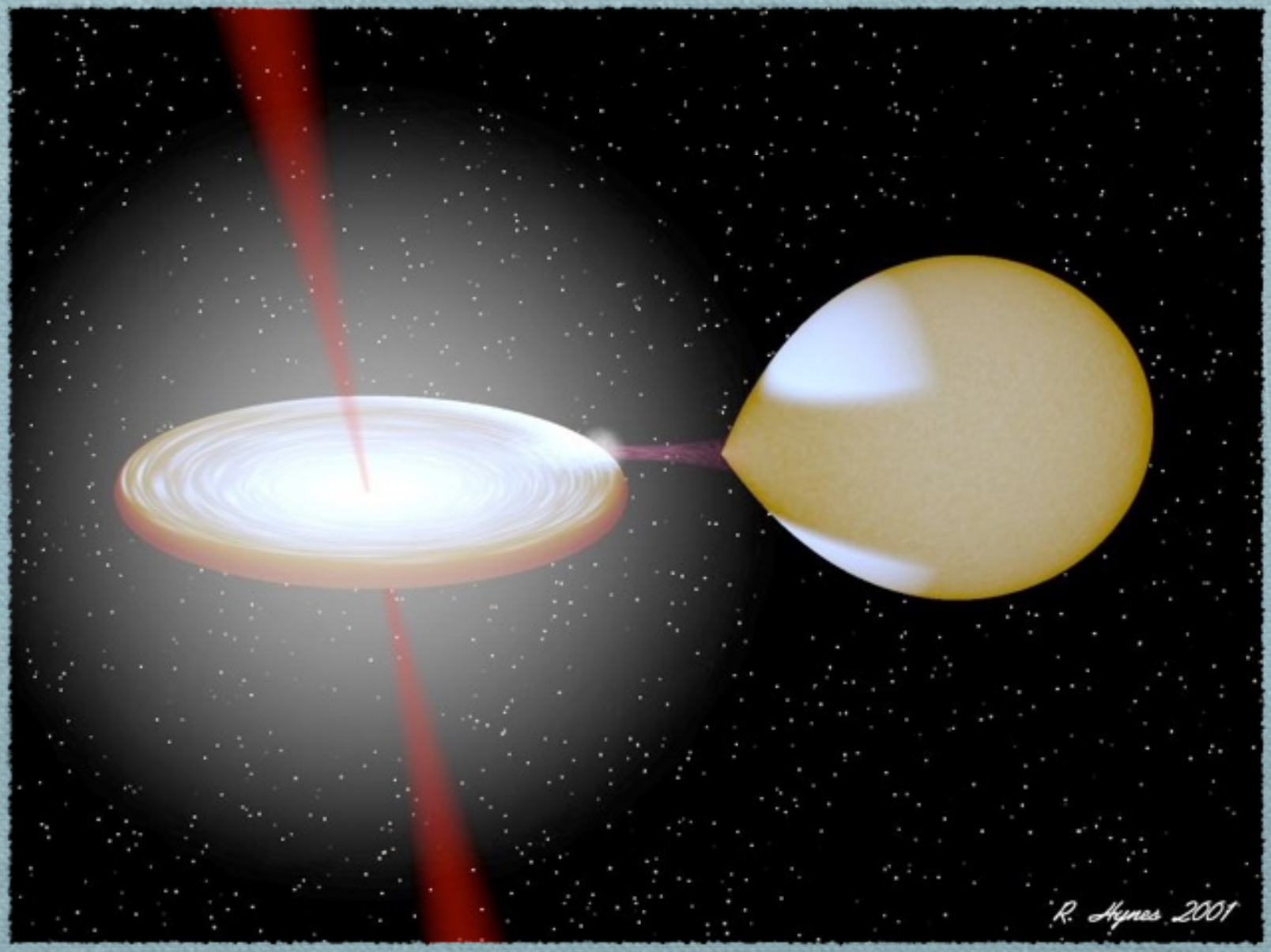

Black-hole binaries

Tomaso M. Belloni

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OUTLINE

- Lecture I: Accretion onto compact objects, X-ray binaries, black hole candidates, X-ray pulsars
- **Lecture II: High-energy emission and spectra**
- Lecture III: Time variability on all scales
- Lecture IV: Radio emission, jets, accretion/ejection
- Lecture V: BH parameters & GR, AGN connection
- Lecture VI: Neutron-Star binaries + ULX + more

Thin disk spectrum

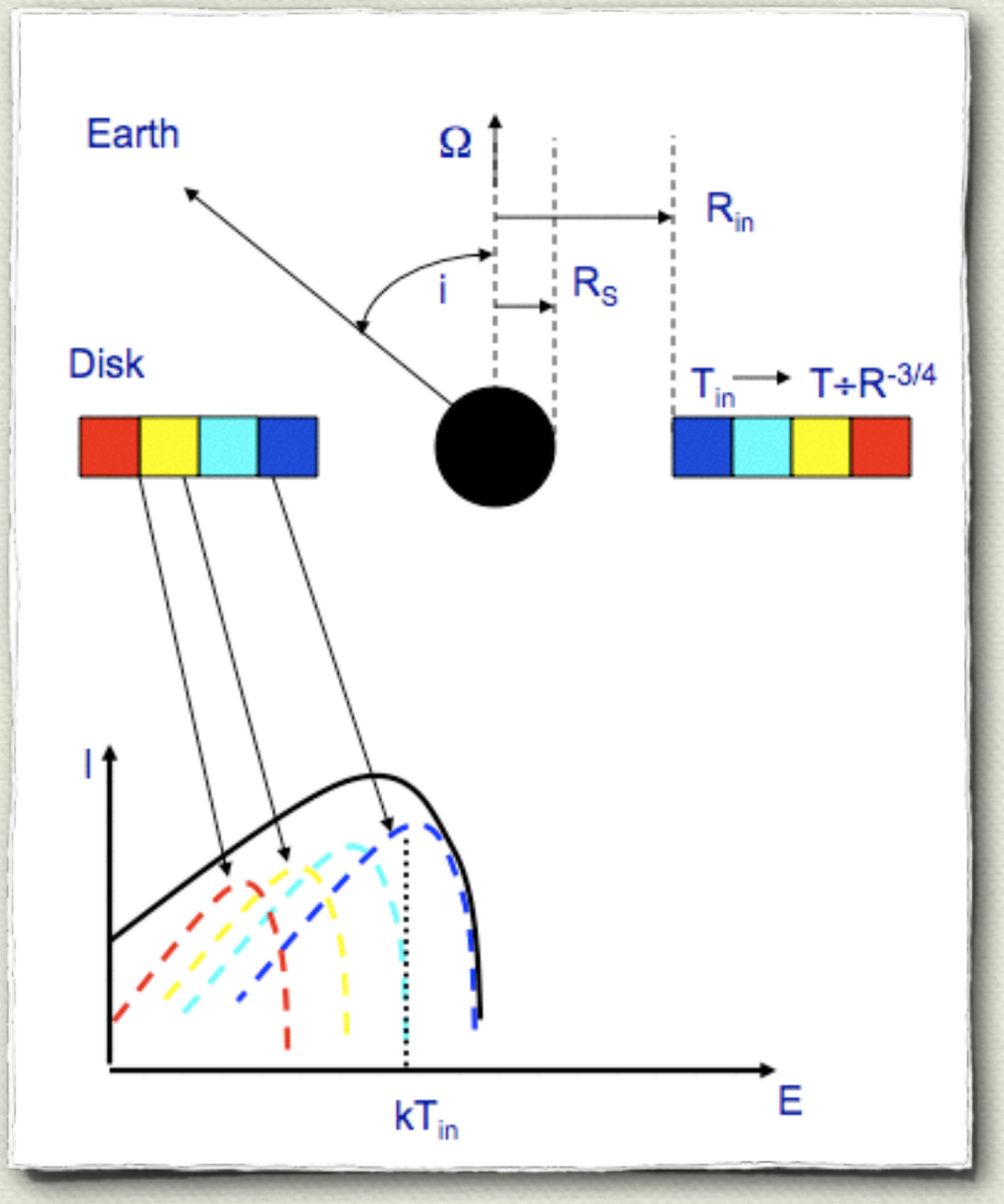
$$f = \left[1 - \left(\frac{R_\star}{R}\right)^{1/2}\right]^{1/4}$$

- Model for thin disks (1973)
- Optically thick disk
- Each radius a blackbody with

$$T(R) = \left\{\frac{3GM\dot{M}}{8\pi R^3\sigma}\right\}^4 f$$

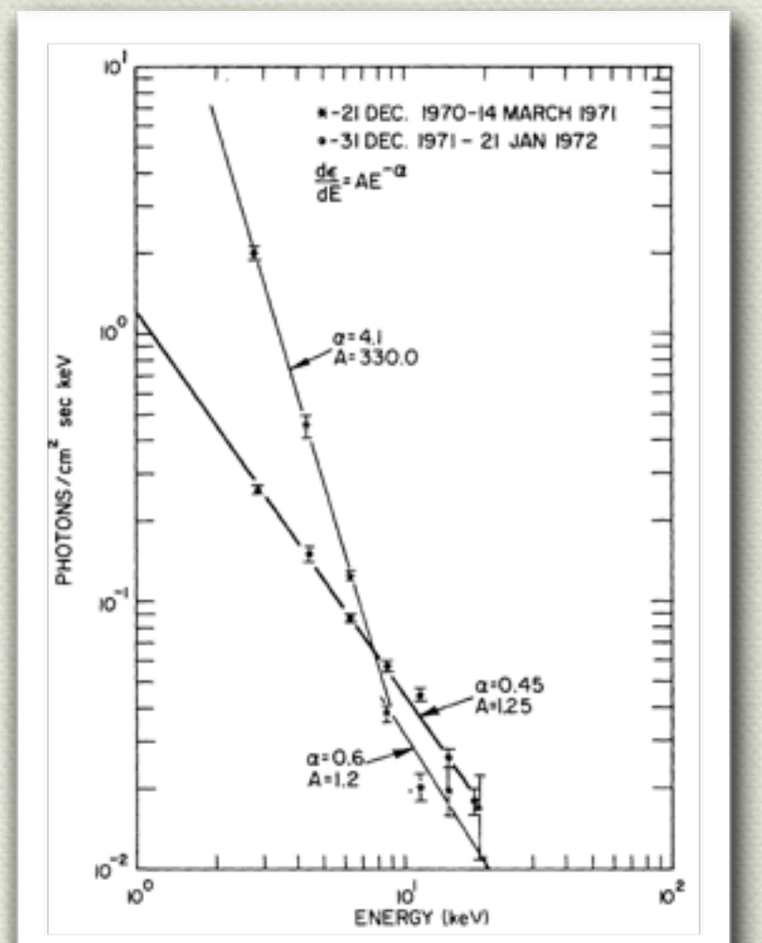
- *T(R)* as effective temperature
- Total spectrum is

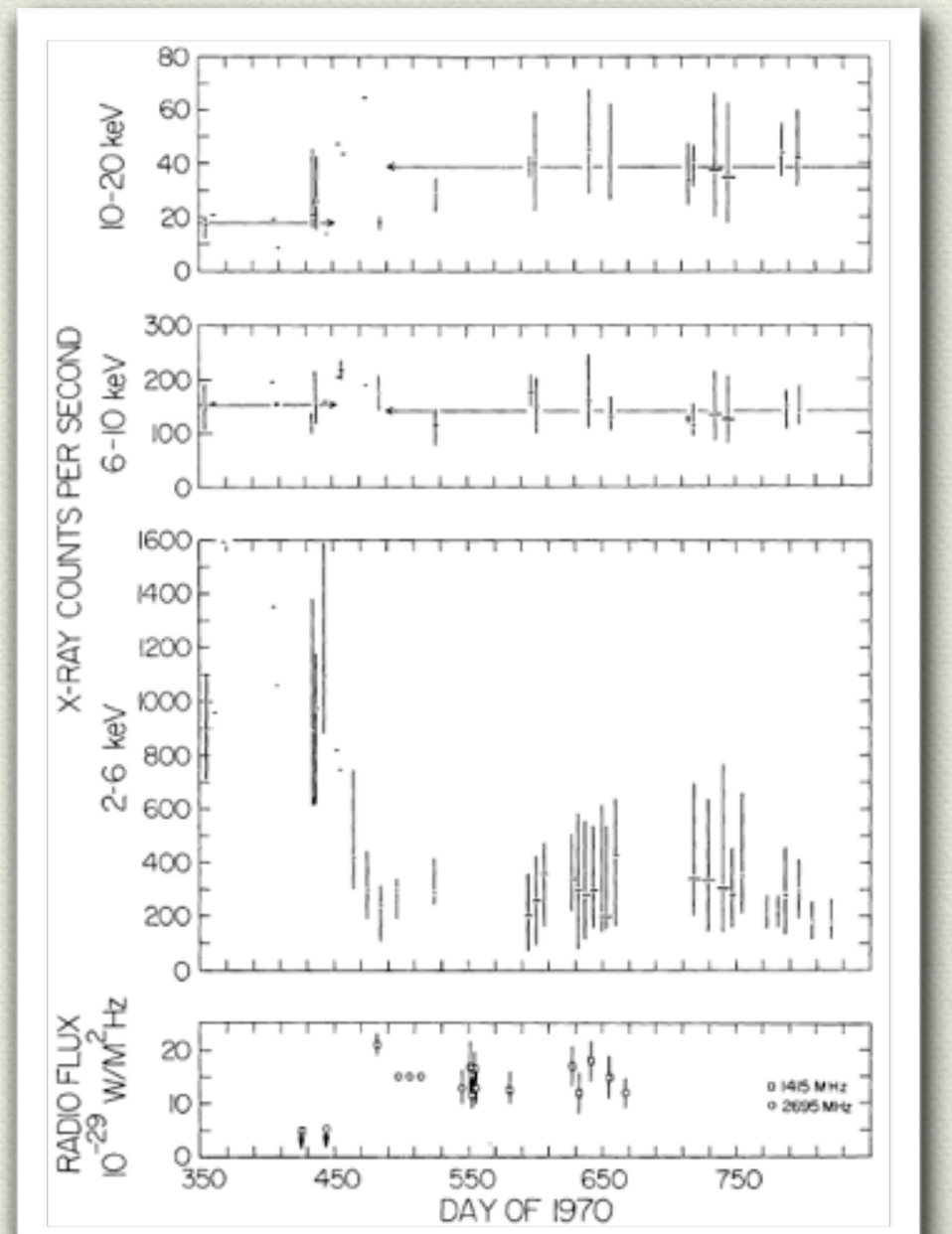
$$F_\nu = \frac{4\pi h \cos i \nu^3}{c^2 D^2} \int_{R_\star}^{R_{out}} \frac{RdR}{e^{h\nu/kT(R)} - 1}$$



First observations

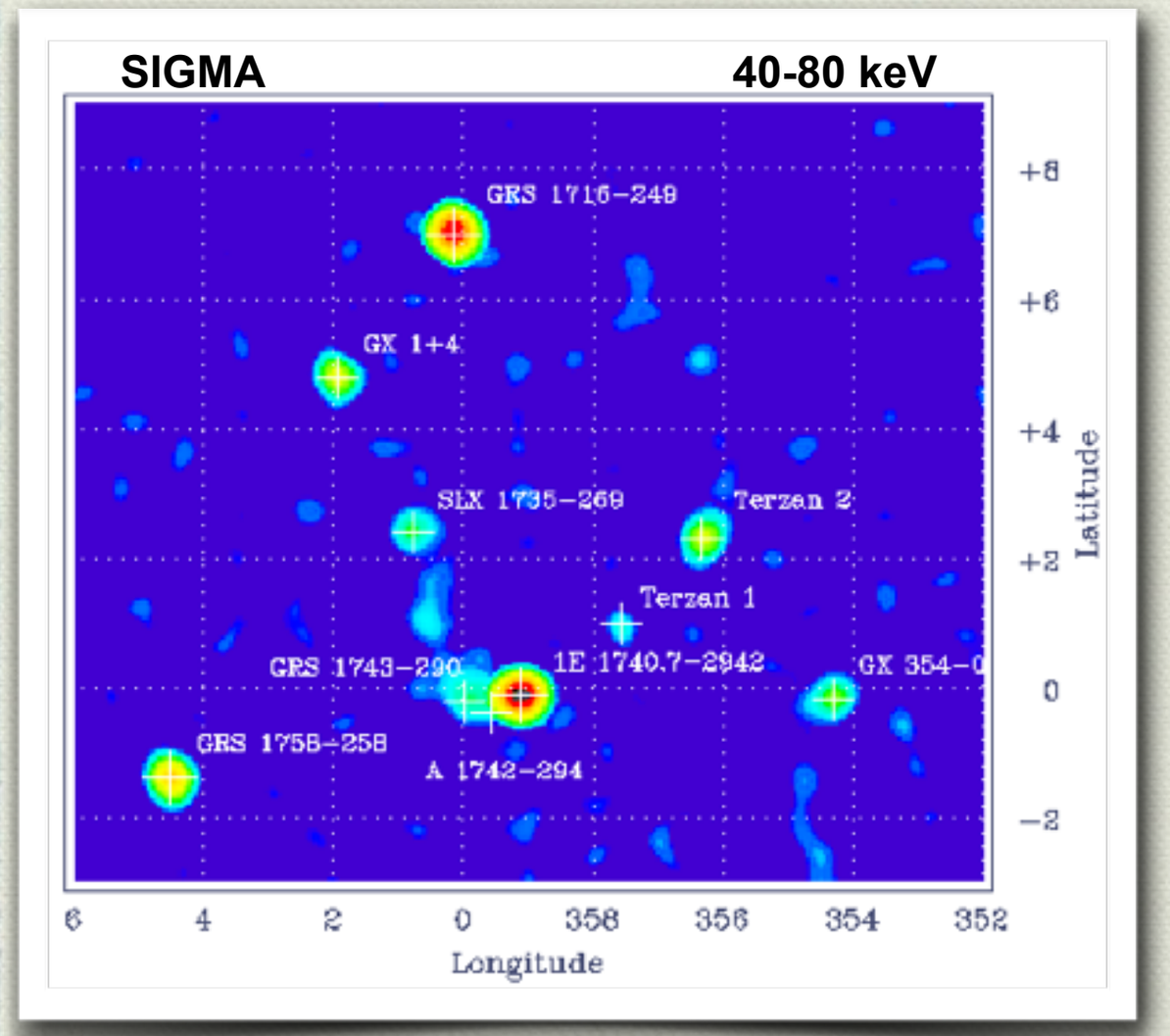
- Uhuru satellite
- Cygnus X-1 shows variations

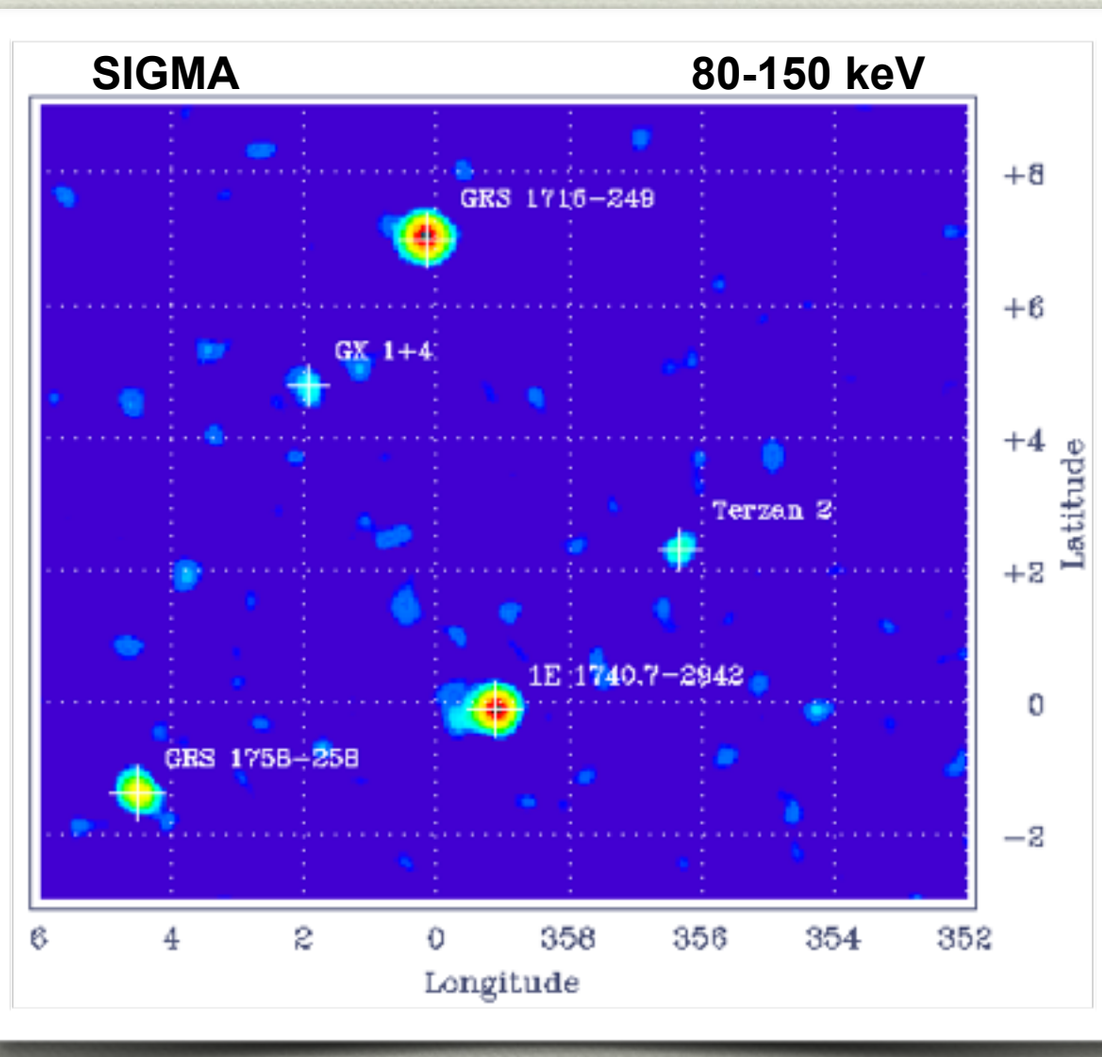




Tananbaum et al. (1972)

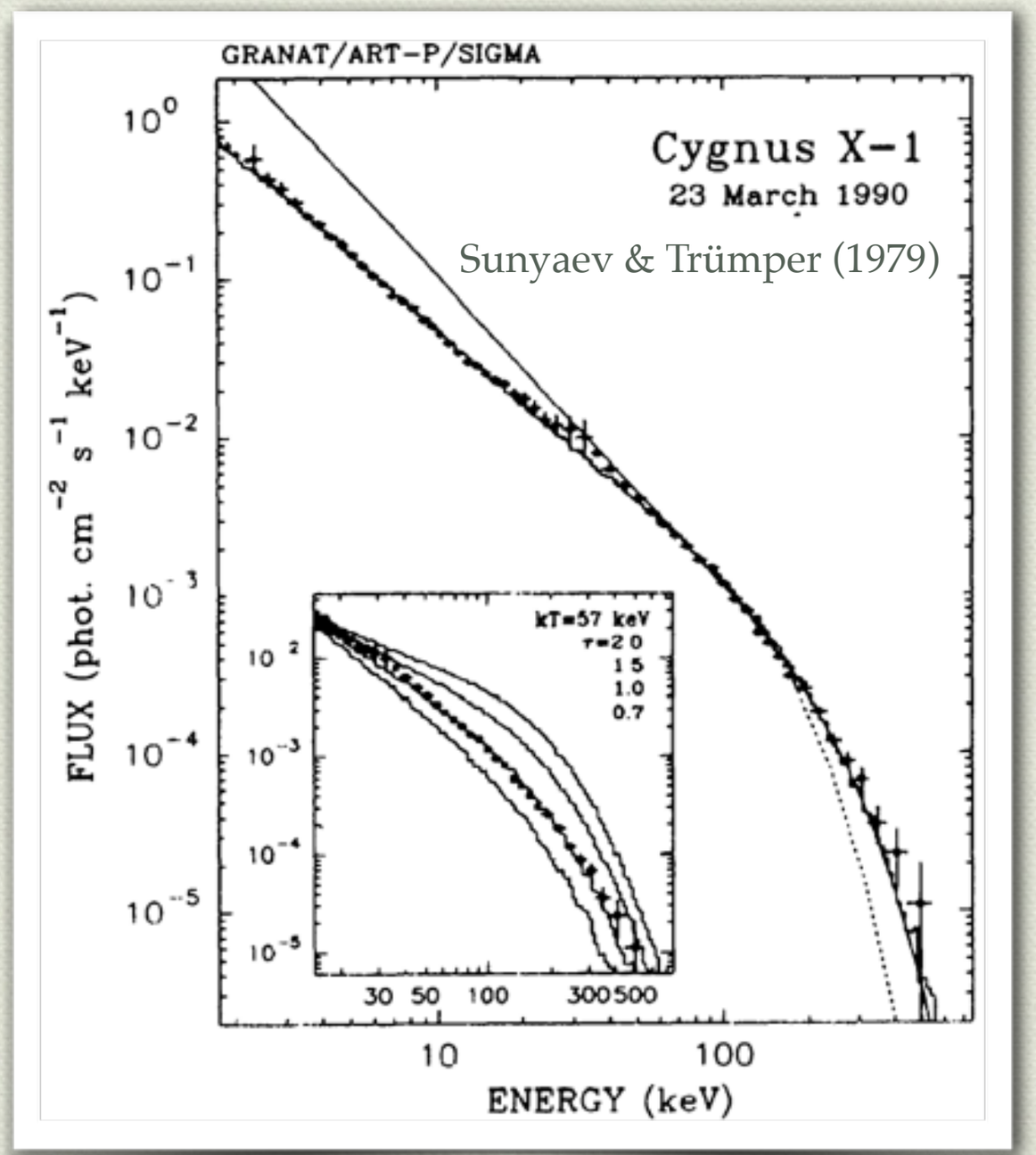
Sources are too hard



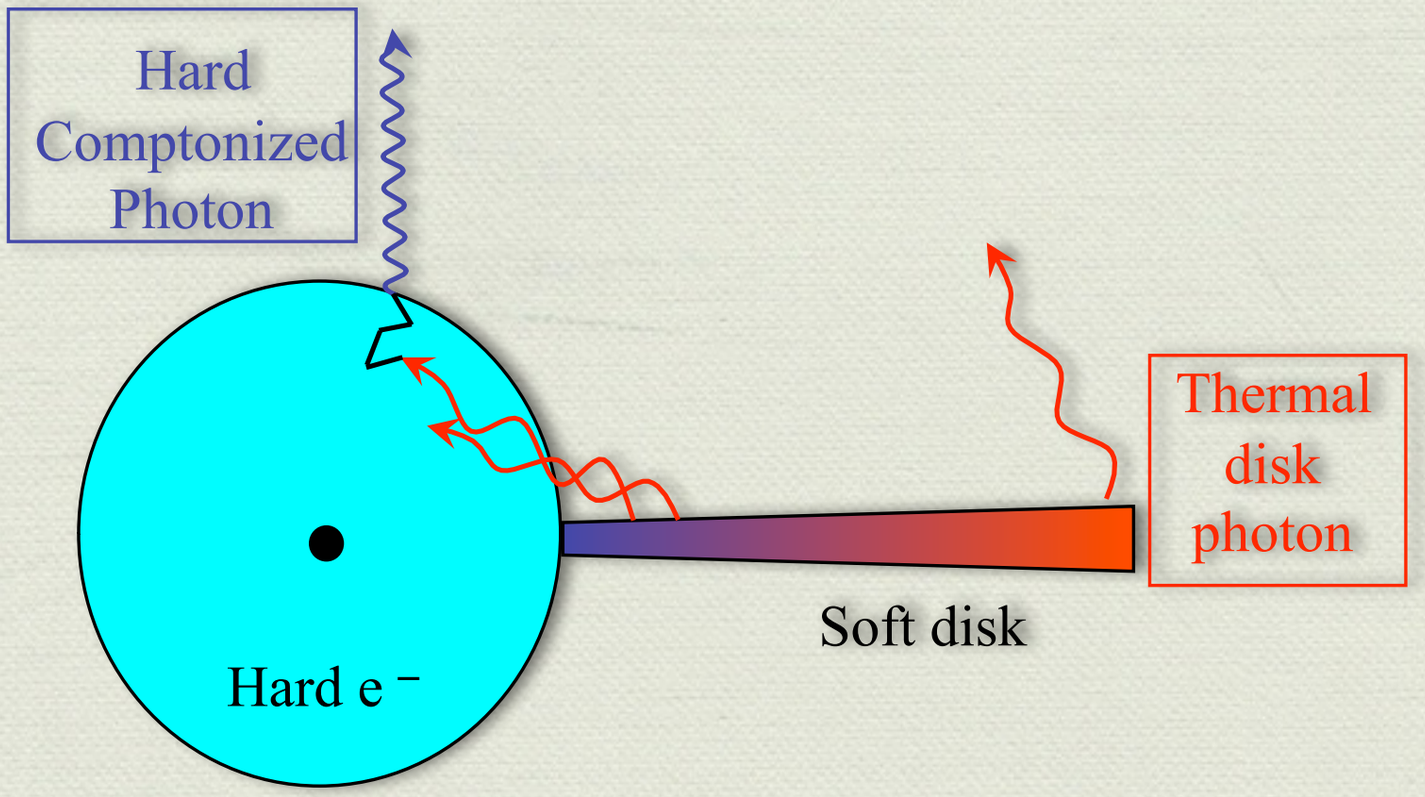


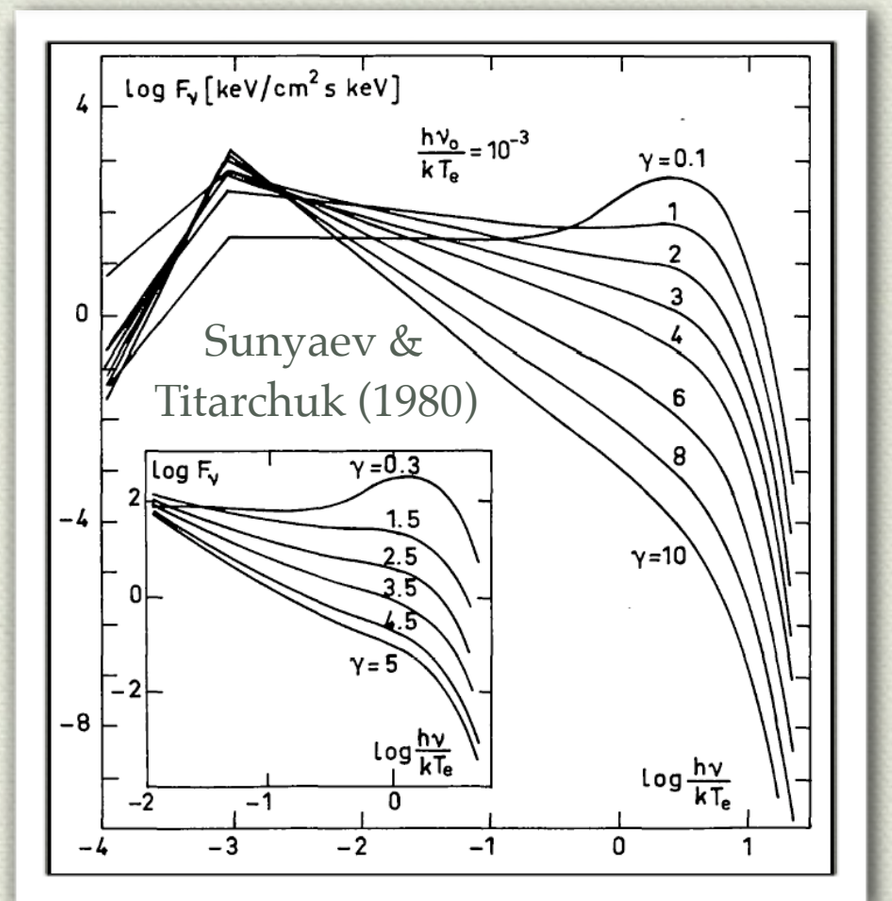
Early observations

- Cygnus X-1
- Spectrum is not a disk!
- Break above 100 keV
- Comptonization



Comptonization





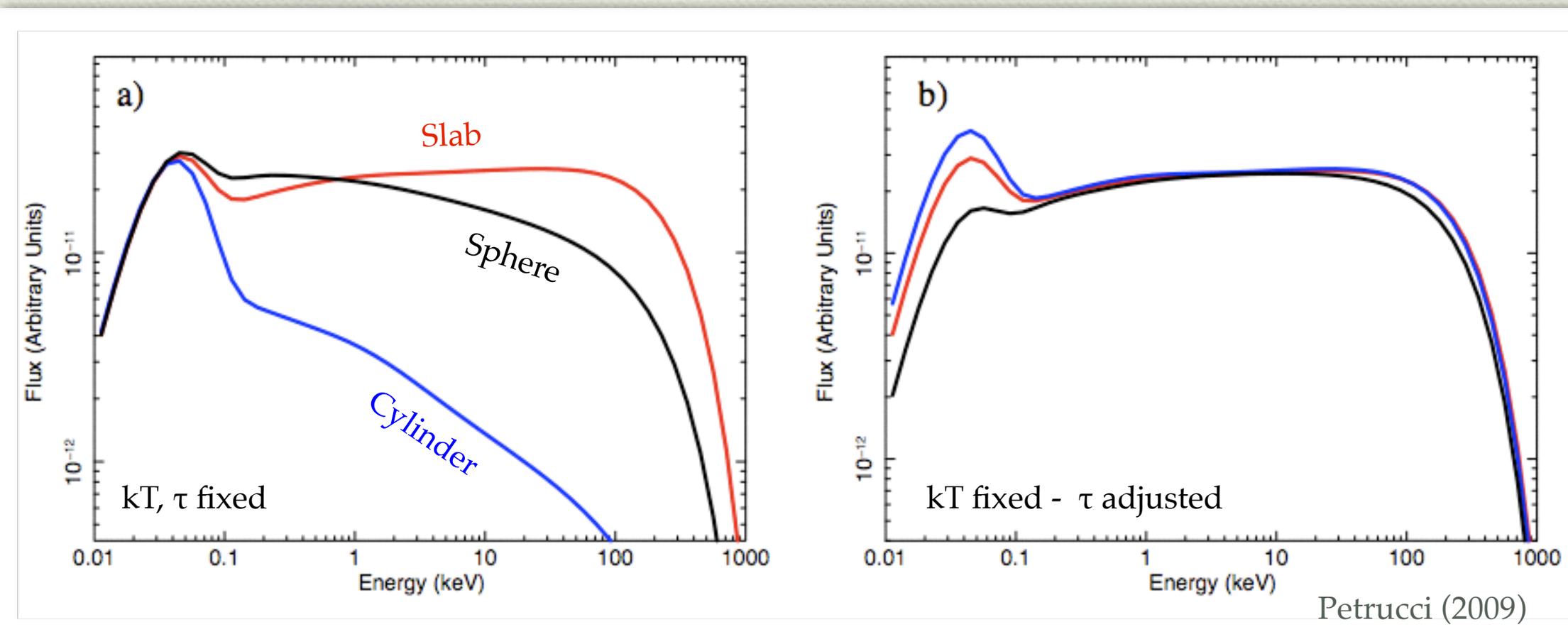
- Thermal hot electrons
- Cyg X-1: $kT_e \sim 60$ keV, $\tau \sim 1$

Comptonization parameter

$$y = \frac{4kT_e}{mc^2} \max(\tau, \tau^2)$$

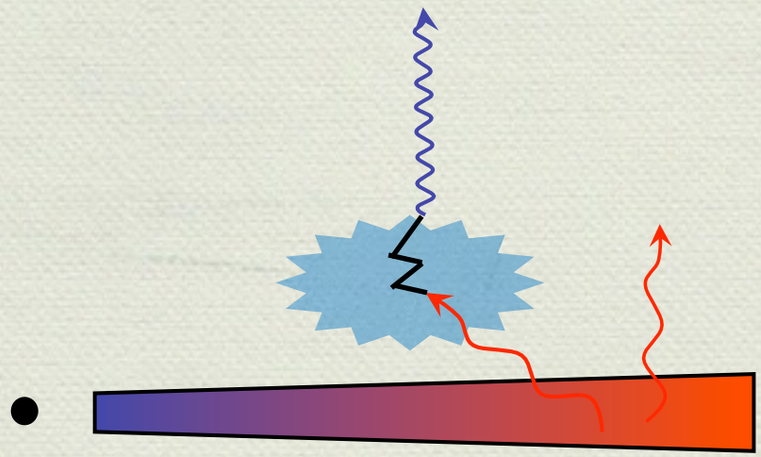
Comptonization

- Model degenerate (geometry, temperature, optical depth)



Petrucci (2009)

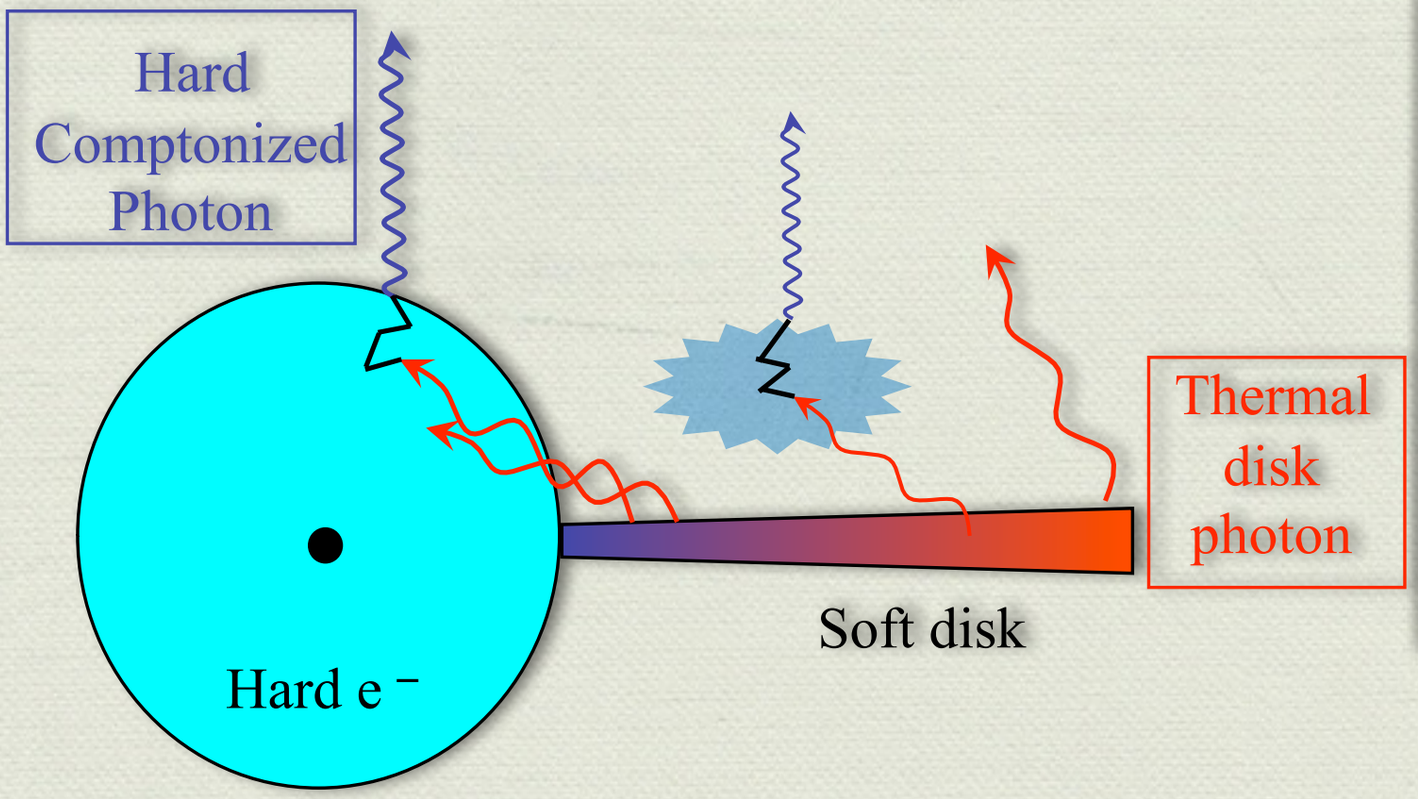
Hybrid models

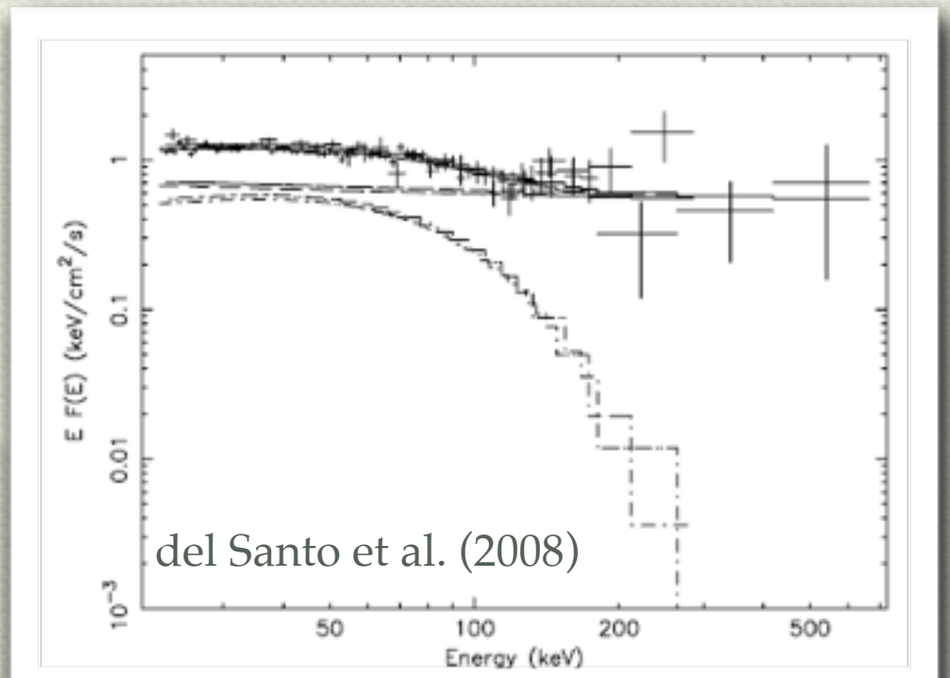


- Non-thermal electrons - no high-energy cutoff
- $\Delta E \approx \gamma^2 E$

$$n(\gamma) \propto \gamma^{-s} \rightarrow F(\nu) \propto \nu^{-\frac{s-1}{2}}$$

Hybrid models

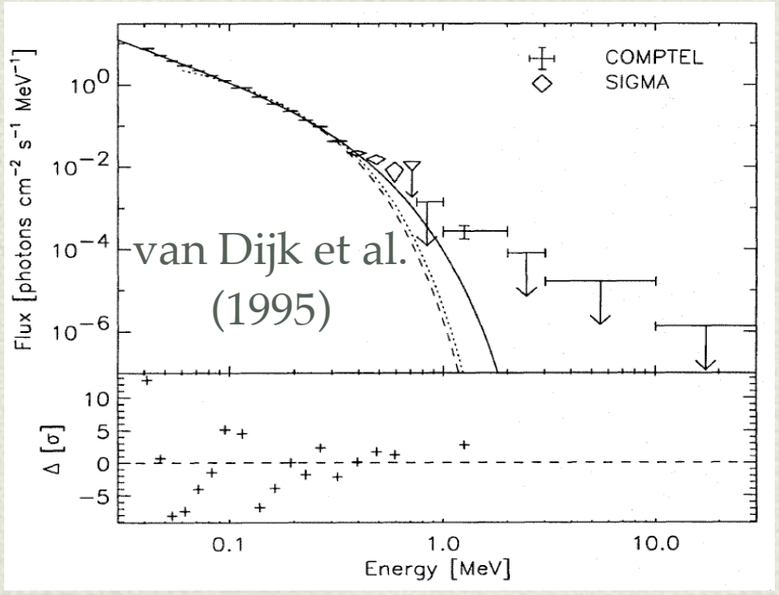


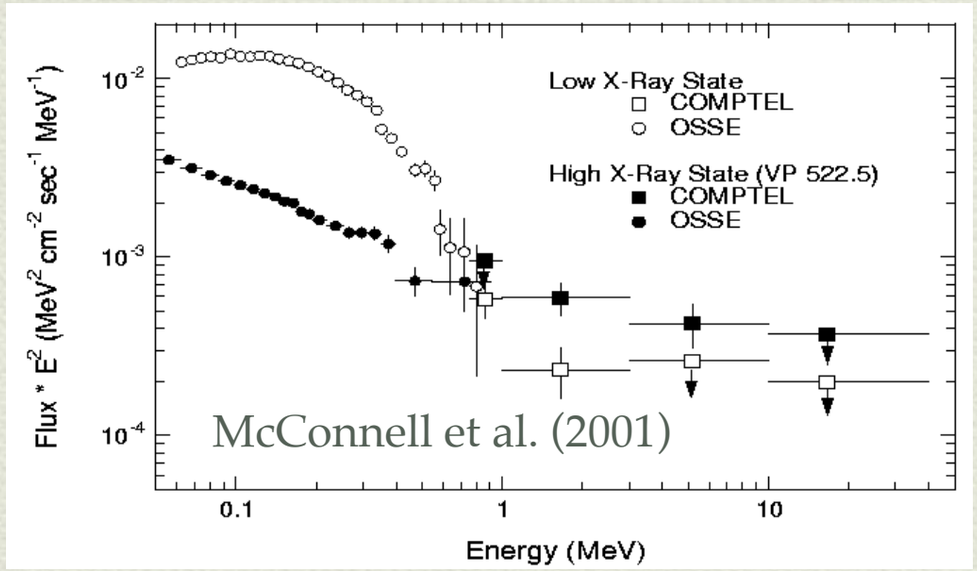


- A hard tail observed in some systems
- Small percentage of non-thermal photons

Hybrid models

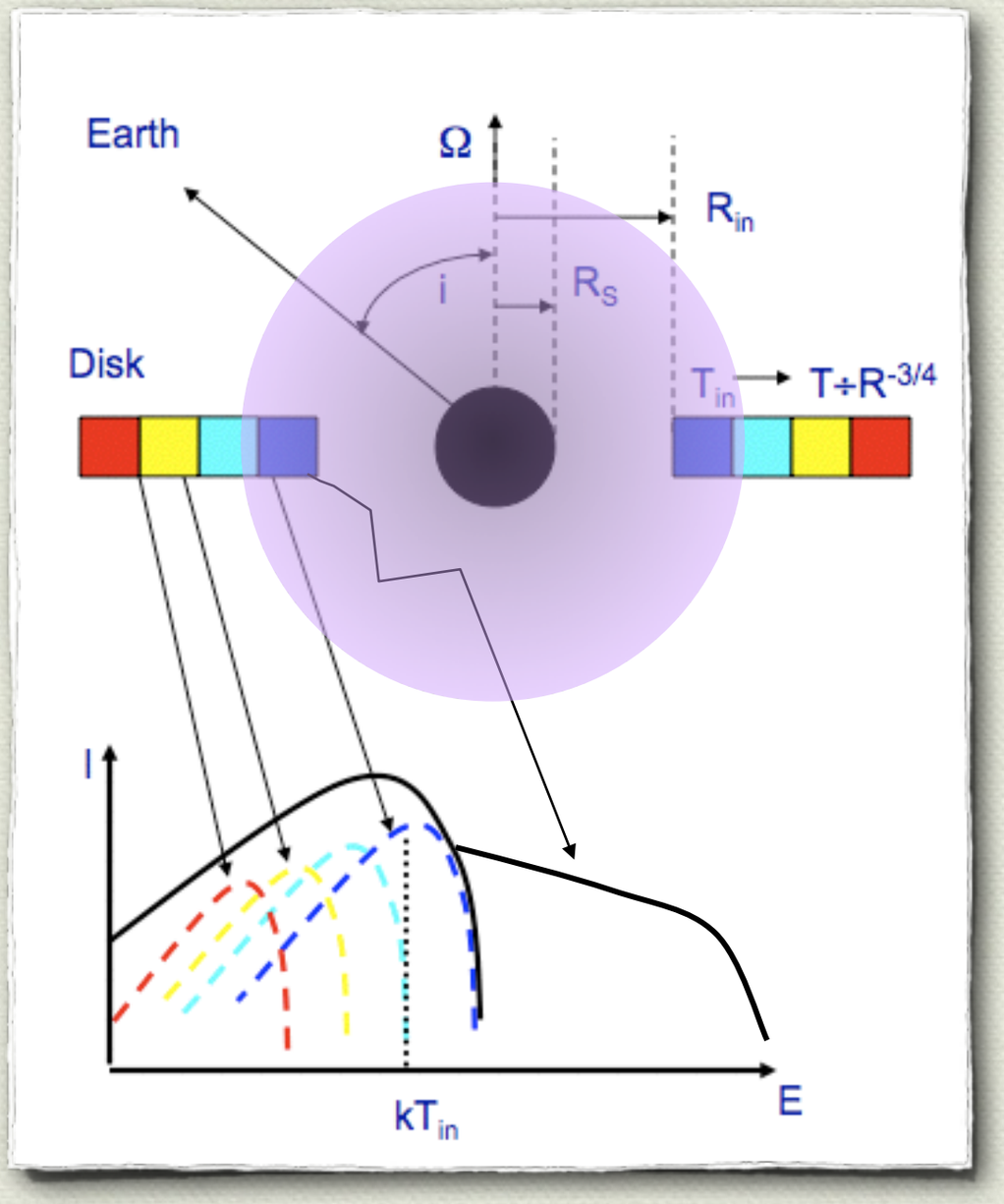
- Seen in a few systems
- Must be non-thermal
- Always difficult measurements
- Long exposures needed





Full spectrum?

- Two components
- Comptonization
- Disk (seen?)
- Spectrum is even more complex
- A little detour

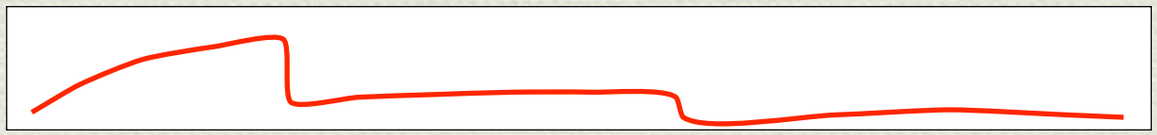


X-ray spectra @ low res.

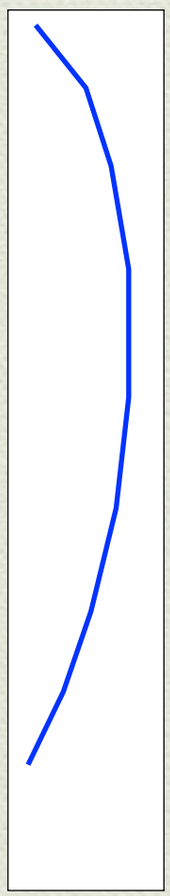
Energy (keV)

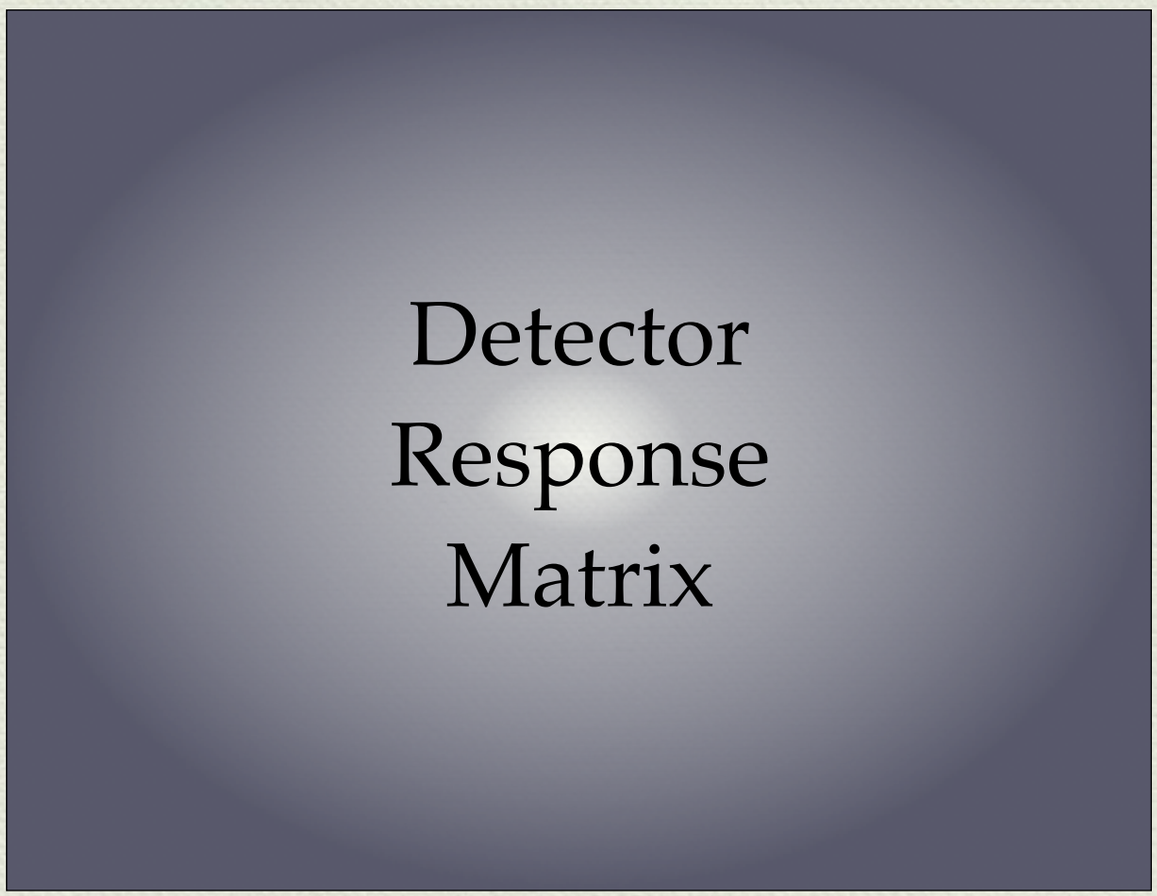
Source spectrum photons/cm²/s/(keV)

Effective area cm²



Observed spectrum counts/s





- Detector response is not diagonal (why?)

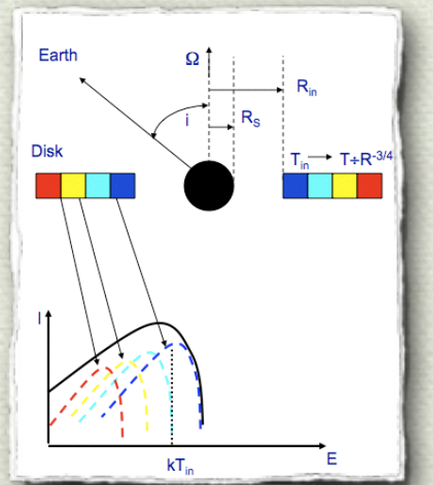
Thick disk is dead...?

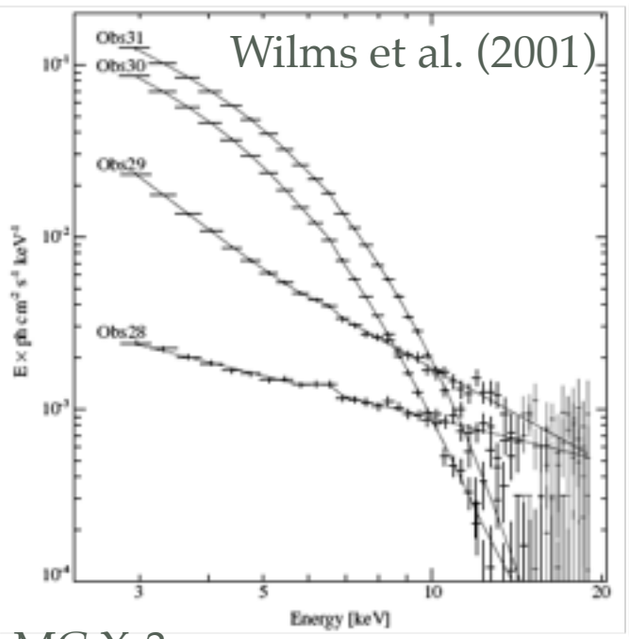
- Not at all
- When spectrum is soft: it fits well!
- With a *disk-blackbody* model - no f

$$f(E) = \frac{8\pi r_{in}^2 \cos\theta}{3D^2} \int_{T_{out}}^{T_{in}} \left(\frac{T}{T_{in}}\right)^{-11/3} B(E,T)\frac{dT}{T_{in}}$$

- Spherical equivalence

$$L_d = \int_{r_{in}}^{r_{out}} 4\pi r \sigma T^4(r) dr \simeq 4\pi r_{in} \sigma T_{in}^4$$

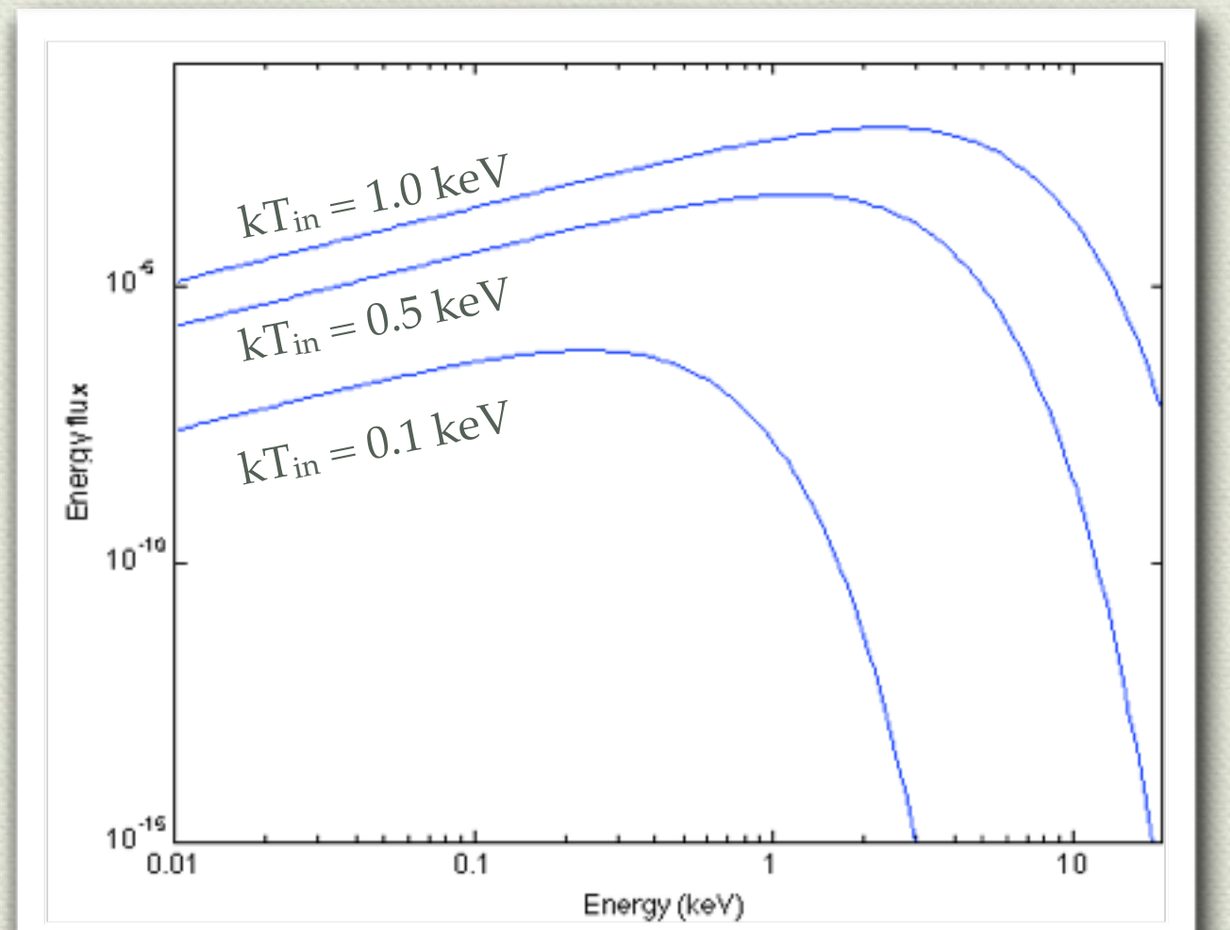


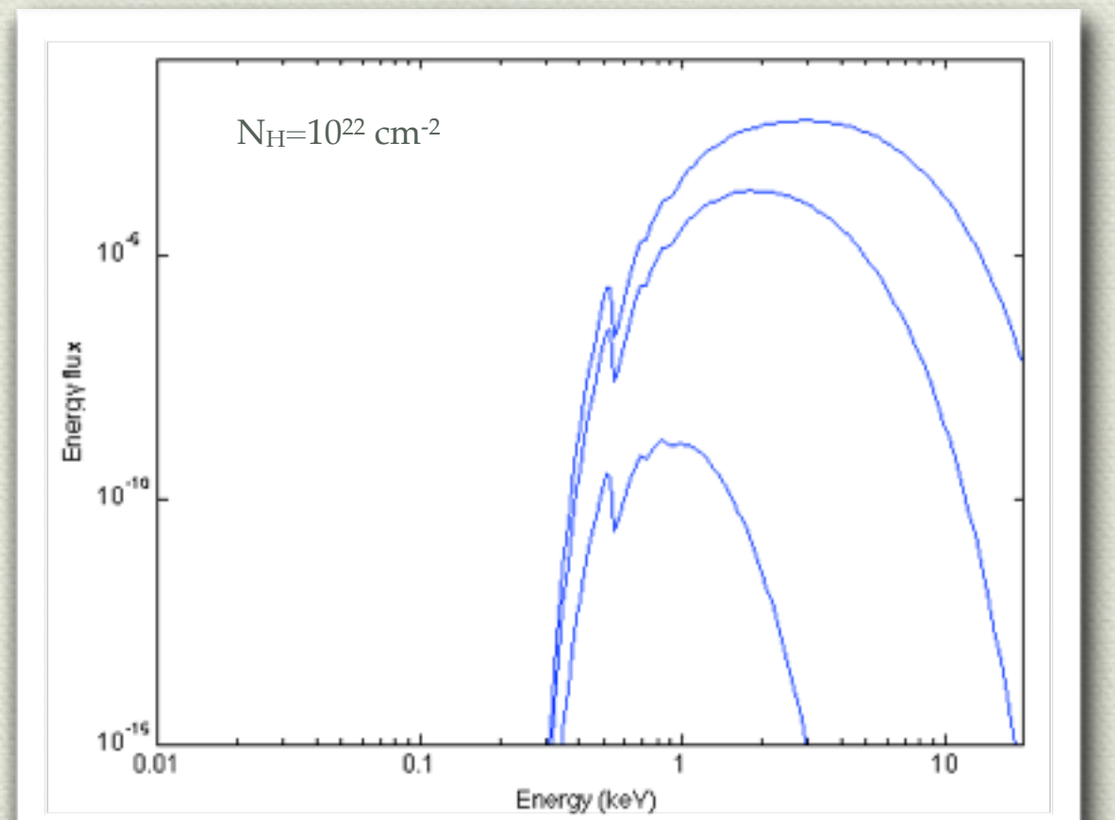


LMC X-3

Disk blackbody

- Very soft spectrum
- Did I mention absorption?





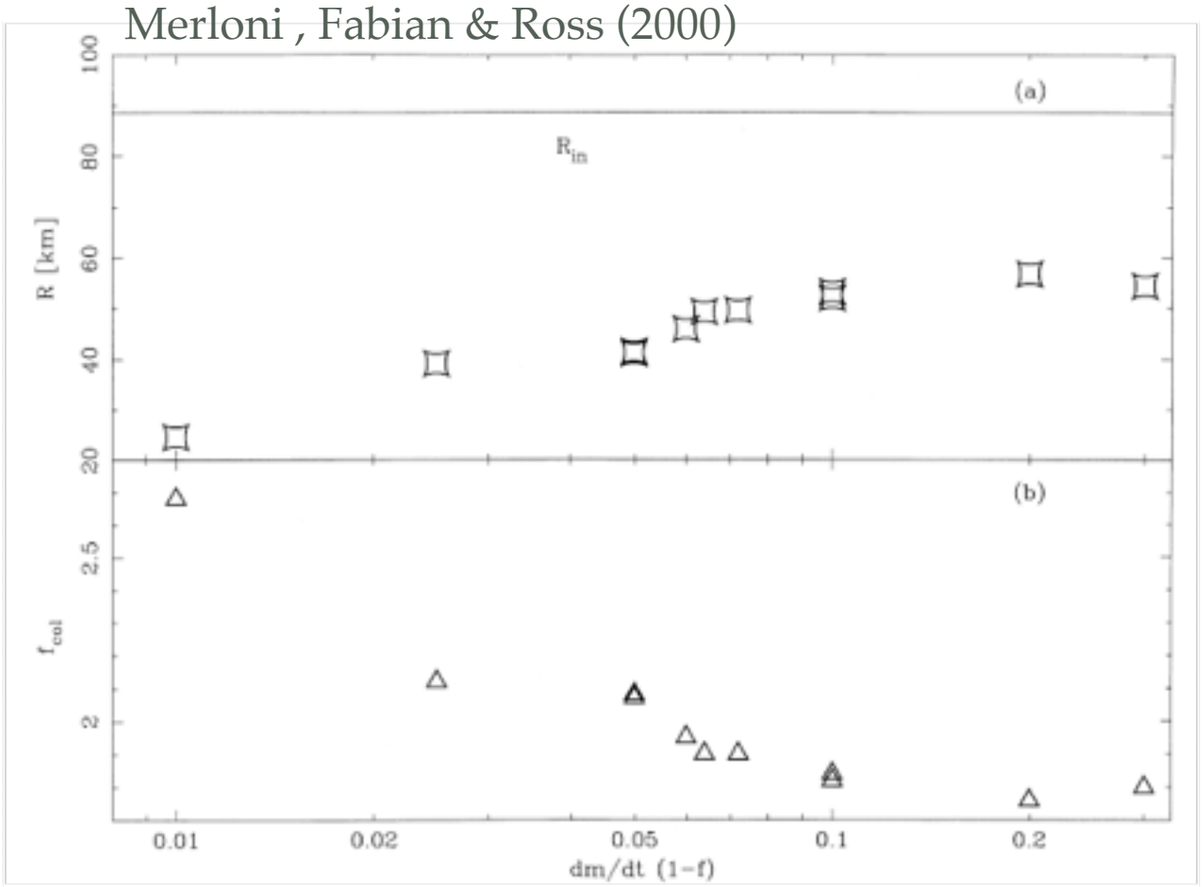
Plus of course detector response

More complex model

- Effect of Comptonization
- Hardening factor $f_{col} = t_{col}/t_{eff} \sim 1.7$
- Constant?
- One has to be very careful
- Real life is even more complex

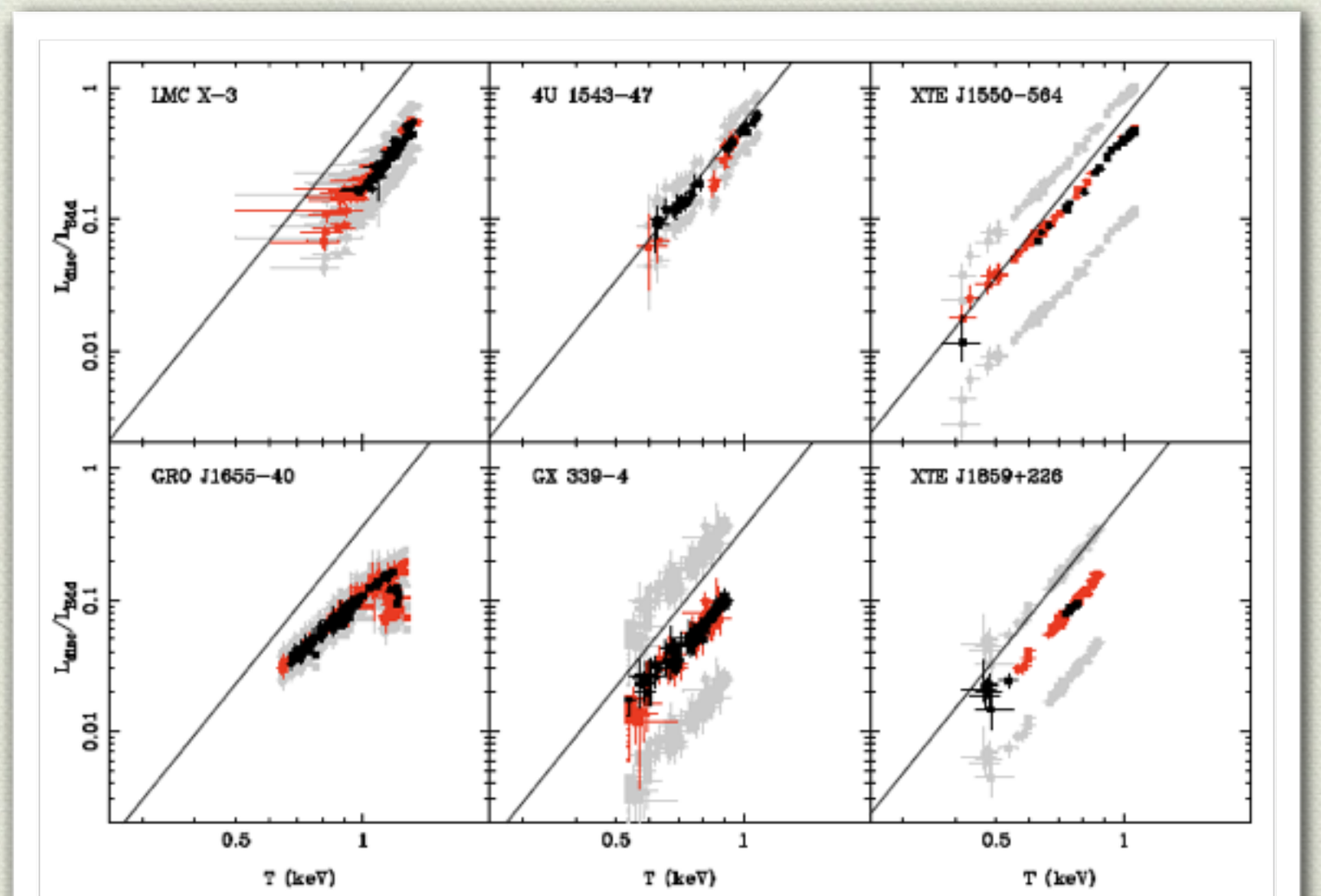
  frame dragging, Doppler boosting, gravitational redshift, light bending, limb darkening, self-reirradiation

Merloni , Fabian & Ross (2000)



kT-Luminosity

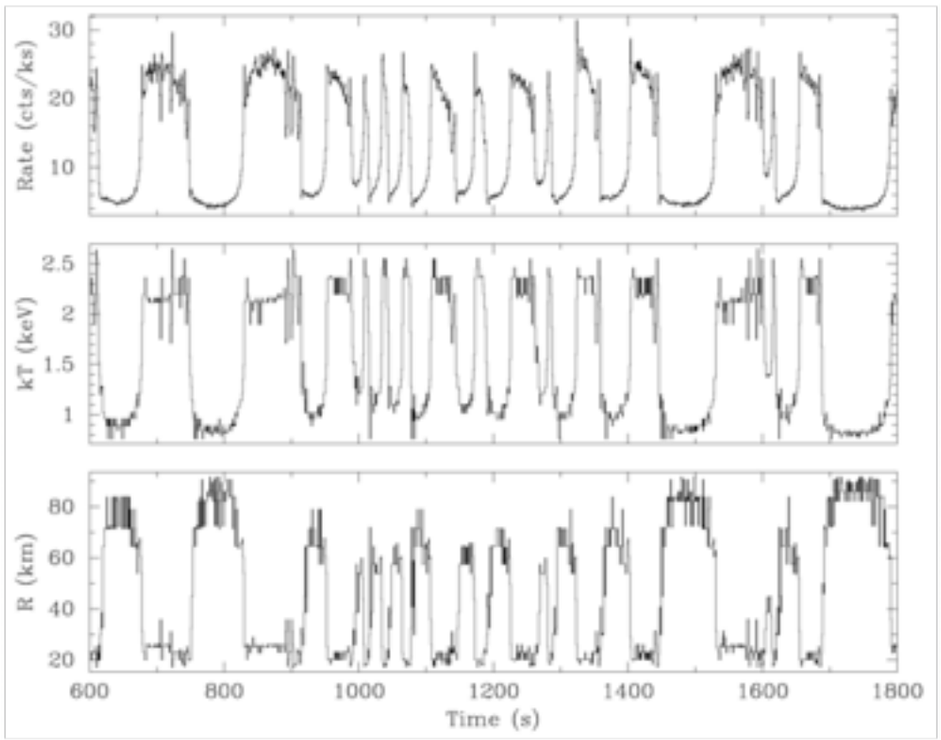
- If it looks like a BB and quacks like a BB...

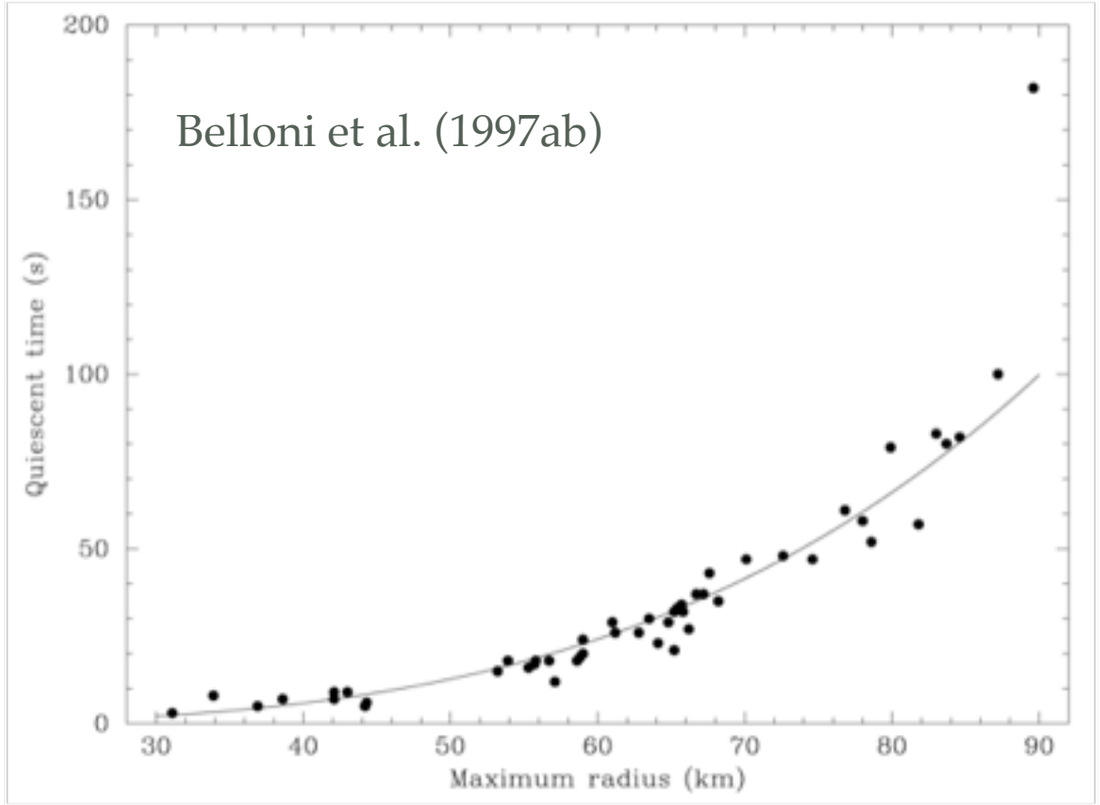


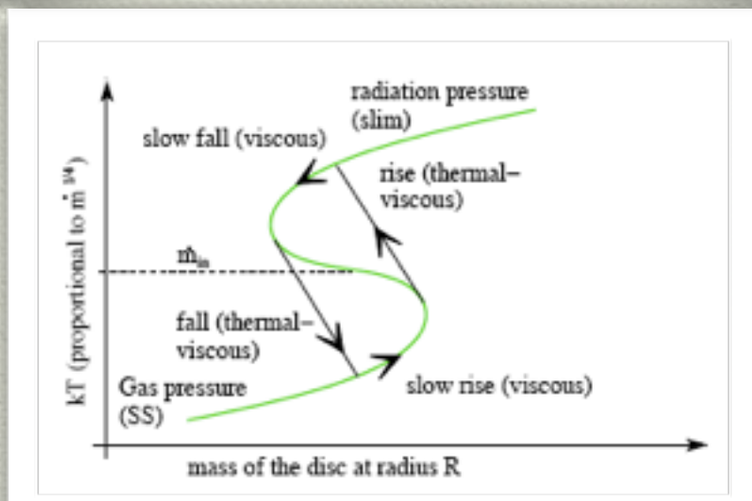
Done, Gierliński & Kubota (2006)

GRS 1915+105

- Weird source
- Radius oscillations

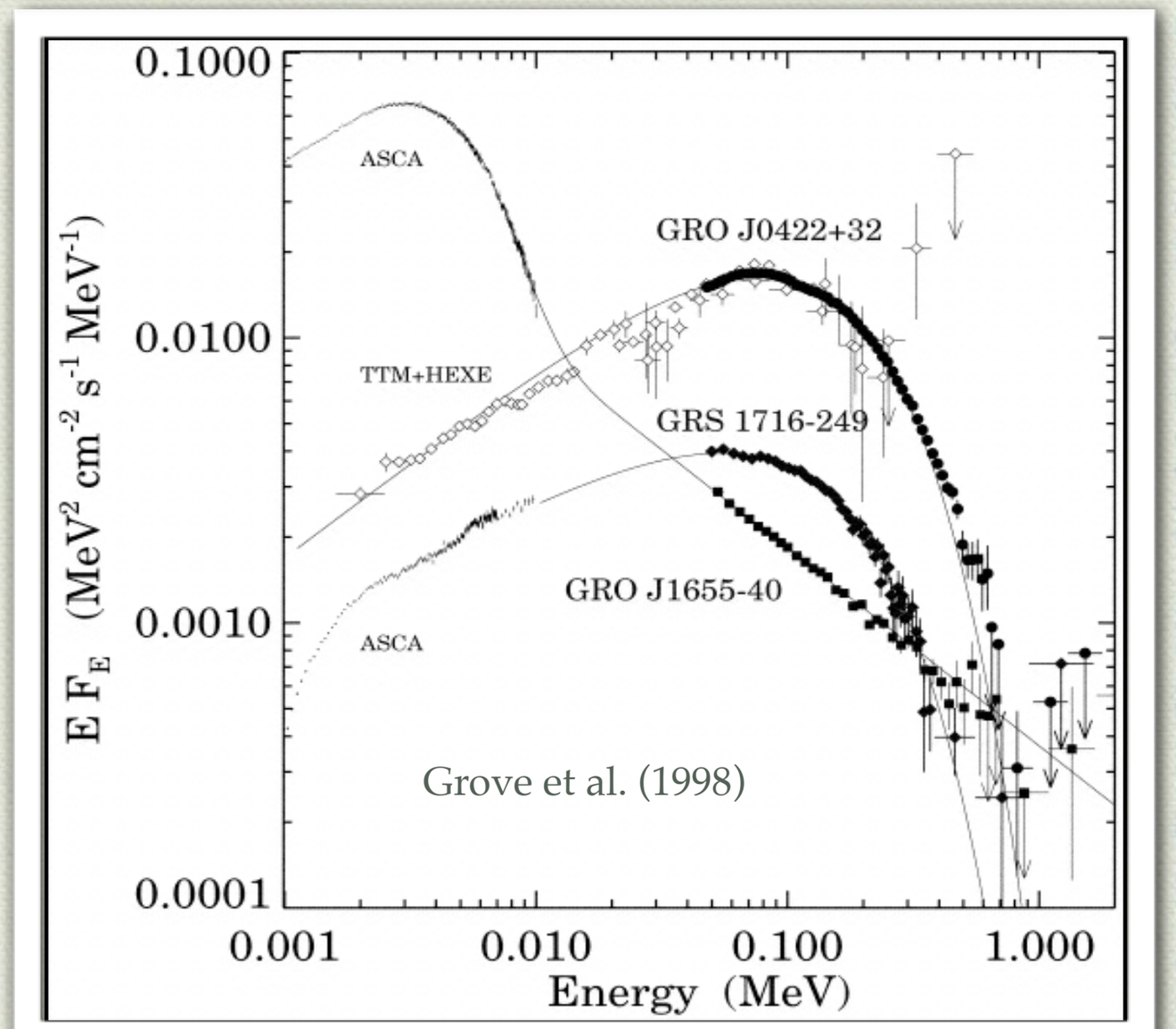






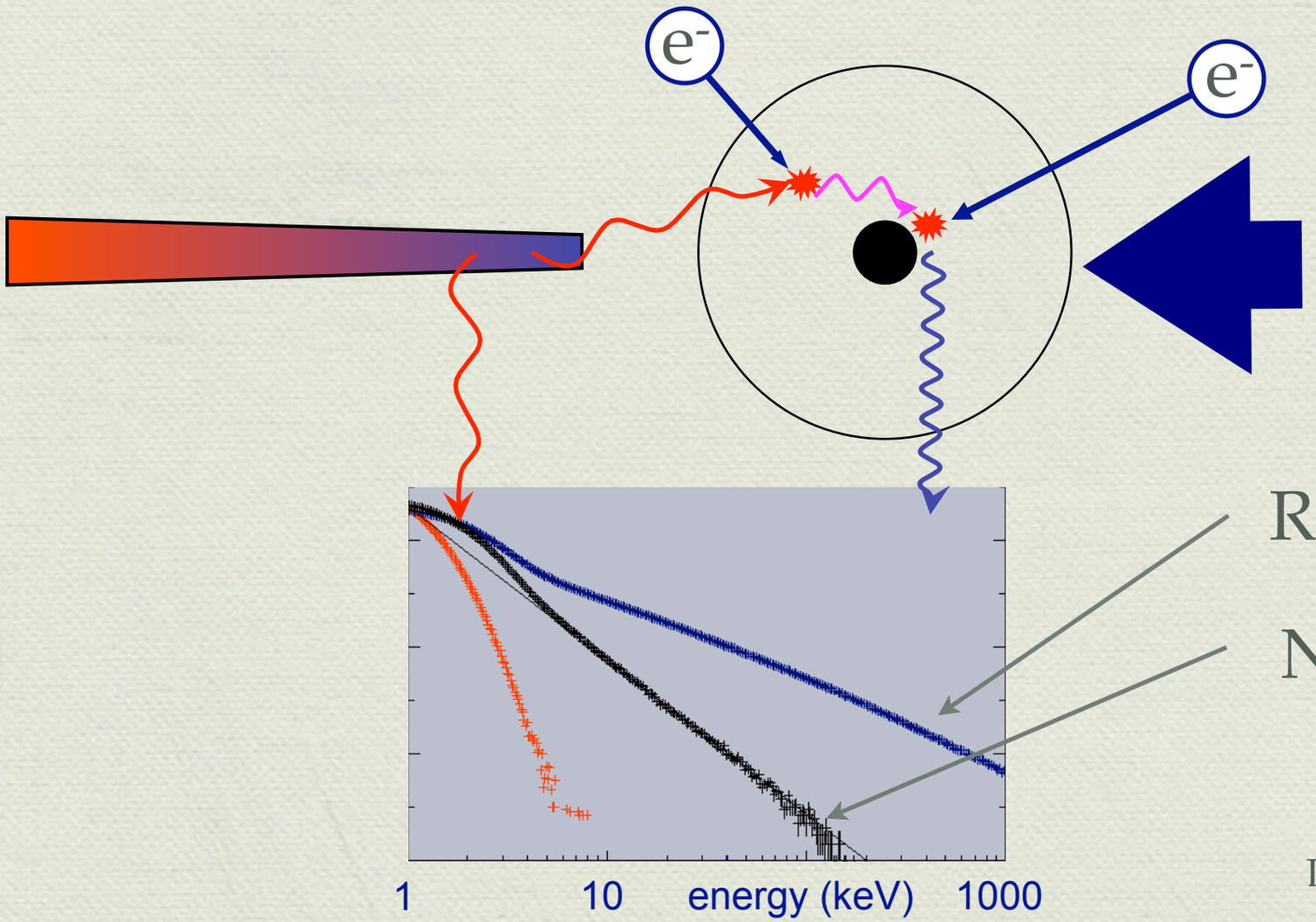
Non-thermal Compton.?

- Disk is not alone
- Non-thermal?
- Bulk motion?
- Single scatterings?



Grove et al. (1998)

Bulk motion Compton.



Converging flow

Relativistic

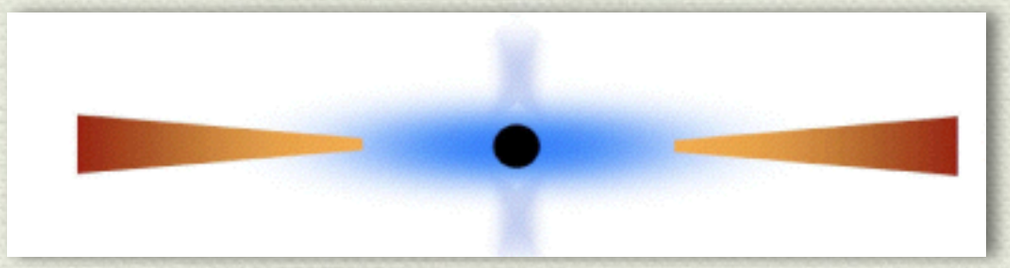
Non-relativistic

Laurent & Titarchuk (1999,2000)

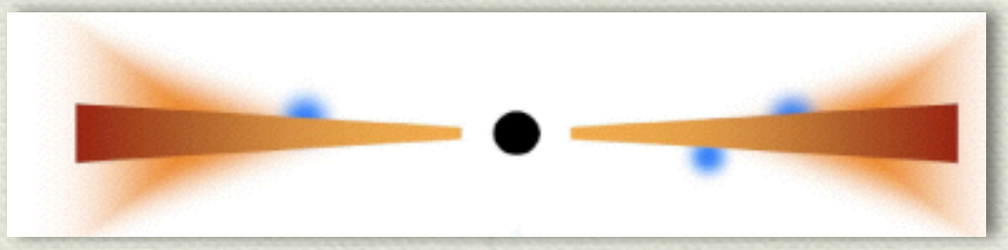
Recap

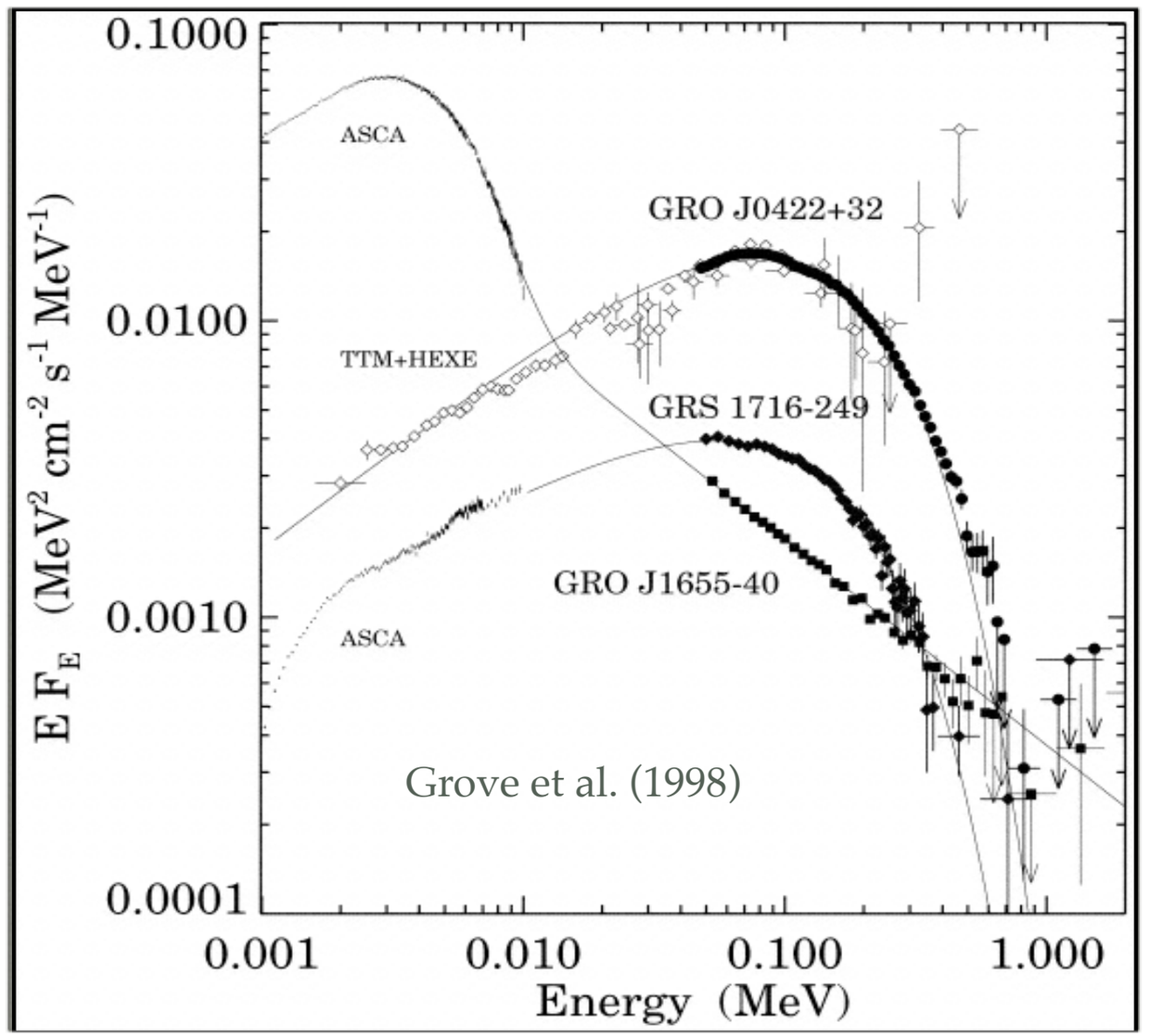
- Two flavors of spectra

Hard



Soft



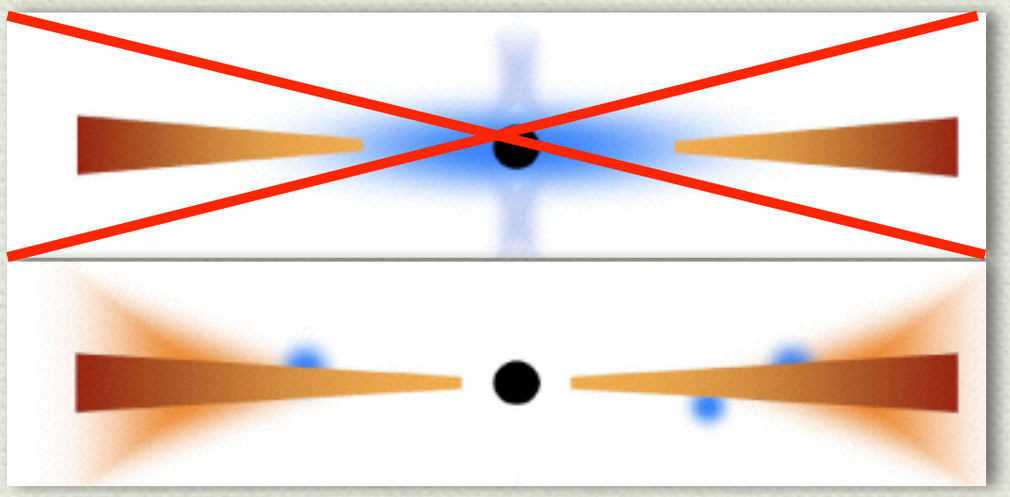


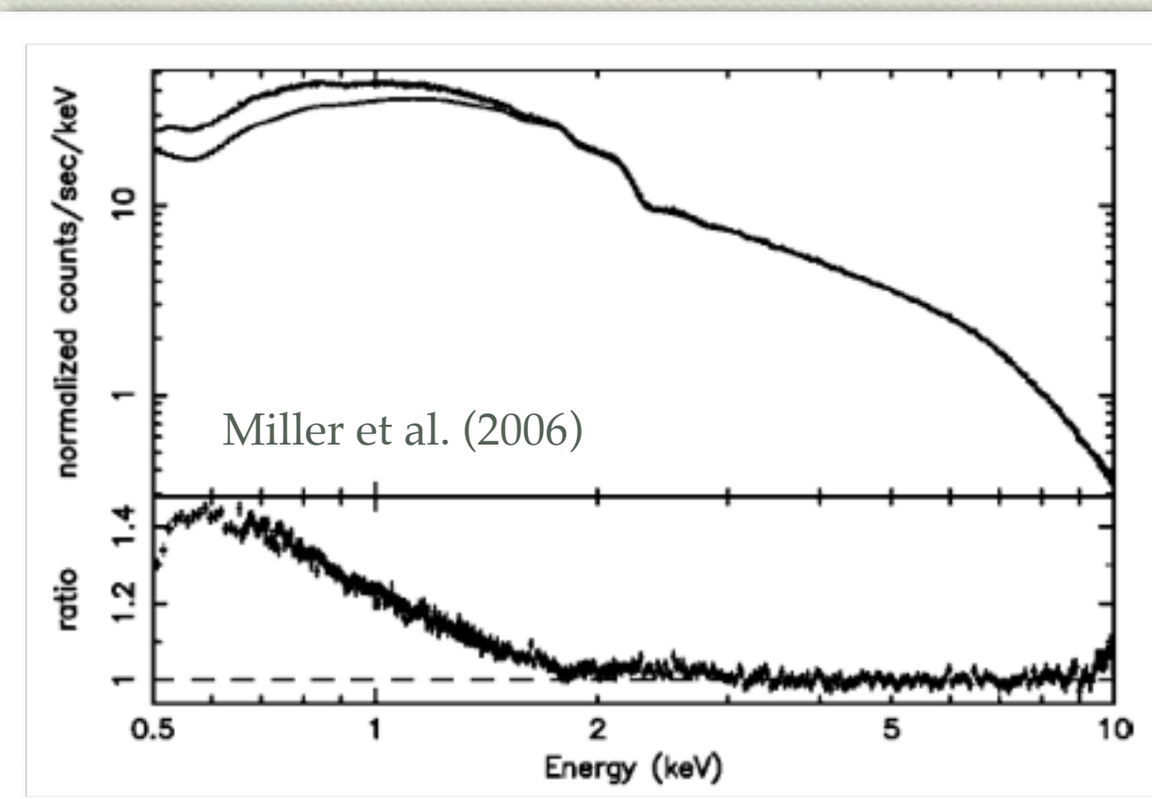
Grove et al. (1998)

ADAF / ADIOS etc models

Inner disk radius

- Recent claims that disk radius is always small





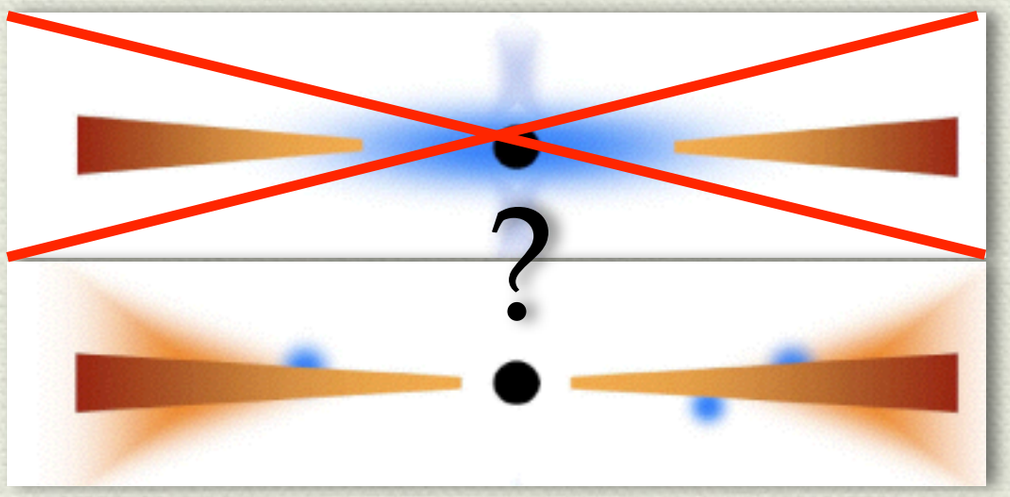
Miller et al. (2006)

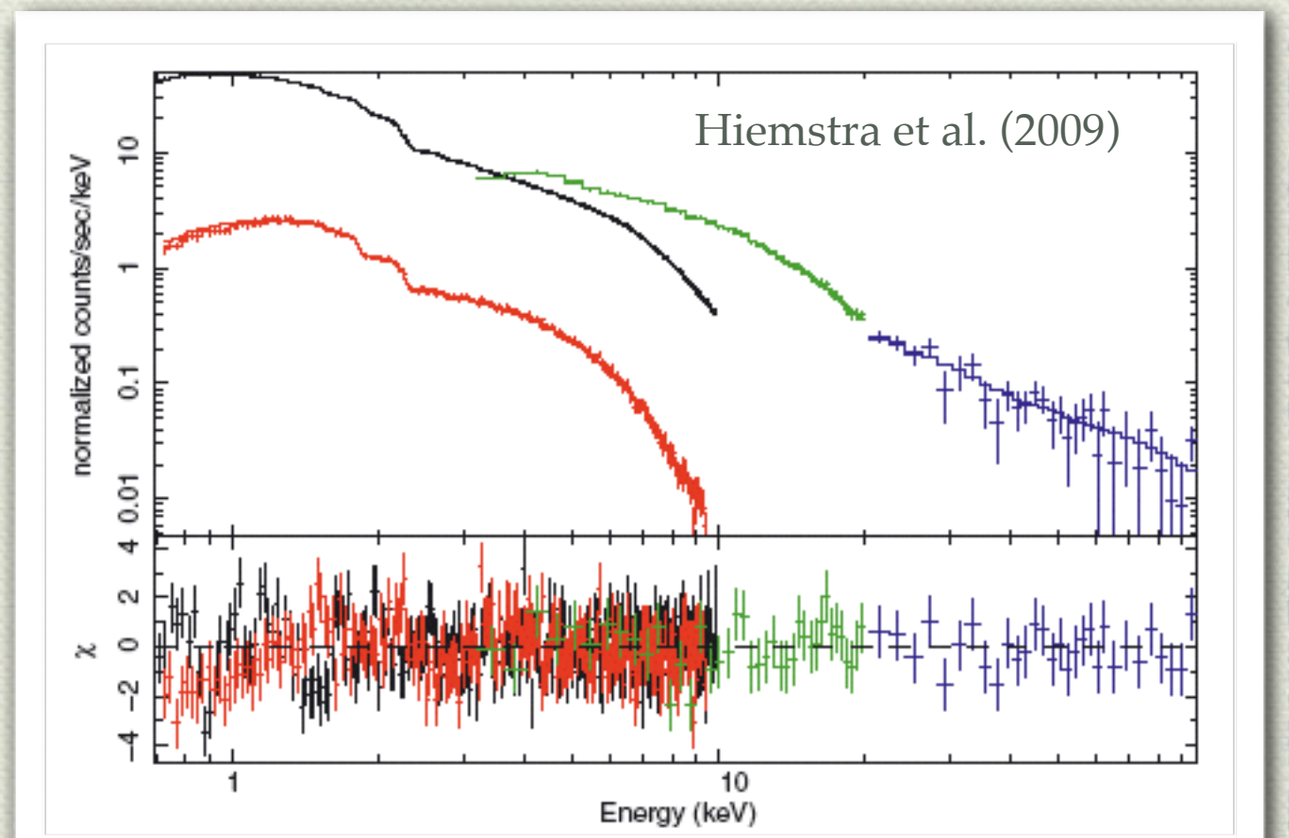
Very sensitive to model

Very sensitive to N_H

Inner disk radius?

- Same source, same data, inconclusive results





Very sensitive to model

Very sensitive to N_H

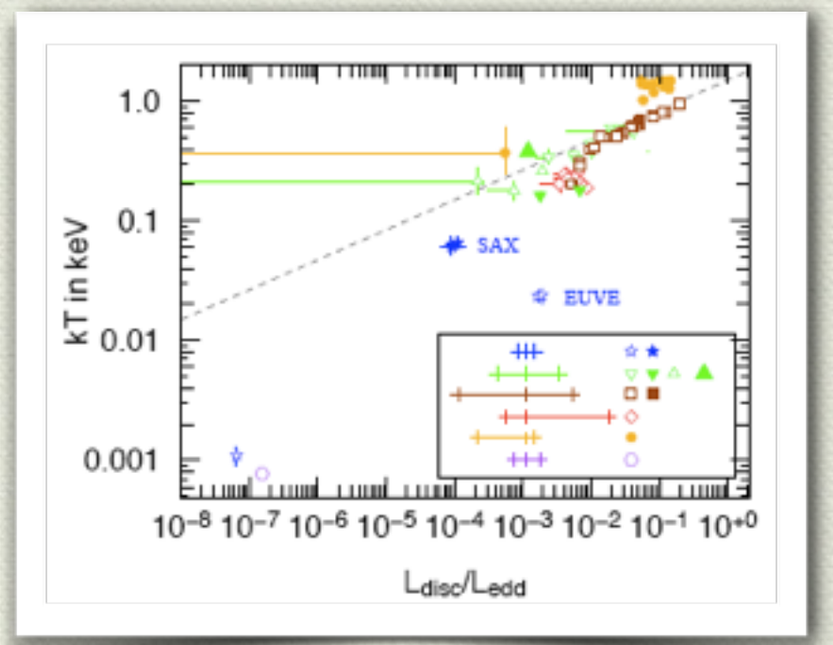
Technical caveat

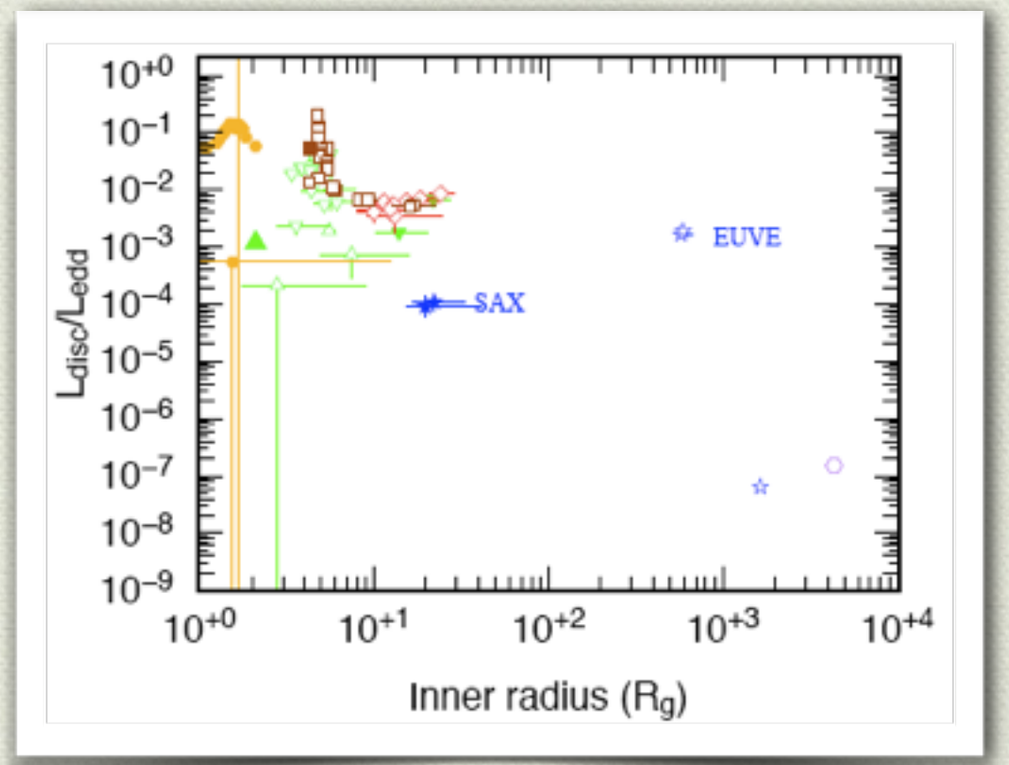
- Inner disk radius is (Norm)$^{1/2}$ $R_{in} = D\sqrt{N \cos i}$
- Small radius -- small normalization
- Small radius -- absence of detection
- Temperature is also low

- I see a small radius = I don’t see the disk very well
- All this under absorption

Recent results

- Inner disk radius from a sample
- Above 0.01 L_{Edd}, $R_{in} < 10\ R_g$
- Between 0.001 and 0.01 in starts to recede
- Remember L vs kT

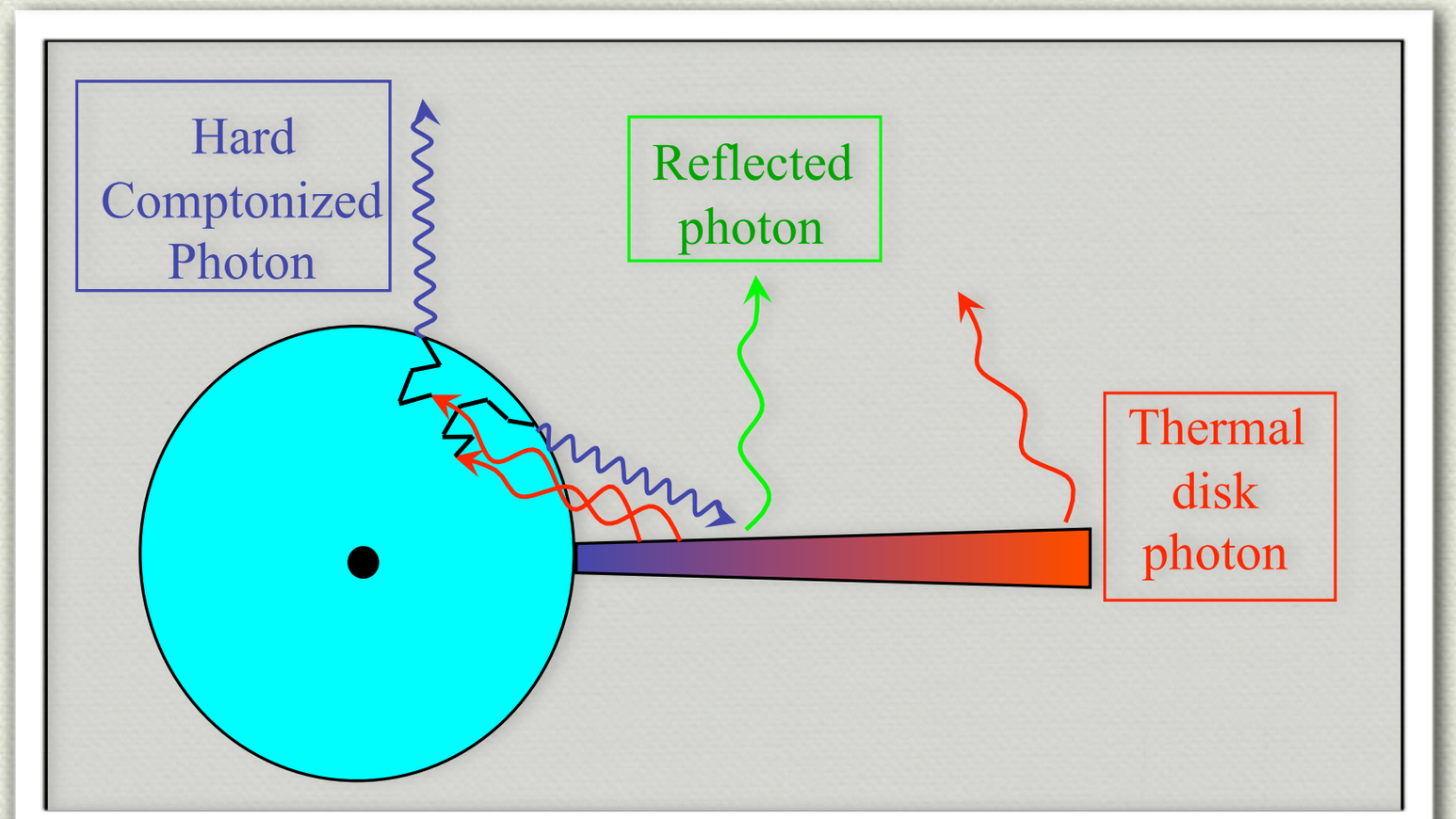




Cabanac et al. (2009)

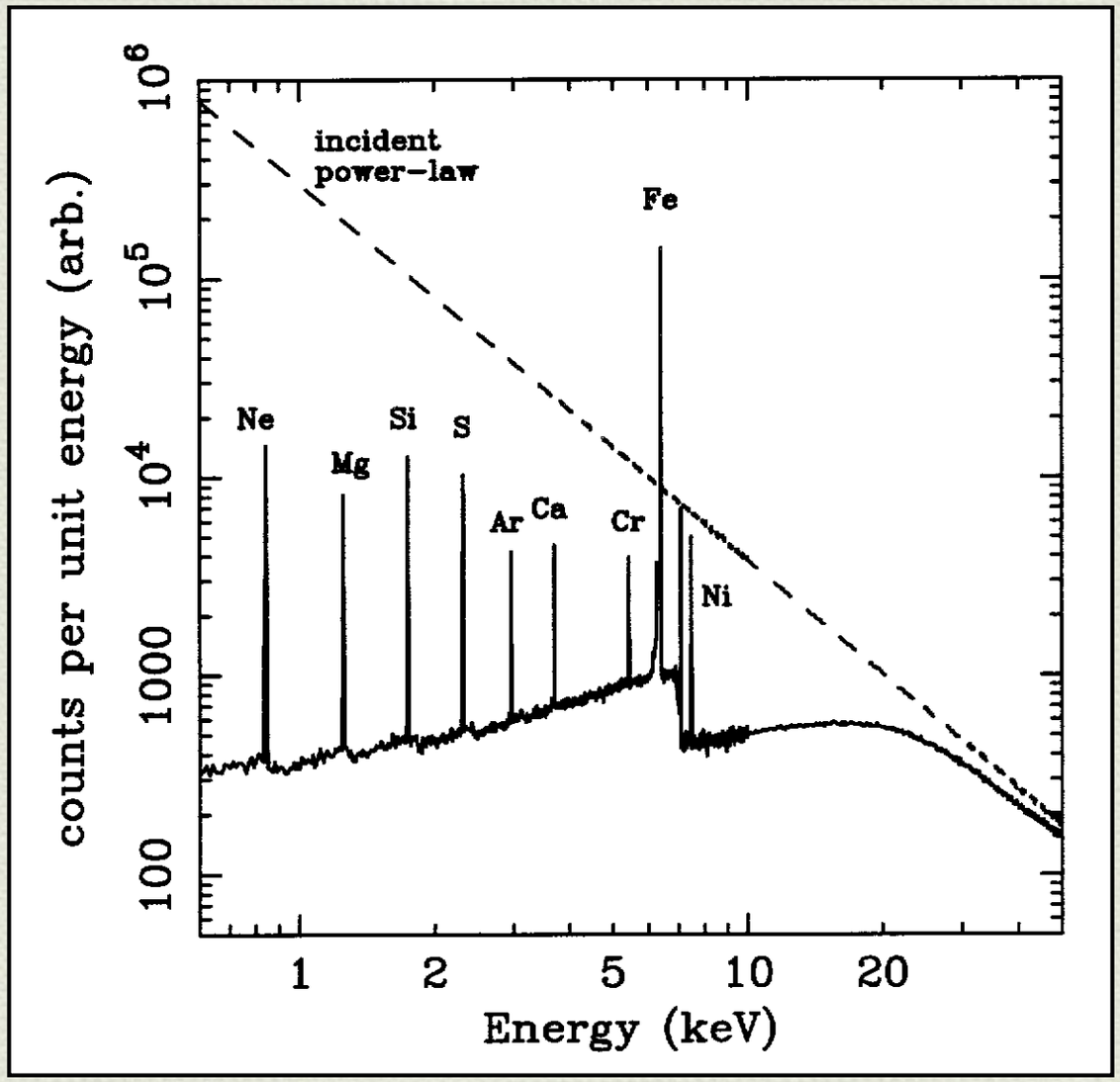
Additional components

- Disk reflects hard radiation
- Additional component present
- What does it look like?



Compton reflection

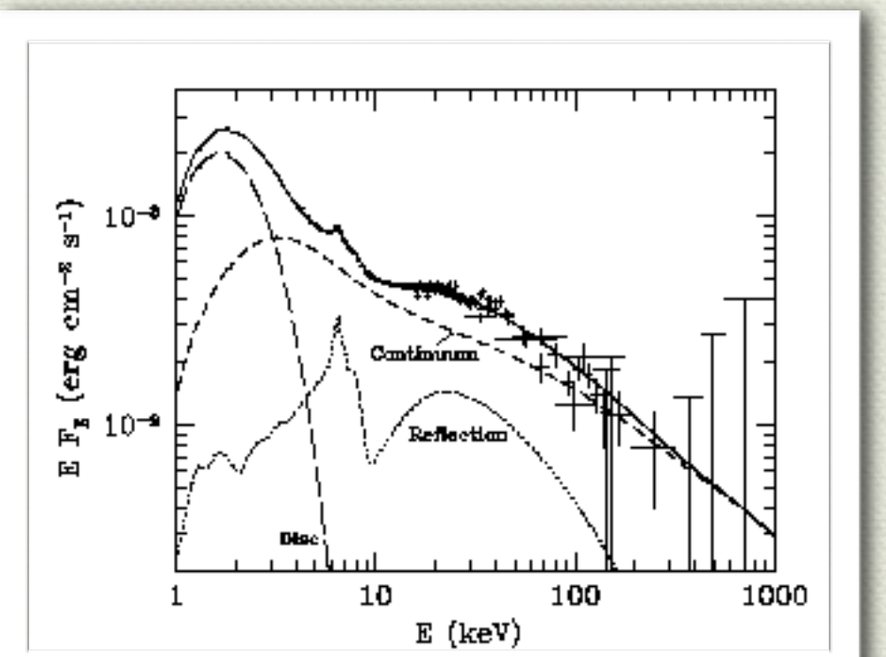
- Reflection bump
- Fluorescent K_α lines
- Iron line dominates
- 6.4 keV / 6.7 keV
- Narrow line+bump
- Related to hard flux and covering factor $\Omega/2\pi$

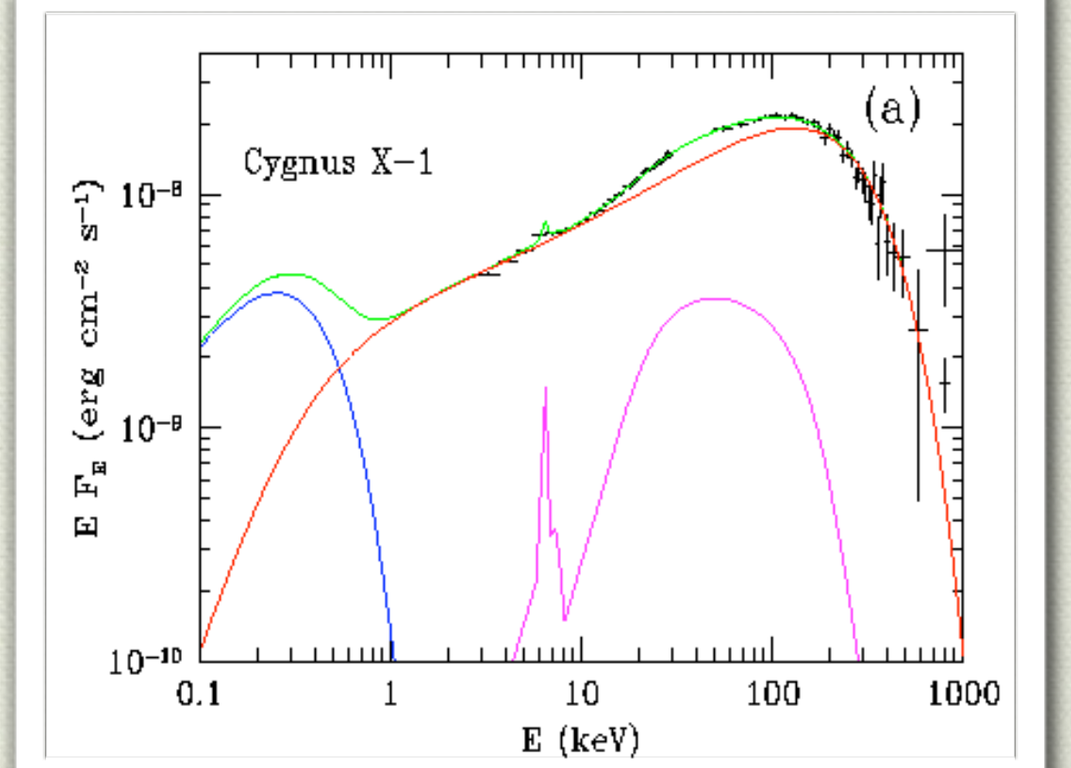


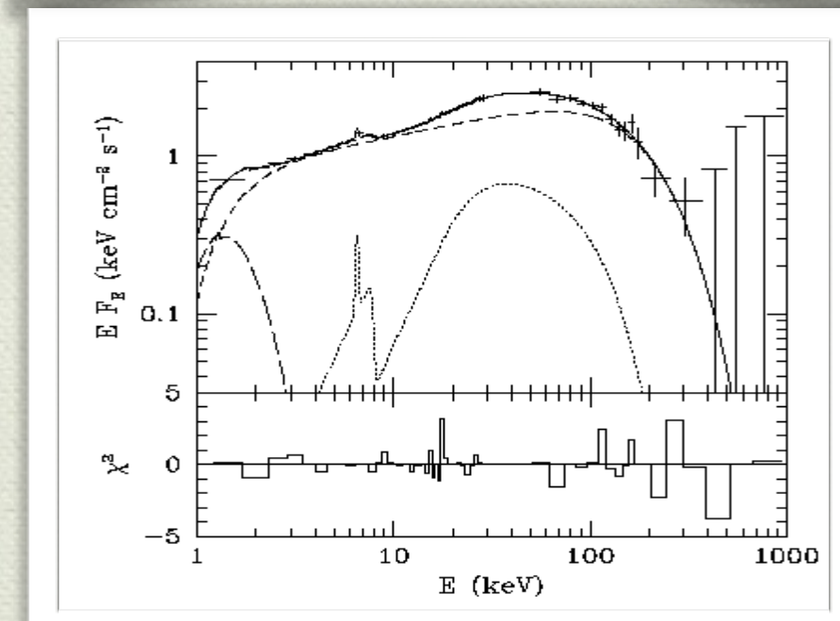
Reynolds & Nowak (2002)

Compton reflection

- Some examples
- Hard spectra but also soft spectra
- $\Omega/2\pi$ depends on inner radius

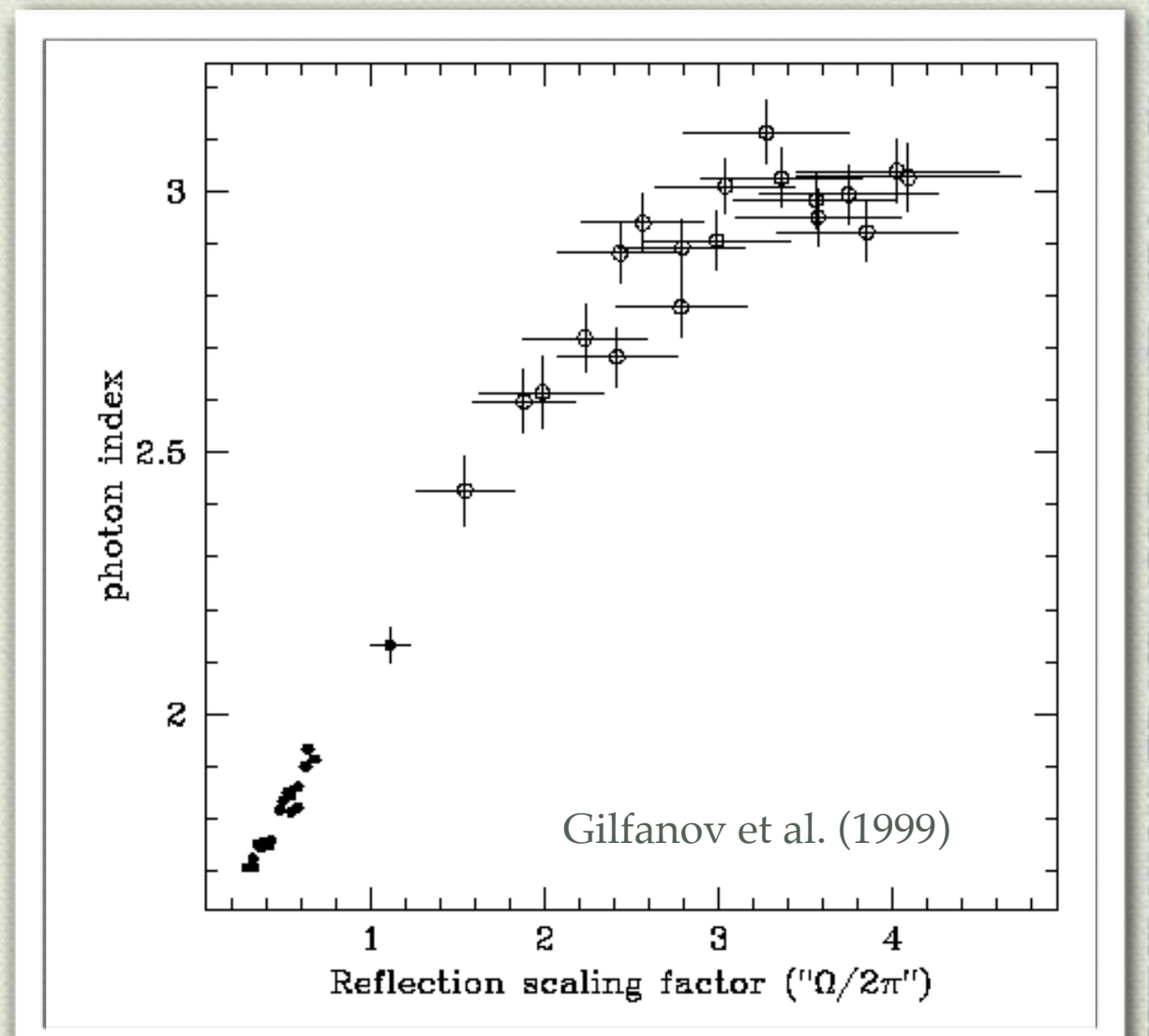






Compton reflection

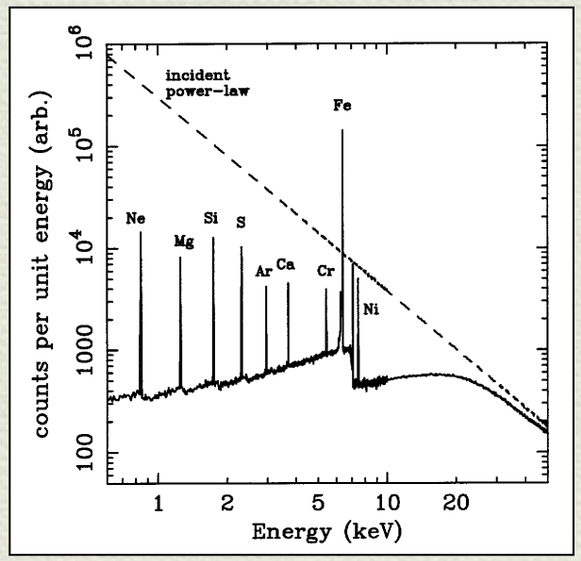
- R correlates with spectral slope
- Inner disk moves in
- More soft-photon input
- Steeper spectrum
- More angle, more reflection
- Does the disk move in?

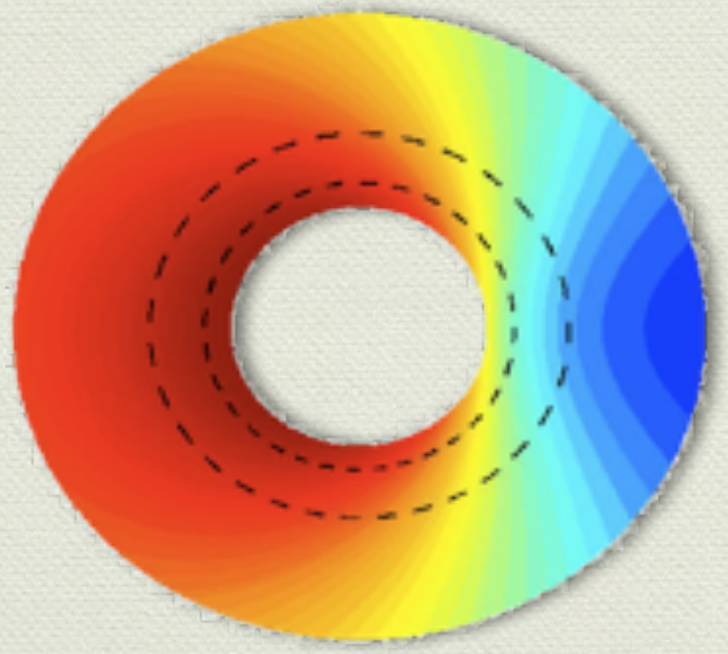


Gilfanov et al. (1999)

Fluorescence lines

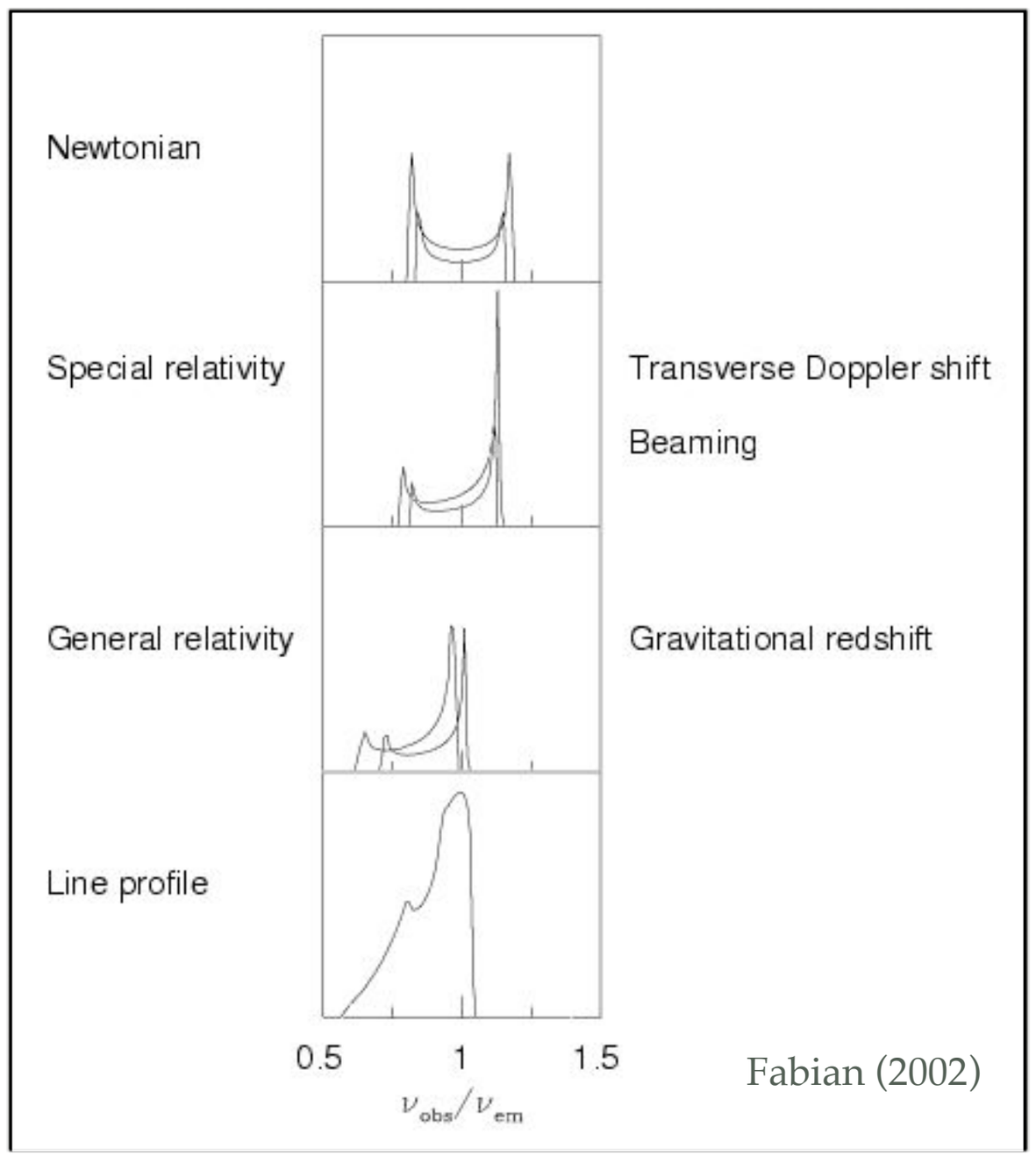
- Narrow lines expected
- Relativistic distortions:
  - Doppler effect
  - Relativistic aberration
  - light bending
  - redshift





Fluorescence lines

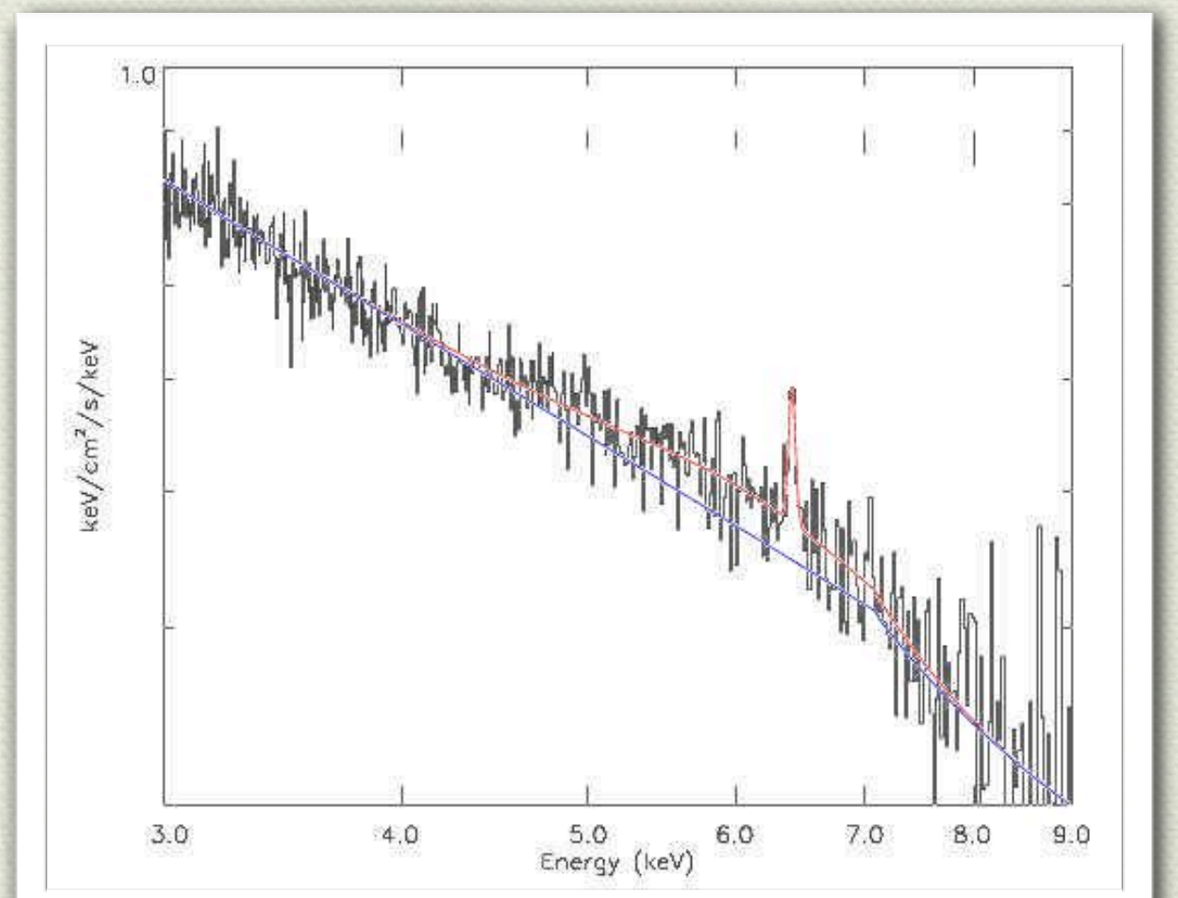
- Broad line expected
- Broadening can be used
- Relativistic effects
- GR evidence
- (Fifth lecture + Steiner)

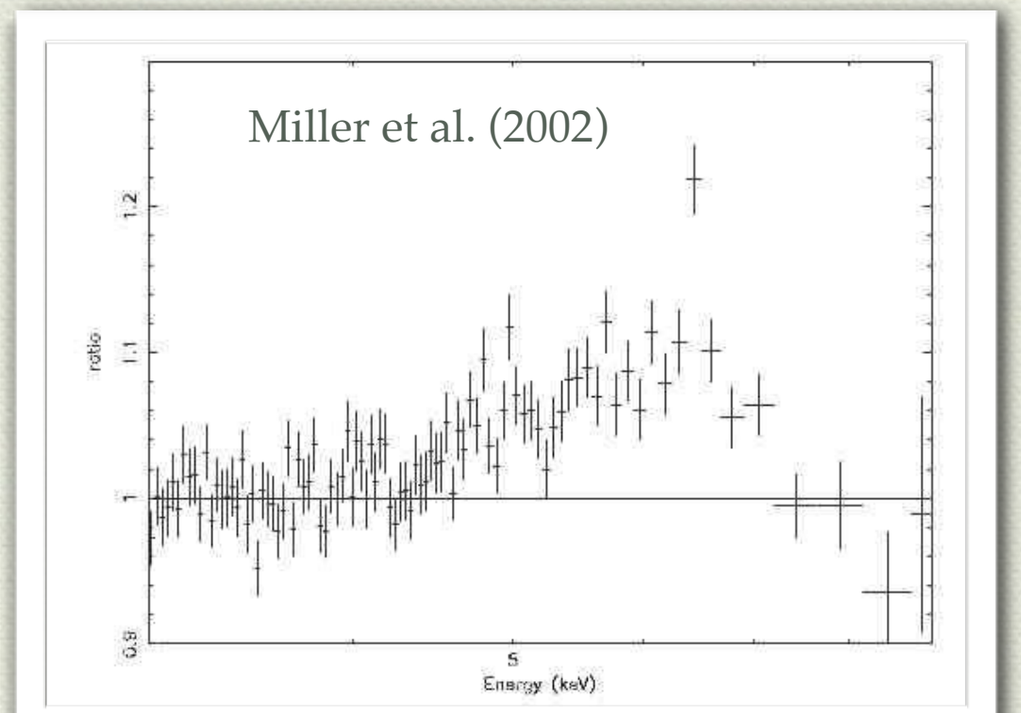


Fabian (2002)

Tricky points

- Ratio plots
- These are “not” lines

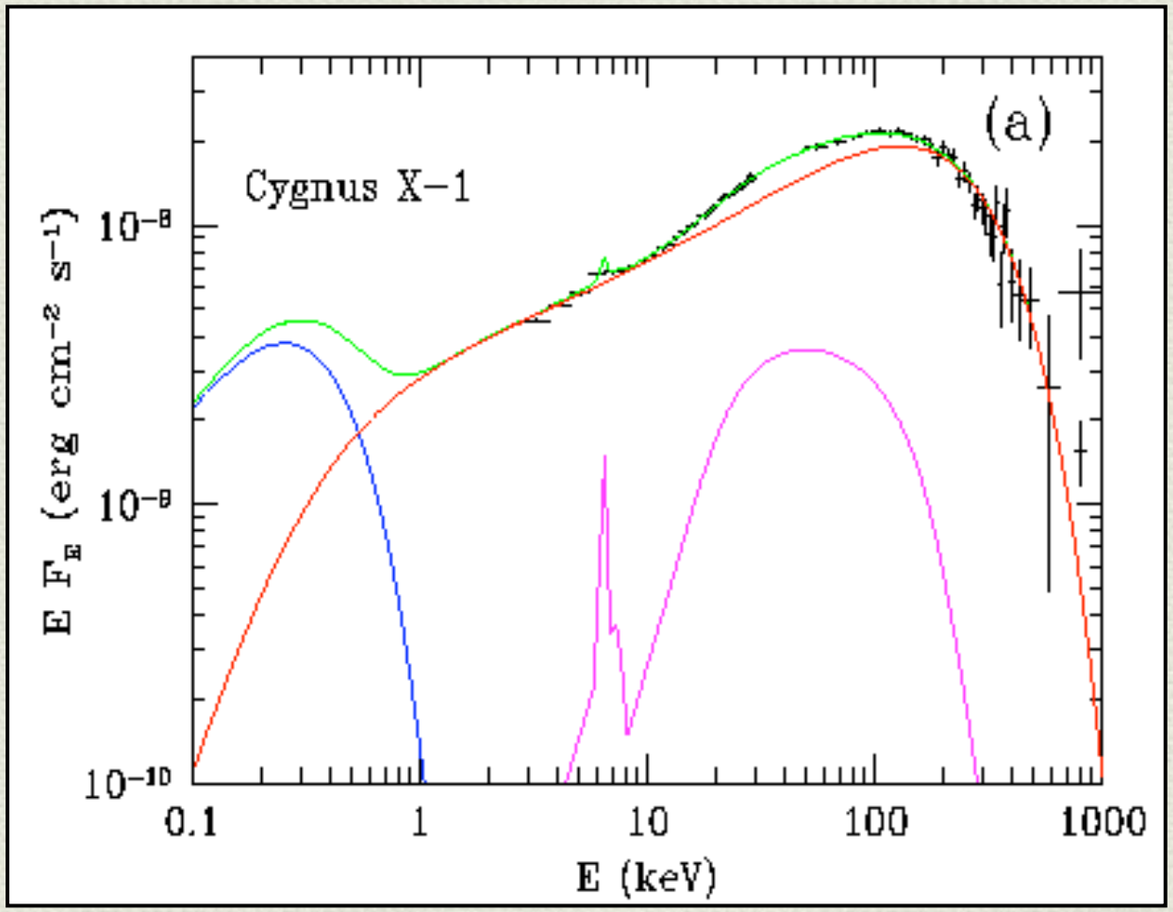




Need very broad baseline
and
very good model for the continuum

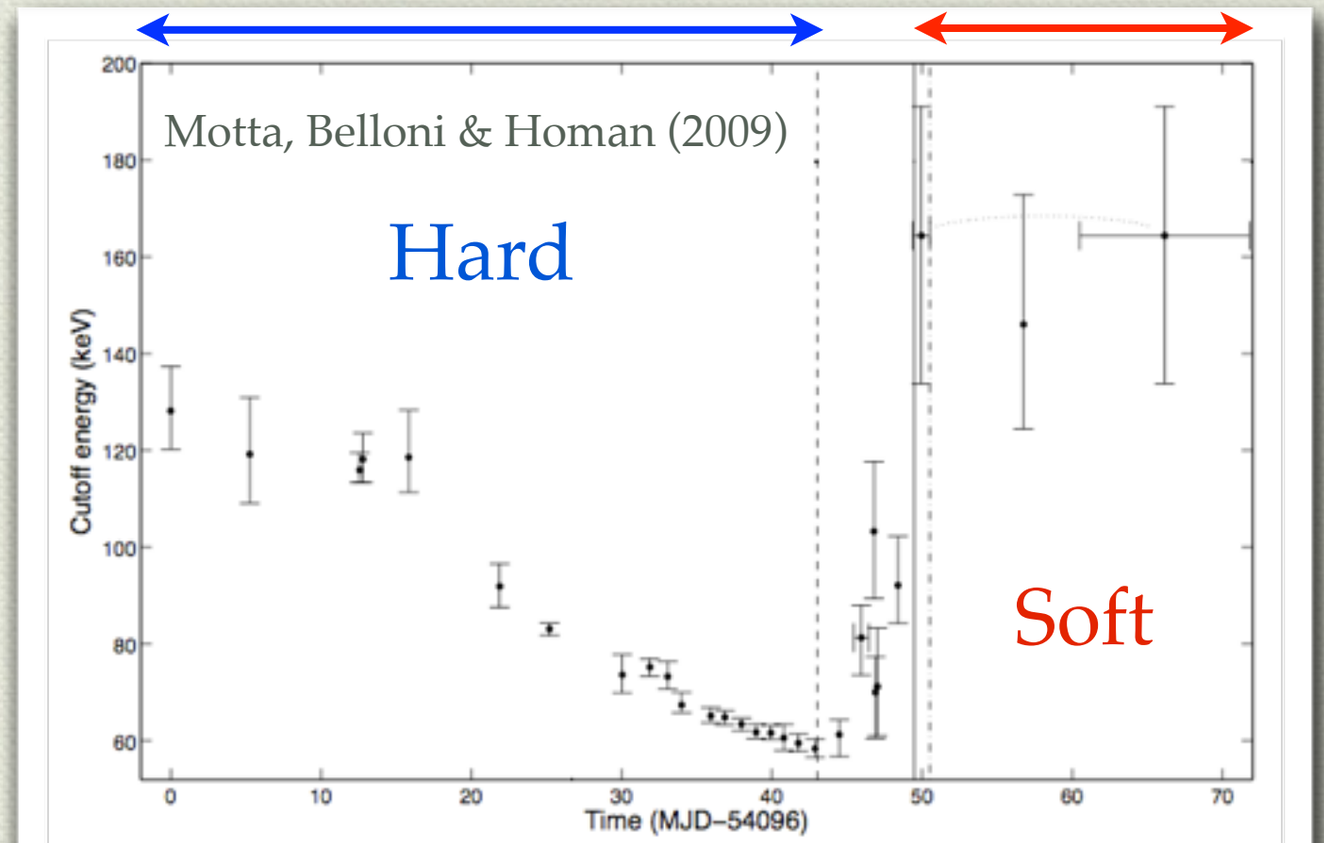
The full model

- Thermal disk
- Comptonization
- Additional hard
- Emission line
- Iron edge
- Reflection component
- Absorption (intrinsic?). Absorption lines (narrow)



Intermediate states

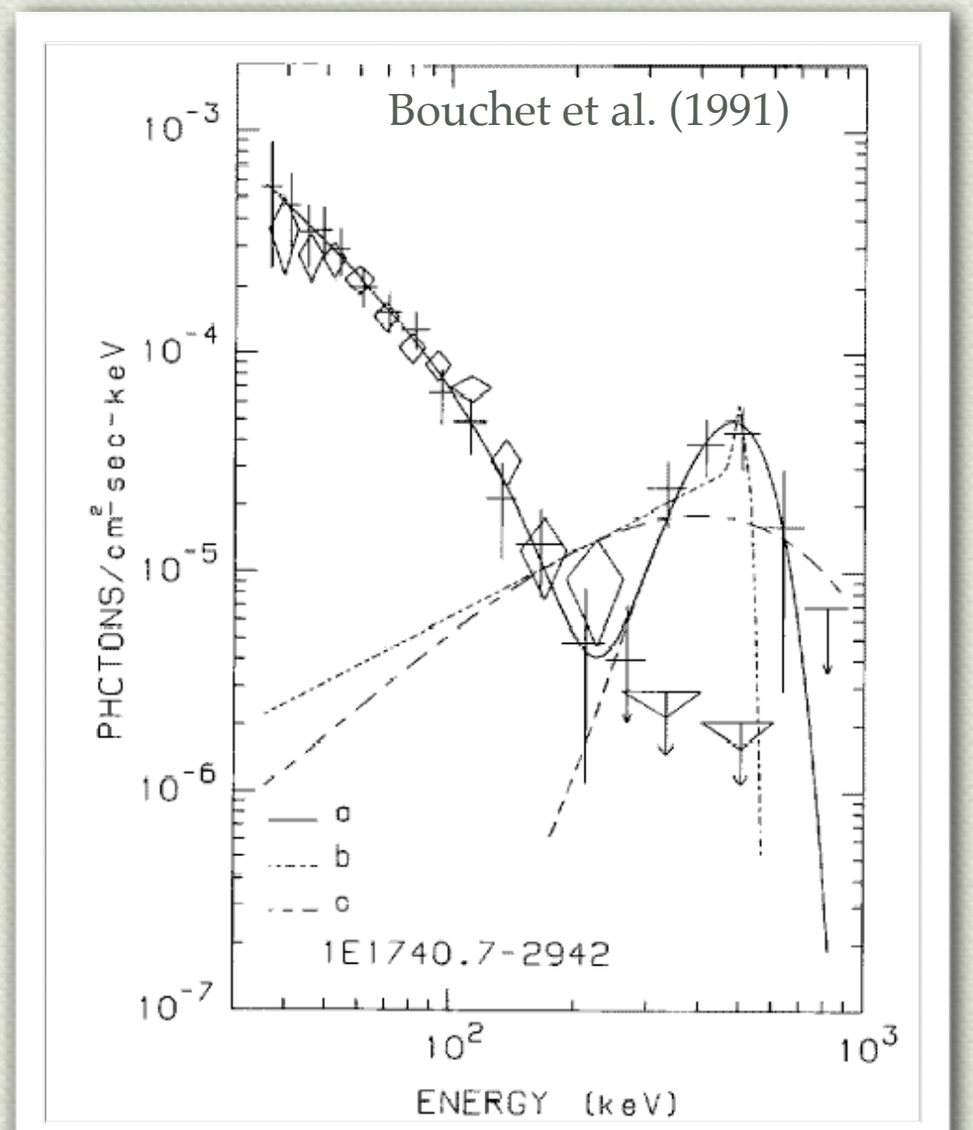
- Disk + hard component
- Both strong (hard 20-80%)
- Short-lived states
- Thermal or non-thermal?

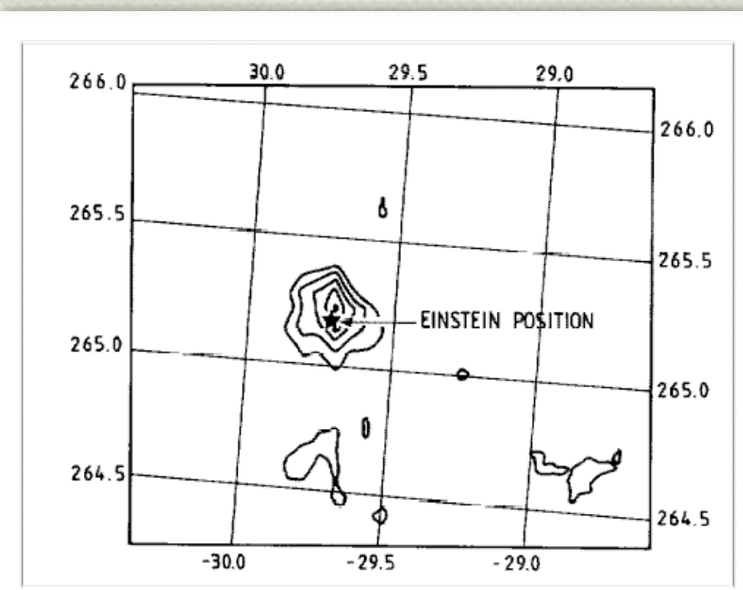


- Transition complex
- Softening ok, but hardening?

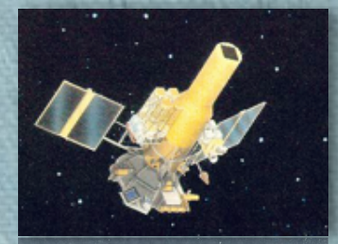
High-energy features

- 1E 1740.7-2942 with SIGMA
- 1990: rise 1d, duration 10d
- Broad line

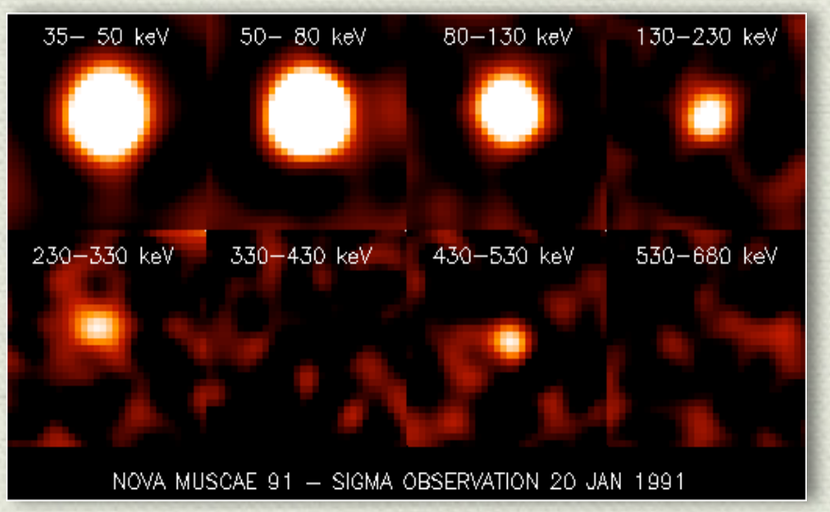


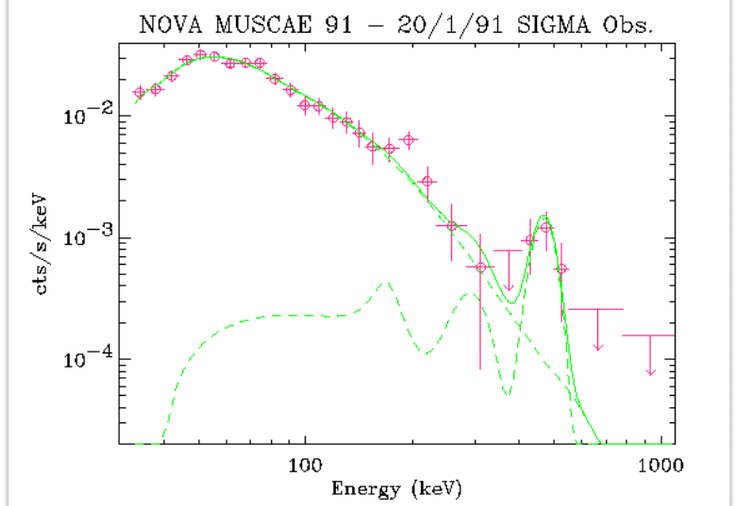


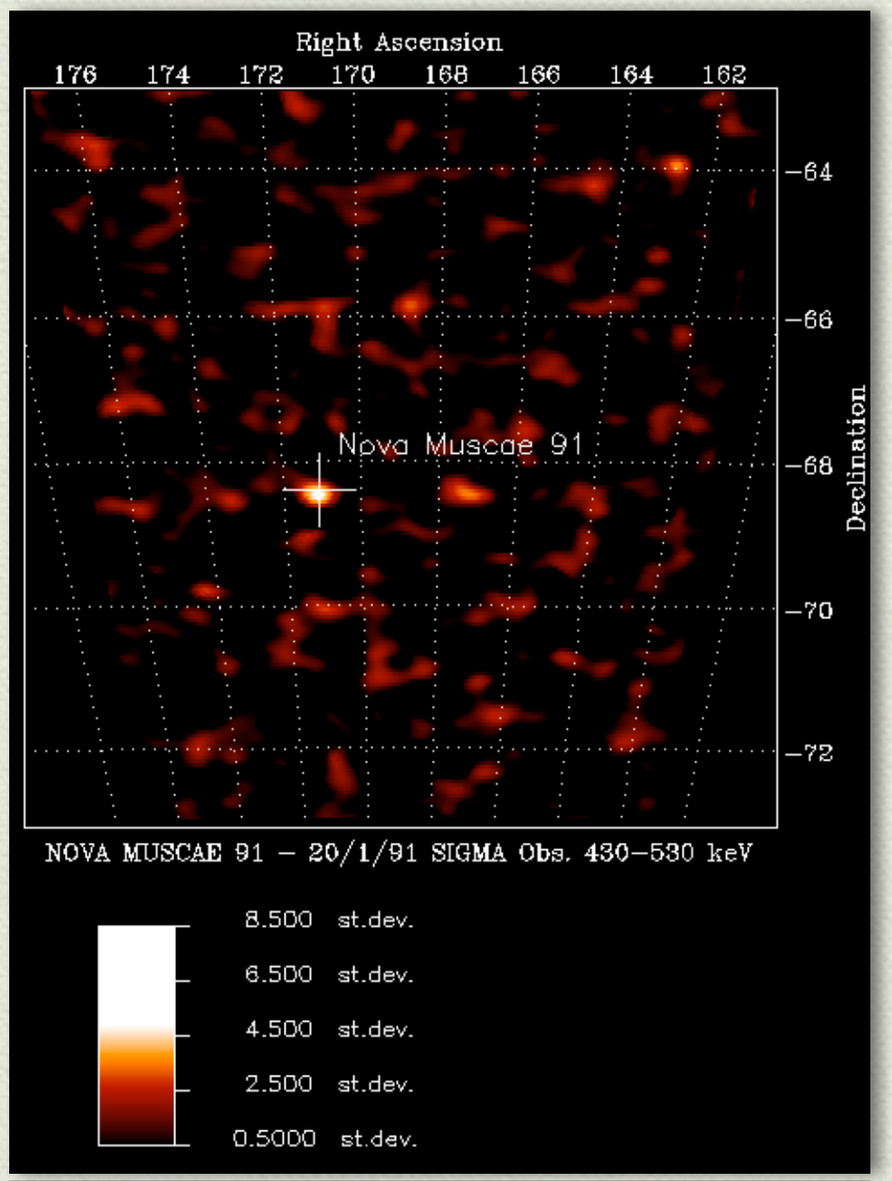
High-energy features



- GS 1124-68
- Transient source
- Transient line

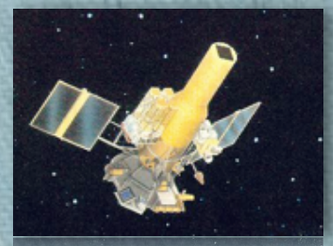




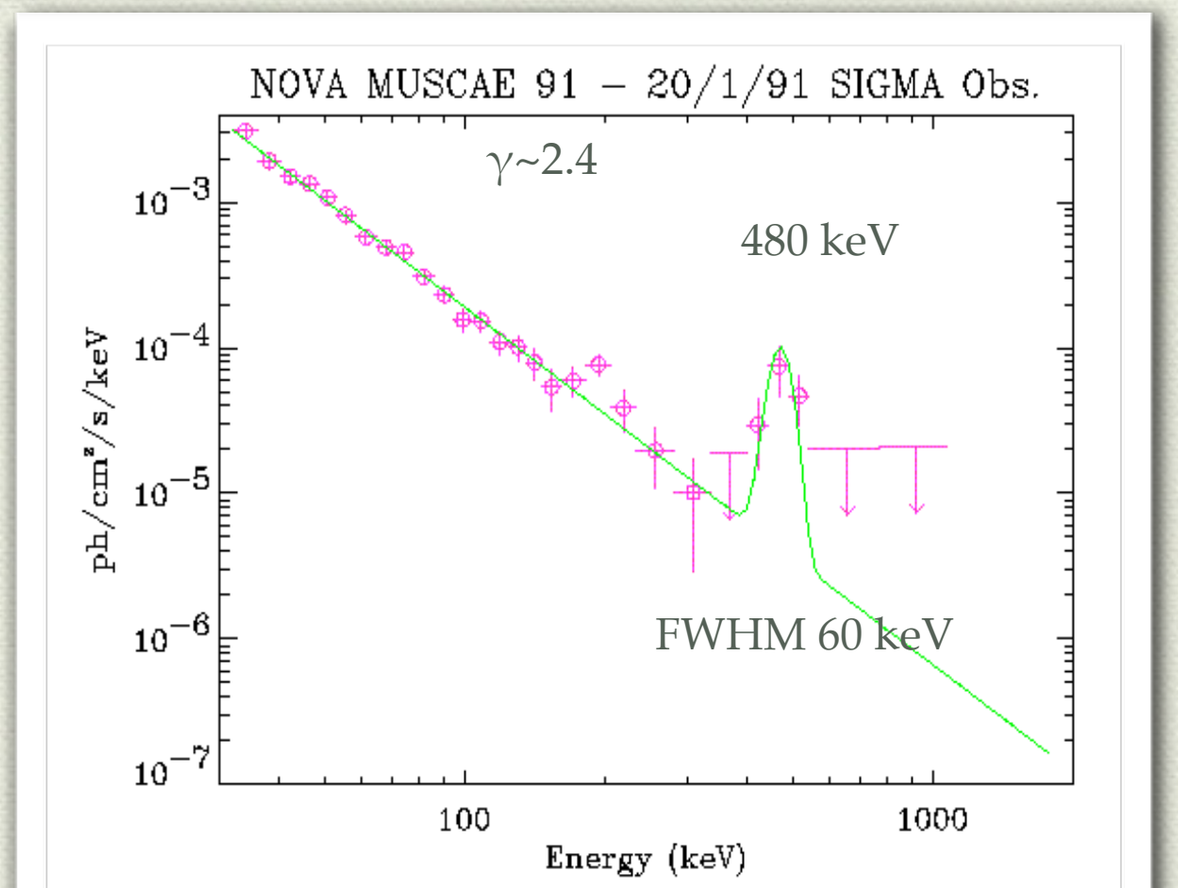


Goldwurm et al. (1992)

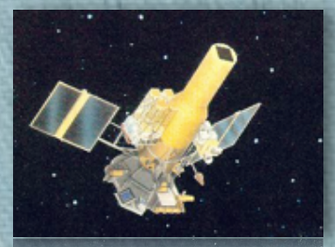
High-energy features



- Bright and narrow line
- If e^+-e^-:
- 7% redshift ⇨ 7Rg
- No Doppler broadening
- No Comptonization
- $L_{511} > 10^{35}$ erg/s ⇨ $N(e^+) > 10^{41}$ s^{-1}
- What can it be?



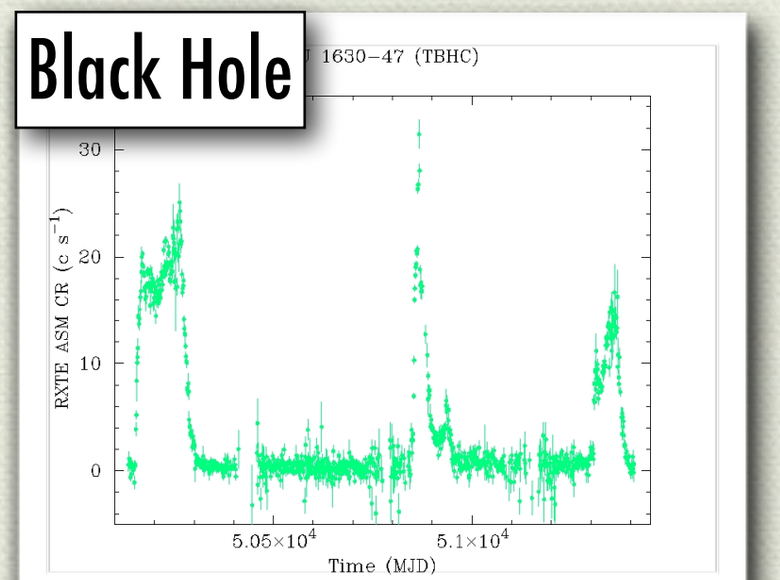
High-energy features

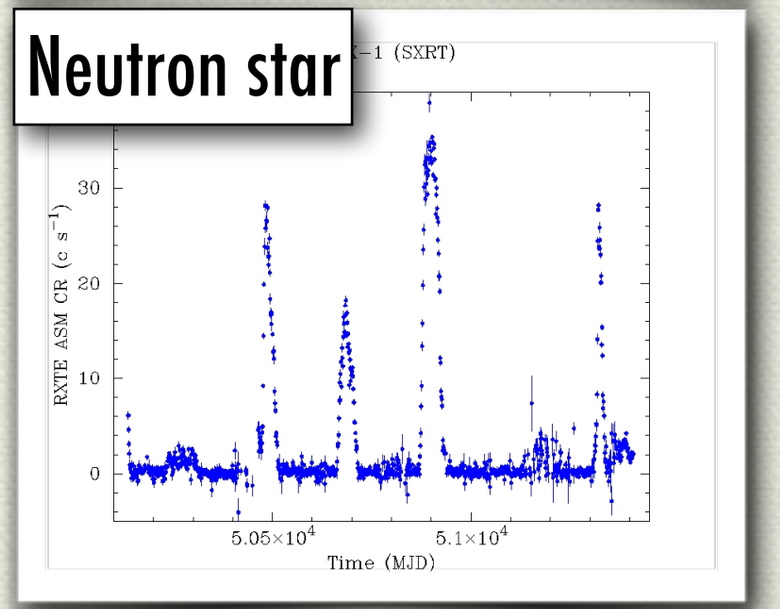


- Annihilation in cold disk with back-scattering
- ^{7}Li decay
- Pairs and annihilation in jets
- γ-γ scattering from jet-disk in the line of sight
- Seen only for 12 hours: why?
- The possible answer later this week

Quiescence

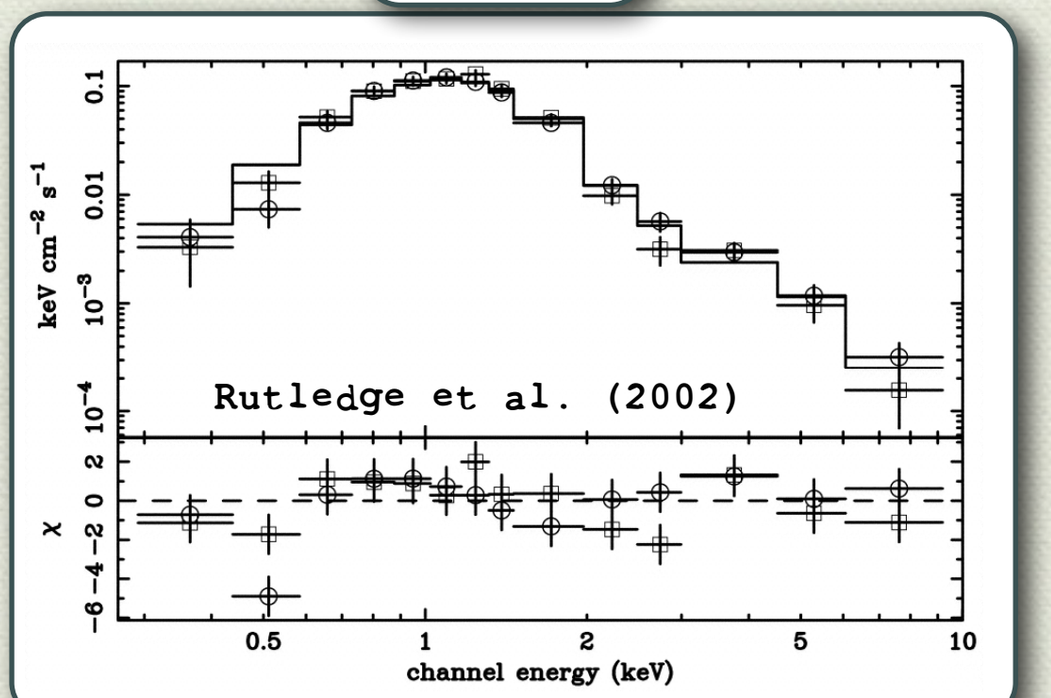
- As we have seen:
  - Outburst: $L_x \sim 10^{37\text{-}39}$ erg/s
  - Quiescence: $L_x \sim 10^{30\text{-}33}$ erg/s
- Important for accretion rate swing
- What do they look like in quiescence?
- Does the surface make a difference?
- A 0620-00: optical bright - X-ray dim



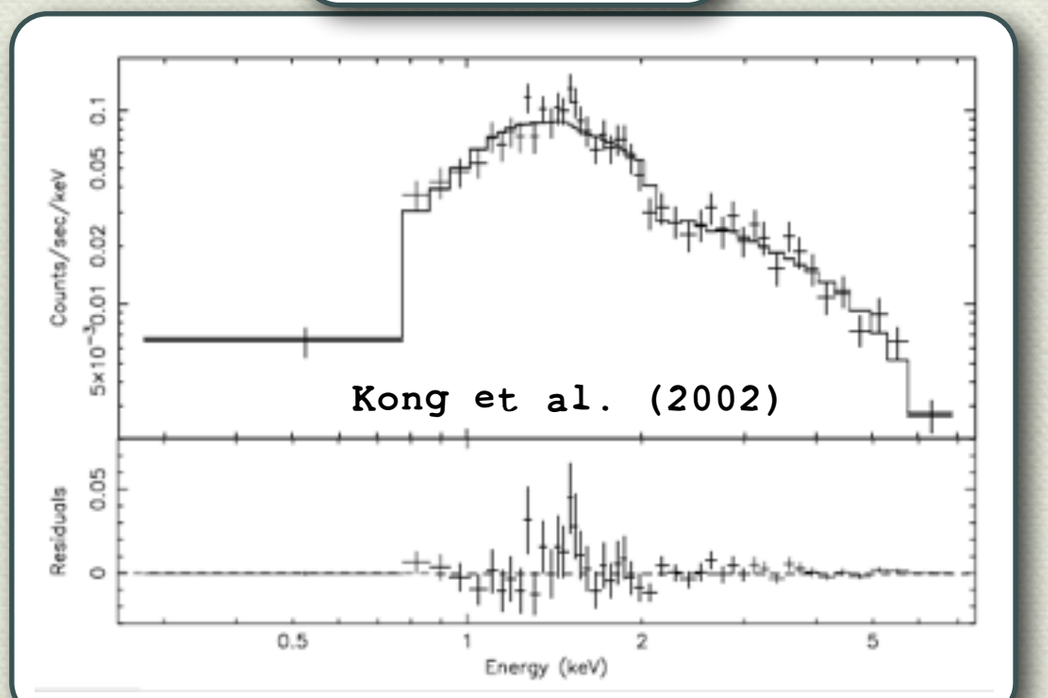


Quiescent spectra

NS: Aql X-1



BH: GS 2023+338

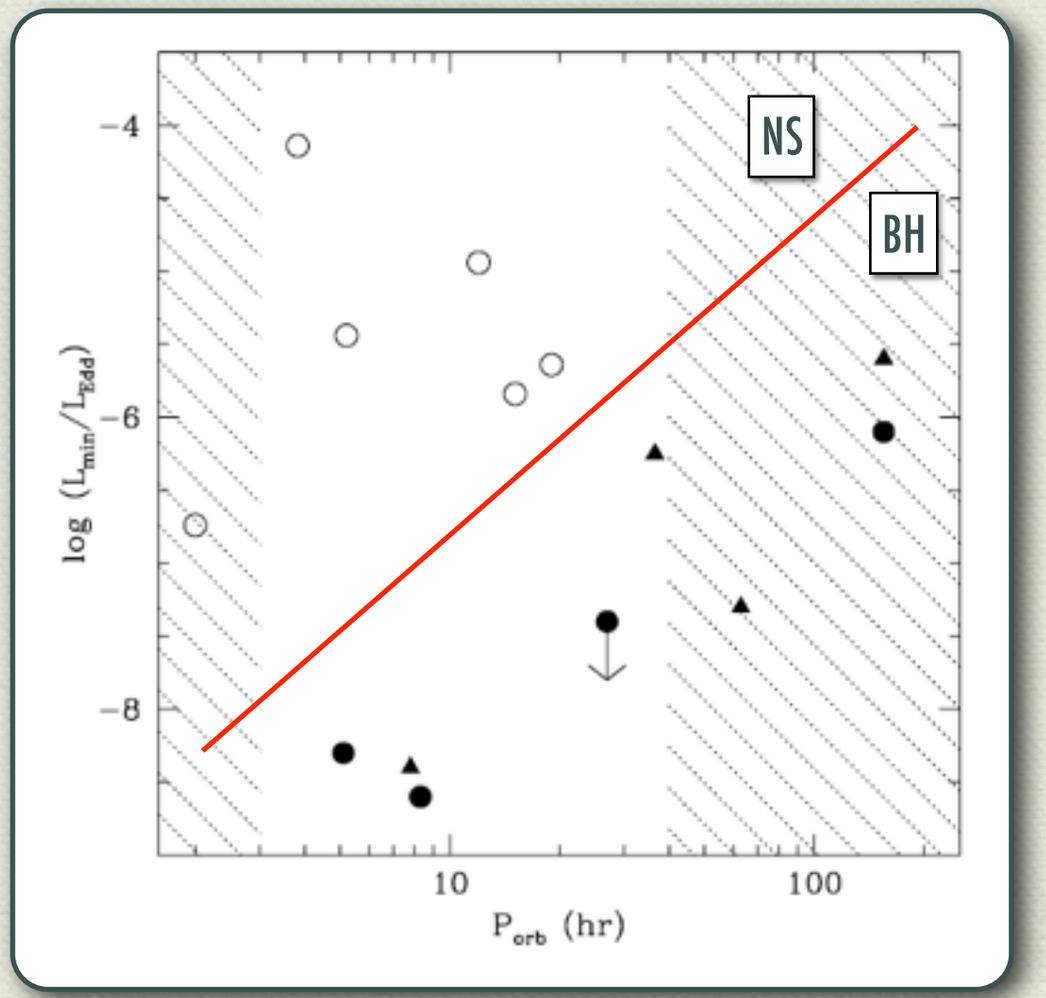


"Canonical" NS spectrum
BB/NS atm, kT=0.1-0.3 keV plus
Power law, index 1-2

Black-hole binary spectrum
Power law, index 1-2 or
Opt. thin plasma kT = 2-3 keV

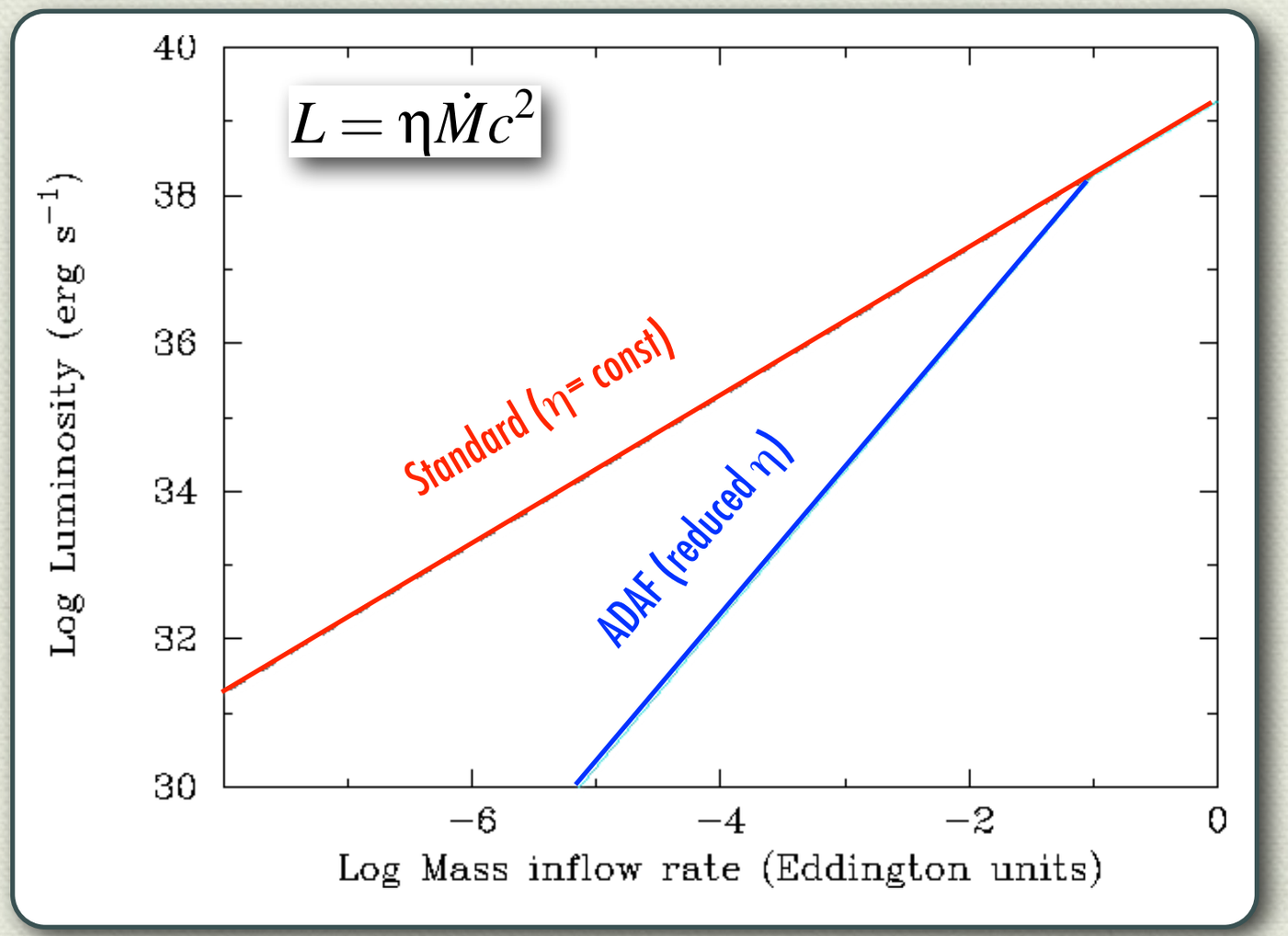
Quiescent luminosity

- Clear segregation in luminosity
- Larger min-max swing in BH
- Why?
- Different mass to energy conversion efficiency?
- Advective flows

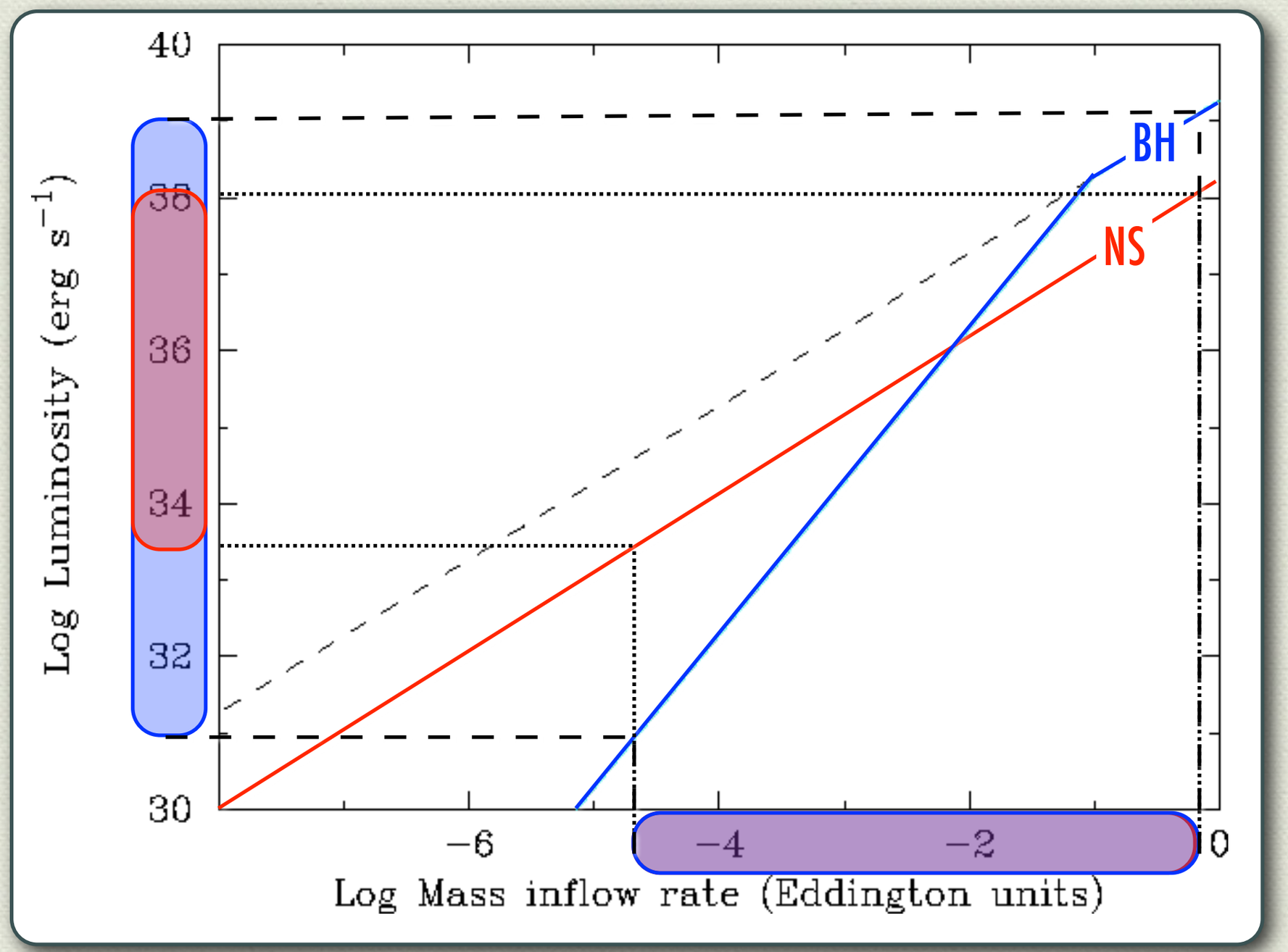


Advection flows

- For low rates, higher fraction of energy stored in accretion flow
- BH lose energy in the hole (reduced eff.)
- NS have a surface (standard eff.)

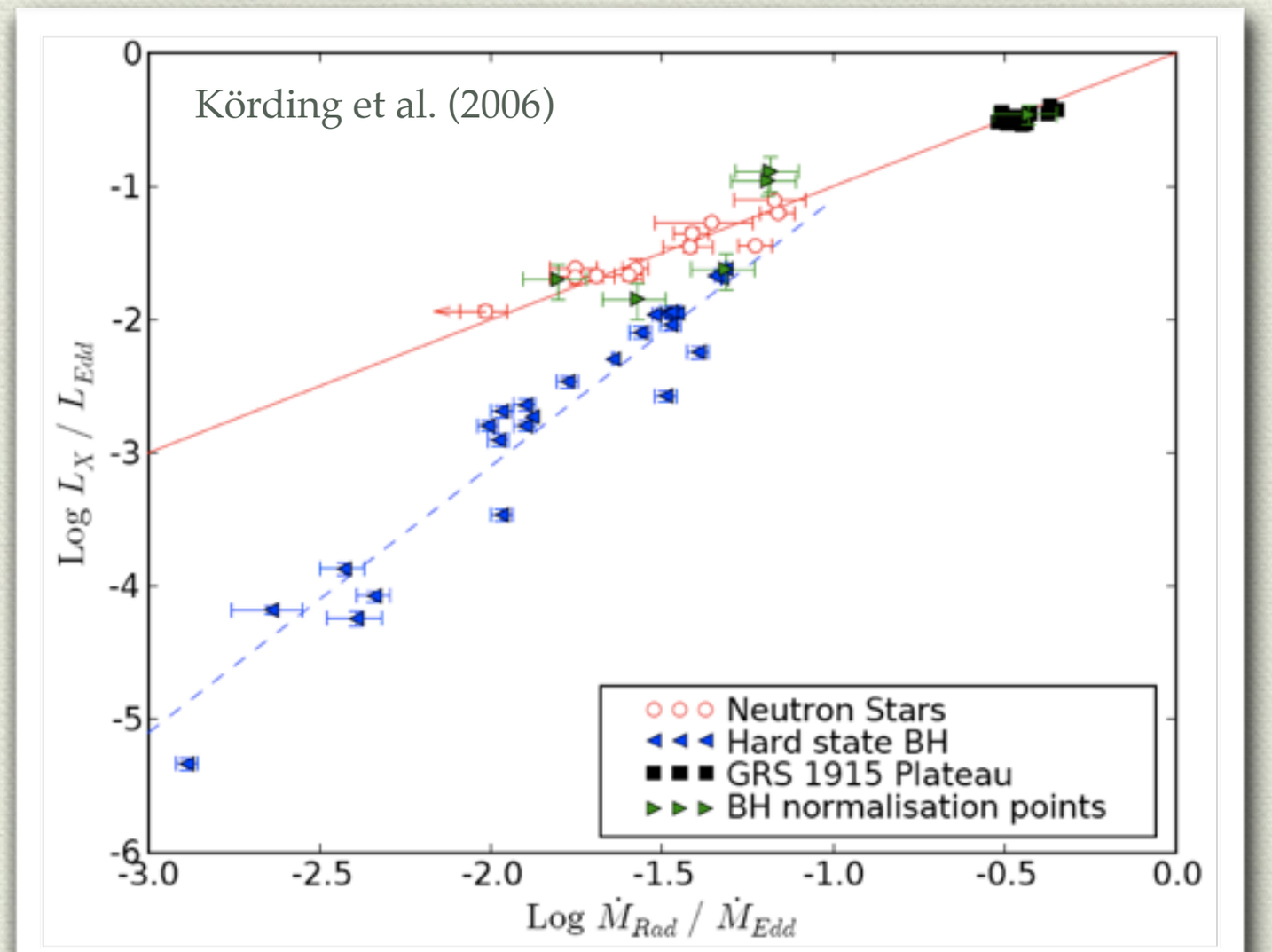


Advection flows



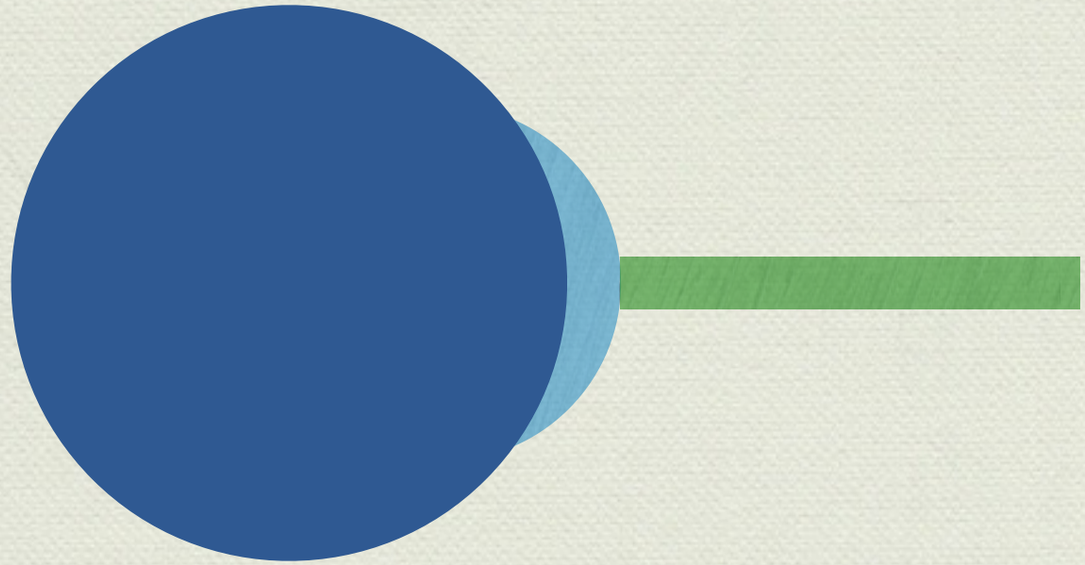
Measurements

- Accretion rate from radio measurements



NS LMXB Energy spectra

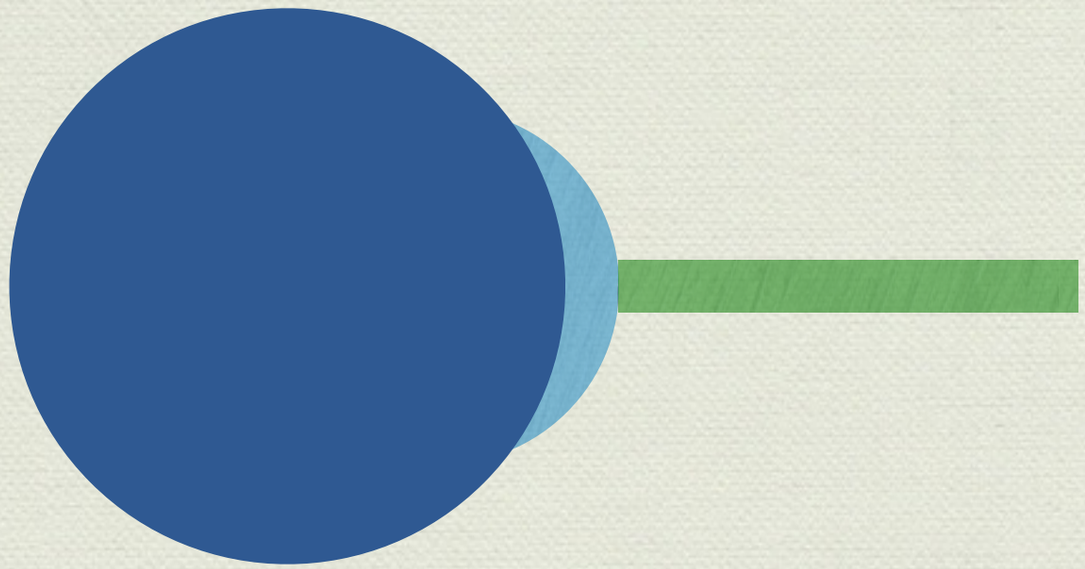
- NS have surfaces - boundary layer
- Spectrum must be different
- Contributions overlap
- Different states
- For soft state, two main models:
  - Eastern model
  - Western model



Eastern model

Mitsuda et al. (1989)

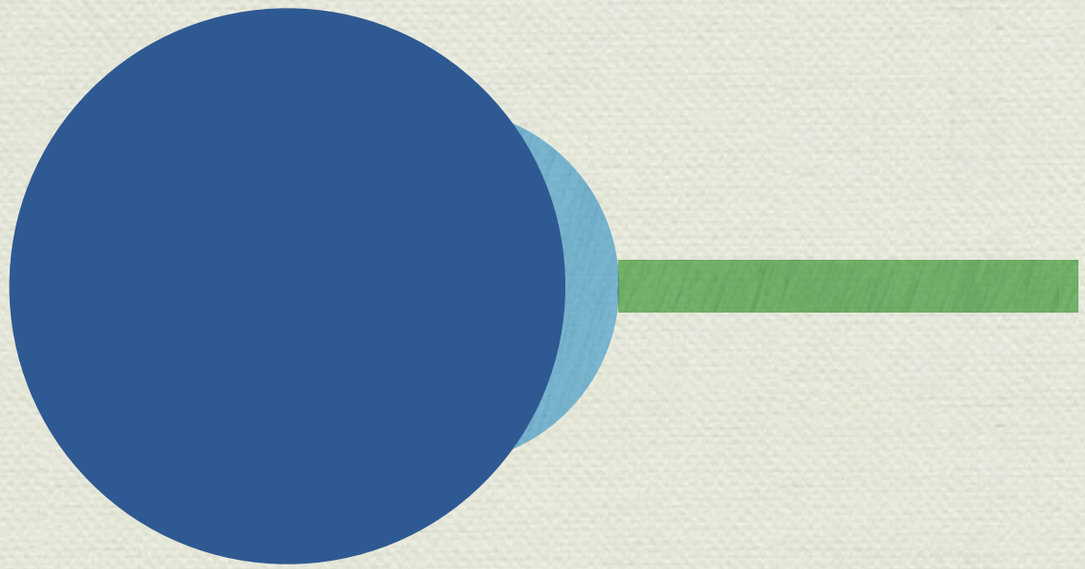
- Thermal component: DBB from disk
- Compton component: BL photons on inner disk



Western model

White et al. (1988)

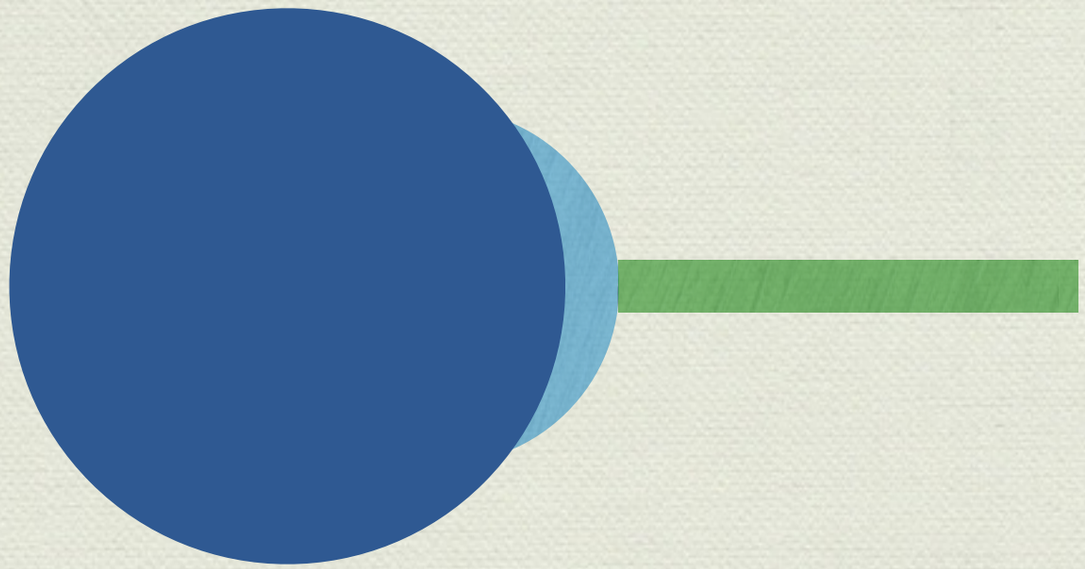
- Thermal component: BB from BL
- Compton component: unsaturated Comptonized disk



BL luminosity in both models is lower than disk luminosity

Hard state

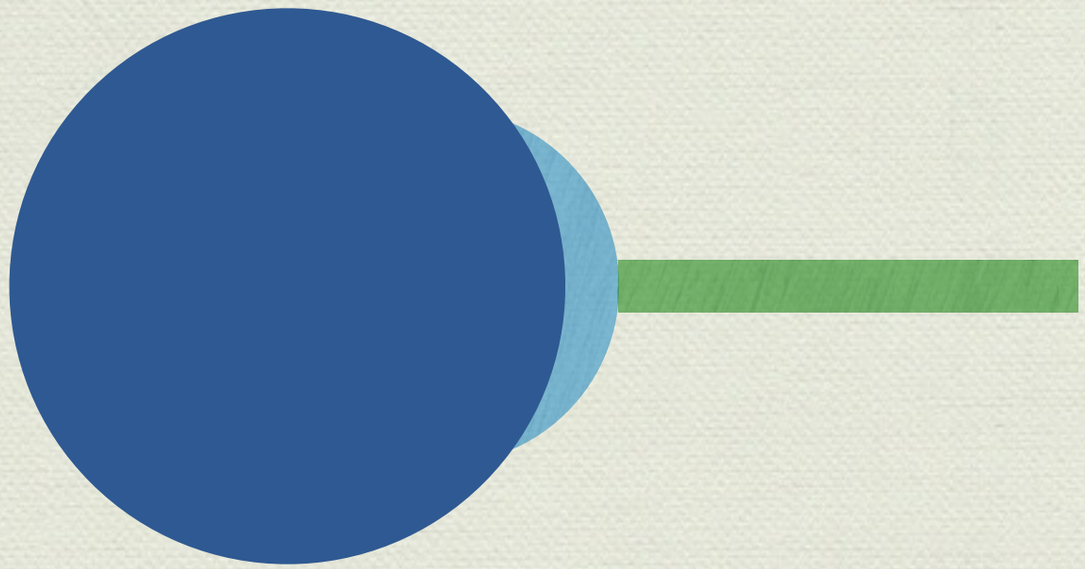
- Spectrum more similar to BH hard states
- Comptonized component ~few tens keV
- Soft component, BB?



New model

Lin et al. (2007)

- Hard state: BB plus broken power law
- Soft state: DBB (disk), BB (BL) + broken power law



As we will see, the problem is complex and variable

Additional complications

- Hard tails discovered in soft states
- Dominate above 30 keV
- 10% flux, power law flat or steep

Not even clear for BHs