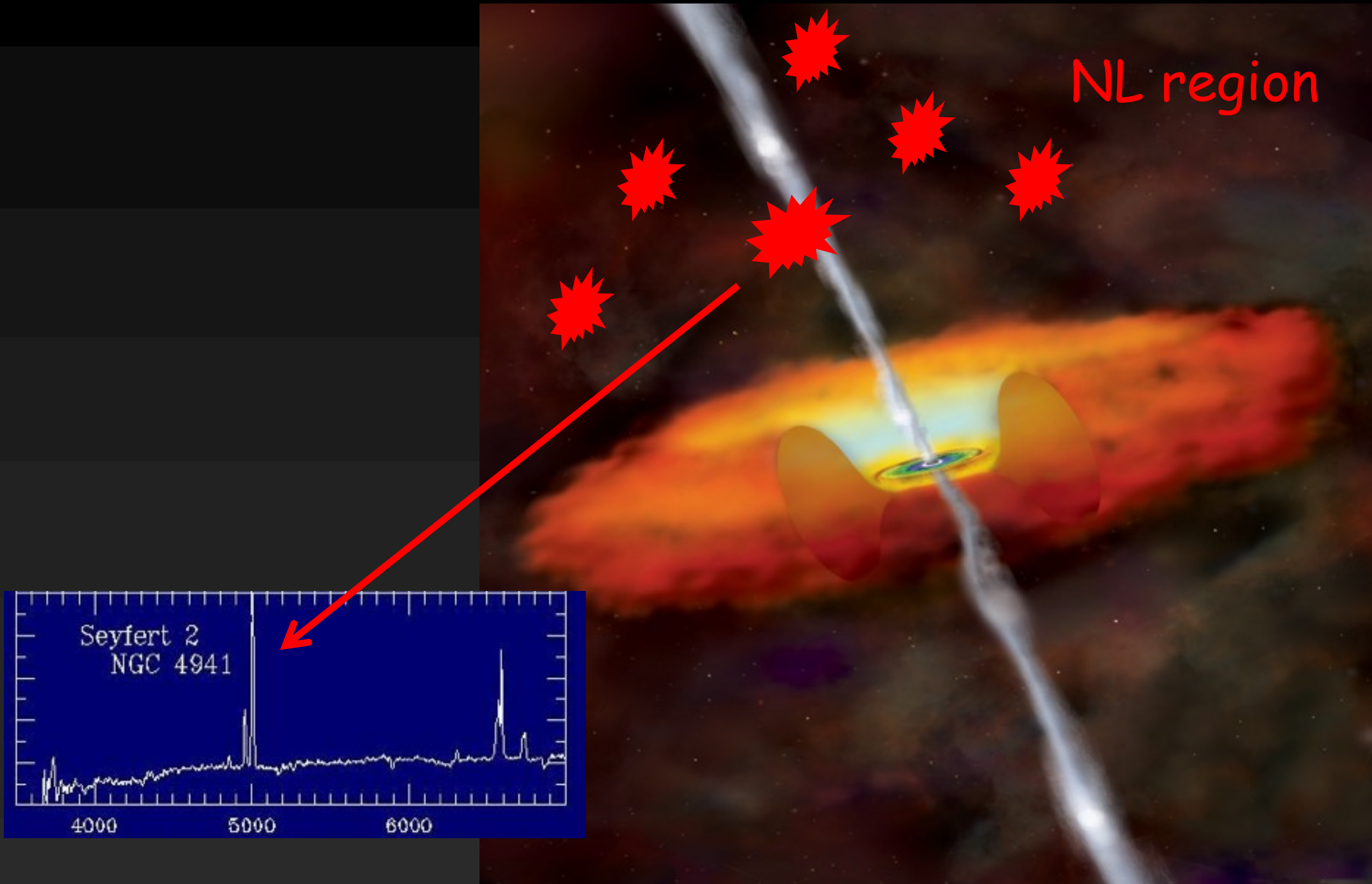

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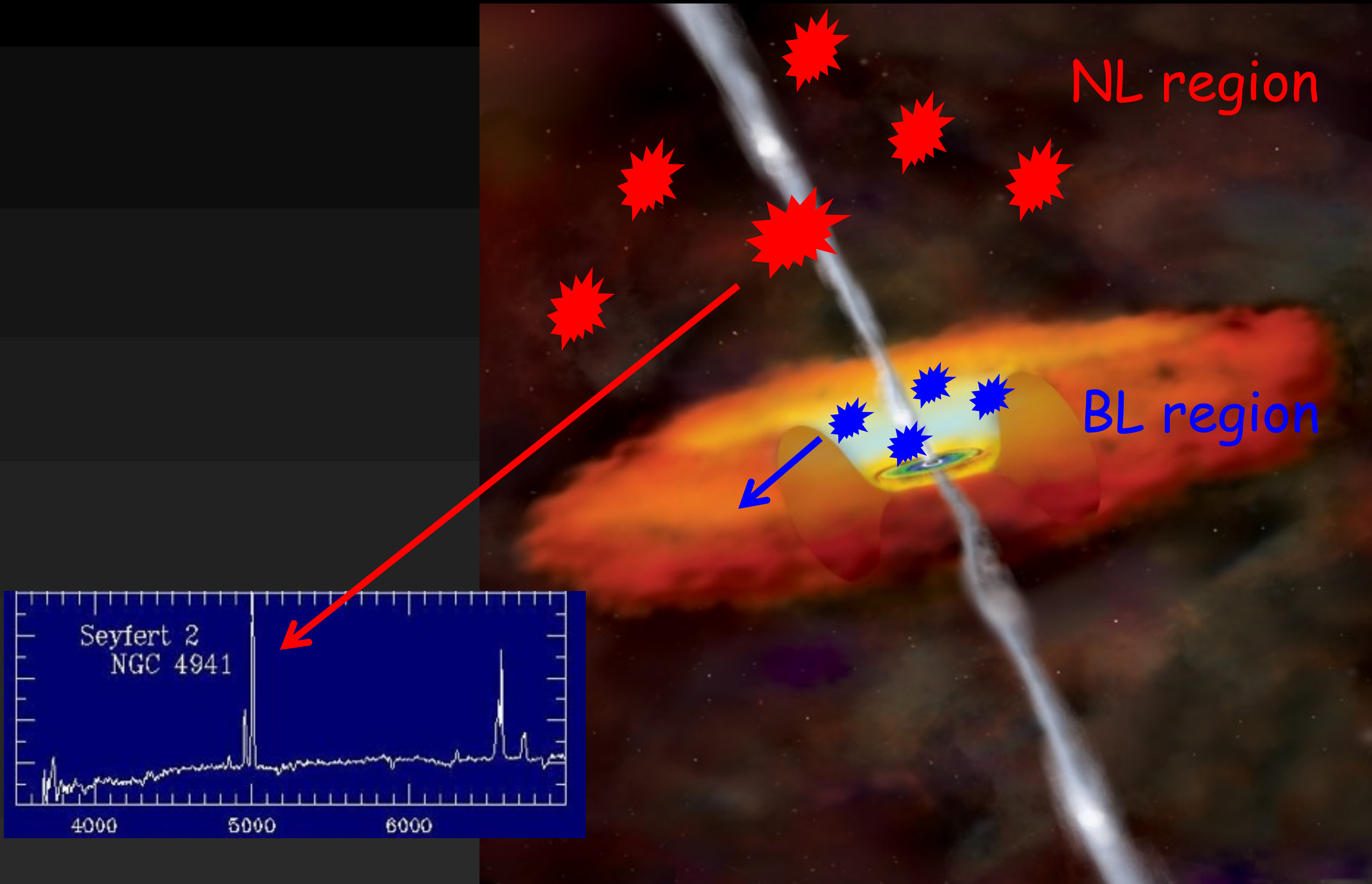

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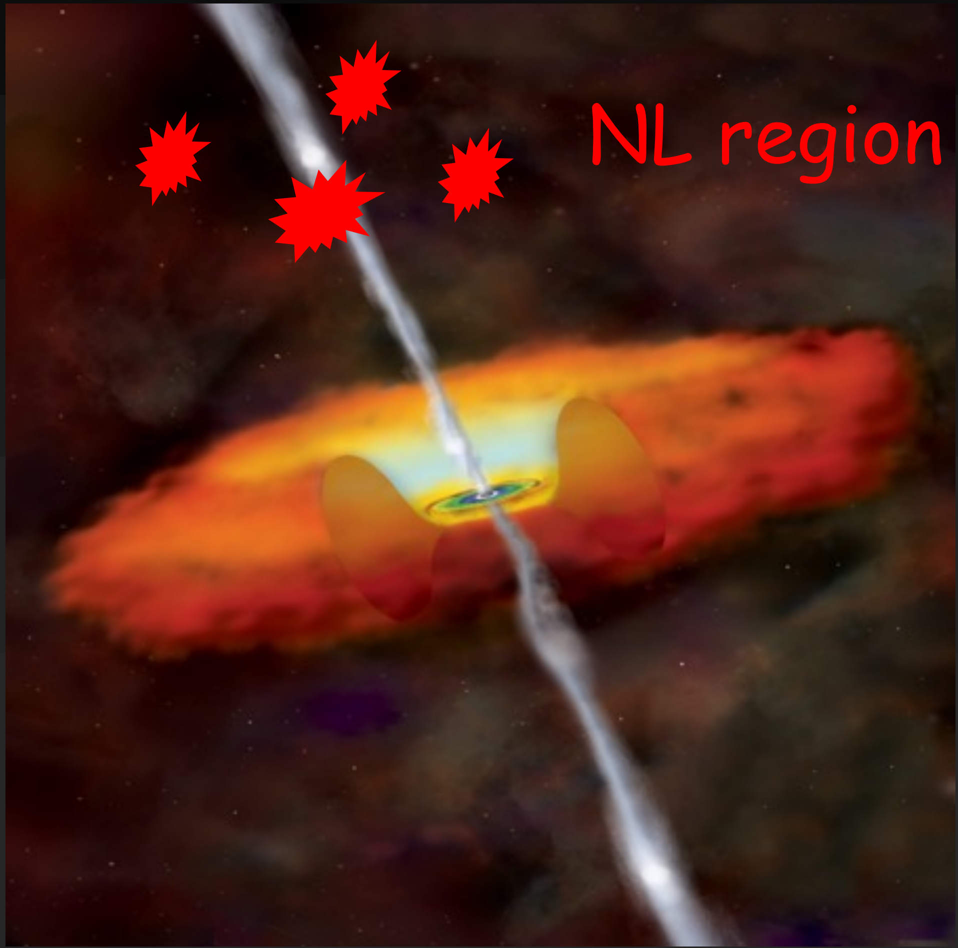
On important confirmation of the genral structure of AGN in the framework of the unified model comes from spectropolarimetry, i.e. from optical spectra taken in polarized light

If a medium with the right properties to act as a scatterer of the broad lines exist, scattering could re-direct the broad lines into the line-of-sight even for obscured type II AGN

The broad lines would then be seen in polarized light



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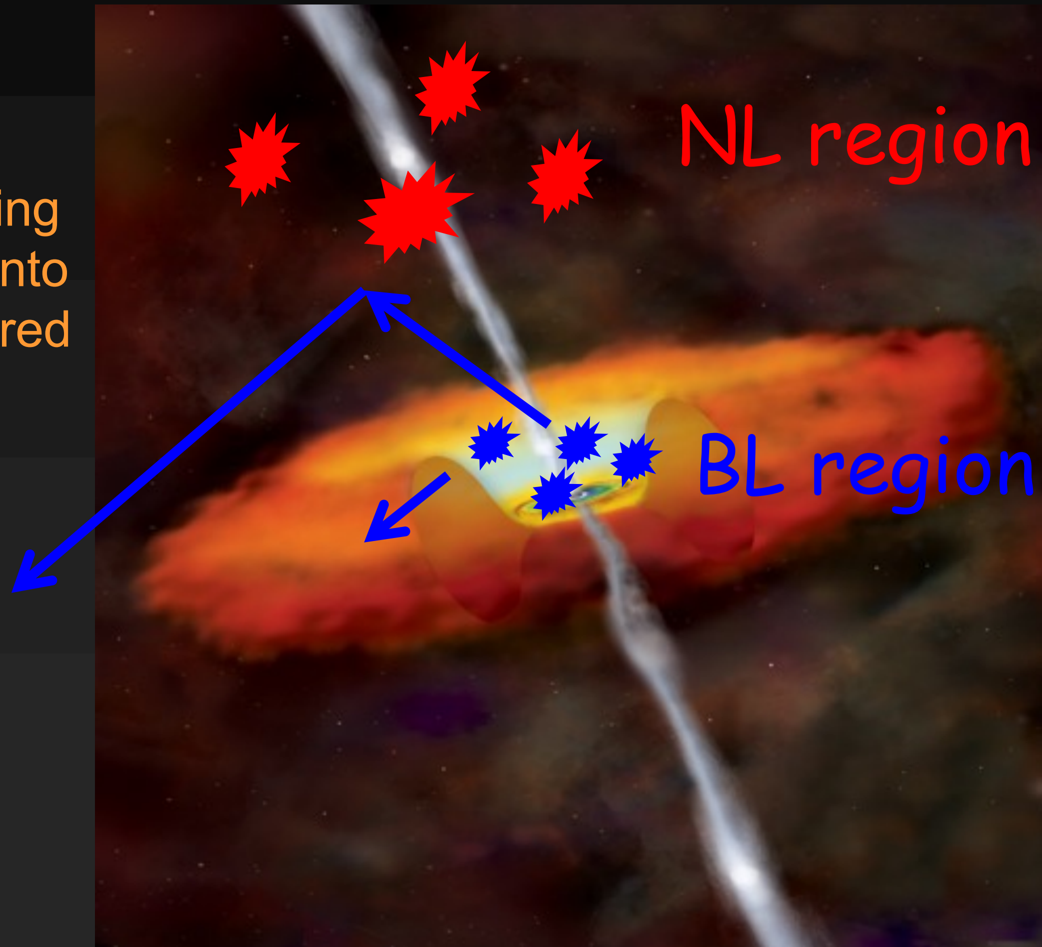

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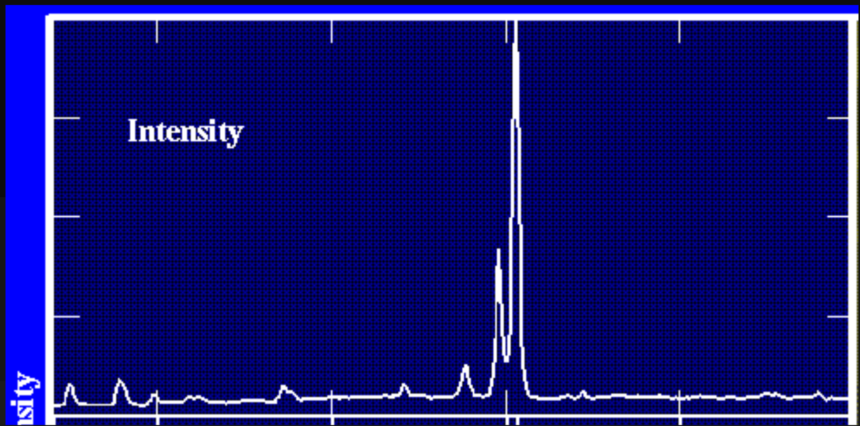

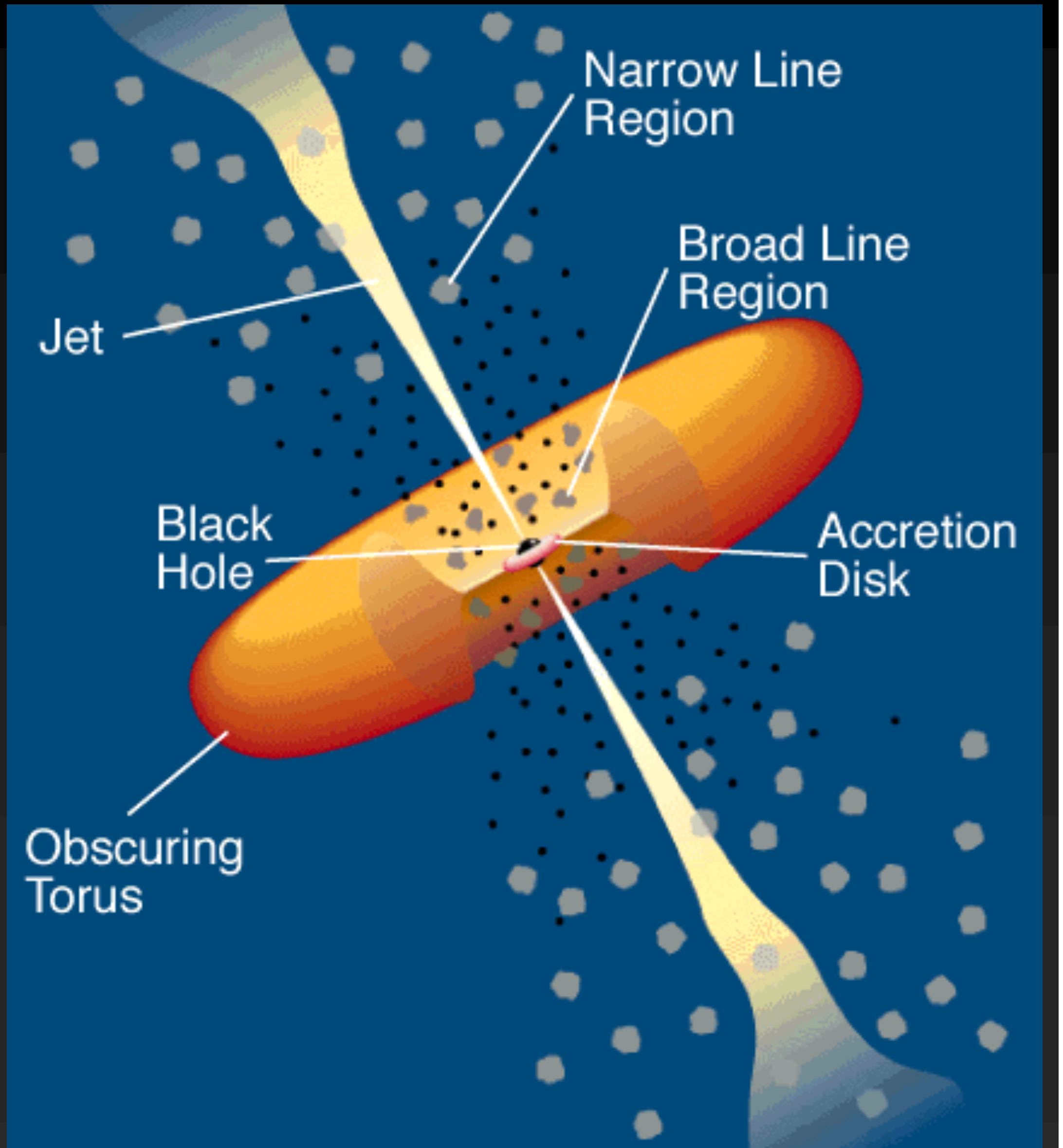

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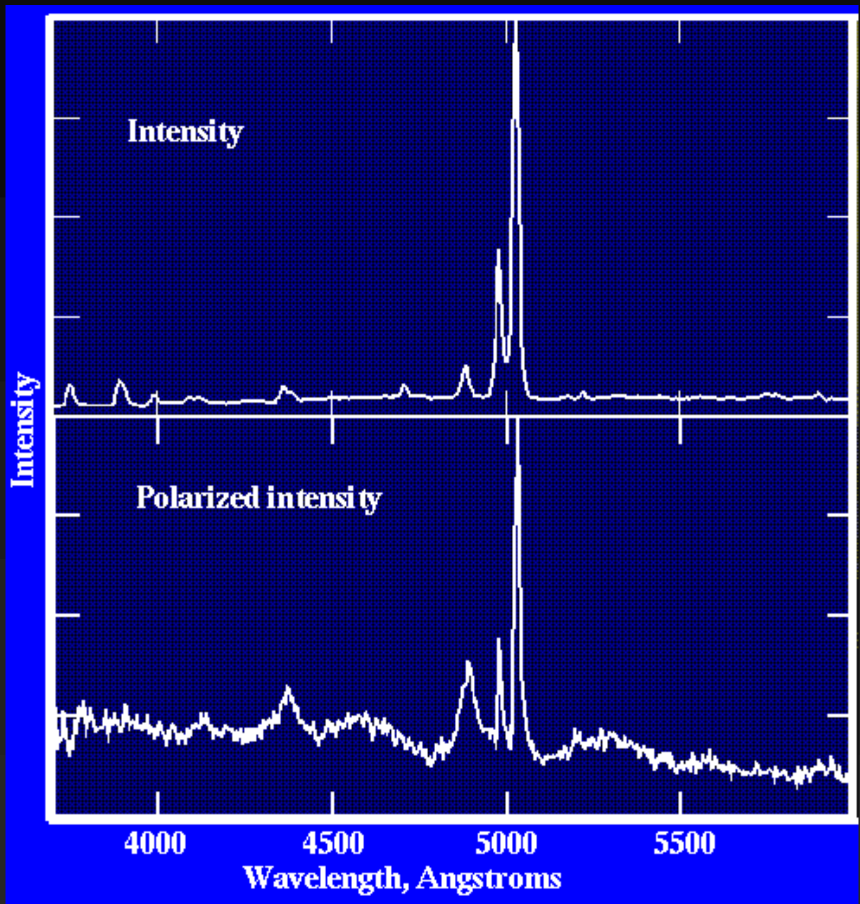

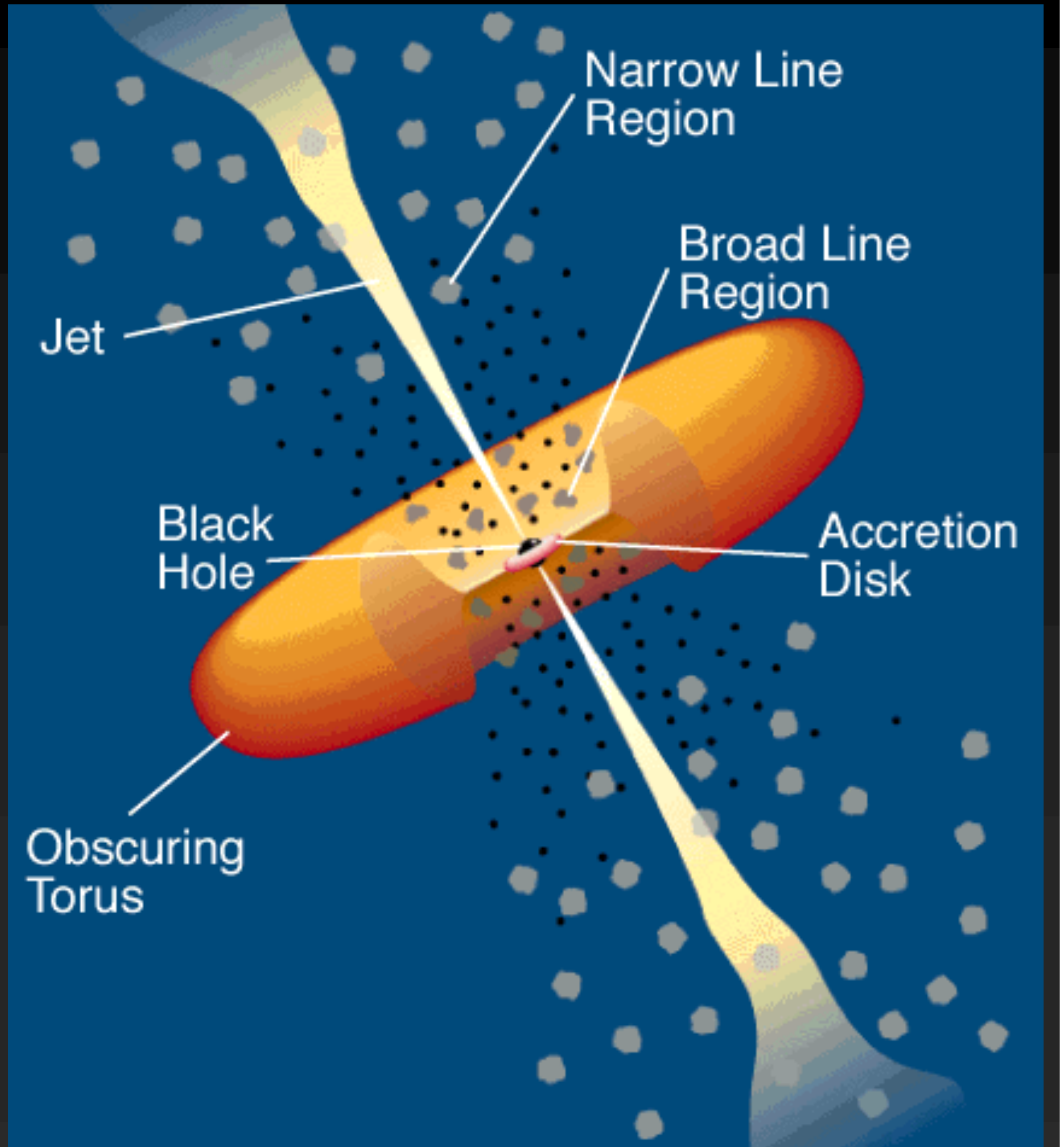

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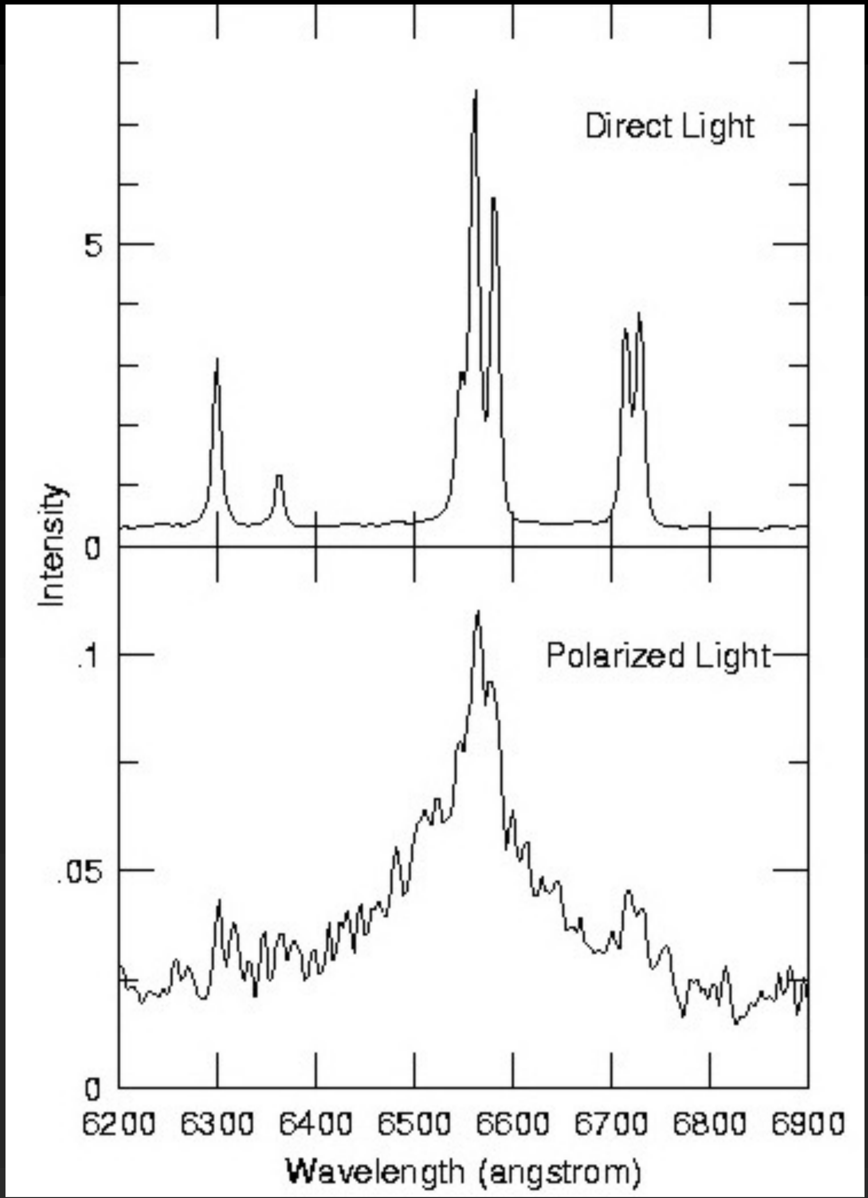
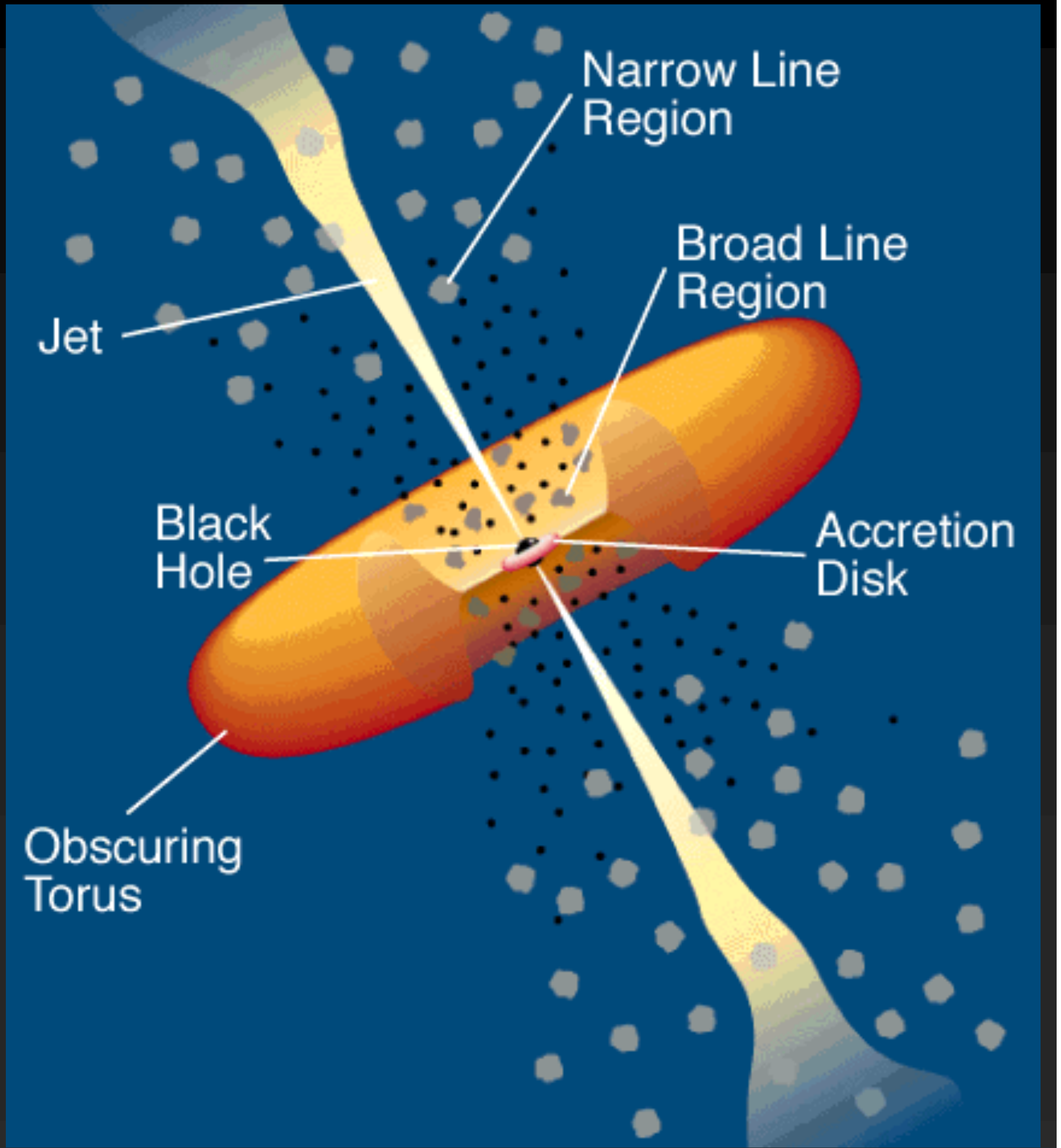
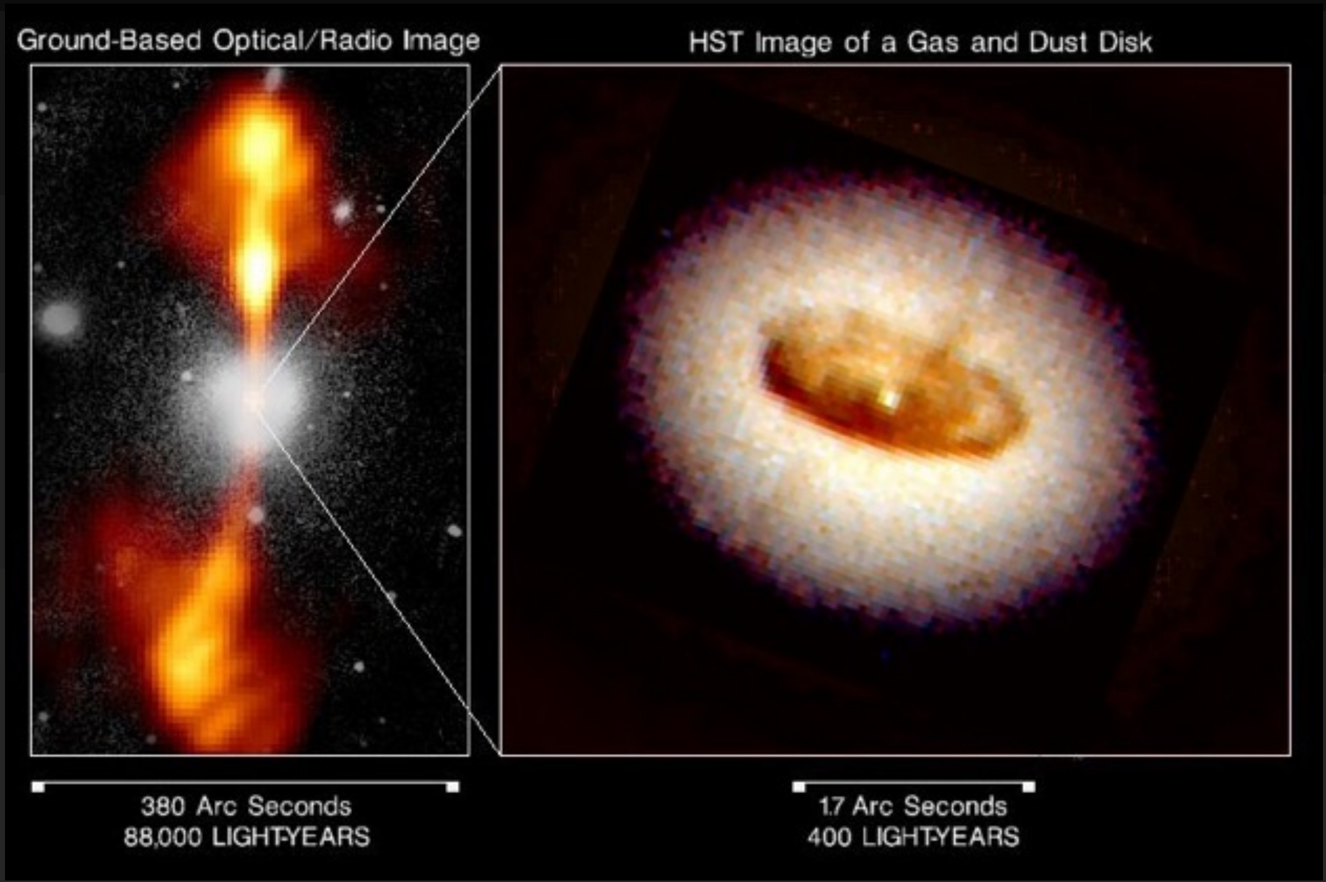




Intro to Active Galactic Nuclei

Although most of the ideas that led to the Unified model are based on spectra rather than imaging (in general we don't have enough angular resolution to detect all these features in an image), in recent years, we are starting to improve, and results seem to confirm beautifully the general idea



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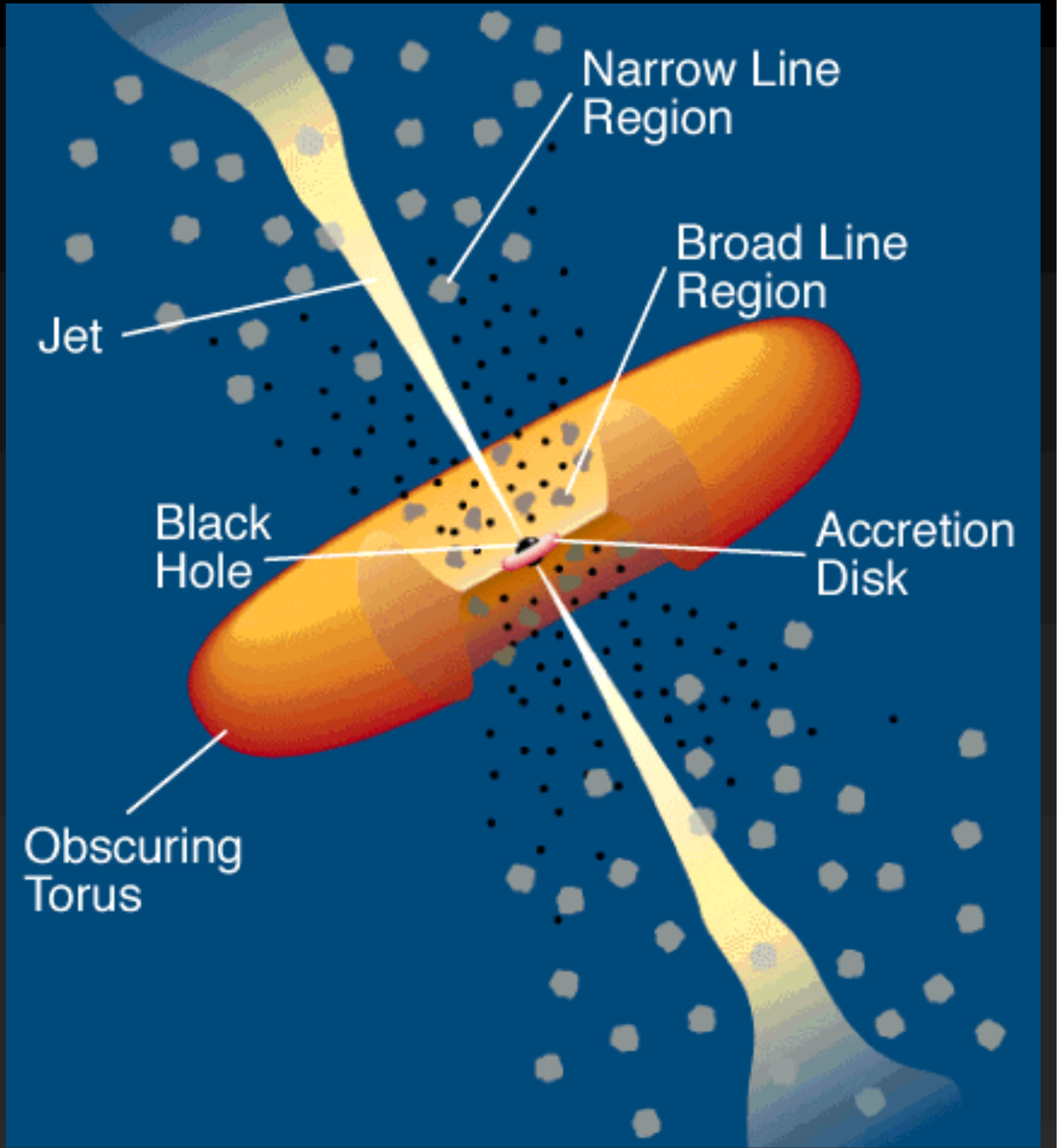

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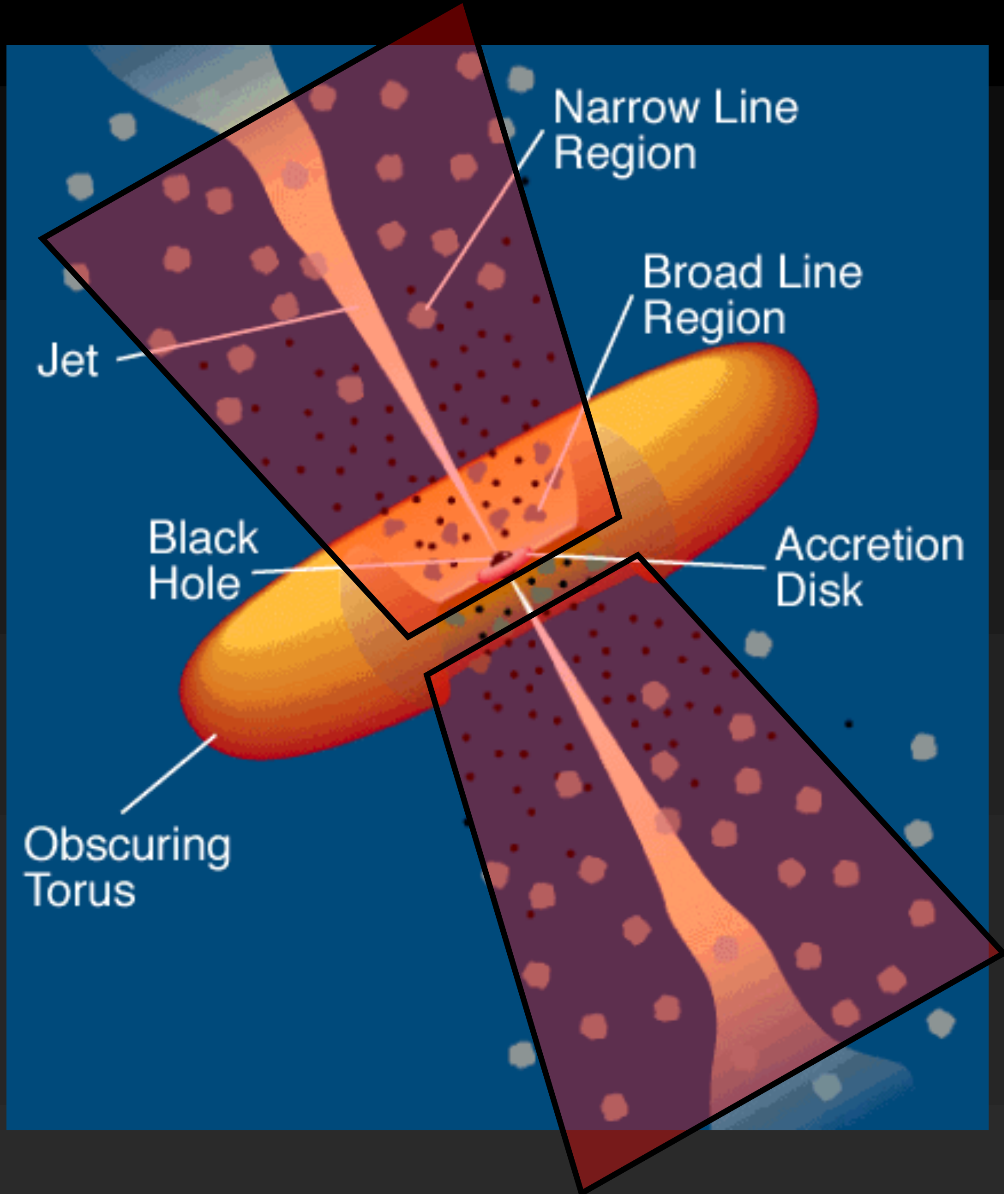

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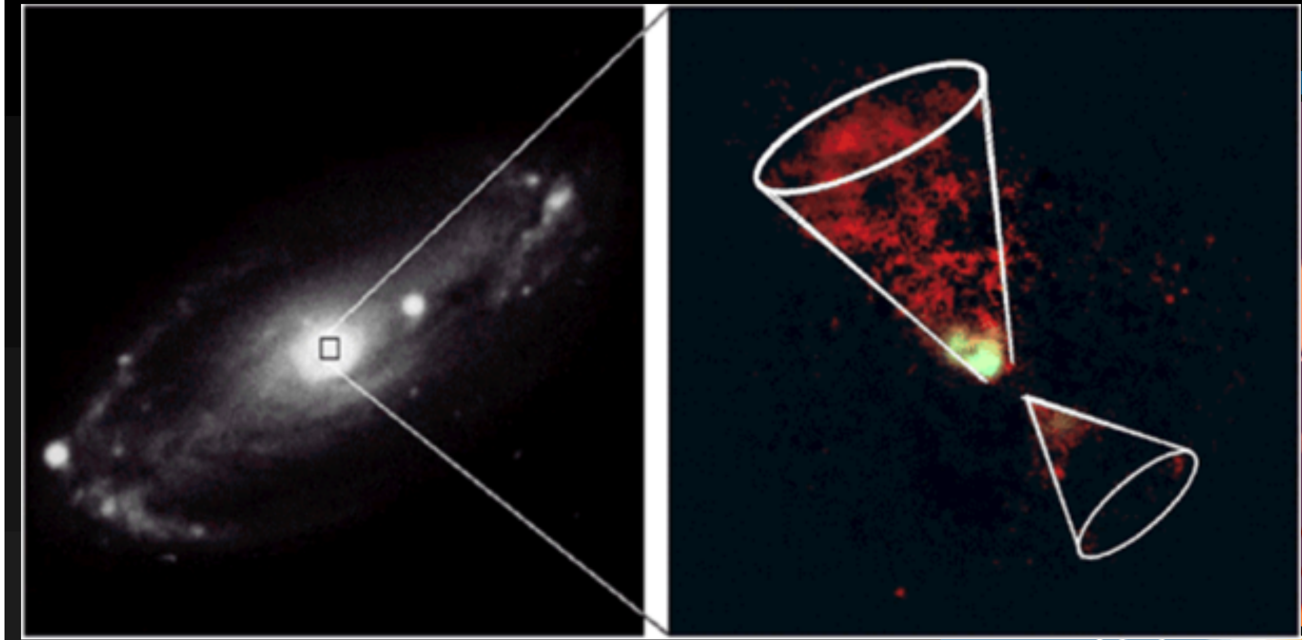

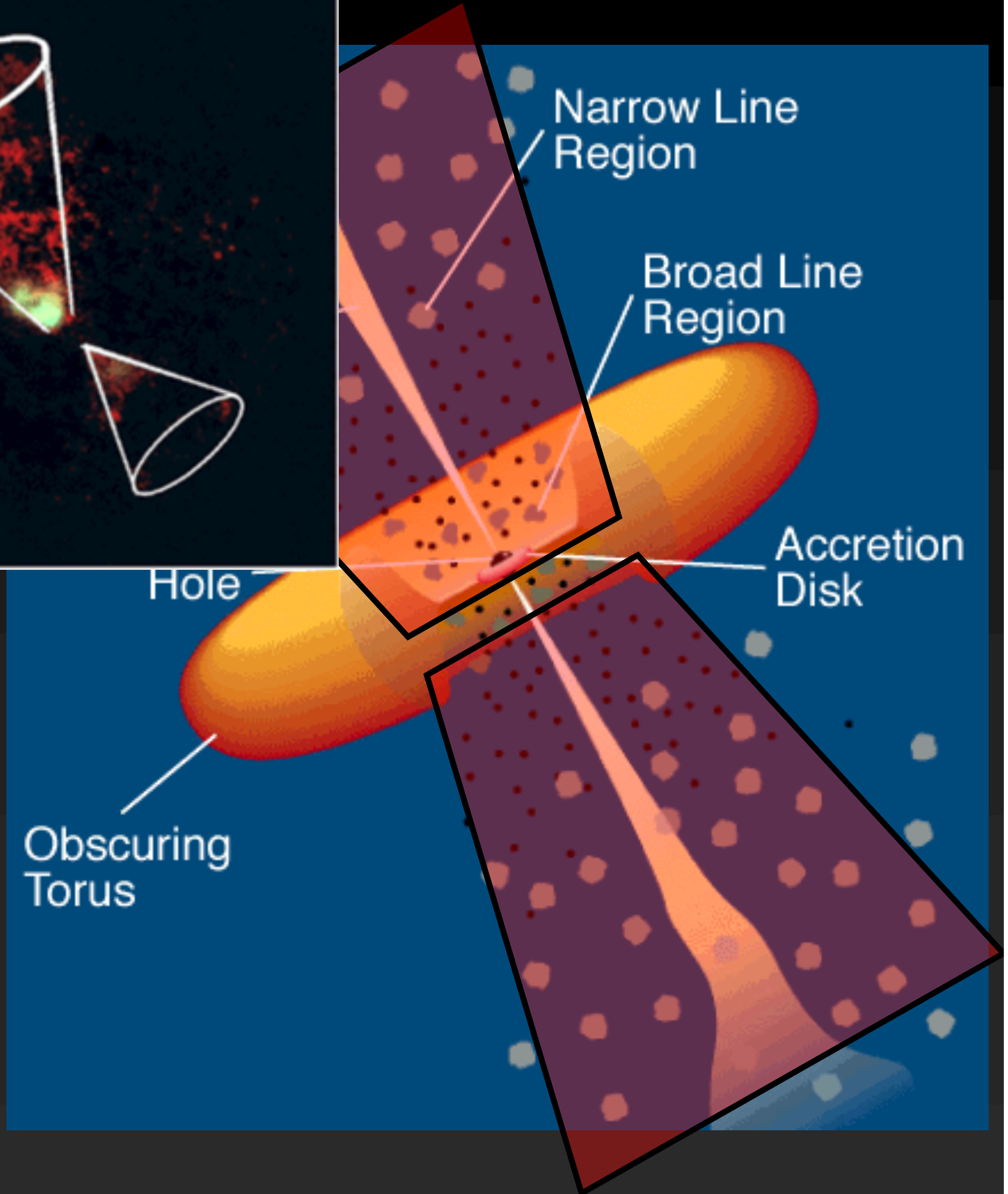

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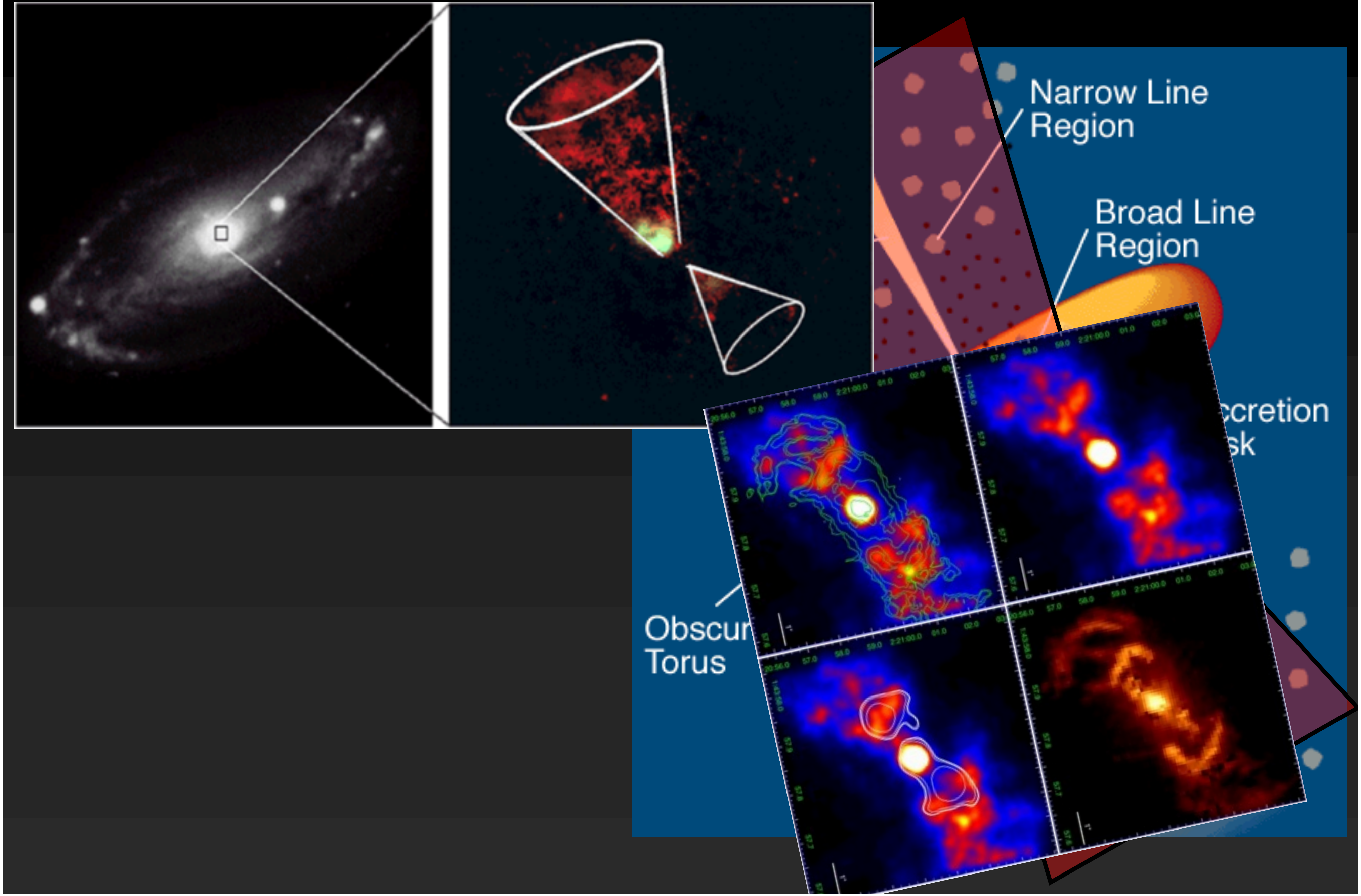

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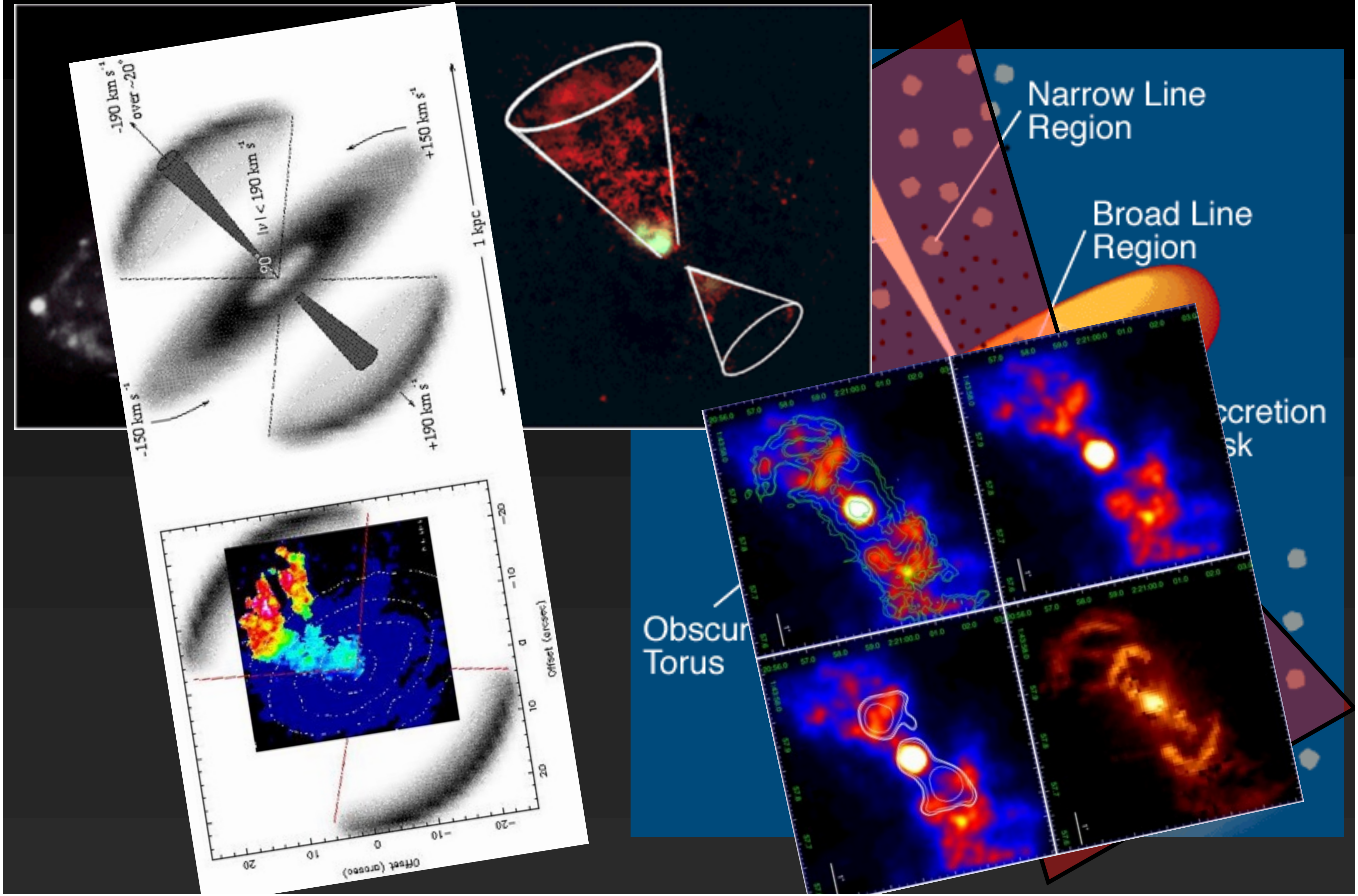

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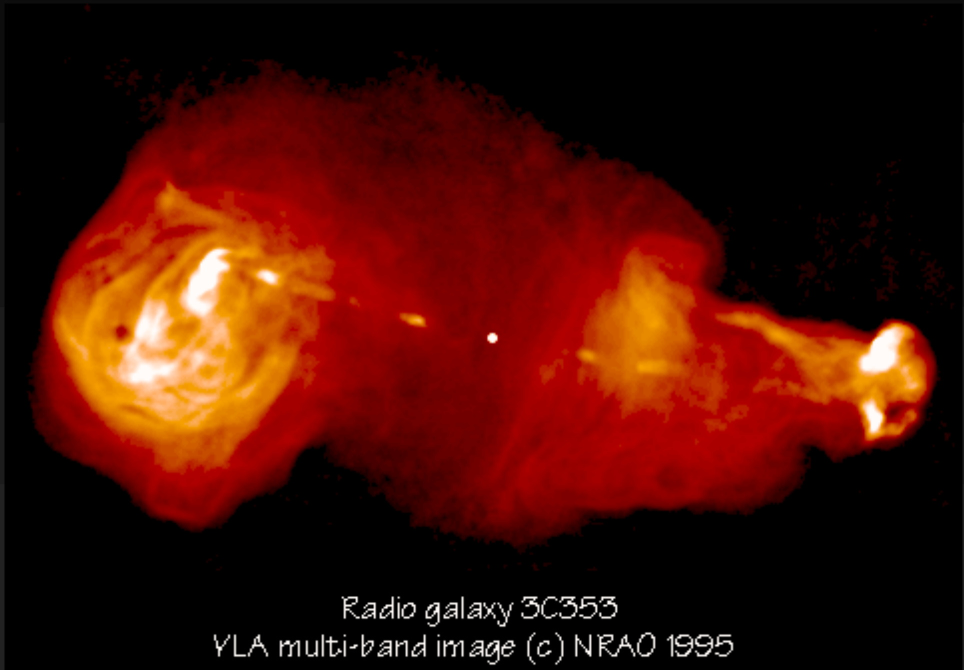
Jets and the associated radio emission (basically synchrotron = charged particles moving in B fields) are another characteristic (although of a small fraction of AGN)



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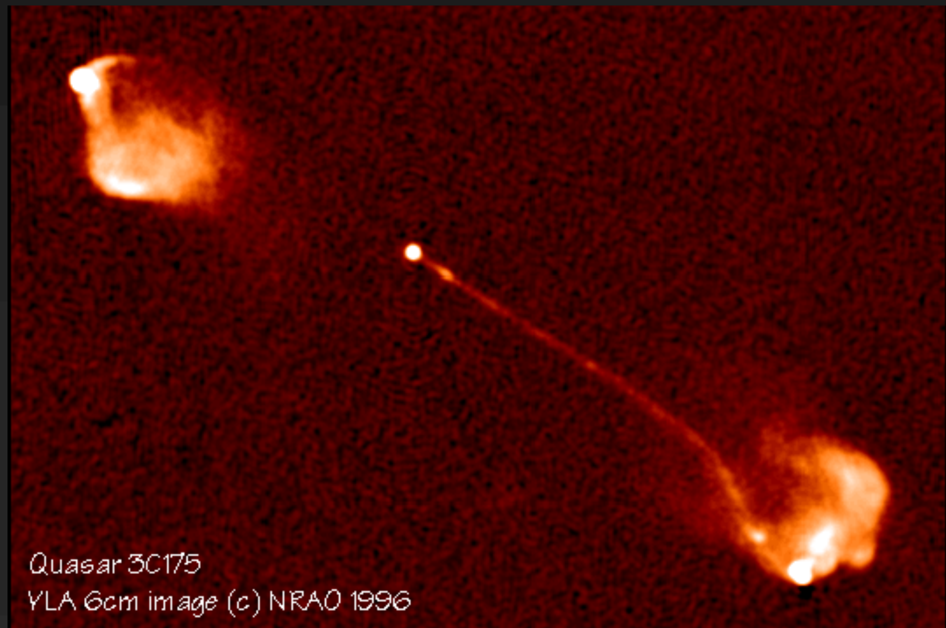

Lobes are formed when they hit the ambient medium

the jet is highly relativistic (which is why we often do not see any counter-jet)

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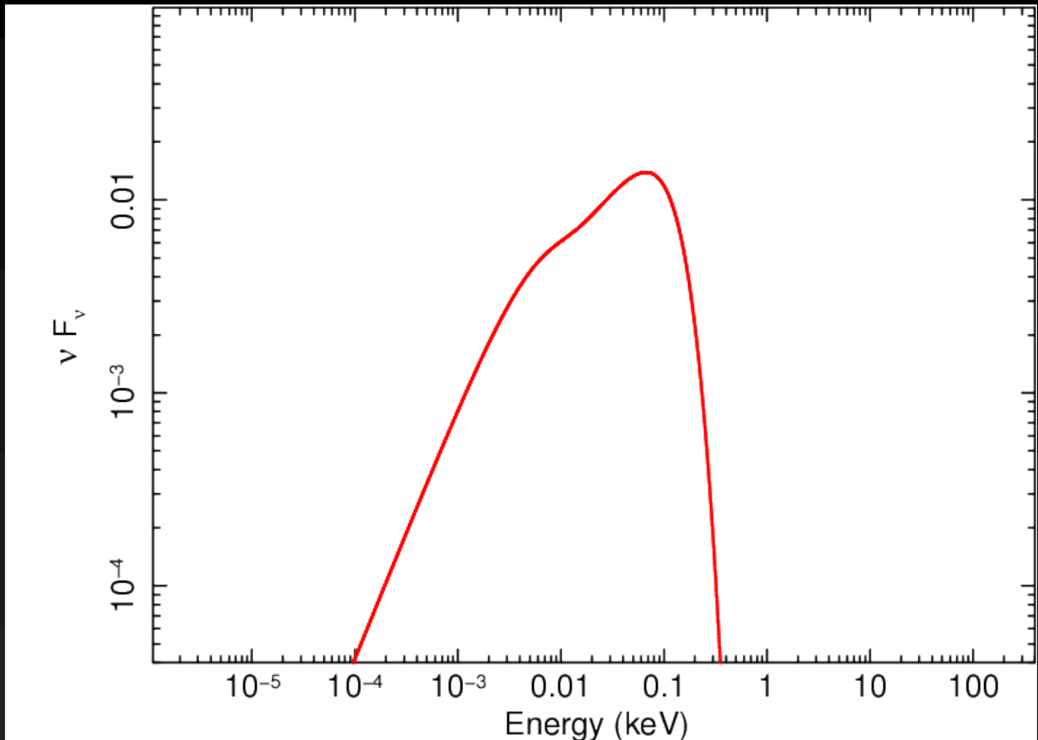

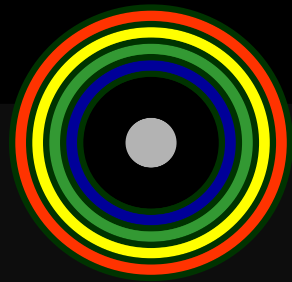

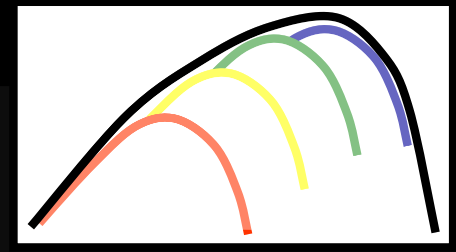

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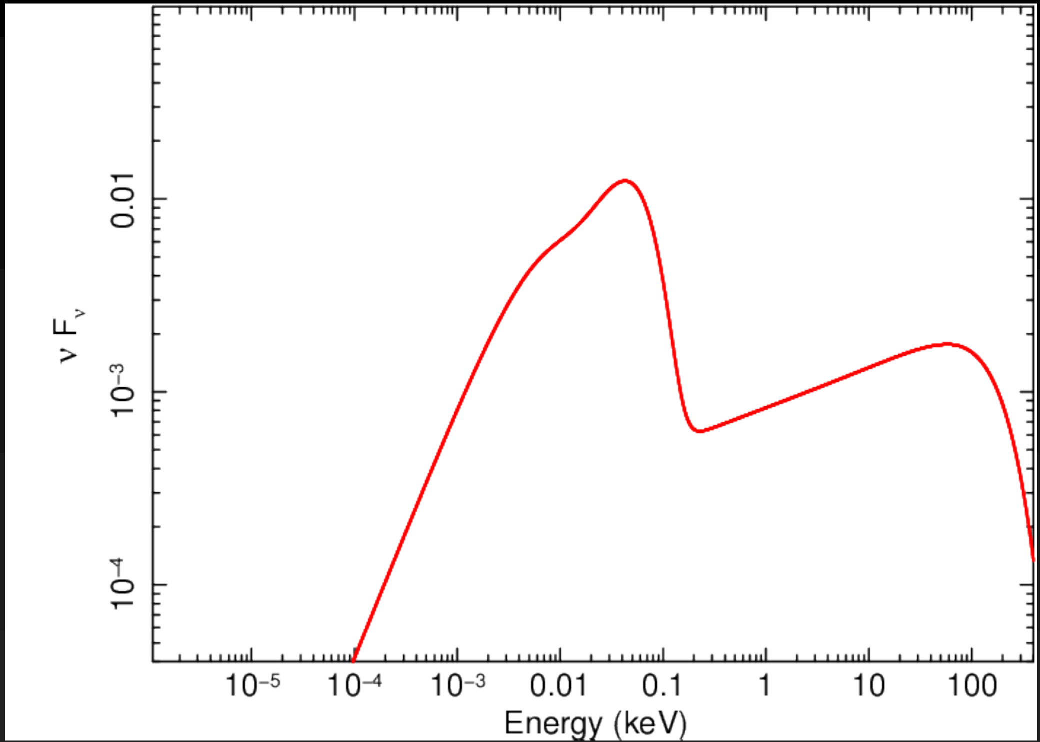

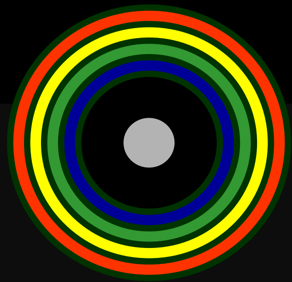

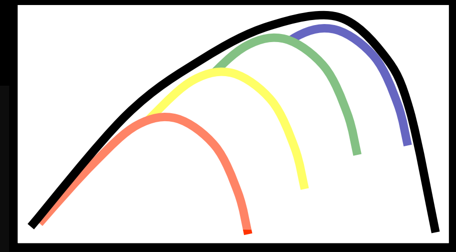

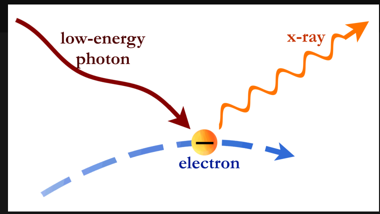

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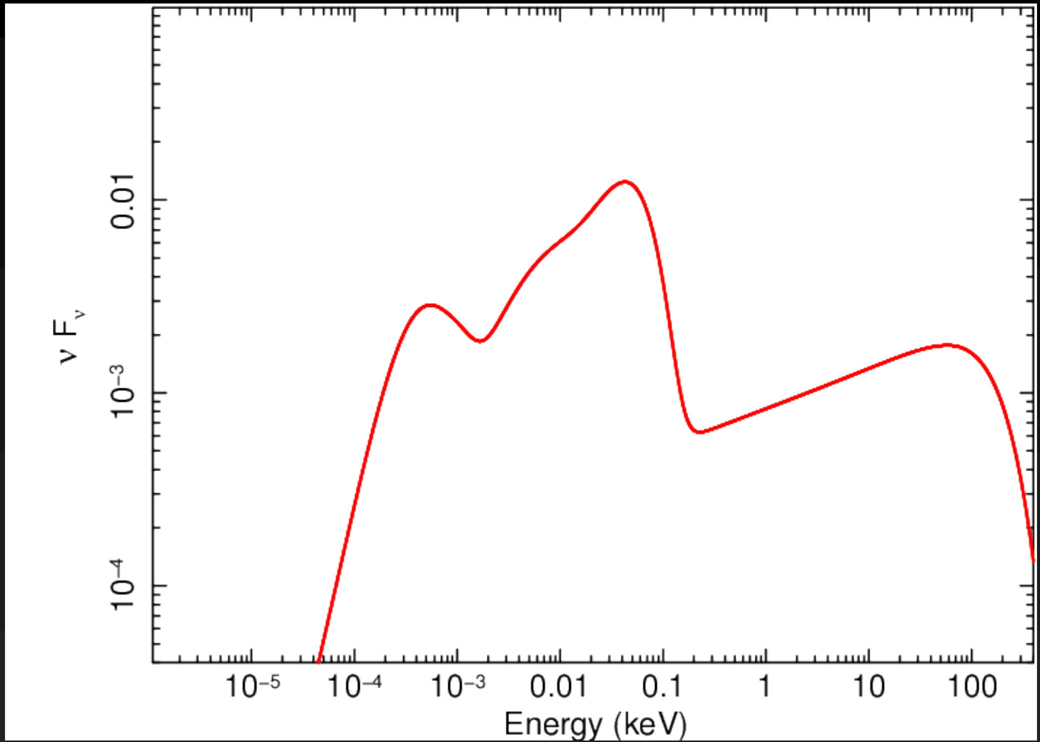

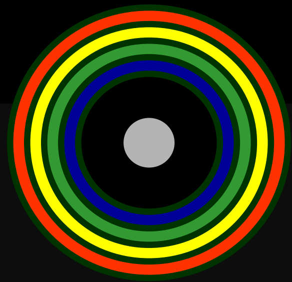

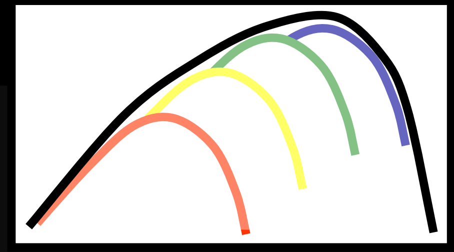

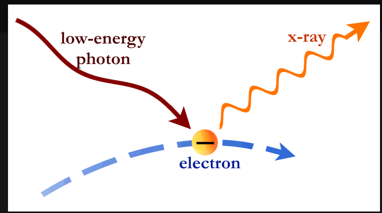

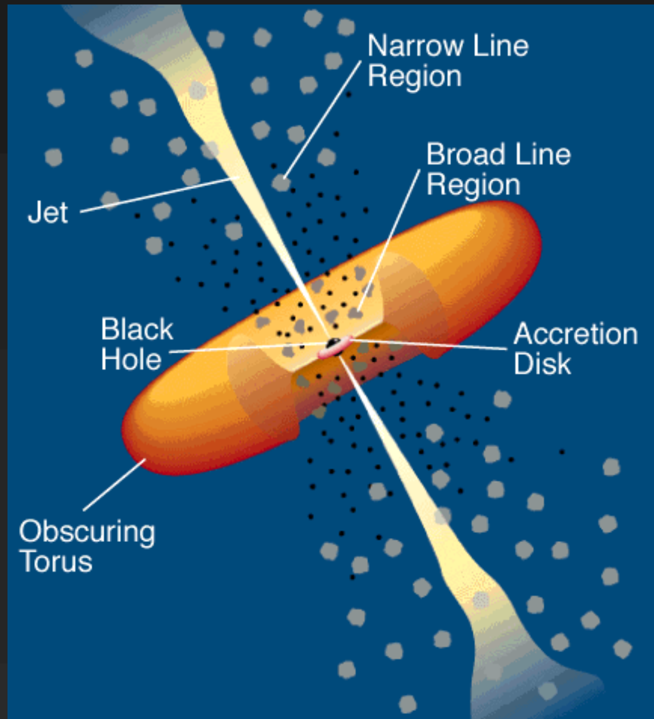

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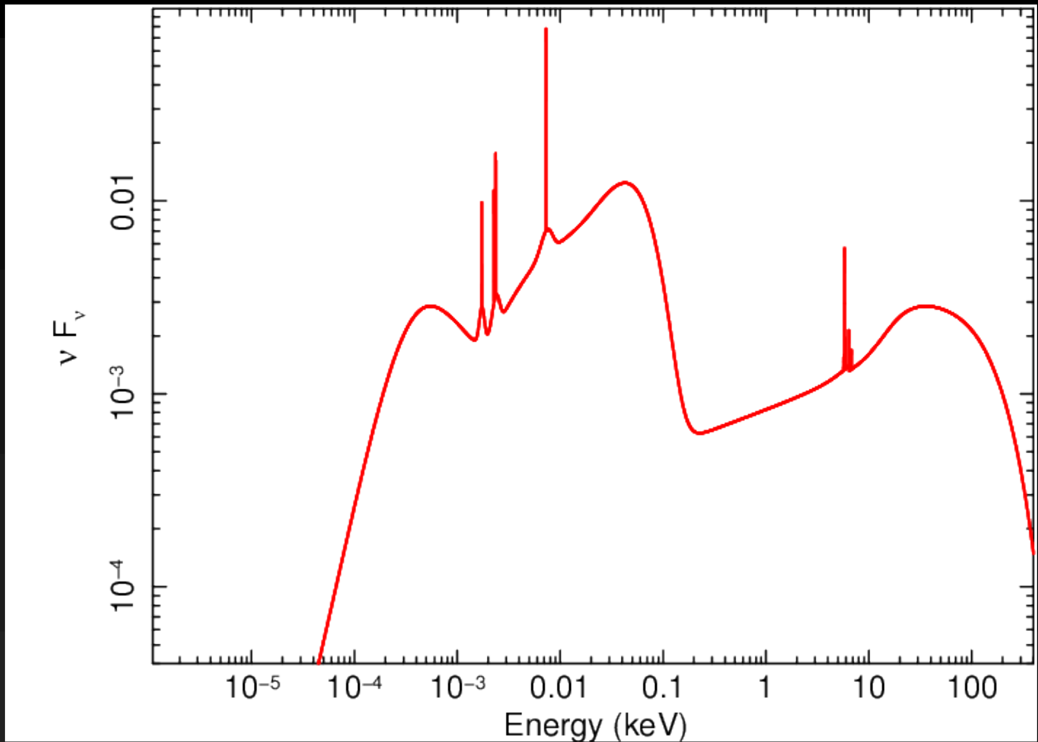

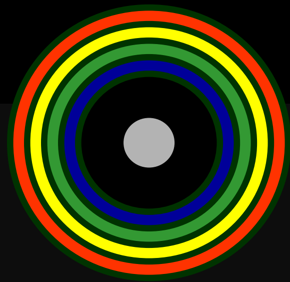

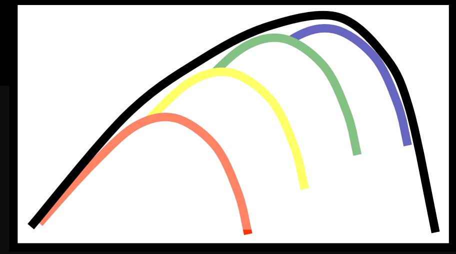

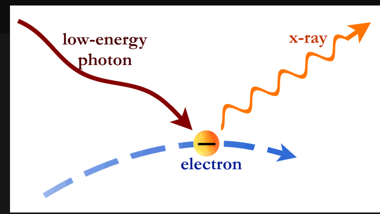

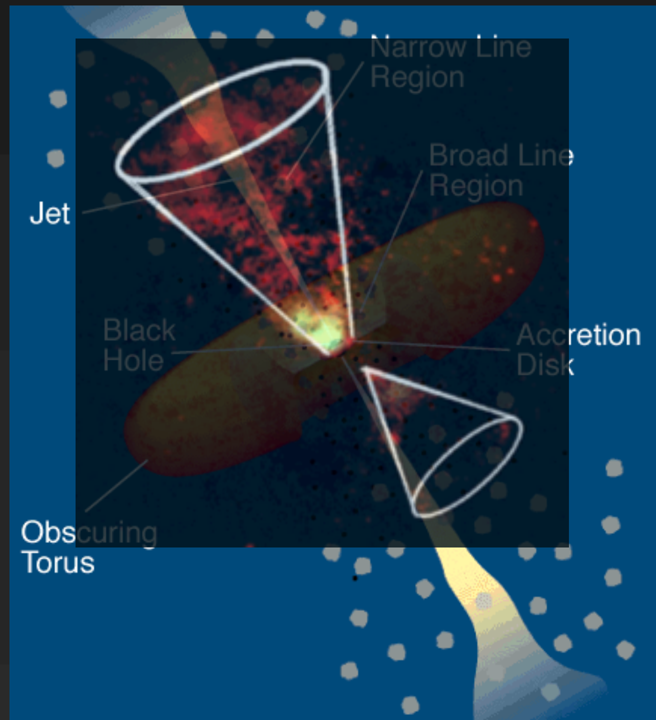

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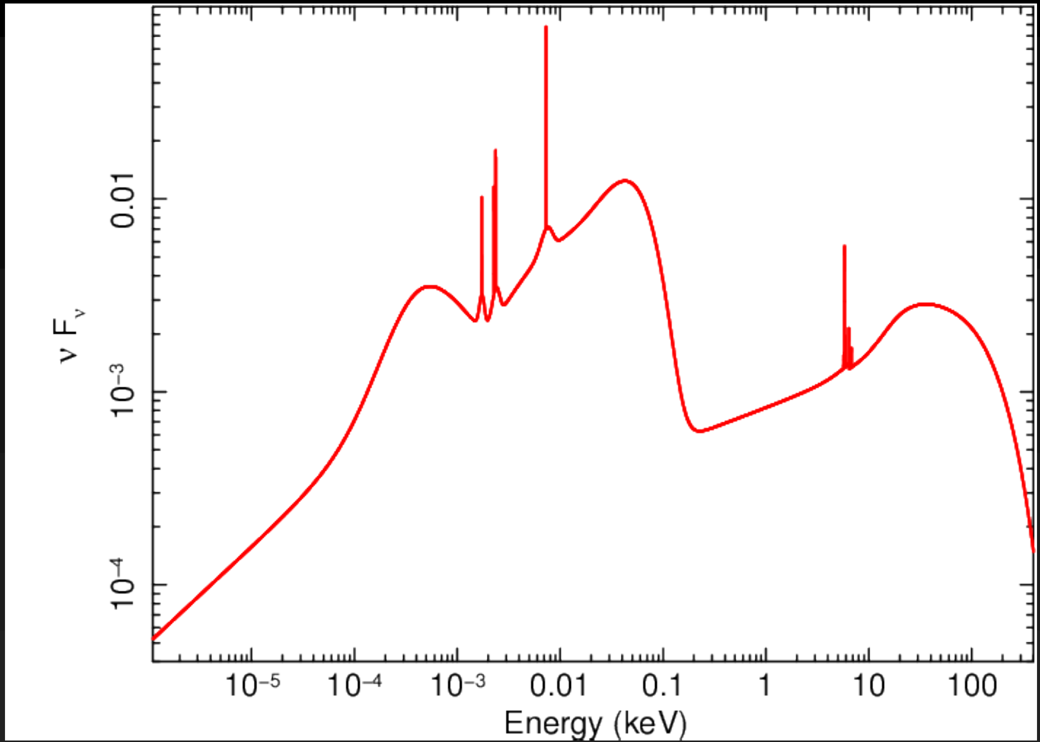

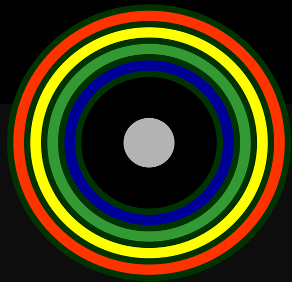

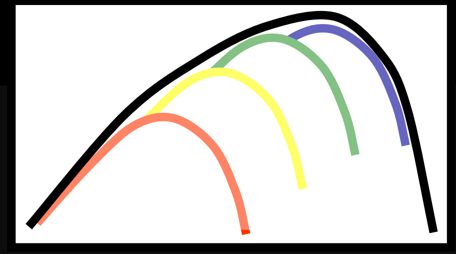

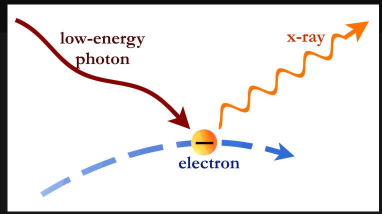

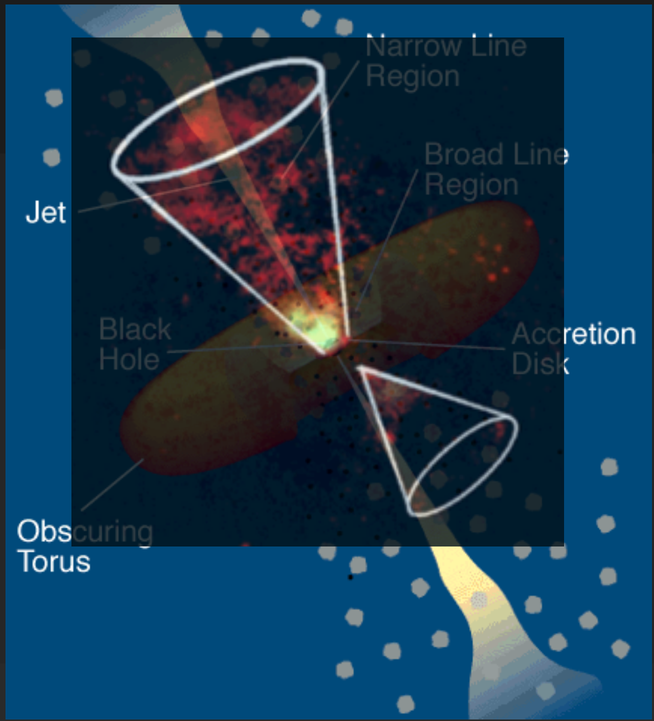

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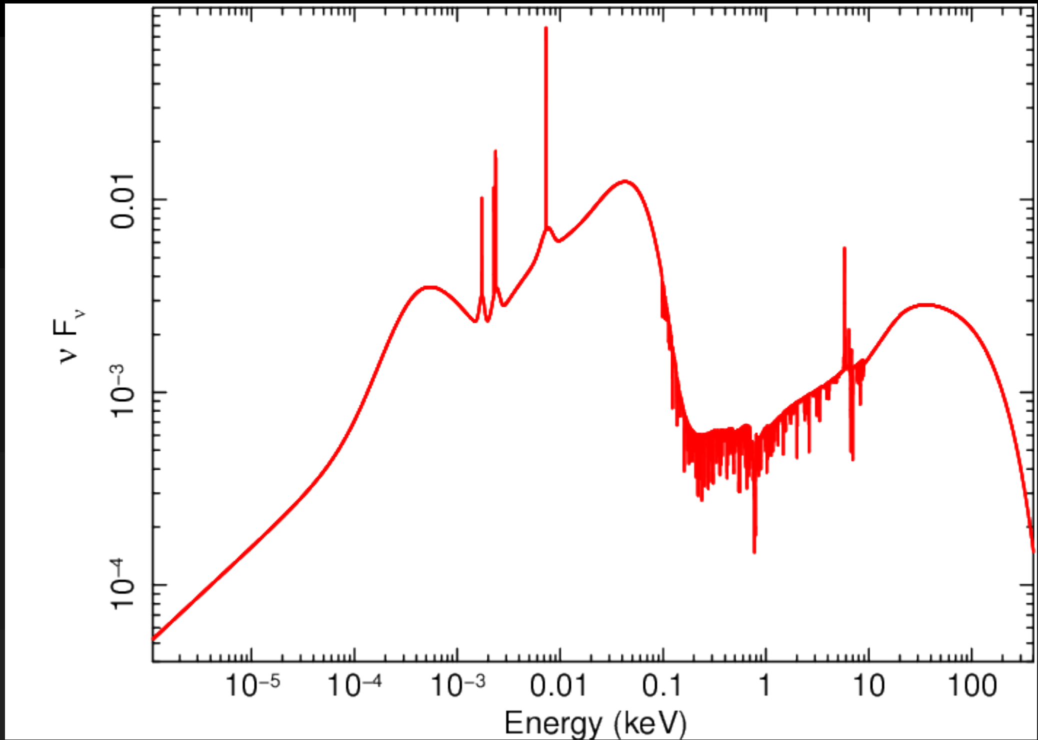
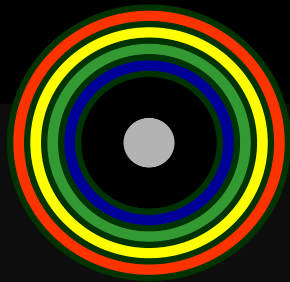
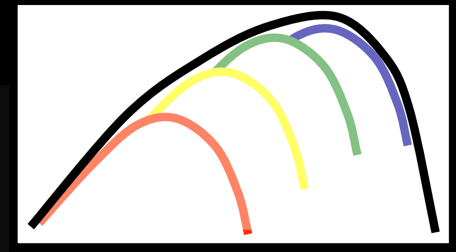
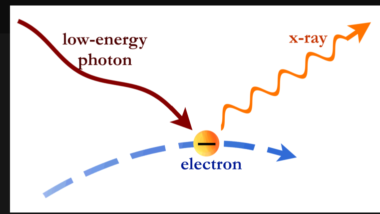
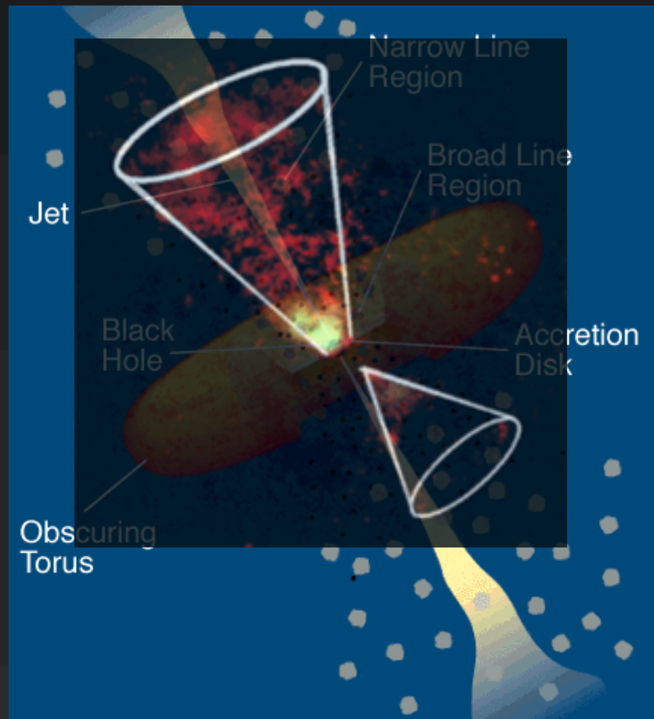






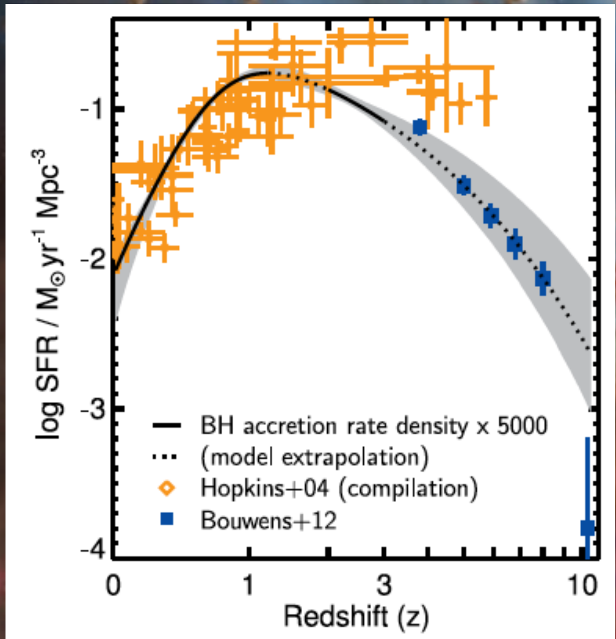




BH-GALAXY CO-EVOLUTION AND AGN FEEDBACK

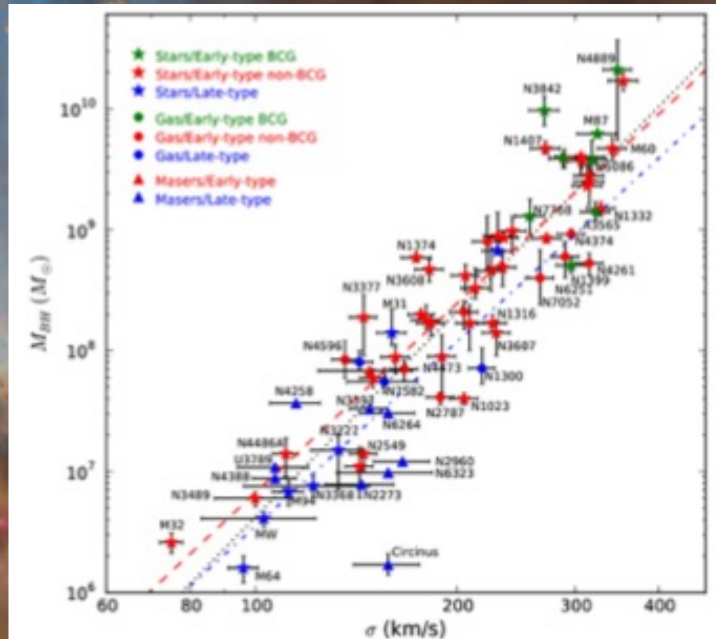
Several pieces of observational evidence call for an intimate link between the central SMBH and the host galaxy properties

Kormendy & Ho 13 (review)



SFR and BH accretion histories

Gebhard et al 00, Ferrarese & Merritt 00, Tremaine 02 ...



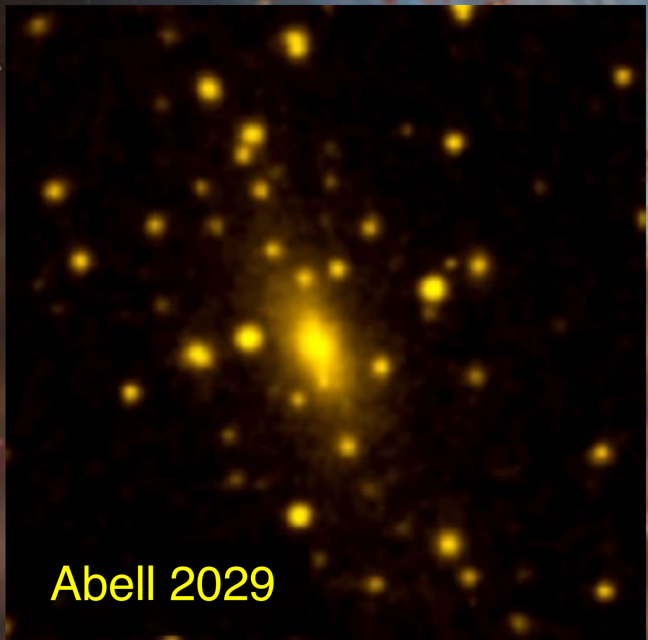
M_{BH}-σ_* (or M_{bulge}) relation

This can be understood (but lively debate) in terms of feedback between the energy release from the central BH and the gas in the host galaxy

BH-GALAXY CO-EVOLUTION AND AGN FEEDBACK

In clusters, observations have revealed that there is much less cold gas in the core than expected from simple radiative cooling models

Either something is heating the gas or the cold gas is disappearing



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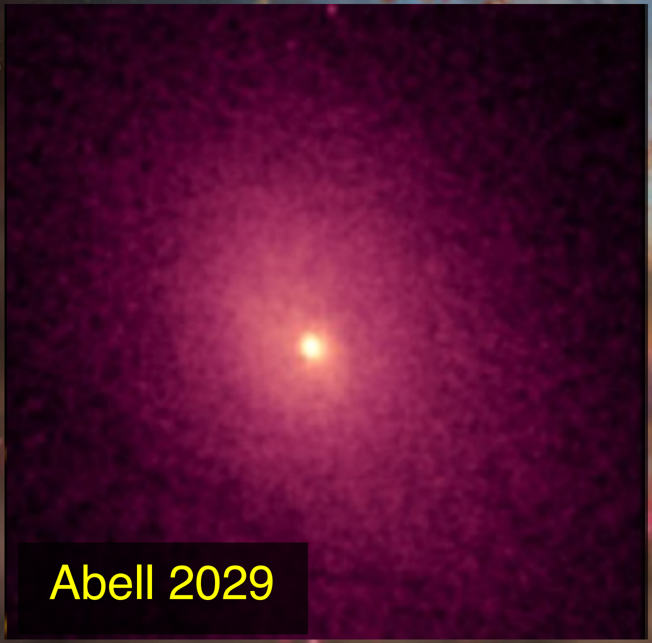
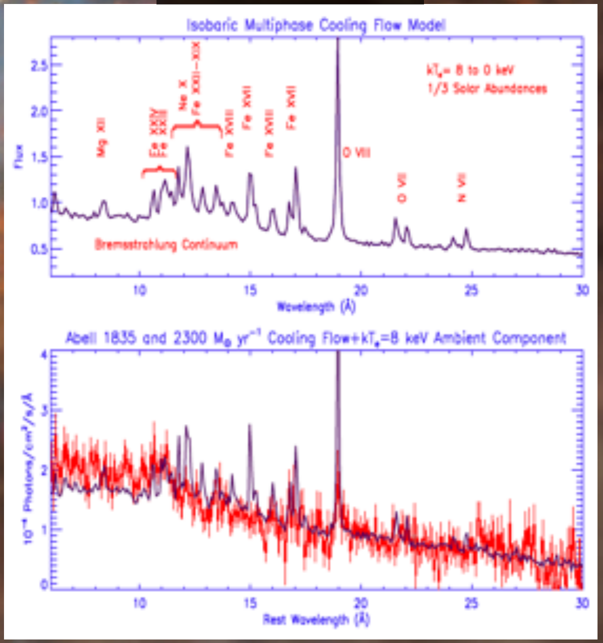


Peterson et al 03



Gas depletion and/or heating by the central AGN seems a very reasonable idea

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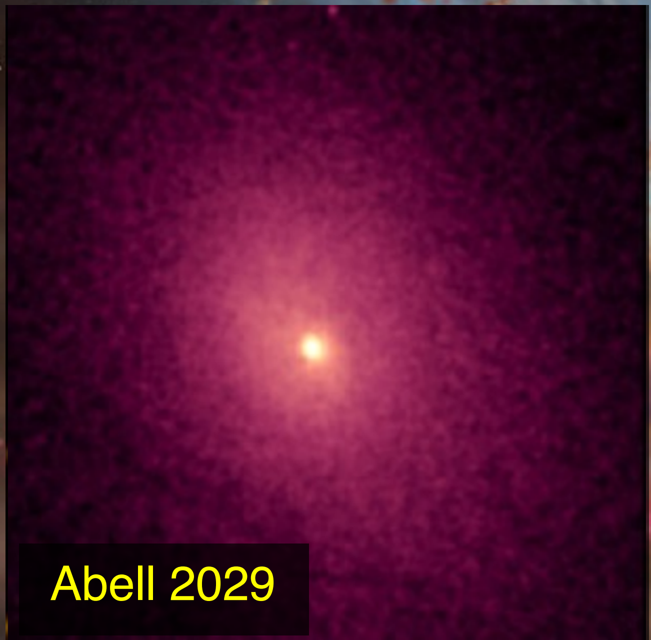
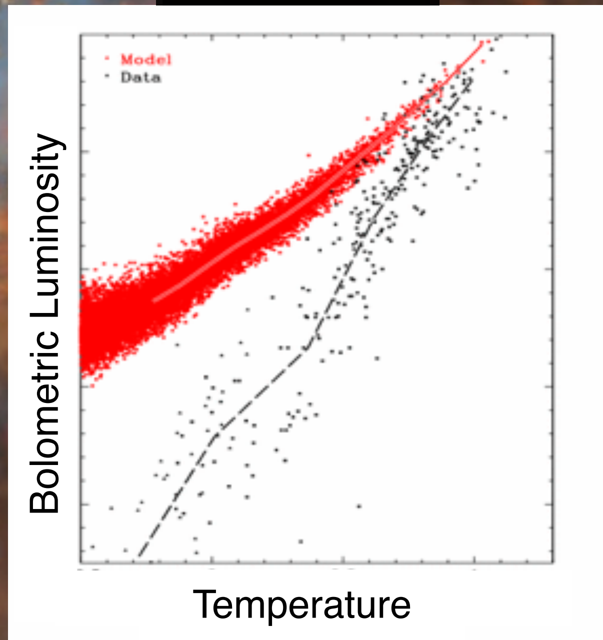
In clusters, observations have revealed that there is much less cold gas in the core than expected from simple radiative cooling models

Either something is heating the gas or the cold gas is disappearing



Bower et al 08



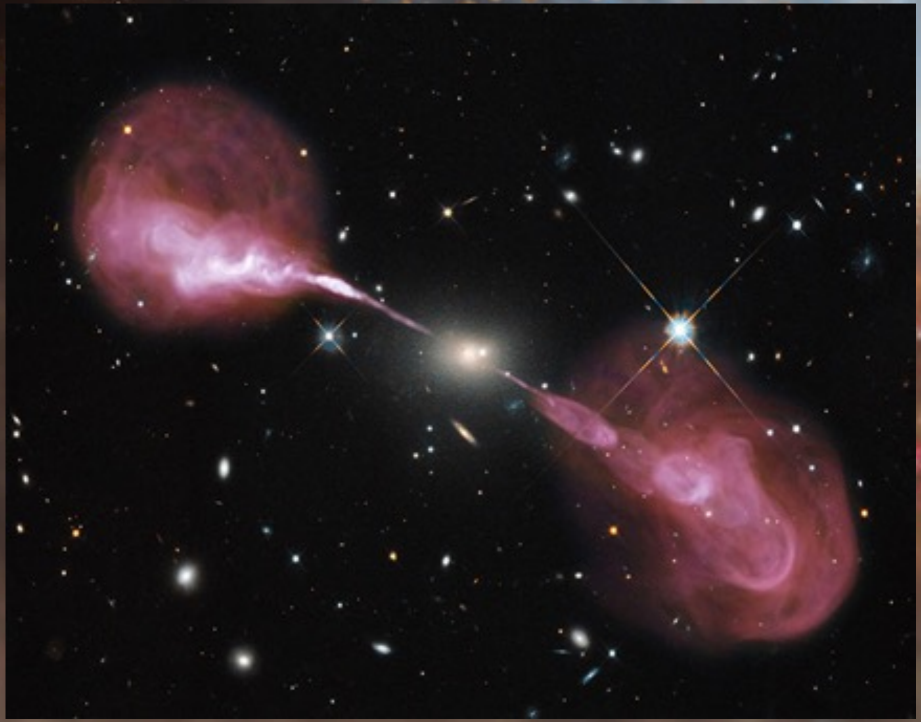
Gas depletion and/or heating by the central AGN seems a very reasonable idea

BH-GALAXY CO-EVOLUTION AND AGN FEEDBACK

Two major modes of AGN feedback are identified

KINETIC MODE: collimated relativistic jets

RADIATIVE MODE: radiation pressure, wide-angle outflows

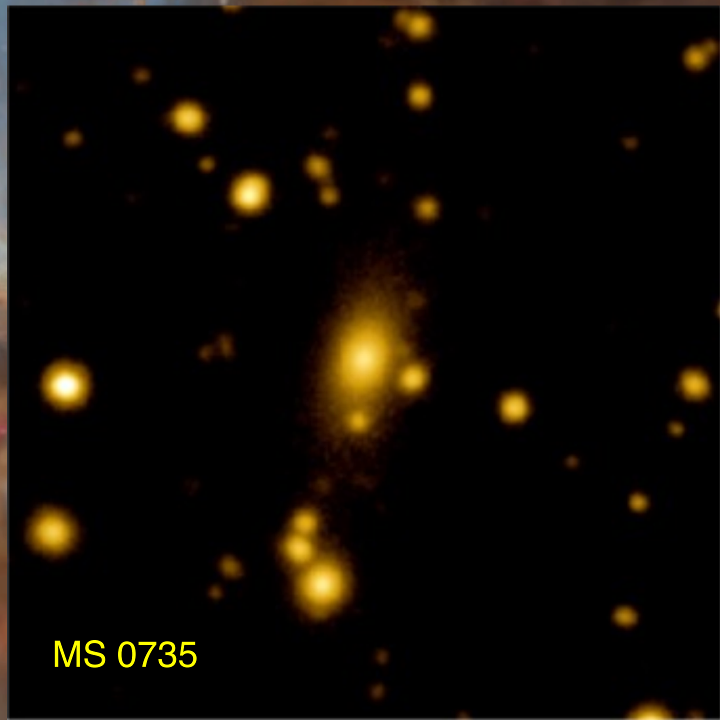


BH-GALAXY CO-EVOLUTION AND AGN FEEDBACK

AGN FEEDBACK - KINETIC MODE

Observational evidence

X-ray cavities: Strong

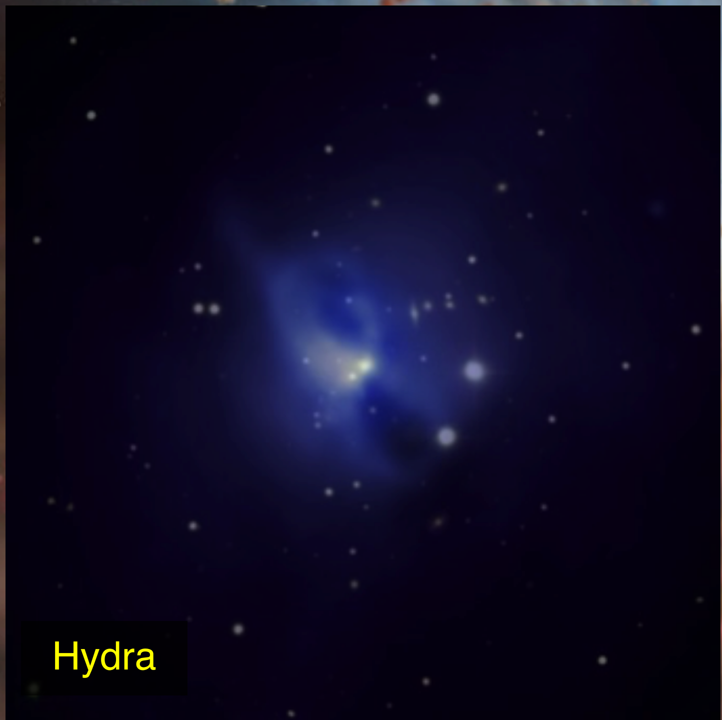


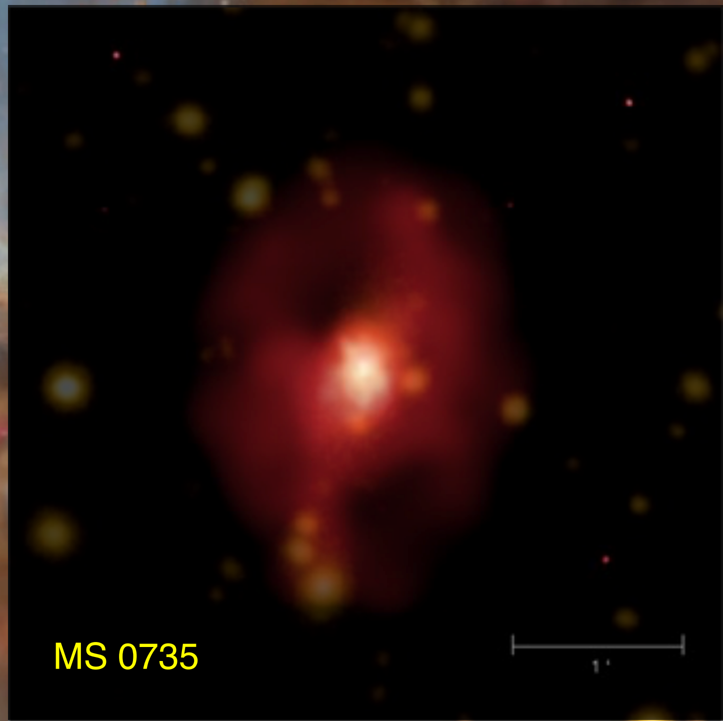
BH-GALAXY CO-EVOLUTION AND AGN FEEDBACK

AGN FEEDBACK - KINETIC MODE

Observational evidence

X-ray cavities: Strong



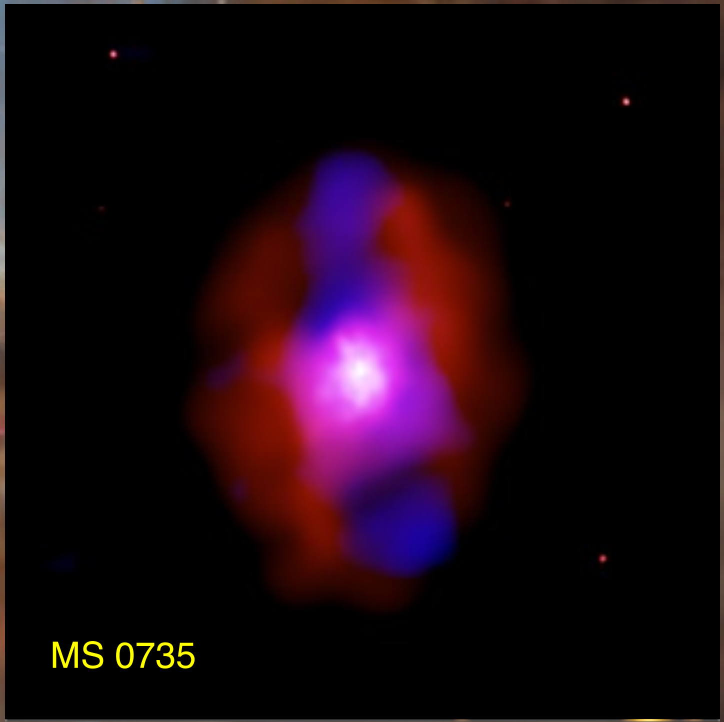


BH-GALAXY CO-EVOLUTION AND AGN FEEDBACK

AGN FEEDBACK - KINETIC MODE

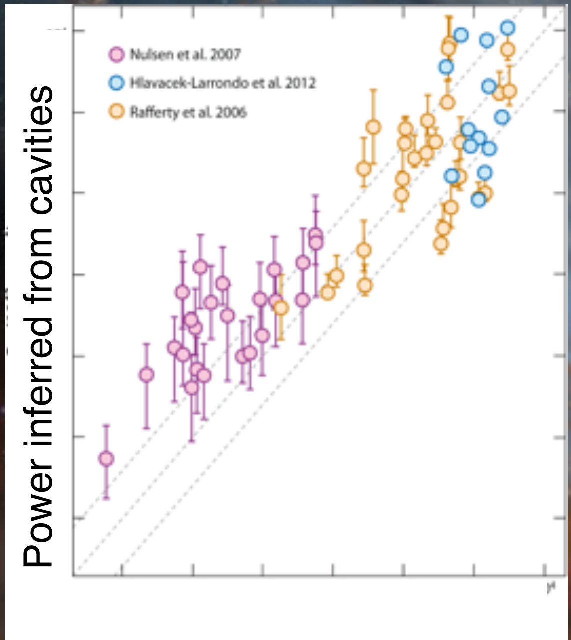
Observational evidence

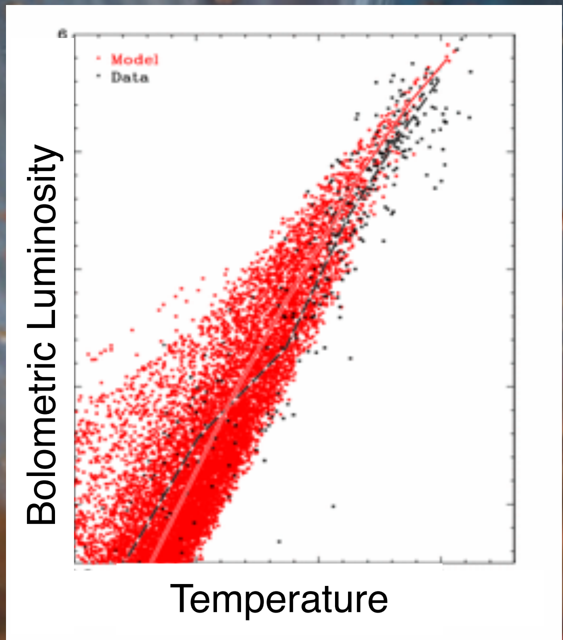
X-ray cavities: Strong

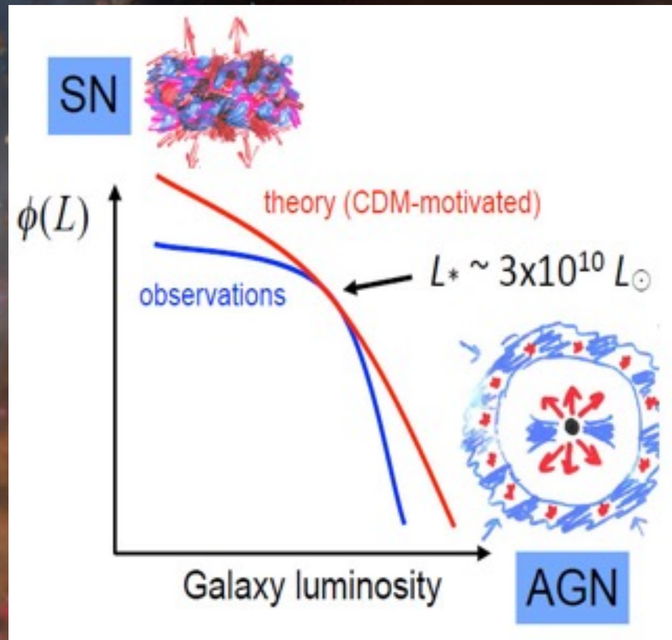


BH-GALAXY CO-EVOLUTION AND AGN FEEDBACK

AGN FEEDBACK - KINETIC MODE







AGN feedback potentially able to account for

- galaxy cluster heating and cold gas depletion
- deficit of massive elliptical in L-functions
- transition from blue star-forming to red passive

BH-GALAXY CO-EVOLUTION AND AGN FEEDBACK

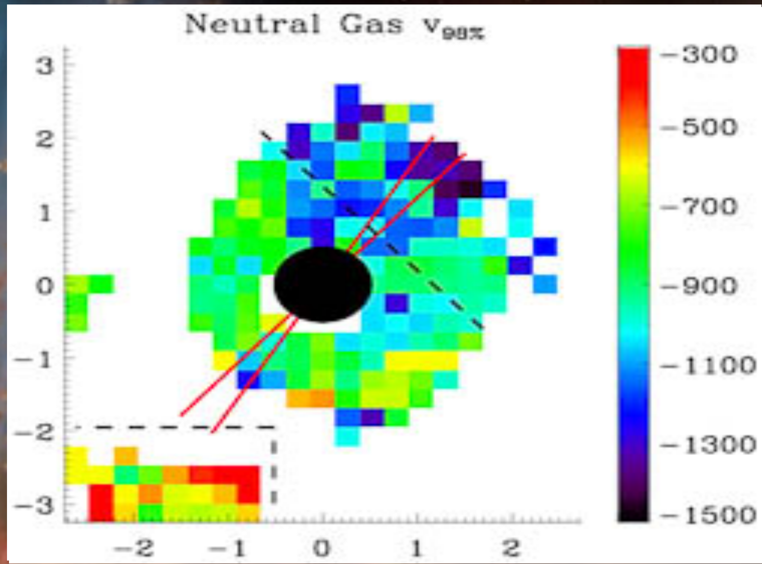
AGN FEEDBACK - RADIATIVE MODE

Observational evidence

~10^4 km/s BAL in quasars: Strong

~ 10^4-10^5 km/s X-ray UFOs: Strong

~10^3 km/s galactic-scale outflows: Strong



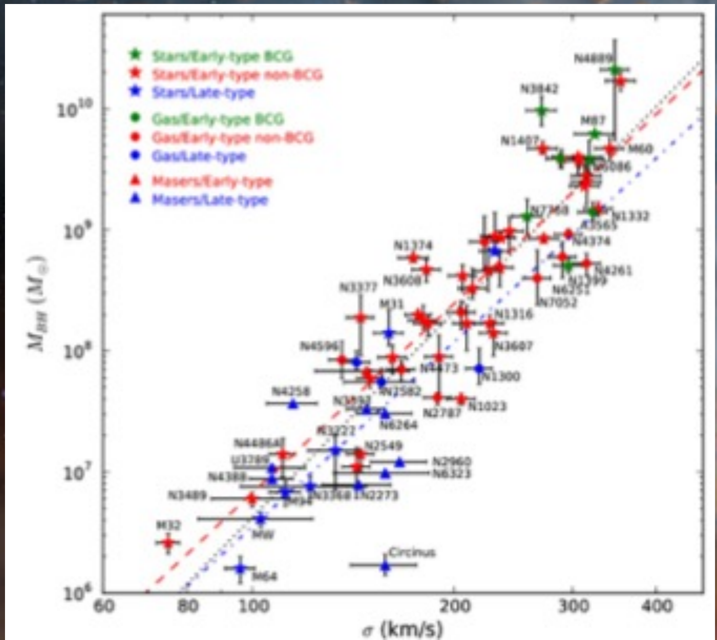
Outflows sweep out the gas from the galaxy and may prevent further growth

Balancing the outwards radiation pressure (assume Eddington limit) with the inward one due to gravity

$$\frac{4\pi G m_p M_{BH}}{\sigma_T} = \frac{G f_{gas} M_{gal}^2}{r^2} = \frac{G f_{gas}}{r^2}\left(\frac{2r\sigma^2}{G}\right)^2 \Rightarrow M_{BH} \propto \sigma^4$$

BH-GALAXY CO-EVOLUTION AND AGN FEEDBACK

AGN FEEDBACK - RADIATIVE MODE



simple prediction

$$M_{BH} \propto \sigma^4$$

and the observed M_{BH}-σ relation

$$M_{BH} = \left(0.31^{+0.04}_{-0.03}\right) \times \sigma^{4.4 \pm 0.3}$$

However, AGN radiating locally at their Eddington limit are far below Eddington when the mass of the galaxy is included → the interaction must be very strong

→ outflow generated close to the BH and pushing the gas out on galactic scales

→ dust-rich medium (much higher cross section to radiation pressure ~ x 500)

BH-GALAXY CO-EVOLUTION AND AGN FEEDBACK

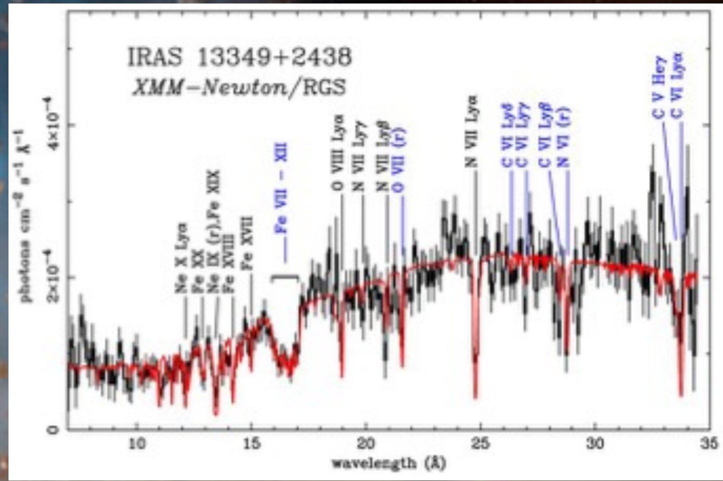
AGN FEEDBACK - RADIATIVE MODE

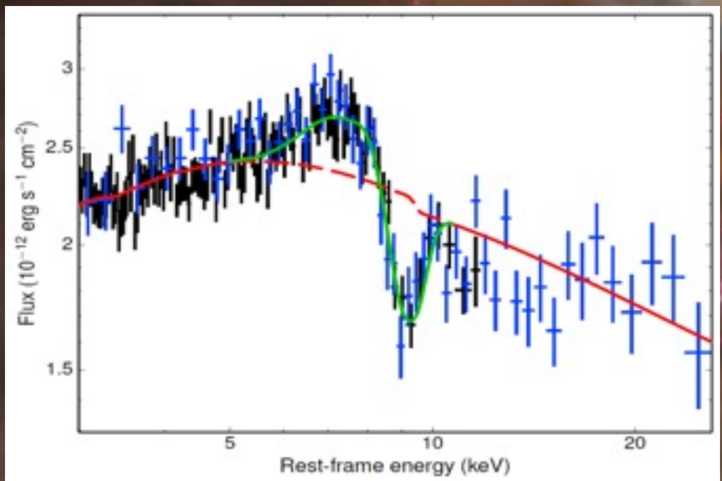
Astrophysics of AGN X-ray outflows

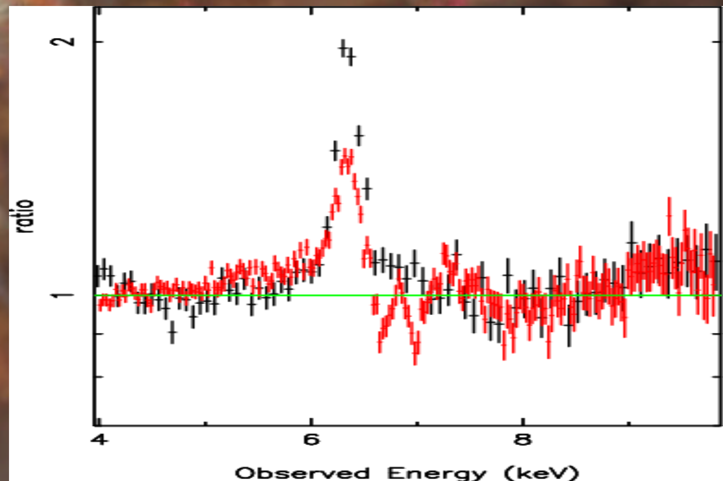
AGN warm absorbers

Fe xxv and xxvi outflows

Ultra Fast Outflows (UFOs)





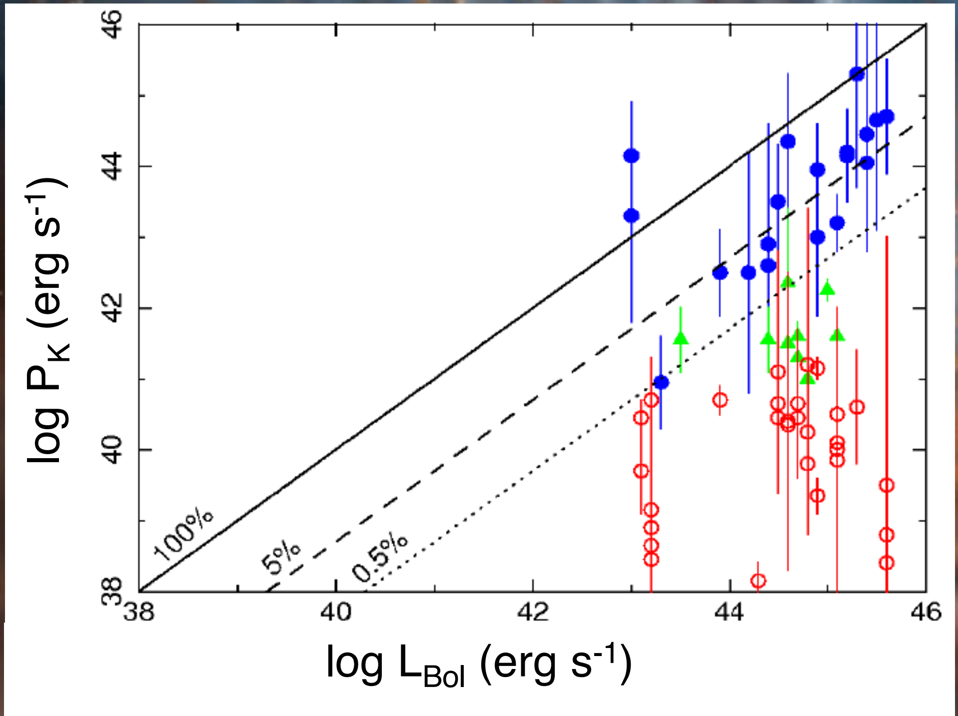


What about their kinetic output ? Is this sufficient to shape the M_{BH}-σ relation ?

BH-GALAXY CO-EVOLUTION AND AGN FEEDBACK

AGN FEEDBACK - RADIATIVE MODE

Astrophysics of AGN X-ray outflows



Ultra Fast Outflows (UFOs)

Fe xxv and xxvi outflows

AGN warm absorbers

Detailed numerical simulation imply that if P_K / L_{Bol} ~ 0.5-5 % AGN feedback is adequate to quench cooling flows and sweep gas out of the galaxy

AGN FEEDBACK

AGN jets (kinetic feedback)

HST optical

AGN FEEDBACK

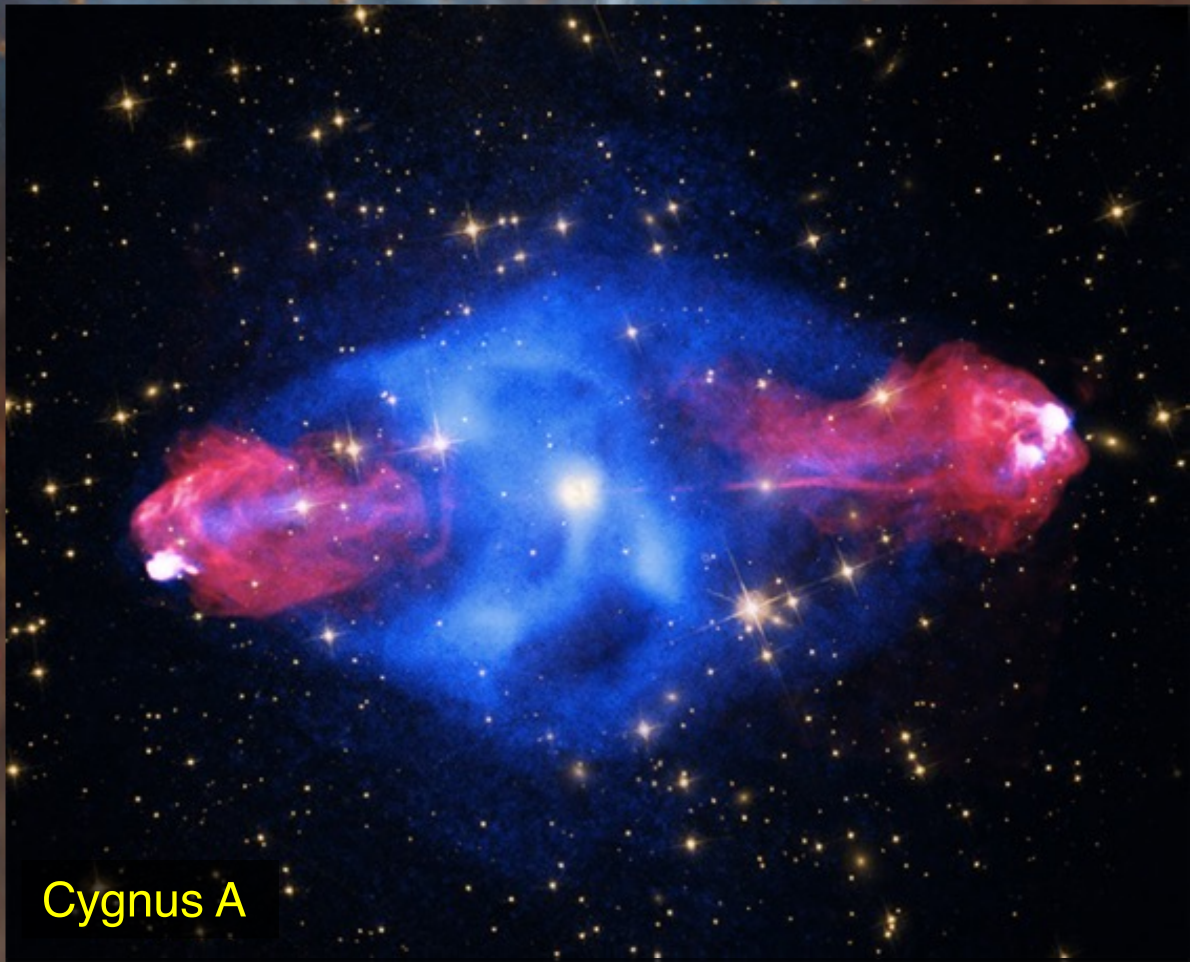
AGN jets (kinetic feedback)

HST optical

VLA radio

AGN FEEDBACK

AGN jets (kinetic feedback)



HST optical

VLA radio

Chandra X-rays

AGN FEEDBACK

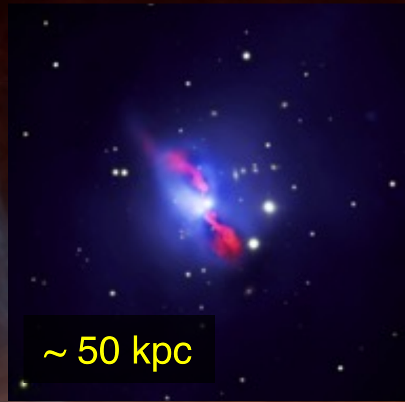
AGN jets in groups and clusters

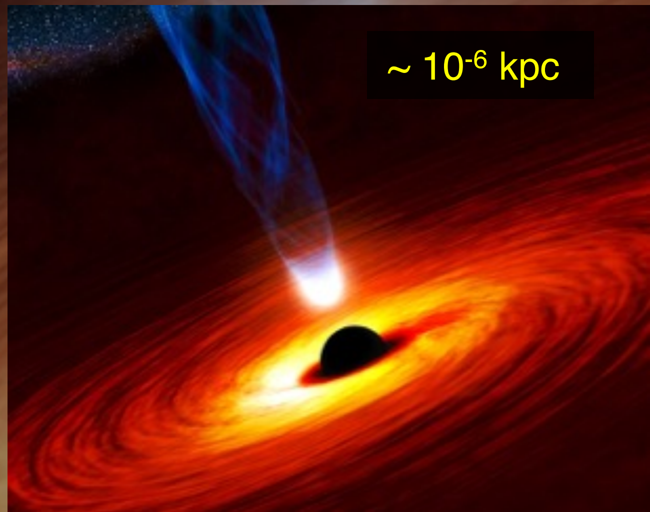
DRAGNs are invariably associated with elliptical galaxies rather than with spirals

→ connection between the ability to launch and maintain the DRAGN and the bulge-to-disc-ratio

Merger --> Starburst + radiatively efficient AGN --> Gas and Dust depletion
--> AGN turns radiatively inefficient --> Elliptical + DRAGN

AGN CENTRAL ENGINE



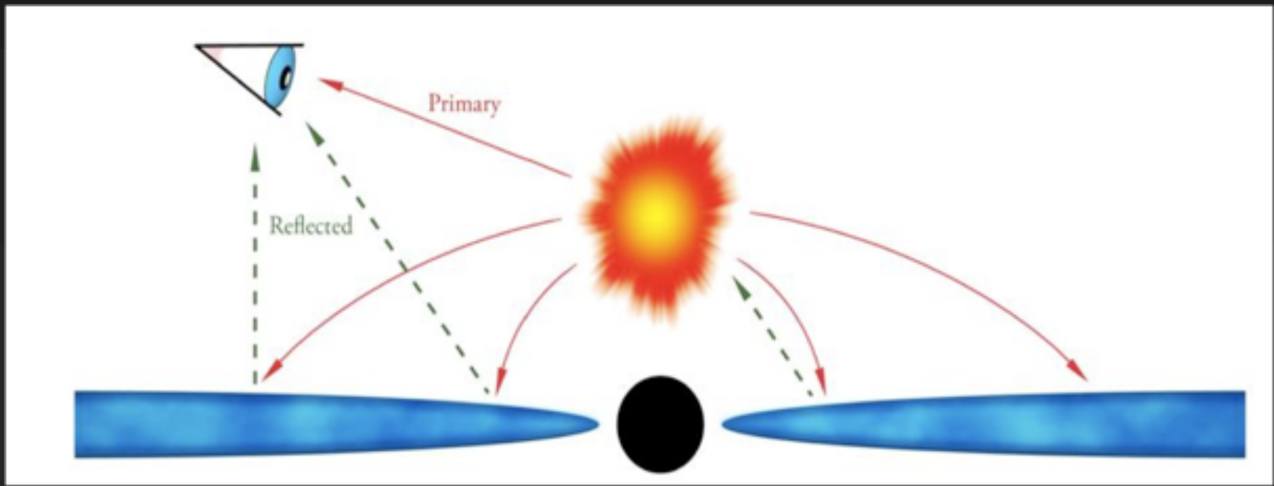


Focus on AGN @ X-rays

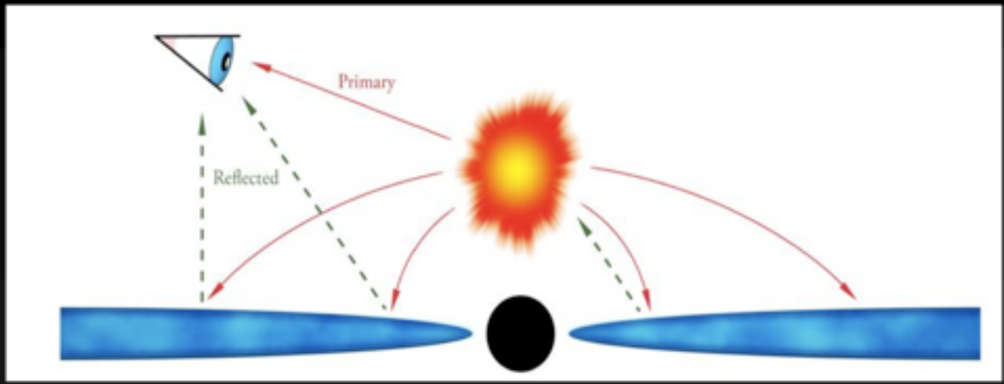
We have seen that the BB emission from the accretion disc peaks, in AGN, in the UV

Compton upscattering (Inverse Compton) in a hot plasma – the so-called X-ray corona - produces a high-energy power law that represents the main spectral component of the X-ray spectrum of AGN

However, part of the X-ray emission from the corona irradiated the accretion disc itself



Focus on AGN @ X-rays

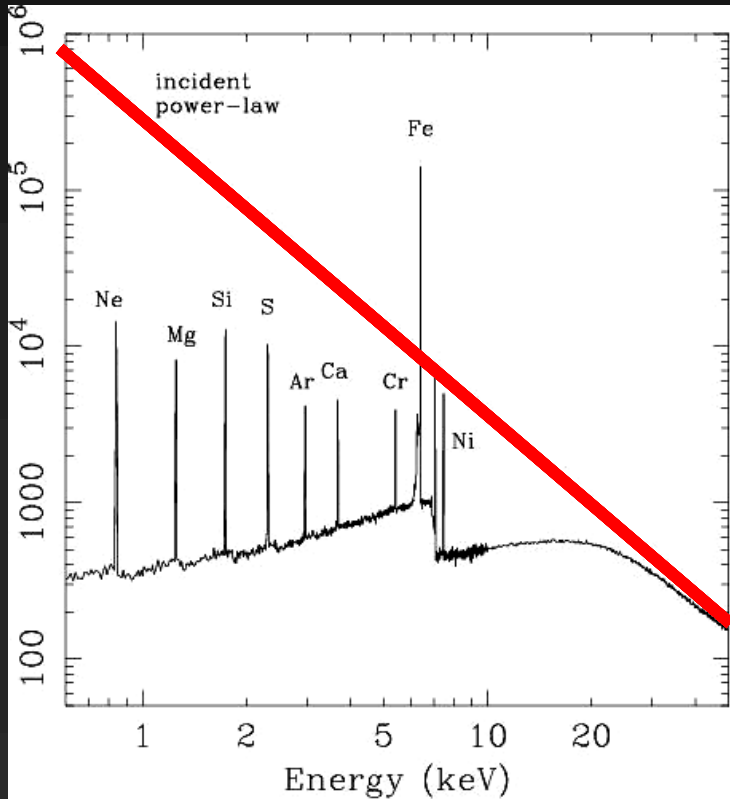


Photons are Compton scattered by the outermost electrons

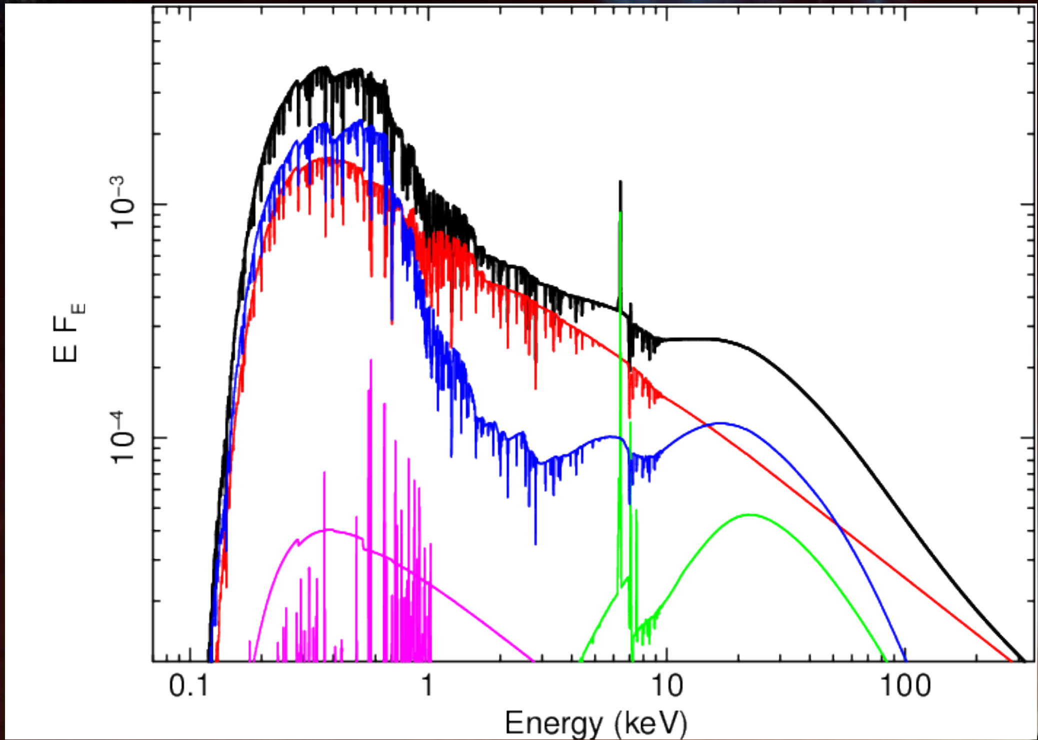
Photoelectric absorption followe by fluorescent line emission

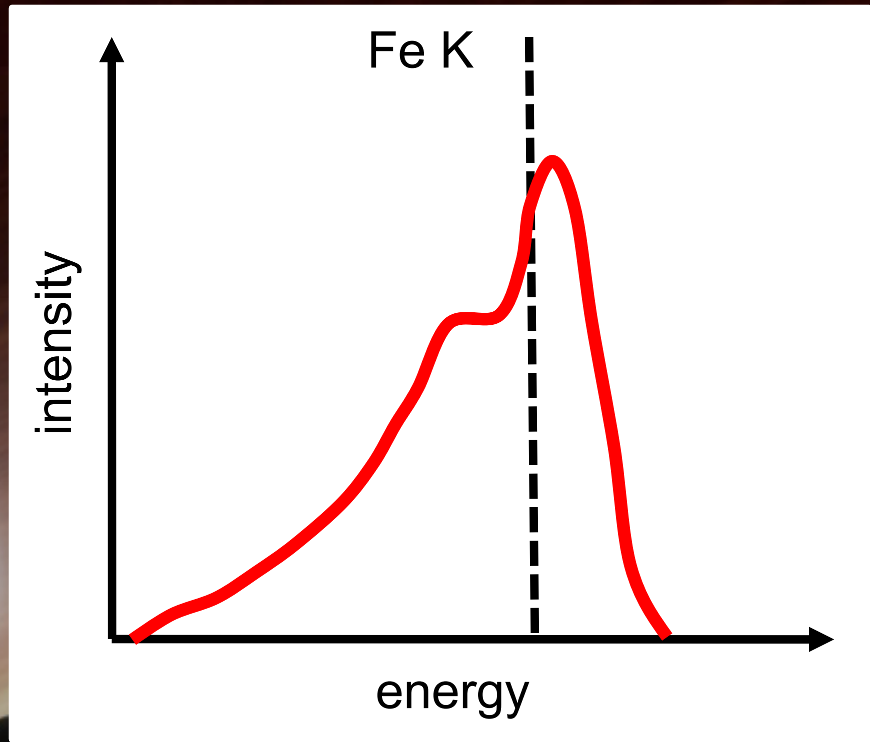
This is known as X-ray reflection producing a spectrum dominated (for neutral gas) by fluorescent line emission and by absorption followed by a Compton hump (scattering) at 20-30 keV

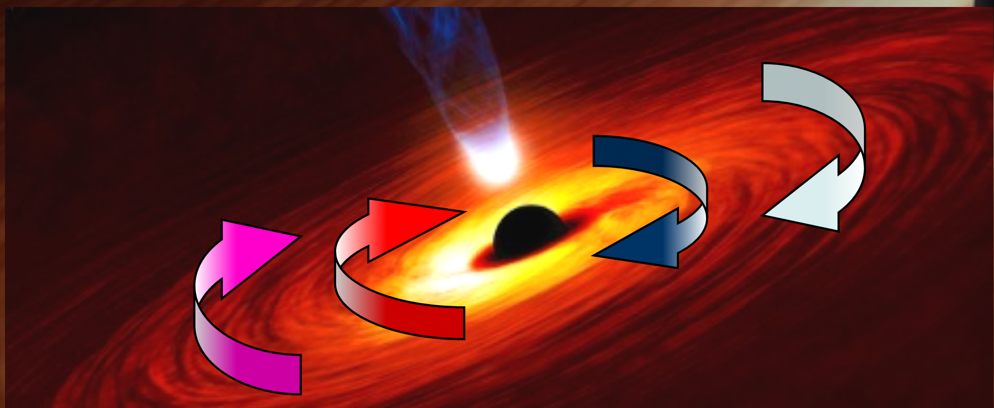
Due to a combination of abundance and fluorescent yield, the Fe K line at 6.4 keV is the most prominent feature



AGN CENTRAL ENGINE







X-ray continuum (corona)

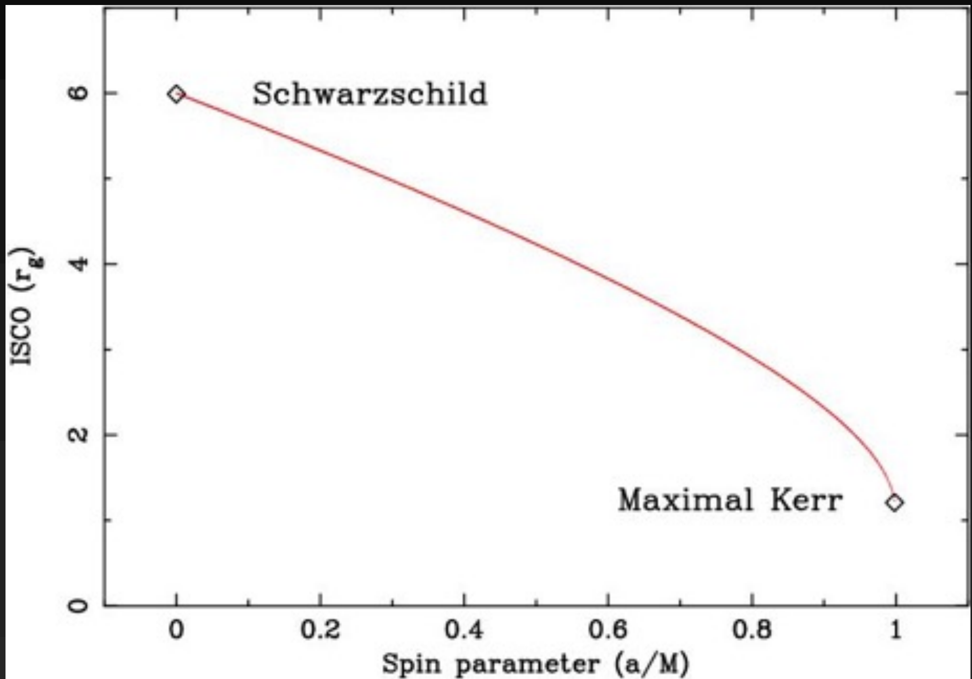
Distant cold reflection (torus),
Photoionized gas (NLR), Star Formation

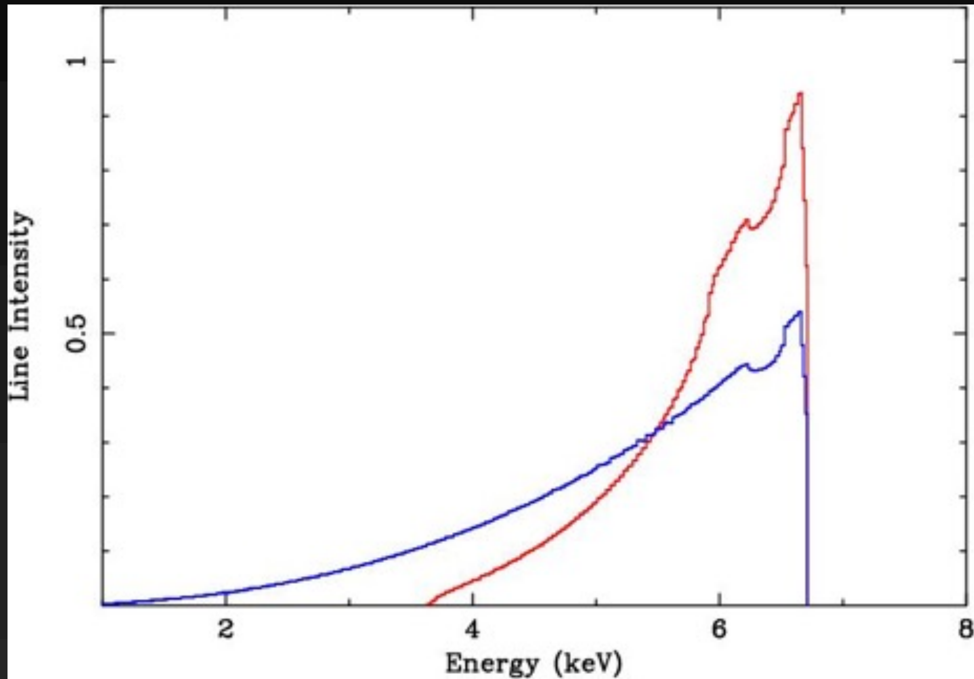
Relativistic ionized reflection (disc)

Intervening absorption

Focus on AGN @ X-rays

The relativistically distorted Fe K line (aka broad Fe line) represents a tool with which to probe the innermost regions of the accretion flow around a BH



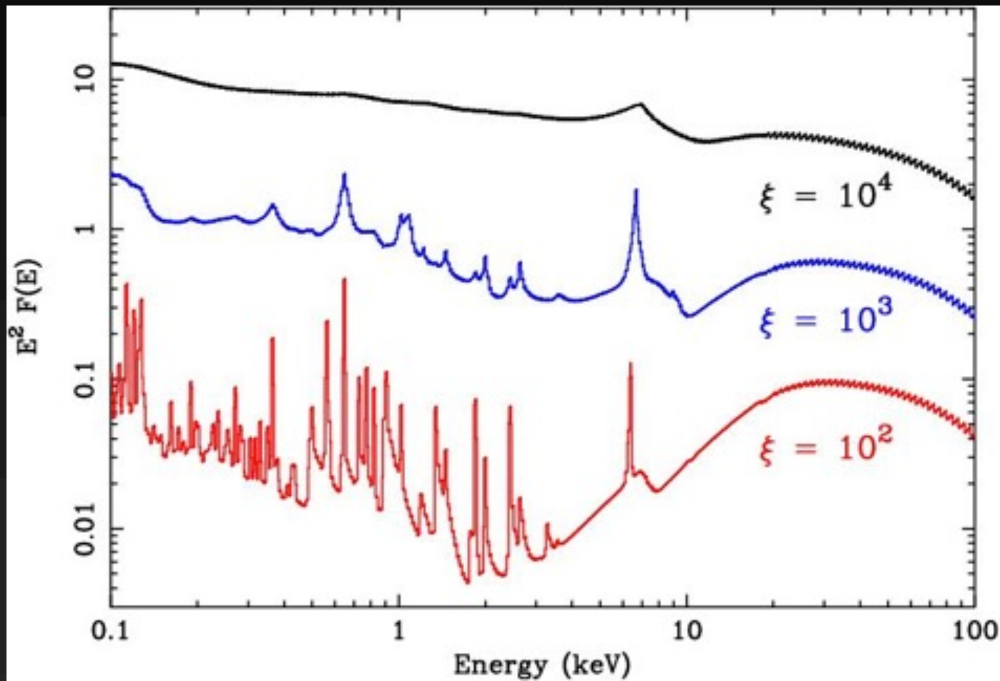


As the accretion disc extends closer to the BH in the Kerr case, GR effects are stronger and the line is broader and more redshifted (gravitational redshift)

Potentially one can measure BH spin

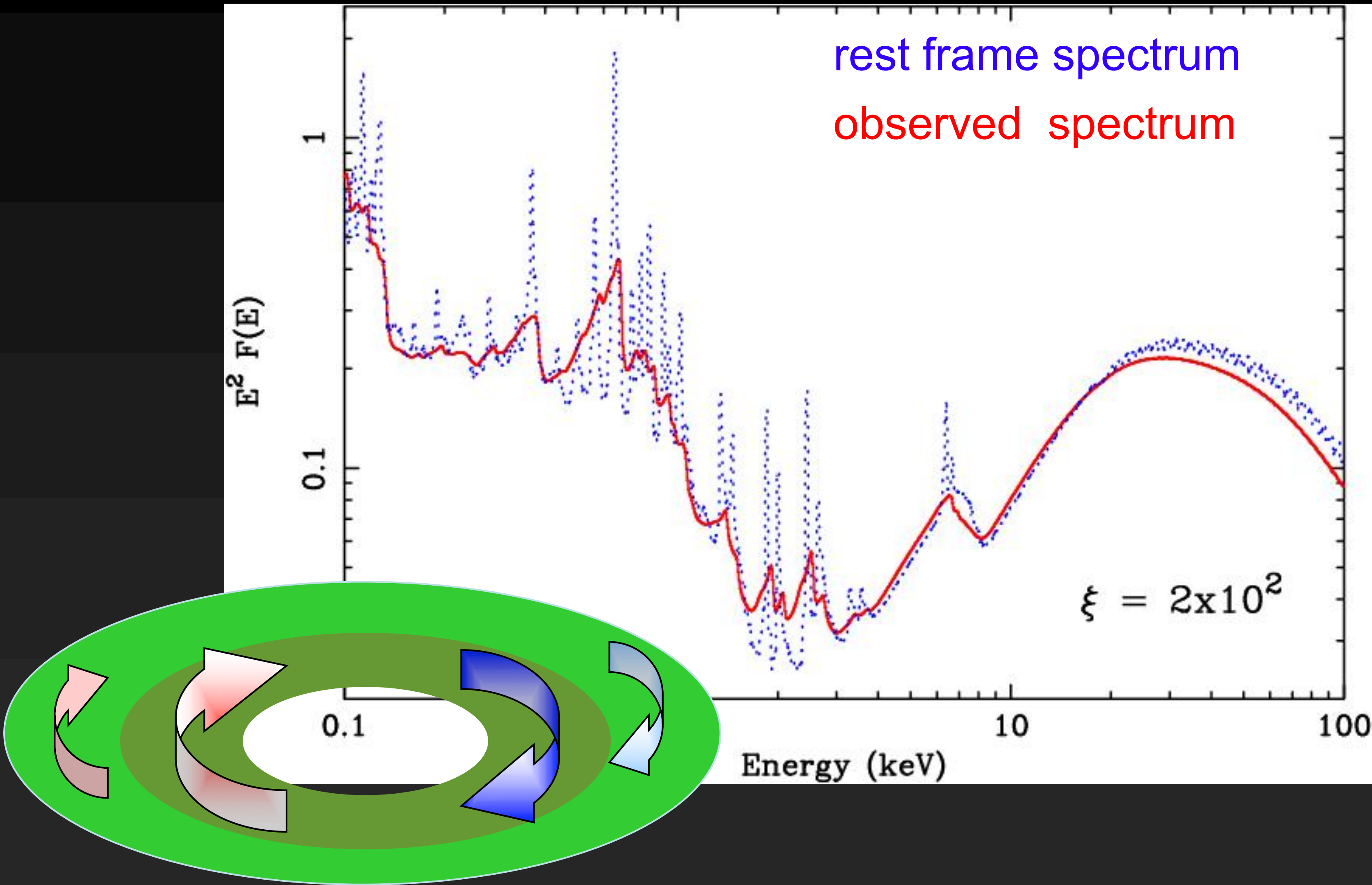
Focus on AGN @ X-rays

In real life, the reflection spectrum is in fact due to ionized rather than perfectly neutral material

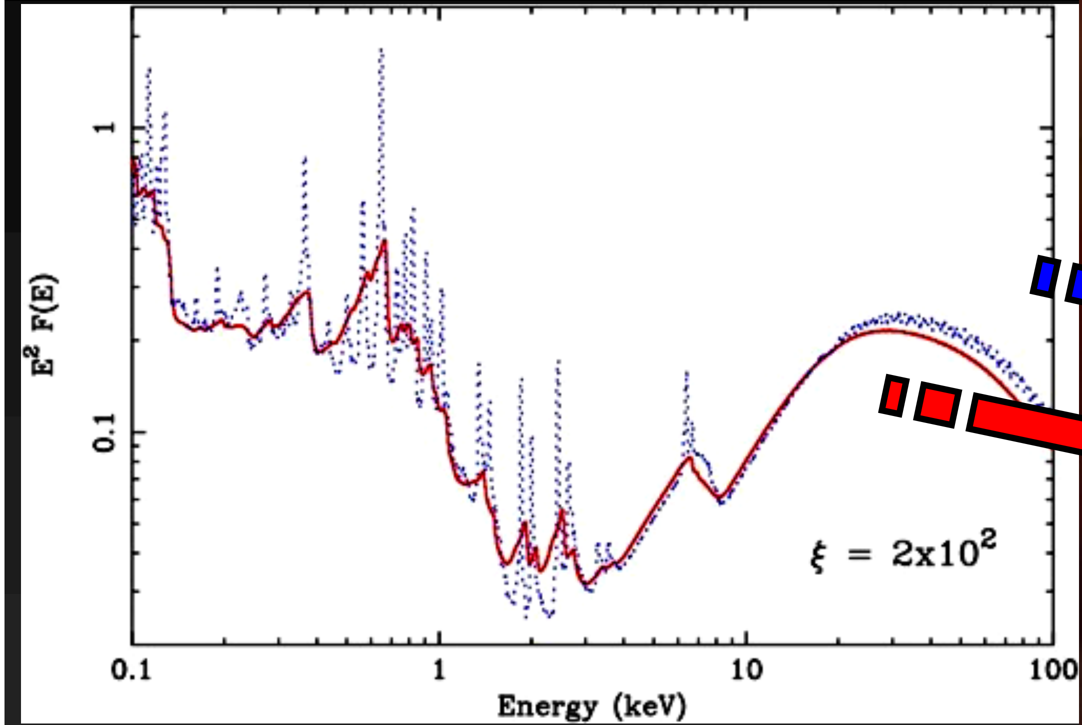


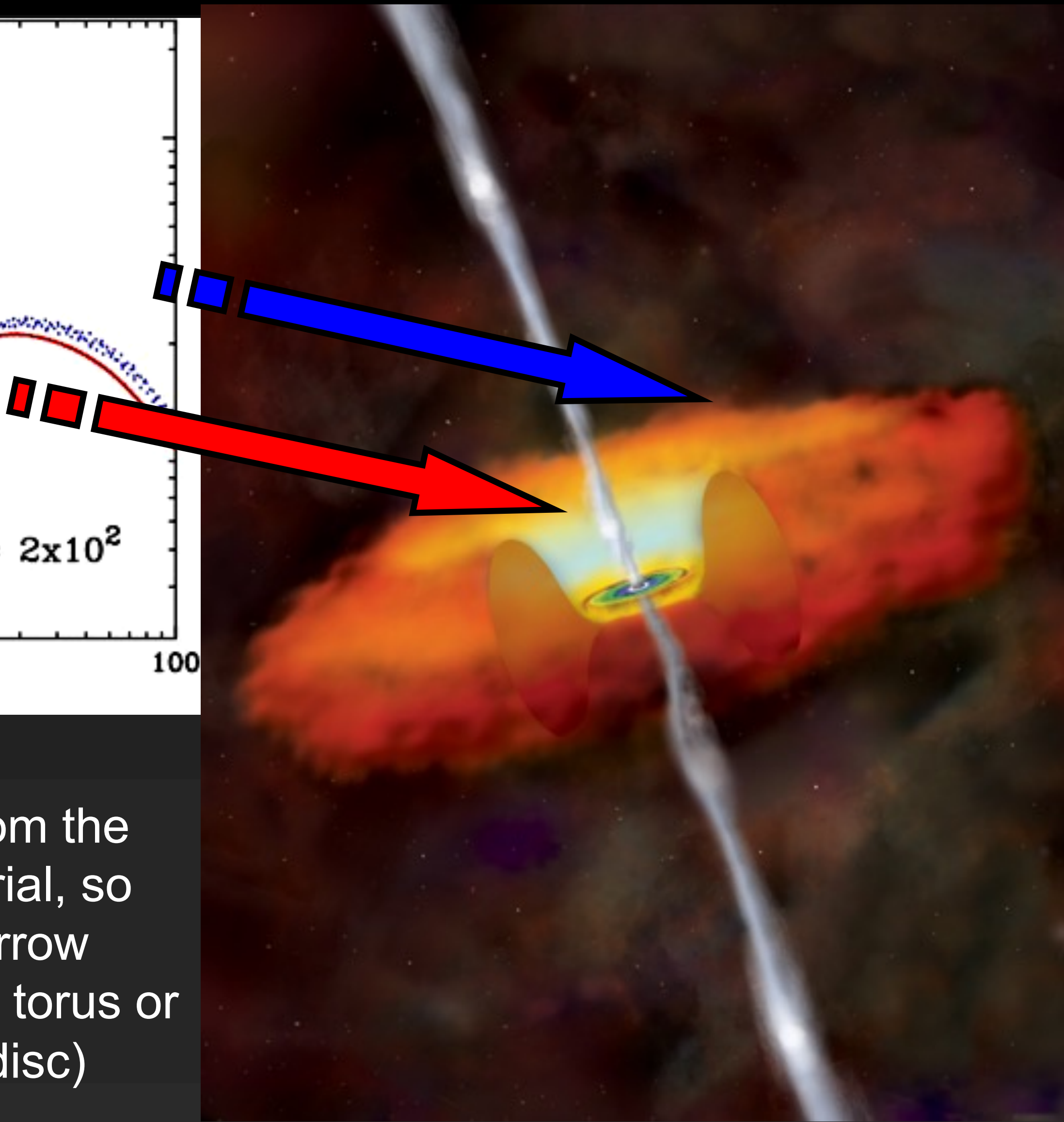
And all the effects we have discussed for the Fe line do apply for the overall reflection spectrum

Focus on AGN @ X-rays



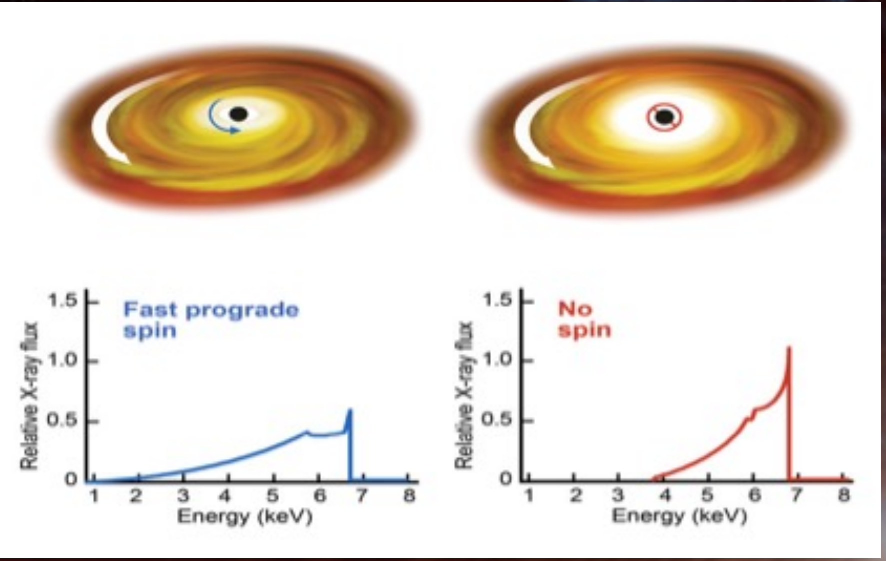
Focus on AGN @ X-rays





The X-ray continuum emission from the inner regions irradiates any material, so in general we should see both narrow and broad components (e.g. from torus or other materia far away and from disc)

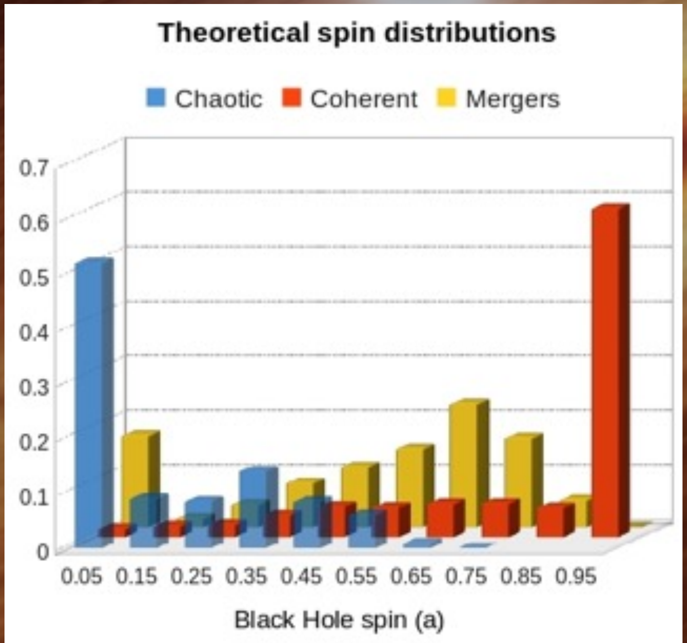
AGN CENTRAL ENGINE



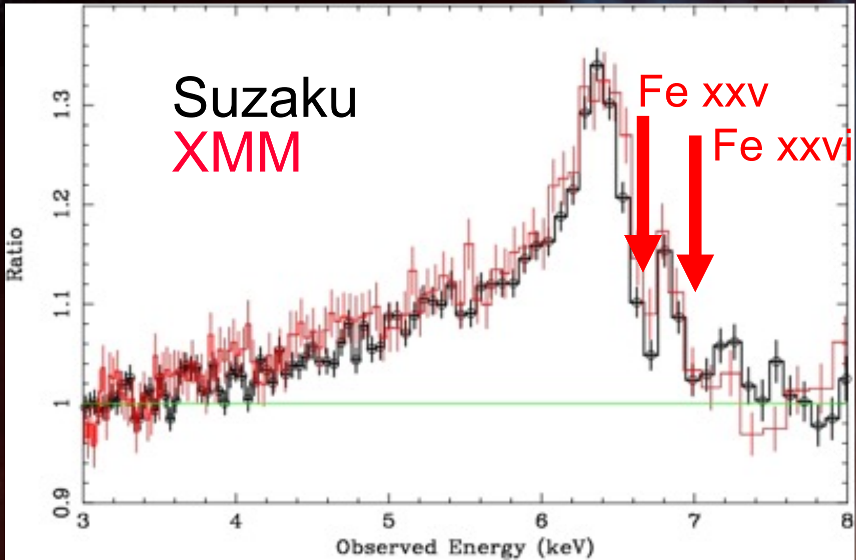
BH spin

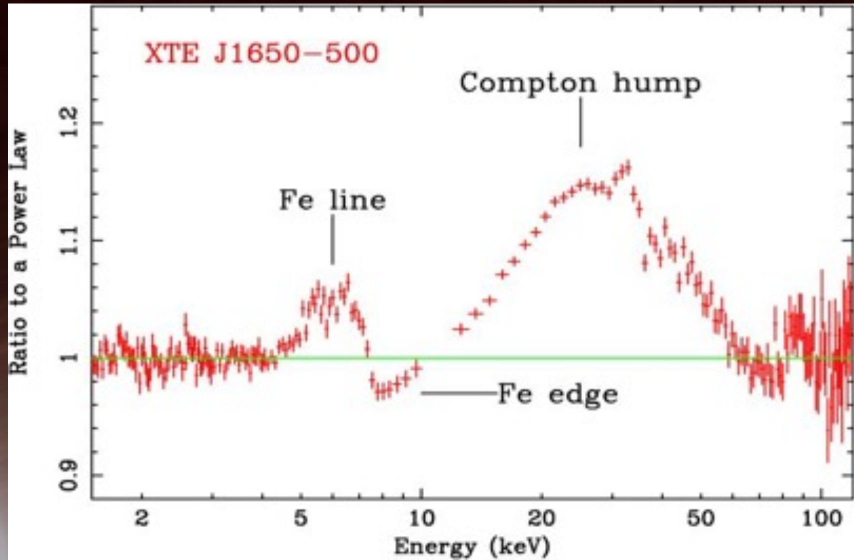
X-ray corona geometry/isotropy (via irradiation/emissivity profiles)

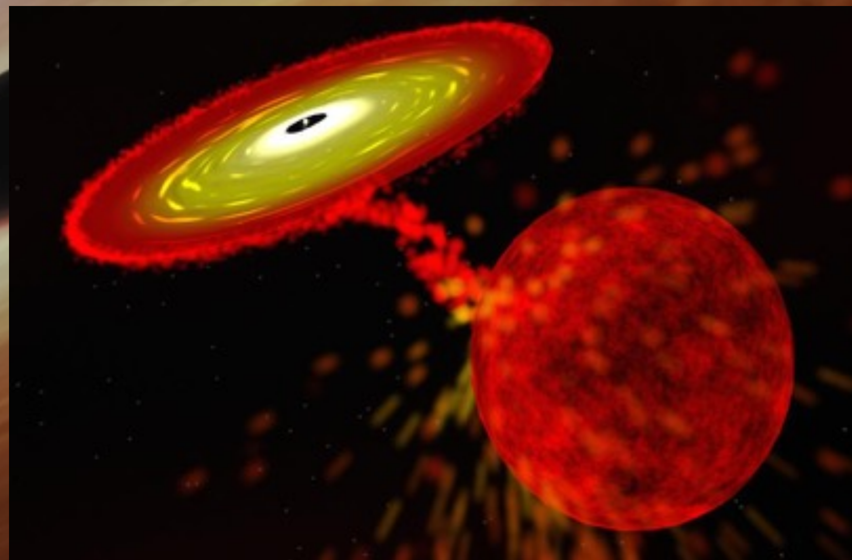
Disc density, inclination, ionization, metallicity



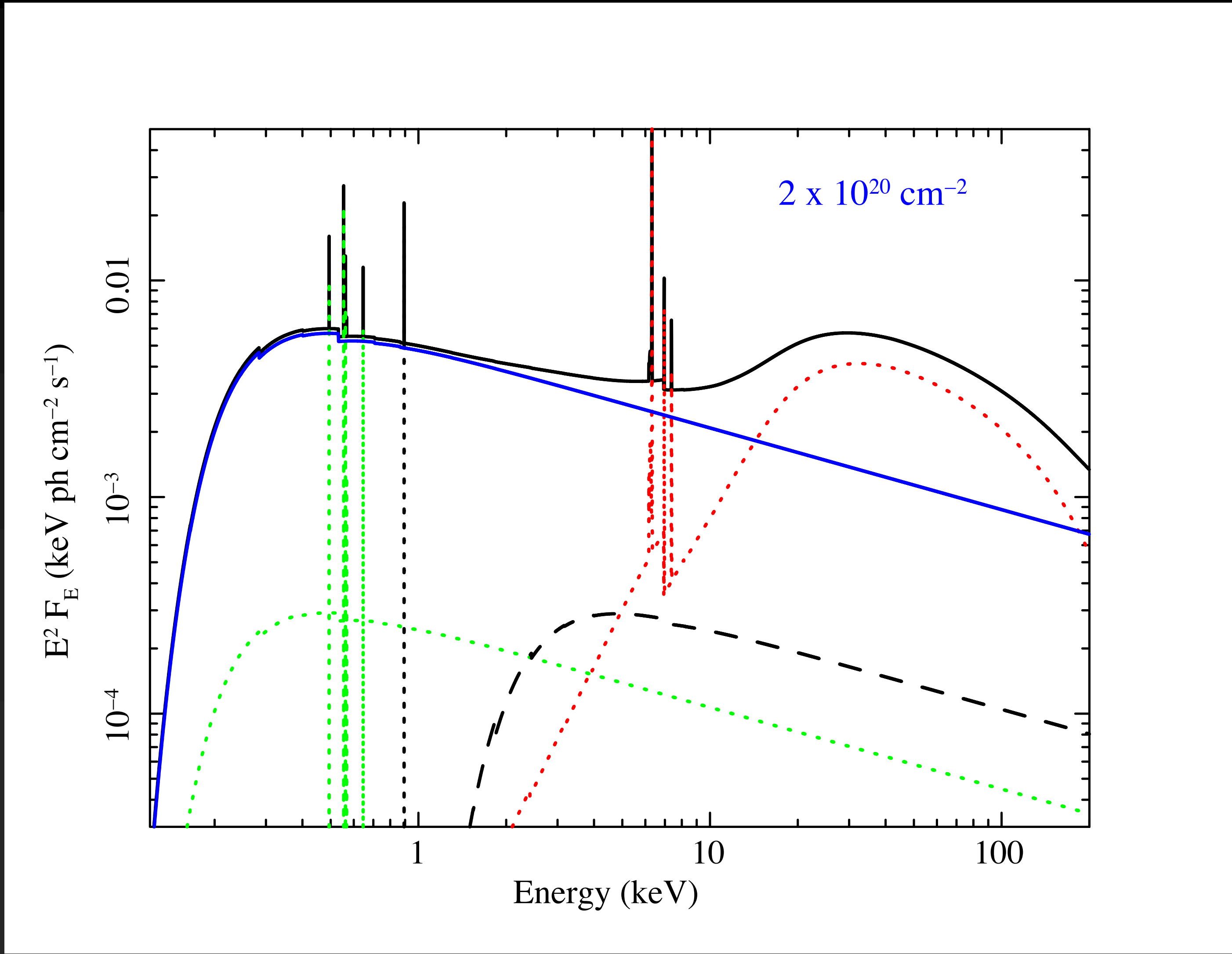
AGN CENTRAL ENGINE





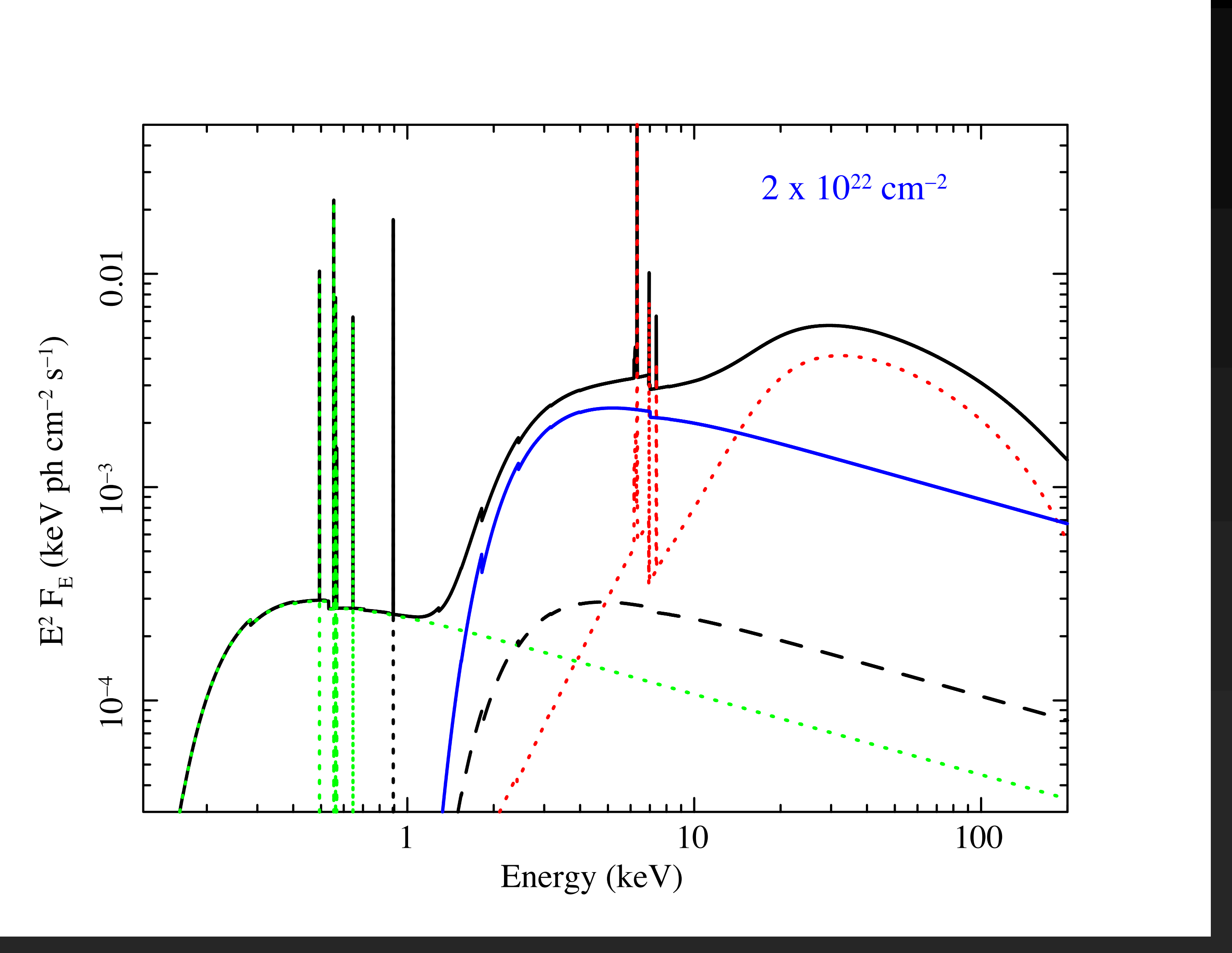


X-ray contributions (some) to the unified AGN model



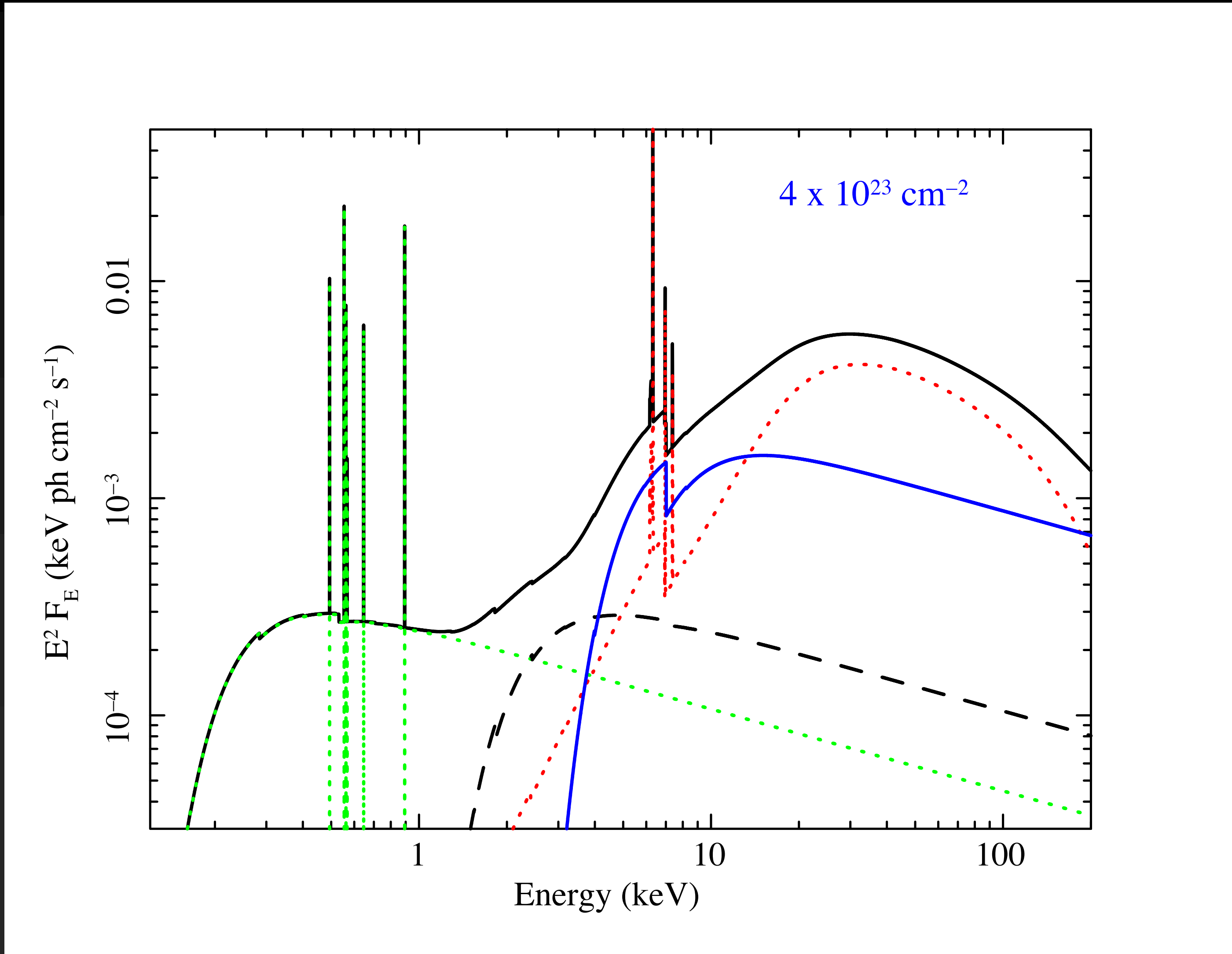
Unabsorbed type I AGN

X-ray contributions (some) to the unified AGN model



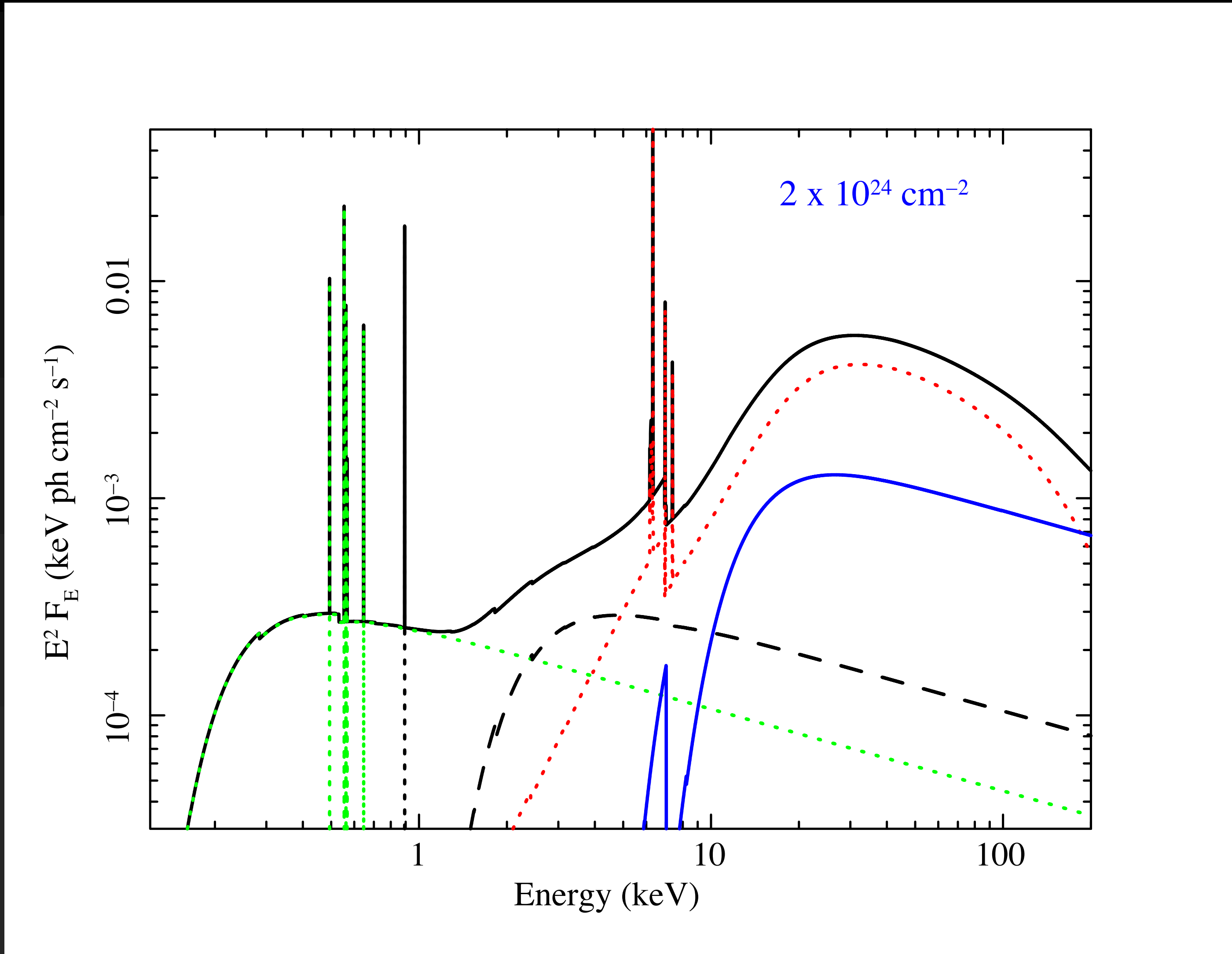
X-ray mildly absorbed type I / type II AGN

X-ray contributions (some) to the unified AGN model



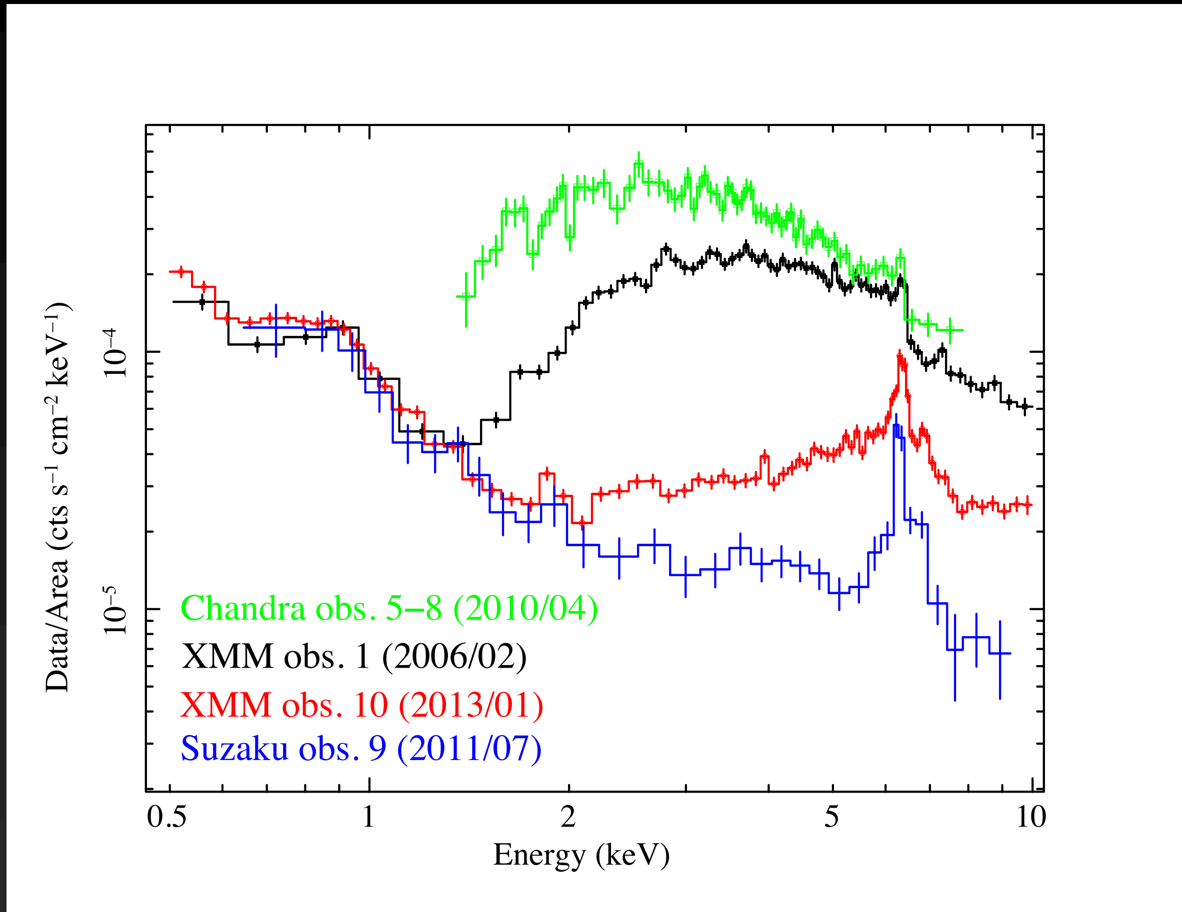
Compton-thin type II AGN

X-ray contributions (some) to the unified AGN model



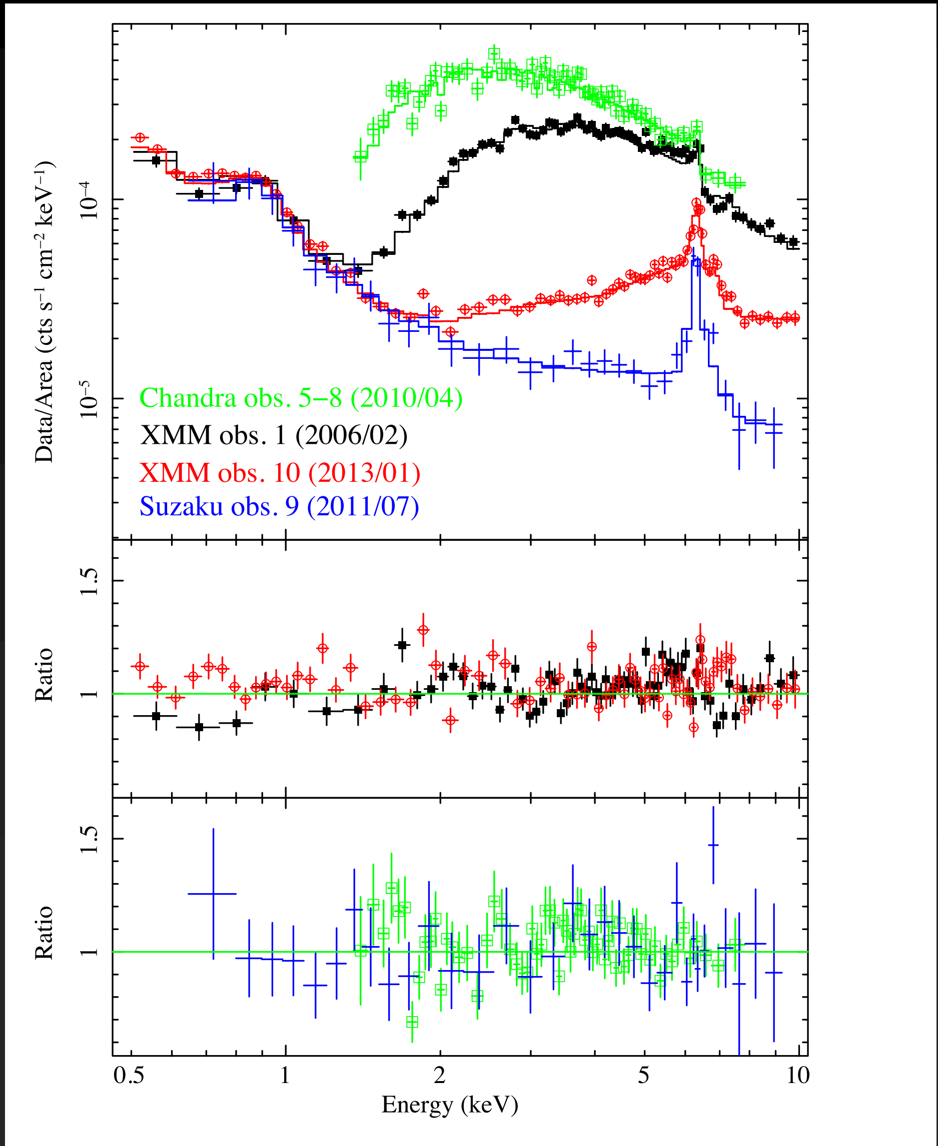
Compton-thick type II AGN

X-ray contributions (some) to the unified AGN model



Some AGN go through many of these different absorption states
→ absorption variability can tell us many things

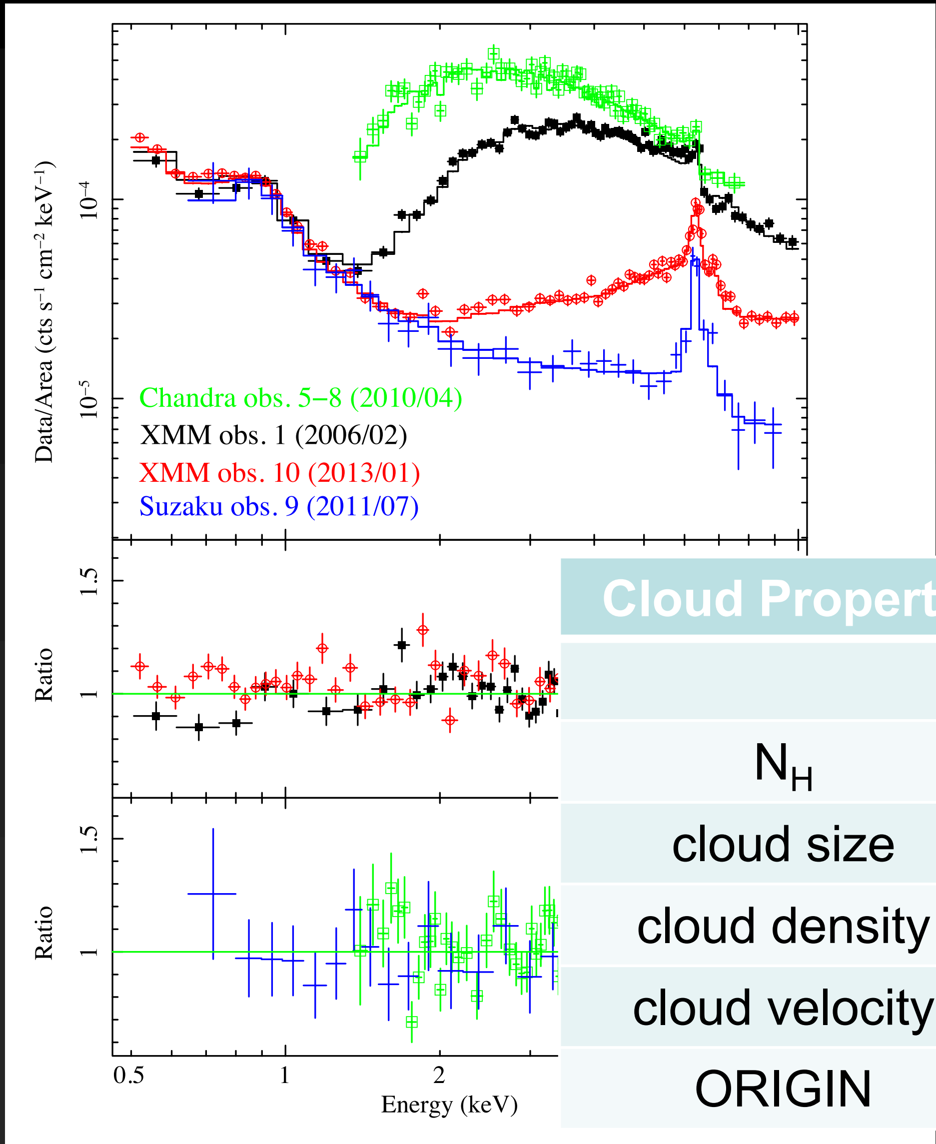
X-ray contributions (some) to the unified AGN model



Detailed modeling of the X-ray spectra and of their variation allows one to put constraints on the properties of the absorbing systems

torus and BLR can be identified in the X-rays

X-ray contributions (some) to the unified AGN model



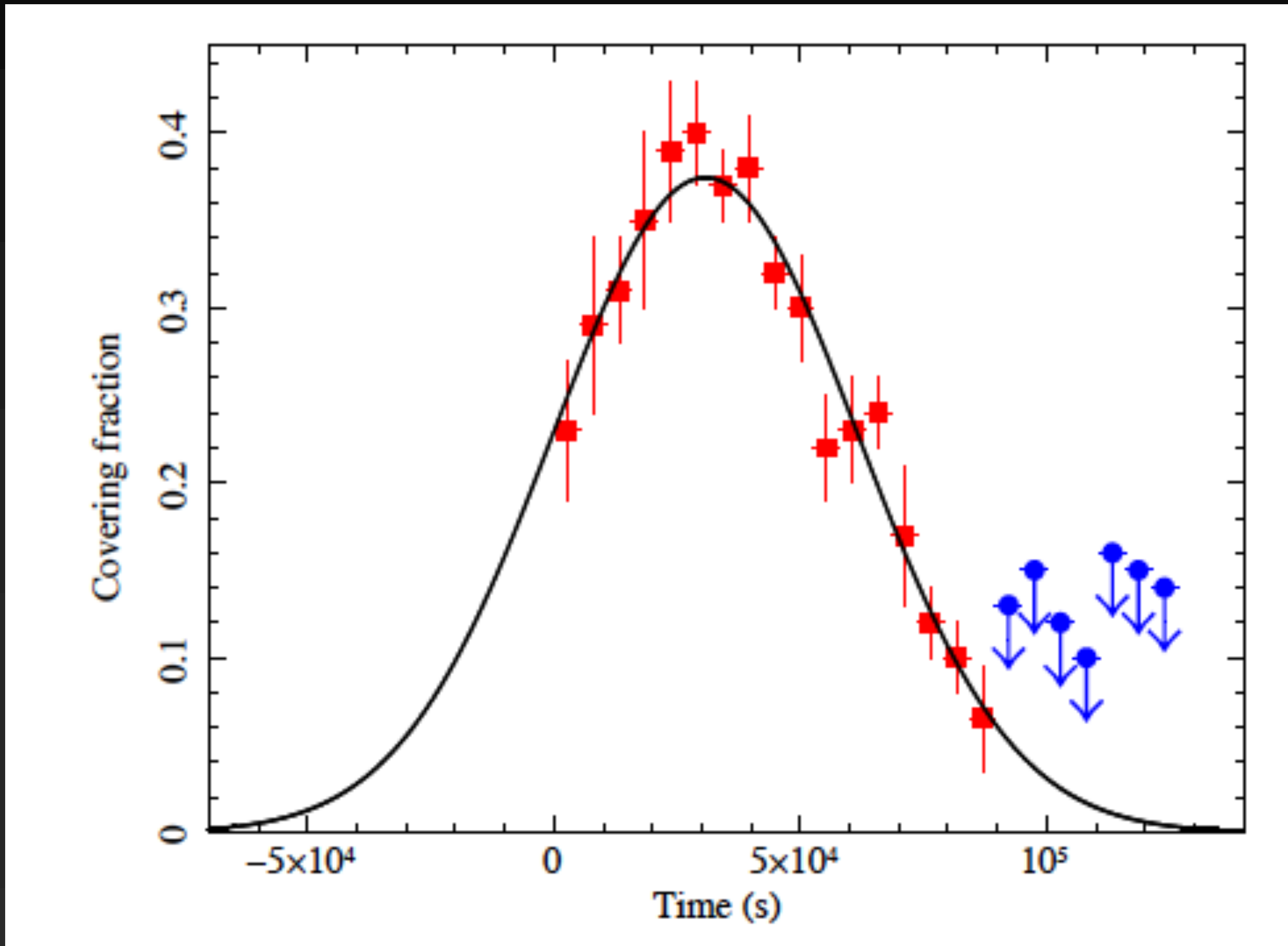
Detailed modeling of the X-ray spectra and of their variation allows one to put constraints on the properties of the absorbing systems

torus and BLR can be identified in the X-rays

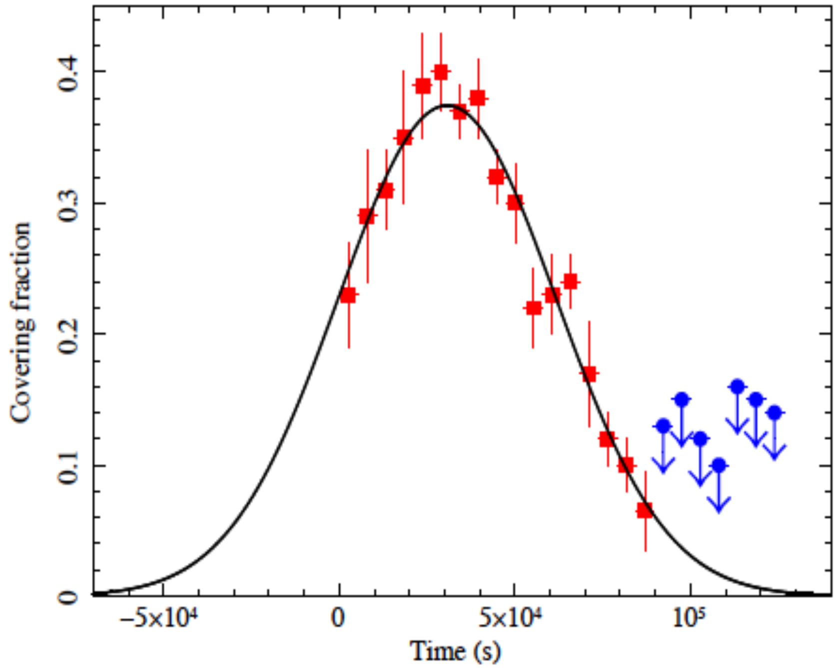
Cloud Property	Obs. 1 3 4 5	Obs. 2 6 7
N_H	$2 - 6 \times 10^{22}$	$3 \times 10^{23} – 3 \times 10^{24}$
cloud size	$3 \times 10^{14} – 9 \times 10^{15}$	$8 \times 10^{13} – 2 \times 10^{15}$
cloud density	$2 \times 10^{6} – 2 \times 10^{7}$	$2 \times 10^{8} – 7 \times 10^{9}$
cloud velocity	150 – 800 km/s	800 – 3000 km/s
ORIGIN	CLUMPY TORUS	BLR

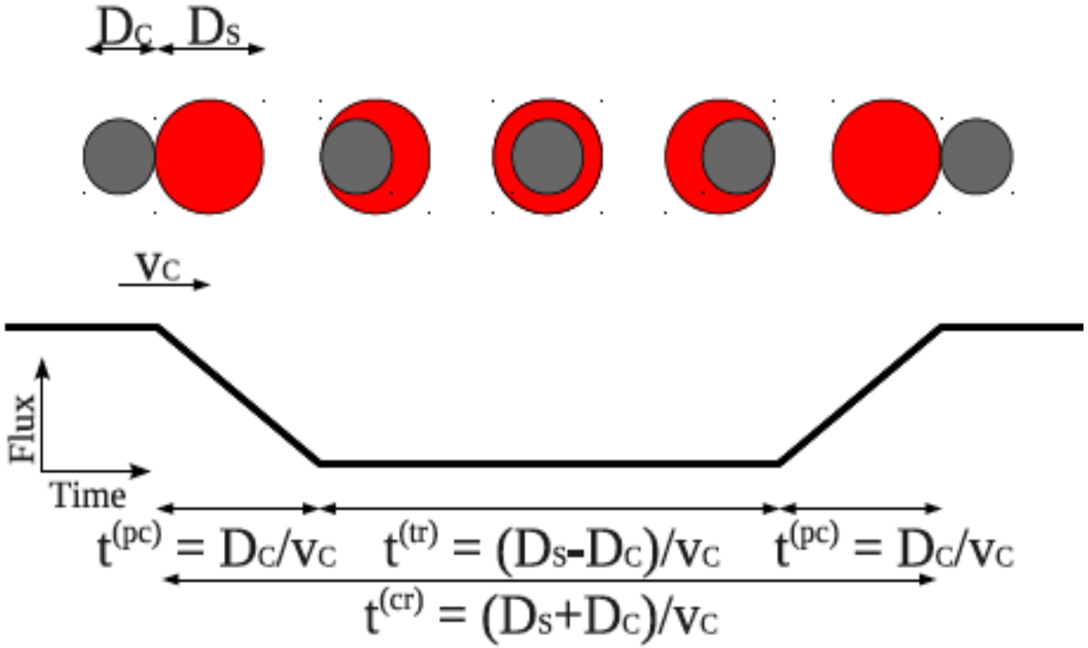
X-ray contributions (some) to the unified AGN model

Absorption variability has also be detected on very short timescales (hours/days) which implies absorption of compact X-ray emitting regions by compact clouds (most likely the same clouds that emit the broad lines in the optical, the BLR clouds)

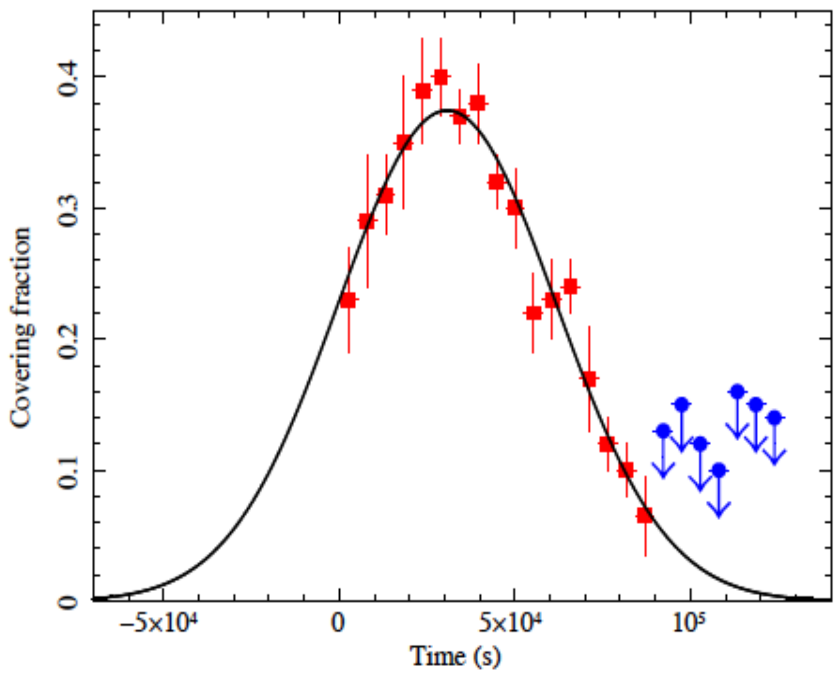


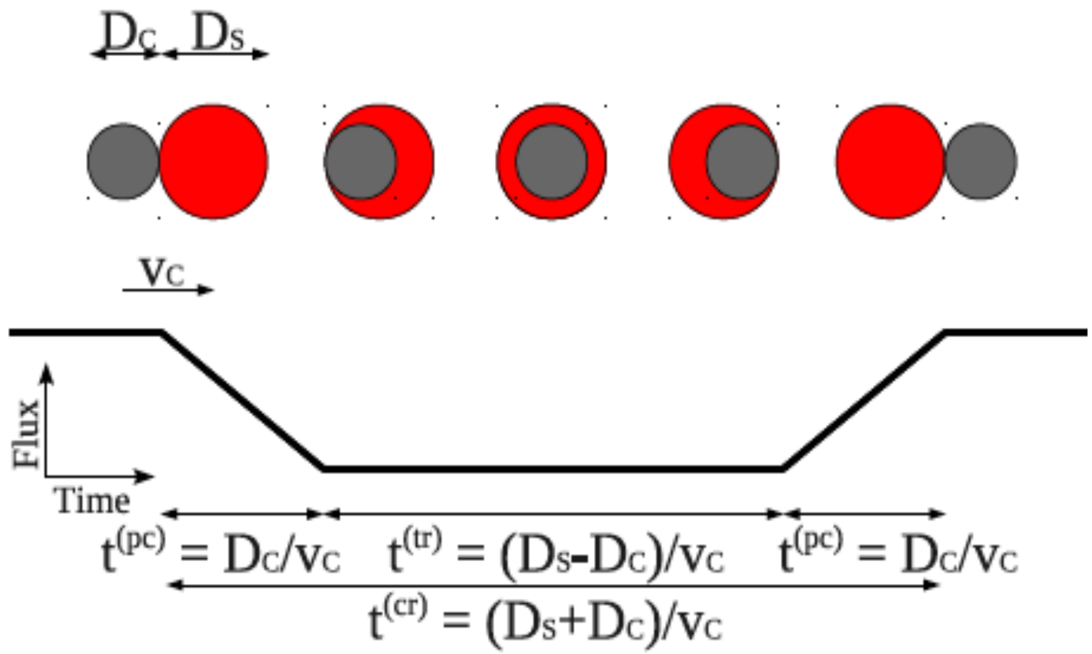
X-ray contributions (some) to the unified AGN model





X-ray contributions (some) to the unified AGN model





RESULTS

→ Cloud number density $n_c \geq 1.5 \times 10^9$ cm^{-3}

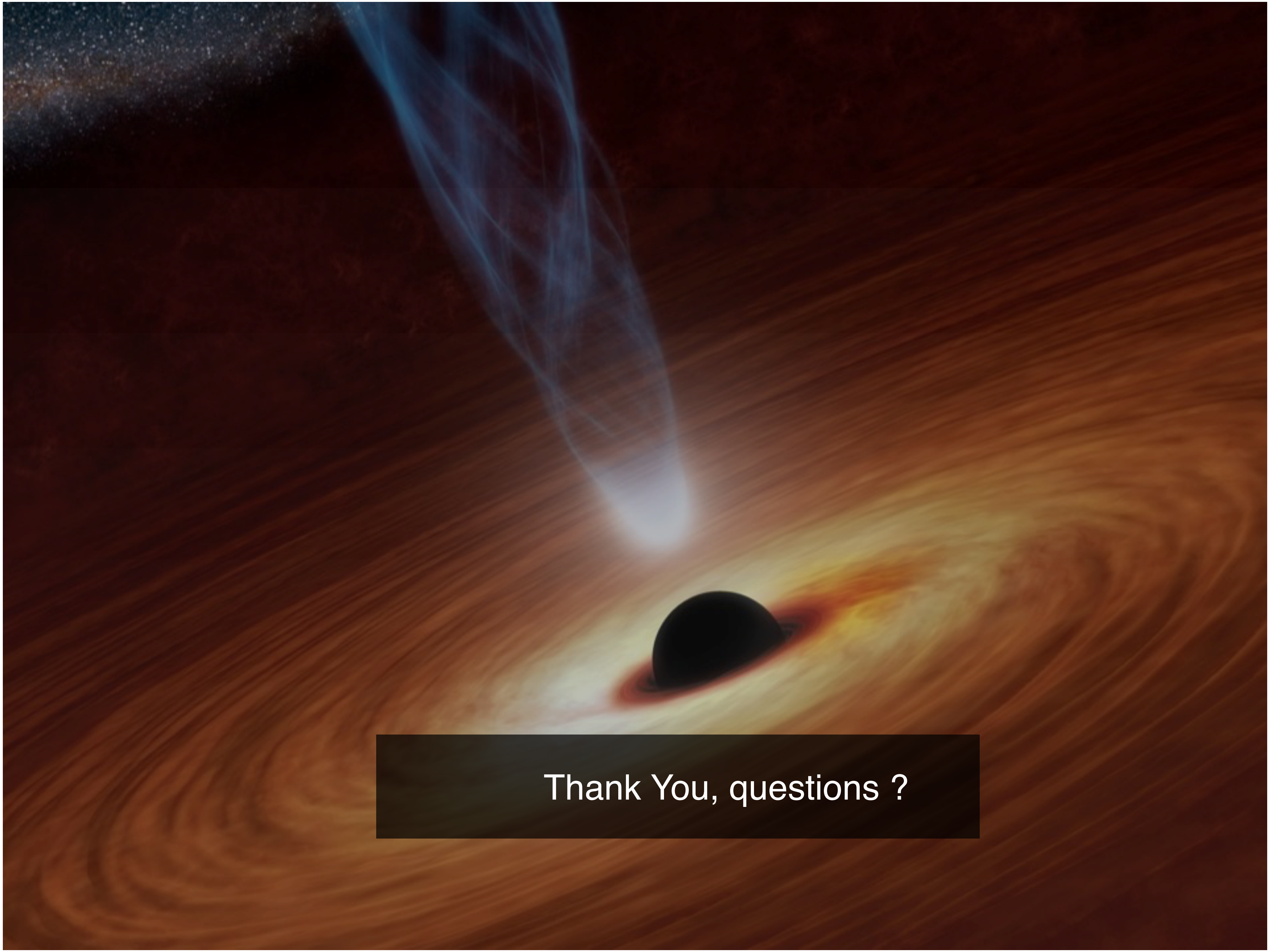
→ Cloud size (diameter) $D_c \leq 1.5 \times 10^{13}$ cm

→ Cloud distance $R_c \geq 4.3 \times 10^{16}$ cm

→ Cloud velocity $v_c \approx 2100$ km/s

} BLR cloud

→ X-ray source size (diameter) is $D_s \leq 2.3 \times 10^{13}$ cm $\approx 10.5\ R_g$ (single-epoch BH mass)


Thank You, questions ?