A premise: the “duties” of (X-ray) astronomers

i) Starting point (fundamental!) :
   What is **<u>the</u>** (open) astrophysical question/problem?
   (i.e. read a lot of litterature!)

ii) Best Instrument?

iii) Best Observation? Archival data?

iv) Propose, (hopefully) get it approved, and perform the observation

v) Data reduction:
   - i) Evt
   - ii) Calibration and attitude
   - iii) Scientific data

vi) Extraction of science information (images, lc, spectra)

vii) Scientific analysis (xspec, etc…)

viii) Physical interpretation

ix) Publish your results
   - i) In english (thus, learn english!)
   - ii) Go through referee peer review
   - iii) And “advertise” with, e.g., PPT at conference + outreach (plus!)

(RQ) AGN Astrophysics

Massimo Cappi
(INAF/OAS-Bologna)

Plan of this Lecture:

- Paradigm(s) (BH, AGN, Accretion disk, Photon ring)
- The "Unknowns" (open issues)
- The "Knowns" (models + basic physics)
- Physics and observations of reflection(s) and absorption(s) features

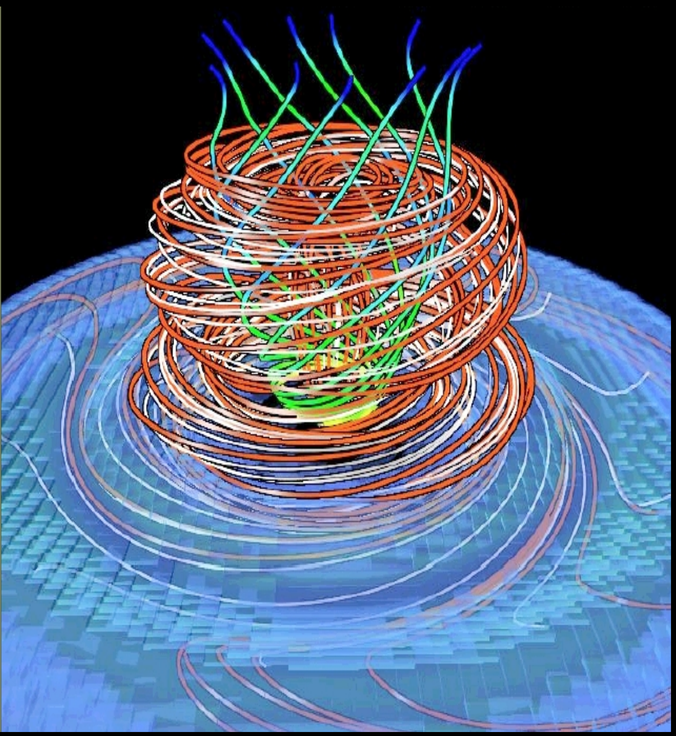
These lectures are "complementary" to the other two on
i) (RL) AGN astrophysics (by P. Grandi) and,
ii) AGN general/classification/evolution/formation (by C. Vignali)

Goal of the lectures: Give introductory informations on general "models" of AGNs,
With only emphasis here on RQAGNs, and address the reflection(s) vs ejection(s) "controversy" and phenomena

Bibliography:

A. Mueller, PhD Thesis, Heidelberg, 2004
C. Done, Lectures, August 2010, arXiv:1008.2287v1
Give a panorama on theoretical models+spectral physics for AGNs&BHs

Goal of the lectures: Give introductory informations on general “models” of AGNs, and in particular on reflection vs absorption hypothesis in RQAGNs



We will review basic physics with basic assumptions for 2 major “models” of AGN

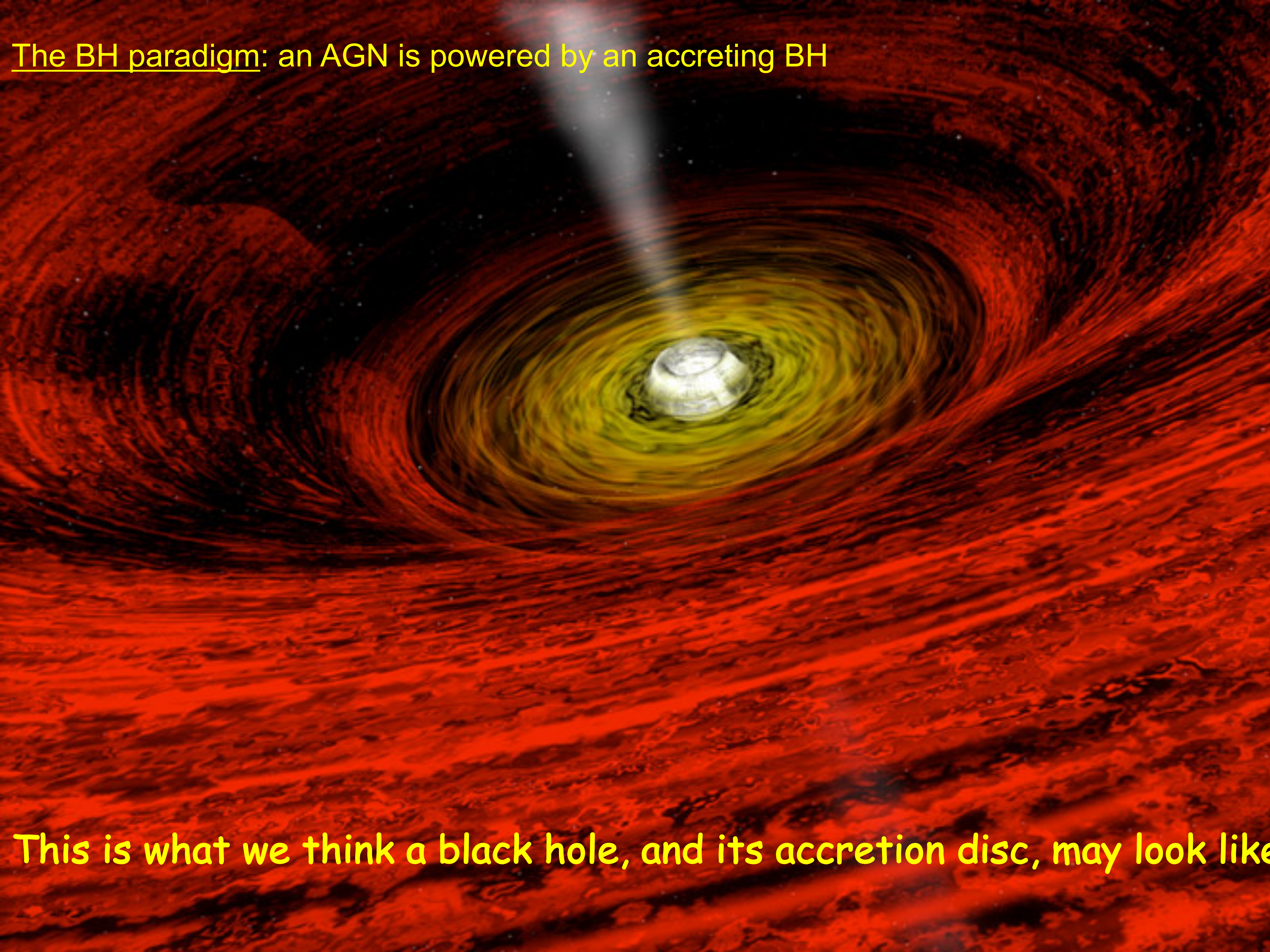
1- The 2-Phases model (RQAGNs)
2- The Jet + Inefficient accretion model (RLAGNs+LLAGNs)

We will focus here mostly on 1, Paola will address 2. I will also address the reflection vs. absorption hypothesis to explain the X-ray spectra of RQAGNs

Not a “mere” fitting exercise but major physical differences in the two hypothesis:

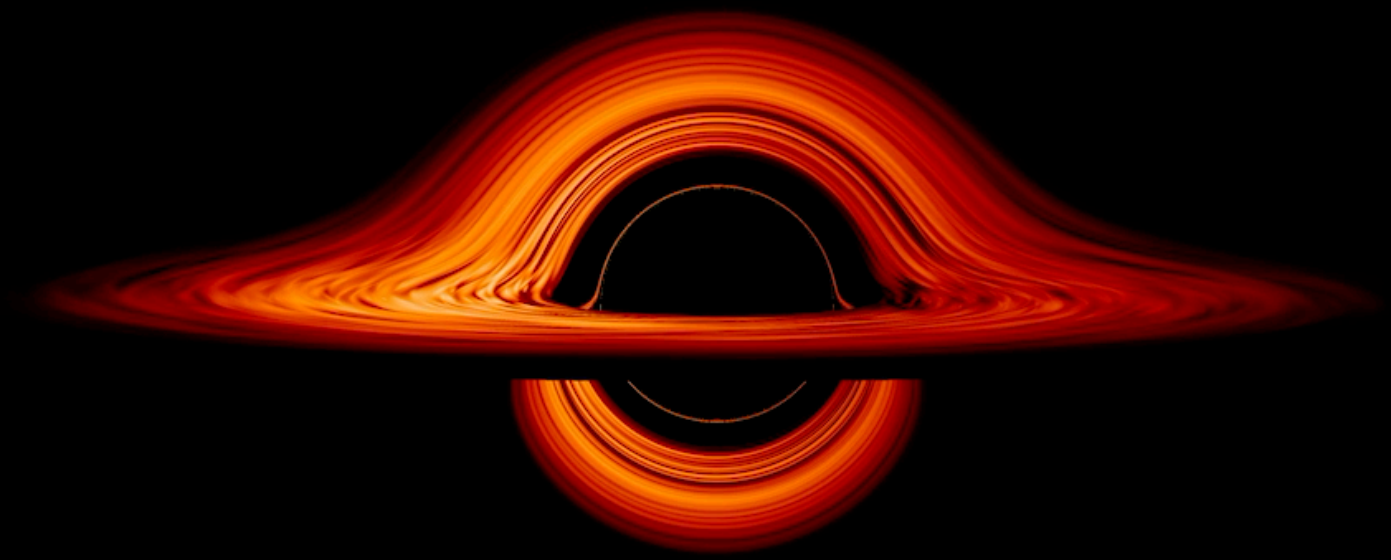
- ✓ Relativistic Reflection: Produced within few (<10) R_g and carries information on BH spin and mass
- ✓ (Very) Complex Absorption: Produced farther away, at >10s R_g and carries information on wind/jet base/feedback
- ✓ But distinguishing between the two is very difficult

The BH paradigm: an AGN is powered by an accreting BH

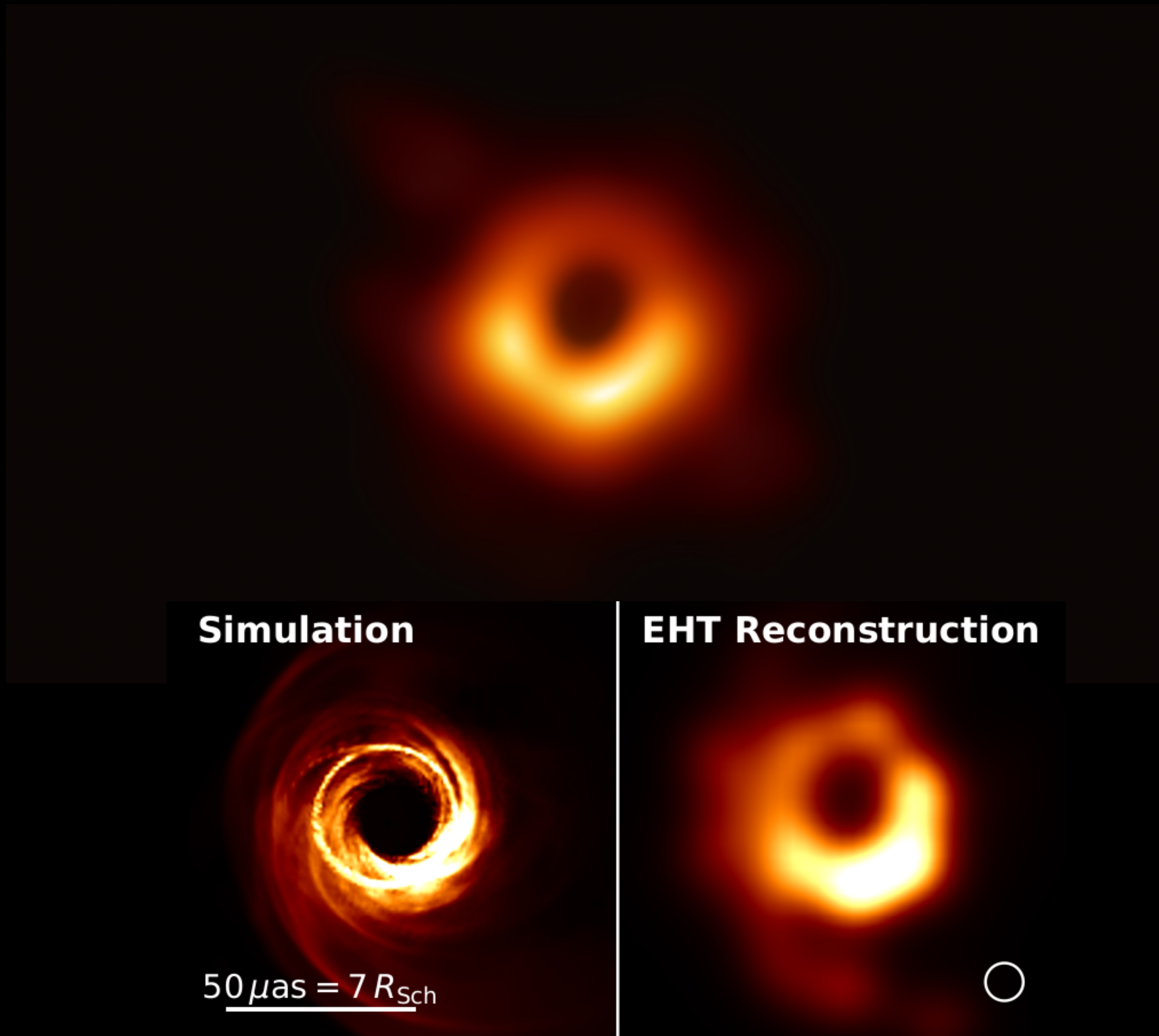


This is what we think a black hole, and its accretion disc, may look like

No, this is what we think a black hole, and its accretion disc, may look like



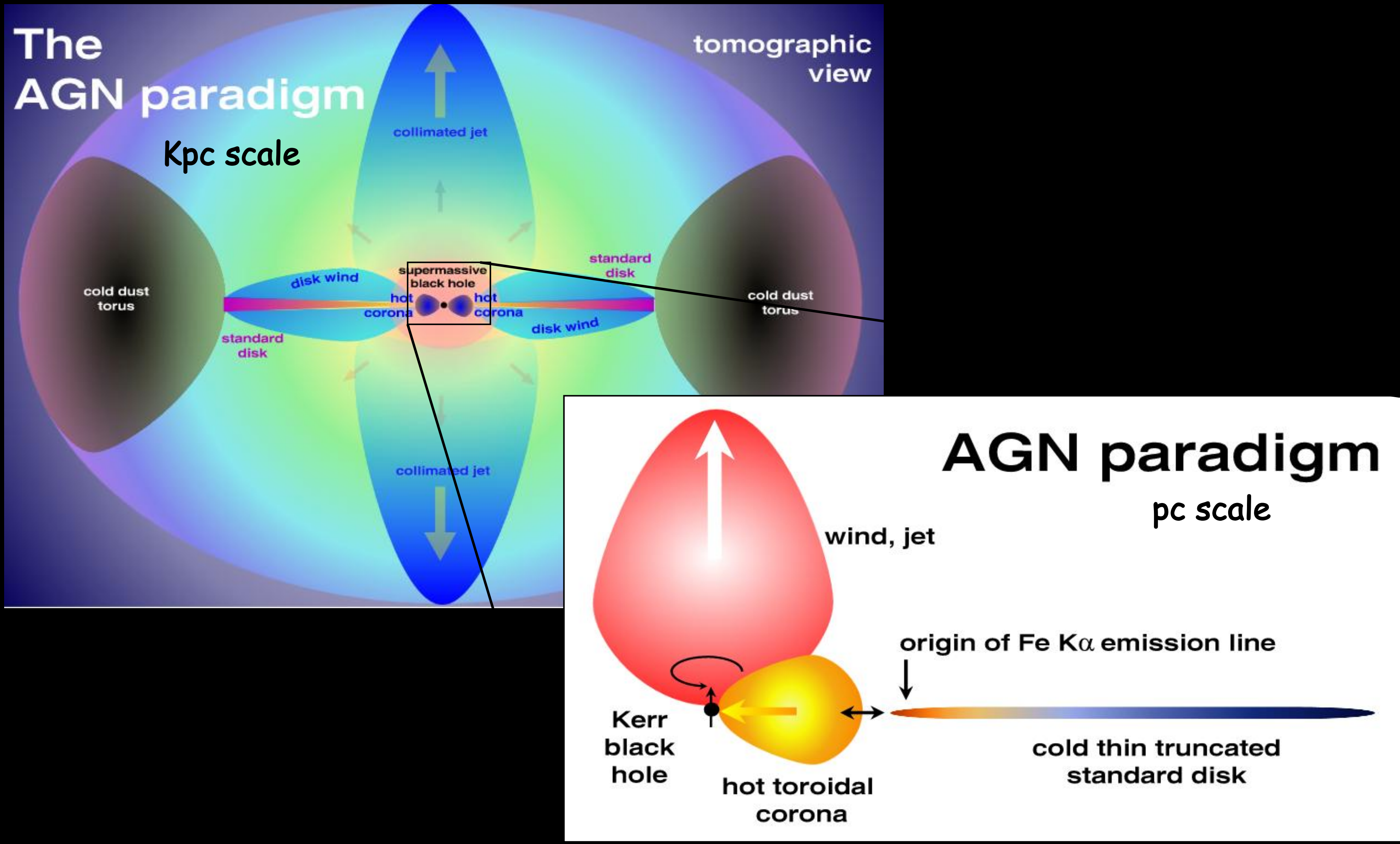
No, No, THIS IS what we think a black hole, and its accretion disc DO look like



EHT collab., 2019, ApJL

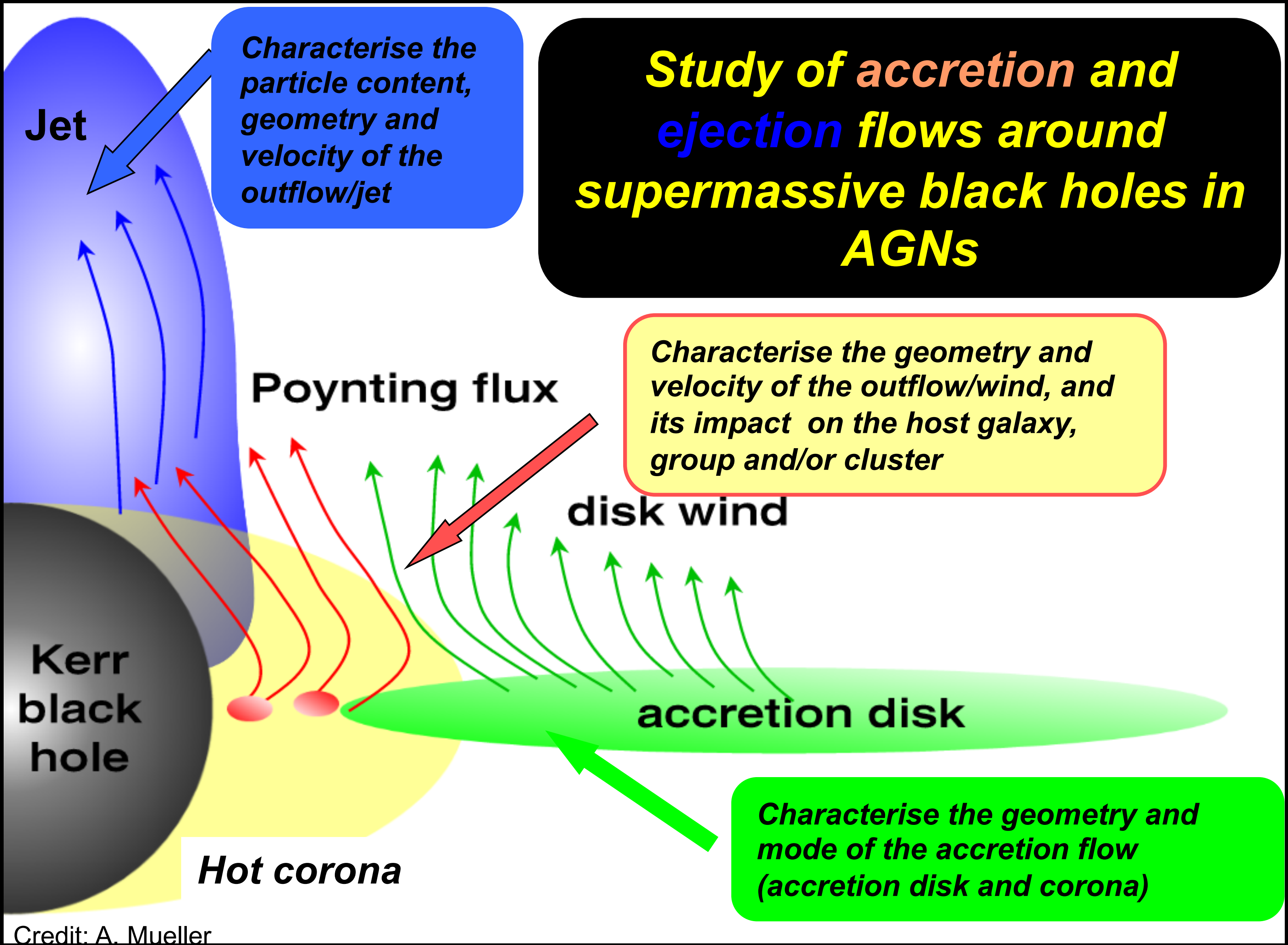
The AGN paradigm: Accretion onto a SMBH

We know (more or less) the ingredients: The AGN paradigm

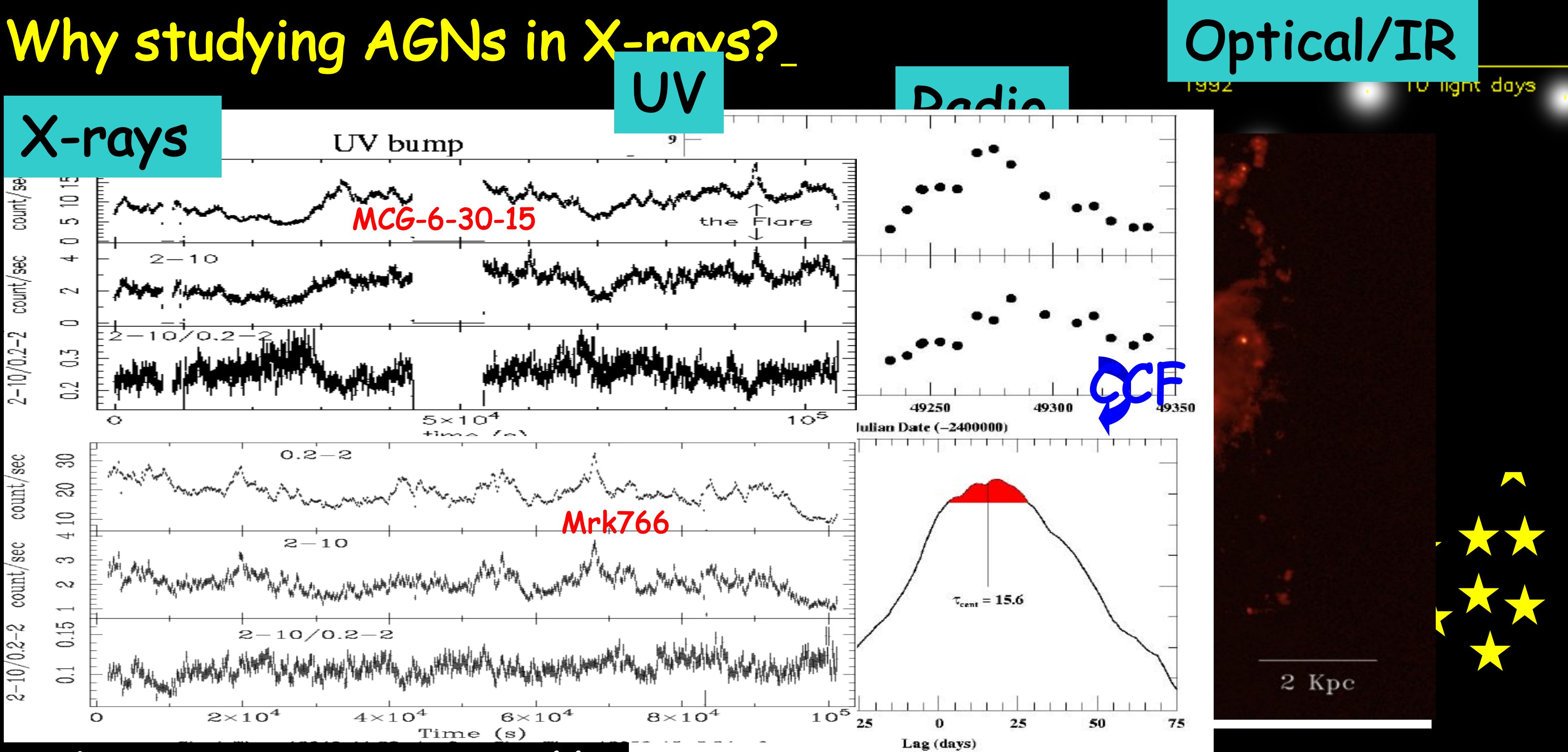


Credit: A. Muller

Open issues/Unknowns



Why studying AGNs in X-rays?



Delta L ~ L ~ up to 10^{44} erg/s

↔

Disklines reverberation mapping (X-rays)

⇓ ⇓

$M_\bullet$, a

(Probe GR within 10 Rs, i.e. strong field)

BLR reverberation mapping (optical)

(v~FWHM∝delay~dist.)

⇓ ⇓

$M_\bullet$

Stellar motions dynamics (rot. Curves) +water masers

(v and σ ∝ dist.)

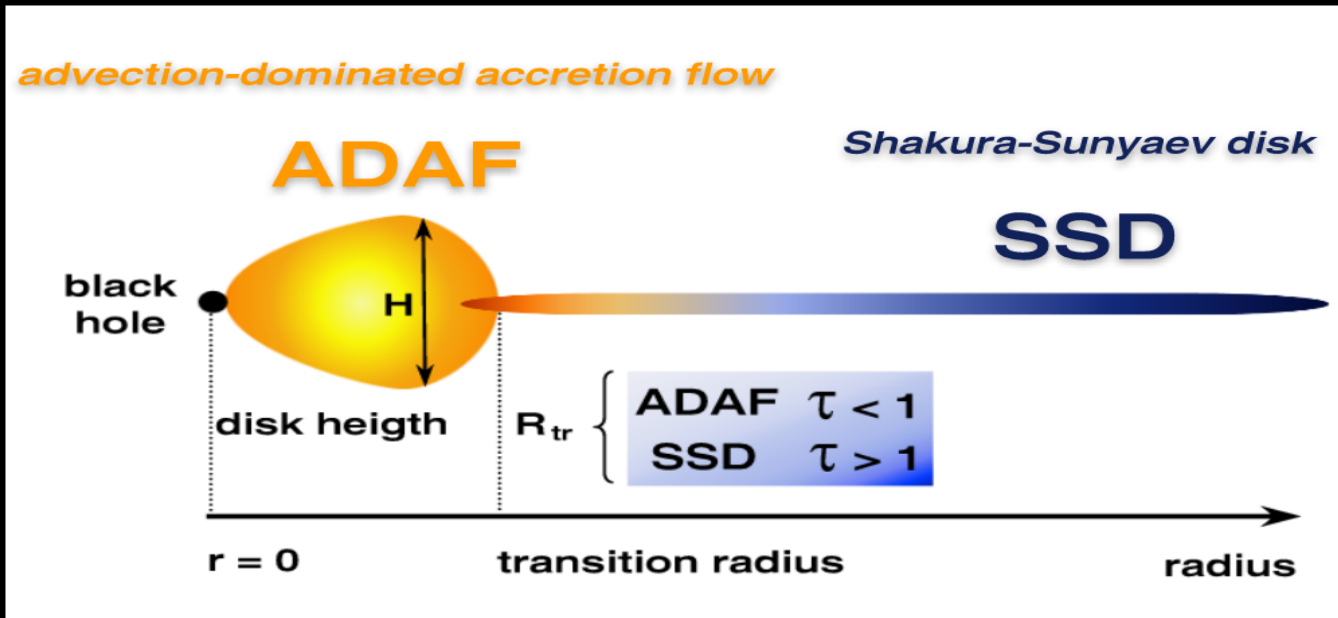
⇓ ⇓

$M_\bullet$

Accretion

Still, we don't know exactly the accretion mode/type (SAD, ADAF, RIAF, CDAF, etc.)…

To simplify here, two classes: SSD (or SAD) vs ADAF

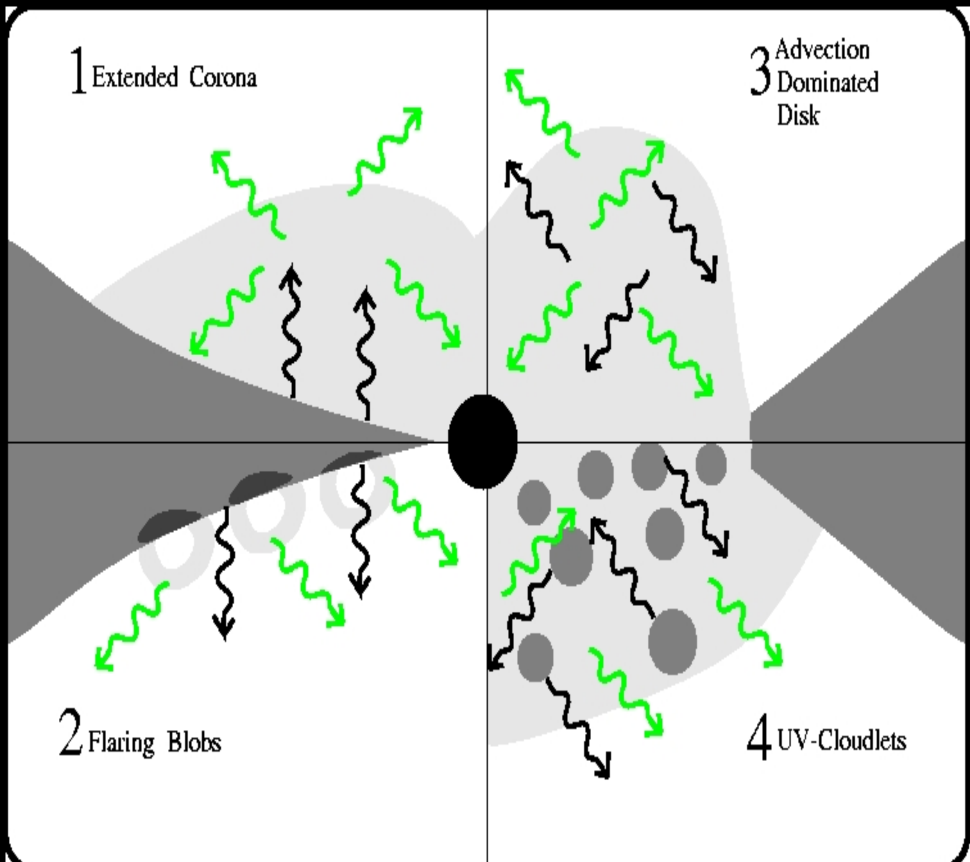


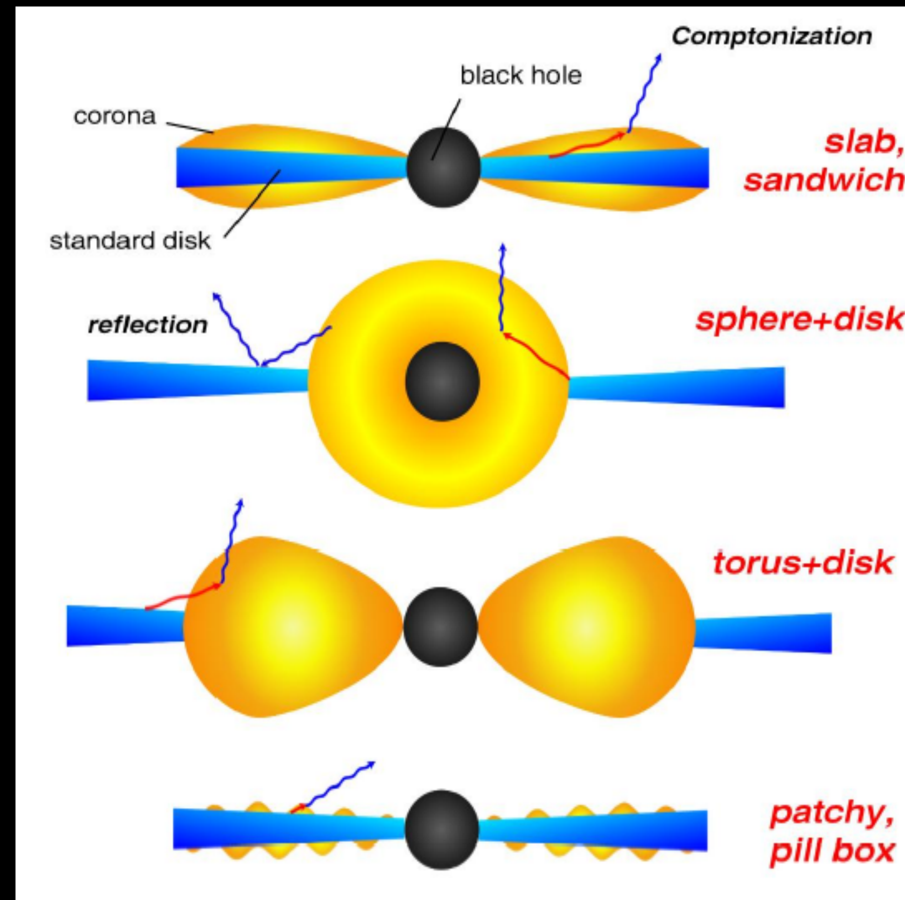
(Müller, '04)

- Shakura–Sunyaev disk (SSD) or equivalently standard accretion disk (SAD)
- advection–dominated accretion flow (ADAF)
- radiatively–inefficient accretion flow (RIAF)
- convection–dominated accretion flow (CDAF)
- slim disk
- truncated disk – advective tori (TDAT)
- non–radiative accretion flow (NRAF)

Accretion

… nor the disk-corona geometry





Lamp-post model

Patchy corona model

(Haardt '96)

BH paradigm + assumptions on geometry + emission mechanisms (physics) + Multi-ν observations

=> AGN "Model"

The two major AGN models are:

1: The Two-Phases (SAD-dominated) model (for Radio-Quiet AGNs)

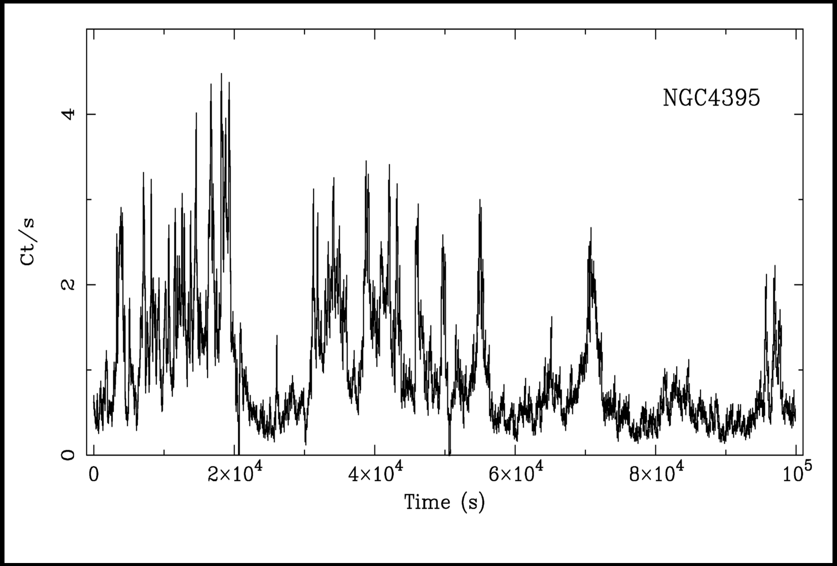
2: The jet model + "inefficient model" (ADAF dominated) (for Radio-Loud AGNs and Low Luminsity AGNs)

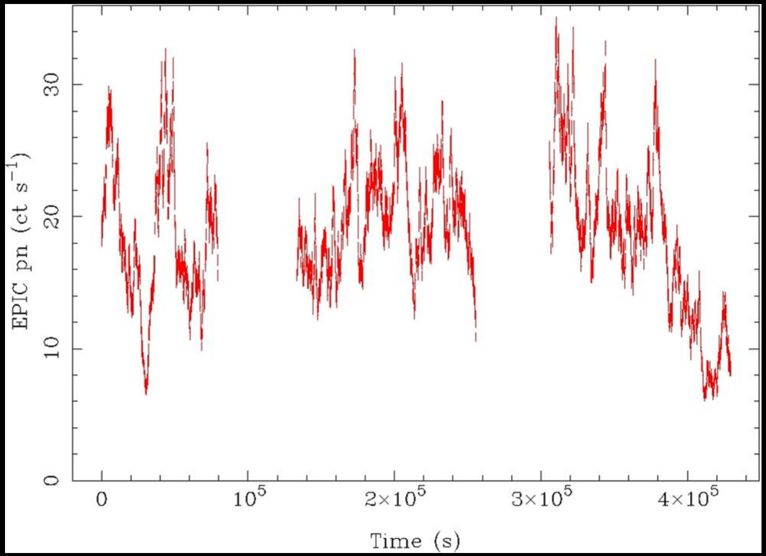
Model 1

The Two-phases (or SAD/efficient) model for RQAGNs

Model I (RQ AGN): X-ray observations - Lightcurves

MCG6-30-15





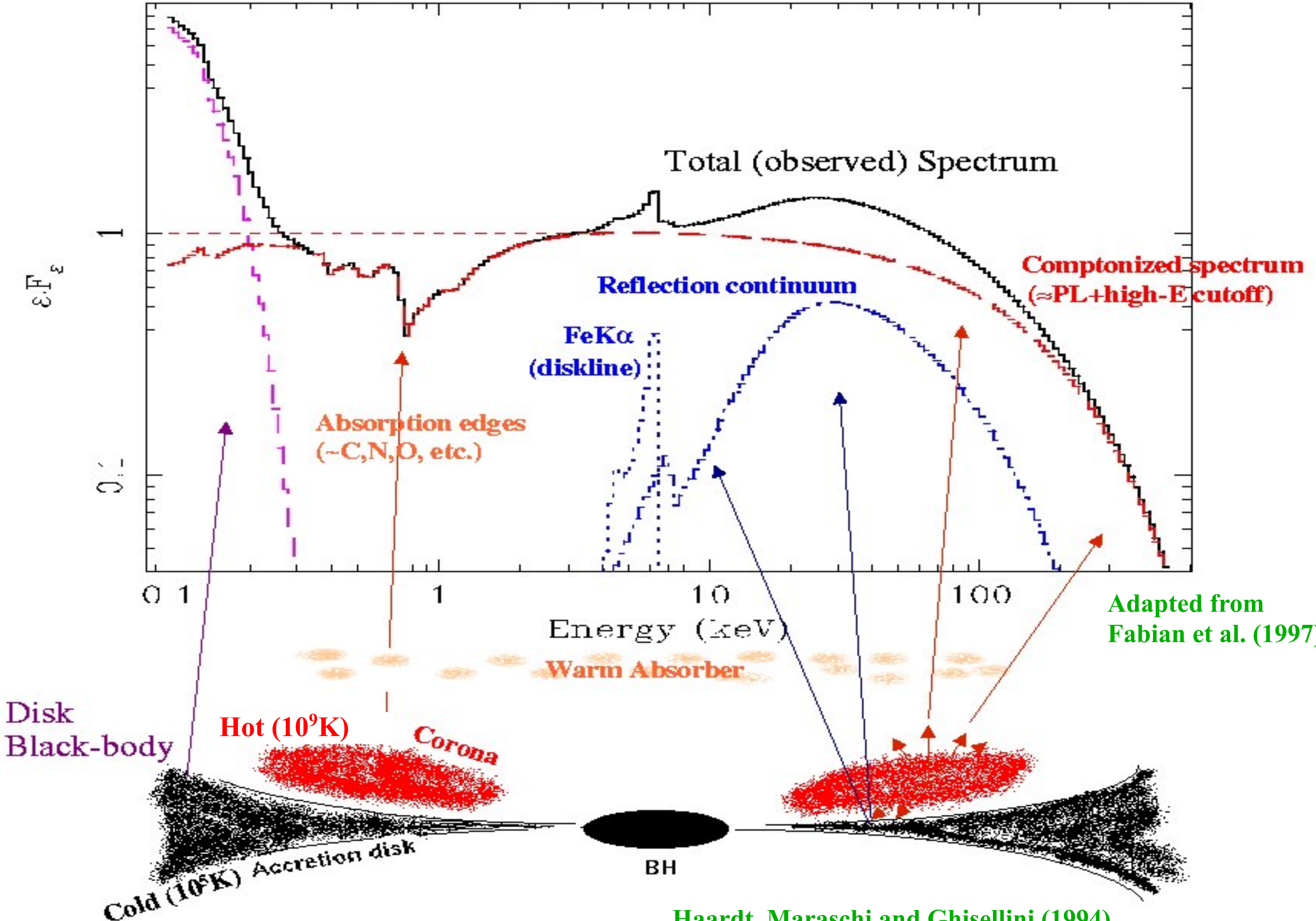
Δ L ~ L ~ up to 10^{44} erg/s

Light curves

N.B: Δt~50 s corresponds to 1 R_g for M=10^7Msol
($t \sim R_g/c \sim GM/c^3 \sim 50\ M_7\ s$)

Implies most of radiation from compact and innermost regions

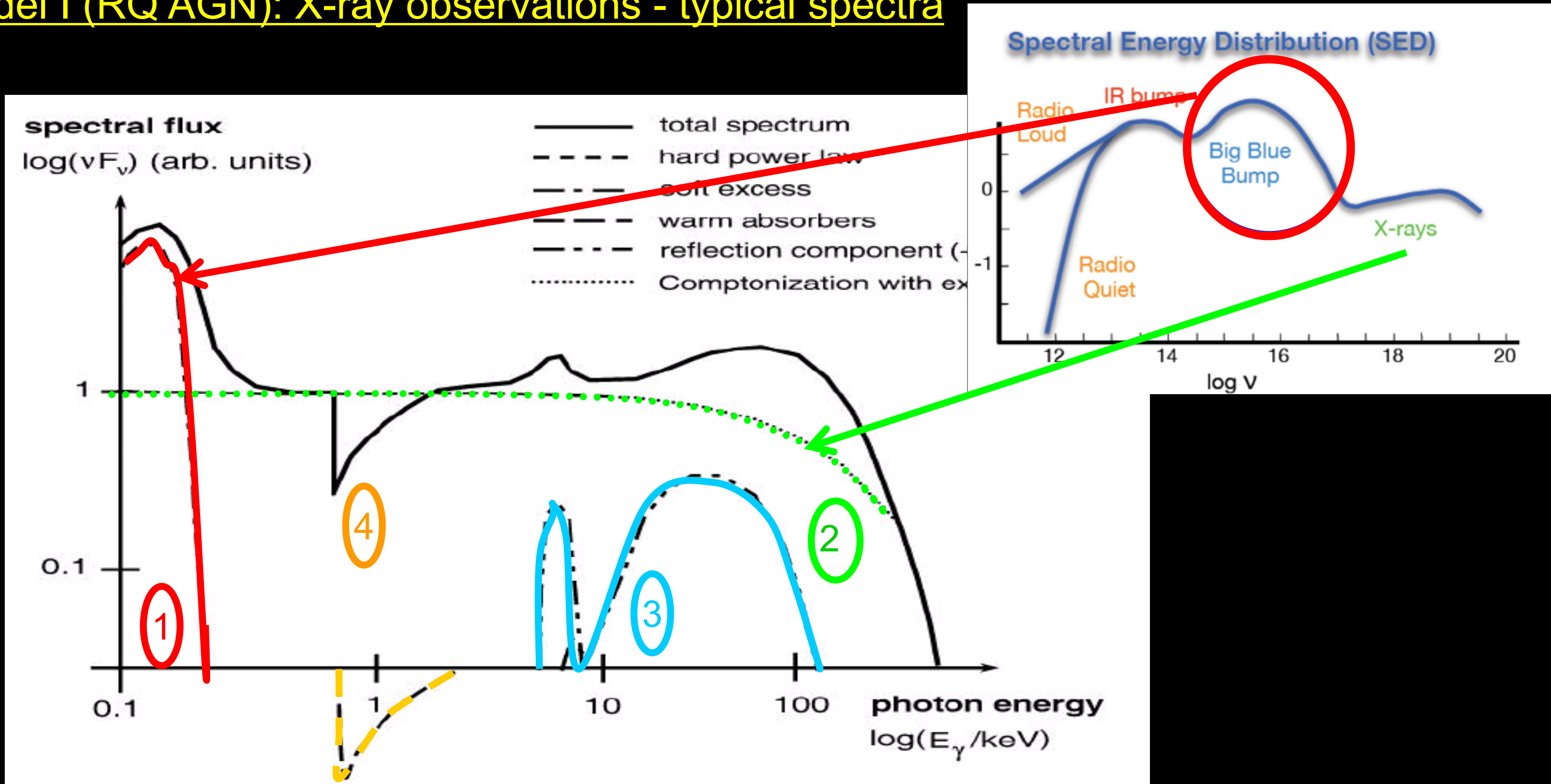
Typical X-ray Spectrum of a Seyfert 1 Galaxy
⇔ Standard two-phase Comptonization model



Adapted from
Fabian et al. (1997)

Haardt, Maraschi and Ghisellini (1994)

Model I (RQ AGN): X-ray observations - typical spectra



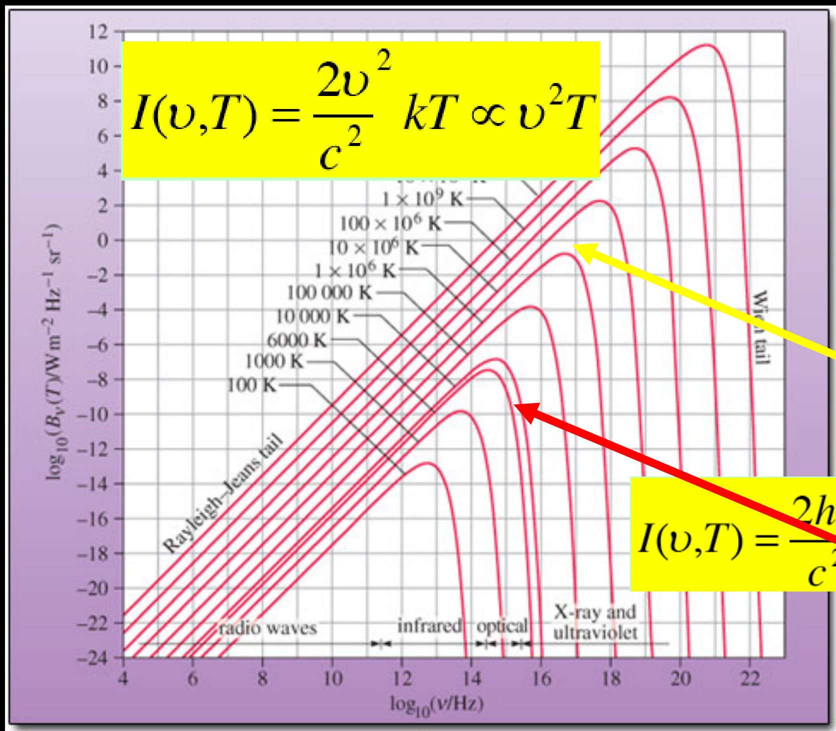
(At least) 4 major spectral components:

1. Soft excess (Black body)
2. Power-law Component (Thermal Comptonization)
3. Reflection component (Fluorescence Lines + Compton hump)
4. Warm absorber (photoelectric absorption)

1- Black Body emission from accretion disk

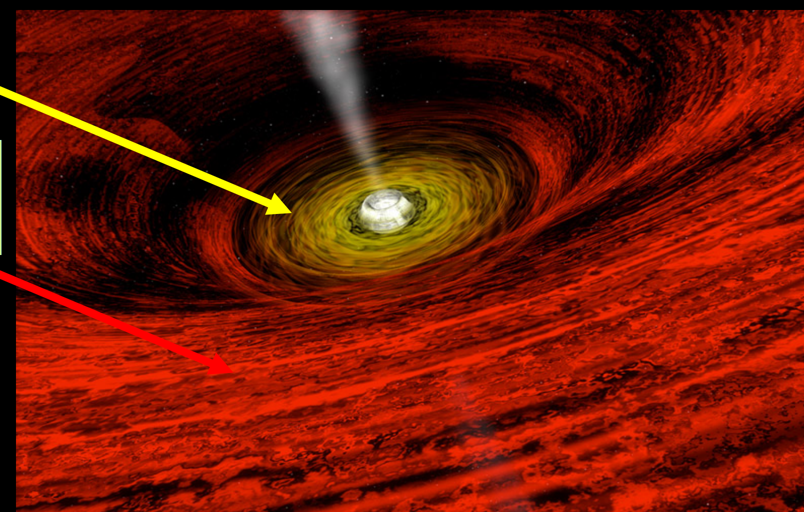
Planck radiation law:

$$I(\upsilon,T) = \frac{2h\upsilon^3}{c^2}\frac{1}{e^{h\upsilon/kT}-1}$$

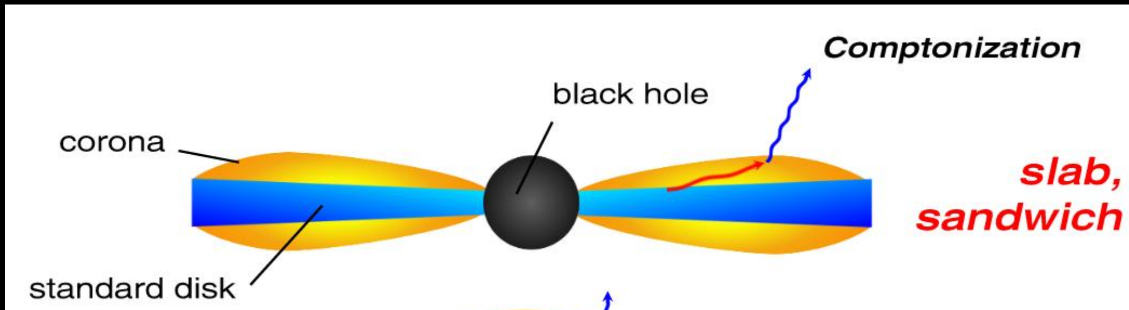


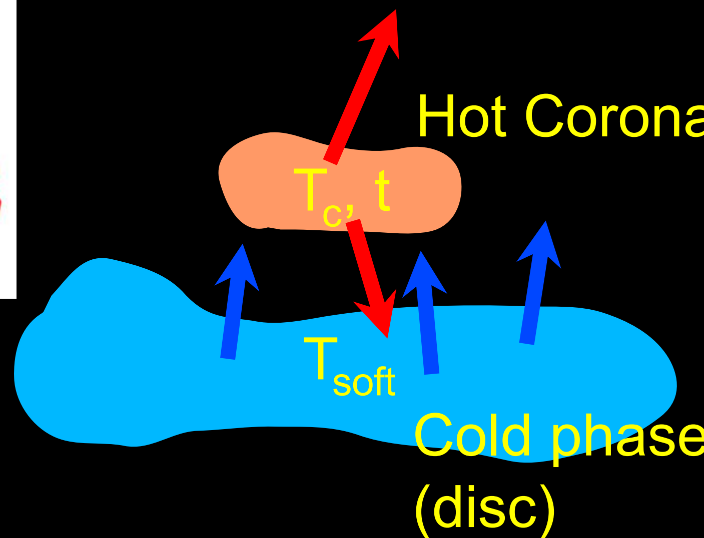
$$I(\upsilon,T) = \frac{2\upsilon^2}{c^2}kT \propto \upsilon^2 T$$

$$I(\upsilon,T) = \frac{2h\upsilon^3}{c^2}e^{-h\upsilon/kT}$$

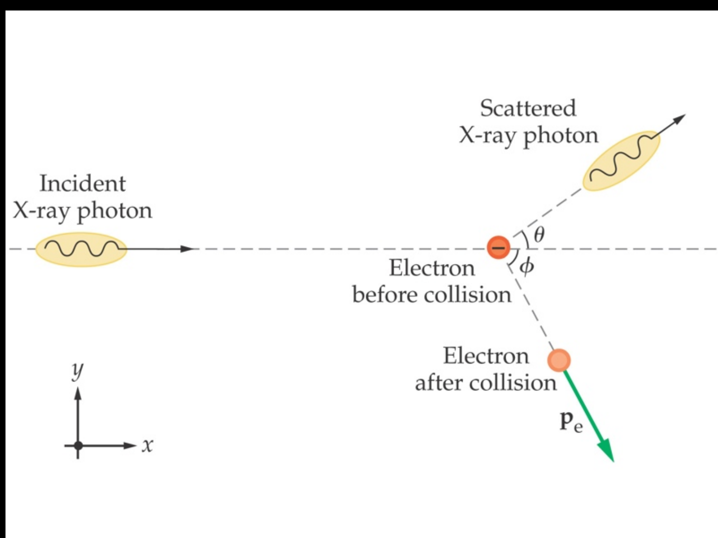


II - Power-law (Thermal Comptonization from the corona)





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



If electron at rest:

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

For non-stationnary electron:

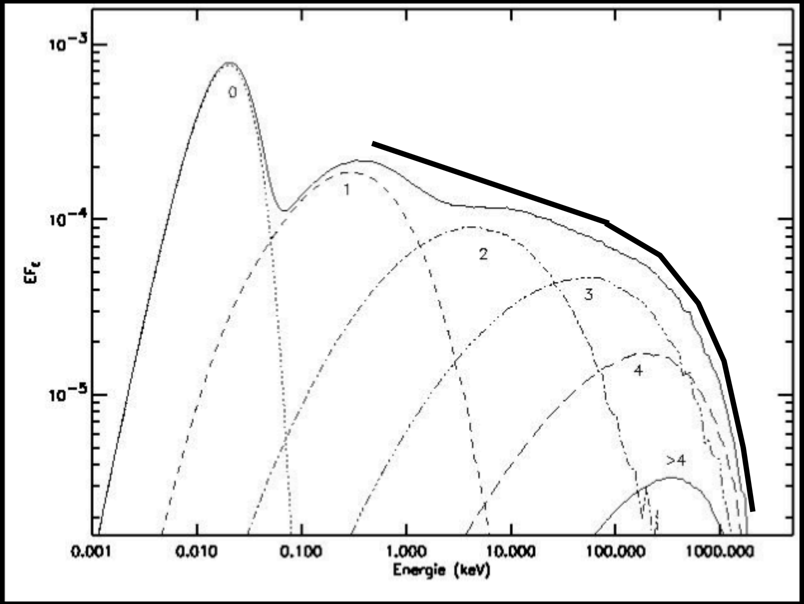
$\Delta E < 0 \rightarrow$ Compton

$\Delta E > 0 \rightarrow$ Inverse Compton

II - Power-law (Thermal Comptonization from the corona)

$$f_\epsilon(\epsilon)\, d\epsilon = \sqrt{\frac{1}{\pi \epsilon kT}}\ \exp\left[\frac{-\epsilon}{kT}\right]\, d\epsilon$$

Maxwellian Distribution of electron energies
⇒produce power-law + high energy cut-off



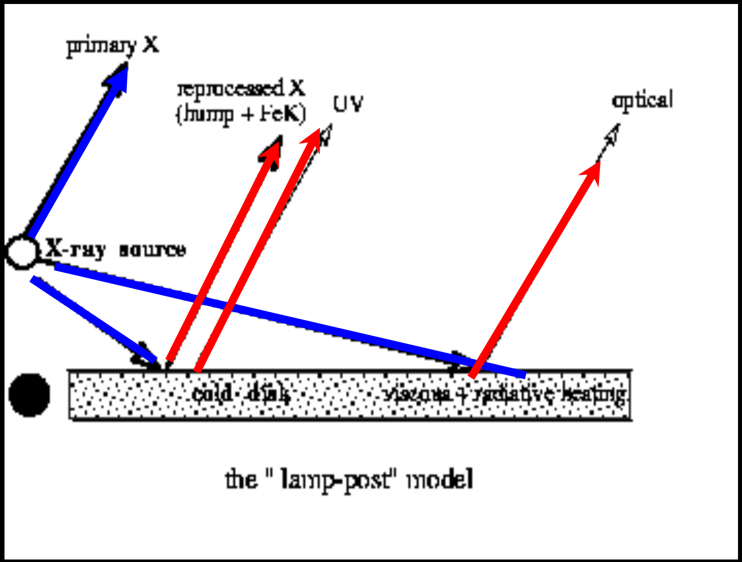
$$F_E \propto E^{-\Gamma(kT,\tau)} \exp\left(-\frac{E}{E_c(kT,\tau)}\right)$$

$$\begin{cases} \Gamma \propto \left(\frac{L_{heat}}{L_{cool}}\right)^{-\delta} \propto f(kT, \tau) \\ E_c \simeq kT \end{cases}$$

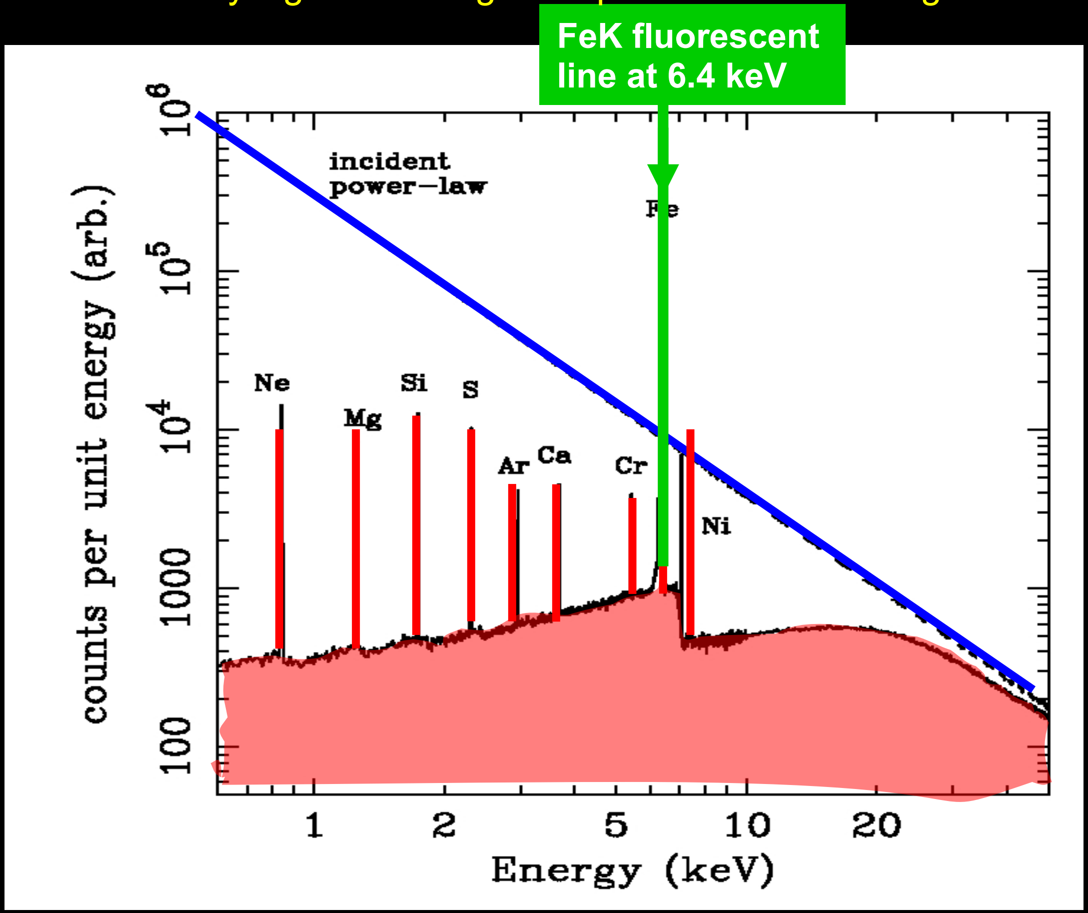
$\Gamma(kT, \tau)$ ➥ Spectral degeneration since different (kT, τ) can yield same Γ

III - Reflection component (line + continuum)

Photoelectric absorption+fluorescence+Thomson/Rayleigh scattering+Compton down-scattering



(e.g. Reynolds et al. '94; Zycki and Czerny '94)



i) Inclination
ii) Ω/2pi (coverage, isotropy)
iii) Ab

Major modifications expected:

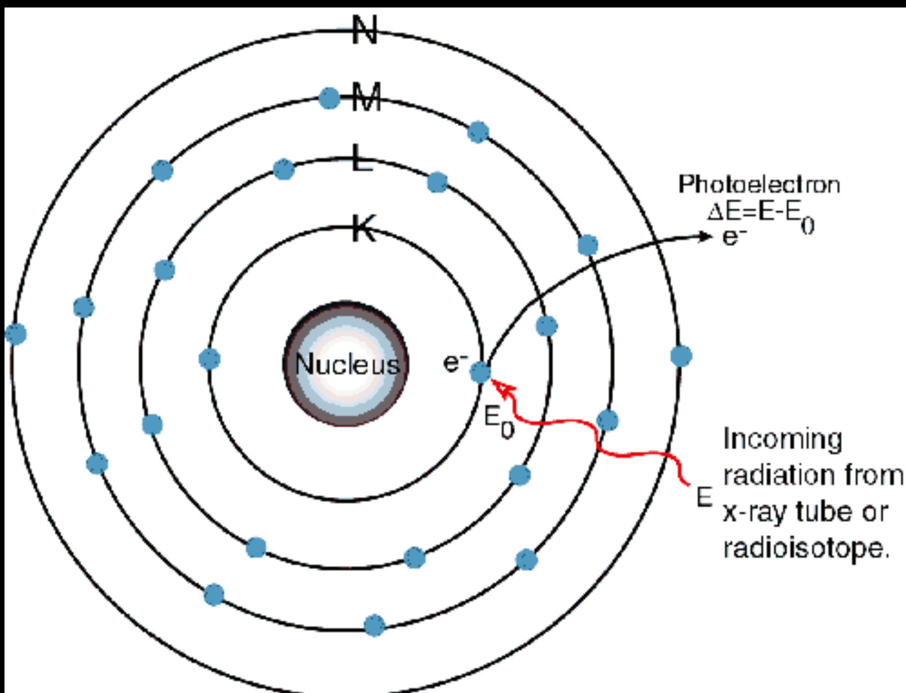
a) Ionization effects

b) Relativistic effects

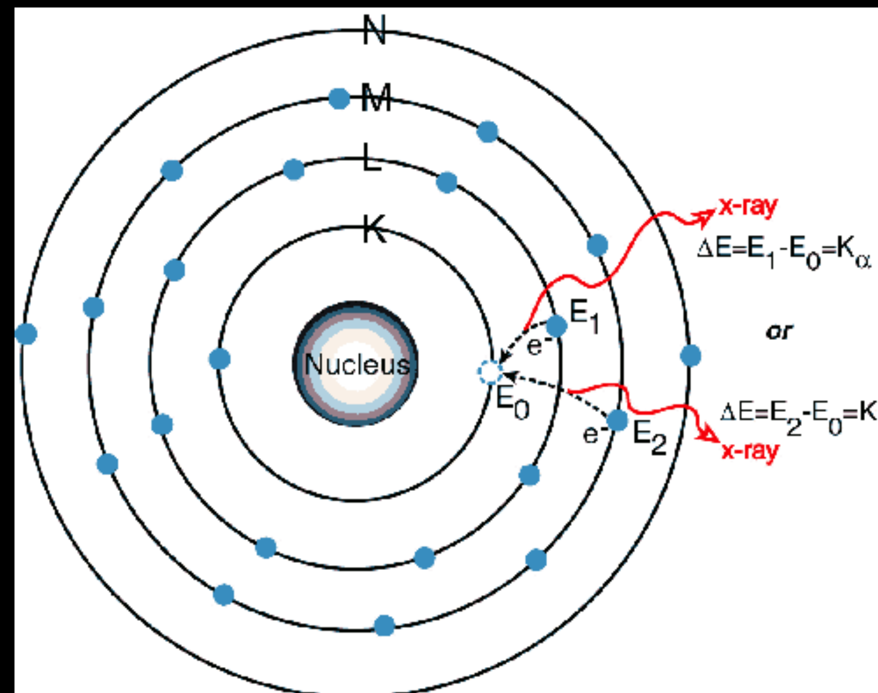
or a combination of both…

(Fe) Fluorescence Emission Line

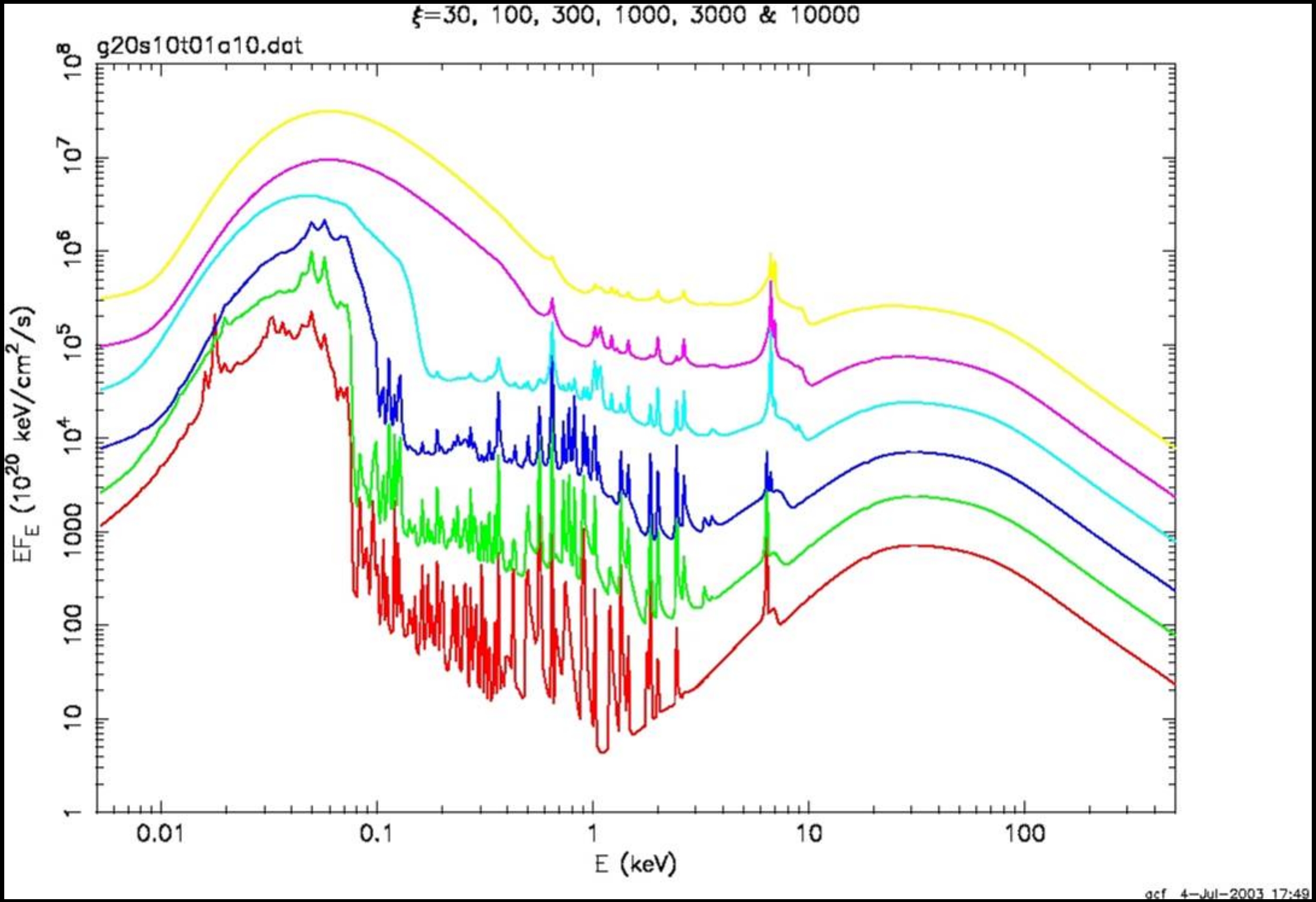
Photoelectric Absorption



Fluorescence (+ Auger for 60%)



A- Ionization effects



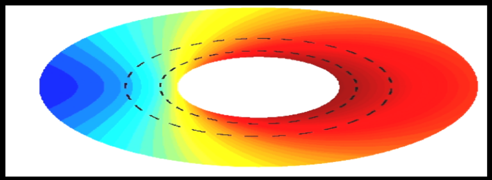
$\xi = L/nR^2$

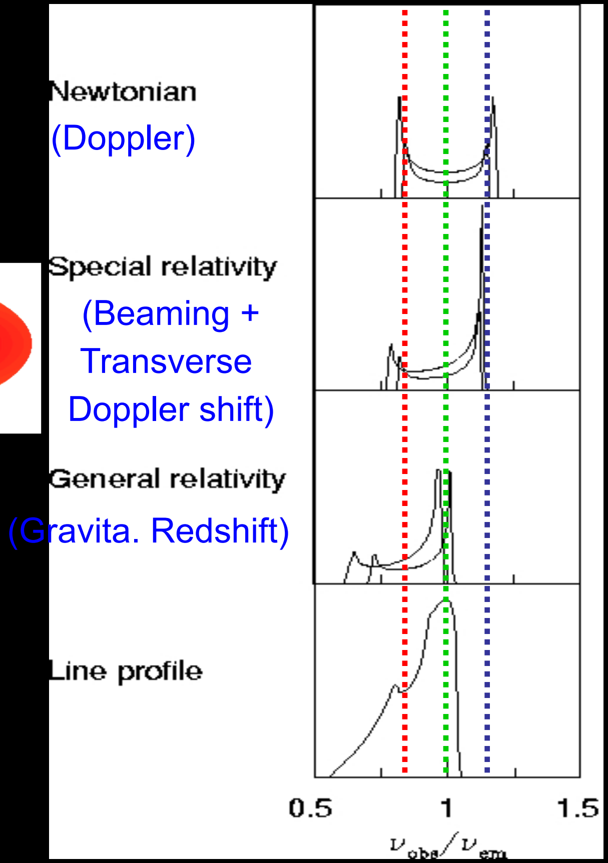
Major variations:

1) FeK energy (↑)
2) FeK intensity (↓,↑,↓)
3) Soft lines intensity/energy (↑,↓)

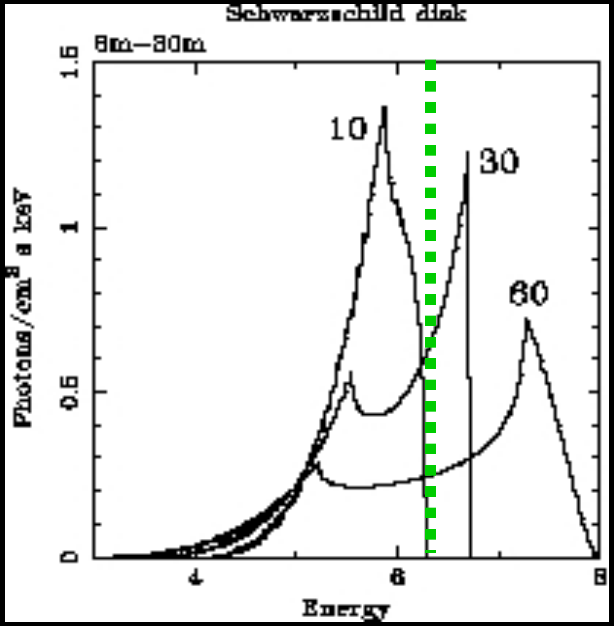
Ballantyne & Fabian '02, Ross & Fabian '93, '05, Young+, Nayakshin+, Ballantyne+, Rozanska+, Dumont+

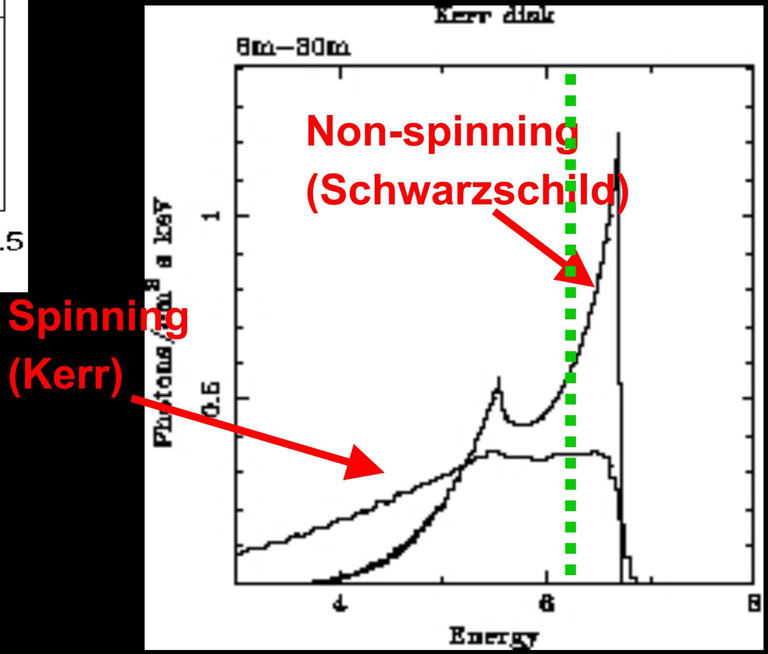
B - Relativistic effects





(e.g., Fabian et al. '89)





(Fabian et al. '00)

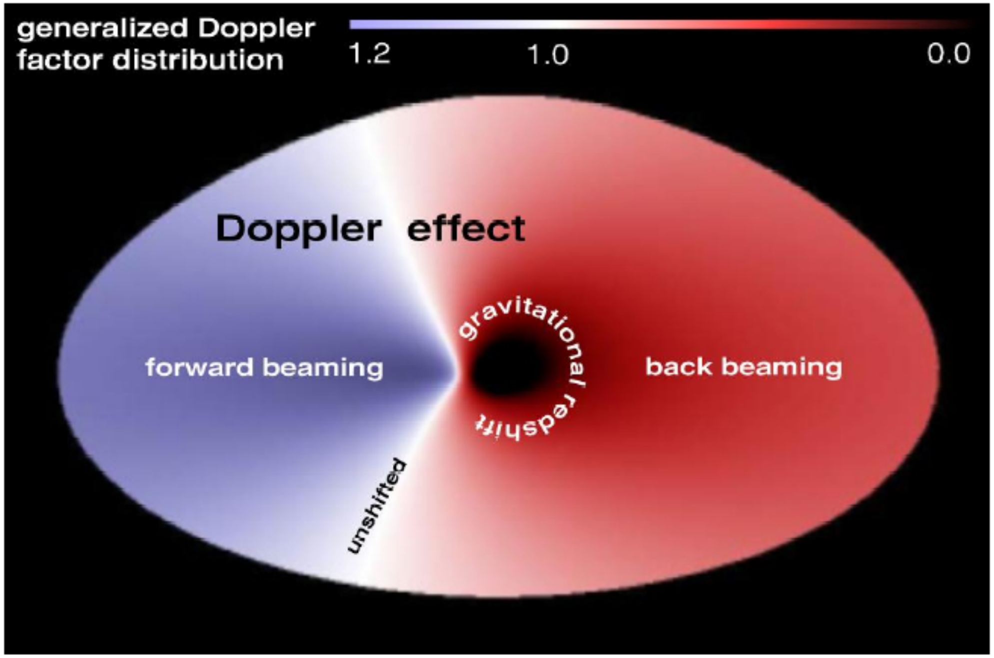


Figure 6.2: Simulated disk image around a central Kerr black hole color–coded in the generalized Doppler factor g. The distribution illustrates redshift $g < 1$ (*black* to *red*), no shift $g = 1$ (*white*) and blueshift $g > 1$ (*blue*). Regions of Doppler effect, beaming and gravitational redshift are marked. The inclination angle amounts $i = 60°$.

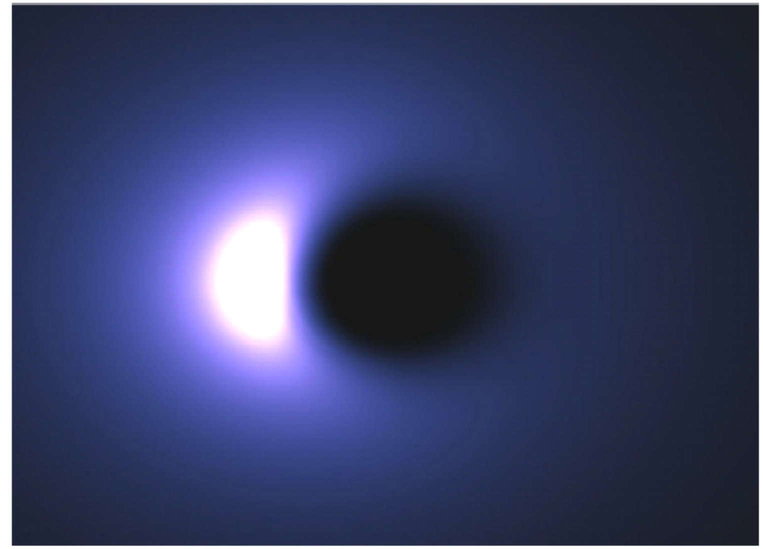
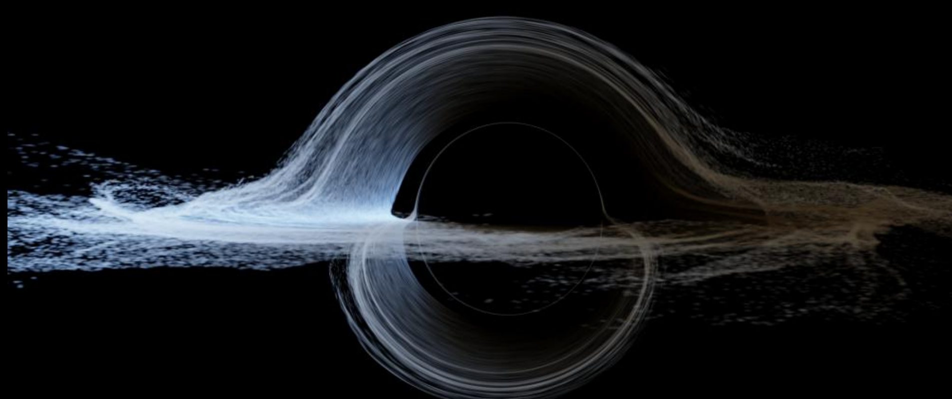
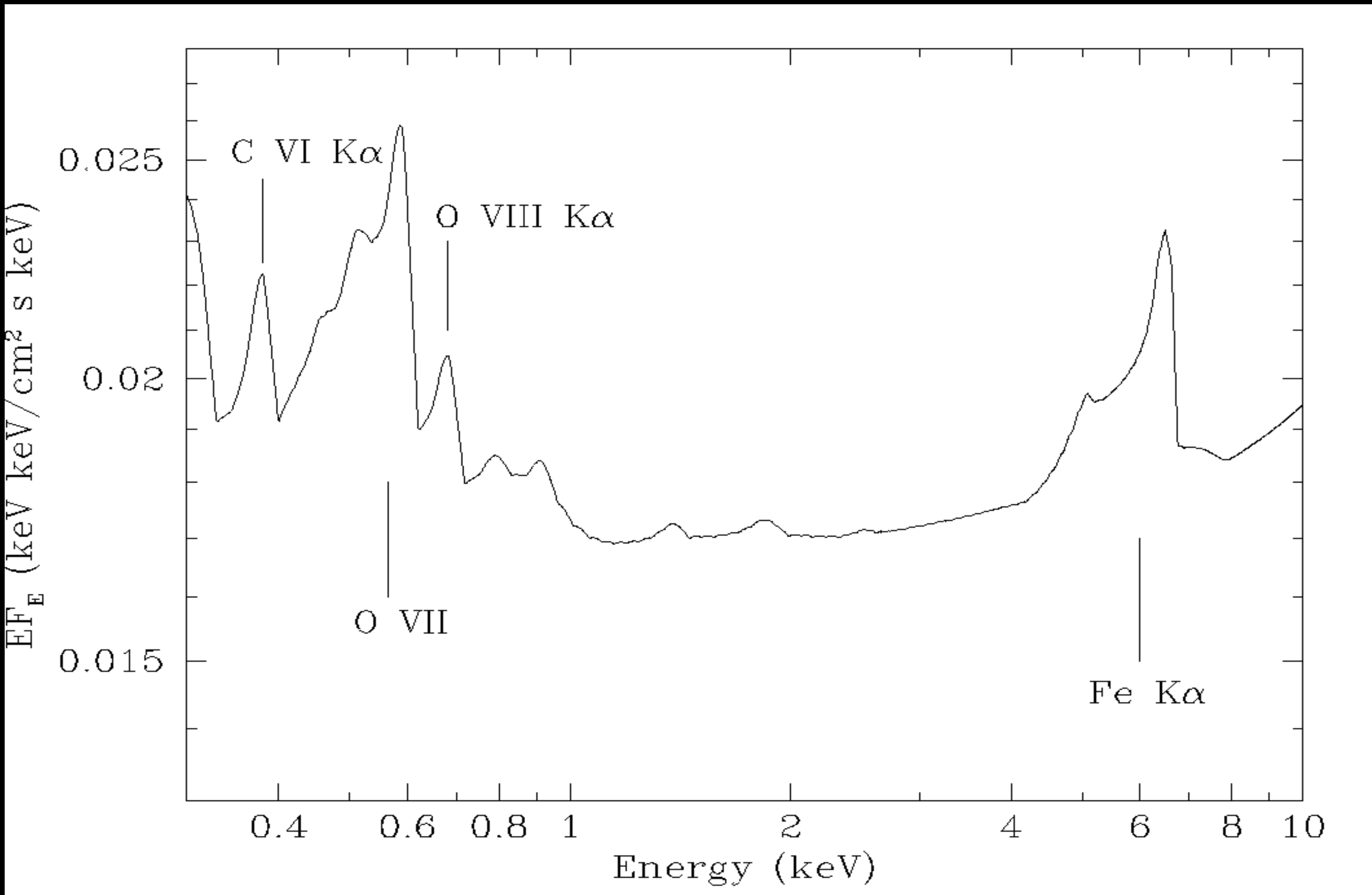


Figure 6.3: Simulated appearance of a uniformly luminous standard disk around a central Kerr black hole, $a \simeq 1$. The emission is color–coded and scaled to its maximum value (*white*). The disk is intermediately inclined to $i = 40°$. The forward beaming spot of the counterclockwisely rotating disk is clearly seen on the left whereas the right side exhibits suppressed emission due to back beaming. The black hole is hidden at the Great Black Spot in the center of the image.



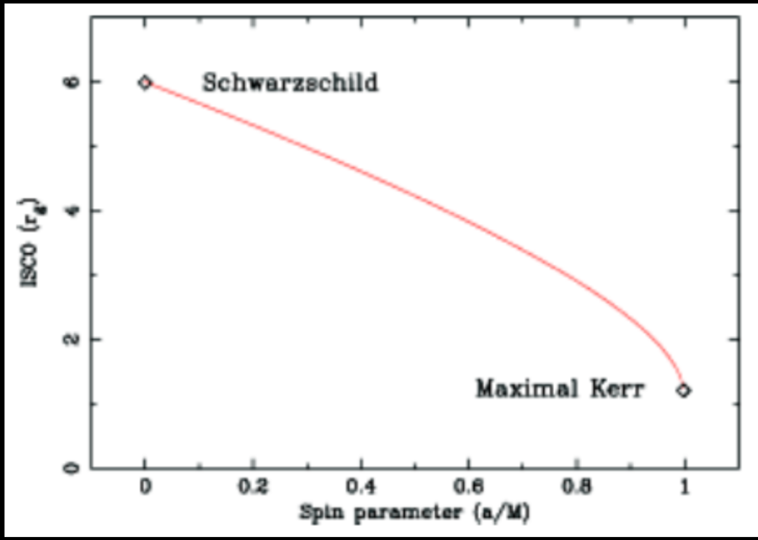
James, Tunzelman, Franlin
and Thorne, '95, arXiv:1502.03808
Black hole Gargantua in Interstellar

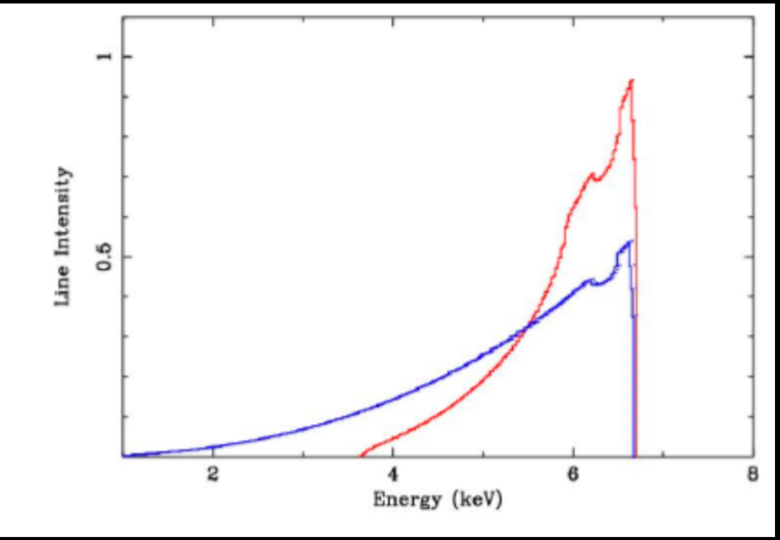
C - Ionization + relativistic effects

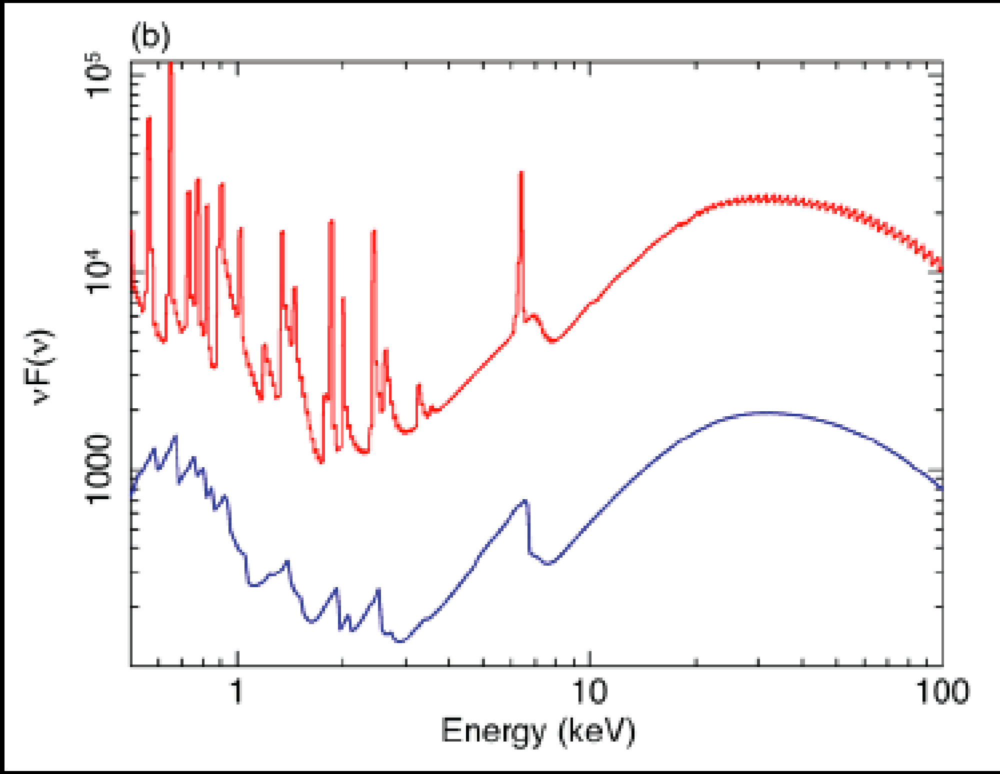


(e.g., Ballantyne & Fabian '02, Matt et al. '93)

C - Ionization + relativistic effects



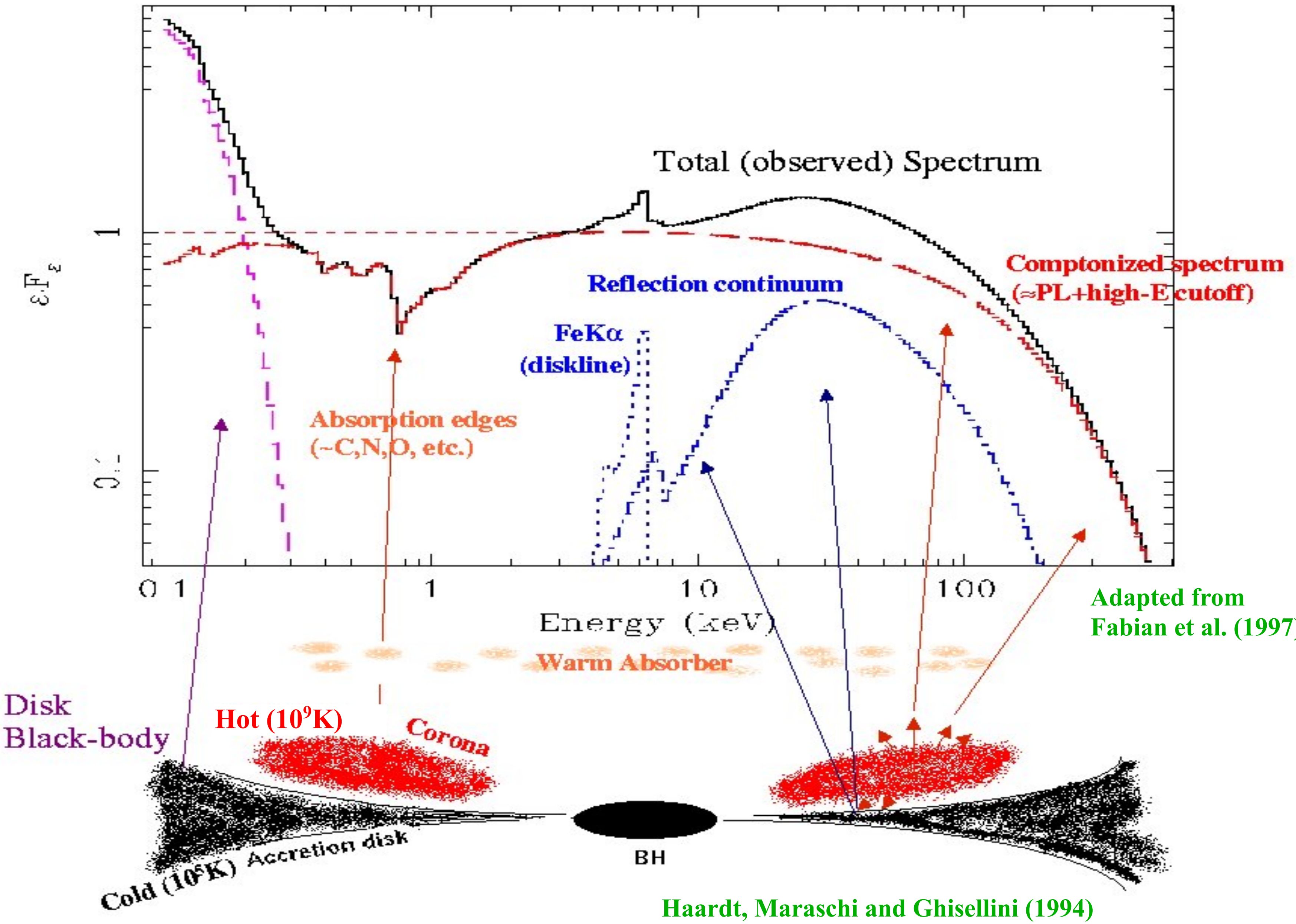




XSPEC models:

Pexrav→pexriv
Reflionx + kdblur
Kerdisk+kerconv
Relxill (=relconv+xillver)
Kyrline+Kyrconv

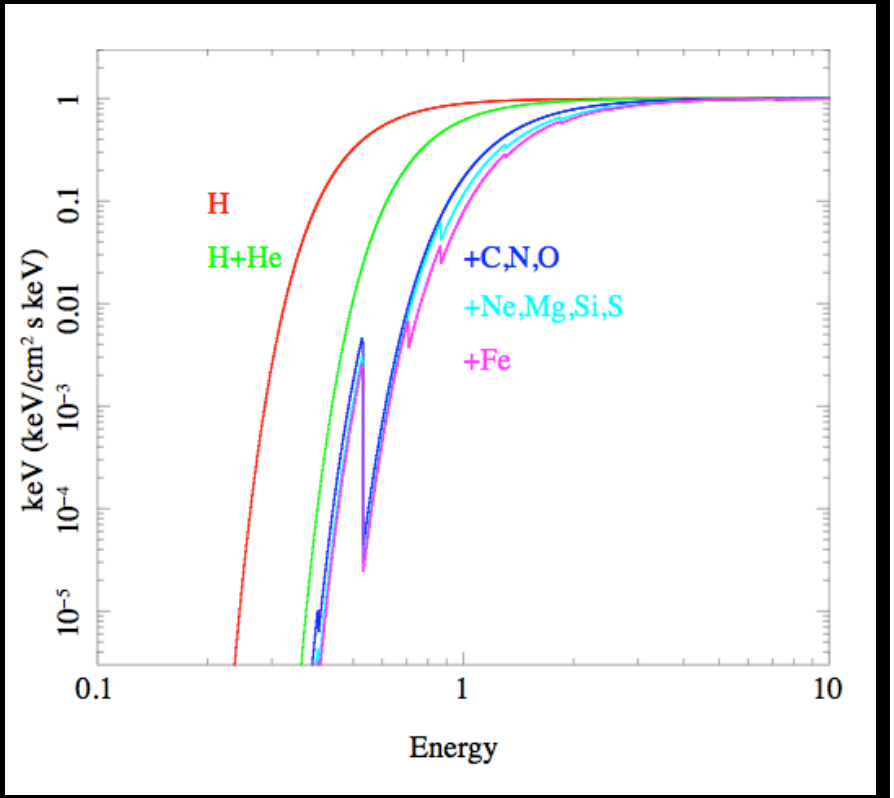
Typical X-ray Spectrum of a Seyfert 1 Galaxy
⇔ Standard two-phase Comptonization model



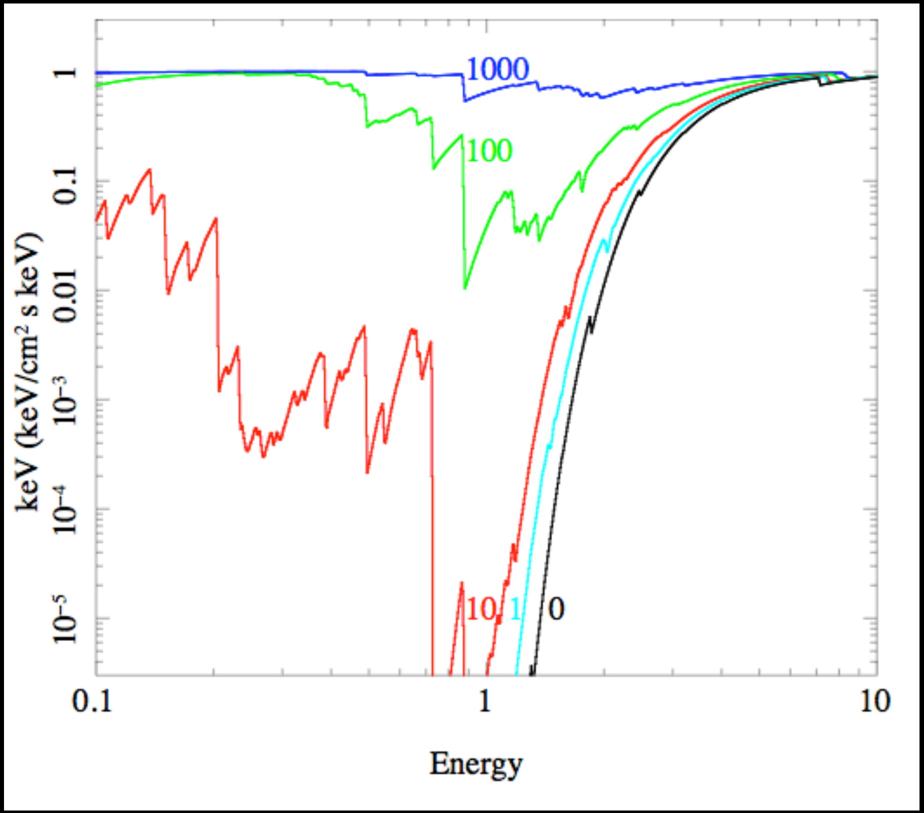
IV - Ionized absorption along the line of sight

Photoelectric absorption

Neutral

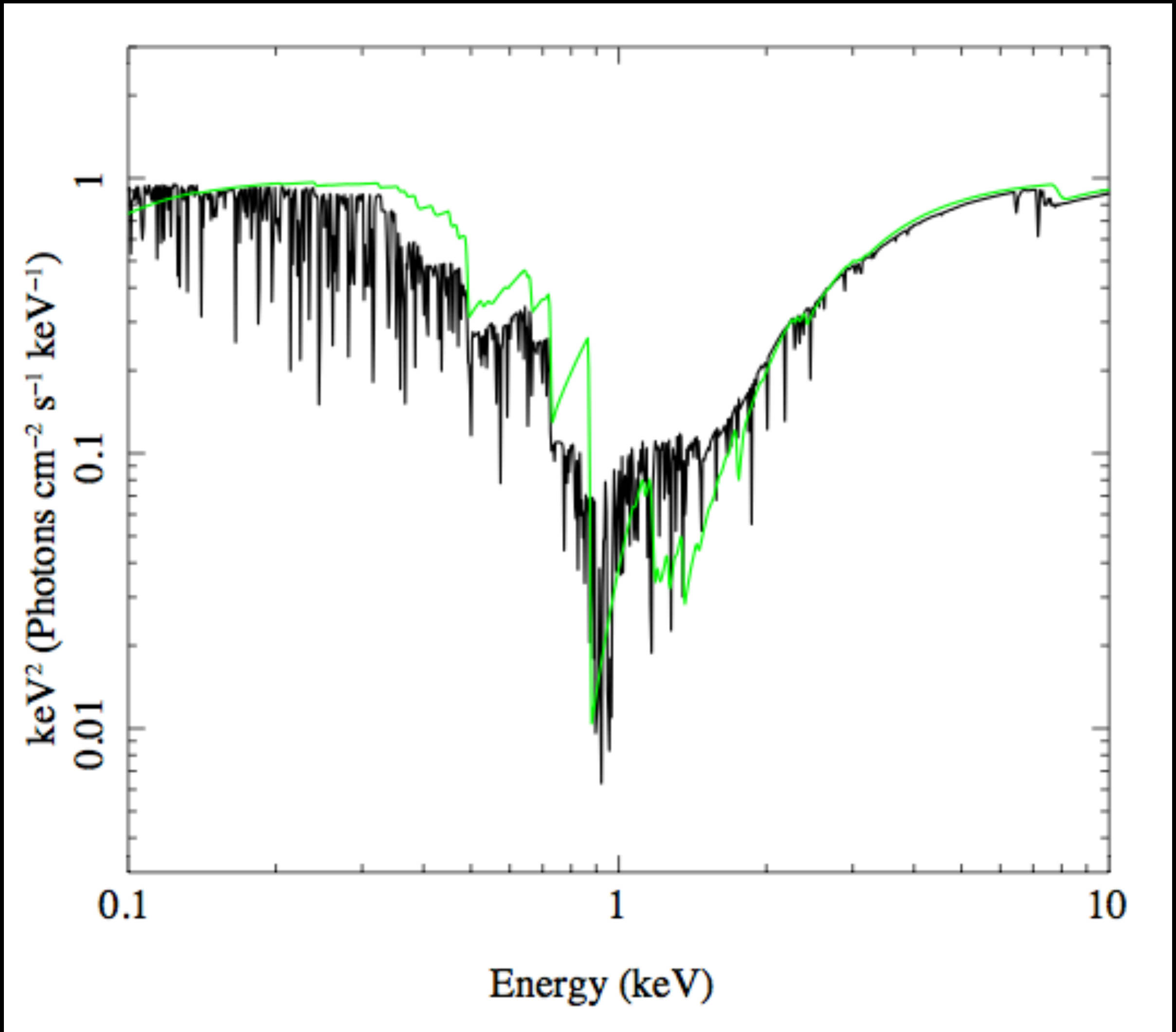


Ionized (Xi=L/nR**2)



IV - Ionized absorption along the line of sight

XSTAR warm absorber model

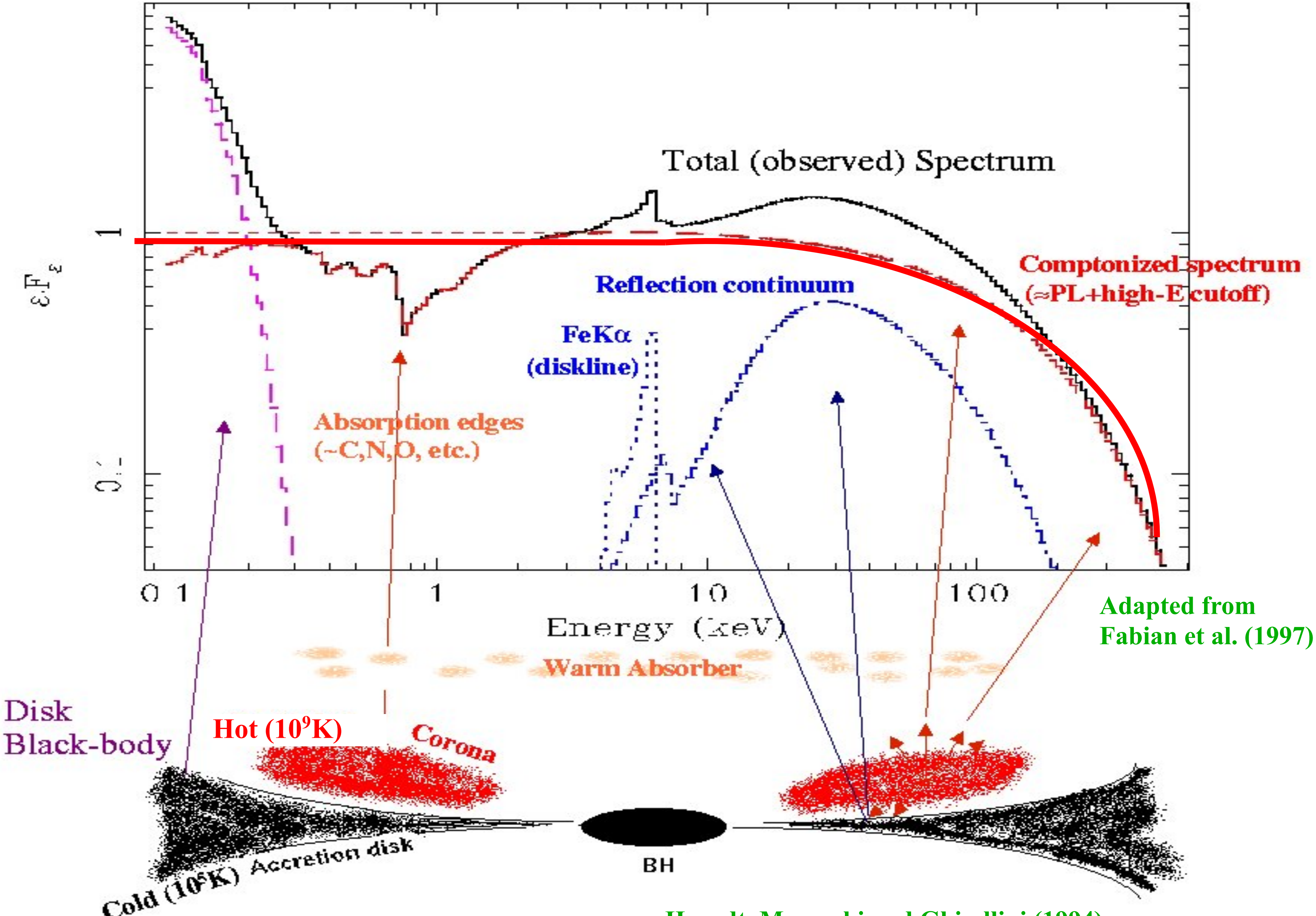


Questions

?

Reflection(s)
vs
Ejections(s)

Typical X-ray Spectrum of a Seyfert 1 Galaxy
⇔ Standard two-phase Comptonization model



Adapted from
Fabian et al. (1997)

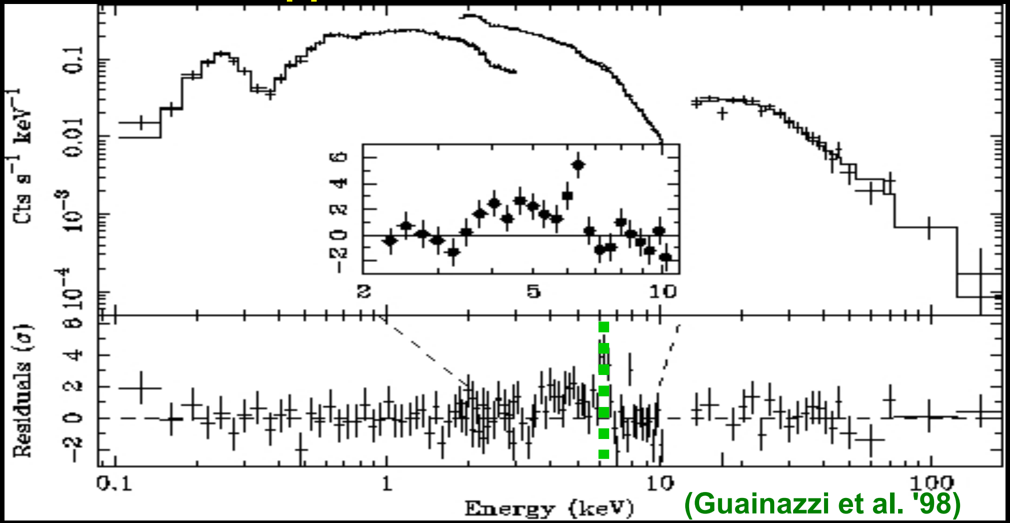
Haardt, Maraschi and Ghisellini (1994)

Emission lines…
i.e. pointing to Reflection(s)
(i.e. accretion)

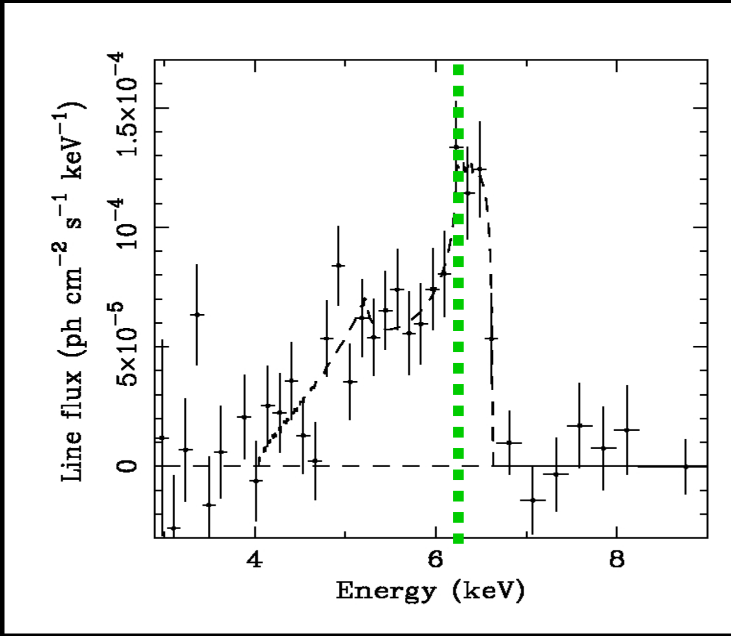
Reflection: Observations

Pre-Chandra & XMM-Newton

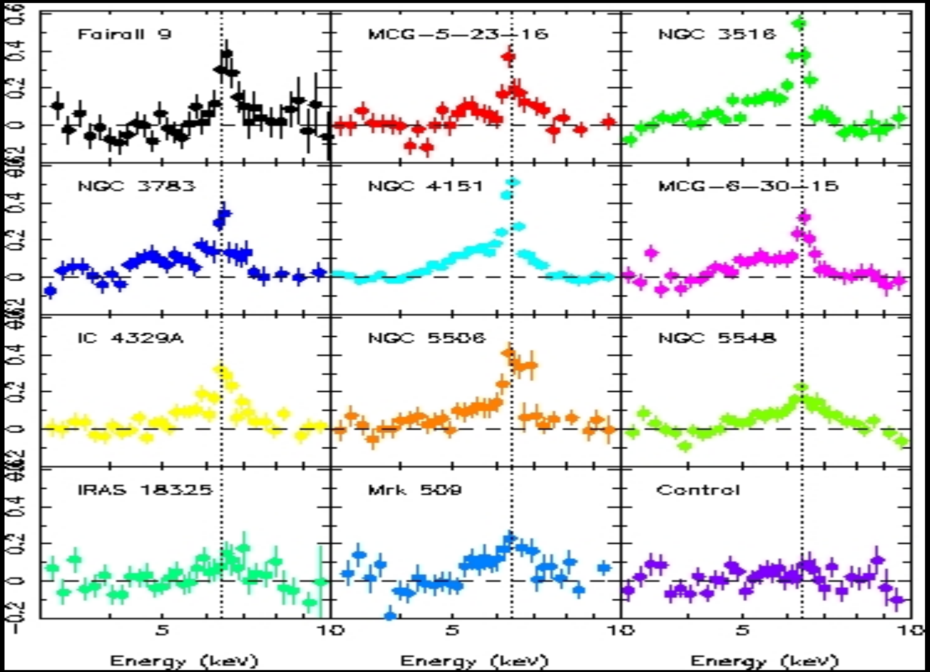
BeppoSAX obs. of MCG-6-30-15



(Guainazzi et al. '98)



(Tanaka et al. '95)



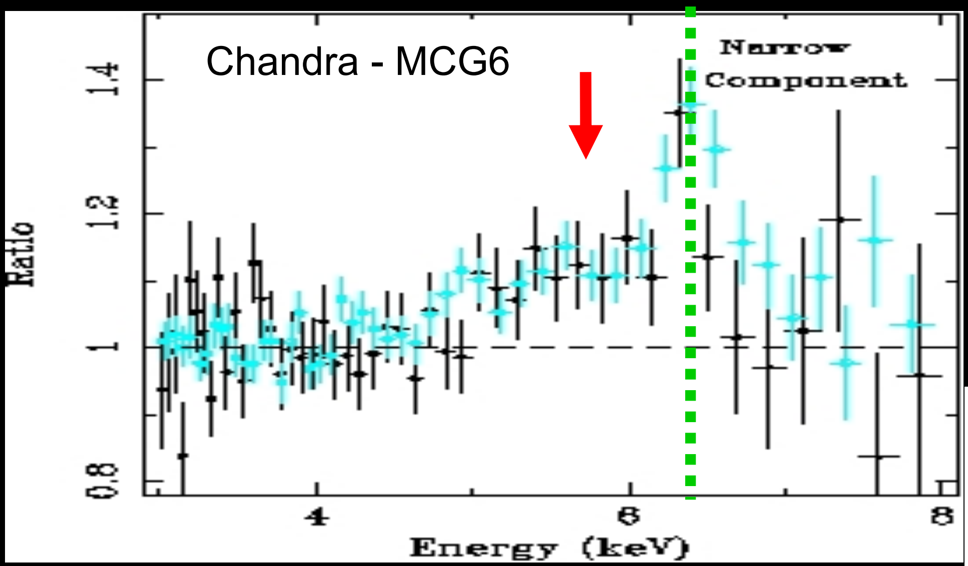
(Nandra et al. '98)

ASCA ---> Broad (relativistic) lines are common, and ubiquitous (?) in Seyfert1s!

Reflection: Observations

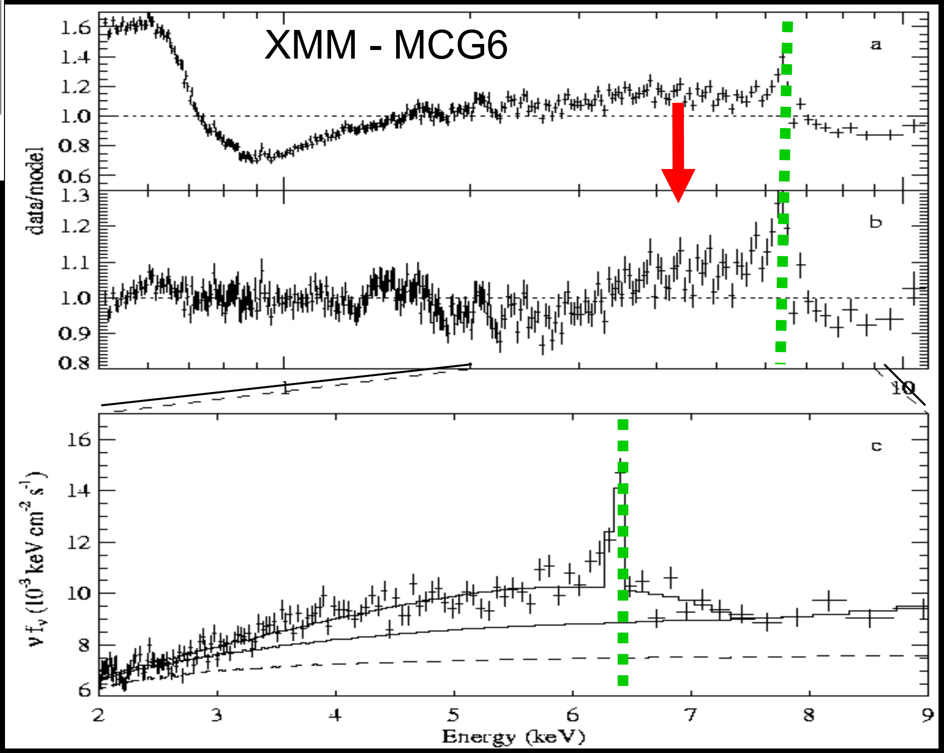
Post-Chandra & XMM-Newton

Yes, we see broad lines indeed!



(Lee et al. '02)

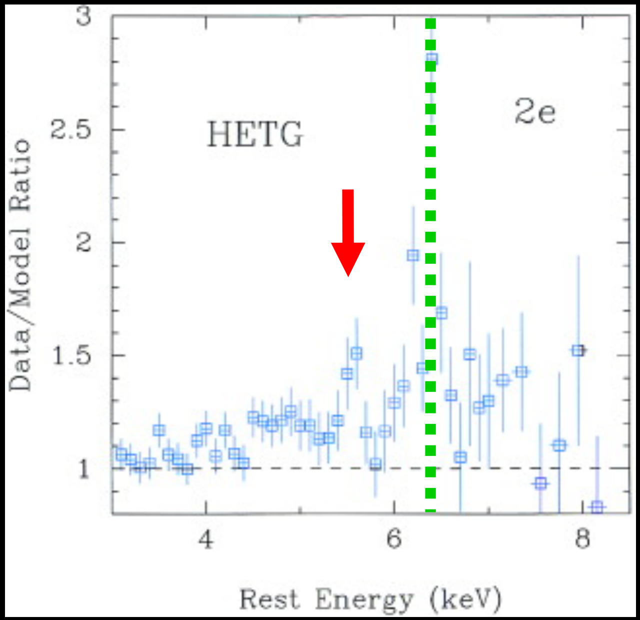
(Wilms et al. '02
Fabian et al.' 04)



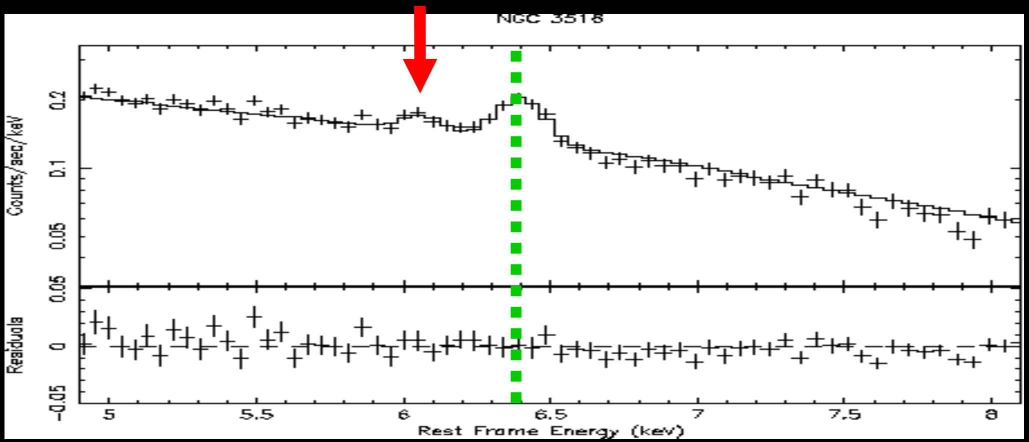
Origin in innermost regions of accretion disk

Post-Chandra & XMM-Newton

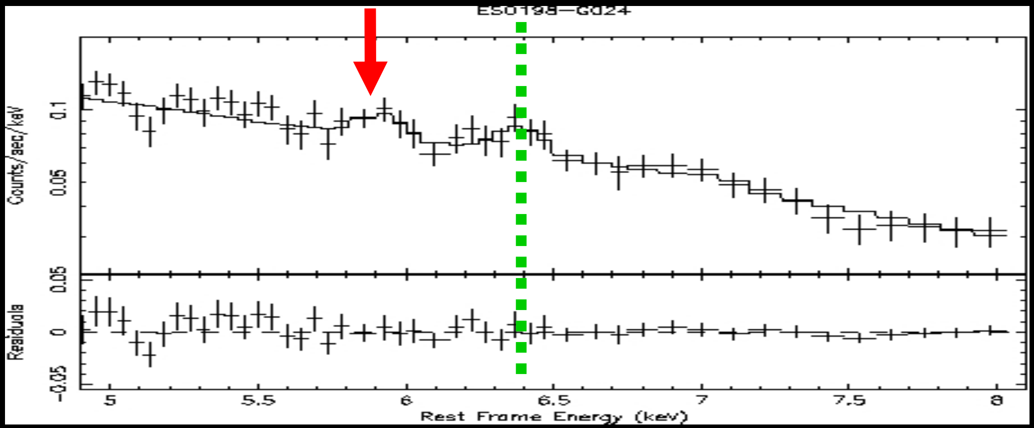
Also some narrow redshifted lines...



(Turner et al. '02)



Bianchi et al., 2004



Guainazzi et al., 2003

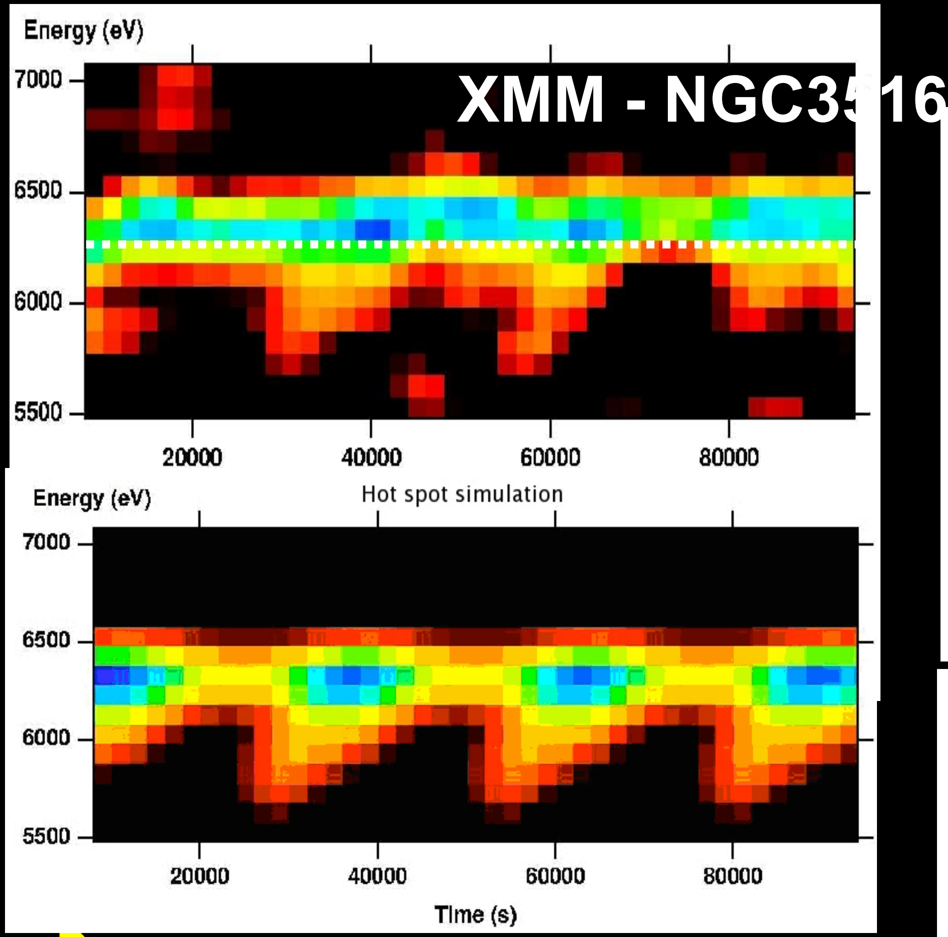
Origin in innermost regions of accretion disk+ blob-like structure (or inflowing blobs?)

Dovciak et al., 2004

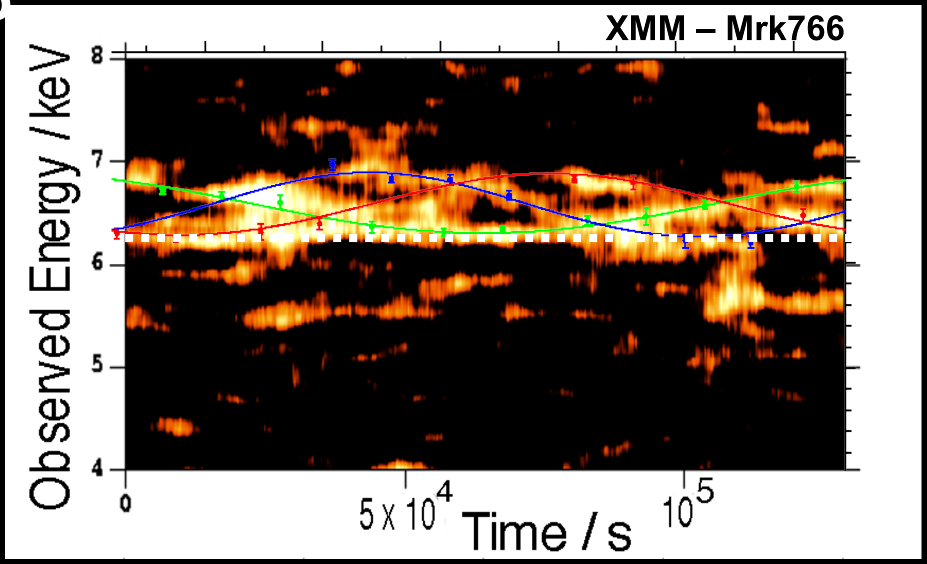
Reflection: Variability

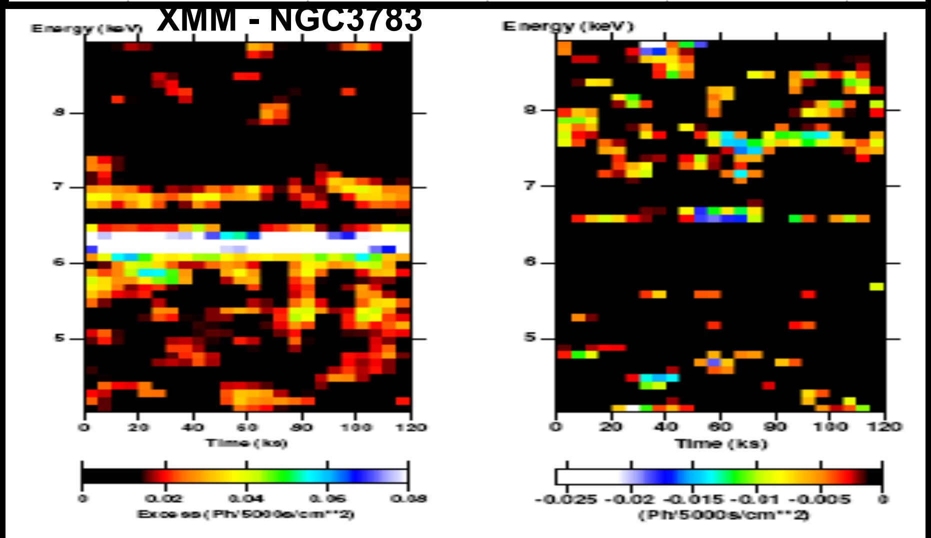
Post-Chandra & XMM-Newton

Everything is getting more complex, but key point is that Fe lines DO show fast time variations and redshifted energies!!



Can fit line maxima by three Keplerian orbits with *same* inclination & central mass !! (Turner et al. 2005)





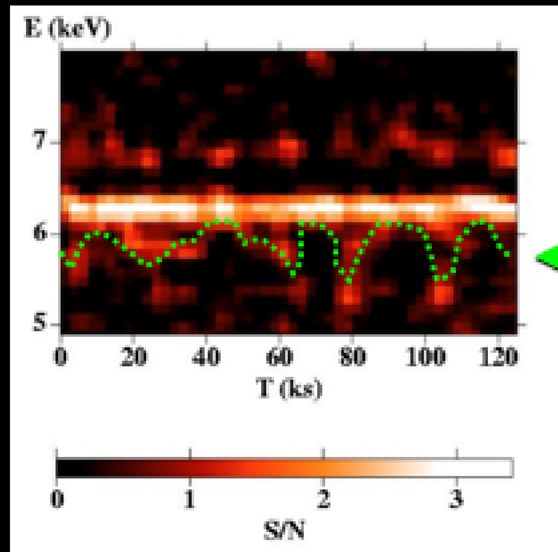
Origin from hot spots in innermost regions of accretion disk?

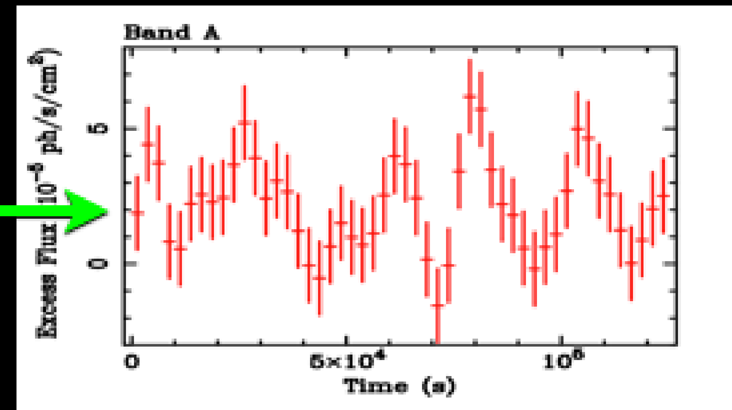
De Marco et al., 2009, PhD Thesis

Reflection: Variability

NGC3783

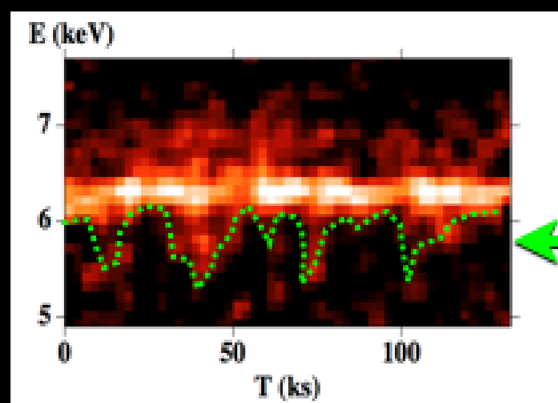
Tombesi et al. 2007

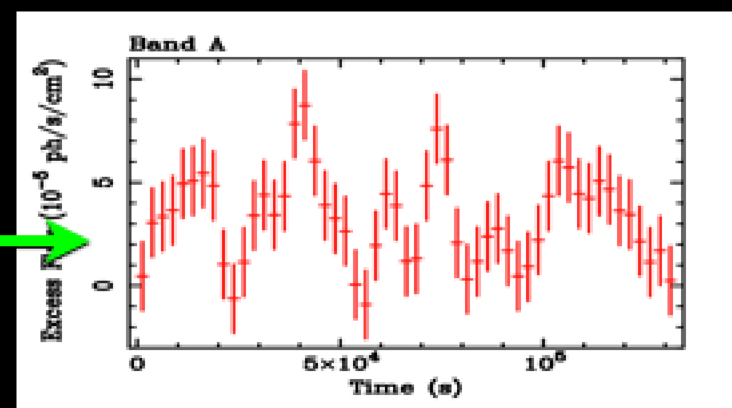




IC4329a

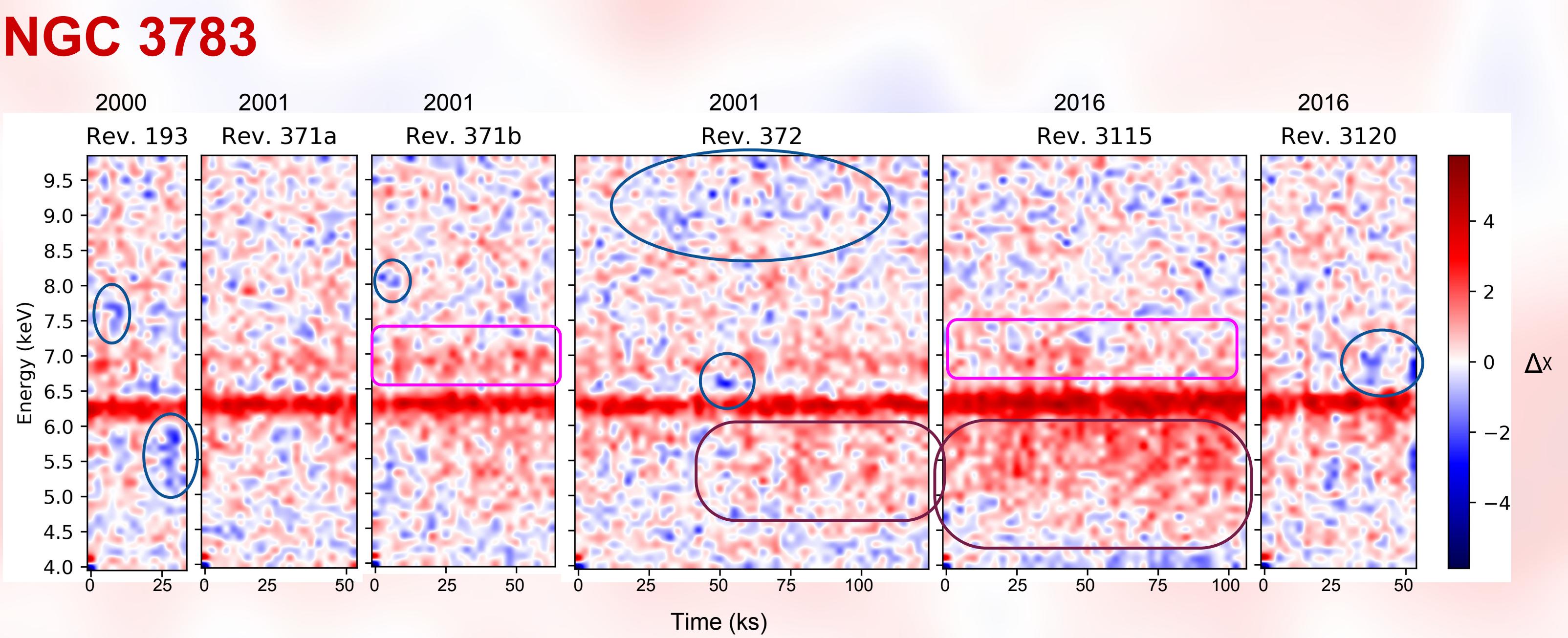
DeMarco et al. 2010b





$\Rightarrow$ Consistent with origin from hot spots, or spiral waves, in inner regions of accretion disk?

Reflection: Variability



- Fe Kα always present, variable intensity
- Variable Fe Kβ/ ionized Kα blend
- Variable broadened line component
- Multiple absorptions

NGC3783

Costanzo et al. 2019,

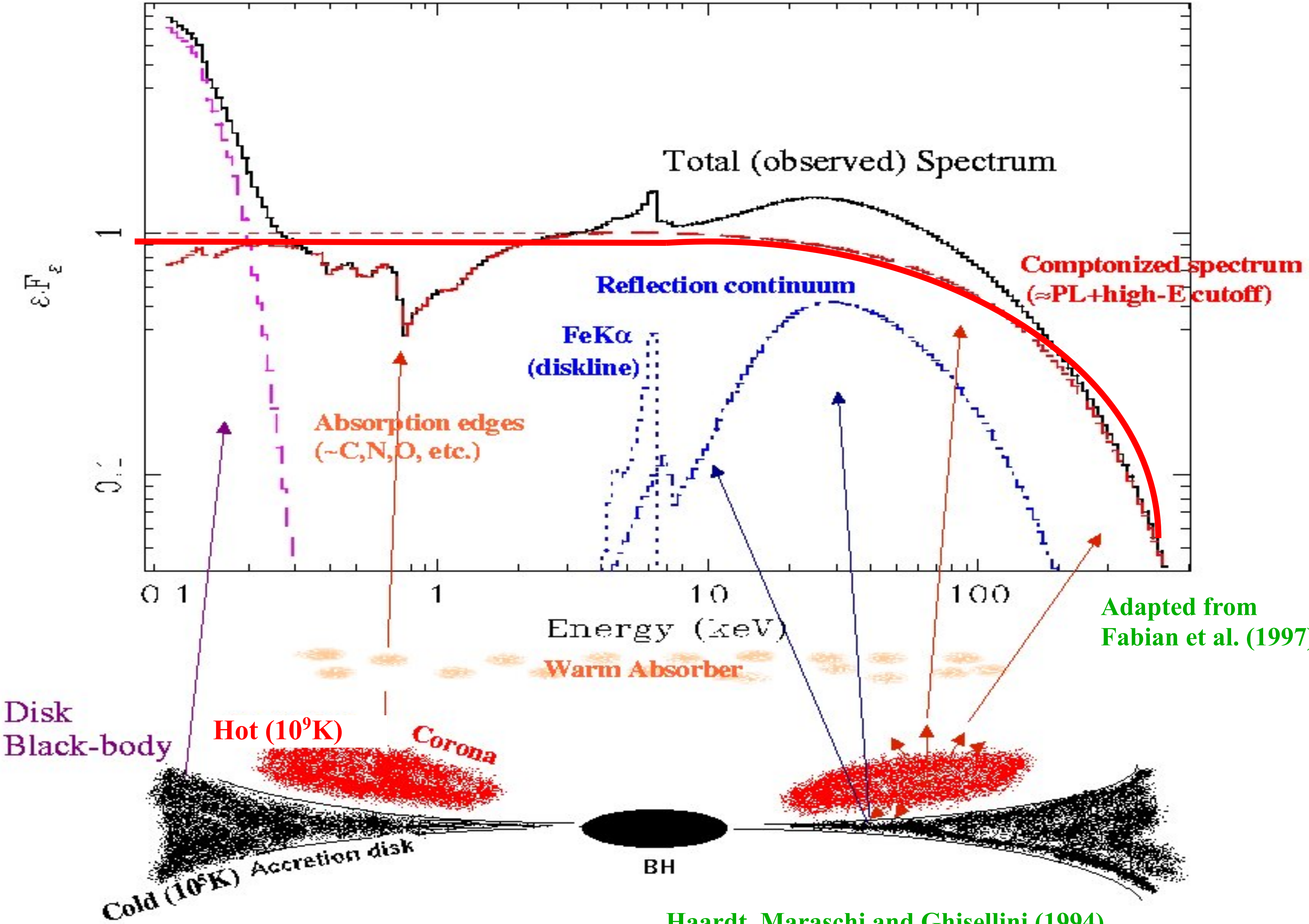
Tesi di Laurea, paper in prep

⇒ Consistent with origin from hot spots, or spiral waves in inner regions of accretion disk?

Questions ?

Absorption lines…
i.e. pointing to absorber(s)
(i.e. ejection(s))

Typical X-ray Spectrum of a Seyfert 1 Galaxy
⇔ Standard two-phase Comptonization model

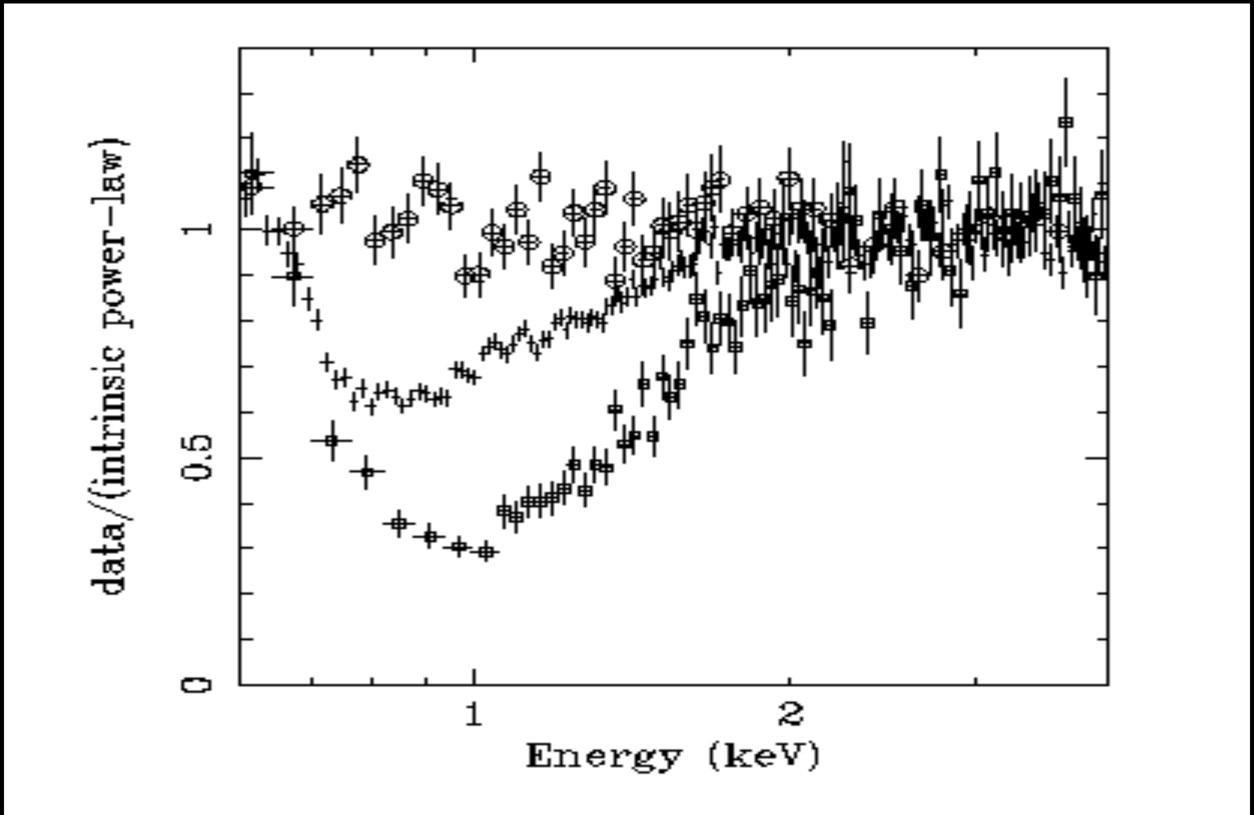


Adapted from
Fabian et al. (1997)

Haardt, Maraschi and Ghisellini (1994)

Absorption: Warm absorbers

Pre-Chandra & XMM-Newton



Reynolds et al. '97
Georges et al. '97

Clear since years that warm absorbers must be dynamically important (radiatively driven outflow located in BLR and NLR)

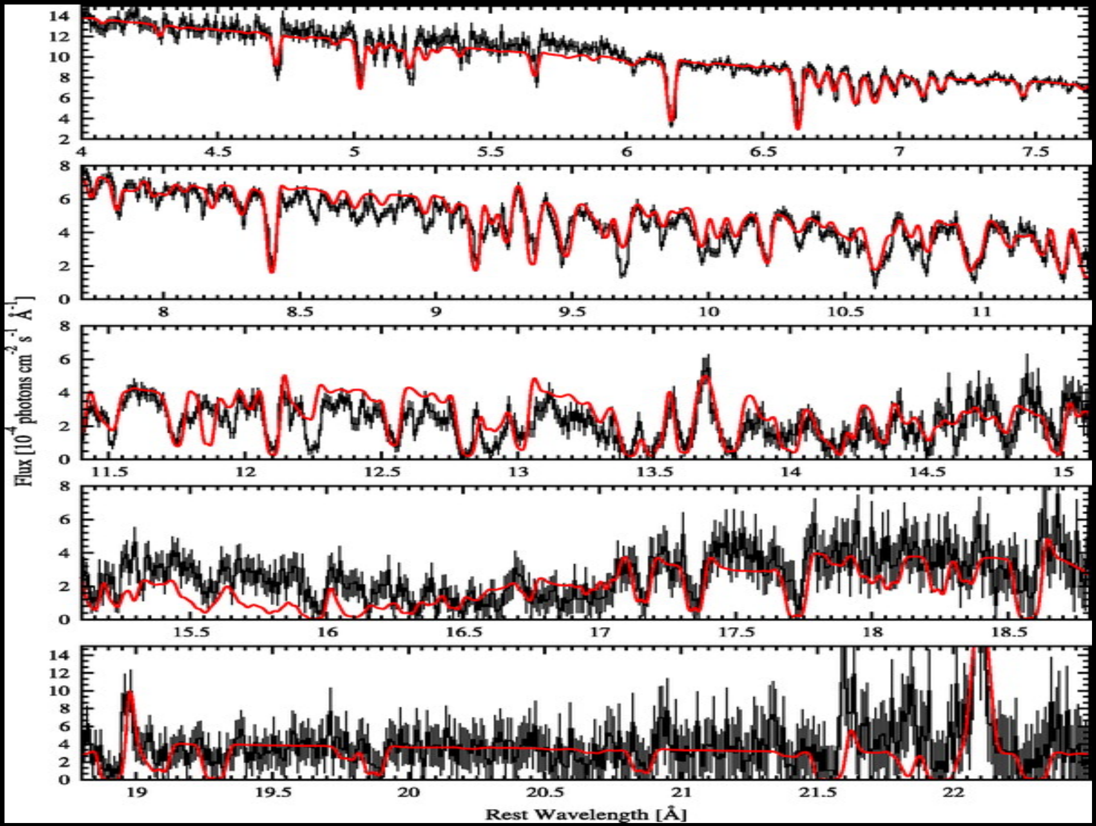
Open Problem: Characterisation of warm absorber? (cov. Factor, ion. state, mass/energy outflow, etc.)

Absorption: warm absorbers

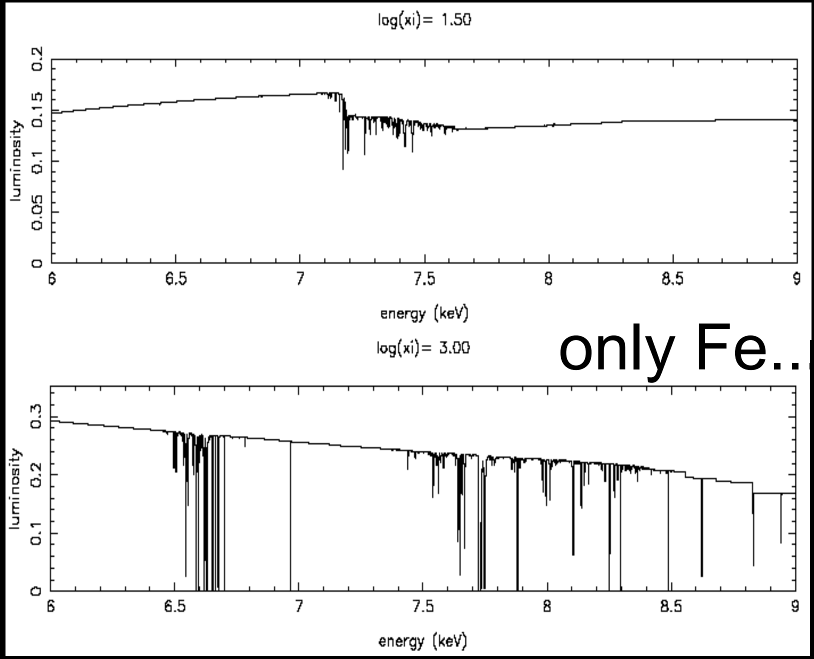
Post-Chandra & XMM-Newton

Many more details from Chandra gratings

NGC3783 Exp=900 ks



Consistent with models which predict many absorption features



only Fe...

Kallman et al. '05

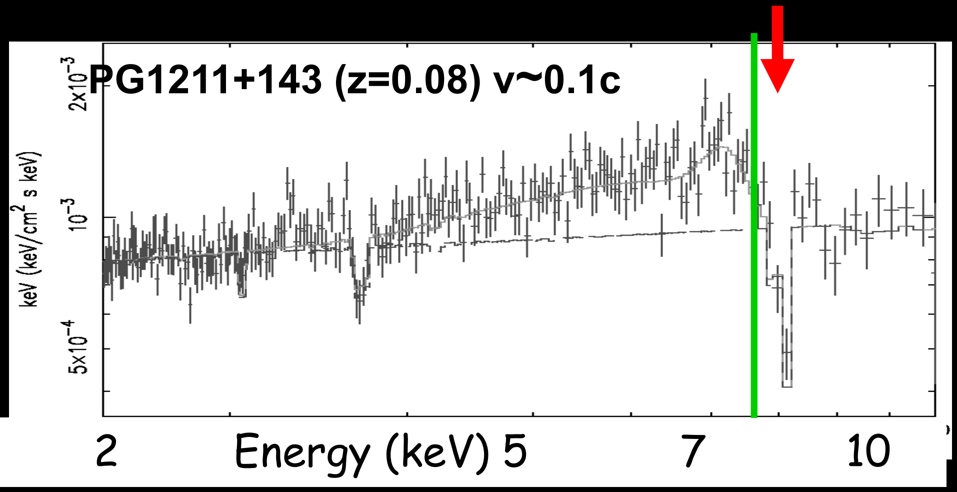
Kaspi et al. '01
Netzer et al. '02
Georges et al. '03

Clear now that often multiple ionization & kinetic components: outflows with ~100-1000 km/s

Absorption: UFOs

Post-Chandra & XMM-Newton

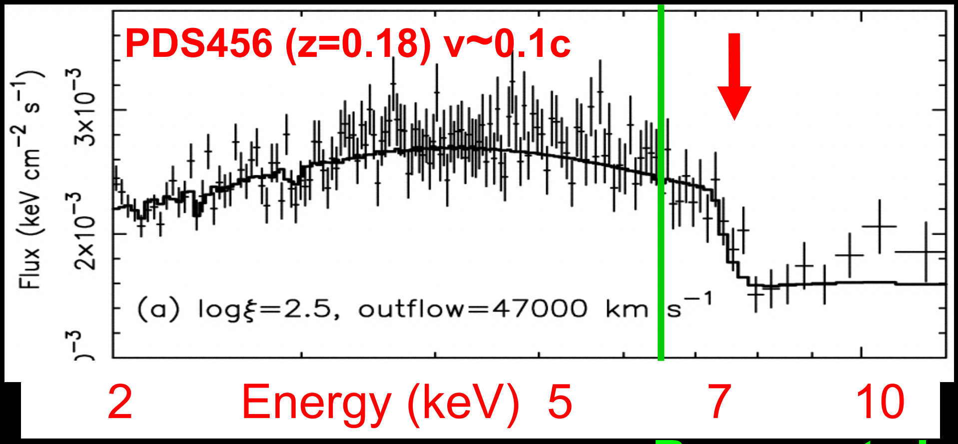
New and unexpected results from Chandra and XMM-Newton observations



Blue-shifted absorption lines/edges – **High-v**

Pounds et al. 2003a,b

(If) interpreted as Kα resonant absorption by Fe XXV (6.70 keV) or FeXXVI (6.96 keV)

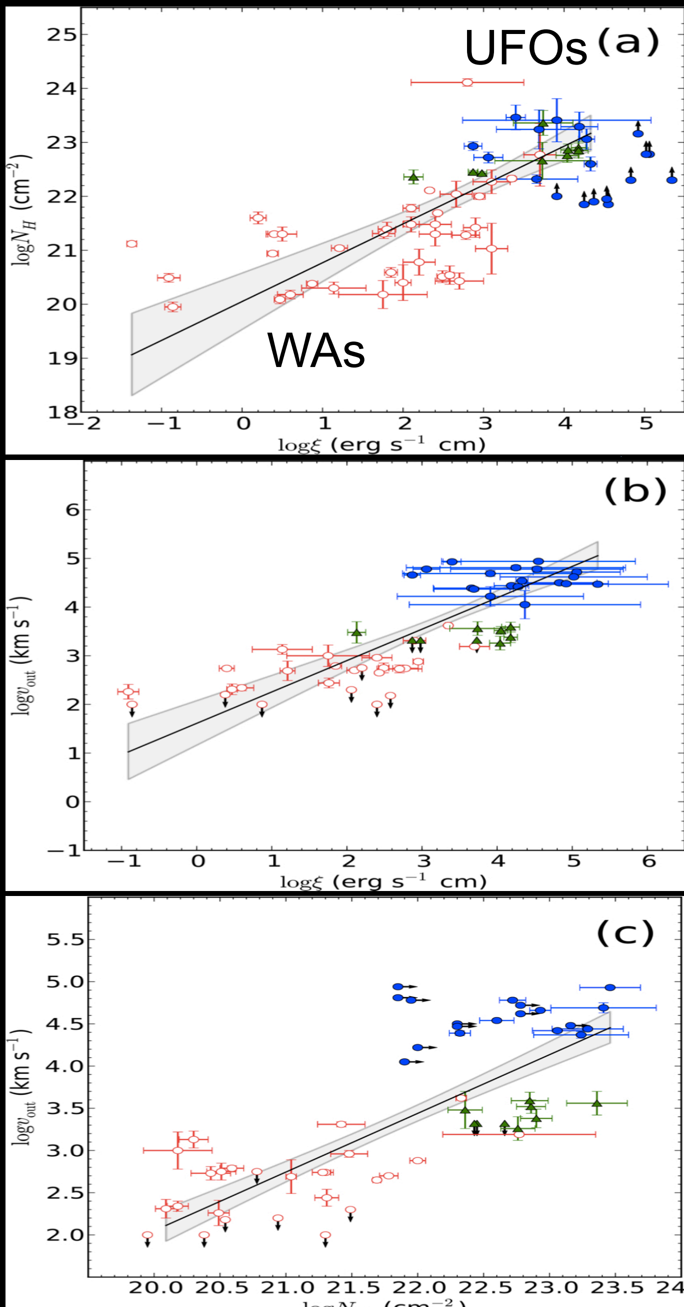


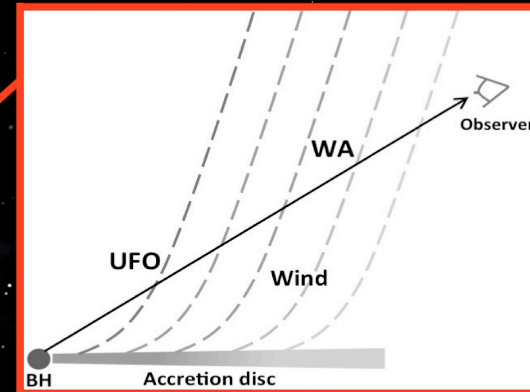
Reeves et al. 2003

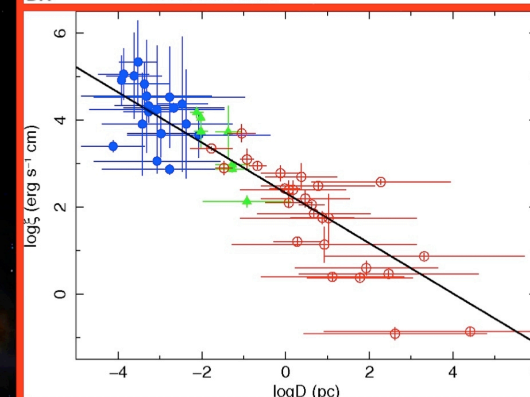
⇒ massive, **high velocity** and highly ionized outflows in several RQ AGNs/QSOs

Mass outflow rate: comparable to Edd. Acc. rate (~$M_\odot$/yr); velocity ~0.1-0.2 *c*

A (unifying) X-ray view of UFOs and non-UFOs (WAs)

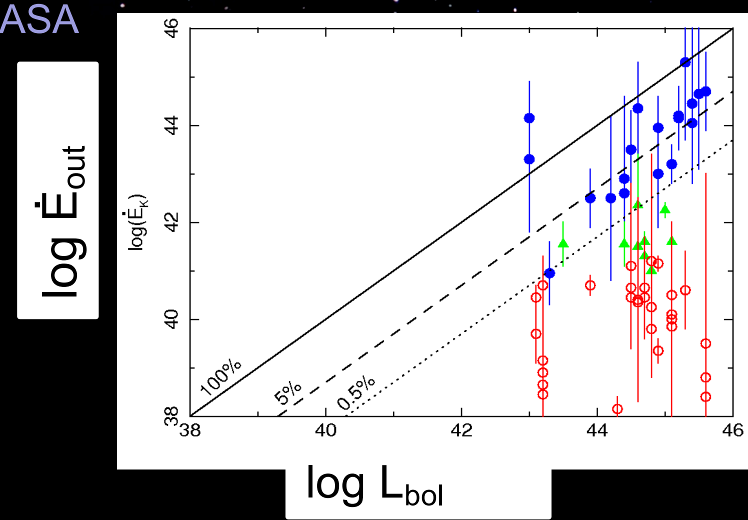






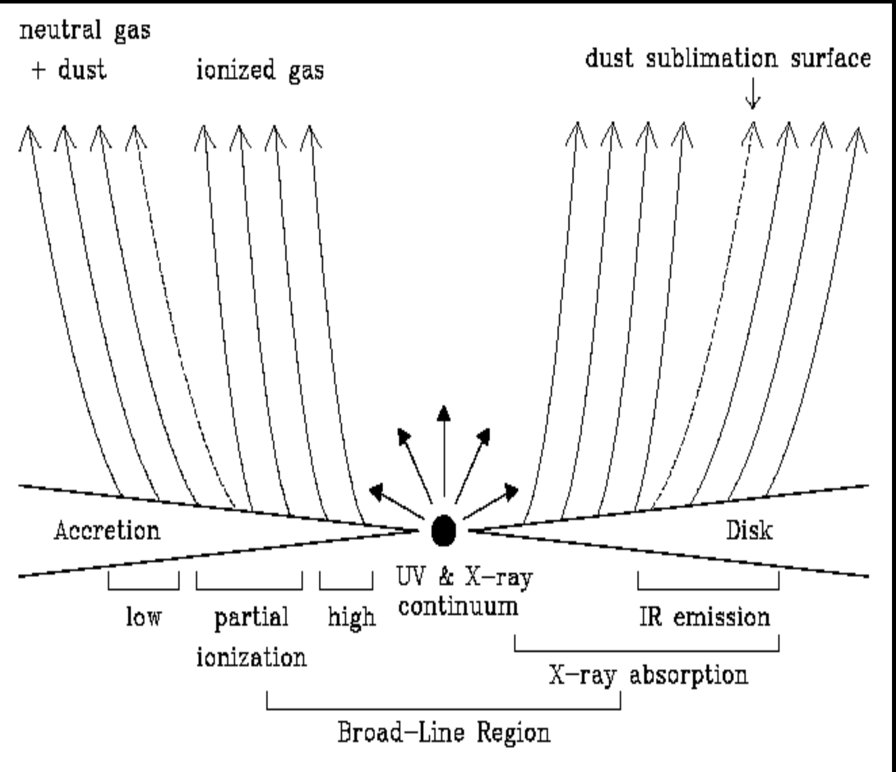
INAF Press releases
in ’10, ’12, ’13, plus NASA
and ESA in 2012

Tombesi, MC
et al., ’12a,b, ‘13



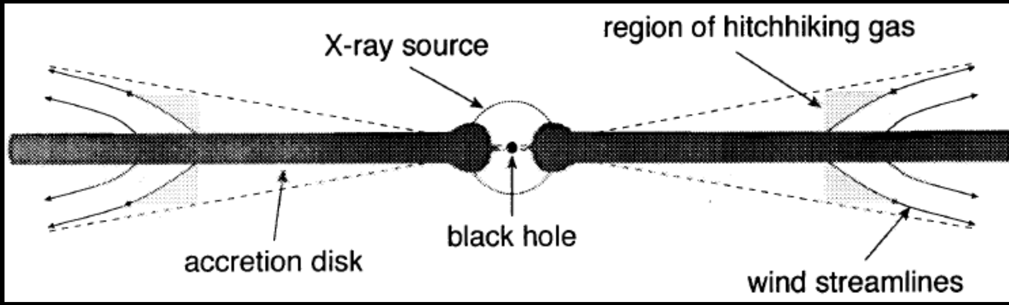
Absorption: Interpretation - Three main wind dynamical models

i) Thermally driven winds from BLR or torus



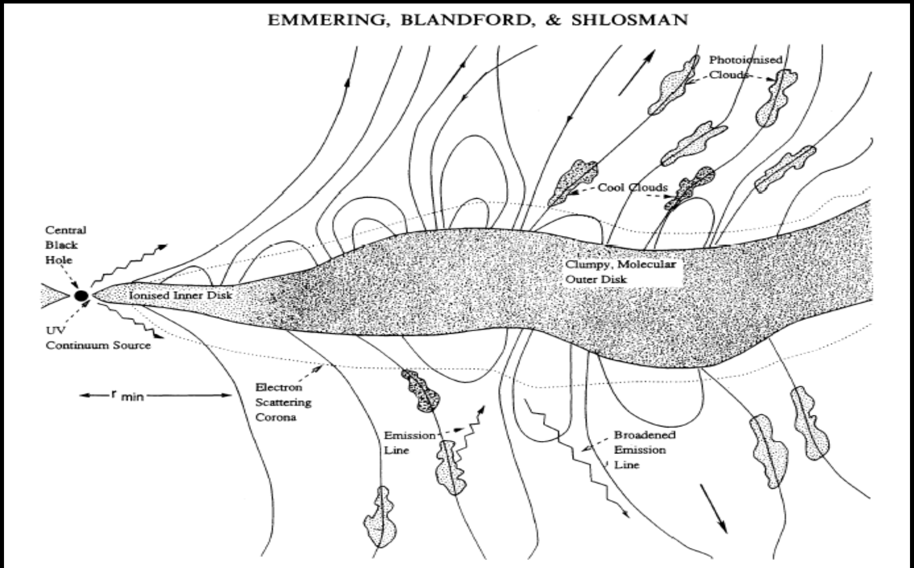
Balsara & Krolik, 93; Woods et al. '96

ii) Radiative-driven wind from accretion disk



Murray et al. '95, Proga et al. '00

iii) Magnetically driven winds from accretion disk



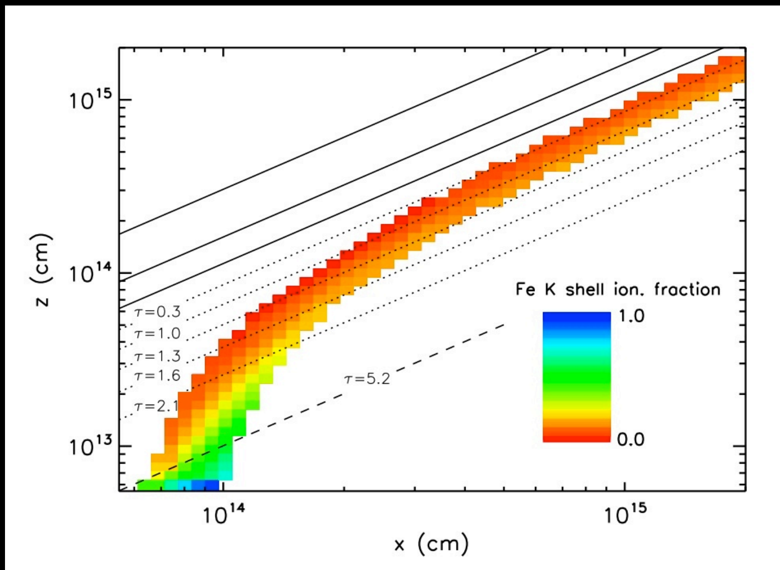
Emmering, Blandford & Shlosman, '92; Kato et al. '03

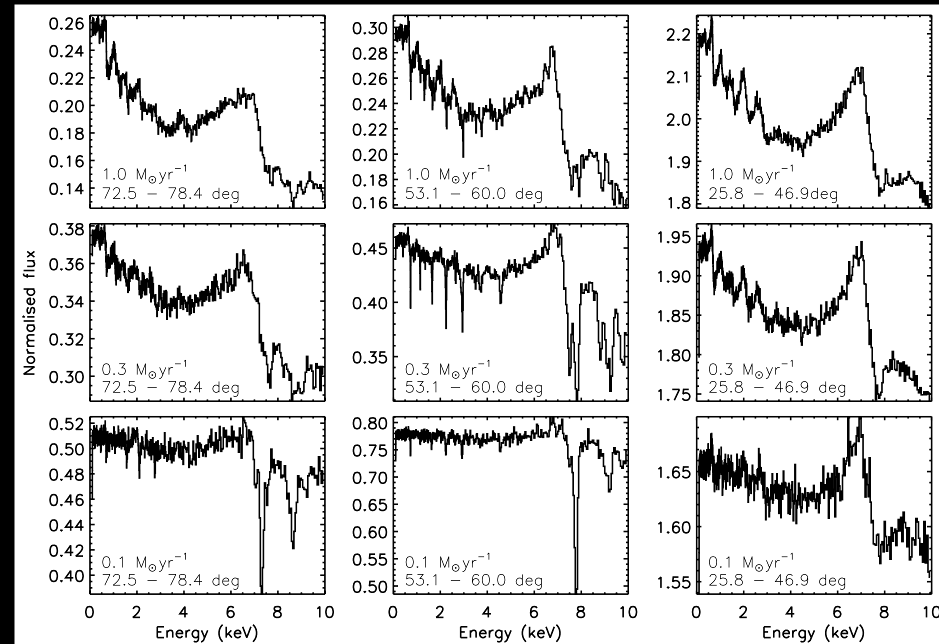
i) ⇒ Large R, low v

ii) and iii) ⇒ Low R and large v

UFOs/outflows/winds in AGNs & QSOs: Possible models

Radiatively driven accretion disc winds



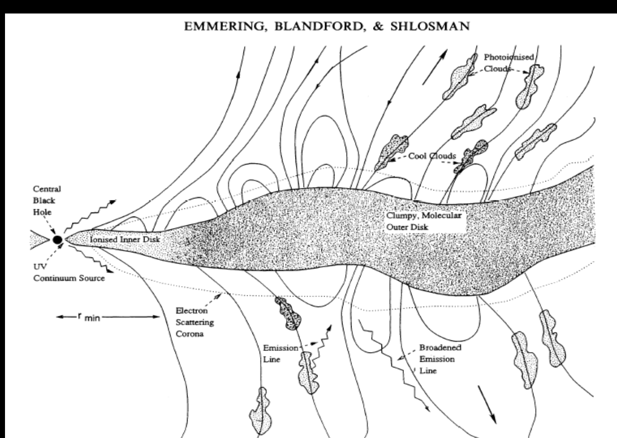


Sim et al., ’08, ’10ab

Murray et al. ‘95,

Proga et al. ’00; ‘10

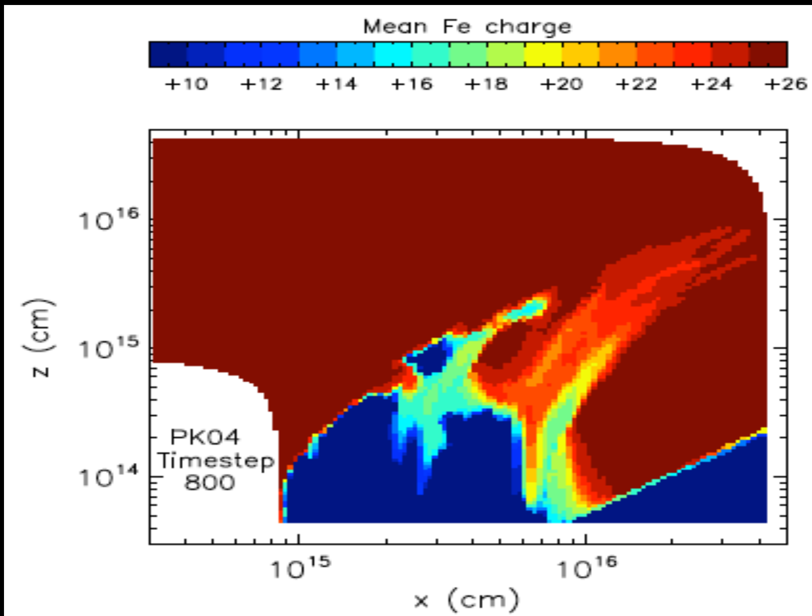
Magnetically driven winds from accretion disk

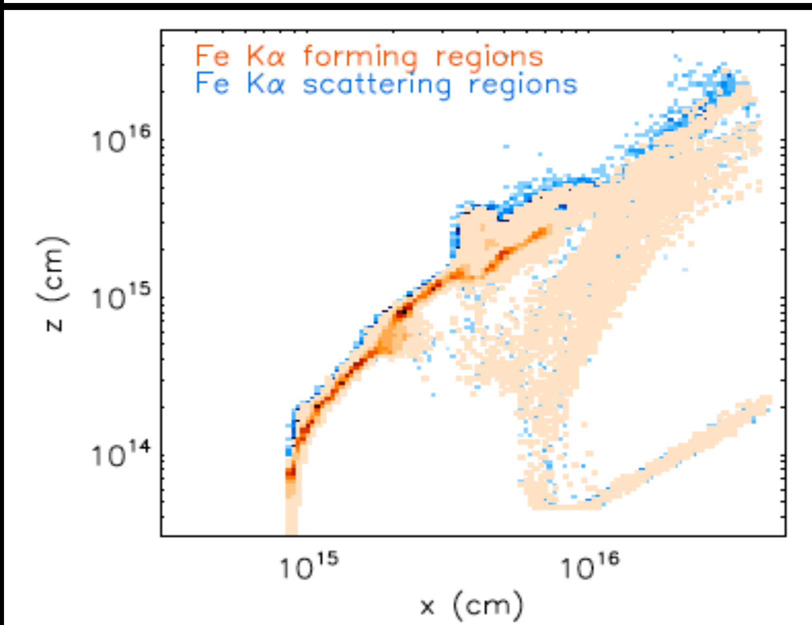


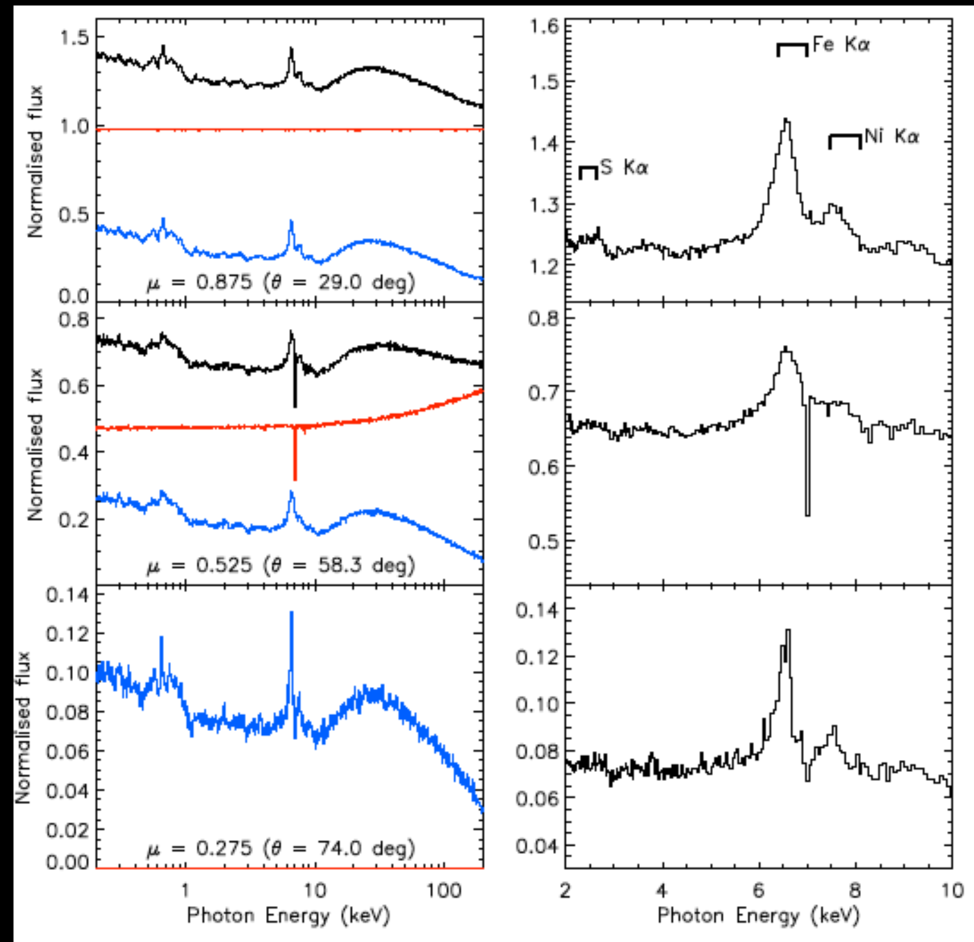
Emmering, Blandford & Shlosman, ’92;
Kato et al. ‘03

Fukumura, et al. 2010
Kazanas et al. 2012

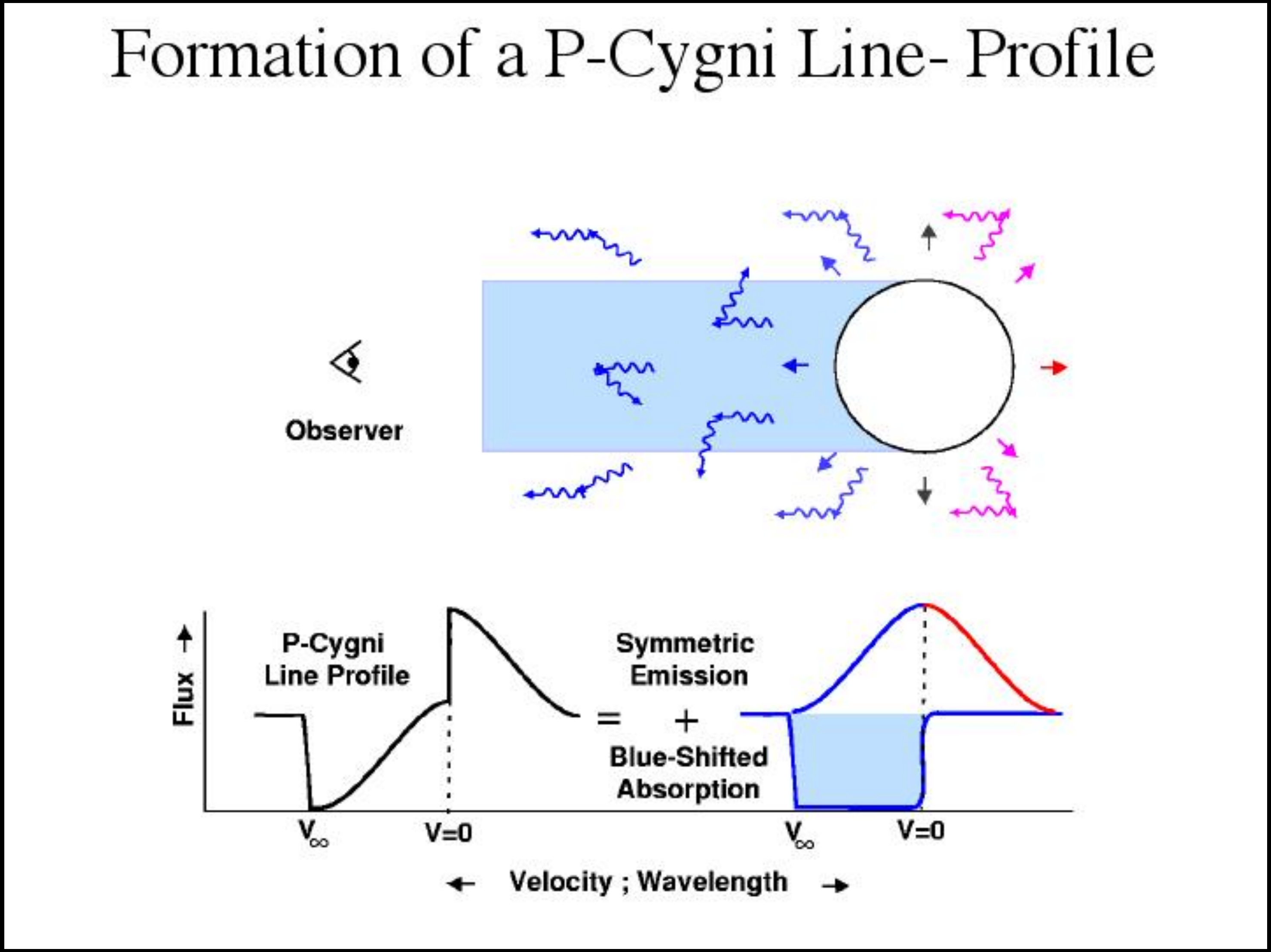
Absorption: Data Interpretation





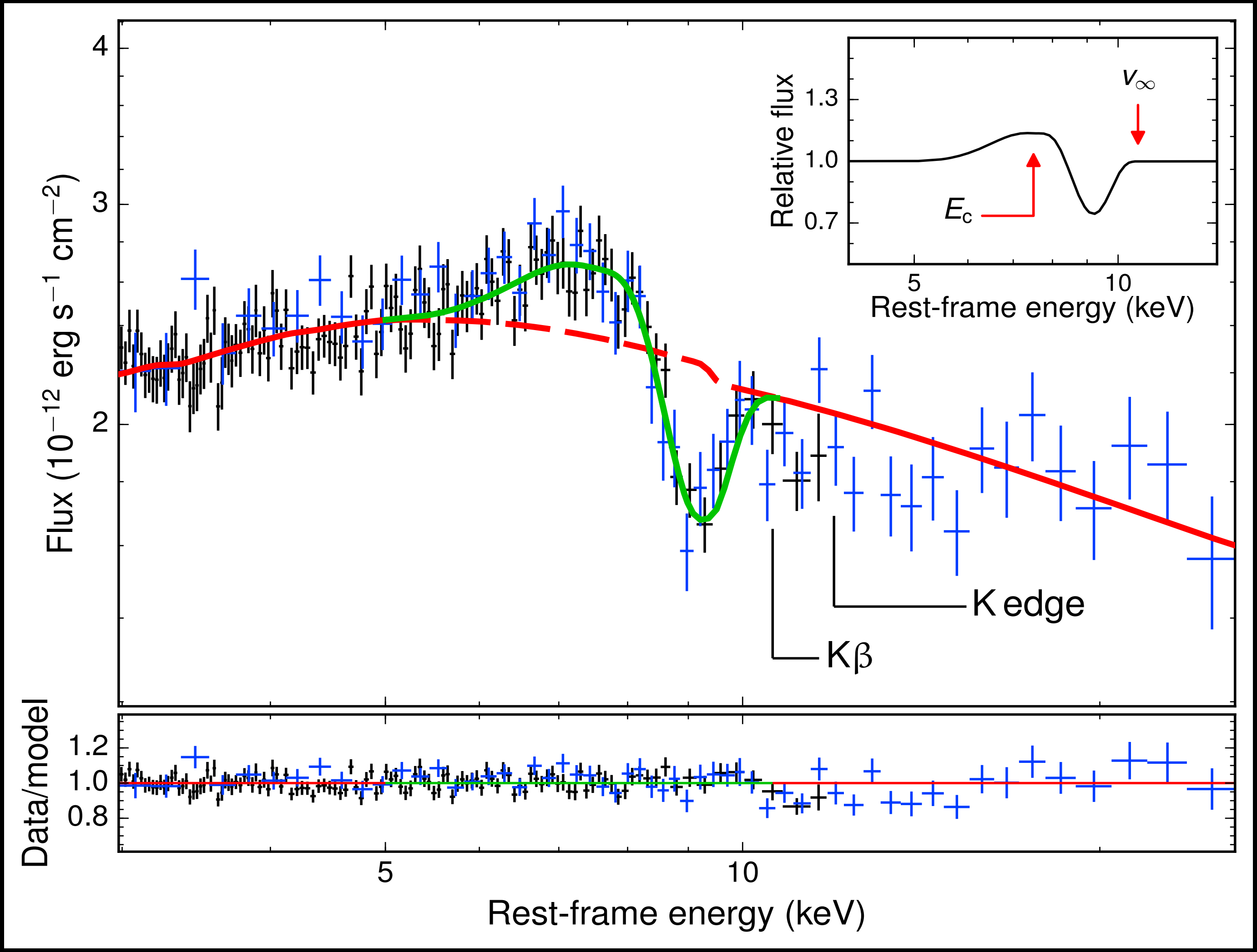


X-ray spectra of winds/outflows



Covering factor measured DIRECTLY from P-Cygni profile

PDS456 (z=0.18)



Nardini, Reeves et al., Science '15

Vout~0.3c and Ω>2π sr

Summary (1/2)

After introducing the BH and AGN paradigm, we have reviewed 1 major "model" of AGN:

Model I: 2-phase/SAD model (radio-quiet AGNs)

1. Multi-T black-body emission (soft-excess)
2. Thermal Comptonization (power-law)
3. Reflection (FeK line + Compton hump)
4. Absorption (ionized, partially covering, etc.)

Model IIa: Jet Model (radio-loud AGNs)

1. Synchrotron
2. Inverse Compton (non-thermal)

Model IIb: Inefficient model (LLAGNs)

1. Synchrotron
2. Bremsstrahlung (thermal)

See Paola Grandi's lesson

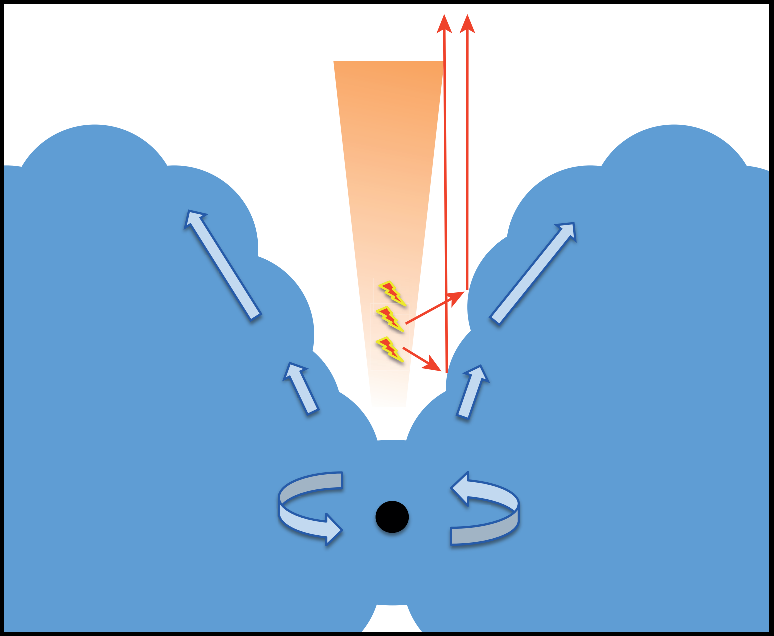
Summary (2/2)

Goal of the lectures: Give introductory information on the two-phases model of RQAGNs, and in particular on reflection vs absorption phenomena

N.B: This is not a "mere" fitting exercise but major physical differences in the two hypothesis:

- ✓ Relativistic Reflection: Produced within few (<10) R_g and carries information on BH spin and mass
- ✓ (Very) Complex Absorption: Produced farther at 100s R_g and carries information on wind/jet base/feedback
- ✓ Very difficult to distinguish, case by case, between the two hypotheses. Maybe interlinked phenomena!?

A unified view? within 100Rg?:
A relativistic, outflowing, accretion disc?



Kara et al. '16
Super-Edd. discs

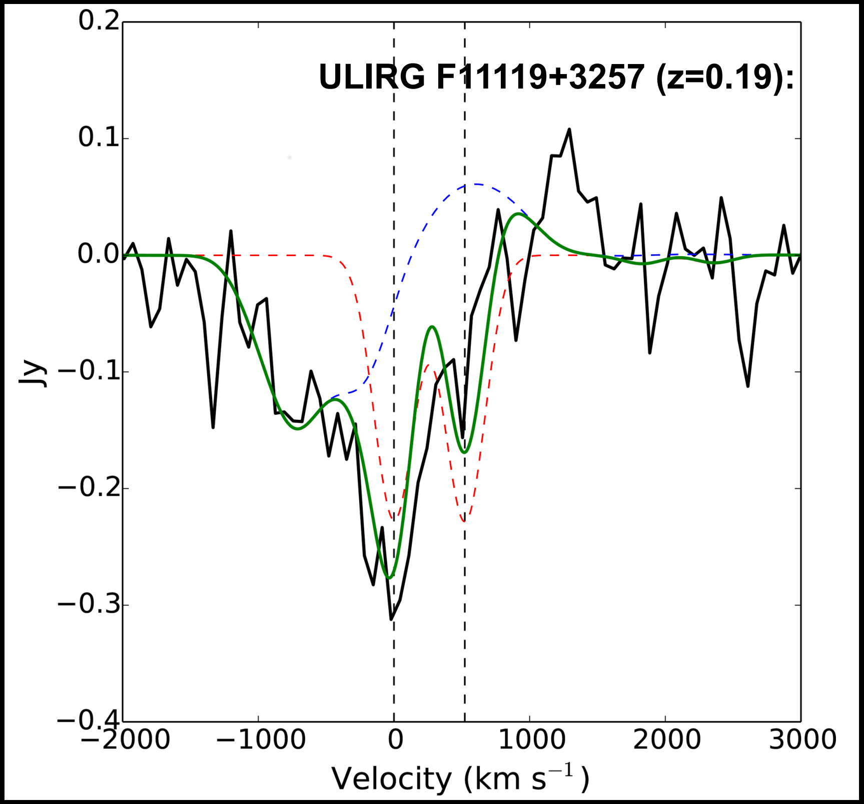
Grazie per la vostra attenzione

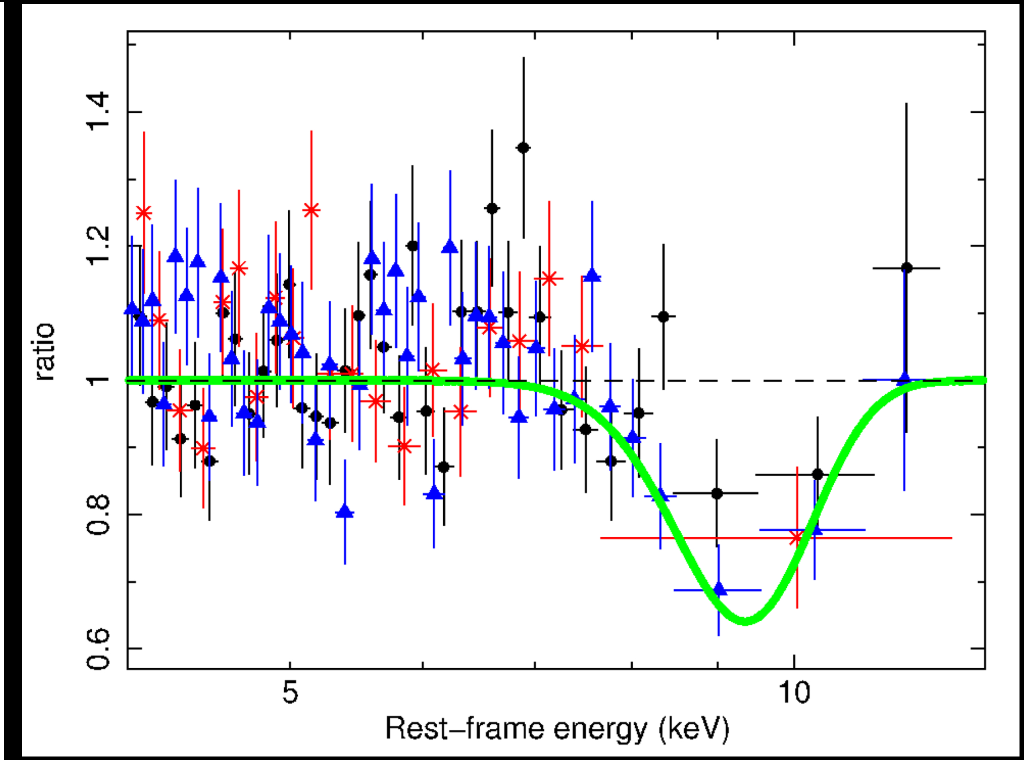
e divertitevi al laboratorio!

(approfittatene…)

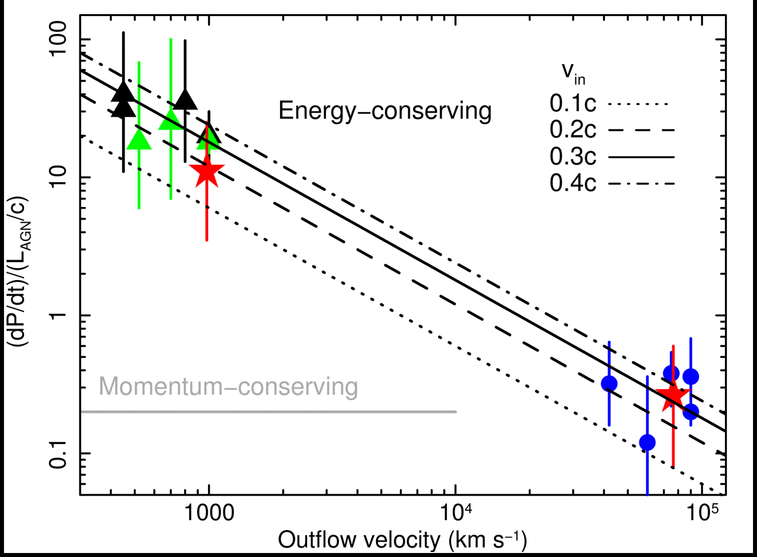
Questions ?

Are galaxy-scale massive molecular outflows energized by UFOs?





Veilleux et al. 2013

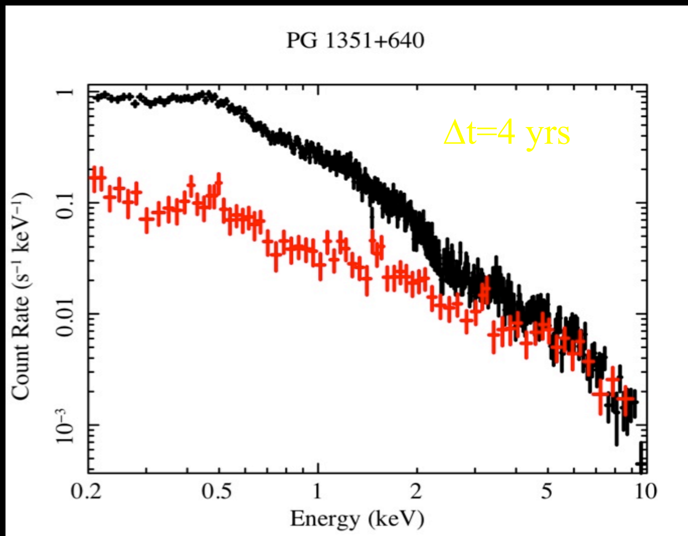


UFO detection (v~0.3c) consistent with energy-conserving outflow from Inner X-rays to outer molecular outflow

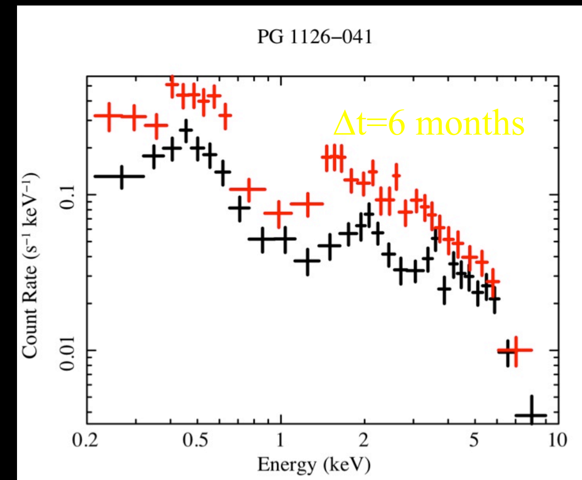
Tombesi et al. 2015, Nature

The "new" X-ray view: *Variability in (nearby) PG QSOs*

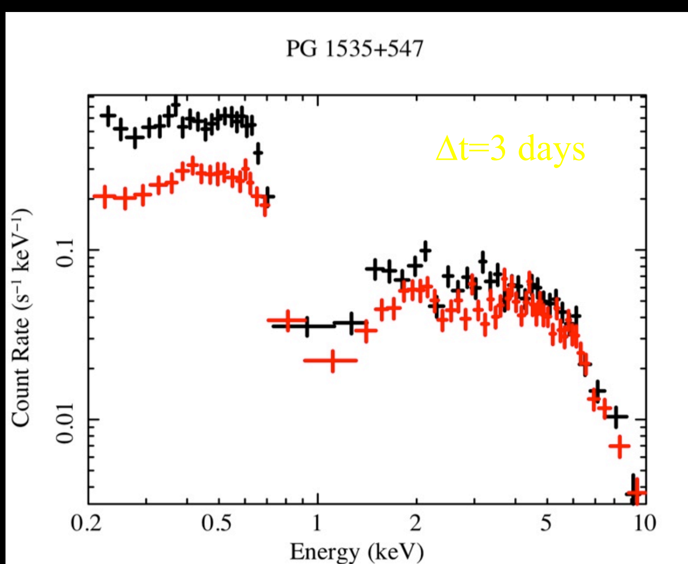
Sample: 15 UV *AL QSOs with 32 XMM exposures



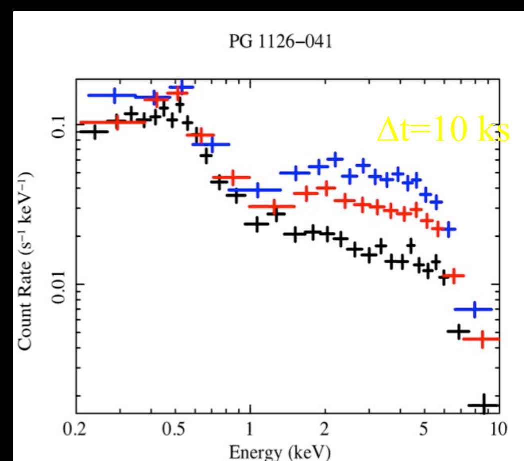
on time scales of years

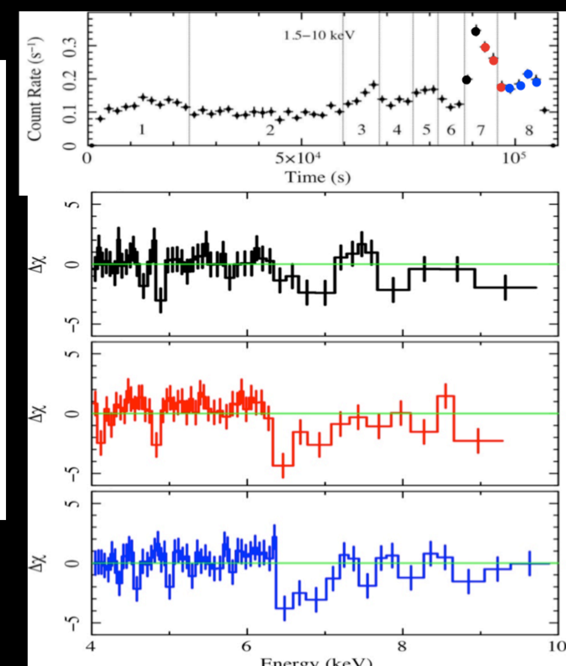


on time scales of months



on time scales of days

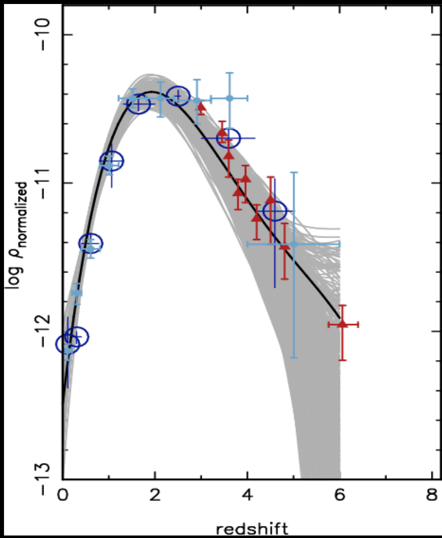




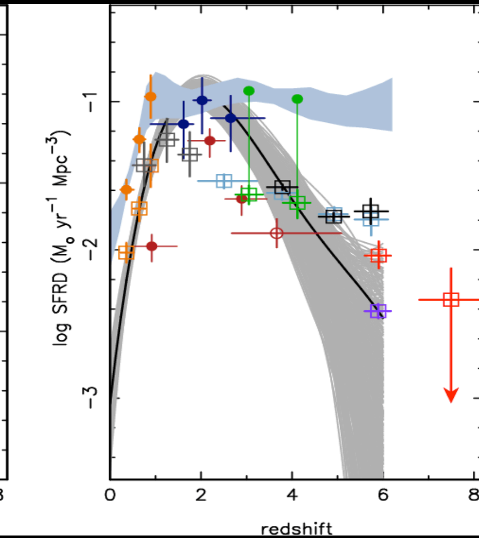
on time scales of hours

Giustini, MC, et al. 2012

UFOs and/or FeK complex features seen also (no, always!) in lensed high-z QSOs

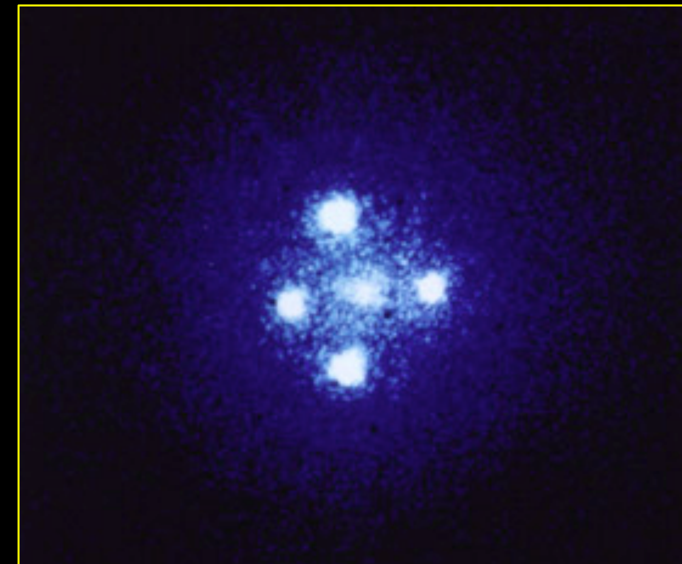


QSO space density



SFR space density

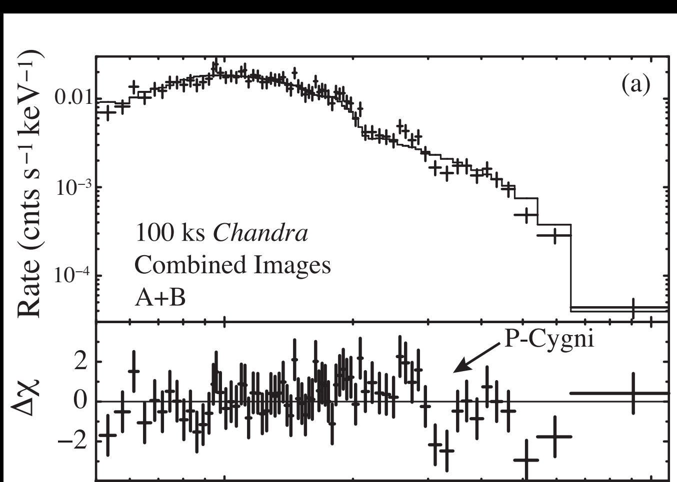
Madau et al. '96; Wall et al. '05

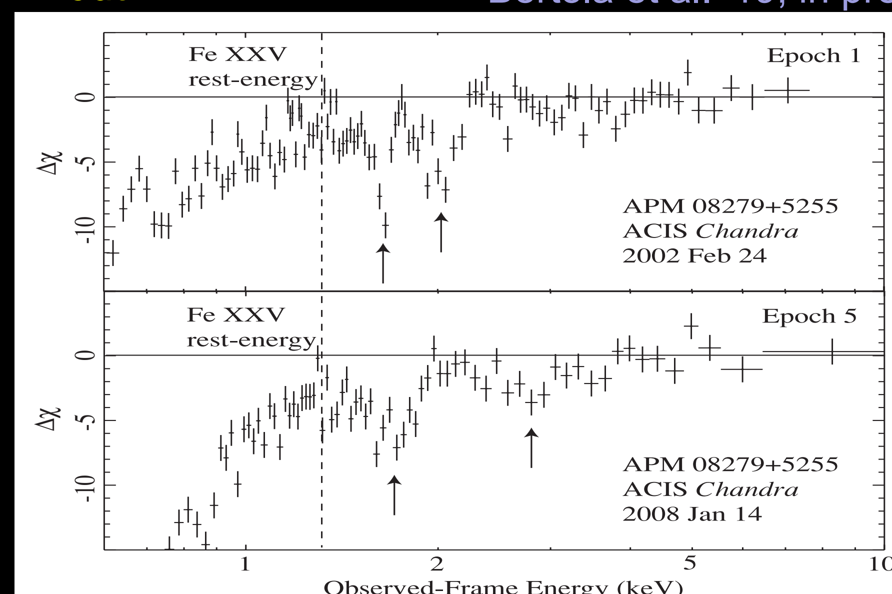


V_{out}~0.2-0.76 c

Chartas et al. 2009
Bertola et al. '19, in prep

Chartas et al. 2014



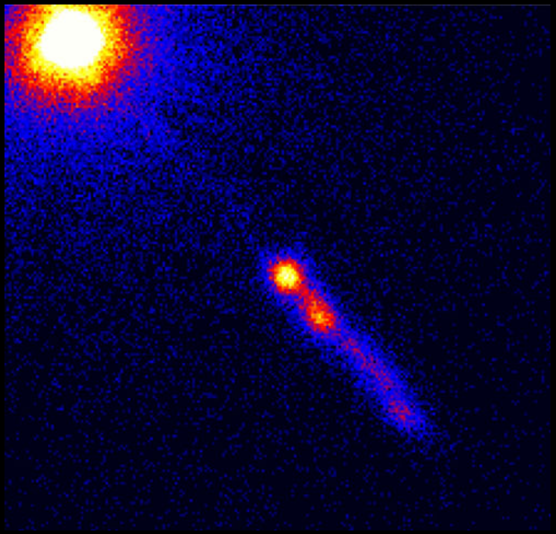


Model 2

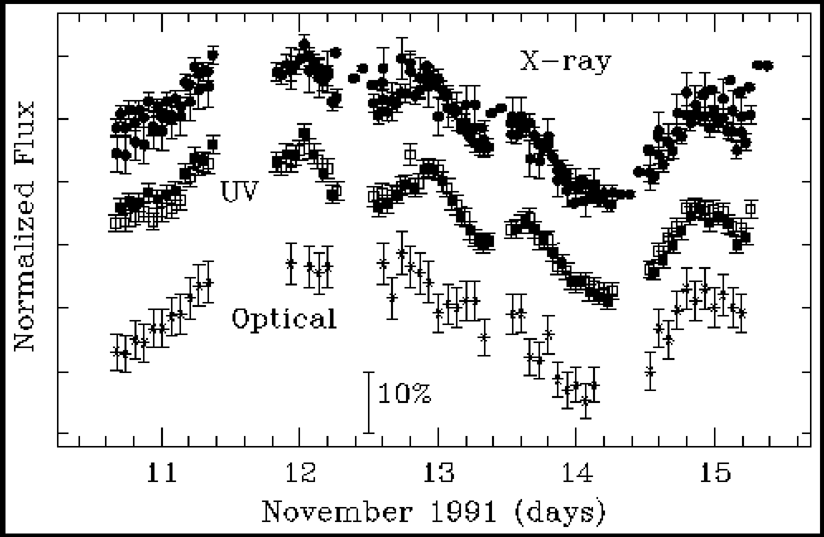
The relativistic Jet model (RLAGNs)

Model II (RL AGNs): X-ray observations - Images + lightcurves

Images + Light curves PKS2155-304

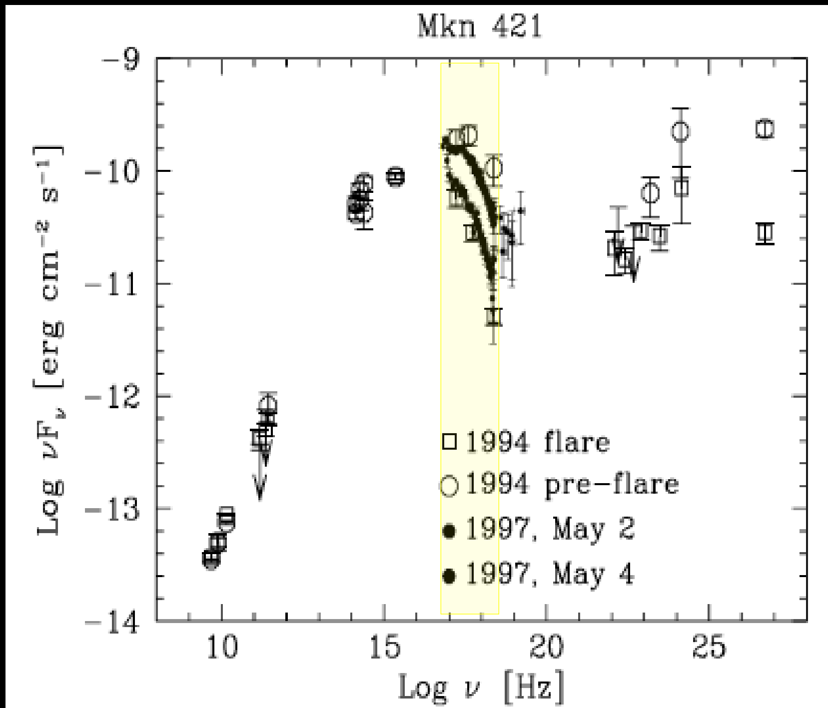


X-ray jets

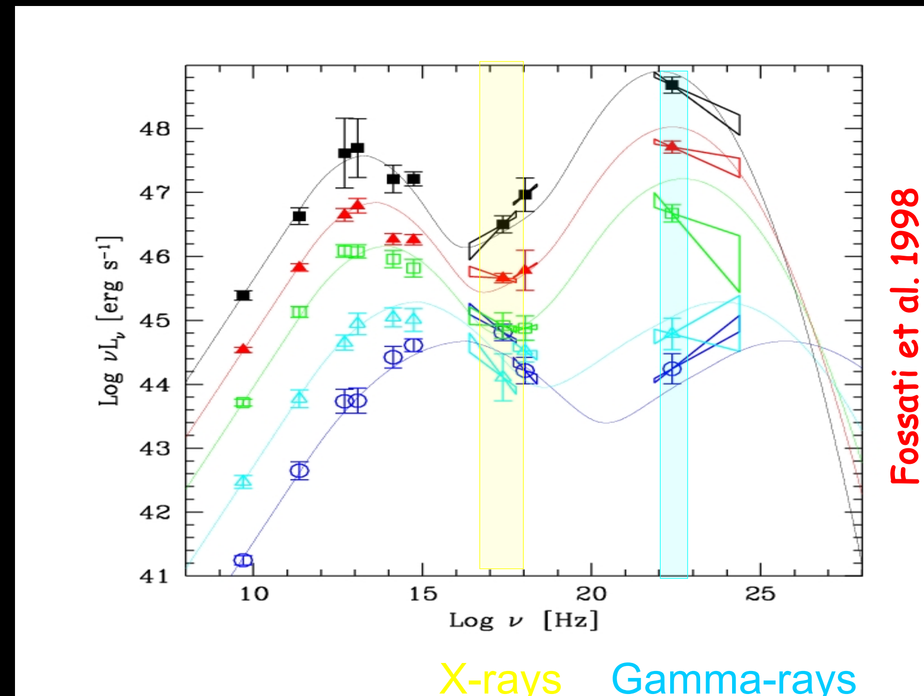


Most of radation produced in a relativistic jet

Spectra (SEDs):



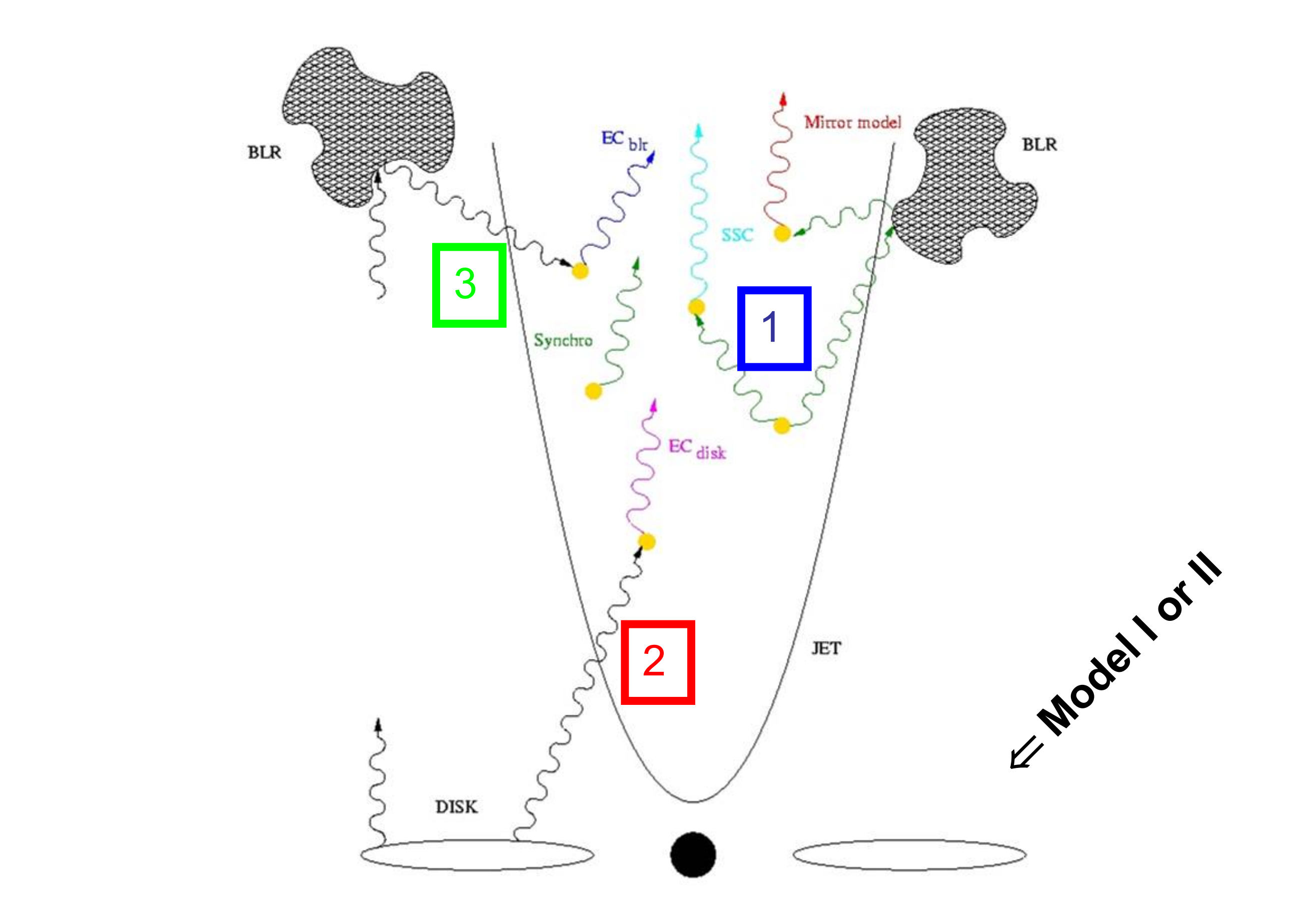
The Blazars "Sequence"



➡ (At least) 2 major spectral components:

1. Low frequency peak (Synchrotron)
2. High frequency peak (Compton inverso)

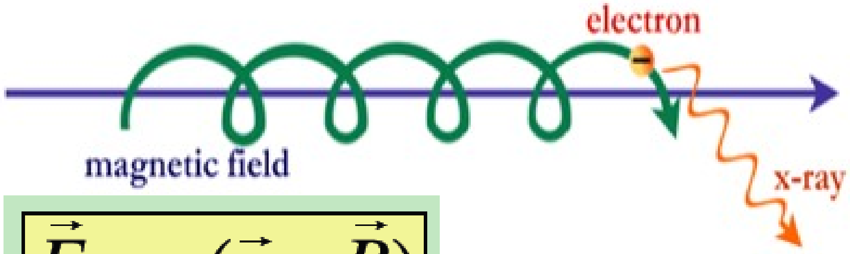
Modello II (RL AGNs) = Model I + Relativistic Jet



3 likely possibilities:

1. Synchrotron + Self Compton
2. Synchrotron + External Compton (disk)
3. Synchrotron + External Compton (BLR)

Modello II (RL AGNs) = Model I + Relativistic Jet

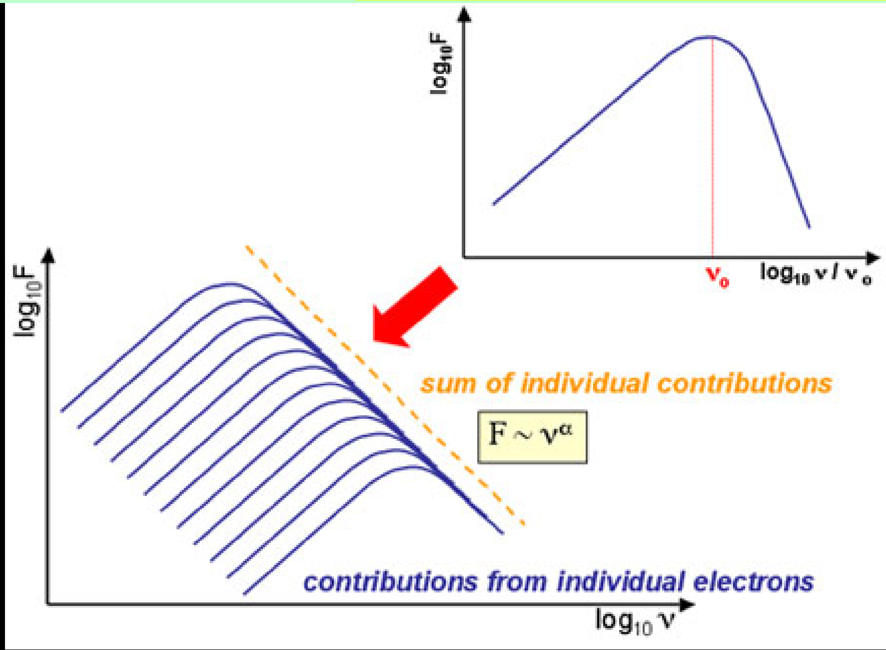


$$\vec{F} = q(\vec{v} \times \vec{B})$$

Lorentz Force

Synchrotron (non-thermal emission)

Emission from one electron	$-dE/dt = \frac{4}{3} c \sigma_T \beta^2 \gamma^2 U_B \propto E^2 B^2$

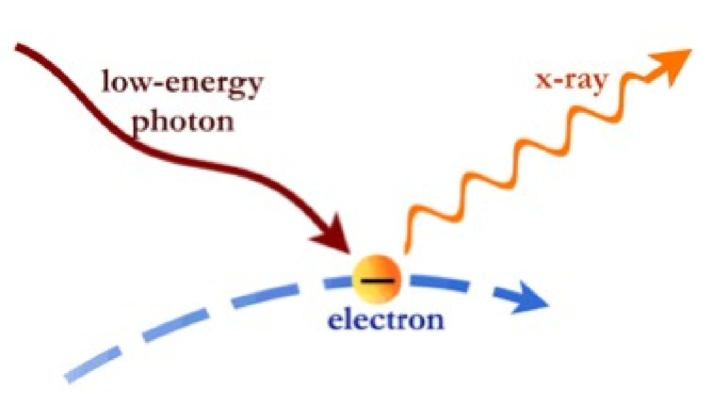


Multiple electrons:

$$N(E) = N_0 E^{-\delta}$$

$$F(\nu) = A(\delta) K B^{(\delta+1)/2} \nu^{-\alpha}$$

Modello II (RL AGNs) = Model I + Relativistic Jet



Inverse Compton Scattering:

SSC if IC onto Synchrotron radiation
SEC if IC onto BLR or disc photons

Inverse Compton scattering: volume emissivity
Population of relativistic electrons, each of energy $\gamma m_e c^2$, with $\gamma >> 1$, in a sea of photons with energy density U_{ph}, and photon energies negligible compared with the IC upscattered energies

$$j_{IC} = \frac{4}{3}\sigma_T c \gamma^2 \beta^2 n_e U_{ph}$$

Integrated volume emissivity [W/m³]

($\gamma h\nu << m_e c^2$, $h\nu_{av} << h\nu_{S,iso}$)

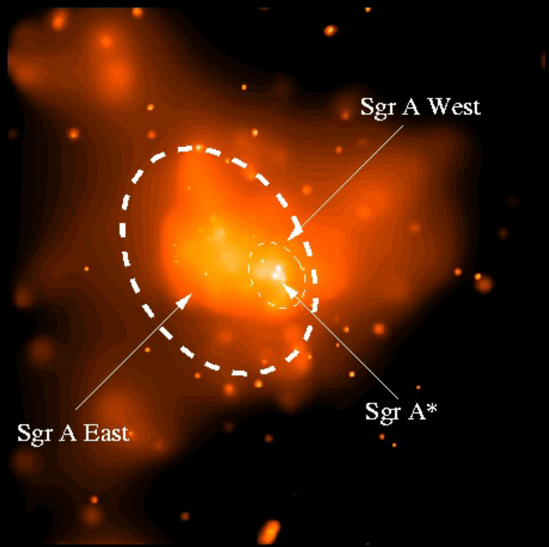
$$N(E) = N_0 E^{-\delta} \Longrightarrow j_{IC}(\nu) \propto \nu^{-(\delta-1)/2} = \nu^{-\alpha}$$

Model 3

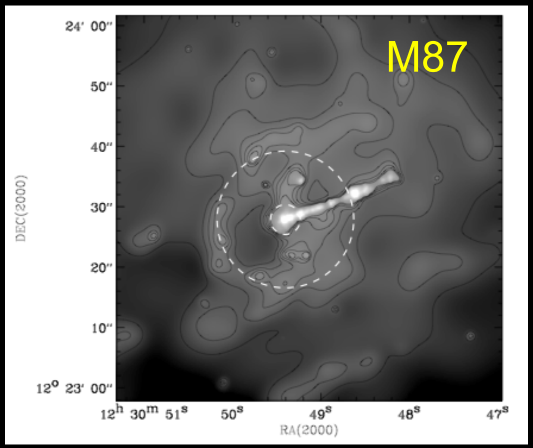
The radiatively inefficient model (LLAGNs)

Modello III (LL AGN): X-ray observations - Images and Lightcurves

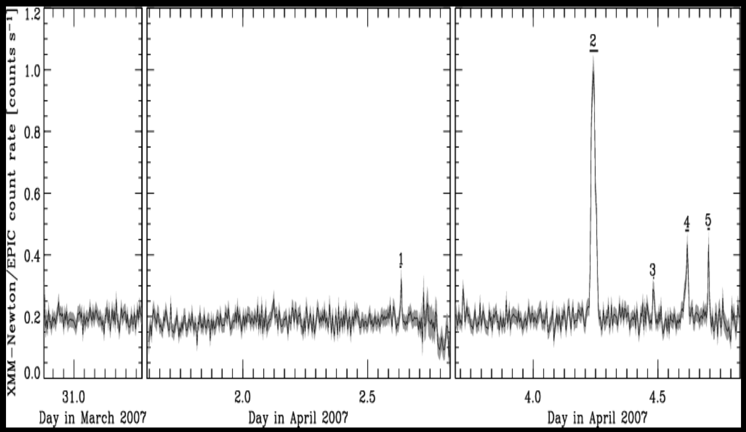
SgrA*



Images + Lightcurves



SgrA*



Low-L and diffuse X-ray source

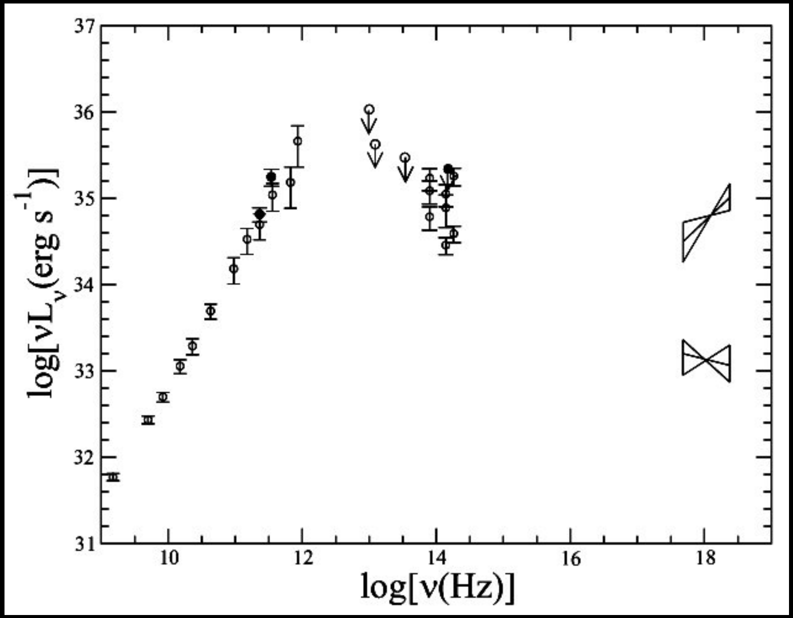
N.B: Δt~50 s corresponds to 1 R_g per $M=10^7 M$

($t \sim R_g/c \sim GM/c^3 \sim 50\ M_7$ s)

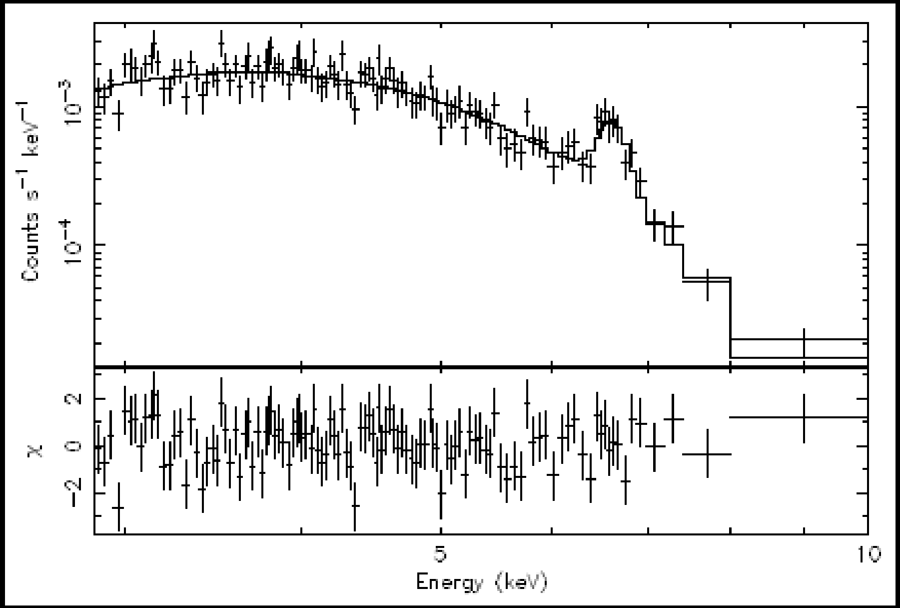
Low-L, likely diffused emission
+ isolated flares (otherwise quiescent)

Model III (LL AGN): X-ray observations - Typical Spectra

Spectra:



Lx~2x10^{33} erg/s<10^{-11} L_{Edd}

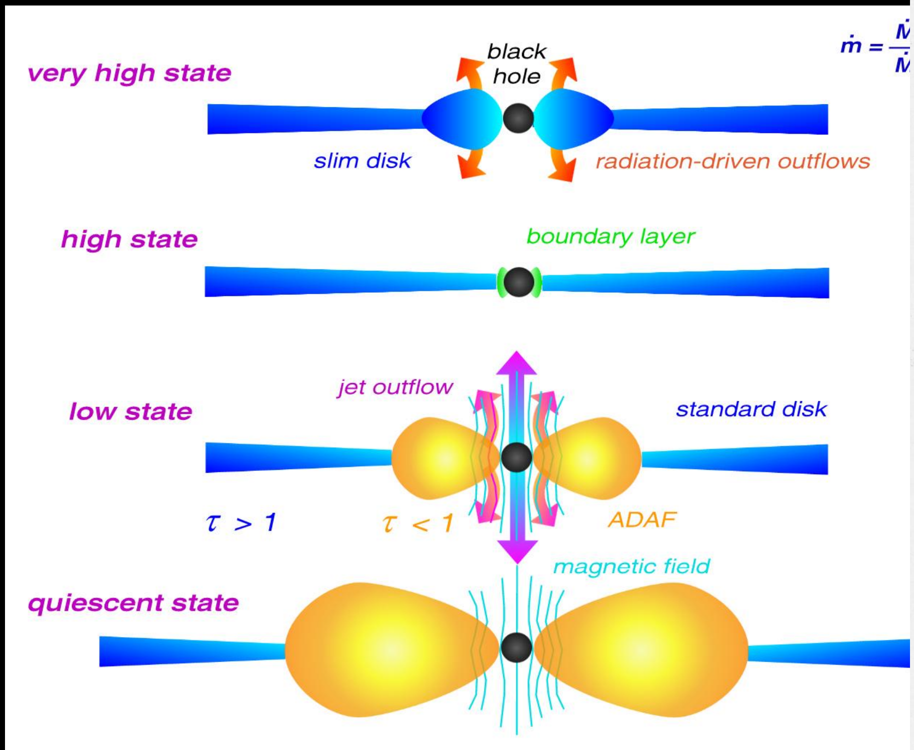


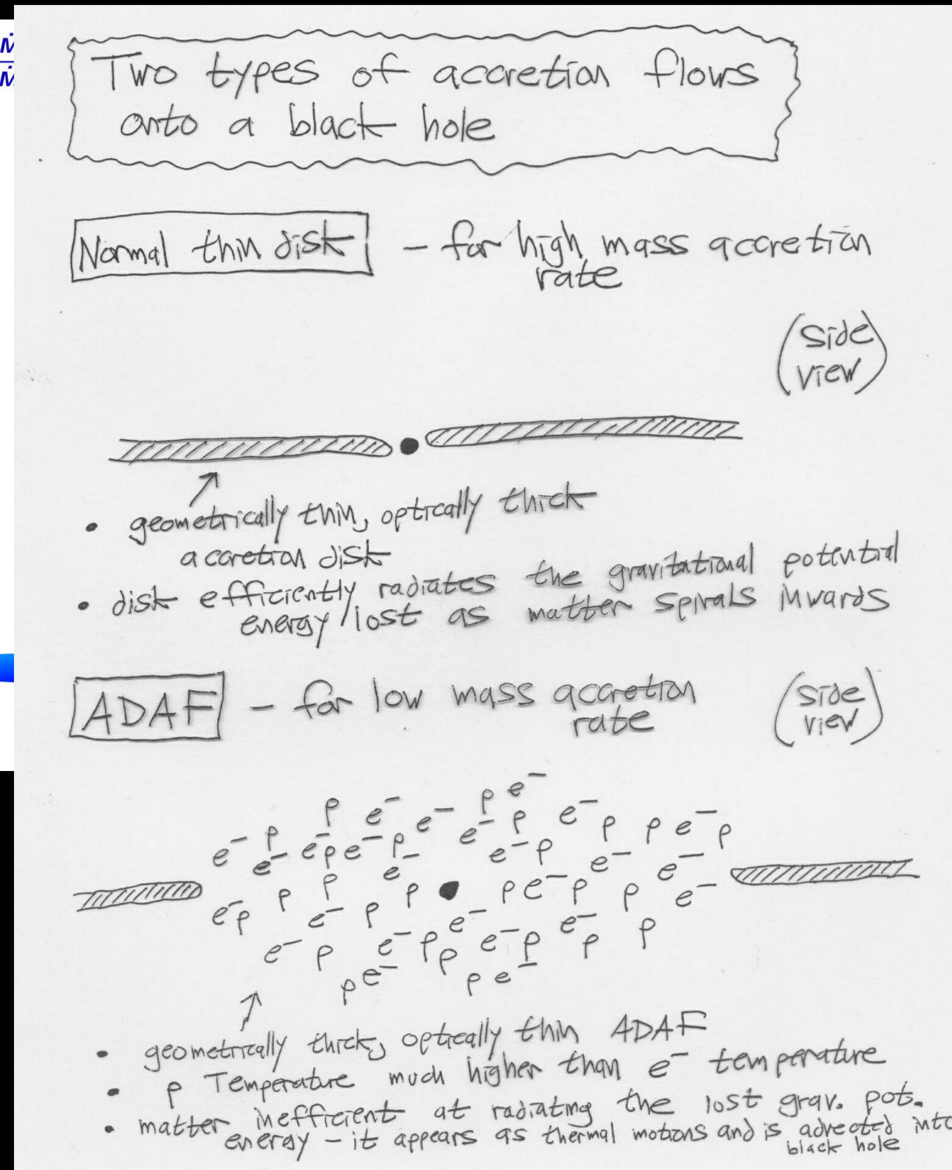
Bremsstrahlung Thermal-like quiescent spectrum

(At least) 2 major spectral components:

1. Synchrotron emission
2. Bremsstrahlung (+ power-laws during flares)

Model III (LL AGN):



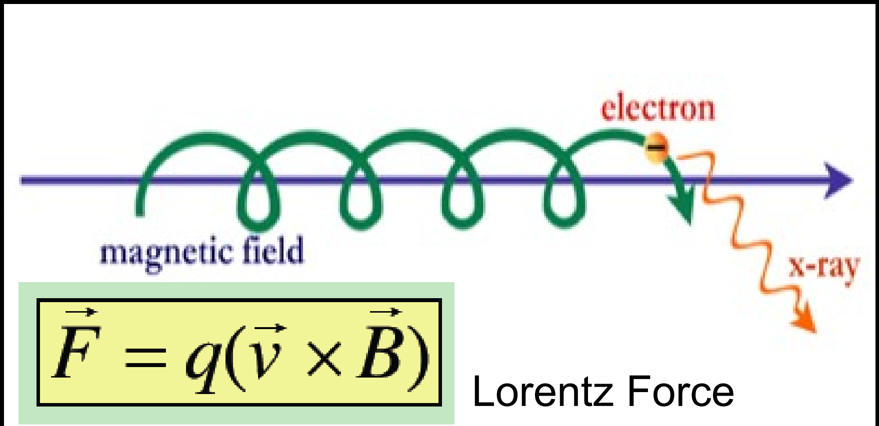


Simil-ADAFs:

- advection–dominated accretion flow (ADAF)
- radiatively–inefficient accretion flow (RIAF)
- convection–dominated accretion flow (CDAF)
- slim disk
- truncated disk – advective tori (TDAT)
- non–radiative accretion flow (NRAF)

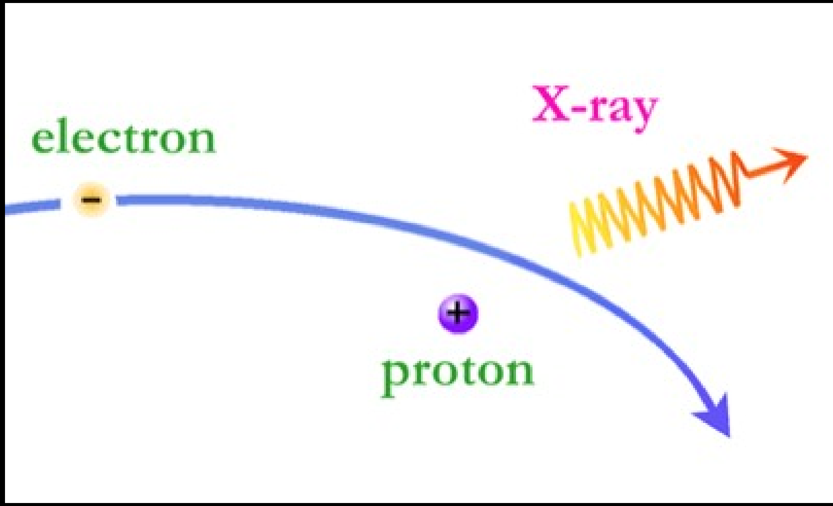
From N. Brandt (I think)

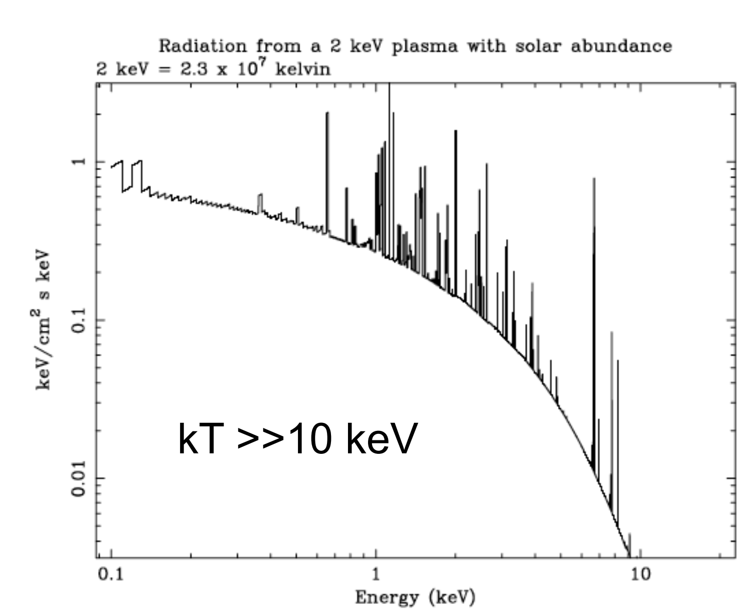
Modello III (LL AGN): ADAFs model



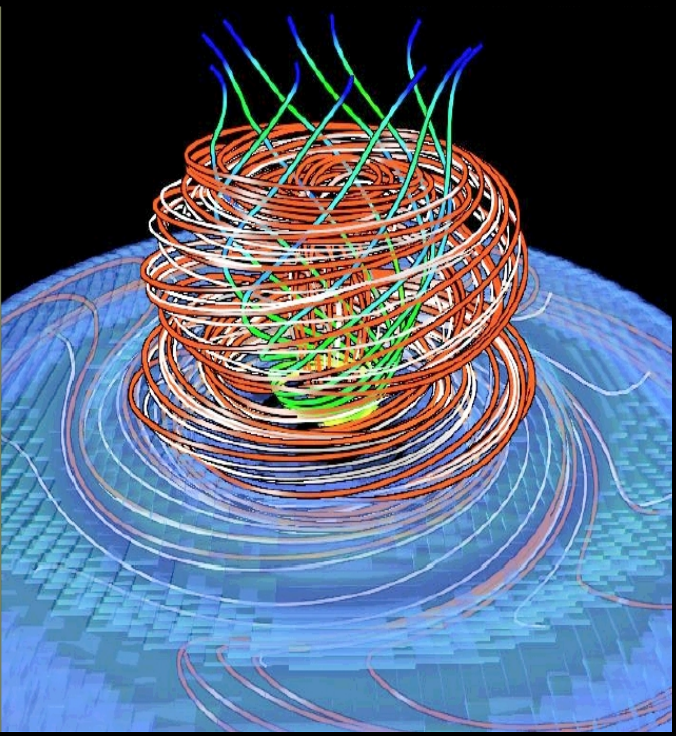
Synchrotron
(non-thermal emission)

+ Thermal Bremsstrahlung from a very hot, optically thin, geometrically thick flow





Goal of the lectures: Give introductory informations on general "models" of AGNs, and in particular on reflection vs absorption hypothesis in RQAGNs



We have reviewed basic physics with basic assumptions for 3 major "models" of AGN

1- The 2-Phases model (RQAGNs)
2- The Jet model (RLAGNs)
3- The Inefficient model (LLAGNs)

We have focused mostly on 1, and address the reflection vs. absorption hypothesis to explain the X-ray spectra of RQAGNs

Not a "mere" fitting exercise but major physical differences in the two hypothesis:

- ✓ Relativistic Reflection: Produced within few (<10) R_g and carries information on BH spin and mass
- ✓ (Very) Complex Absorption: Produced farther at 100s R_g and carries information on wind/jet base/feedback