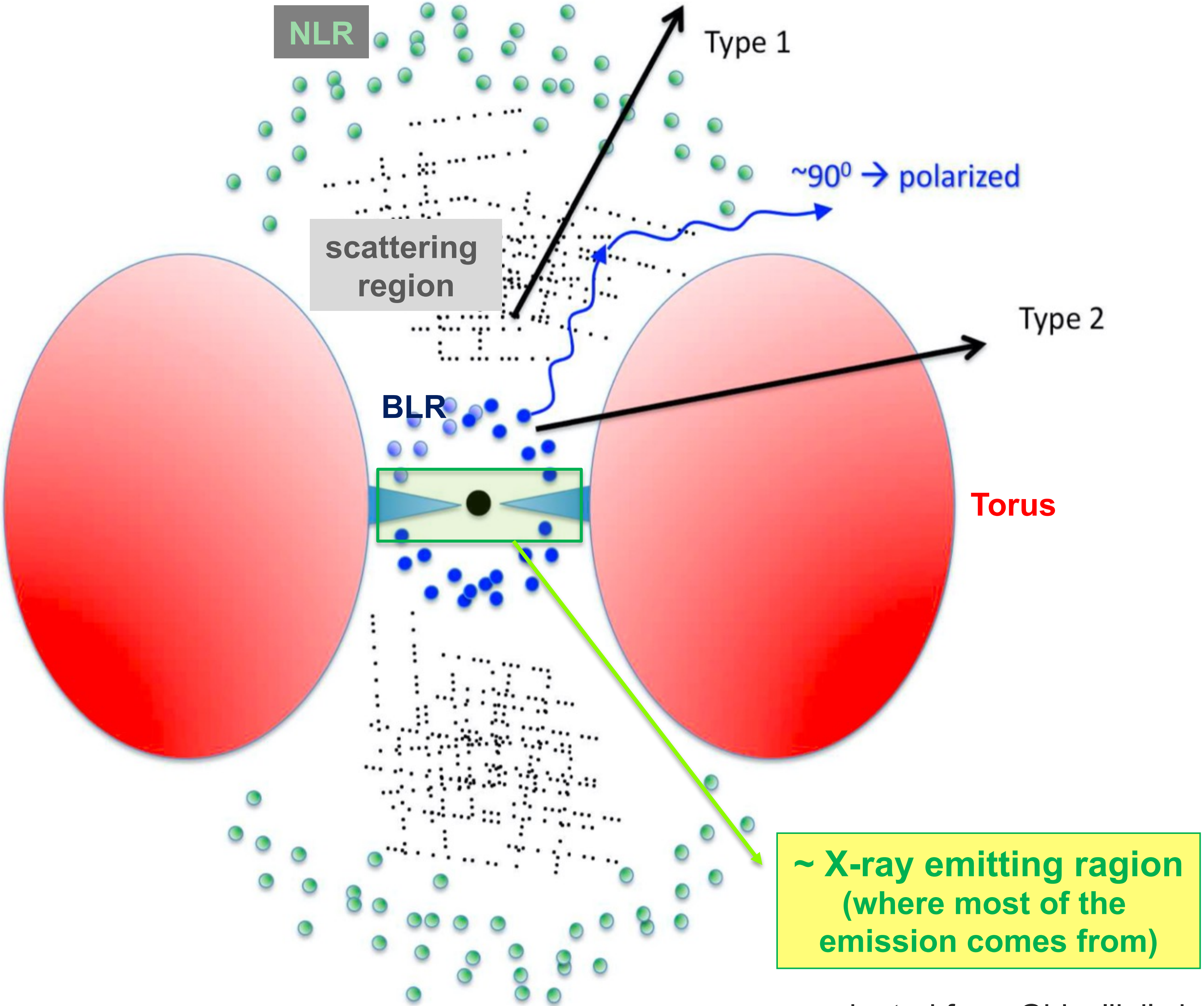
AGN: X-ray emission and “inner” structure

AGN X-ray emission

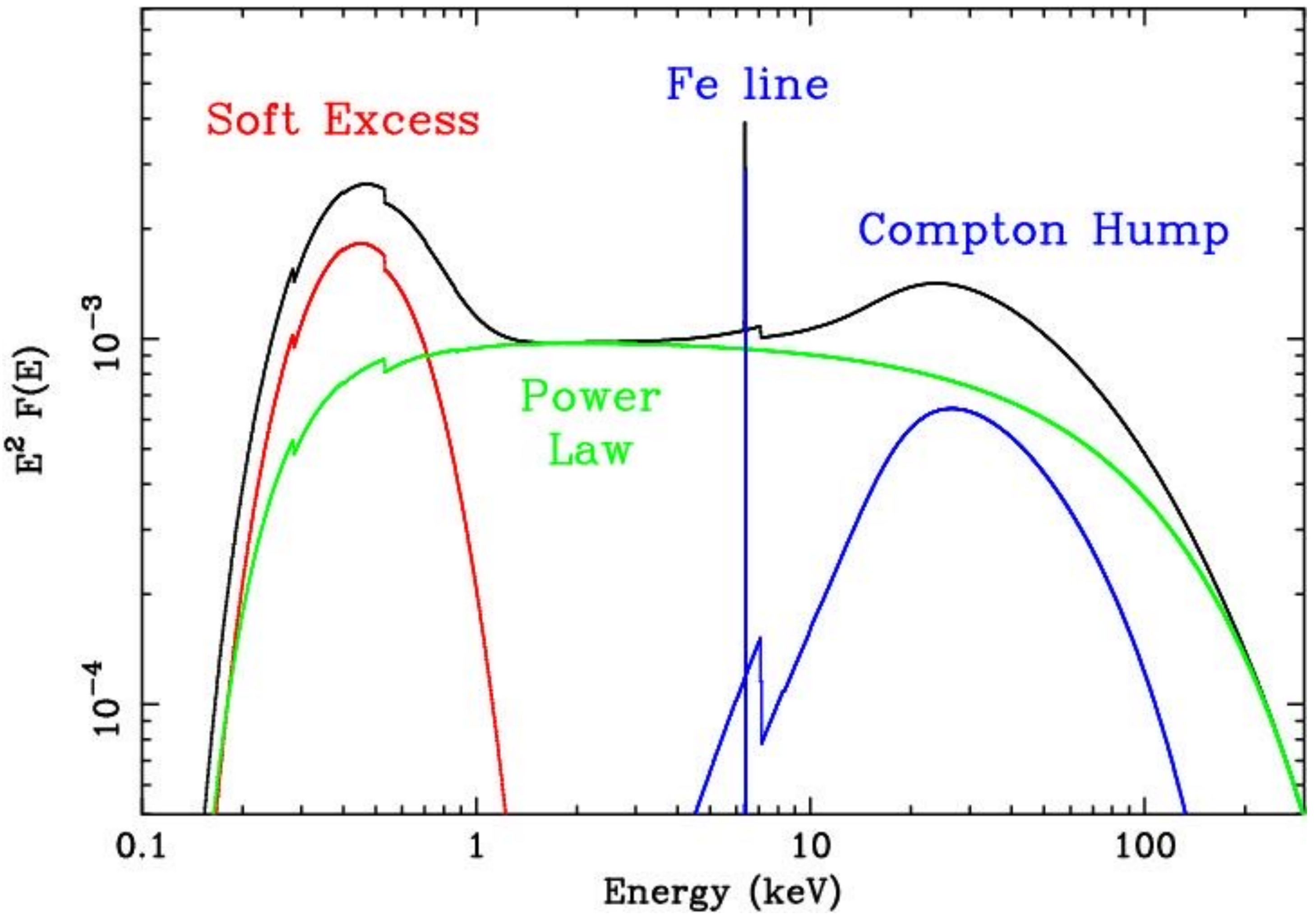
Further in-depth disussion in the complementary High-Energy Astrophysics course
(Prof. Marcella Brusa)



~ X-ray emitting ragion (where most of the emission comes from)

adapted from Ghisellini's book

High-energy emission from AGN

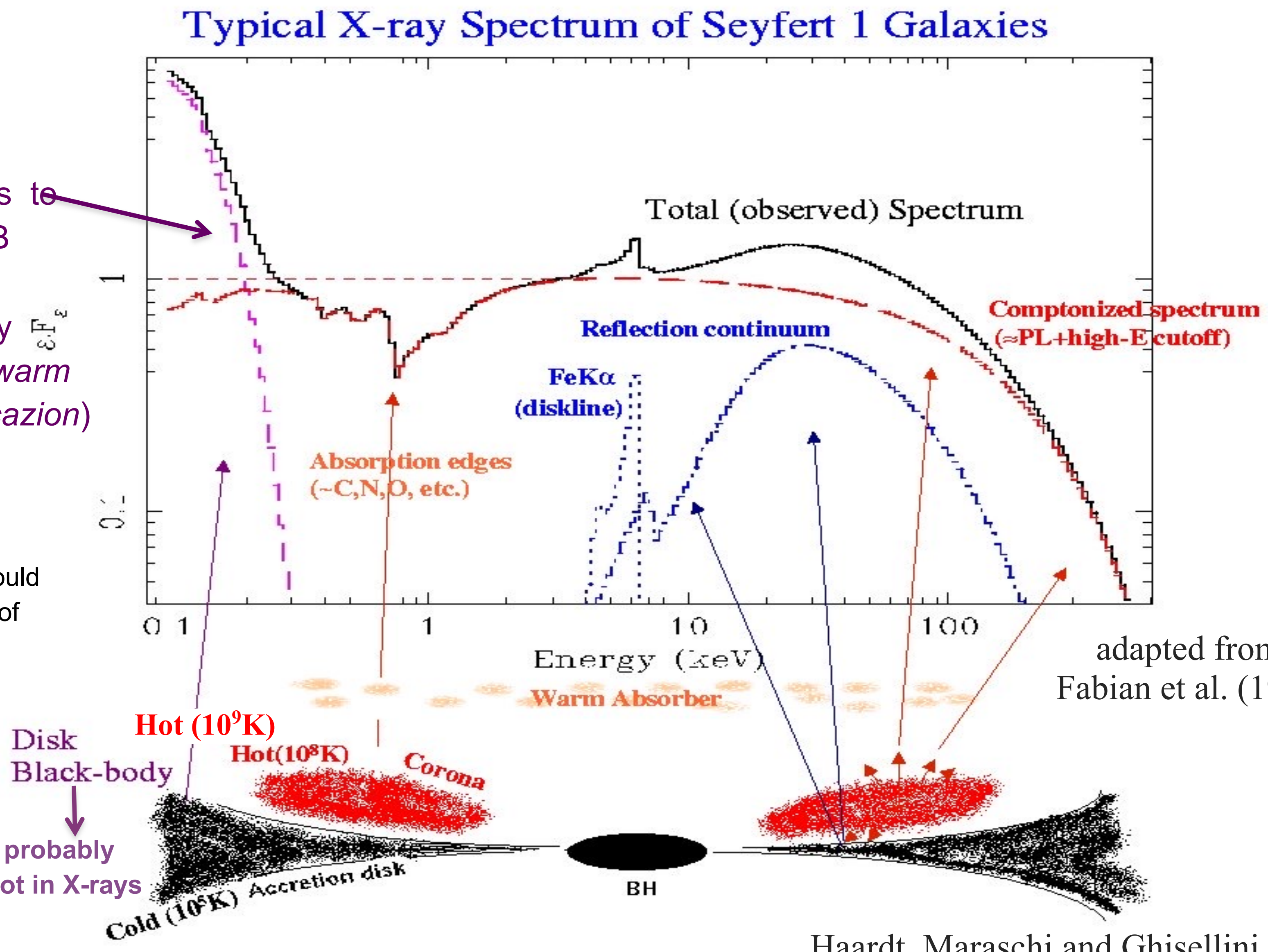


High-energy emission from AGN

Alternative hypotheses to the disc BB emission (more likely related to *warm Comptonicazion*)

↓

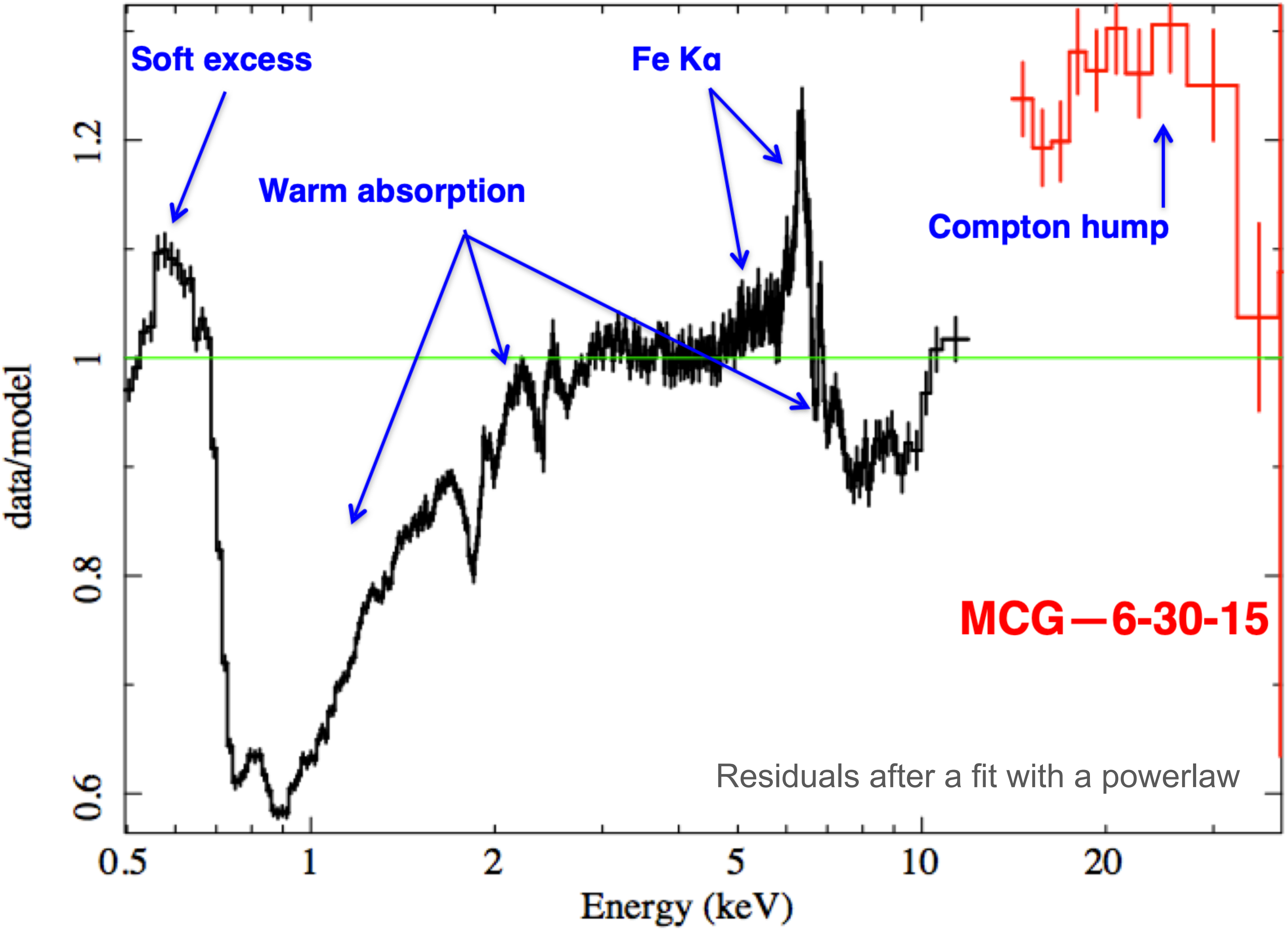
if BB, we should see a range of kT in X-rays, which is not observed



probably not in X-rays

adapted from Fabian et al. (1997)

Haardt, Maraschi and Ghisellini (1994)

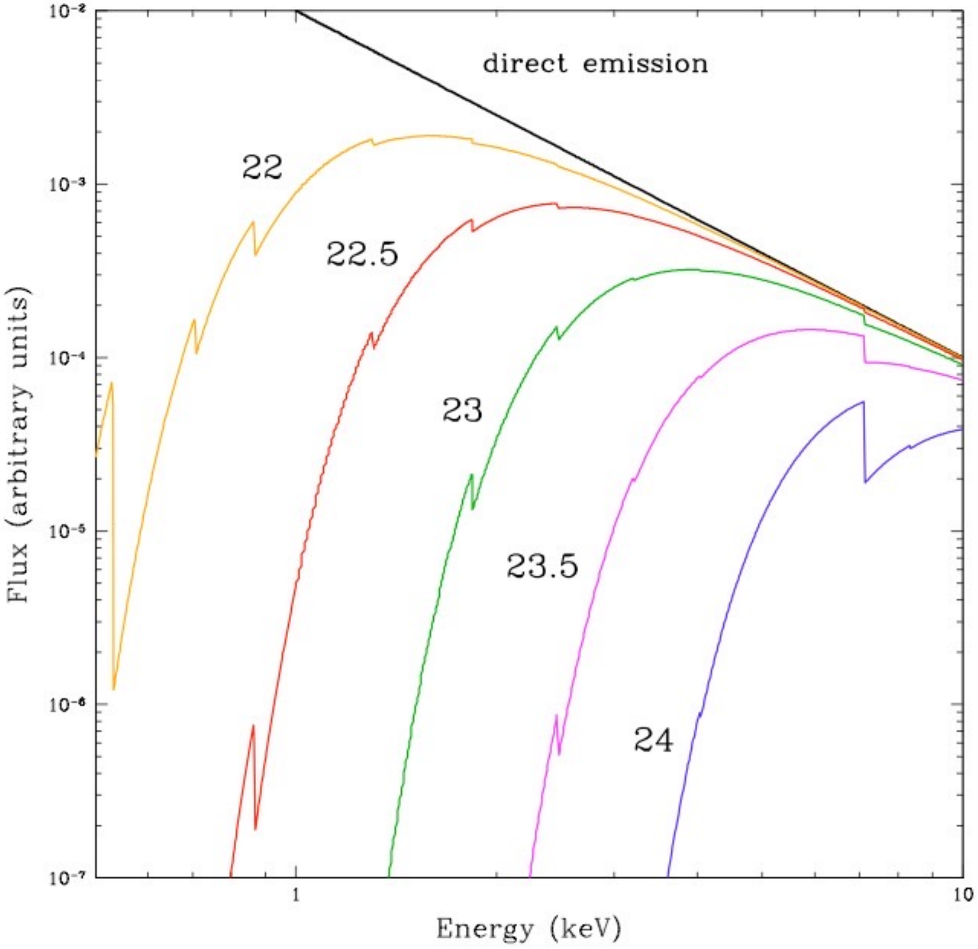


Residuals after a fit with a powerlaw

Photoelectric absorption

Interaction between the primary X-ray emission and the circumnuclear medium. This produces the ’loss’ of X-ray photons, with *the photoelectric cutoff energy depending on the amount of obscuration*

→ in heavily obscured AGN, the soft X-ray emission can be totally absorbed



N_H: hydrogen column density (assuming solar metallicity)

$N_H \sim$ a few$\times 10^{21}$ cm^{-2}: $\tau_{OPT} \sim 1$, absorption at E<1 keV

$N_H \sim 1.5\times 10^{24}$ cm^{-2}: $\tau_{Compton} \sim 1$; ~total absorption at E<10 keV (Compton-thick AGN)

Photoelectric absorption: absorption of a photon by a bound electron. If the photon has an energy higher than the ionization energy of the electron, the residual energy is transferred to the electron as kinetic energy. Dominant process: absorption by K-shell (1s) electrons.

$$\sigma_K = \frac{e^{12} m_e^{3/2} Z^5}{12\sqrt{2}\pi\epsilon_0^6 h^4 c}(h\nu)^{-\frac{7}{2}}$$

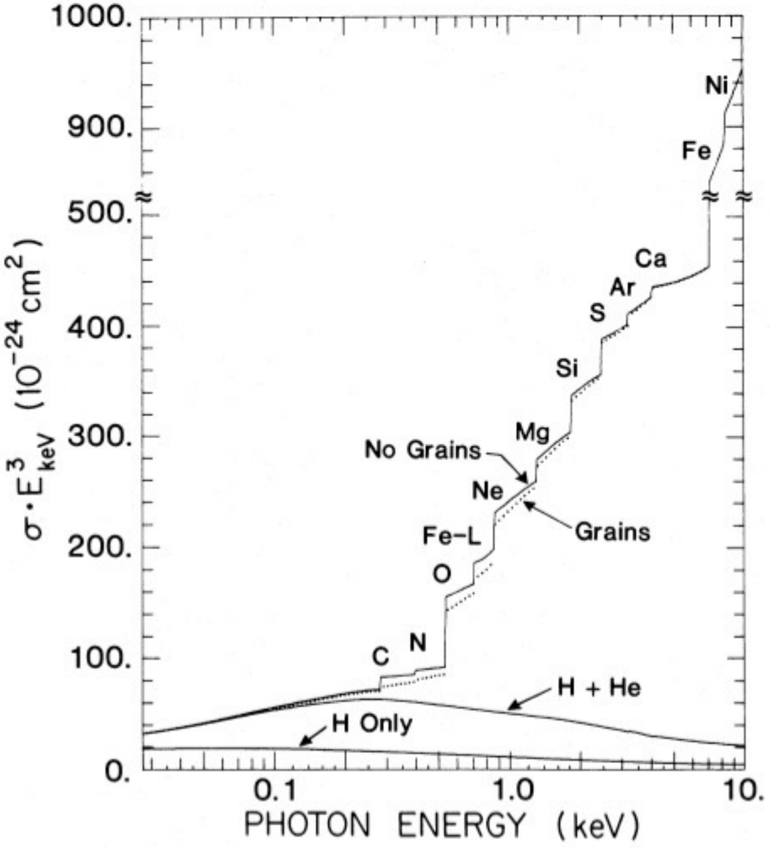
$E^{-3.5}$ dependence

Total cross section: $\sigma_e = \frac{1}{n_H}\Sigma_i n_i \sigma_i$

n_i = density of individual elements

Total optical depth for photoelectric absorption

$$\tau_e(h\nu) = \int \sigma_e n_H dl = 2 \times 10^{-26} \left(\frac{h\nu}{1\ \mathrm{keV}}\right)^{-\frac{8}{3}} \int n_H dl$$



In optical/near-IR we ‘talk’ about dust extinction, in X-rays about gas absorption. Although expressed in hydrogen column density, it is meant as H-equivalent, because absorption is mostly done by metals (assumed metallicity allows one to convert from metal abundance to H abundance)

High-energy emission from AGN: thermal Comptonization (I)

[I] Primary power-law emission: Comptonization: hot electrons vs. cold photons from the accretion disc (Inverse Compton emission).
The heating mechanism of the corona is largely unknown (magnetic reconnection?)

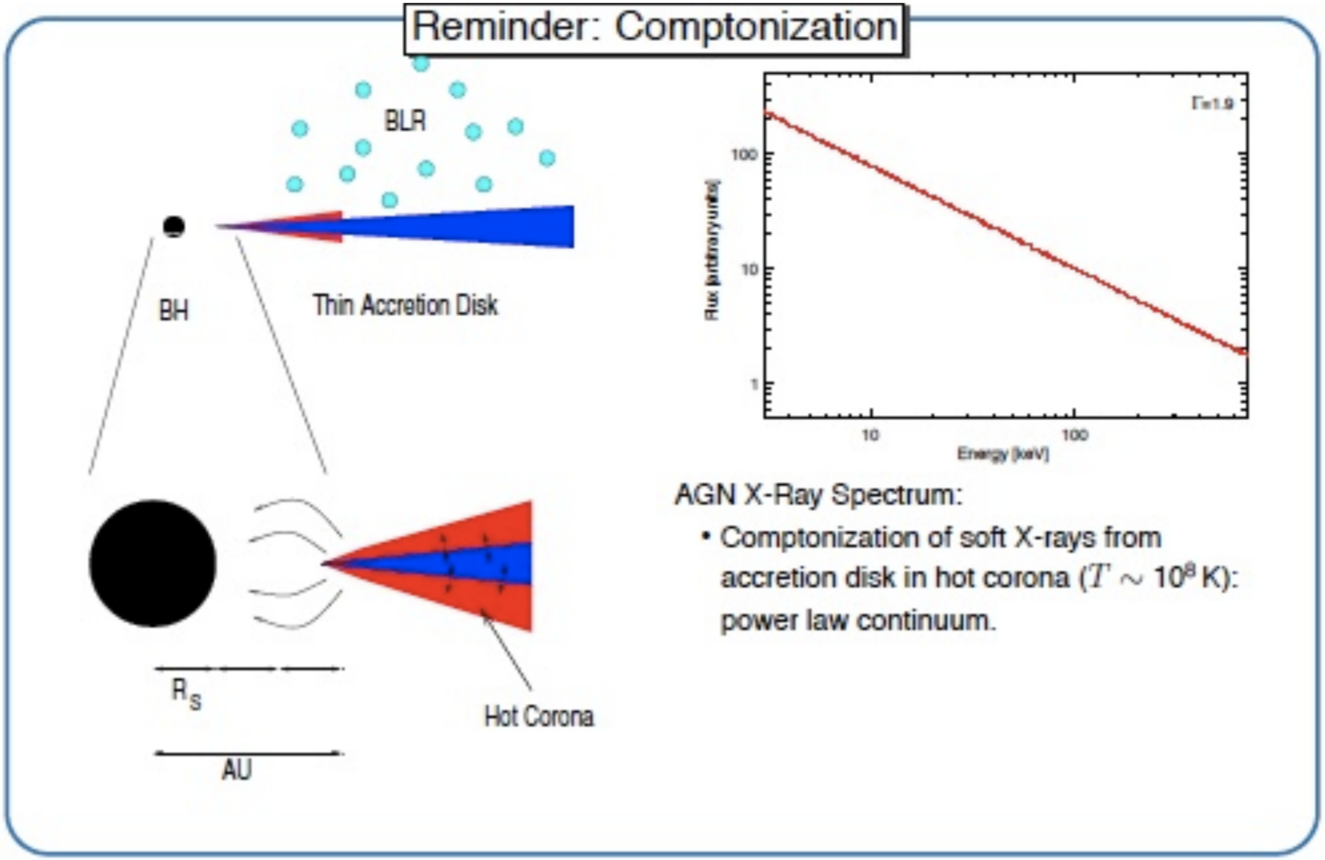
$E \ll 4kT_e$: the photon can gain energy in each of the N scatterings event (IC)

$\Delta E/E \approx 4kT_e/m_ec^2$

y=Compton parameter≈ $\approx 4kT_e/m_ec^2 \max(\tau,\tau^2)$

N depending on the optical depth of the electron gas

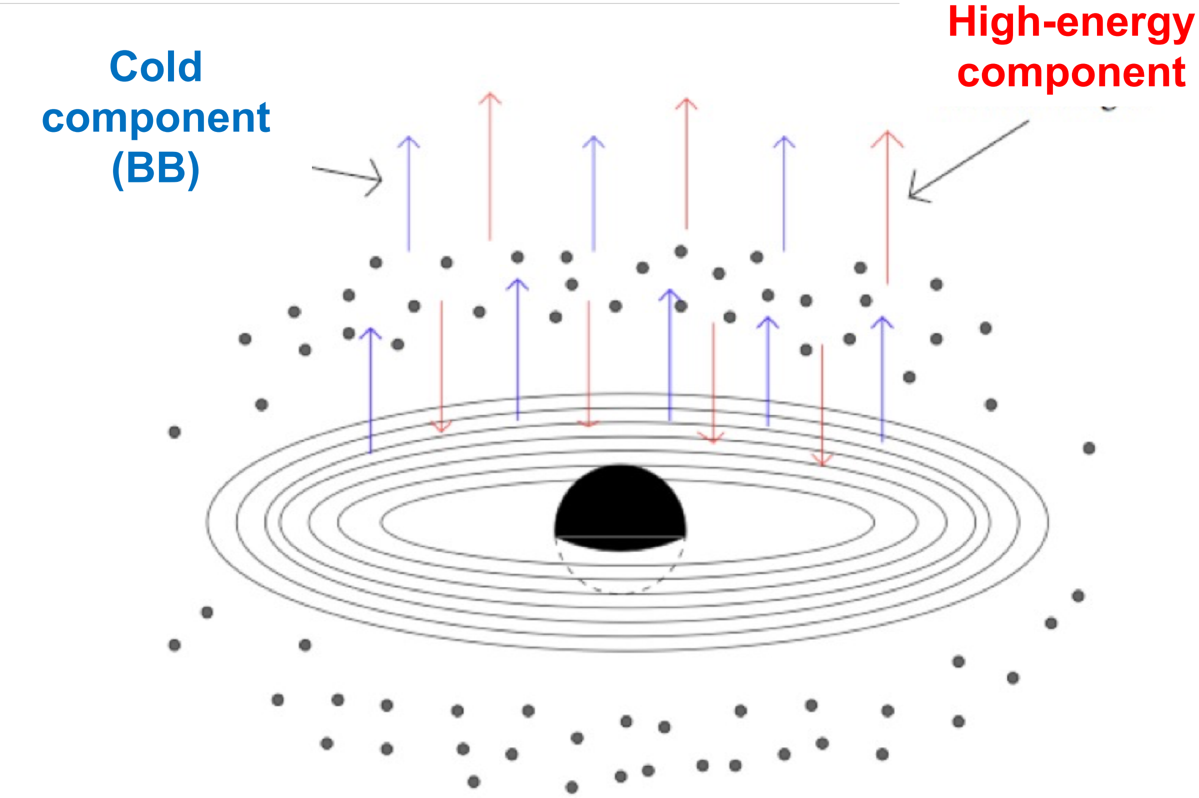
$$E_f \approx E_i \exp\left(N\frac{4kT_e}{m_ec^2}\right) \approx E_i \exp(y)$$



AGN X-Ray Spectrum:

- Comptonization of soft X-rays from accretion disk in hot corona ($T \sim 10^8$ K): power law continuum.

Two-phase model: thermodynamic equilibrium between a “hot” phase (corona) and a “cold” phase (disc)

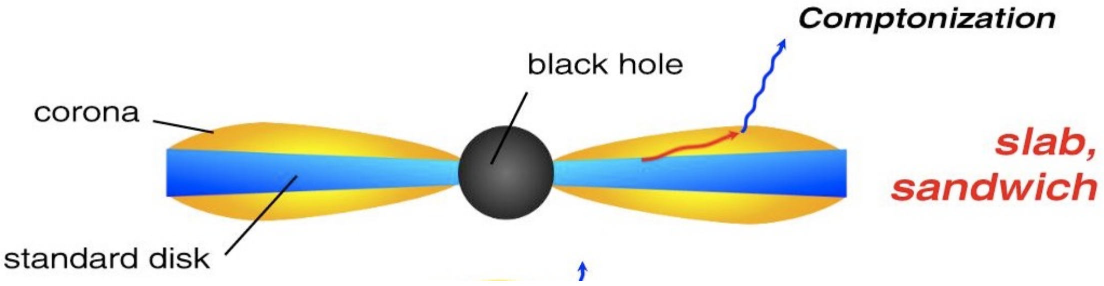


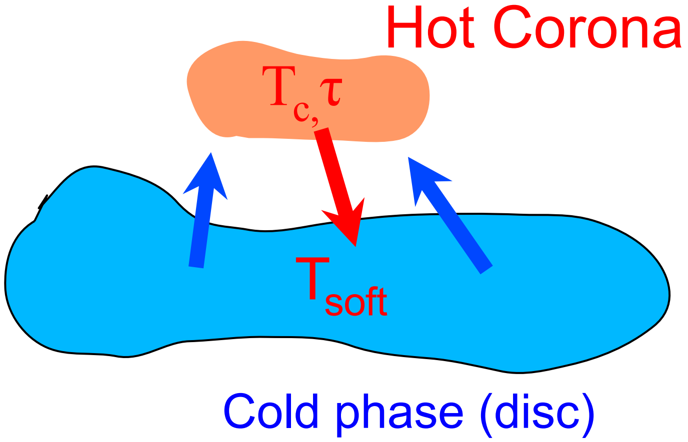
Open issues for the corona

- Position
- Geometry
- Energy transfer from the disc to the corona

Recent studies have placed significant contraints …
at most few tens of RG
(Kara+ … Chartas+)

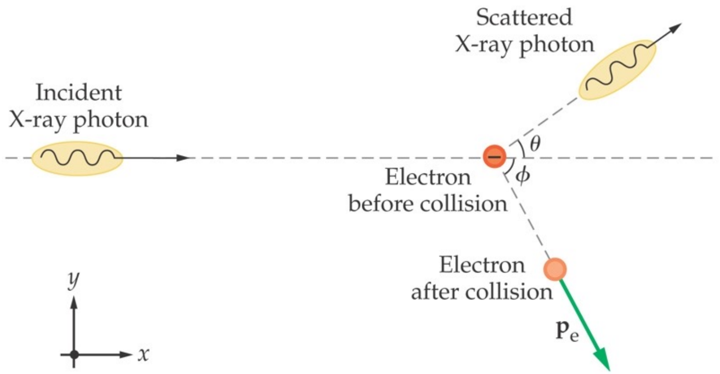
High-energy emission from AGN: thermal Comptonization (II)





Thermal Comptonization from thermal electrons plasma with kT and optical depth τ

Structure of the corona still unknown



Location of the corona ≈ within tens of Rg from the corona (Chartas+, Kara+, De Marco+), estimated for few AGN thus far

If electron at rest:

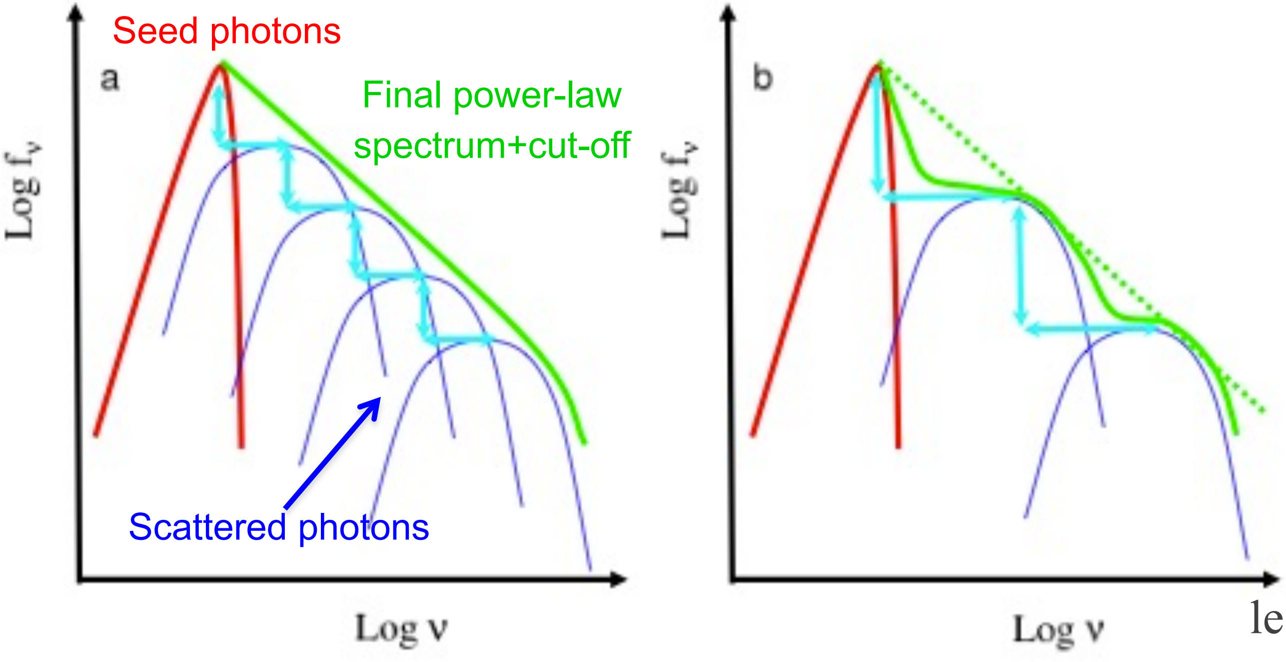
$$\begin{aligned}\Delta E &= E' - E \\ &\simeq -\frac{E^2}{m_e c^2}(1 - \cos\theta)\end{aligned}$$

For non-stationary electron:

$\Delta E < 0 \longrightarrow$ Compton

$\Delta E > 0 \longrightarrow$ Inverse Compton

High-energy emission from AGN: thermal Comptonization (III)



Seed photons

Final power-law spectrum+cut-off

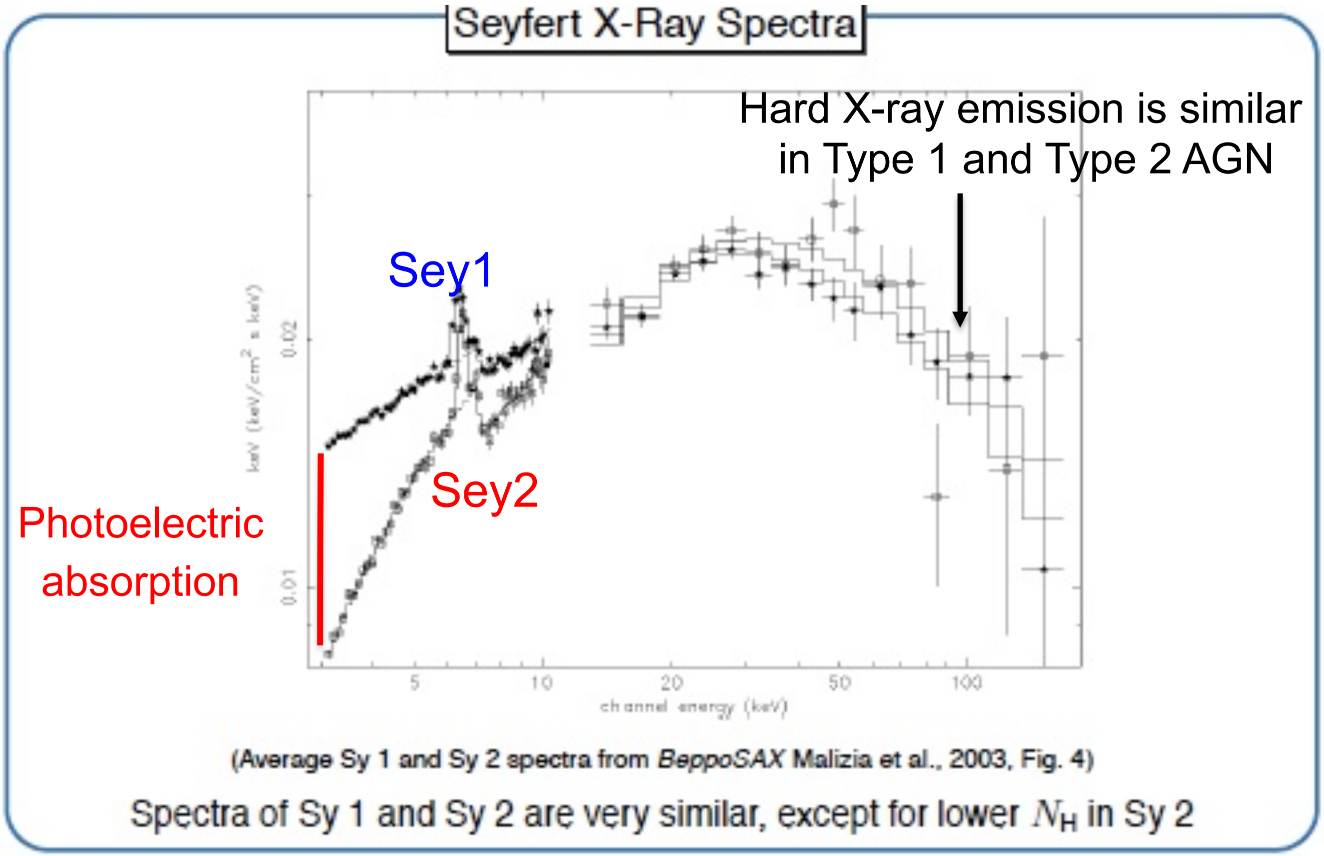
Scattered photons

τ lower,
less scatterings

Seed photons are up-scattered, then become the “new” seed photons for following scatterings ➔ the overall spectrum resembles that of a powerlaw

Thermal Comptonization: electrons have a Maxwellian distribution. Cut-off in the powerlaw when the process of transferring energy from electrons to photons is not efficient anymore ($E_{\text{cut-off}} \approx kT_{\text{electrons}}$)

High-energy emission from AGN: thermal Comptonization (IV): Type 1 vs. Type 2 AGN



Seyfert X-Ray Spectra

Hard X-ray emission is similar in Type 1 and Type 2 AGN

Photoelectric absorption

(Average Sy 1 and Sy 2 spectra from *BeppoSAX* Malizia et al., 2003, Fig. 4)

Spectra of Sy 1 and Sy 2 are very similar, except for lower N_H in Sy 2

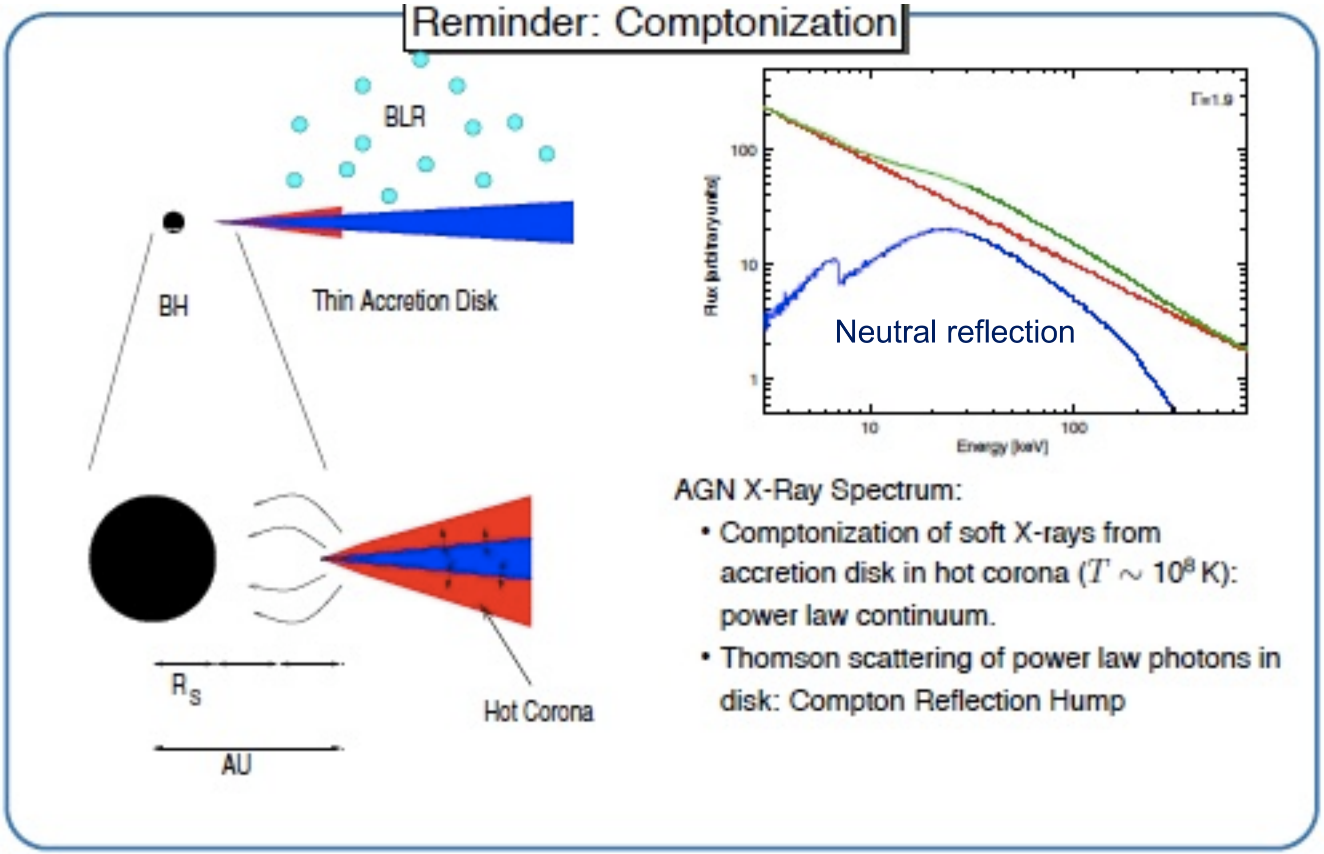
High-energy emission from AGN: Reflection (I)

[II] Compton reflection hump: **Reflection**: power-law photons produced by Inverse Compton are partly scattered by the disc and partly arrive to the observer.

Approx. half of the photons from Comptonization reach the observer, half are directed to the accretion disc

➔ reflection + fluorescence emission

Bump due to photoelectric absorption at low energies, and Compton recoil at high energies (i.e., photons penetrate deeply in the disc because of the Klein-Nishina cross section and lose energy, hence absorption becomes relevant again)



Reminder: Comptonization

AGN X-Ray Spectrum:

- Comptonization of soft X-rays from accretion disk in hot corona ($T \sim 10^8$ K): power law continuum.
- Thomson scattering of power law photons in disk: Compton Reflection Hump

High-energy emission from AGN: Reflection (II)

Recap on the **reflection component**: if the corona emits isopropically, half of its flux will be intercepted by the disc (which is ‘cold’). X-rays will interact with the material of the disc in the following ways

- At E$\lesssim$10 keV, X-rays will be subject to photoelectric absorption by the metal content of the disc (look at the shape of the reflection component).

- At E≈10-40 keV, they will be Thomson scattered and part of them in the upward direction.

- At E$\geqslant$40 keV, the Klein-Nishina effects will start becoming important (not in the Thomson regime anymore): the scattering is preferentially forward directed (the scattered photons will penetrate more deeply into the disc) and the photon energy will be reduced. In other words, photoelectric absorption, initially negligible, is again important, and the photon will eventually be absorbed.

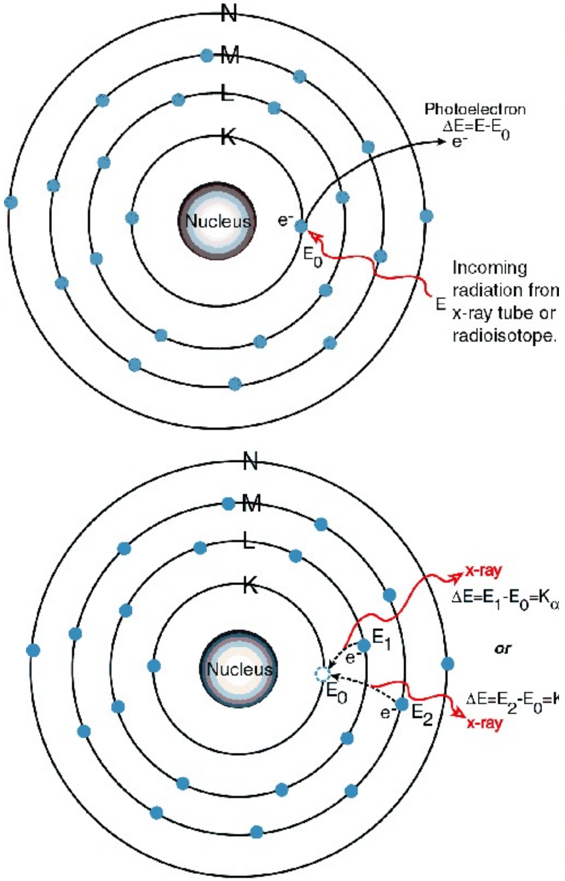
→ *Some of the incoming radiation will be scattered back with a modified, hump-like shape*

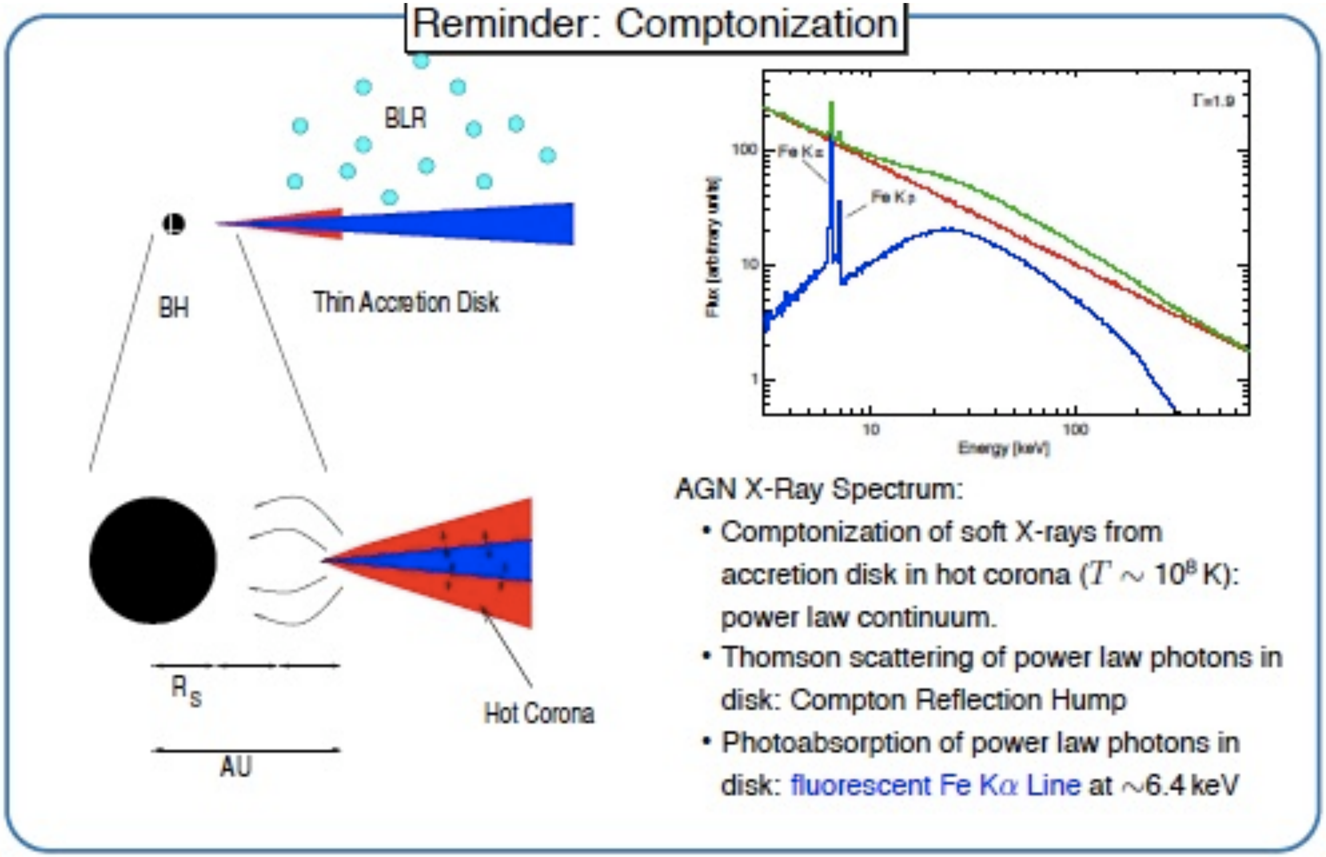
In case of hot (and partially ionized disc), the amount of free electrons will increase the importance of Thomson scattering, thus increasing the ‘left shoulder’ of the Compton reflection → overall, no big ‘hump’, i.e., Compton reflection retains the slope of the original powerlaw

High-energy emission from AGN: Fluorescence emission (I)

[III] **Fluorescence Fe Kα emission** (neutral or ionized, depending on the ionization status of the matter)

already introduced at the beginning of the course



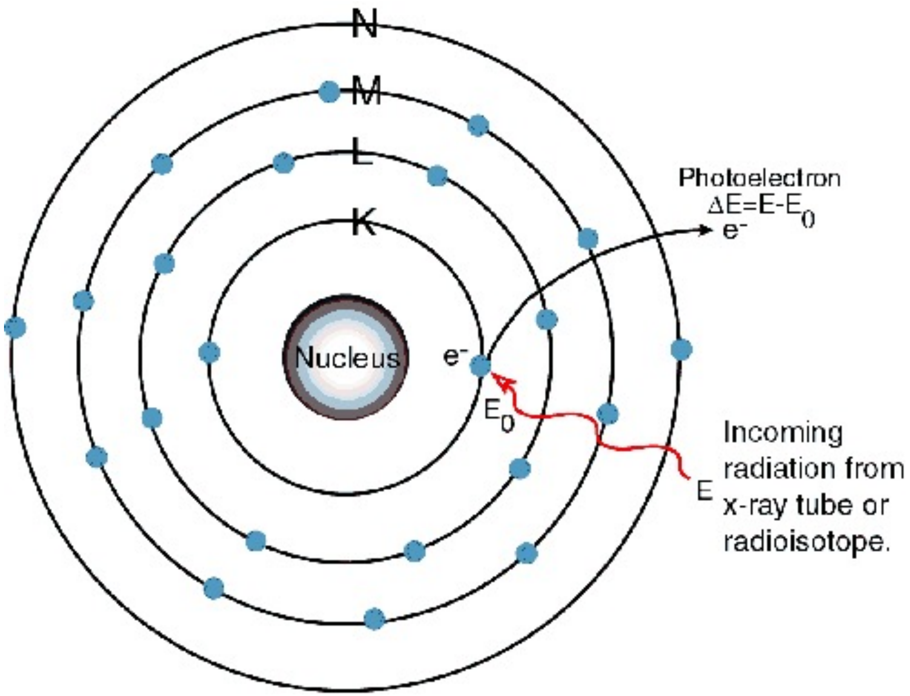


AGN X-Ray Spectrum:

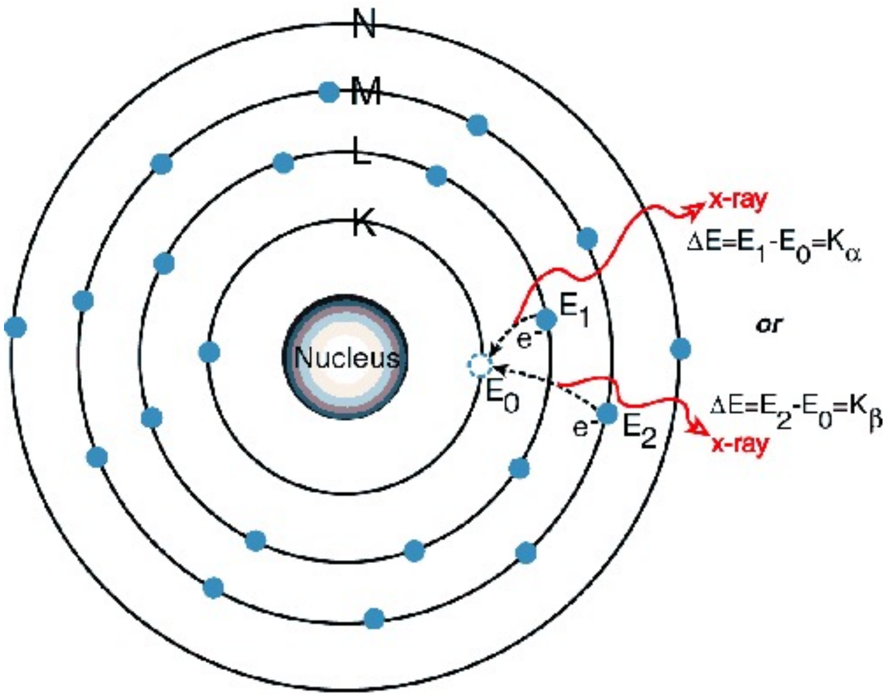
- Comptonization of soft X-rays from accretion disk in hot corona ($T \sim 10^8$ K): power law continuum.
- Thomson scattering of power law photons in disk: Compton Reflection Hump
- Photoabsorption of power law photons in disk: fluorescent Fe Kα Line at ~6.4 keV

High-energy emission from AGN: Fluorescence emission (II)

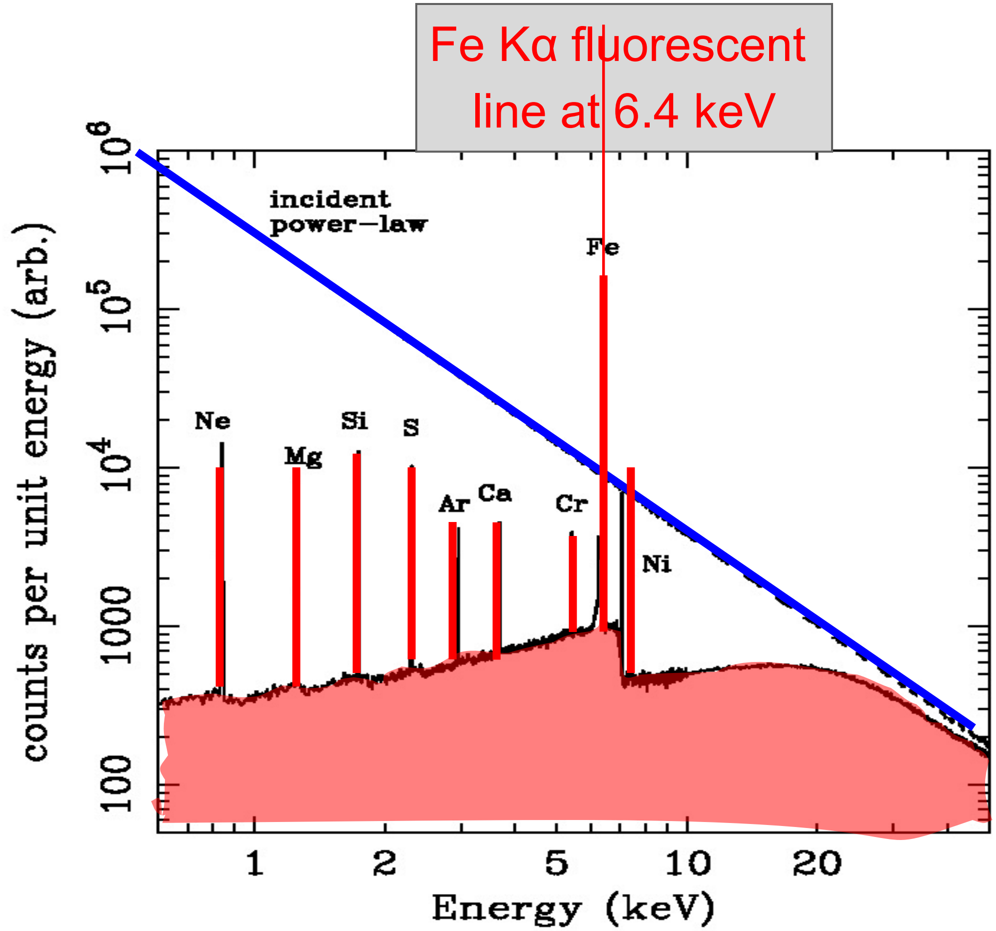
Photoelectric Absorption

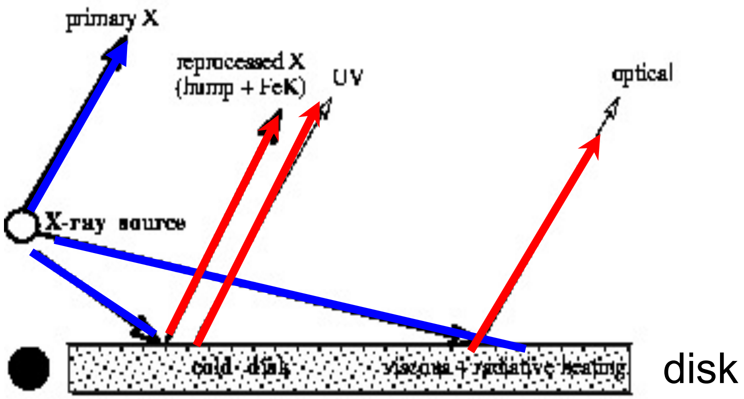


Fluorescence (+ Auger effect)



High-energy emission from AGN: summary of the components

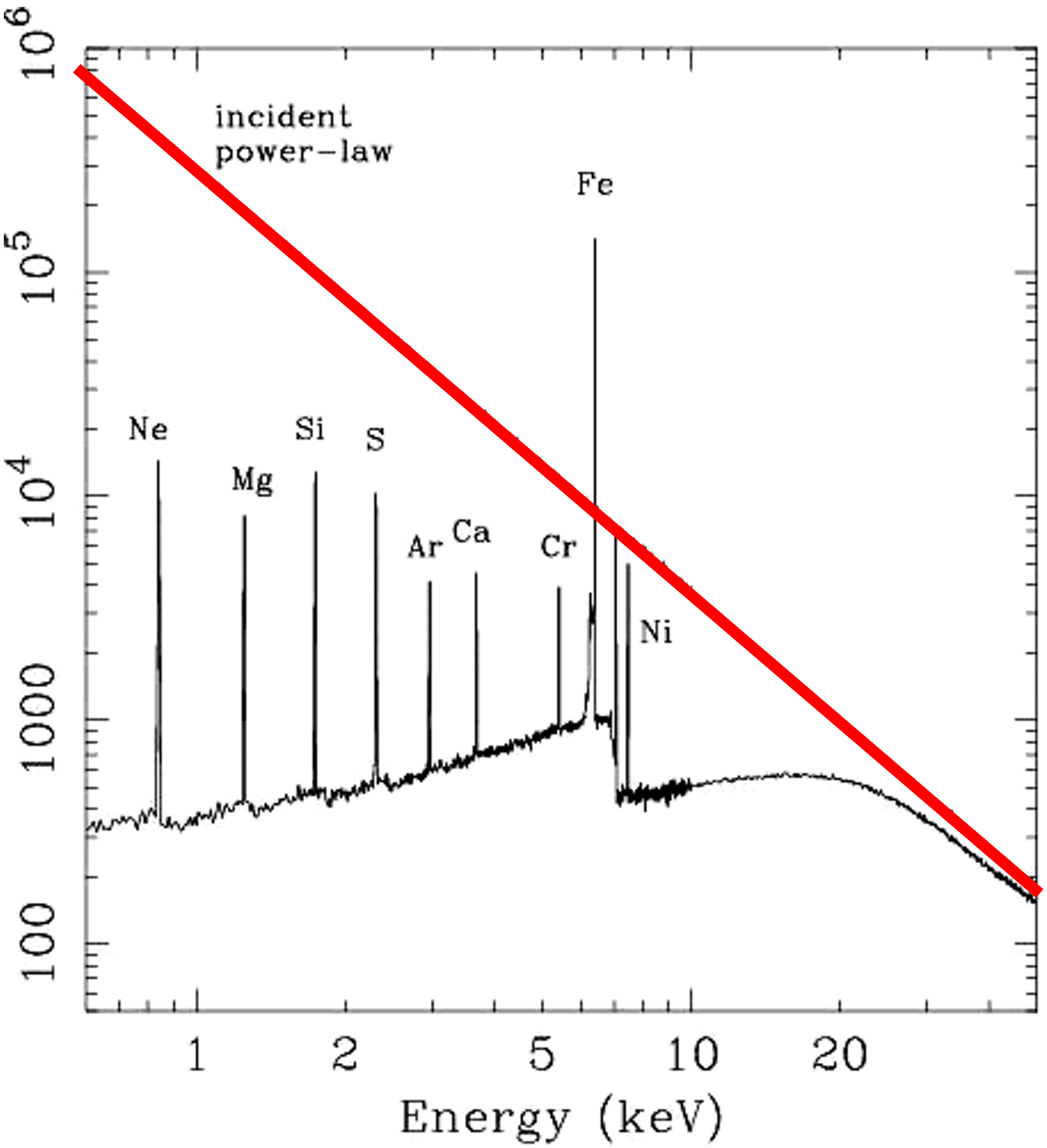

Fe Kα fluorescent line at 6.4 keV



Lamp-post model

Lines from other elements less likely to be observed (higher chances in obscured AGN, where the primary emission is depressed because of photoelectric absorption)

High-energy emission from AGN



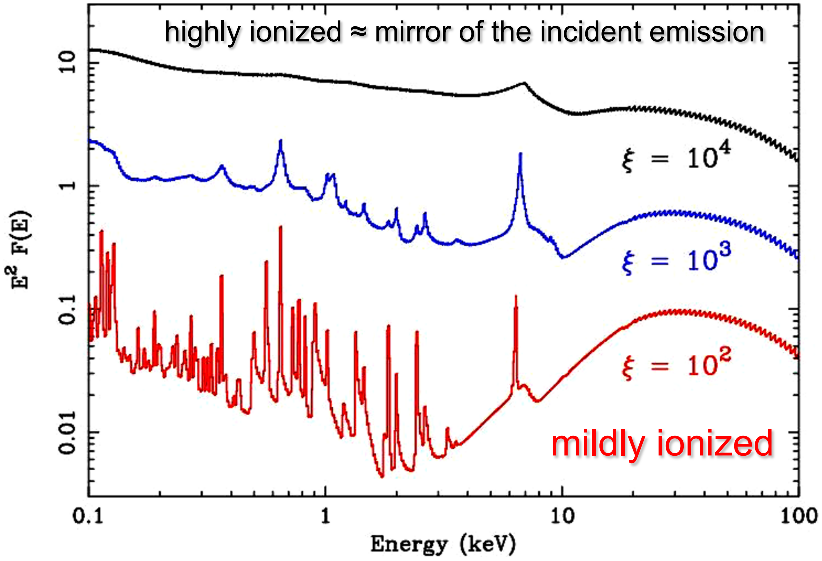
The resulting X-ray reflection spectrum comprises:

- a plethora of fluorescence emission lines from the most abundant metals
- a Compton hump at 20-30 keV due to Compton scattering

In general, the disc upper layers (where reflection arises) are irradiated from above but also heated from below by the main body of the AD ➔ complex structure ➔ radiative transfer problem

One possibility is to mantain the constant density assumption assuming thermal and ionization equilibrium and solve the radiative transfer equations

Ionization parameter

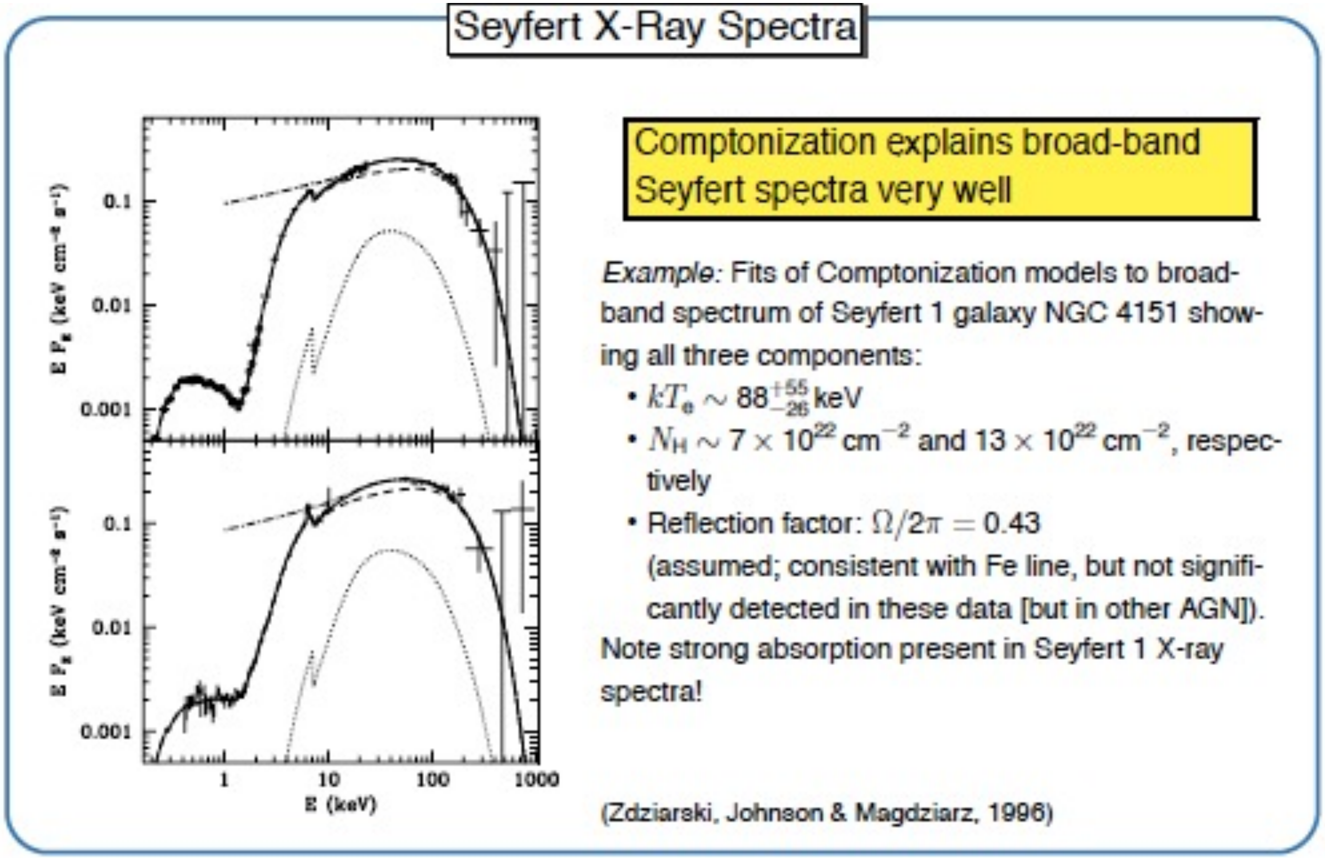


Reflection spectrum in case of **ionized matter**

$$\xi(r) = \frac{4\pi F_X}{n(r)} = \frac{L_X}{nR^2} = \frac{L_X}{N_H R} \ [\mathrm{erg\ cm/s}]$$

In astrophysical cases, the ionization parameter has a non-uniform radial profile

High-energy emission from AGN



Seyfert X-Ray Spectra

Comptonization explains broad-band Seyfert spectra very well

Example: Fits of Comptonization models to broad-band spectrum of Seyfert 1 galaxy NGC 4151 showing all three components:

- $kT_e \sim 88^{+55}_{-26}$ keV
- $N_H \sim 7 \times 10^{22}$ cm^{-2} and 13×10^{22} cm^{-2}, respectively
- Reflection factor: $\Omega/2\pi = 0.43$ (assumed; consistent with Fe line, but not significantly detected in these data [but in other AGN]).

Note strong absorption present in Seyfert 1 X-ray spectra!

(Zdziarski, Johnson & Magdziarz, 1996)

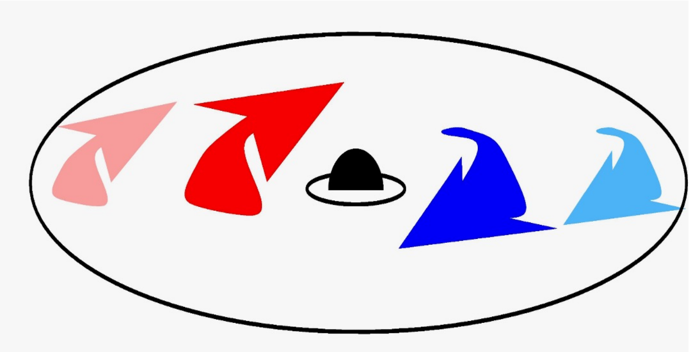
Comptonization seems to work up to high energies (as already experienced in mid ’90)

Need for broad-band X-ray spectra to reveal and characterize all of the components

(better if all data come from the same satellite)

Broad (relativistic) iron lines

Relativistic iron line profile (I)

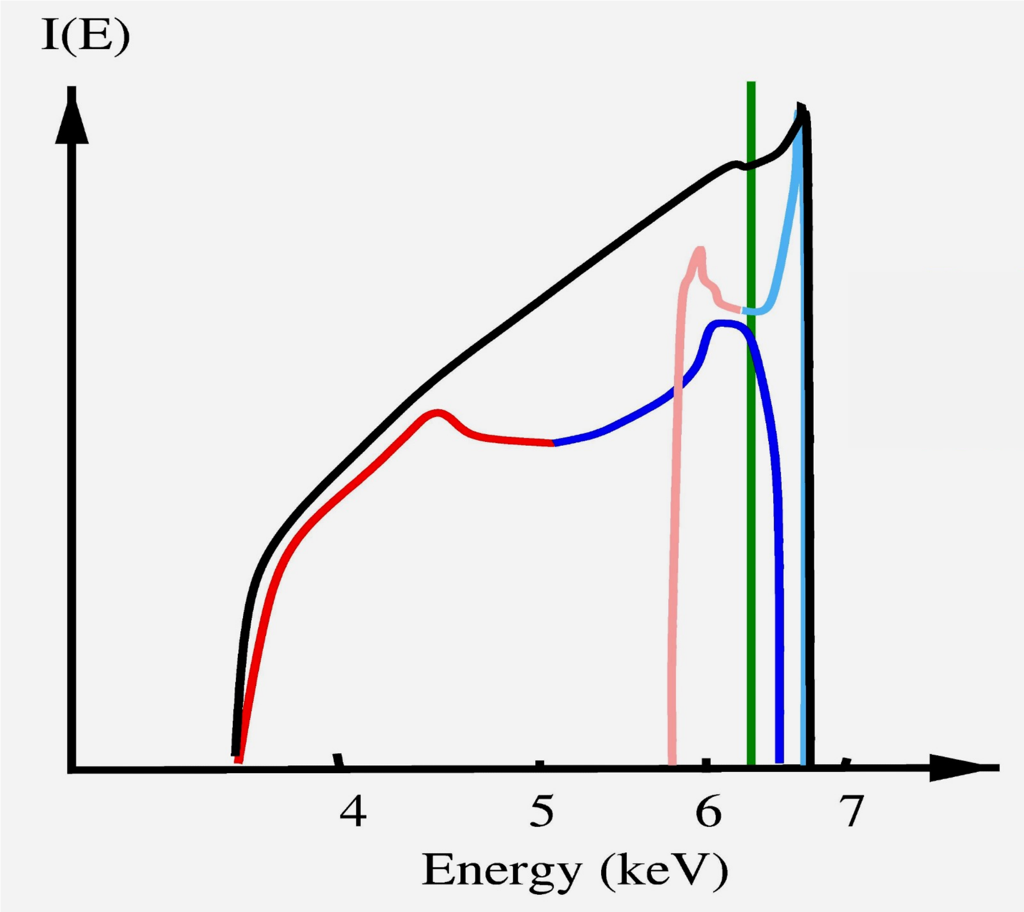


Consider a ring on the disc emitting a narrow Fe line

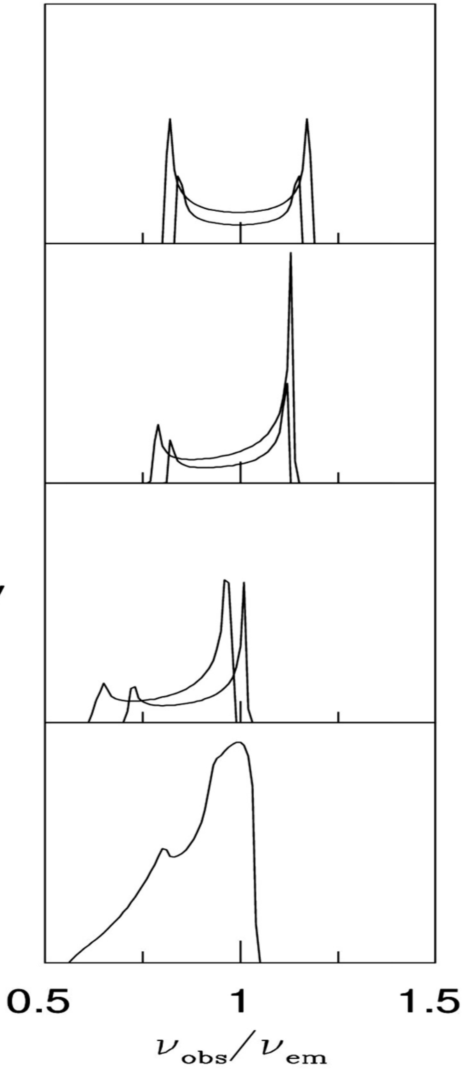
Doppler effect produces a symmetric double-peaked profile

relativistic beaming enhances the blue peak

transverse Doppler and GR redshift shift the overall line profile to the red



Relativistic iron line profile (II)



Newtonian

Special relativity

Transverse Doppler shift

Beaming

General relativity

Gravitational redshift

Line profile

The relativistic line profile depends on:

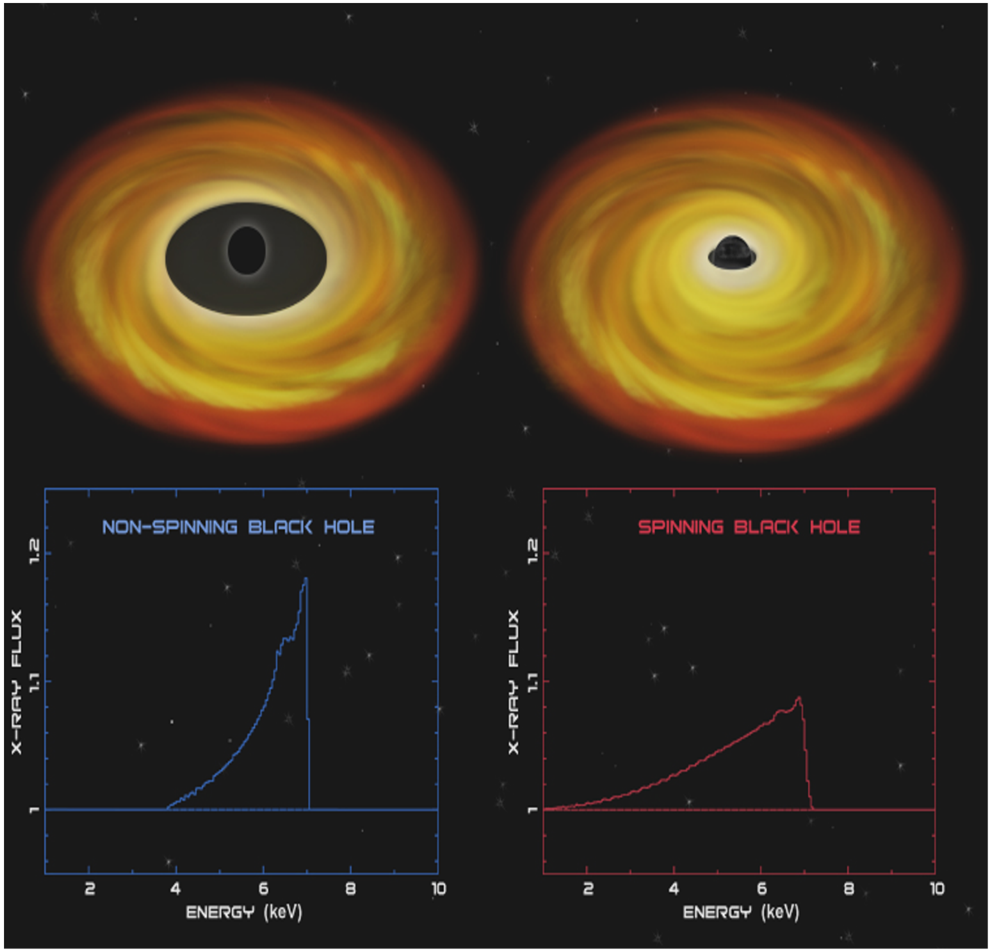
- inner disc radius
- inclination of the disc
- emissivity profile

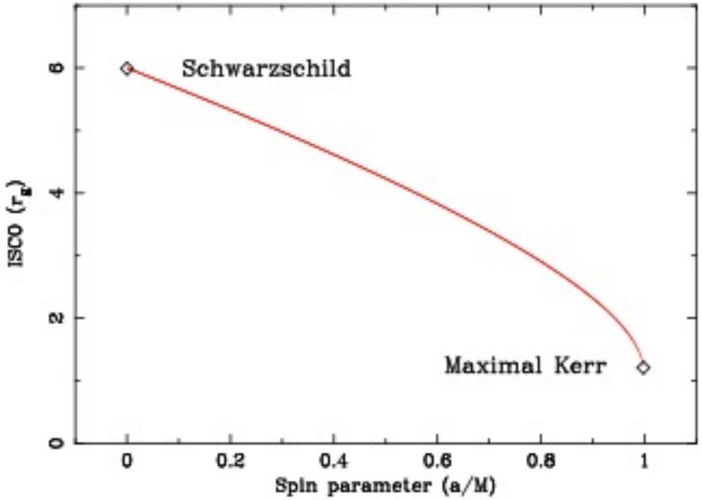
Relativistic iron line profile (III) − Inner disc radius

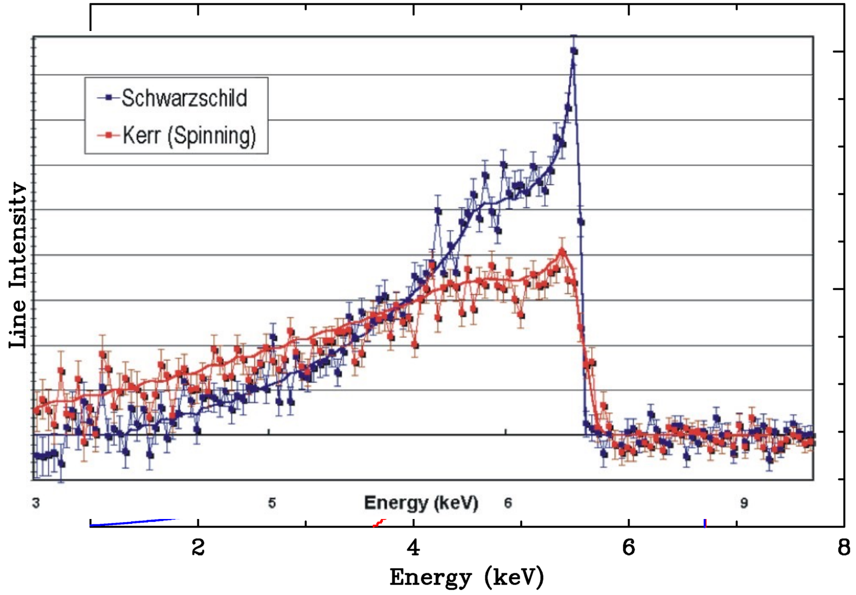
The inner disc radius is generally assumed to be the **ISCO**

Schwarzschild BH: $R_{in}=6R_g$

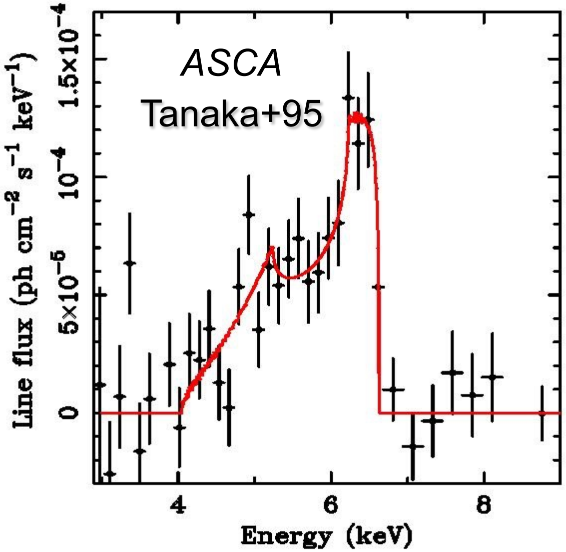
Kerr BH: $R_{in}=1.24R_g$







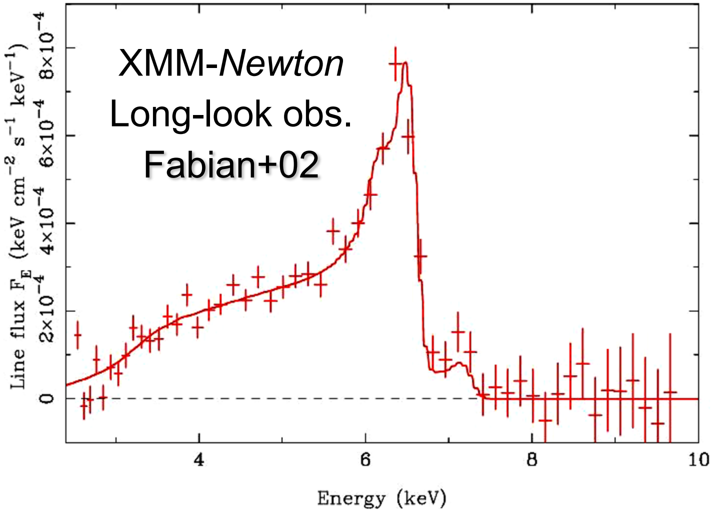
Relativistic iron line profile (IV): Inner disc radius from real X-ray data



ASCA
Tanaka+95

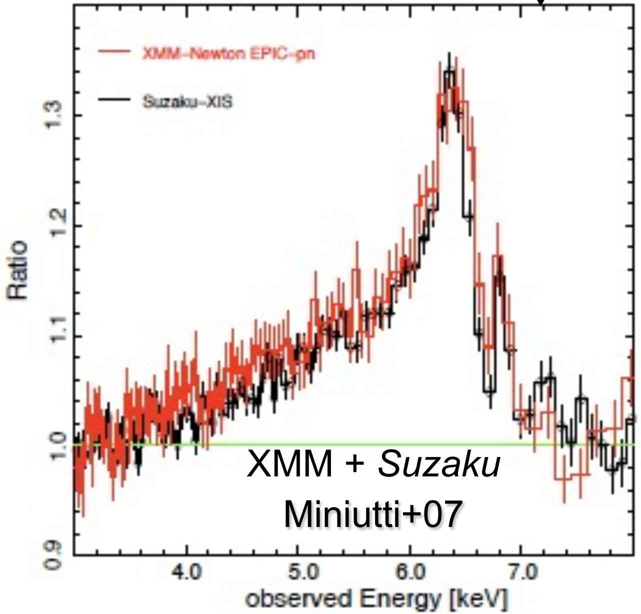
First evidence: MCG-6-30-15 from *ASCA* data (Tanaka+95) − 5 day-obs.

i≈30 deg
Steep emissivity profile
$R_{in} \approx 2R_g$, significant BH spin



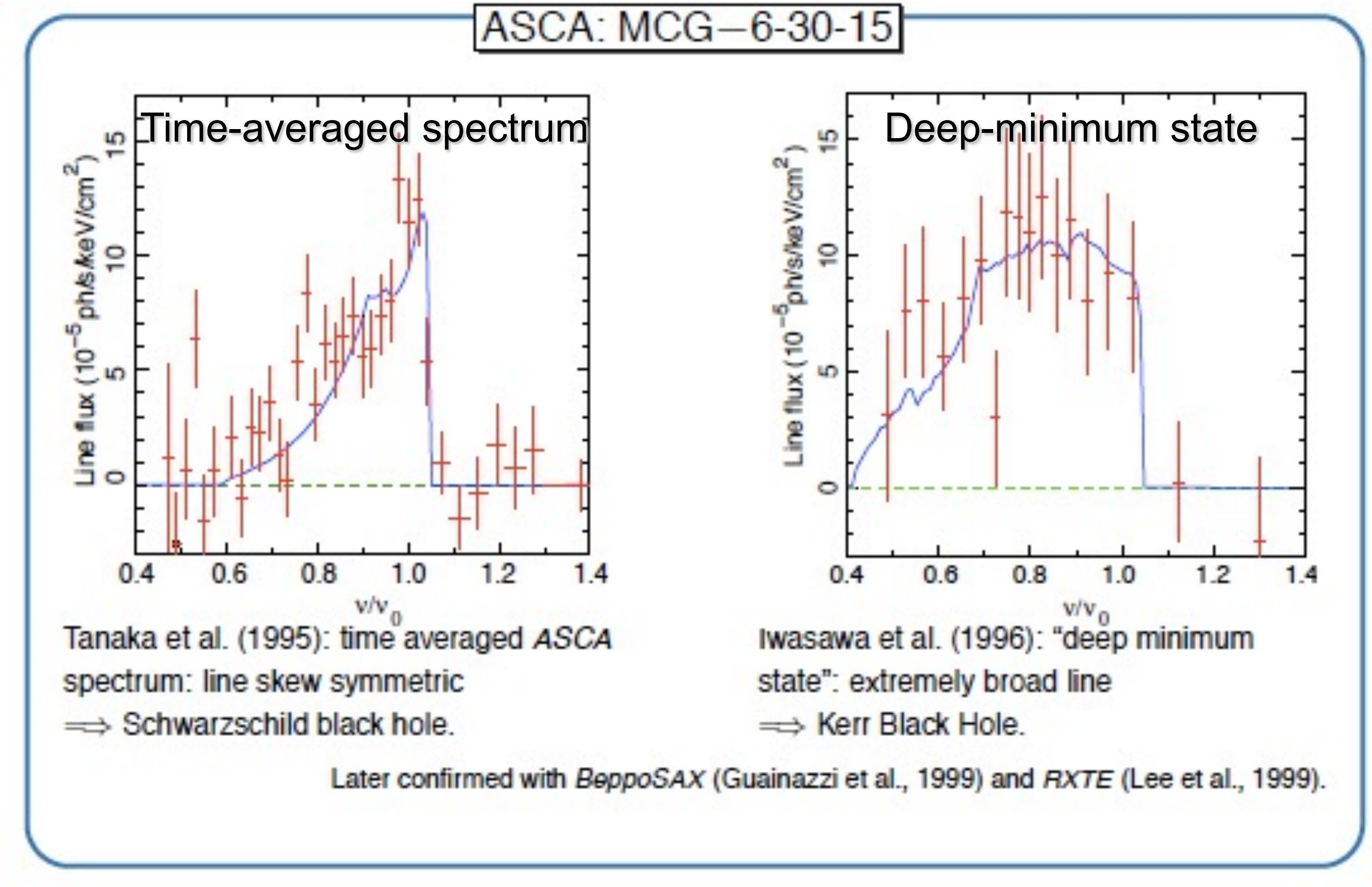
XMM-*Newton*
Long-look obs.
Fabian+02

Large (a>0.985) BH spin



XMM + *Suzaku*
Miniutti+07

Relativistic iron line profile (V)
Inner disc radius from real X-ray data



ASCA: MCG–6-30-15

Time-averaged spectrum

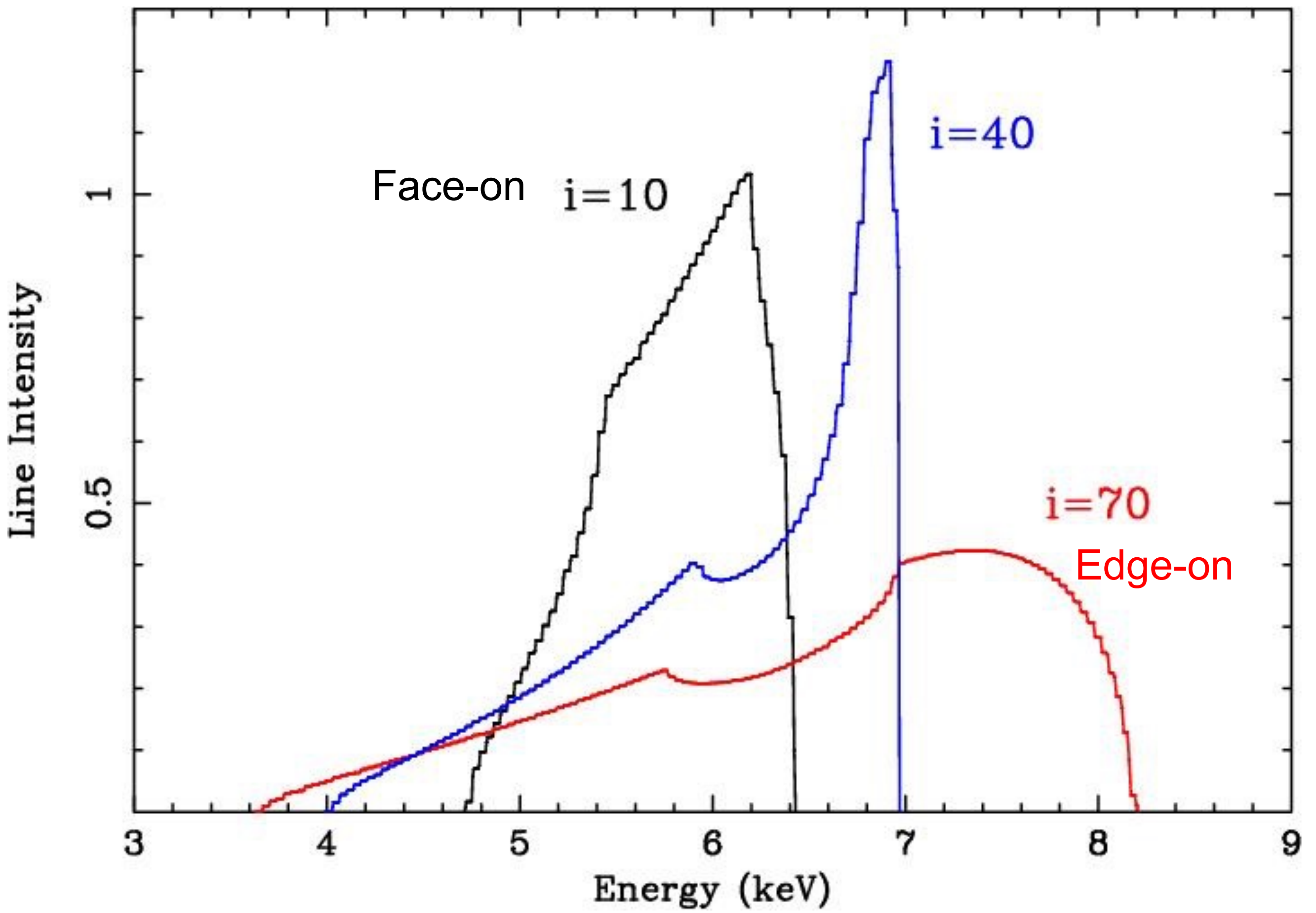
Deep-minimum state

Tanaka et al. (1995): time averaged *ASCA* spectrum: line skew symmetric
⟹ Schwarzschild black hole.

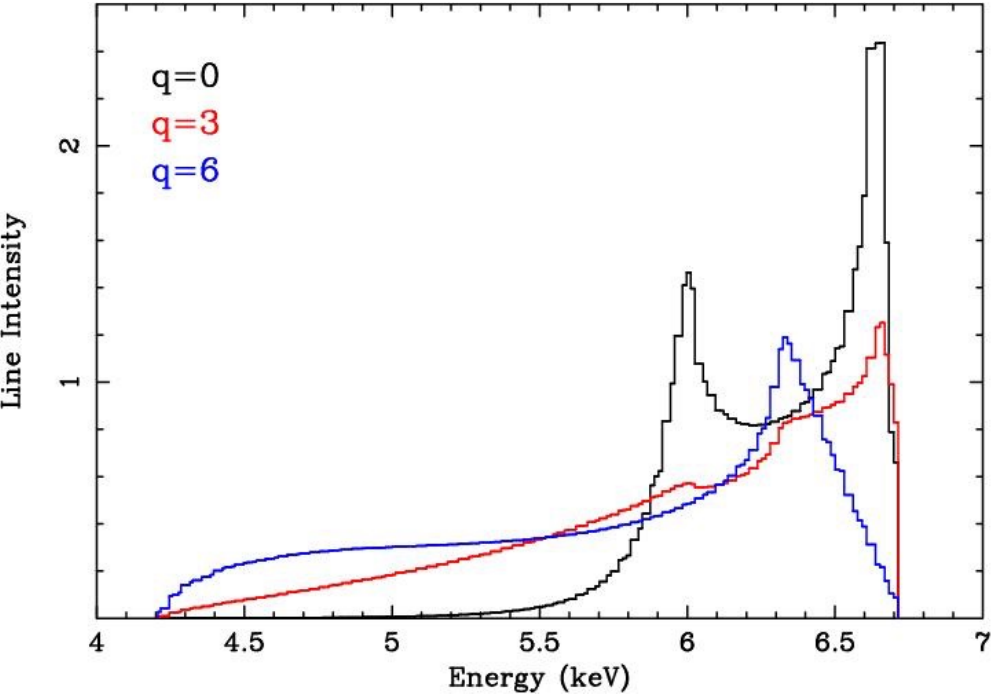
Iwasawa et al. (1996): “deep minimum state”: extremely broad line
⟹ Kerr Black Hole.

Later confirmed with *BeppoSAX* (Guainazzi et al., 1999) and *RXTE* (Lee et al., 1999).

Relativistic iron line profile (VI) − Inclination angle of the disc

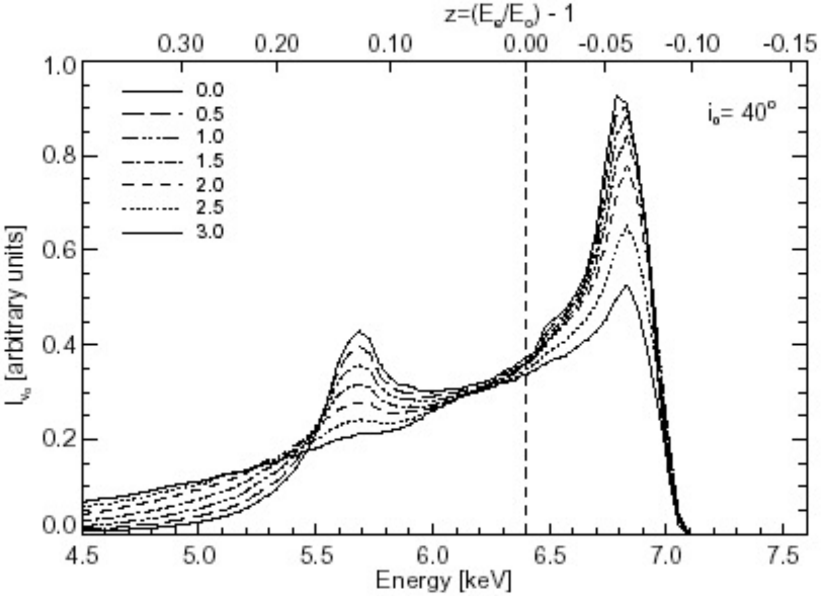


Relativistic iron line profile (VII) − Emissivity profile

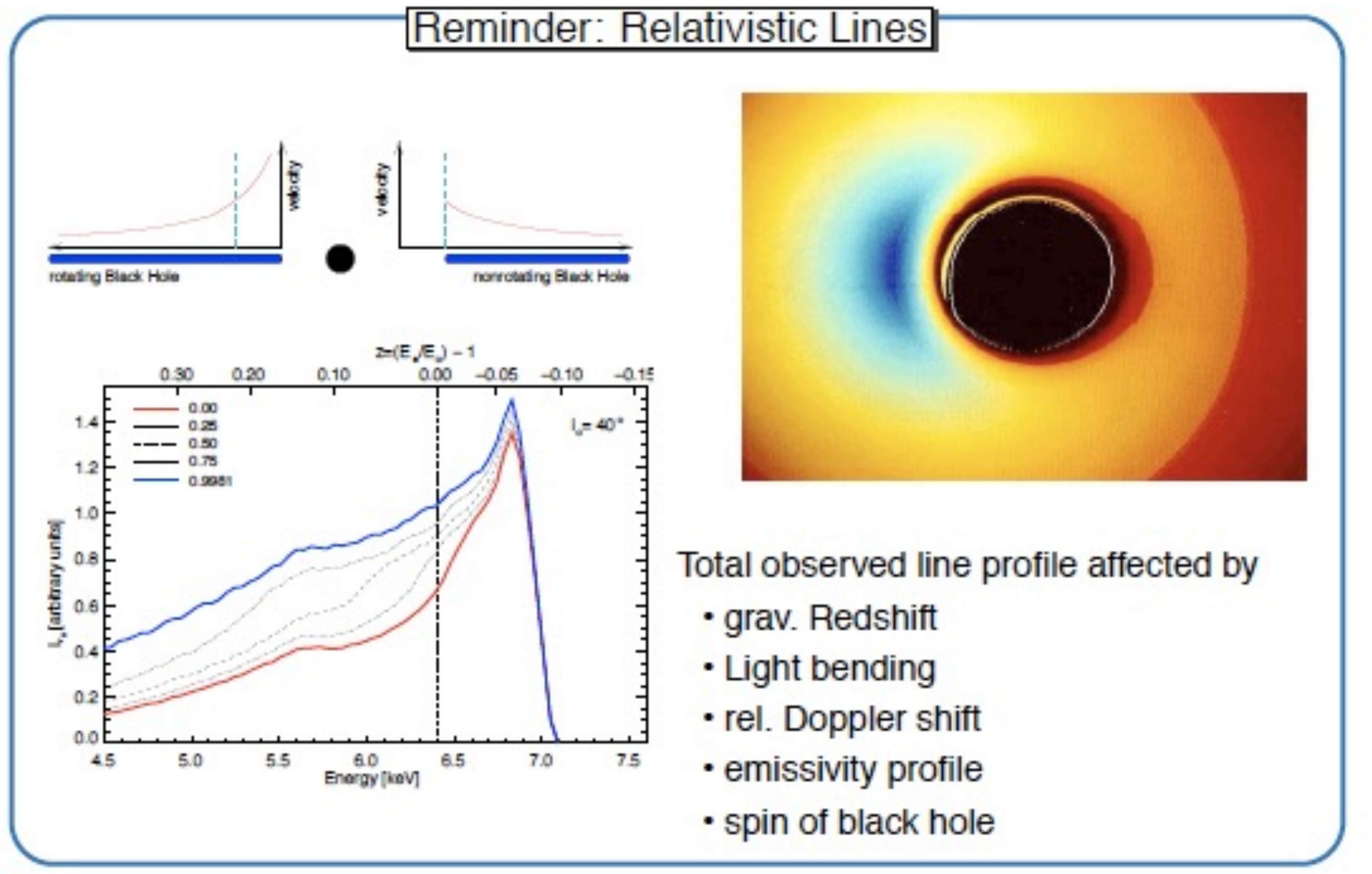


Emissivity profile:

$$\varepsilon(r) \propto r^{-q}$$



Relativistic iron line profile (VIII) − Black Hole spin



Reminder: Relativistic Lines

Total observed line profile affected by

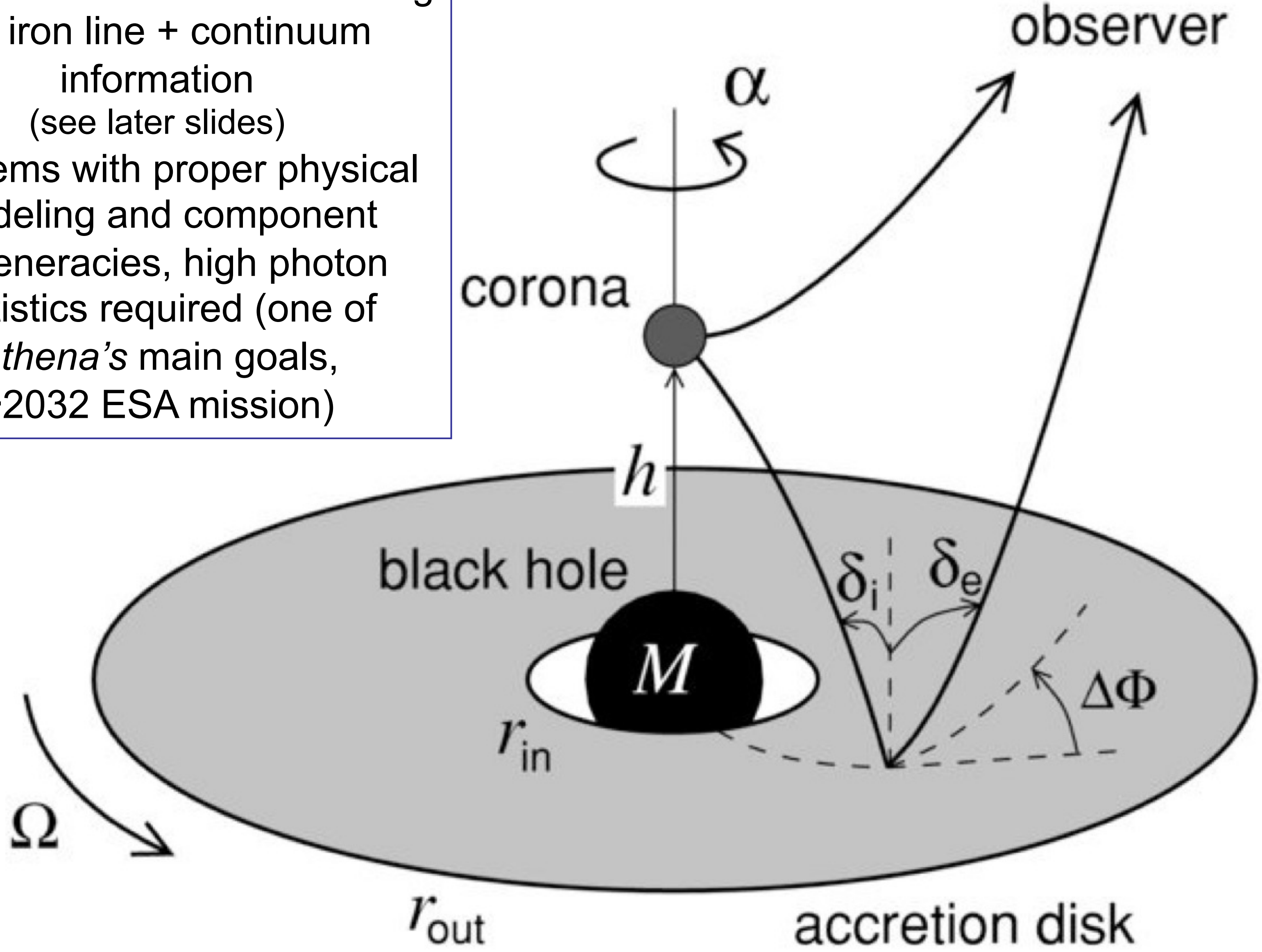
- grav. Redshift
- Light bending
- rel. Doppler shift
- emissivity profile
- spin of black hole

Detailed physical models required to fit these lines and good data, besides a good knowledge of the underlying spectral continuum → spectral component degeneracy may be an issue

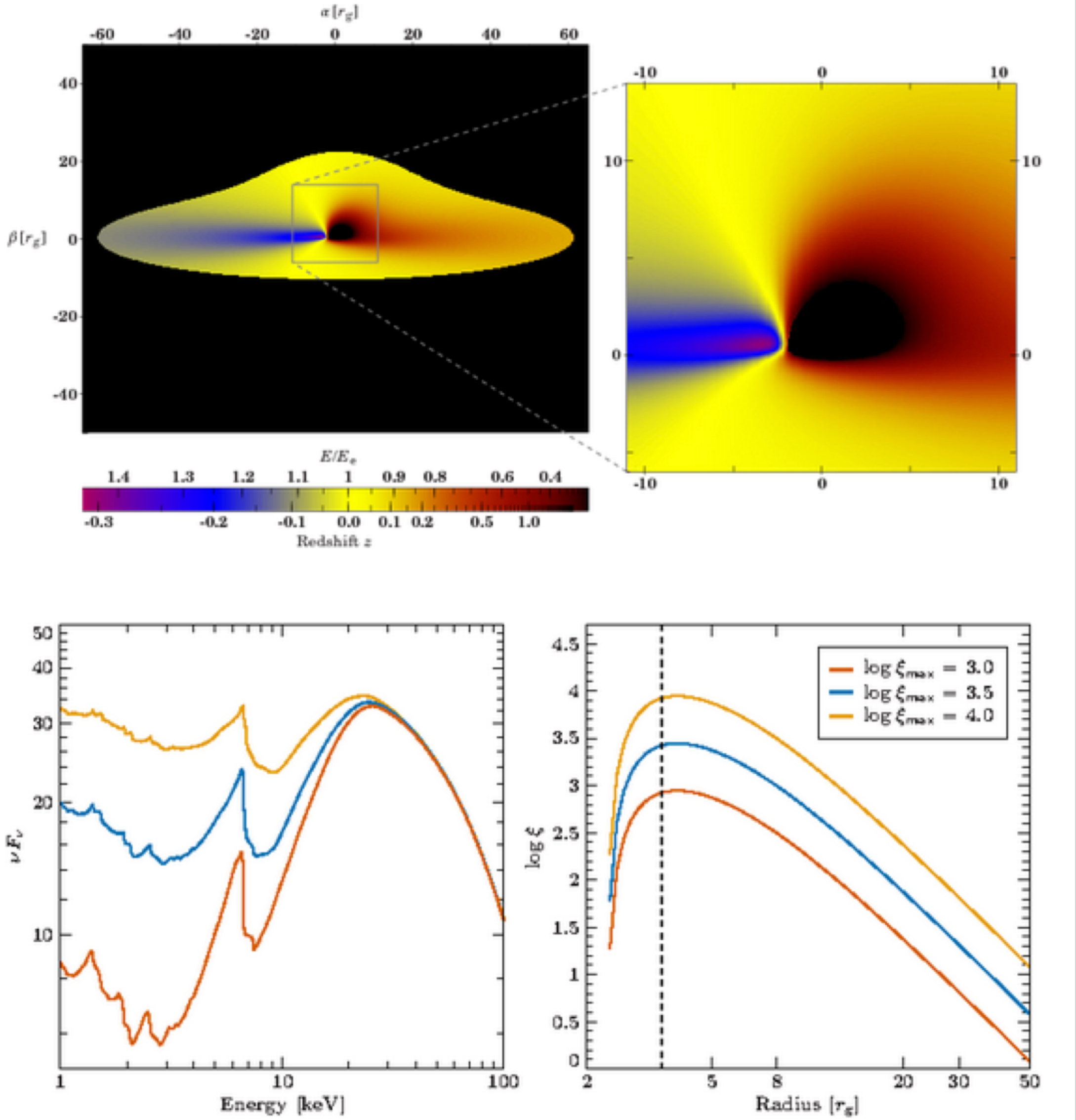
BH spin can be measures using the iron line + continuum information

(see later slides)

Problems with proper physical modeling and component degeneracies, high photon statistics required (one of *Athena's* main goals, ~2032 ESA mission)



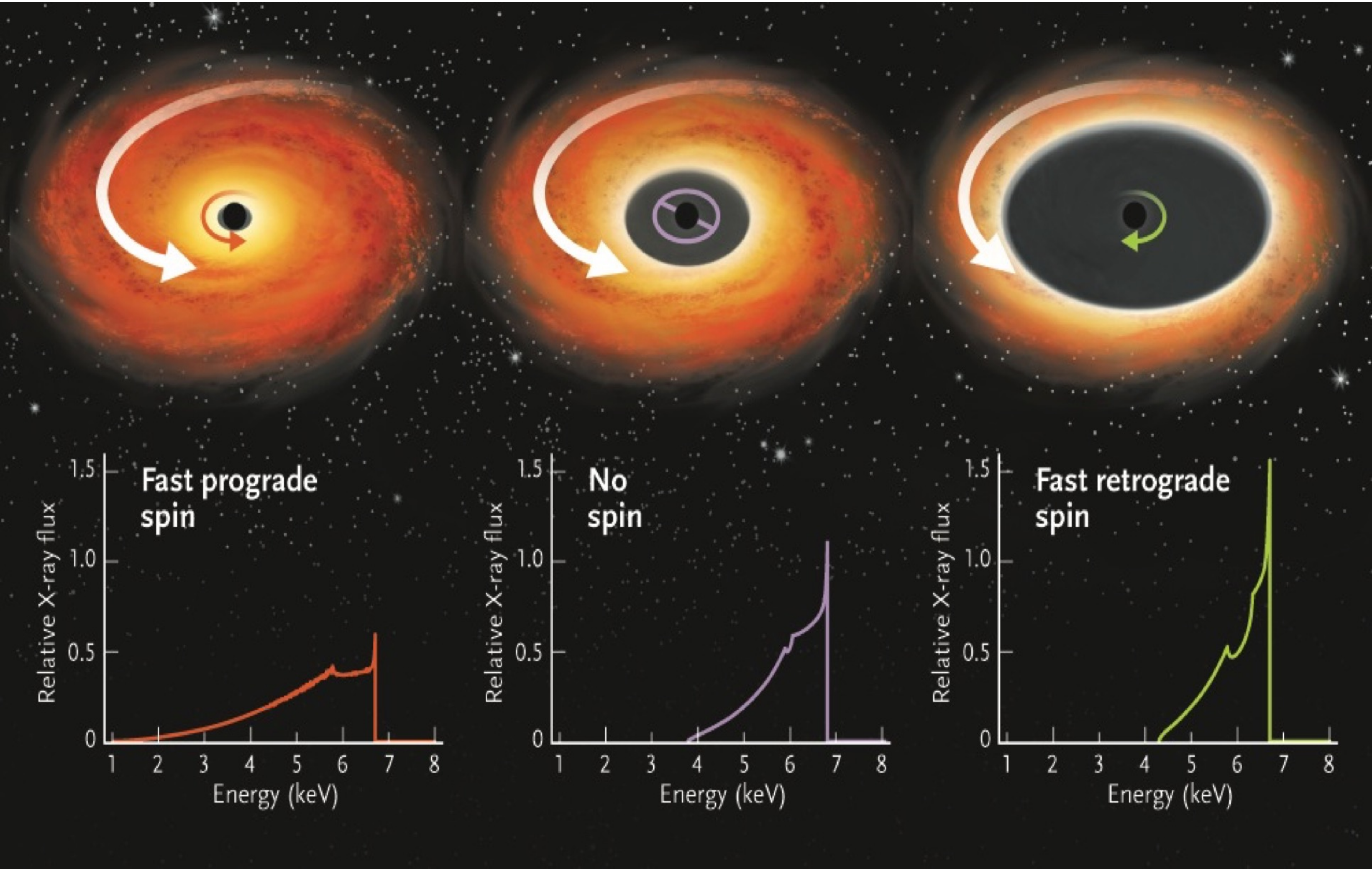
Just an example of more sophisticated modeling



Model **RELXILL**
Emission by a disk illuminated by a nearby (point) source, with complete treatment of (general) relativistic effects.

Complications:
disk emissivity
disk ionization
density of the disk

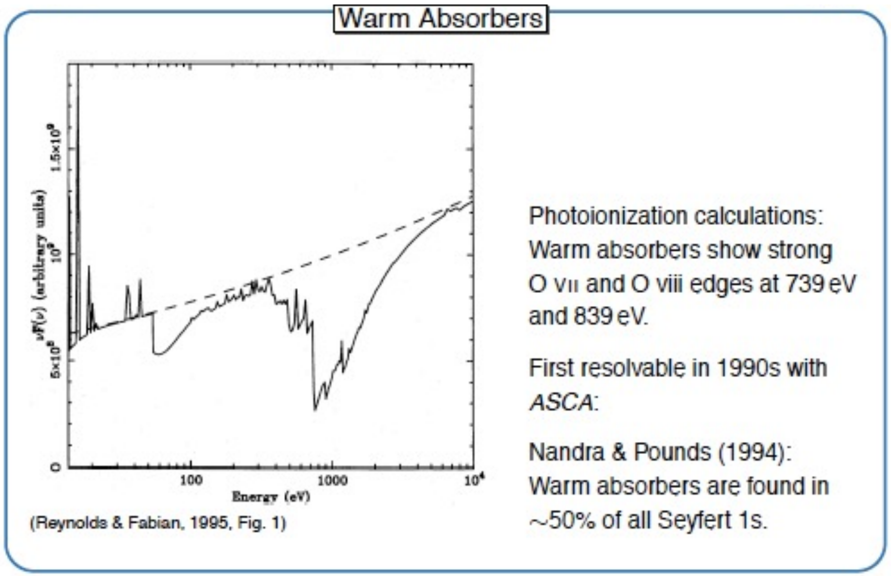
http://www.sternwarte.uni-erlangen.de/~dauser/research/relxill/



Fast prograde spin
No spin
Fast retrograde spin
Relative X-ray flux
0
0.5
1.0
1.5
Energy (keV)
1
2
3
4
5
6
7
8

Warm absorber

Warm absorber (I)



Warm Absorbers

(Reynolds & Fabian, 1995, Fig. 1)

Photoionization calculations: Warm absorbers show strong O vii and O viii edges at 739 eV and 839 eV.

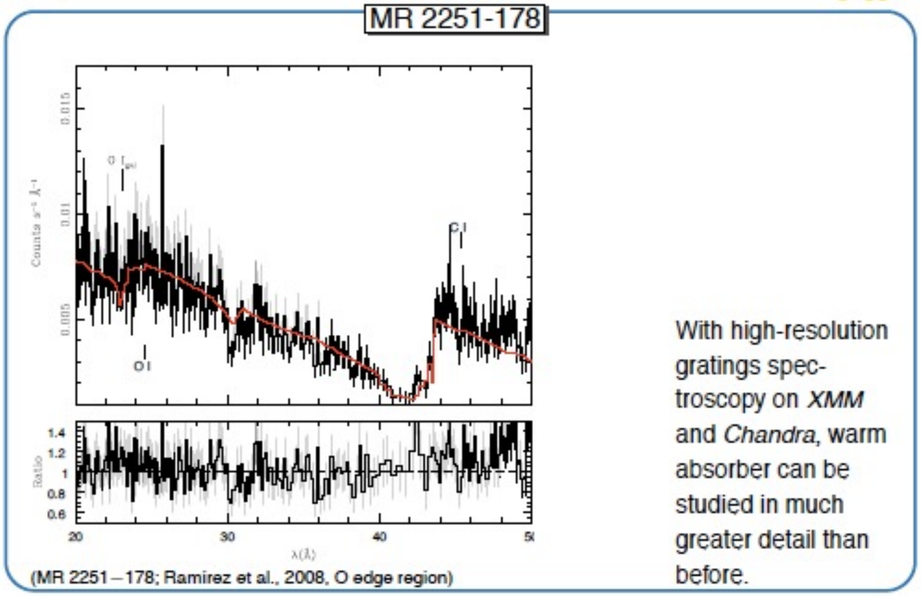
First resolvable in 1990s with *ASCA*:

Nandra & Pounds (1994): Warm absorbers are found in ∼50% of all Seyfert 1s.

In ≈50% of Sey 1s

Prominent ionized O edges (E≈0.74−0.84 keV)
in low-resolution X-ray spectra

More detailed studies and more line profiles
from recent X-ray grating spectroscopy

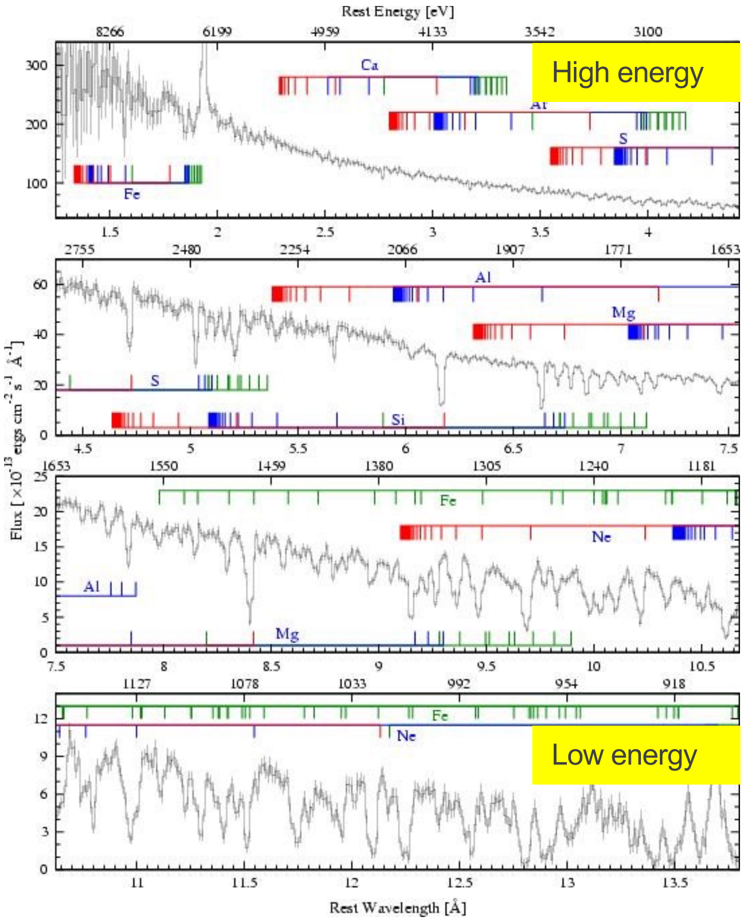


MR 2251-178

(MR 2251−178; Ramirez et al., 2008, O edge region)

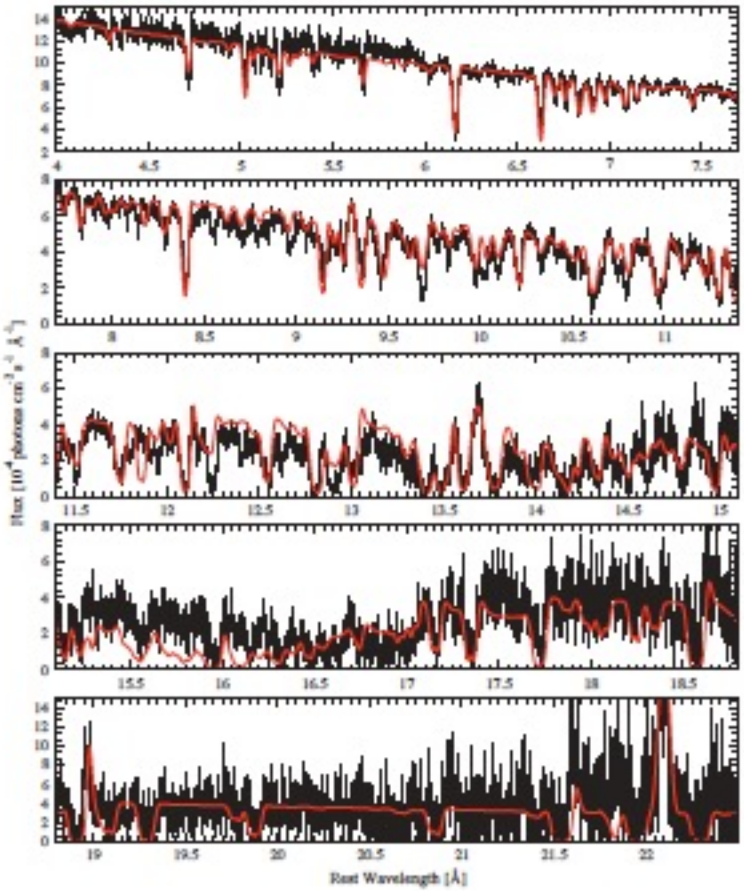
With high-resolution gratings spectroscopy on *XMM* and *Chandra*, warm absorber can be studied in much greater detail than before.

Warm absorber (II)



High energy

Low energy



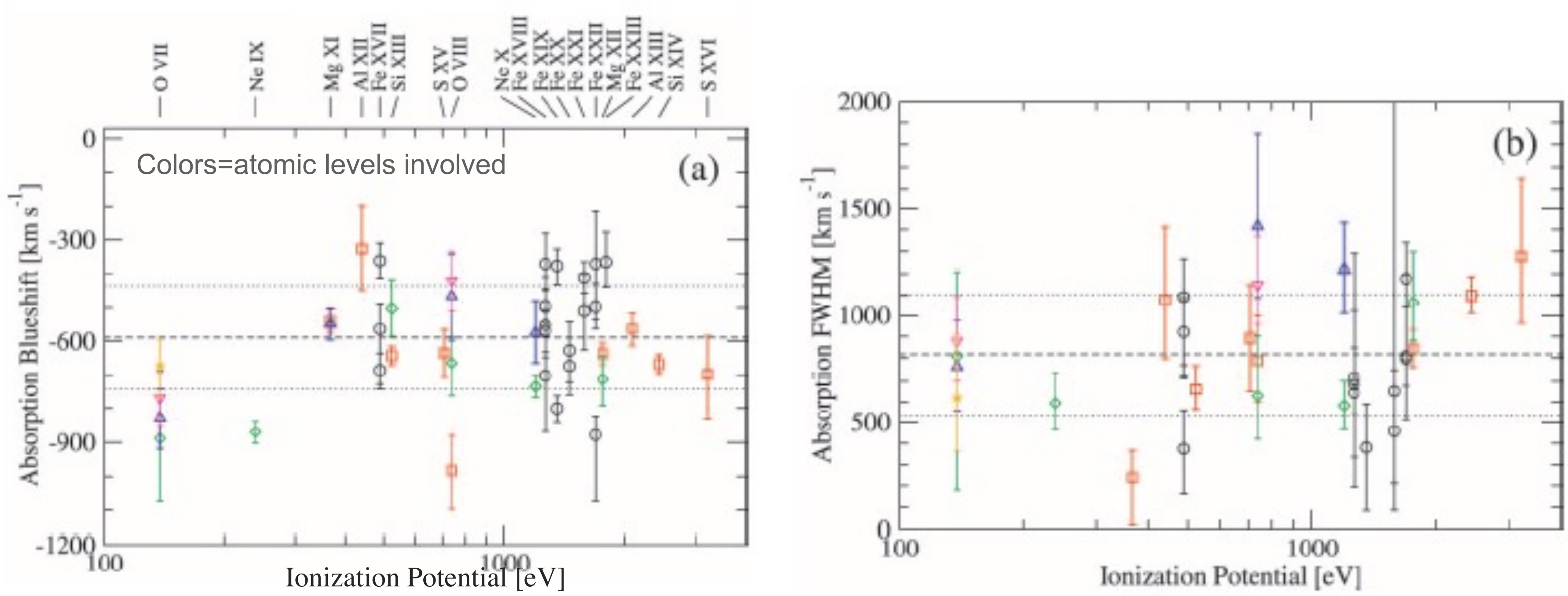
NGC 3783 (≈900 ks *Chandra*) − Kaspi et al. (2002) + Netzer et al. (2002)

➔ Multiple ionization and kinetic components with outflows of ≈100-1000 km/s

Warm absorber (III)

The highly ionized lines in warm absorber spectra are blue-shifted

➔ wind from the accretion disc?

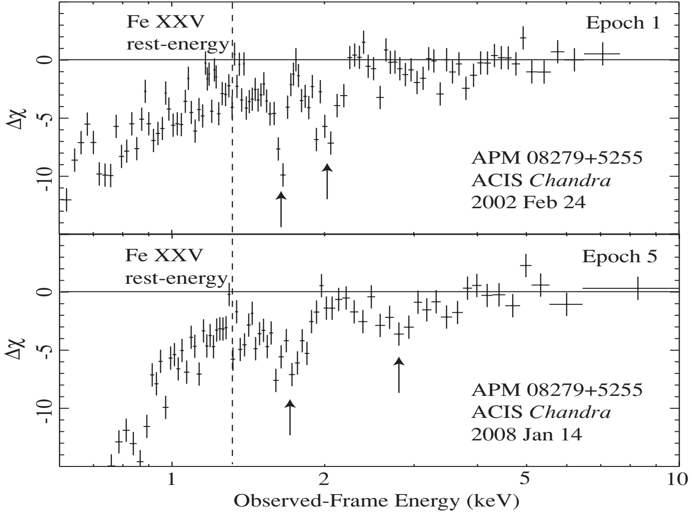


Colors=atomic levels involved

NGC 3783 (≈900 ks *Chandra*) − Kaspi et al. (2002)

Ultra-fast outflows (I)

high-redshift, lensed

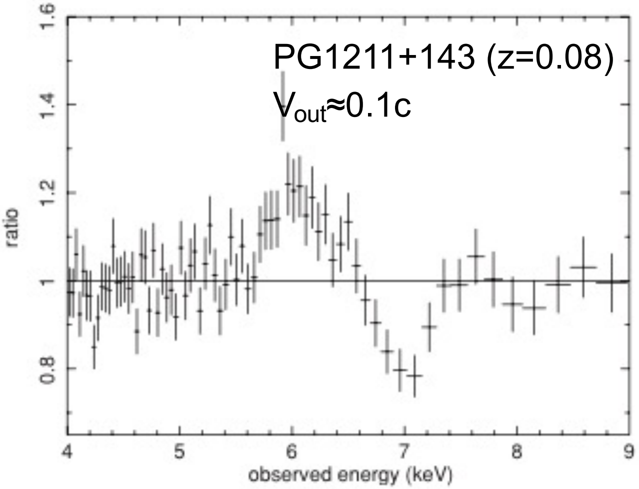


APM 08279+5255 (z=3.91)

$V_{out}\approx(0.2\text{-}0.76)c$

Needs for high statistics for a proper modeling.

Mostly Seyferts at low z or lensed QSOs at high z



PG1211+143 (z=0.08)

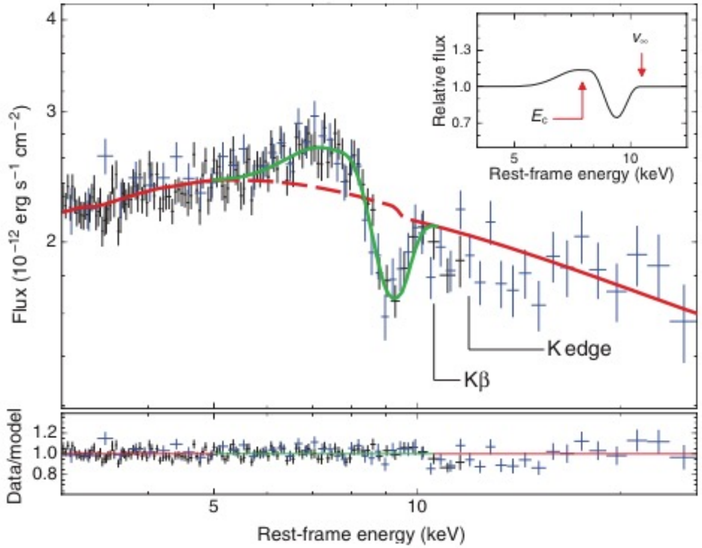
$V_{out}\approx0.1c$

Pounds & Reeves09

Chartas+09; Saez+09

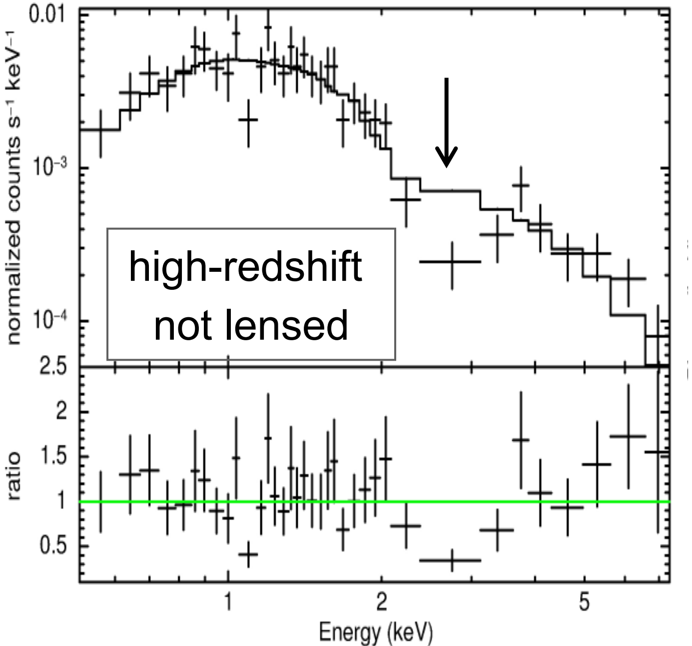
Lanzuisi+12

Nardini+15



PDS456 (z=0.18)

$V_{out}\approx0.3c$

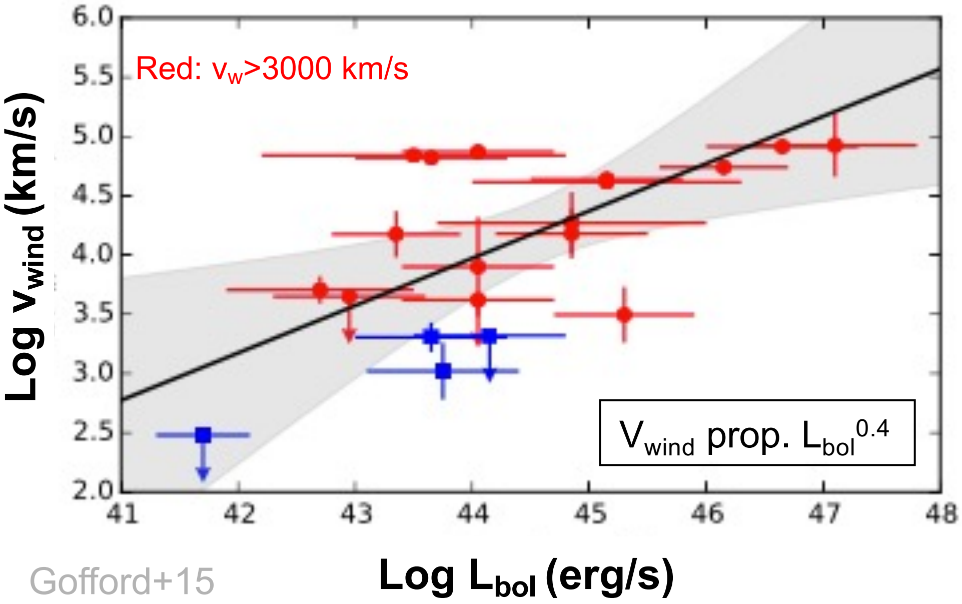


high-redshift not lensed

HS1700+6416 (z=2.73)

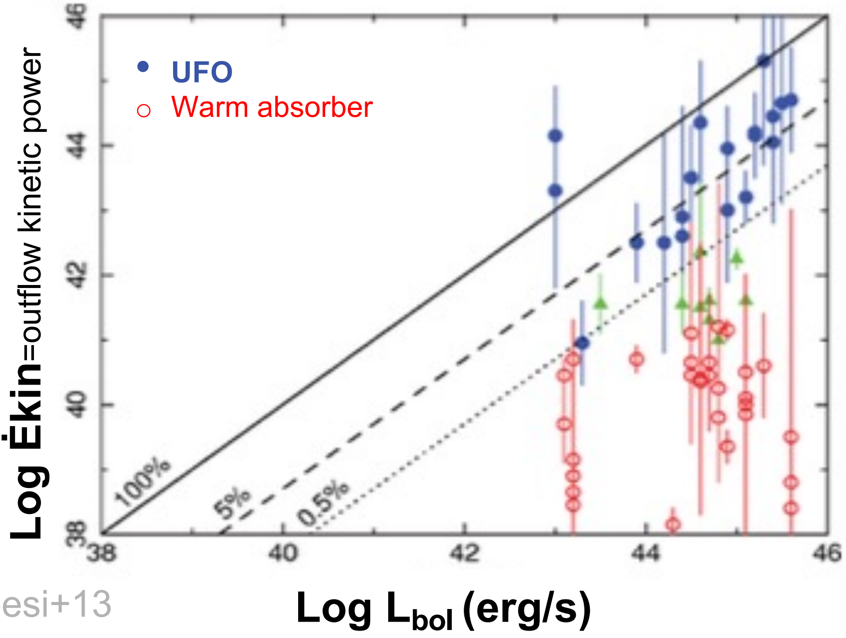
$V_{out}\approx(0.1-0.6)c$

Ultra-fast outflows (II)



Gofford+15

$$\frac{1}{2}\dot{M}v_{out}^2$$

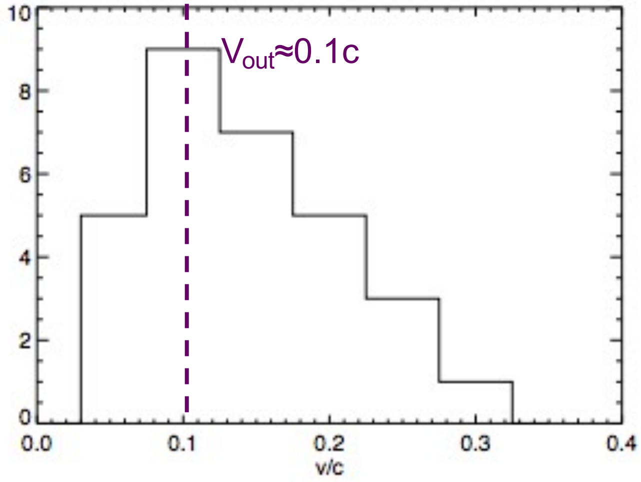


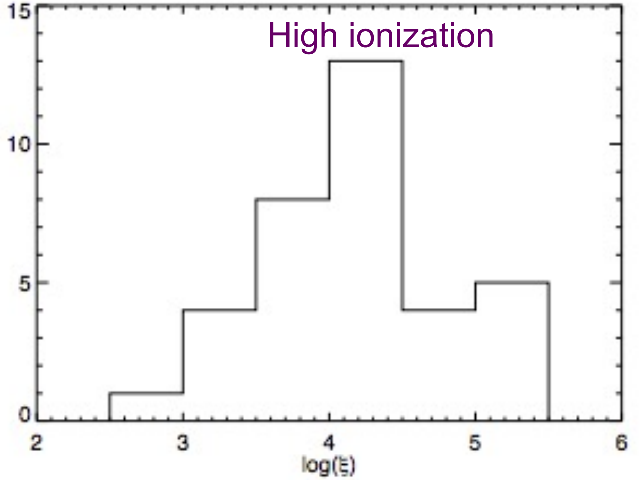
Tombesi+13

Ultra-fast outflows (UFOs)

- Detected in **≈50%** of nearby radio-quiet AGN with good spectral quality
- Similar fraction in RL AGN, still winds are the main actors
- Independent XMM-*Newton* vs. *Suzaku* detection (Tombesi+, Gofford+)
- $<v_{wind}>\approx 0.1c$
- Highly ionized ($<\log\xi>\approx 4$) and large column densities ($<\log N_H>\approx 23$)
- Variable in EW and velocity (Tombesi+)
- Mechanical power ≈5−10% L_{bol}, hence potentially important for **feedback**

Ultra-fast outflows (III)





Pounds+16; see Tombesi, Gofford, etc.

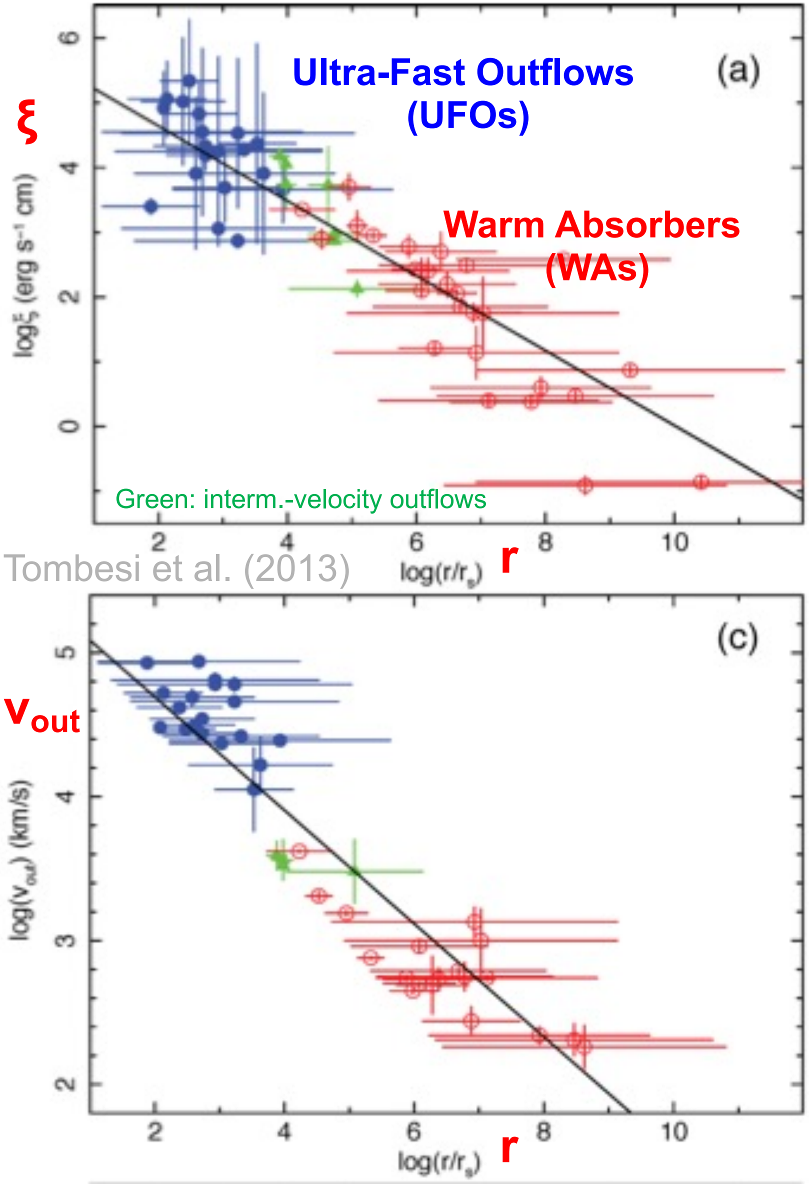
Needs for high photon statistics for a proper modeling

Statistics based on low-redshift samples of Seyferts and RLQs

Approx. 50% of local AGN with good spectral quality show UFOs

Searching for high-z UFOs are ongoing, mostly on lensed QSOs due to the required high photon statistics (see, e.g., Bertola et al. 2020, Chartas et al. 2021) → more common than in the local Universe?

From warm absorbers to ultra-fast outflows (I)



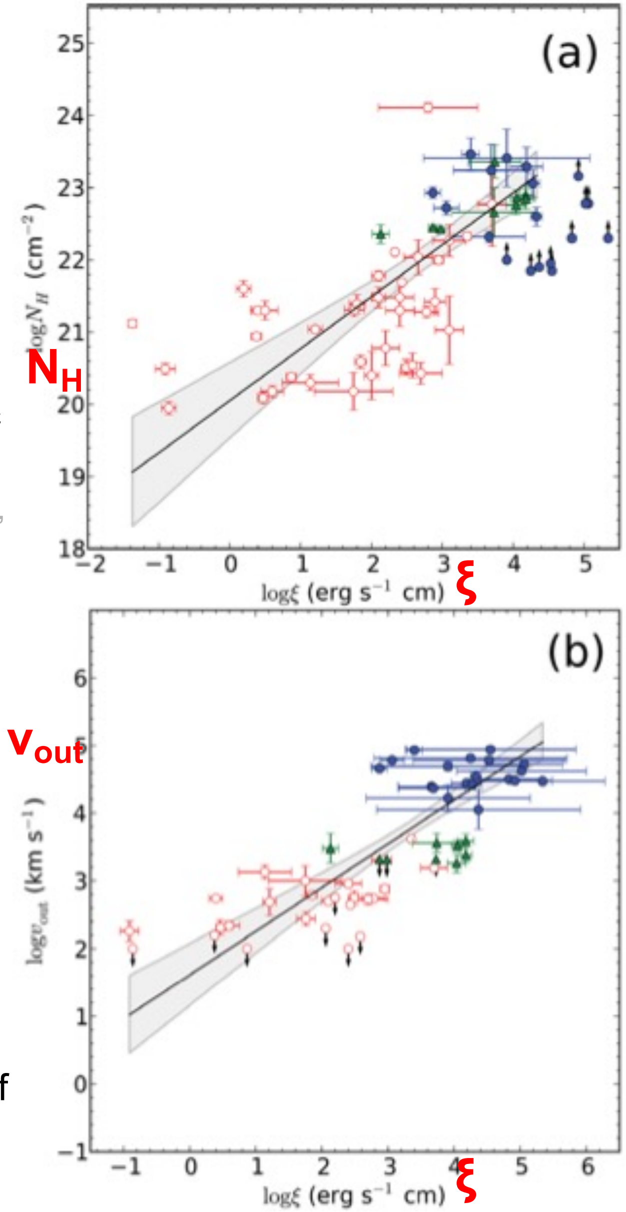
Tombesi et al. (2013)

Warm absorbers (WAs; v≈1000 km/s) (e.g., Blustin+05)

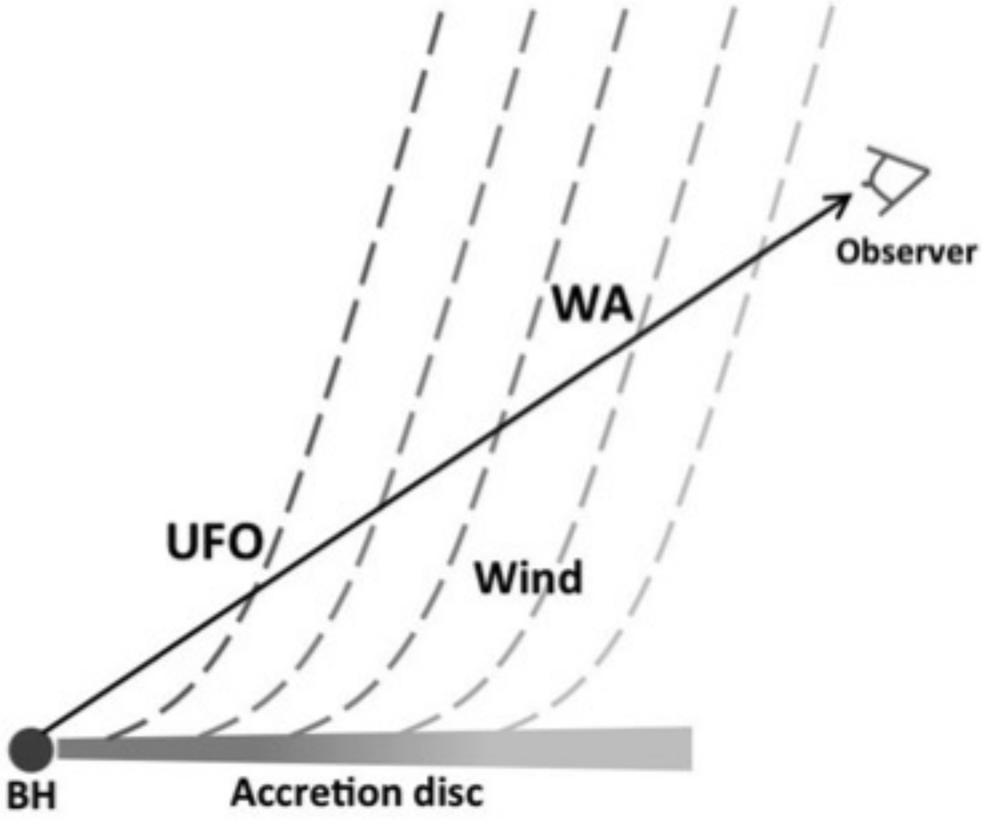
Ultra-fast outflows (UFOs; v≈0.05c up to 0.6c) (e.g., Tombesi+, Gofford+, Chartas+, Lanzuisi+12, […])

The closer the absorber to the BH, the higher ionization (ξ), column density (N_H) and outflow velocity (v_{out})

WAs and UFOs at the two ends of the parameter space



From warm absorbers to ultra-fast outflows (II)



Tombesi et al. (2013) − see also Kazanas et al. (2012)

A single, stratified large-scale outflow?

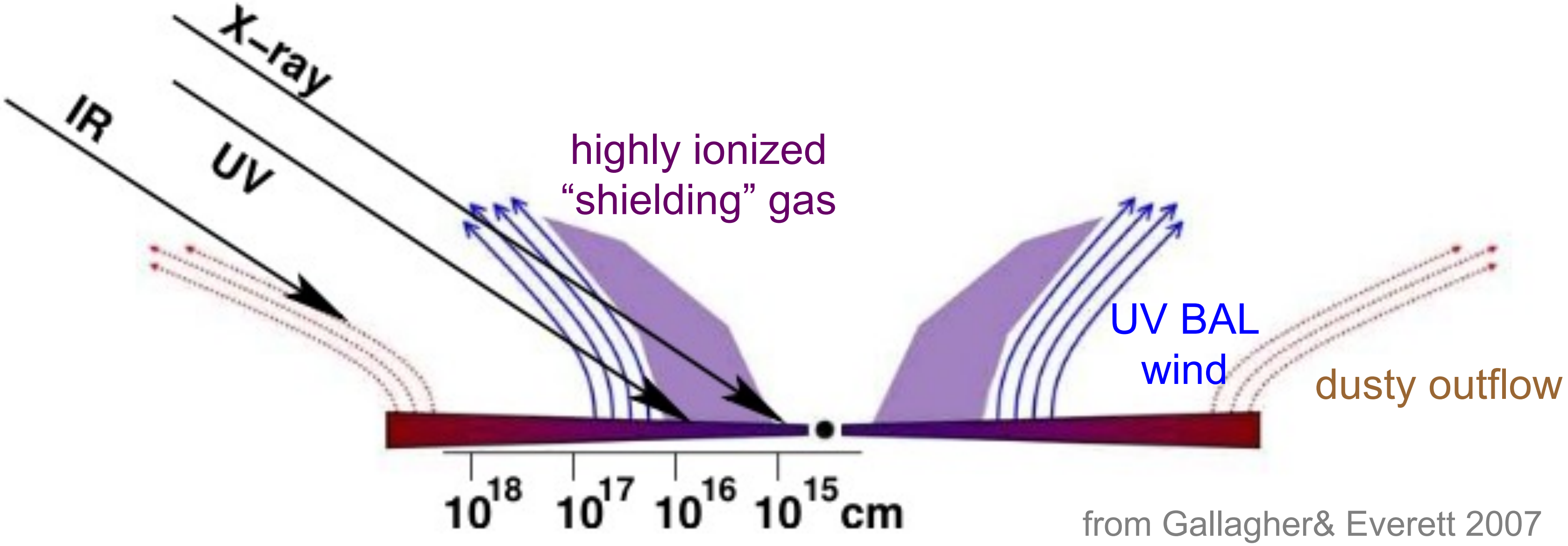
Radiation pressure and magneto-hydrodynamical processes responsible for the acceleration

Launch location: UFOs from the inner accretion disc (see also BALQSOs)

High mechanical power implied (≈0.5% of L_{bol} for UFOs) ➔ feedback issues

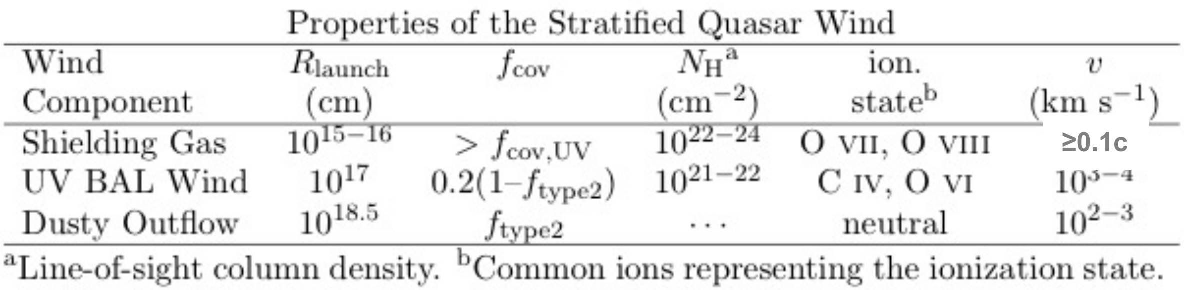
The torus can be an extension of the outer accretion disc

A stratified wind region



from Gallagher& Everett 2007

At work: magnetic forces, radiative acceleration on resonance lines, radiation pressure



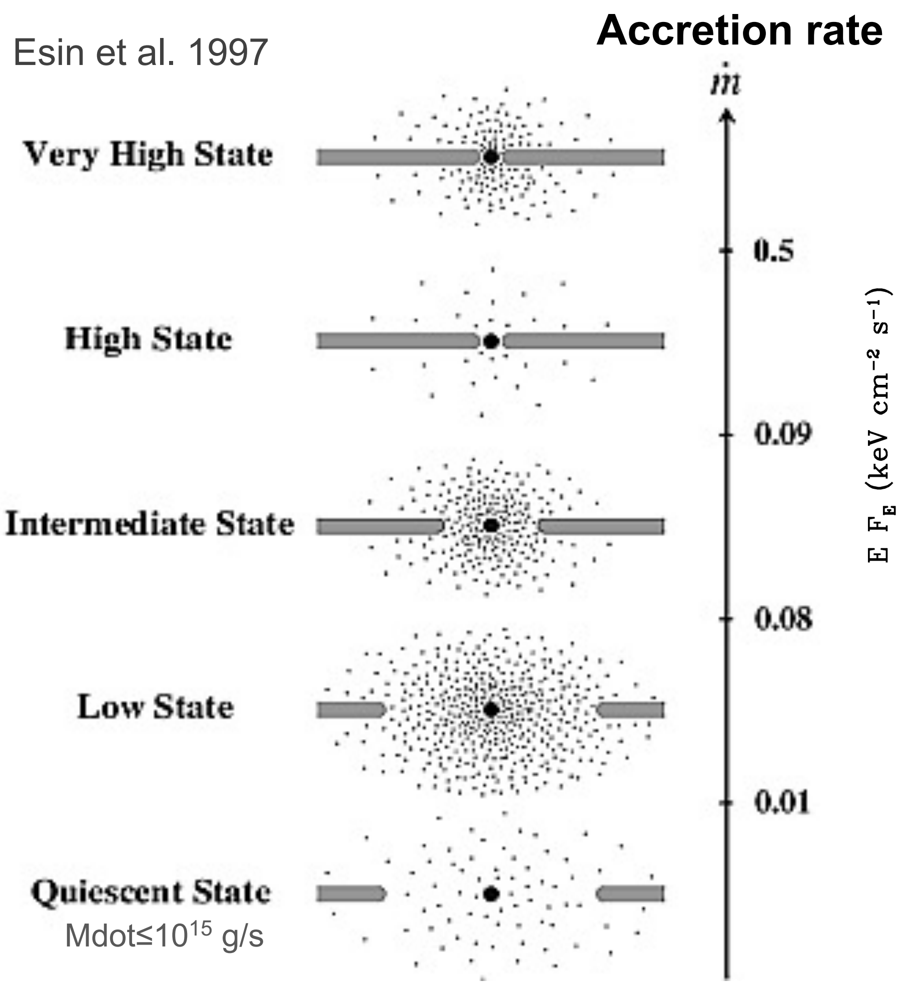
Properties of the Stratified Quasar Wind

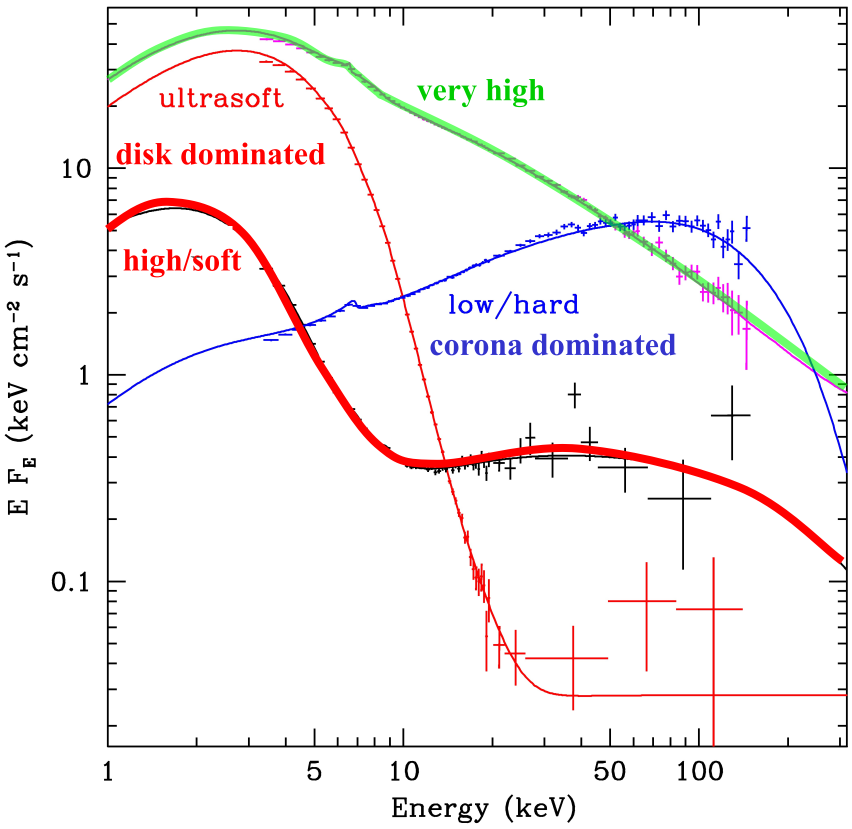
Wind Component	$R_{\rm launch}$ (cm)	$f_{\rm cov}$	$N_{\rm H}$[a] ($\rm cm^{-2}$)	ion. state[b]	v ($\rm km\ s^{-1}$)
Shielding Gas	10^{15-16}	$> f_{\rm cov,UV}$	10^{22-24}	O VII, O VIII	≥0.1c
UV BAL Wind	10^{17}	$0.2(1-f_{\rm type2})$	10^{21-22}	C IV, O VI	10^{3-4}
Dusty Outflow	$10^{18.5}$	$f_{\rm type2}$	···	neutral	10^{2-3}

[a] Line-of-sight column density. [b] Common ions representing the ionization state.

Are ultra-fast outflows present only in AGN?

Esin et al. 1997

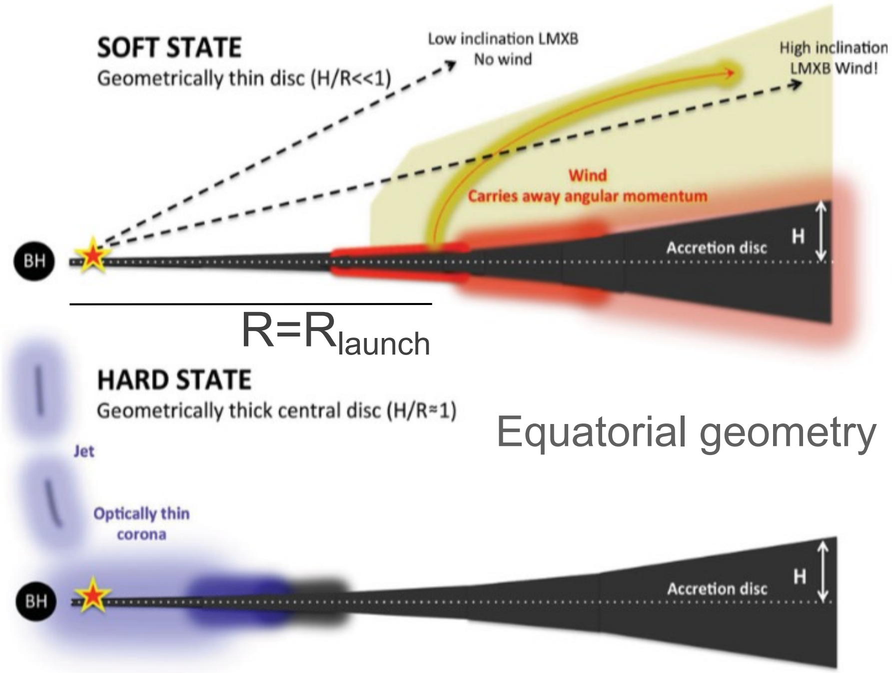




Done 2010; see also Gierlinski & Done 2003

- HS (high/soft): disc dominated − looks like a disc but small tail to high energies (L prop. T^4)
- Very high/intermediate states − resembles the emission of a disc + something else
- LH (low/hard) state − looks really different, not at all like a disc!

Winds in high/soft state (disc-dominated)



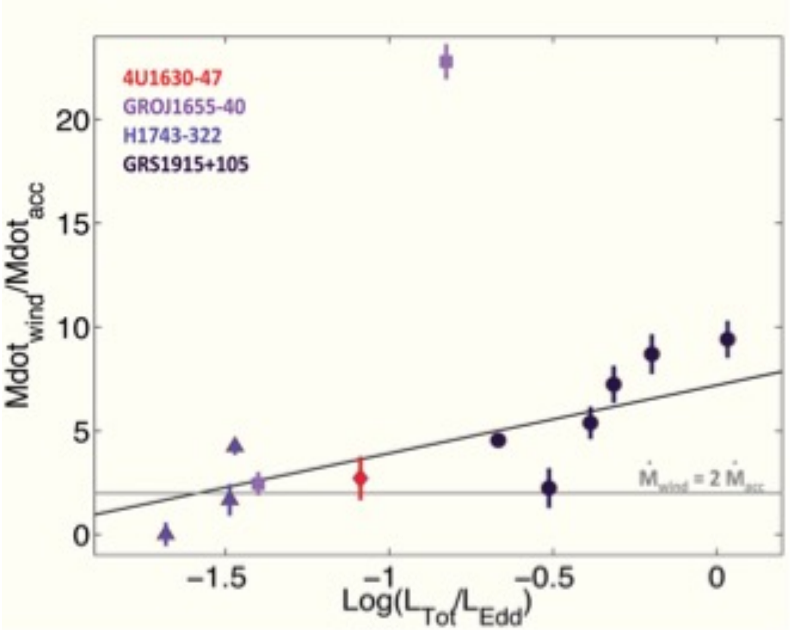
$R=R_{launch}$

Equatorial geometry

$$\dot{M} = 4\pi R^2 n m_p v_{out} \frac{L_X}{\xi} \frac{\Omega}{4\pi}$$

Mdot~10^{19} g/s
L_W~10^{35} erg/s

V_{out}: wind outflow
ξ: ionization parameter (from abs. lines)
Ω: solid angle subtended by the wind
Thermal pressure to launch, then radiative and magnetic pressure

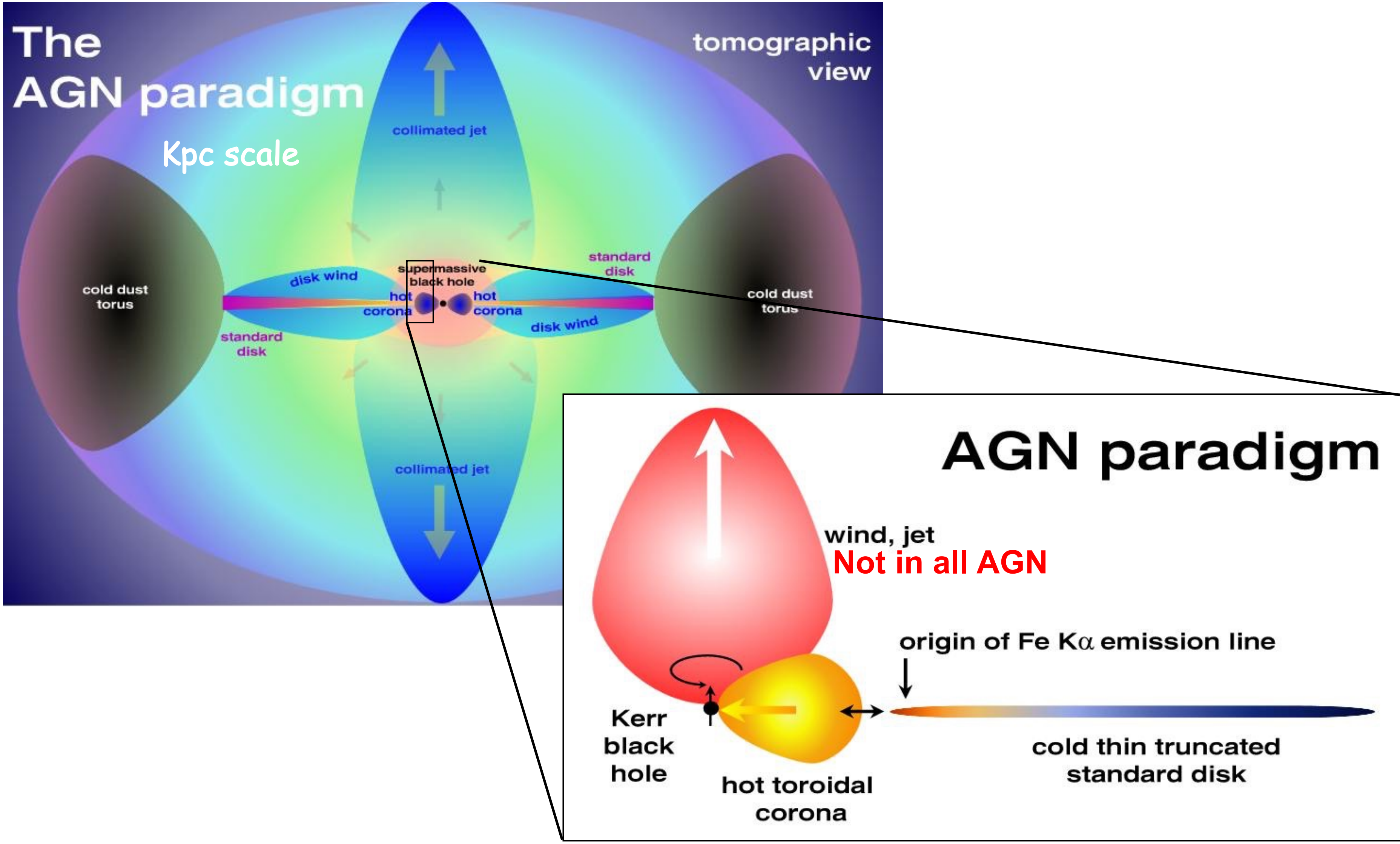


The mass outflow rate carried out by these winds may be higher than the inner accretion rate

➔ Responsible for the quenching of the jet?

Ponti et al. 2012

Placing all the pieces of the puzzle together

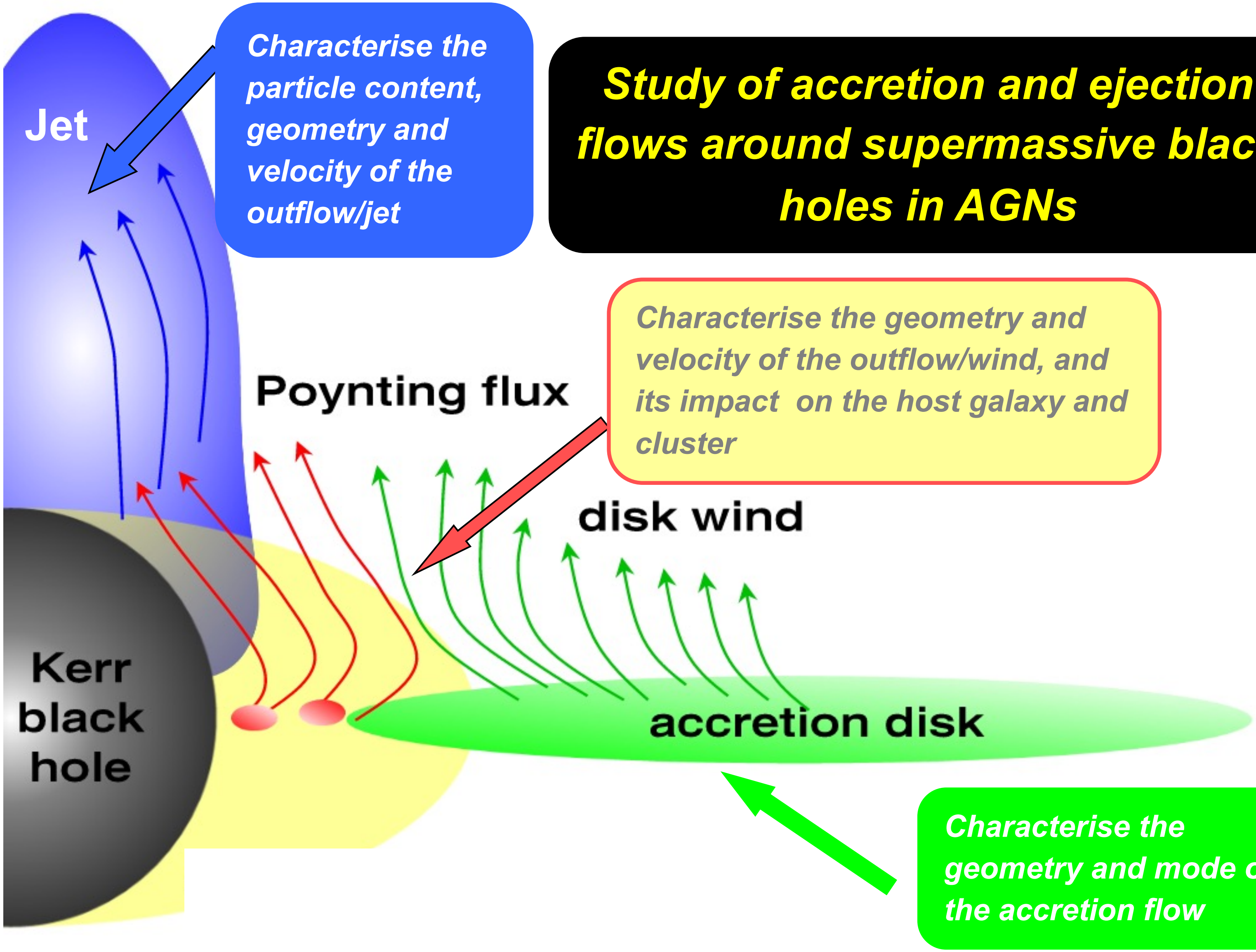


Kpc scale

Not in all AGN

A few open issues

Study of accretion and ejection flows around supermassive black holes in AGNs



Characterise the particle content, geometry and velocity of the outflow/jet

Characterise the geometry and velocity of the outflow/wind, and its impact on the host galaxy and cluster

Characterise the geometry and mode of the accretion flow