Studying compact objects with spectral decomposition methods

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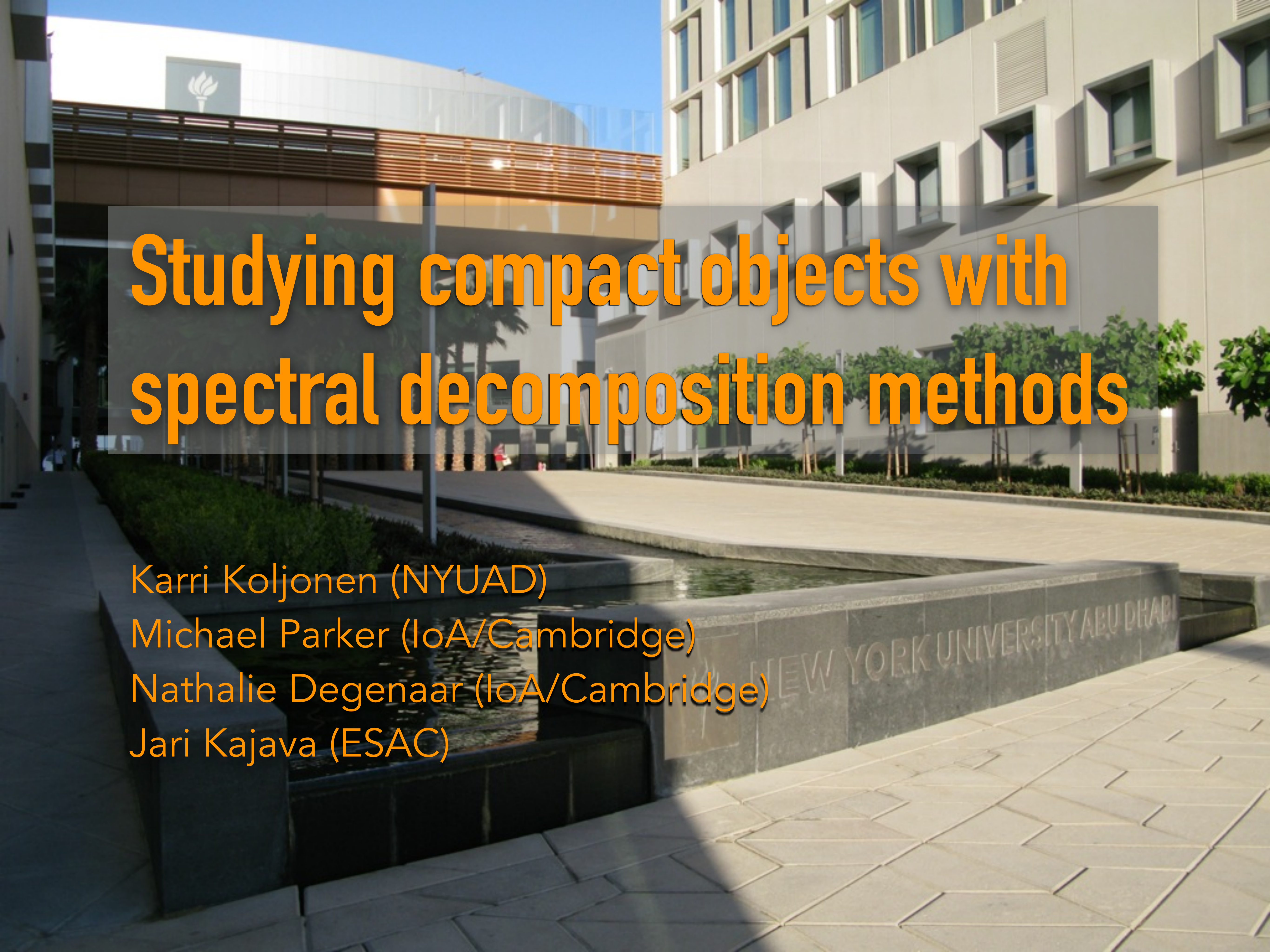

Spectral degeneracy is a problem for us all

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- some examples from X-ray astronomy -

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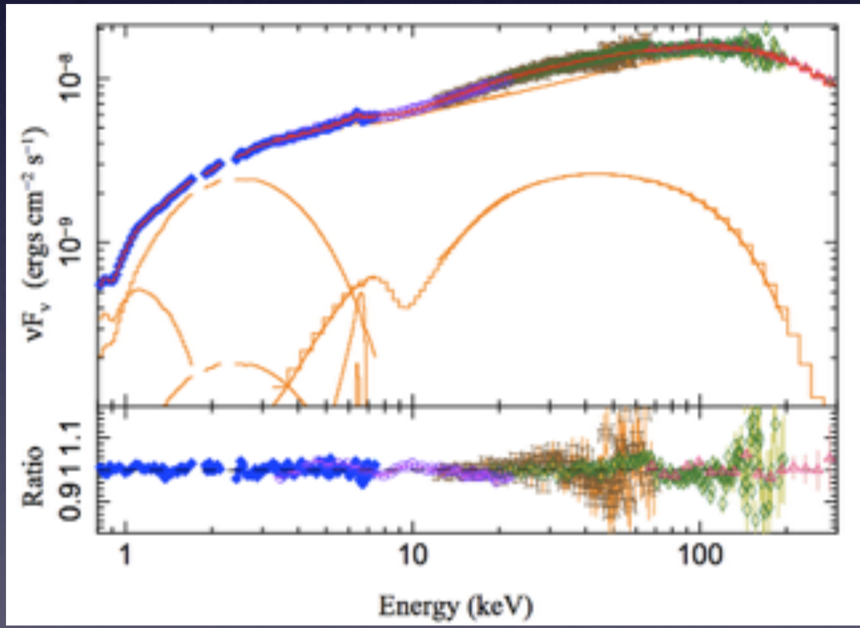
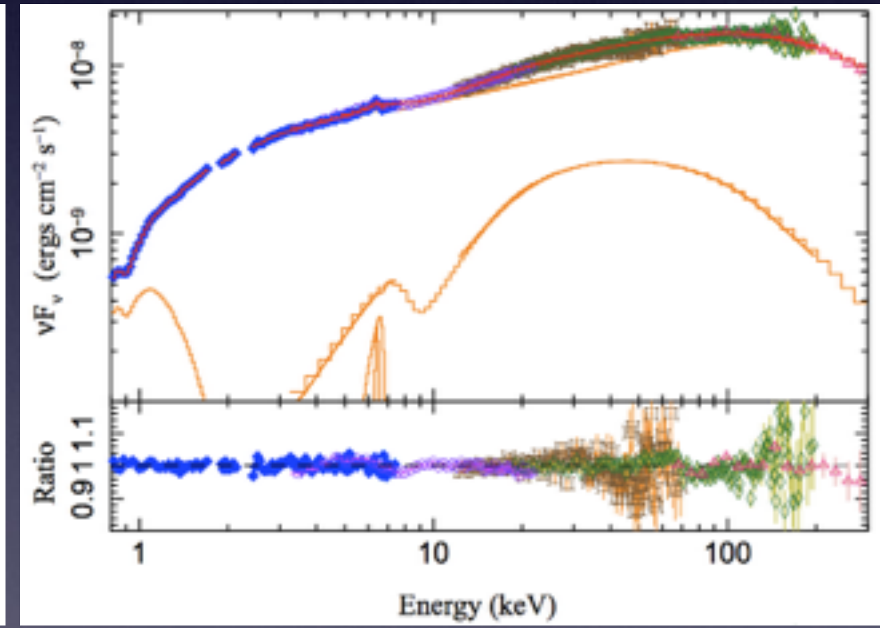
- some examples from X-ray astronomy -

Cyg X-1: Identical data, different fits, similar statistics

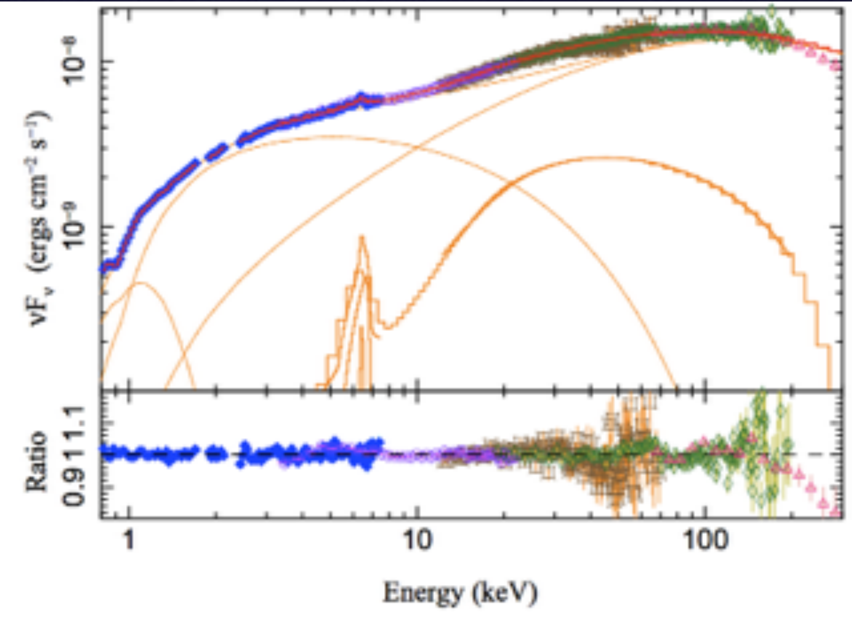
Nowak+ 11



thermal Comptonization with a high seed photon temperature



non-thermal Comptonization with a low seed photon temperature



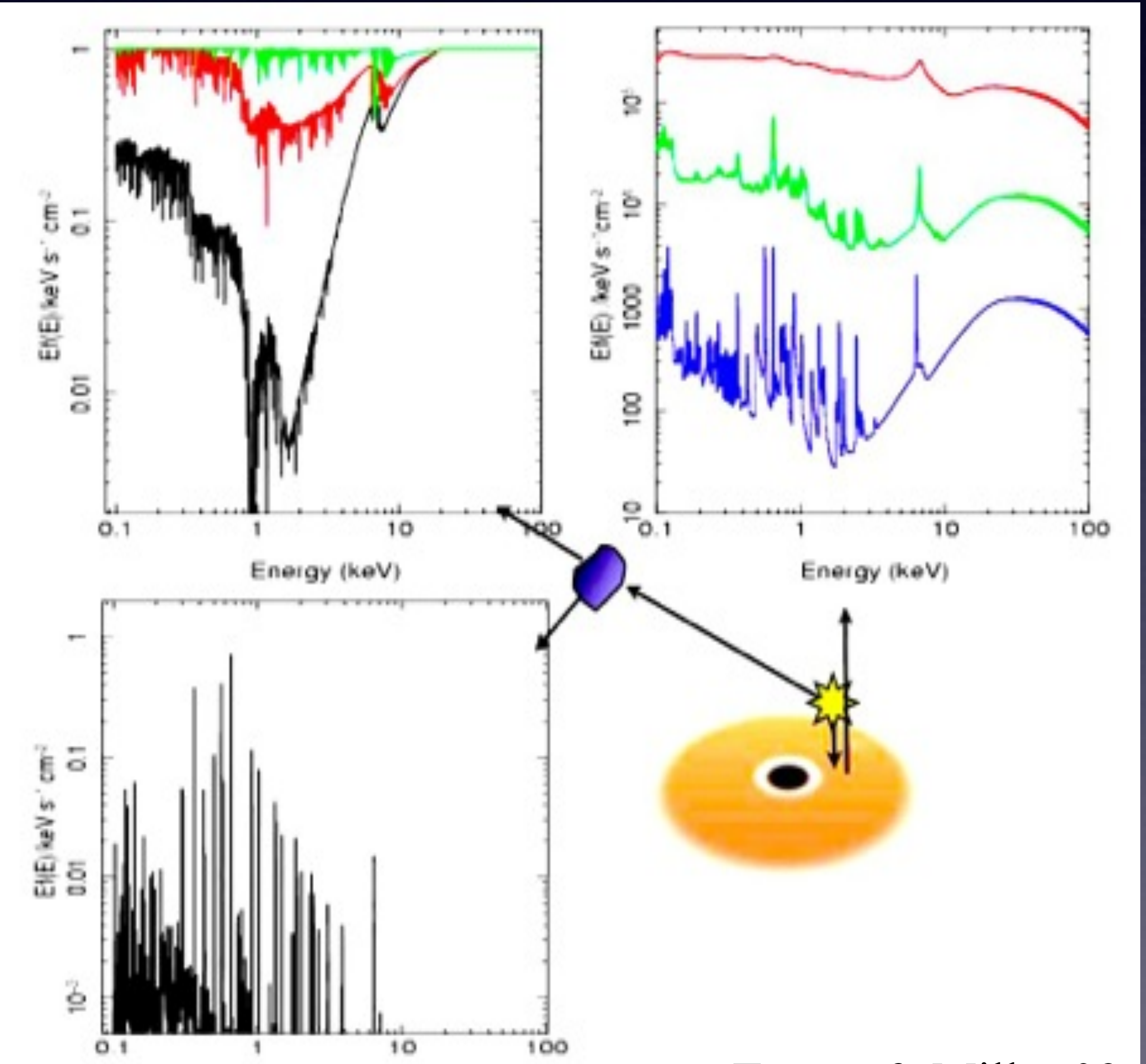
jet model dominated by synchrotron and SSC emission

Spectral degeneracy is a problem for us all

- some examples from X-ray astronomy -

The X-ray spectra of AGN: similar spectra can be achieved with partial covering or reflection. E.g. the case of Mrk 766. Another example Mrk 335 (Gallo et al. 2015).

Partial covering absorption **or** Reflection



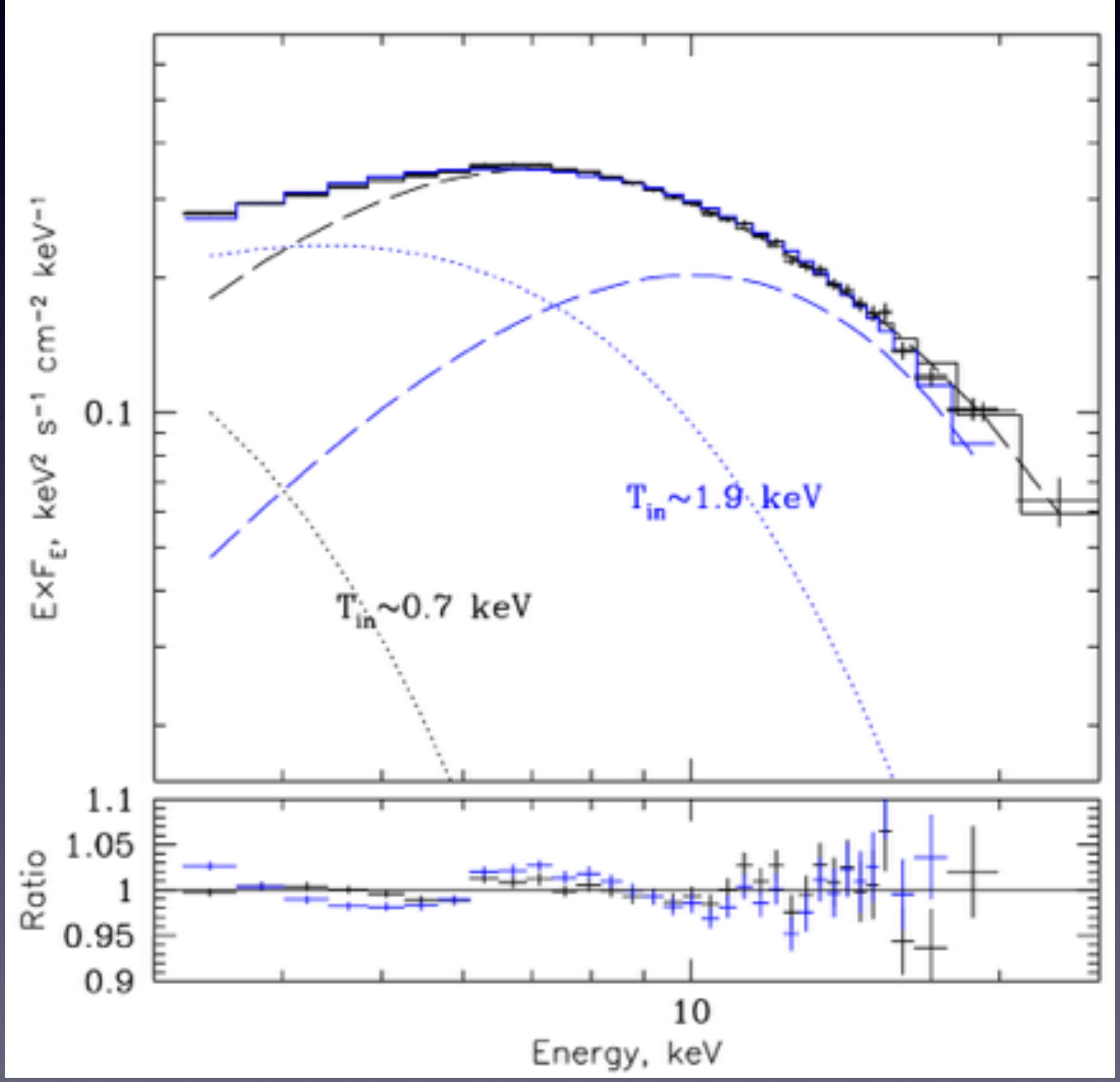
Turner & Miller 09

Spectral degeneracy is a problem for us all

- some examples from X-ray astronomy -

Luminous, low-B, accreting NS: emission from boundary layer and/or NS surface, and accretion disk. But in what proportion?

The spectra are smooth, and cannot be easily decomposed into these anticipated components.



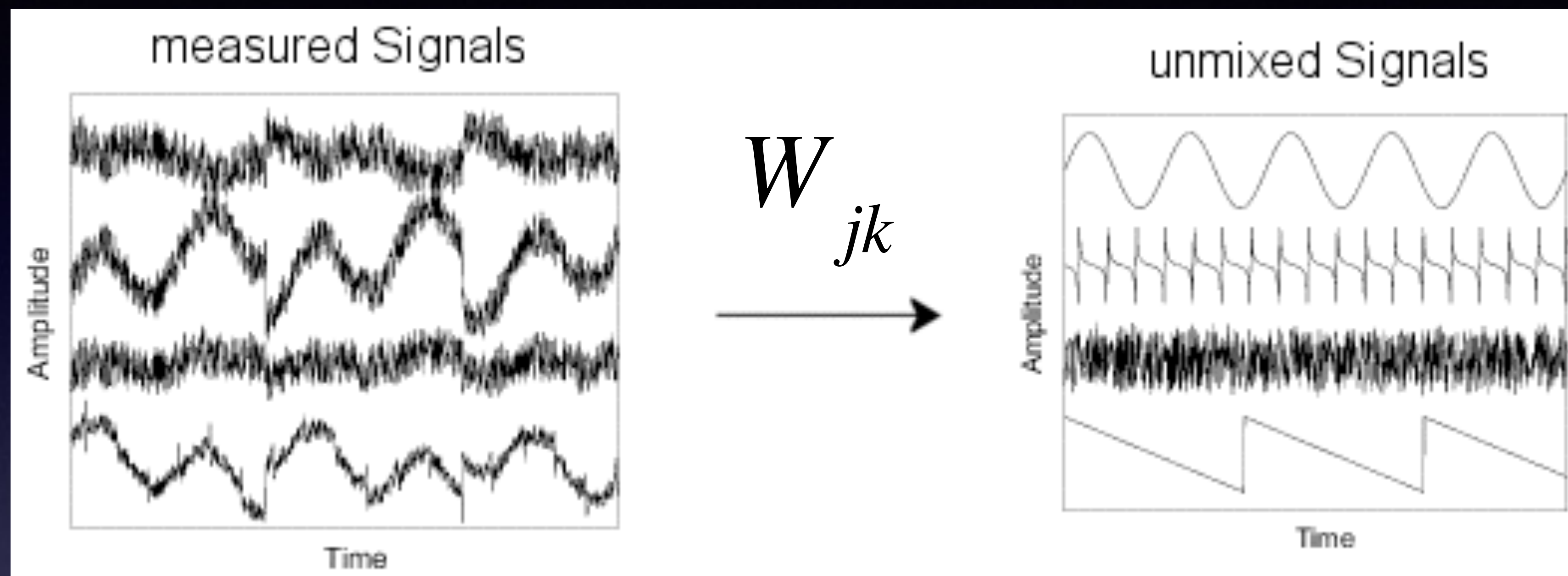
Revnivtsev, Suleimanov & Poutanen 13

Spectral degeneracy is a problem for us all

- Despite the statistical quality and the energy resolution of the data, a variety of spectral models can be fitted to the data with comparable quality
- This makes the approach based only on a χ^2 fitting technique not persuasive
- Clearly there is a need for distinguishing the spectral components that form the total spectra

Blind source separation

$x_1(t)$
$x_2(t)$
$x_3(t)$
$x_4(t)$
.
.
.



$s_1(t)$
$s_2(t)$
$s_3(t)$
$s_4(t)$
.
.
.

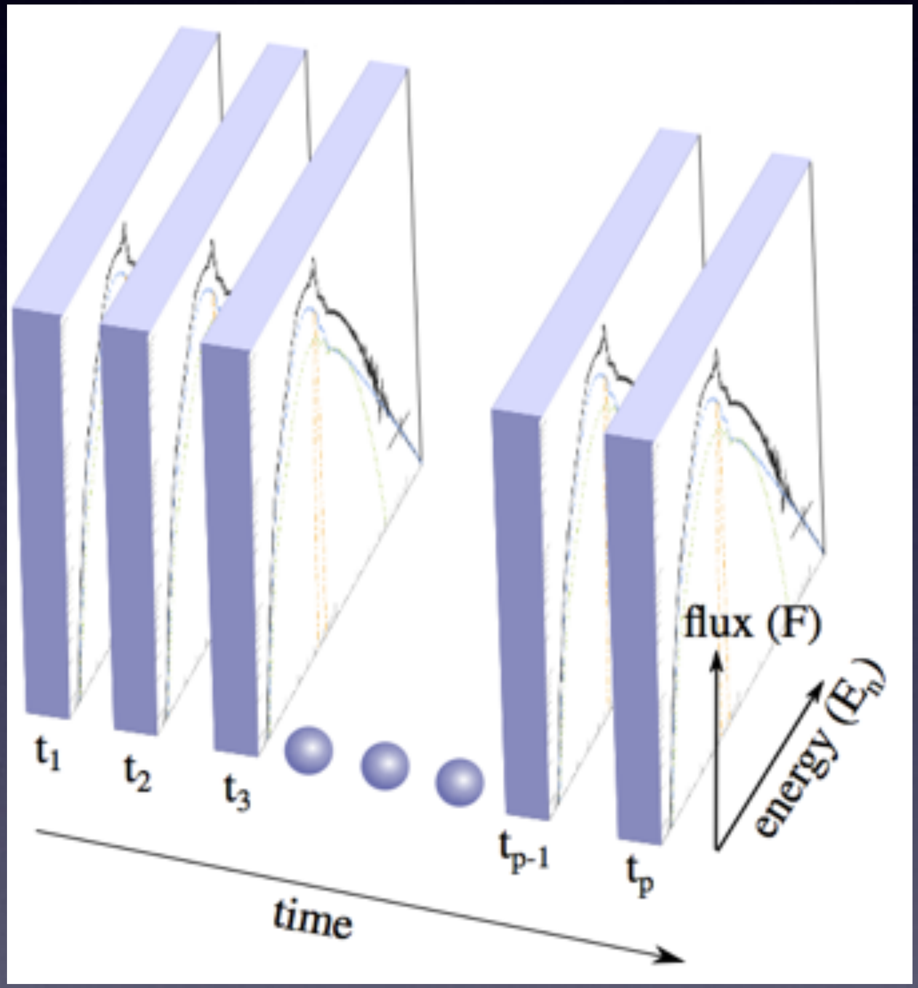
$$X_{ji} \approx \sum_k W_{jk} S_{ki}$$

k = the degree of factorisation

Classical cocktail party scenario: different microphones record the same mixture of sounds from a handful of sources, but receive them slightly differently depending on their spatial location in the room.

Decomposing spectral data

- Now the mixed signals X_{ji} are lightcurves measured over each energy E_j running over all the observations t_i.
- The "cocktail party microphones" are instead the energy bands that record the same mixture of photons from a handful of emission processes but receive them slightly differently depending on the energy of the band in question.



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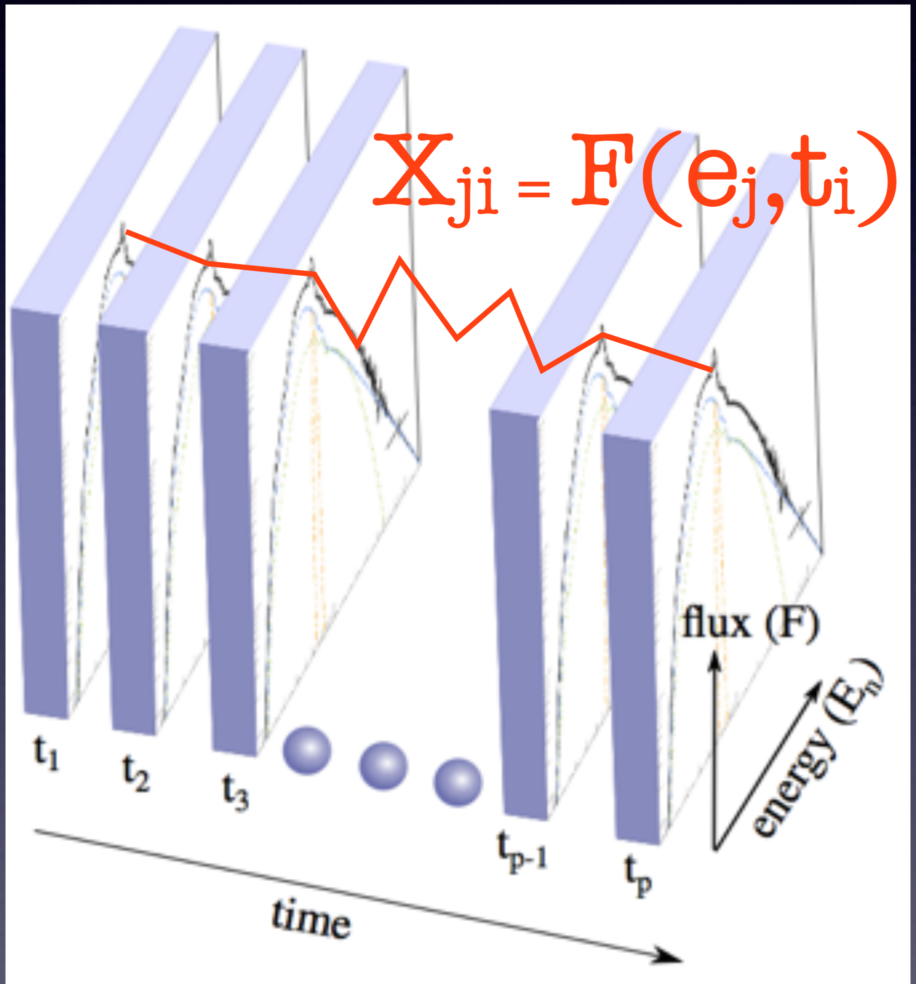

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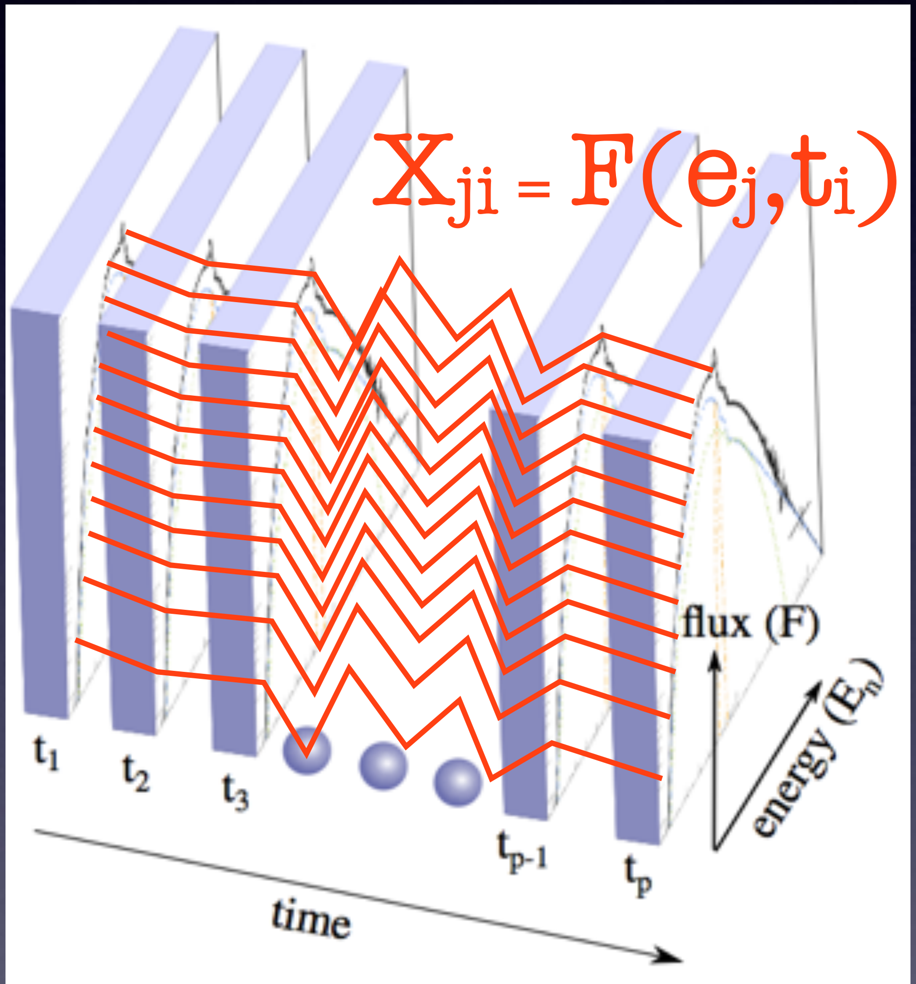

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Mr. Blackbody

Ms. Powerlaw

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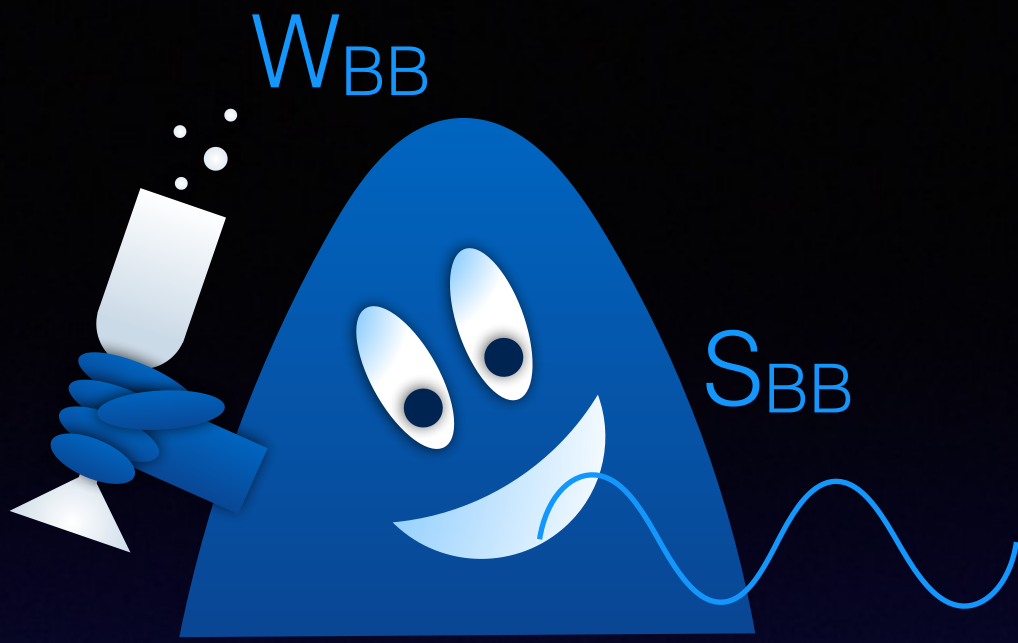

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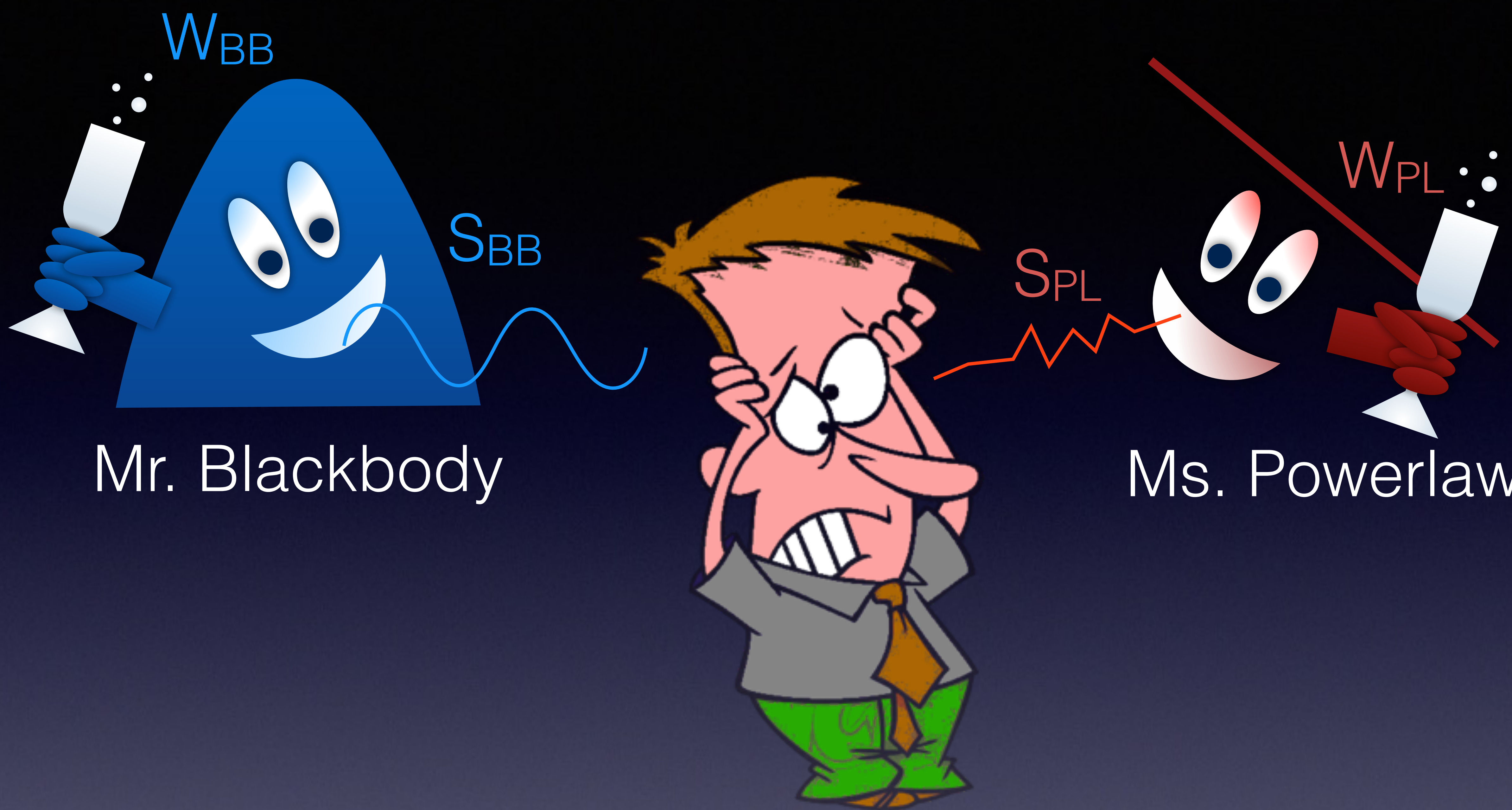
W BB
S BB
Mr. Blackbody
W PL
S PL
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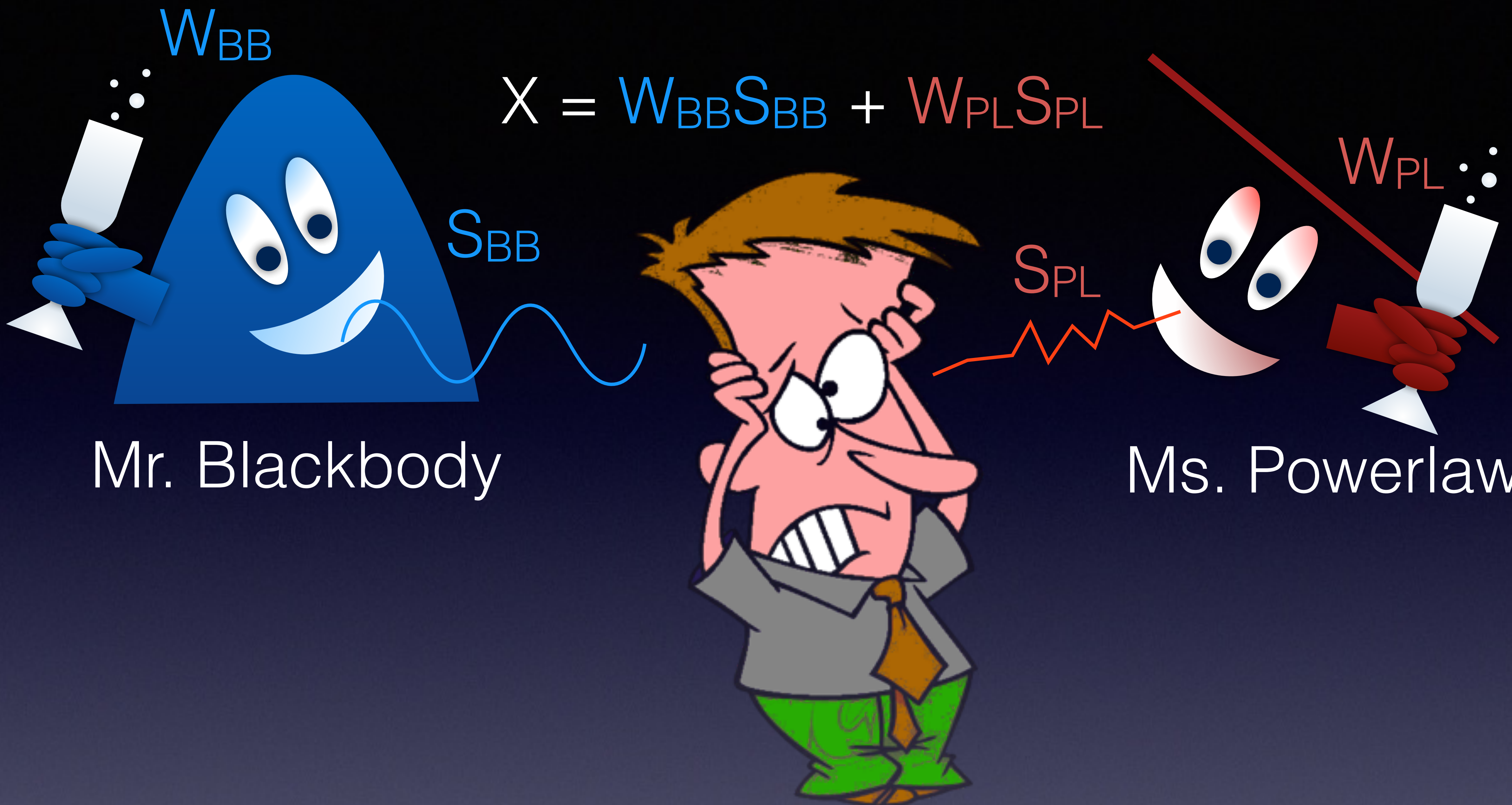
W_{BB}
$X = W_{BB}S_{BB} + W_{PL}S_{PL}$
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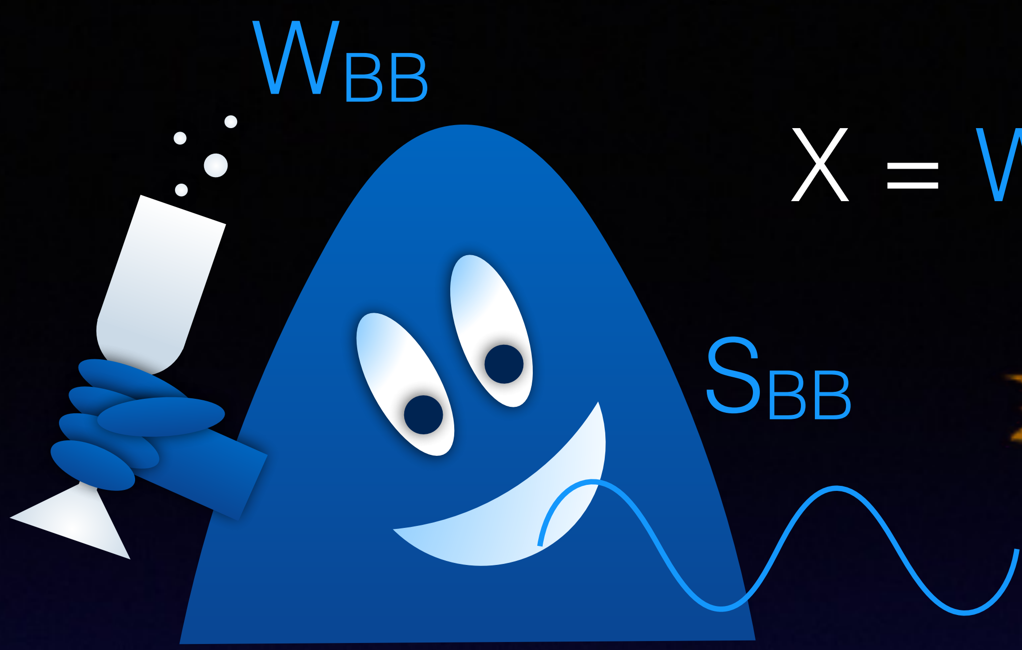

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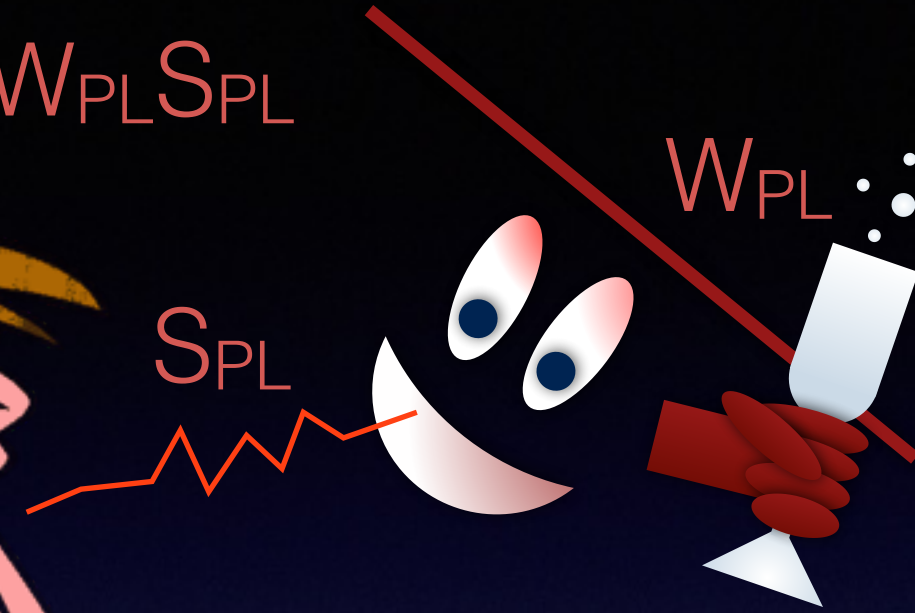

Ms. Powerlaw

Prescription: linear decomposition methods

PCA = principal component analysis

ICA = independent component analysis

NMF = non-negative matrix factorization

(details e.g. Koljonen 2015)

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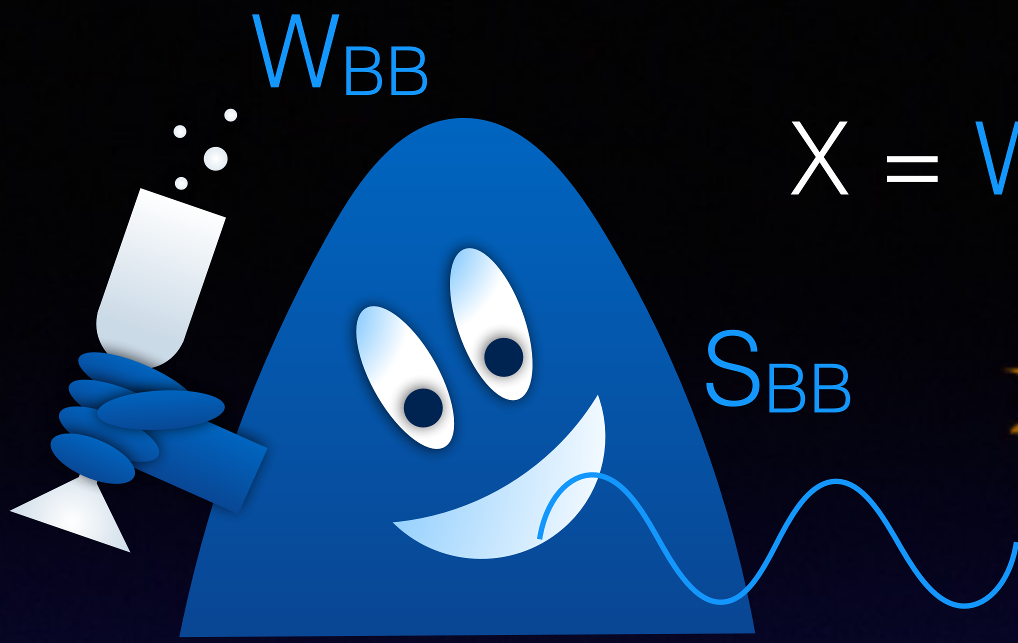

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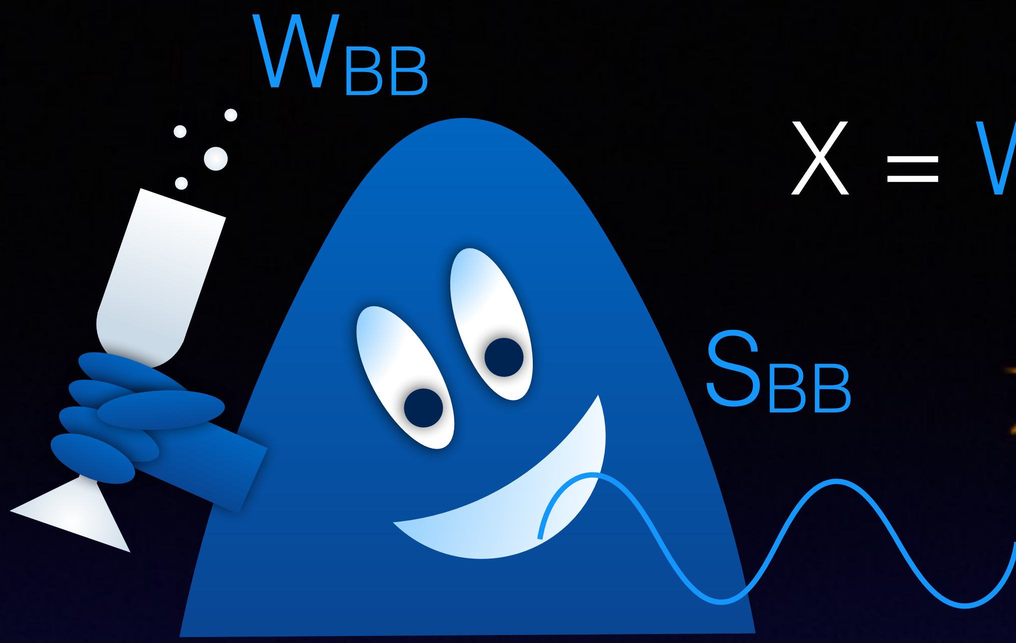

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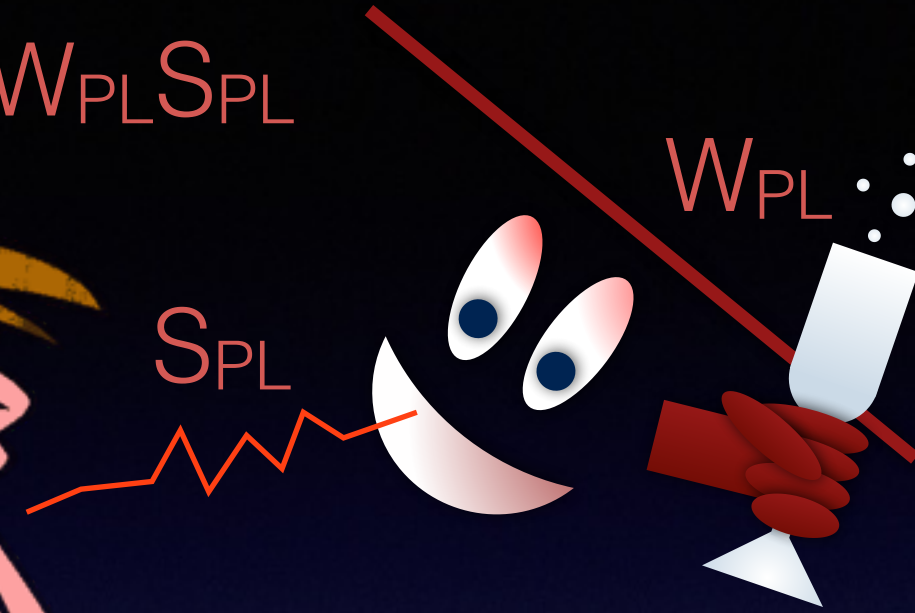

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But, what if $W_{XX}(t)$?

Non-linear effects in e.g. changing the blackbody temperature or slope of the power law

Two approaches to get around non-linearity

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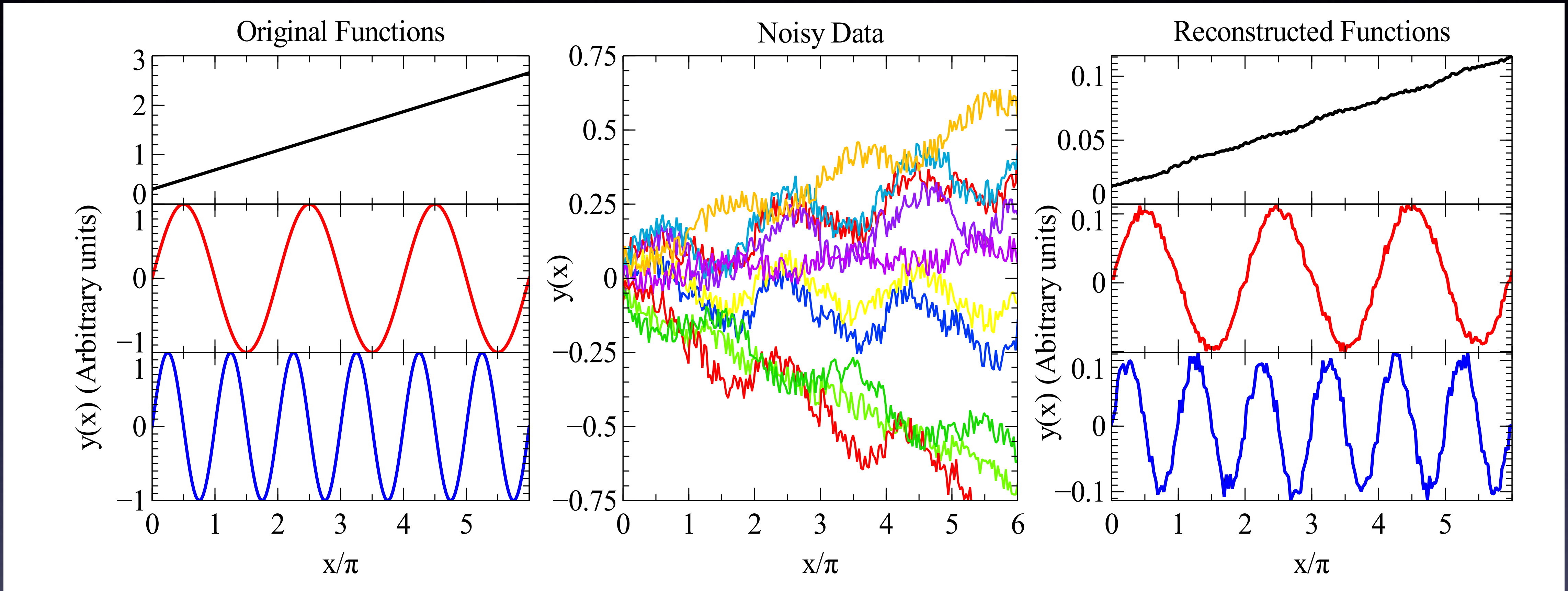
(3) Use non-linear decomposition methods, e.g. Self-Organizing Map, Neural Networks. But this gets very fast very complicated.

(1) Spectral variability library (Parker+ 2015)

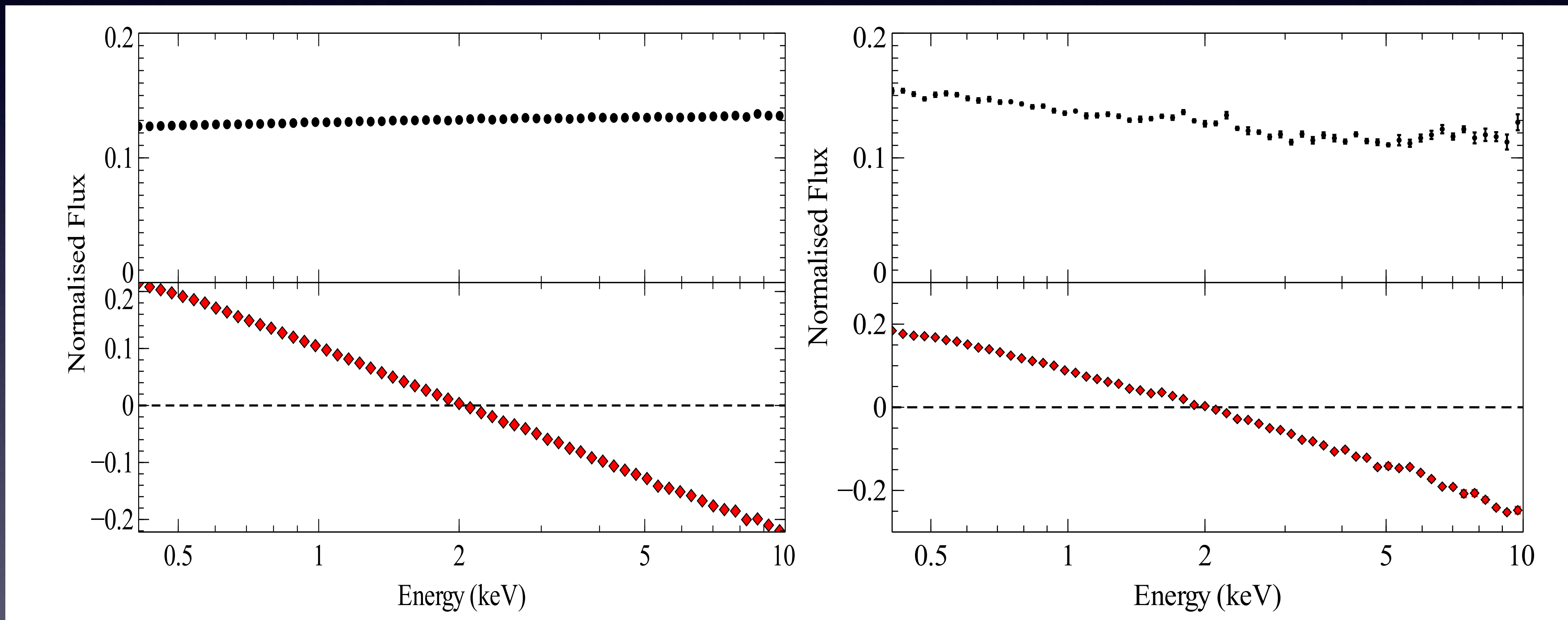


PCA isolates and returns different components of the signal, removing some of the noise. The weights have positive and negative values resulting in pivoting behavior of the spectra. Good for detecting variable power law slope. However, the individual components might not be very intuitive.

(1) Spectral variability library (Parker+ 2015)

Simulated components from power law varying in normalization and photon index.

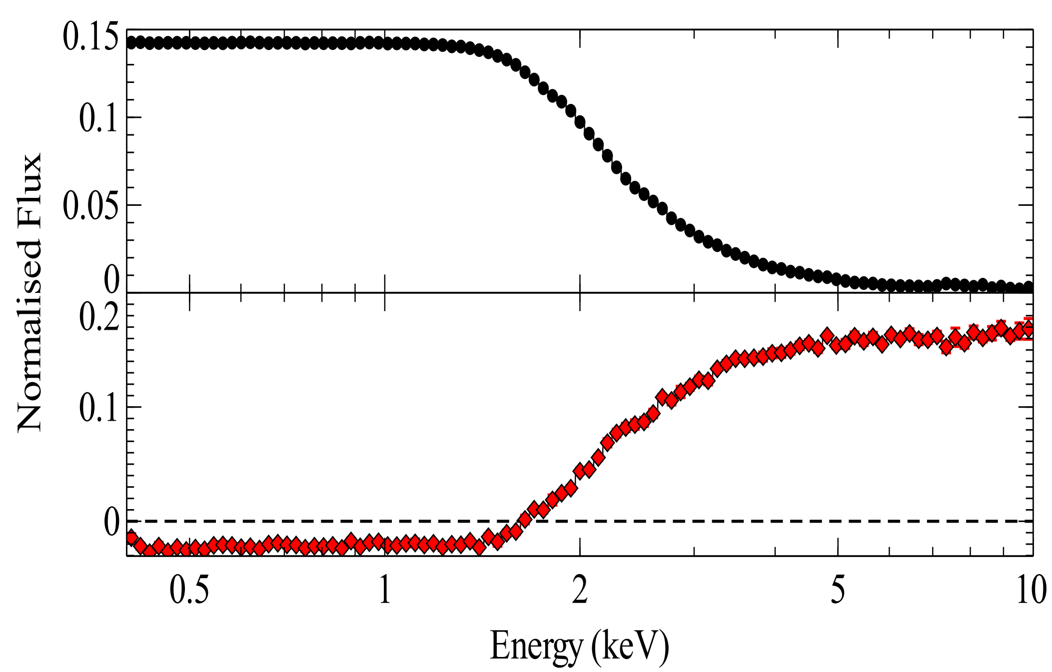
Components from 3C 273. Jet-dominated source

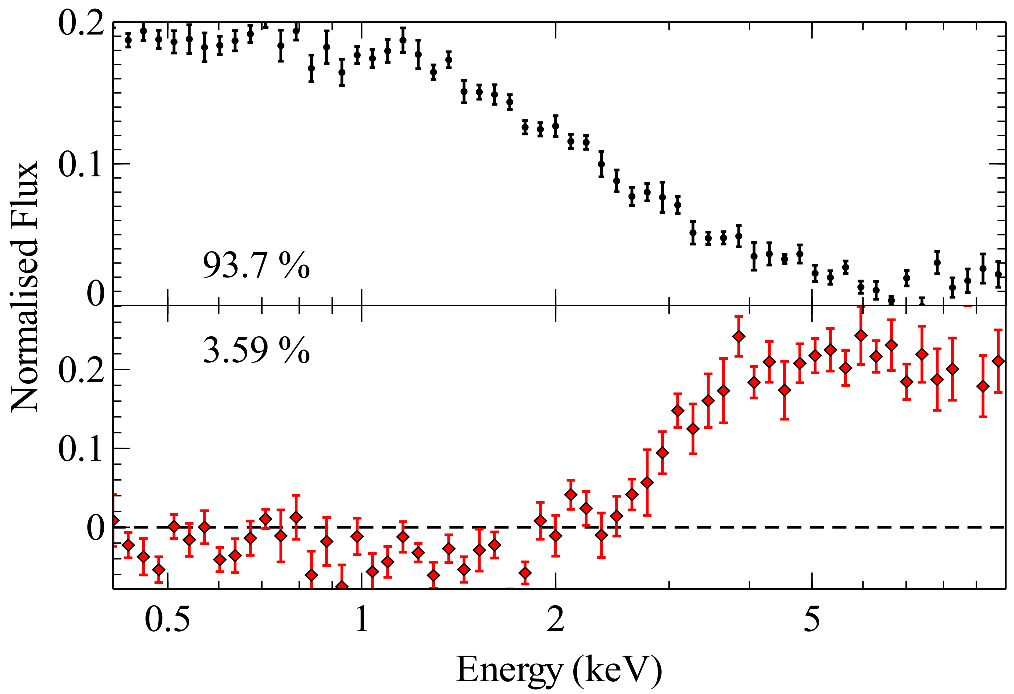


(1) Spectral variability library (Parker+ 2015)

Simulated components from partially covered power law varying in covering fraction and normalization

Components from NGC 4395. Variability dominated by absorption (Nardini & Risaliti 2011)





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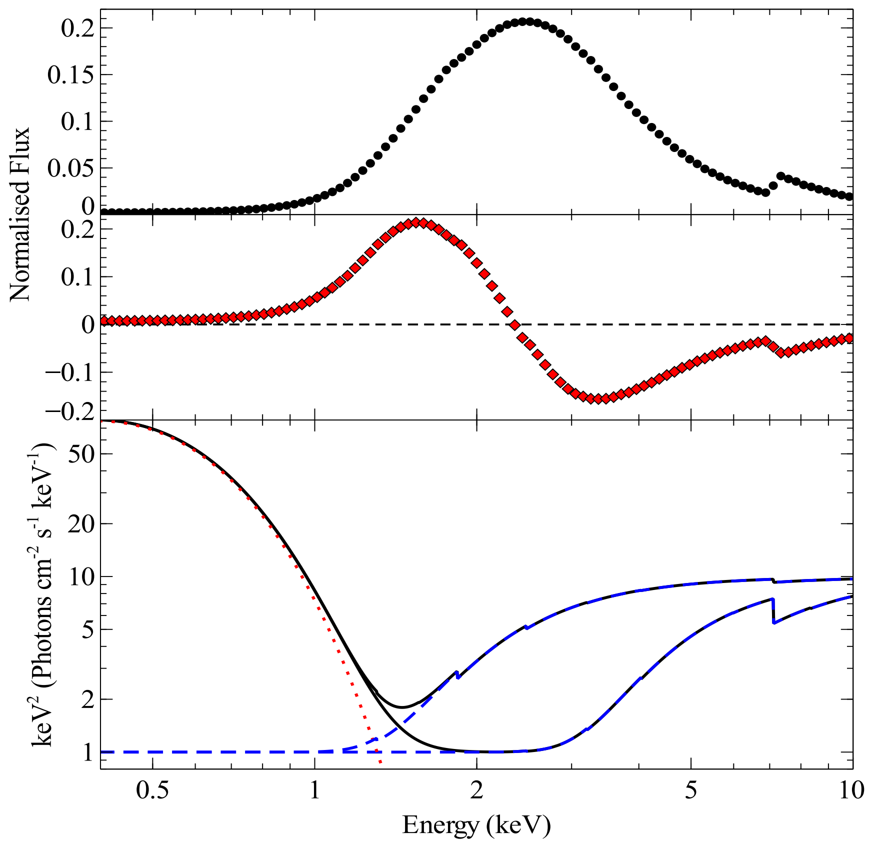
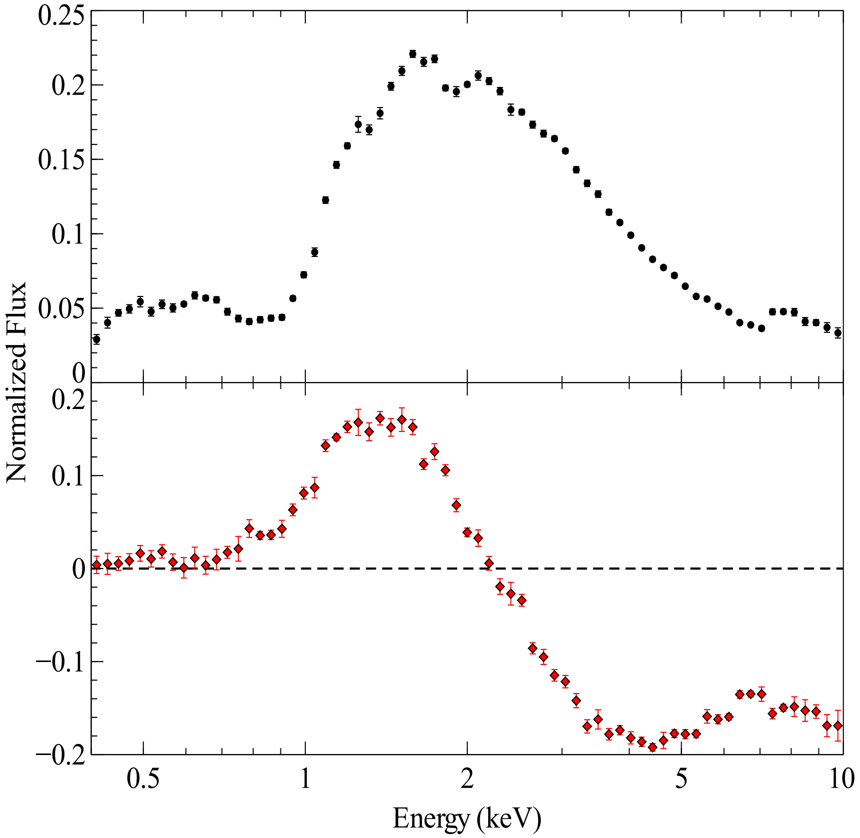
Simulated components from absorbed blackbody with varying column density

Components from NGC 1365. Low energy variability is damped out by diffuse gas around the AGN

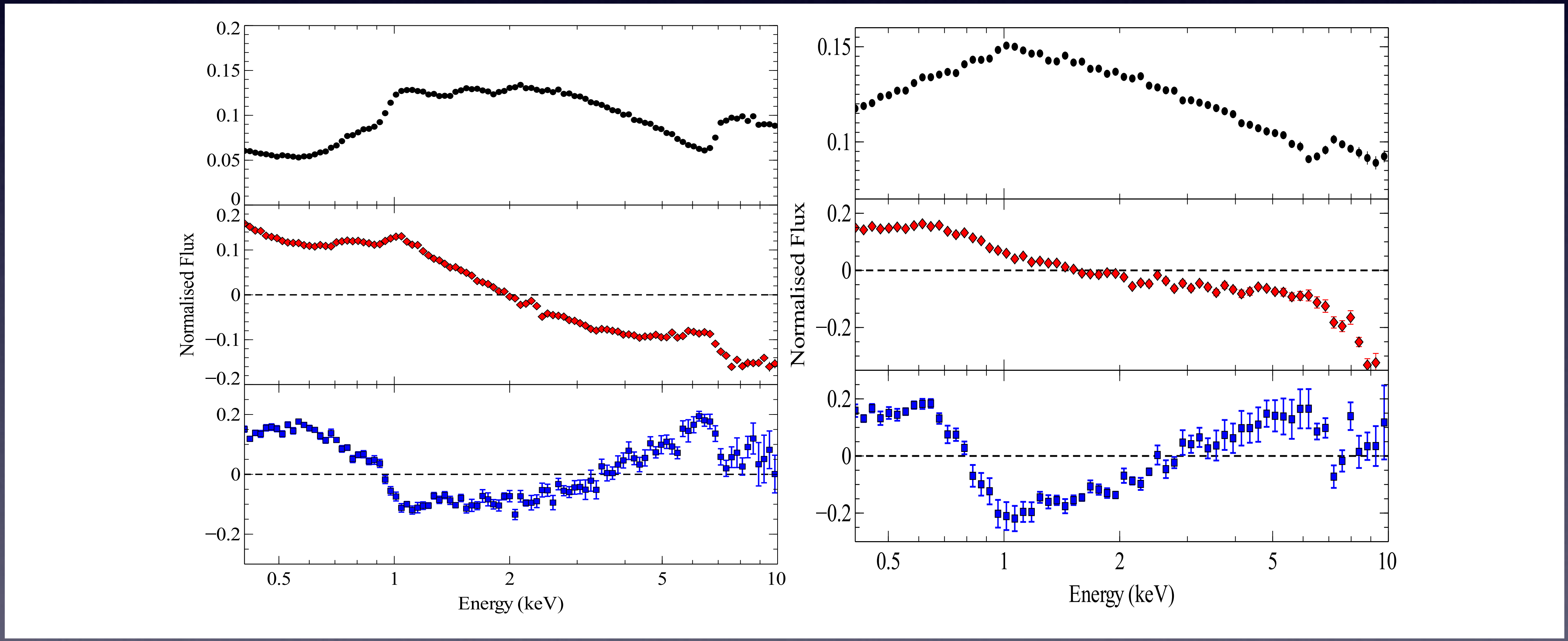




(1) Spectral variability library (Parker+ 2015)

Simulated components from power law varying in normalization and photon index + blurred reflection component

Components from MCG-6-30-15. First AGN in which relativistically broadened iron line was found (Tanaka et al. 1995)



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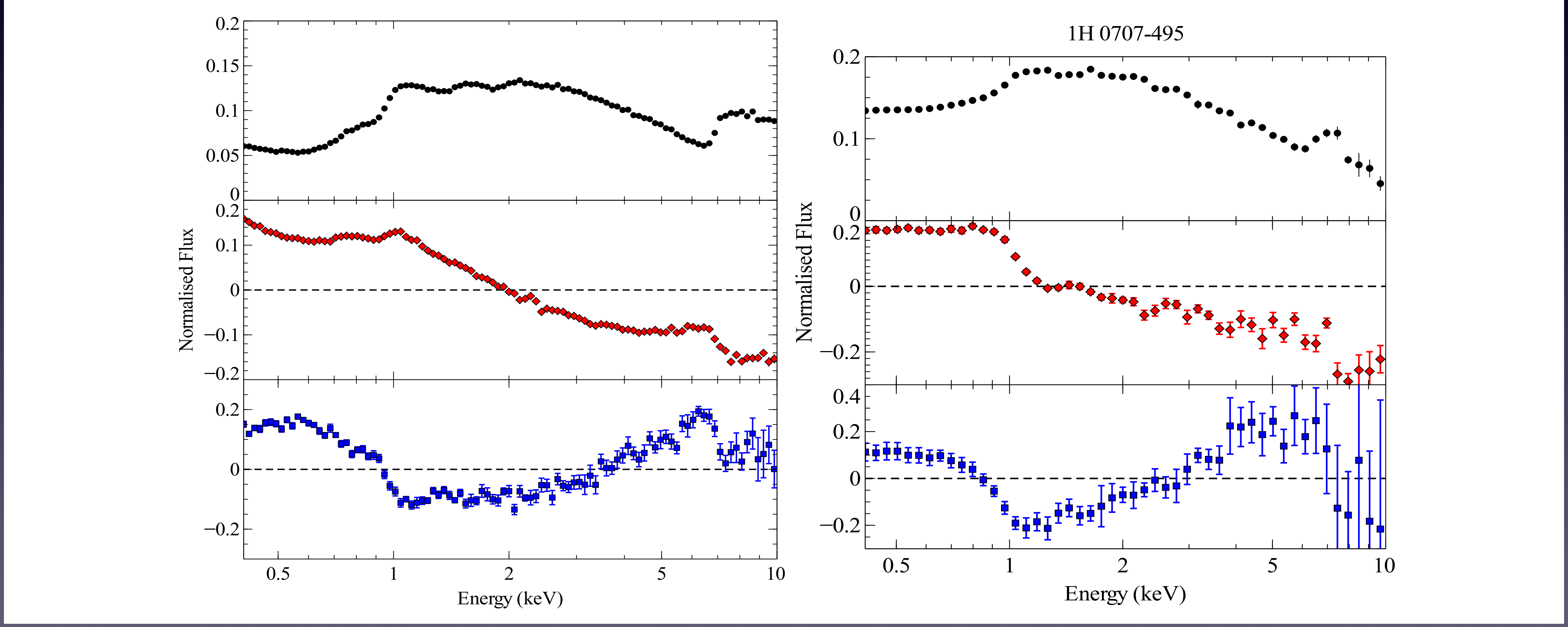
Components from 1H 0707-495



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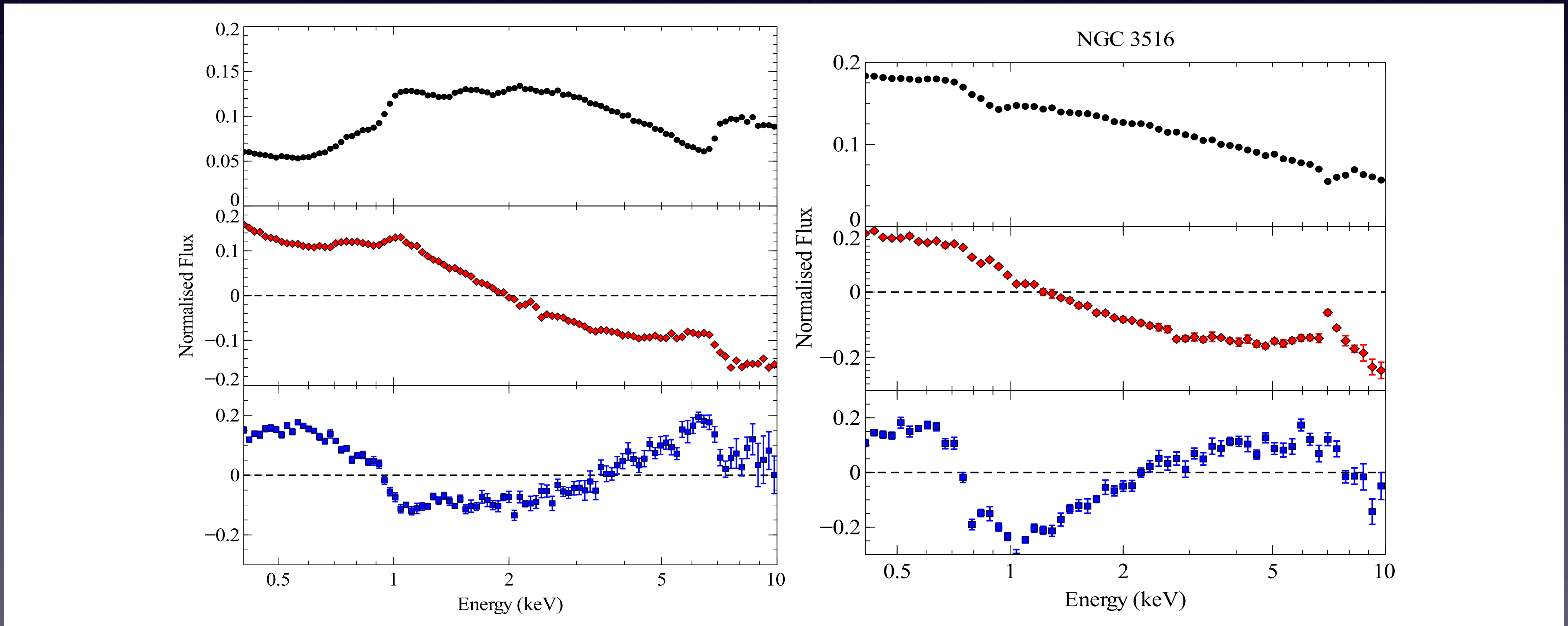
Components from NGC 3516



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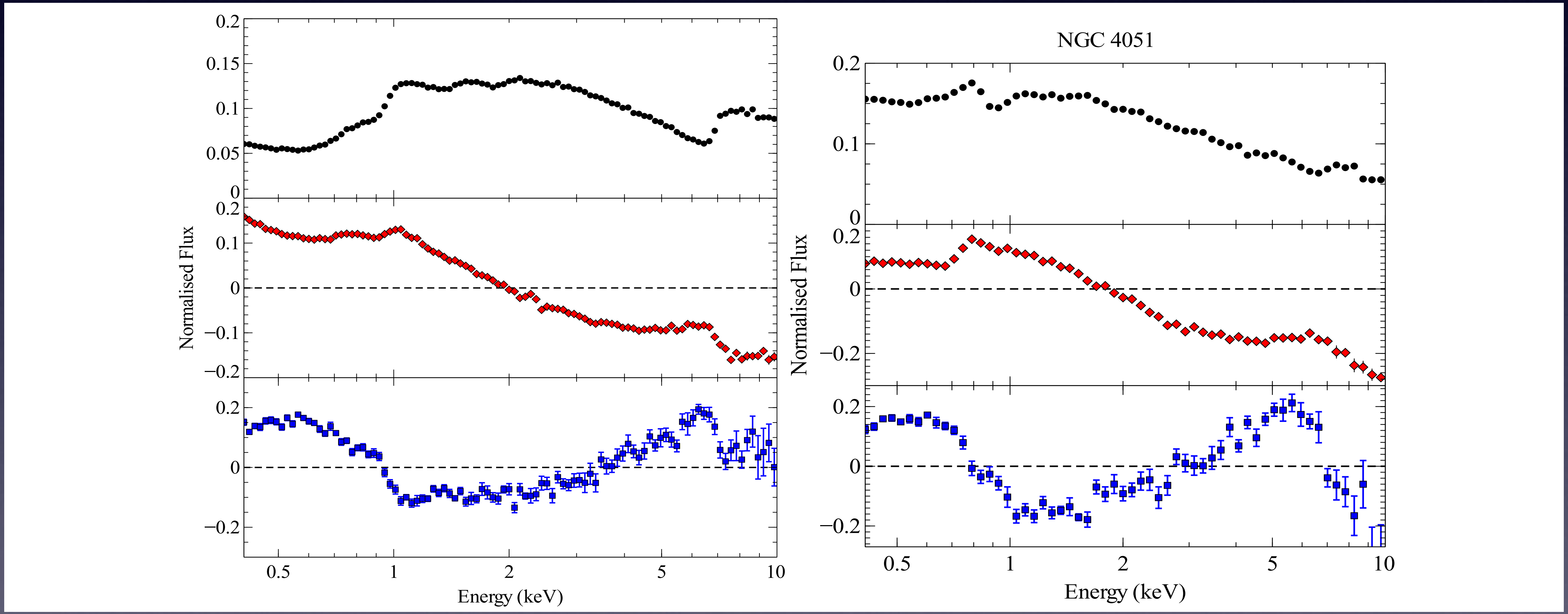
Components from NGC 4051



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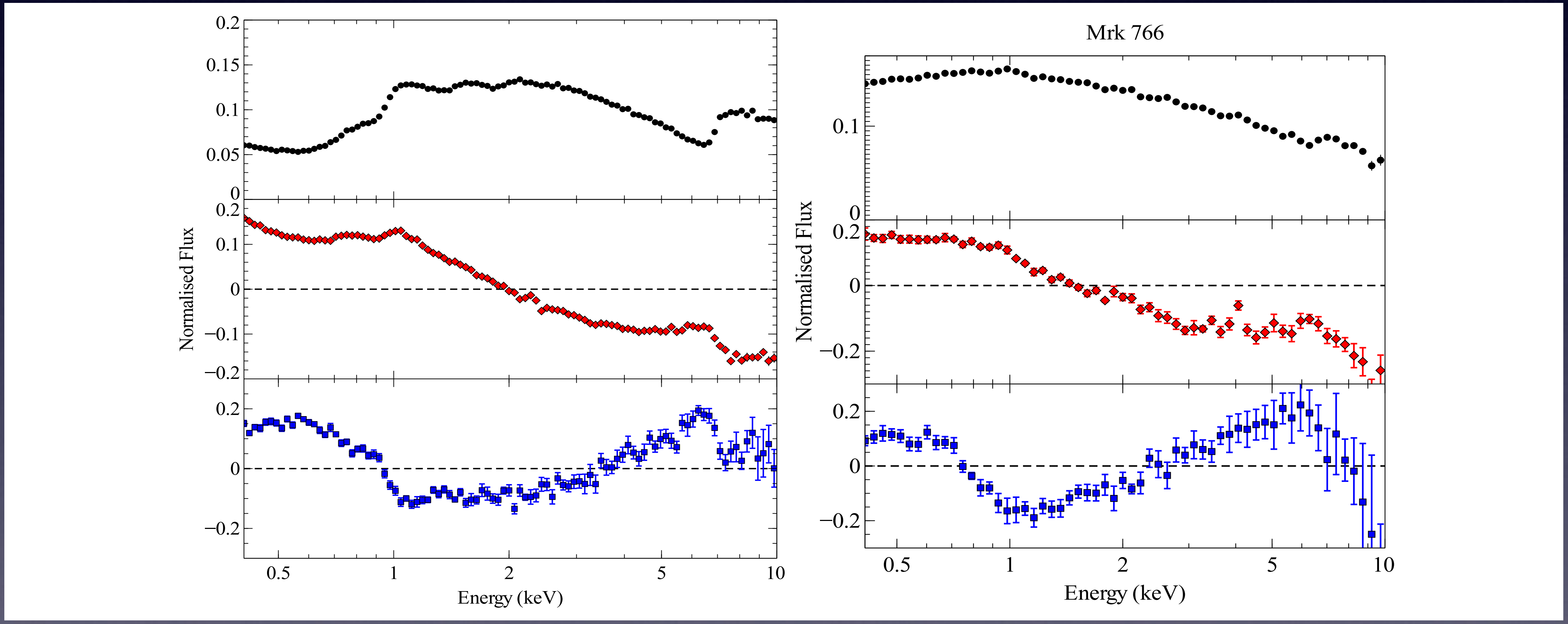
Components from Mrk 766



(1) Spectral variability library (Parker+ 2015)

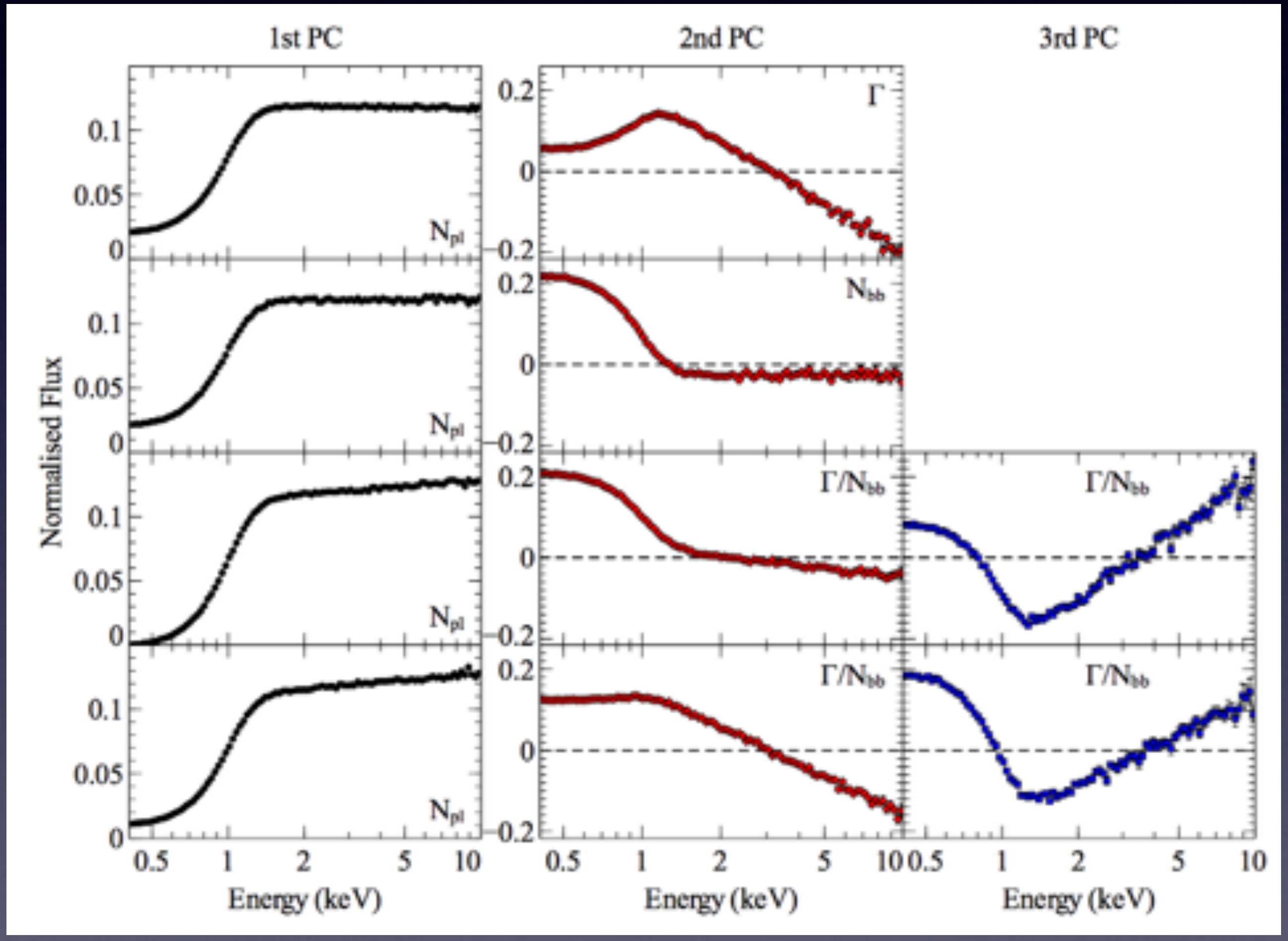
variable power law + blackbody starts to produce trouble. The arrival of correction factors.
Variability of a single spectral component is split into several principal components

Variable PL norm/index, constant BB norm

Variable PL norm, BB norm, fixed index

Variable PL norm/index, BB norm, strong BB

Variable PL norm/index, BB norm, weak BB



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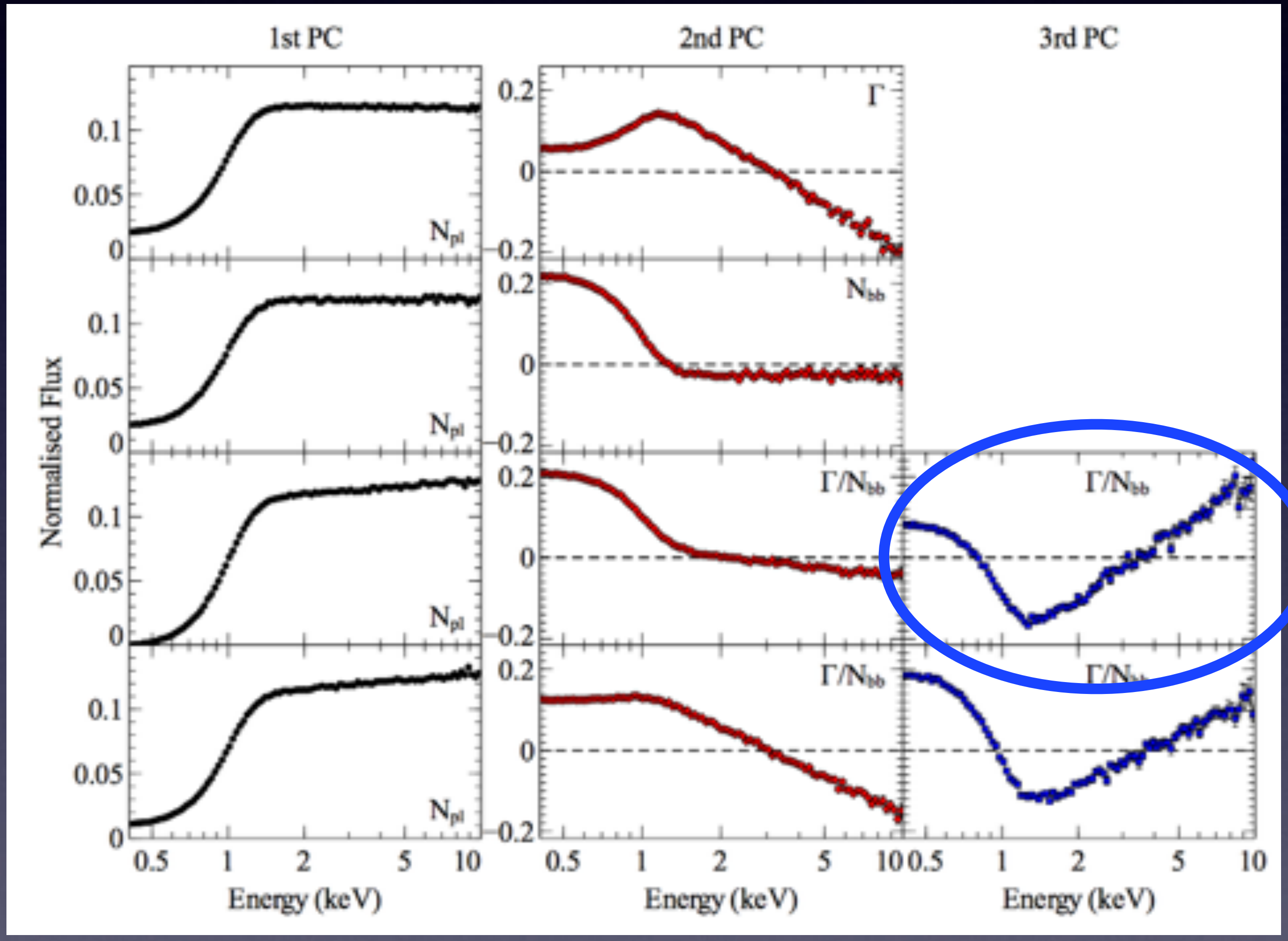

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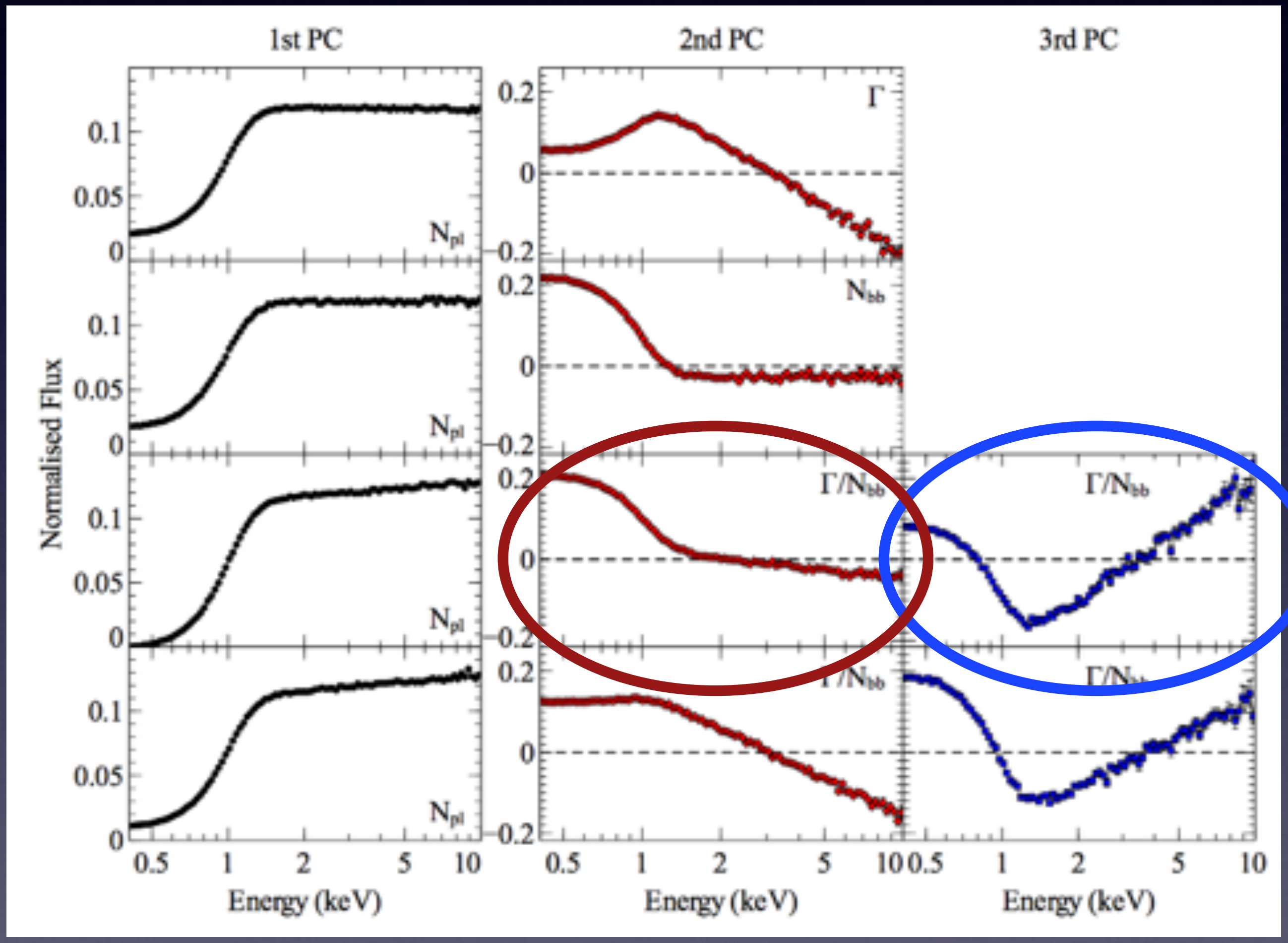

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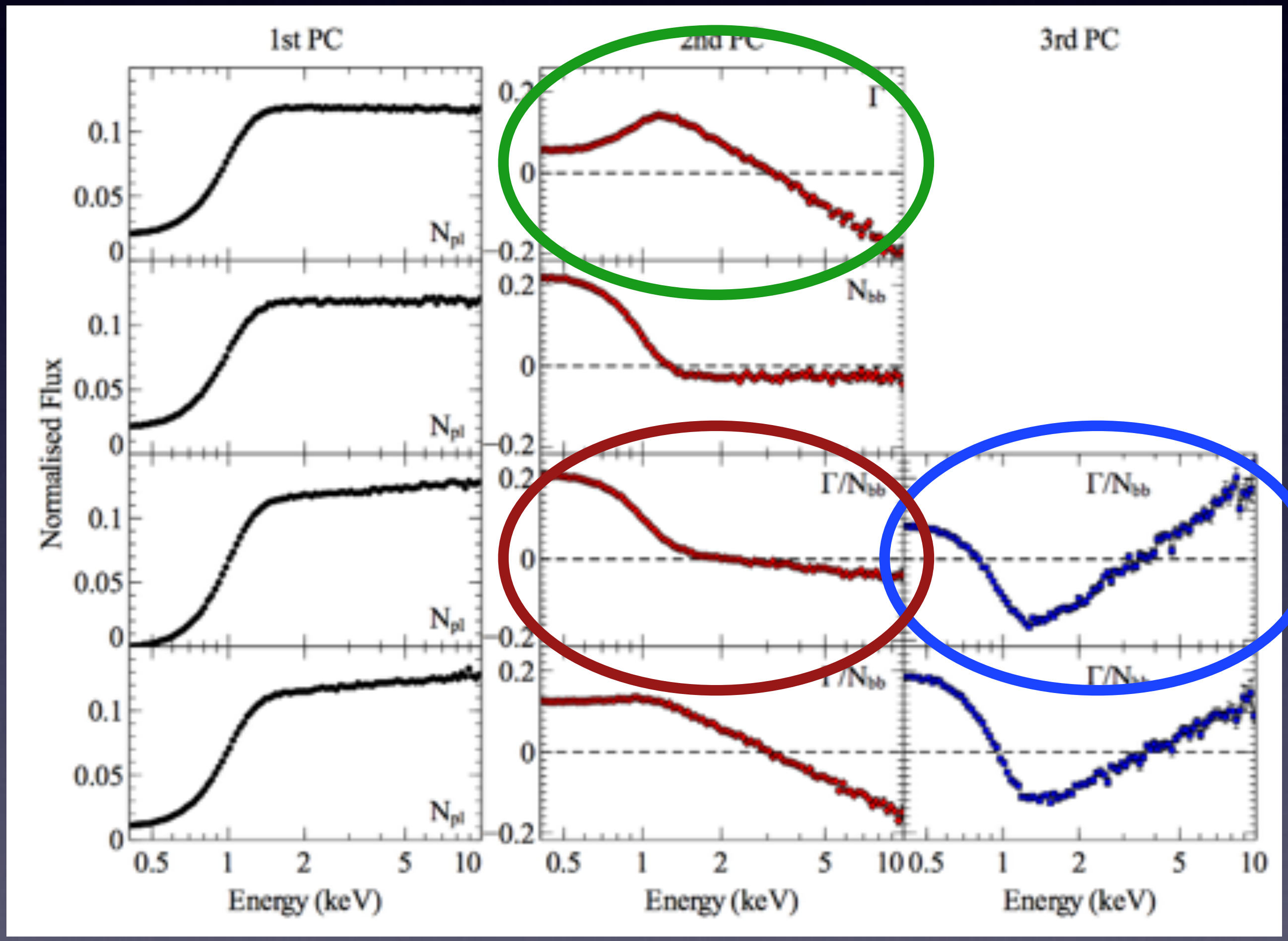

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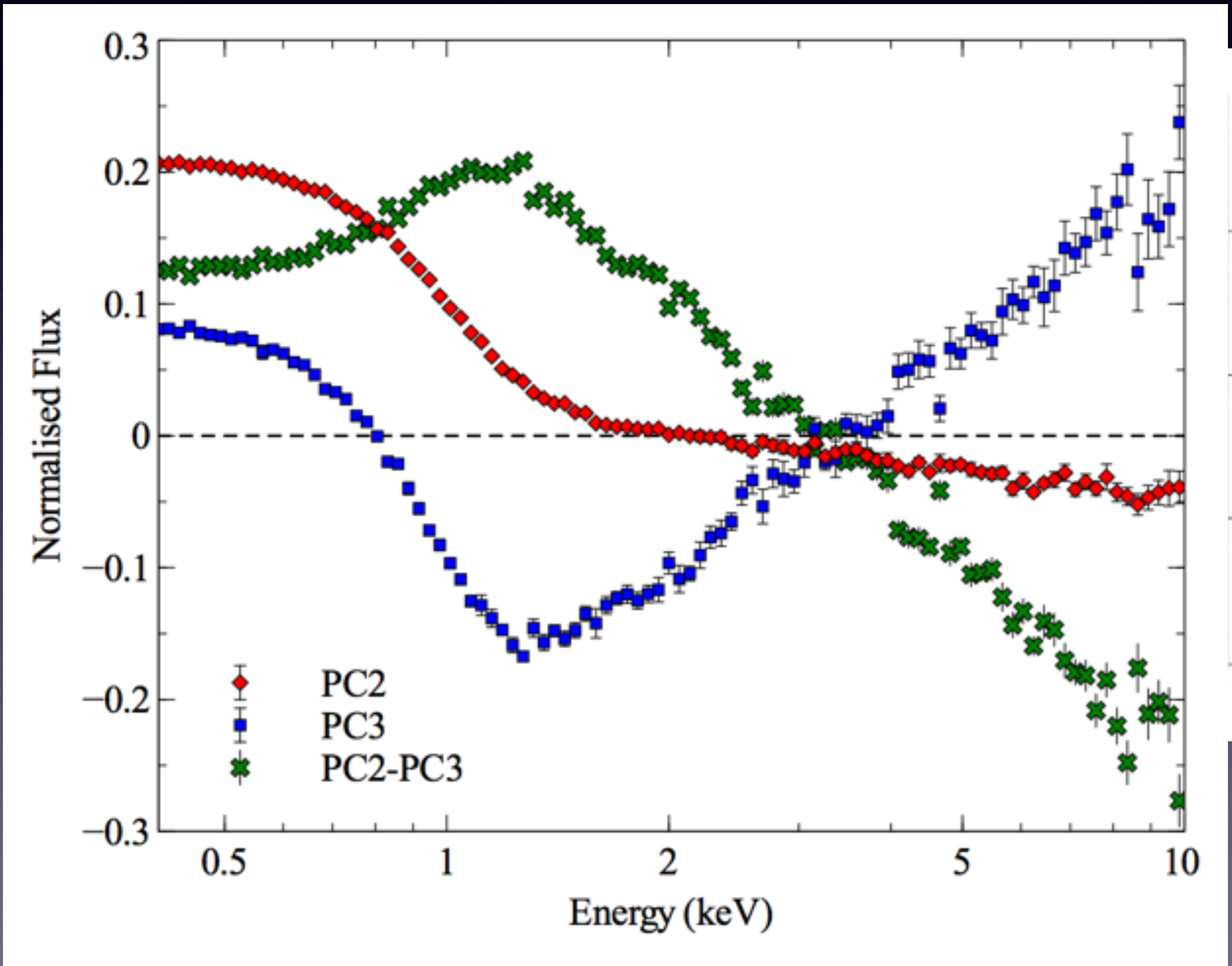
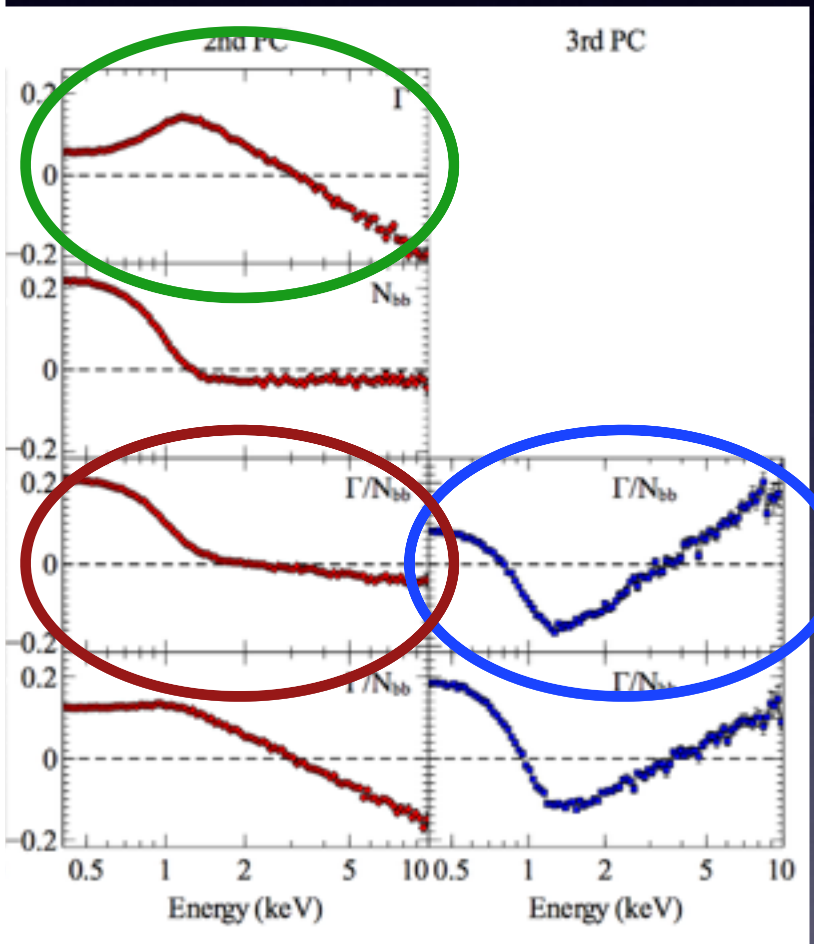
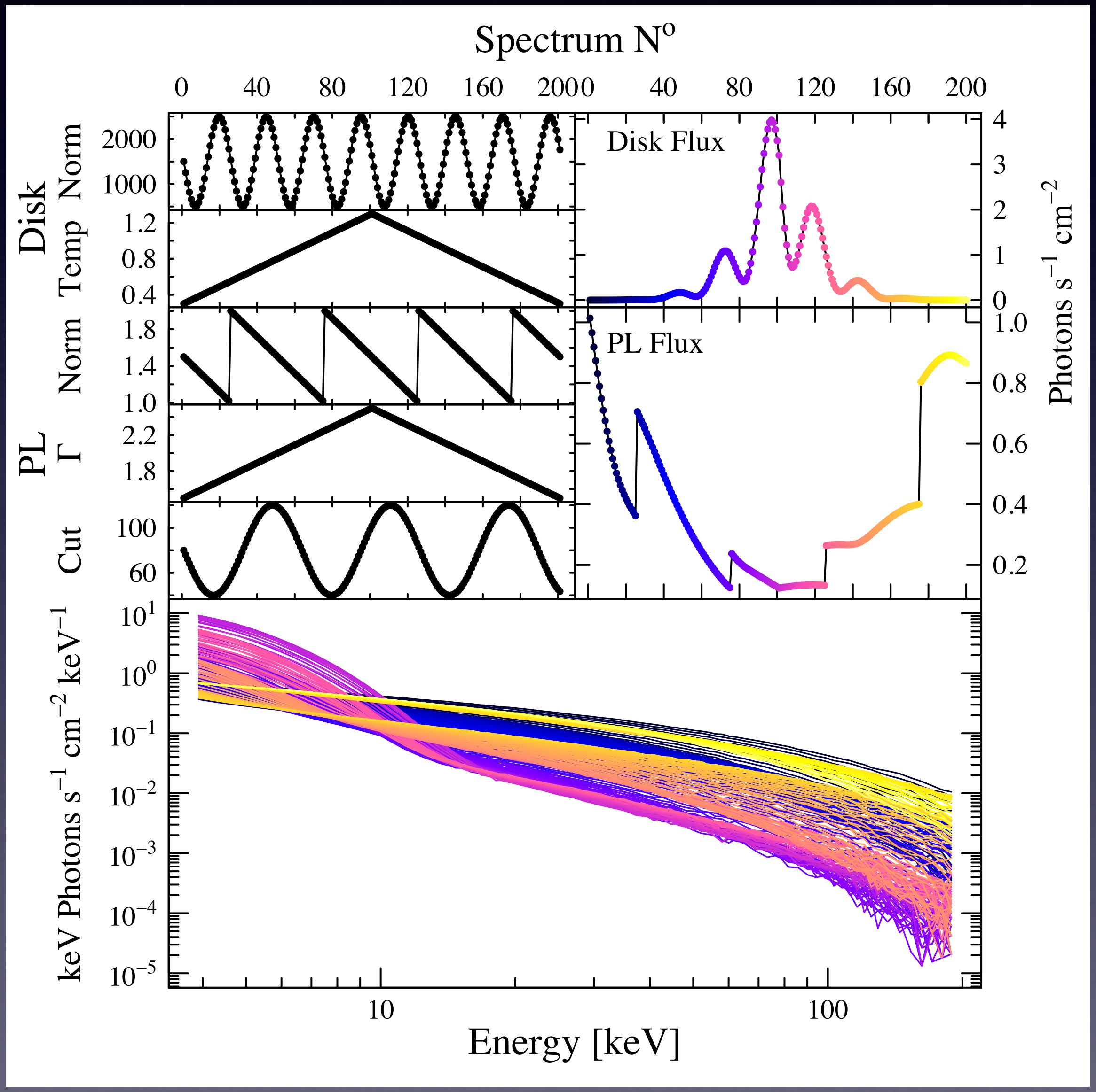




(2) Summing components based on their weight (Koljonen 2015)

- Non-linear changes in the spectral shapes
- Mimics the spectral effects that are present in the usual X-ray data of XRBs:
  - variable absorbed disc black body + cutoff power law
- Sine and saw waves as “spectral pathways”
- Soft and hard X-ray states
- We use ISIS (Houck & Denicola 2000) to fake 200 spectra with an exposure of 5 ks



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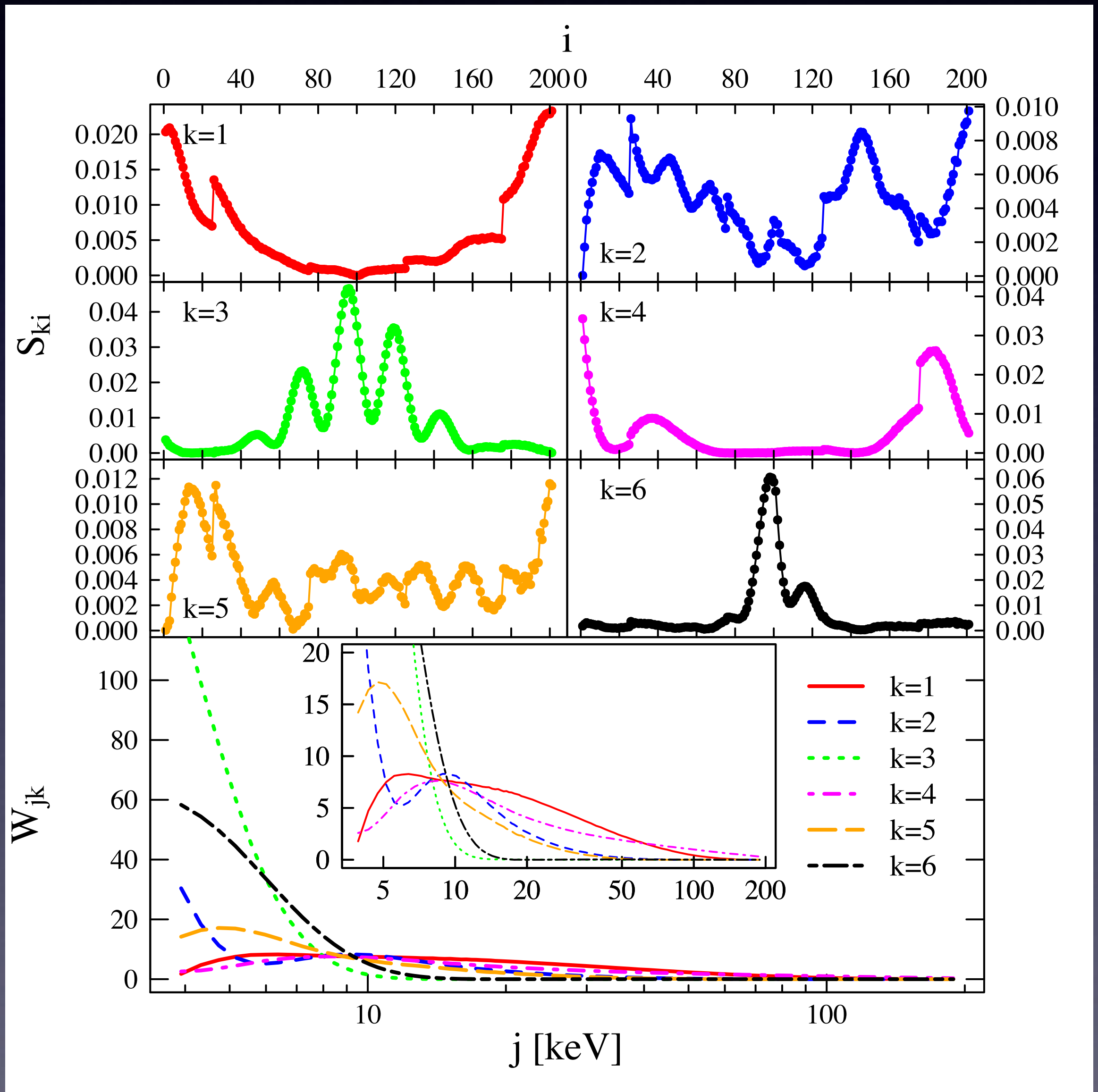
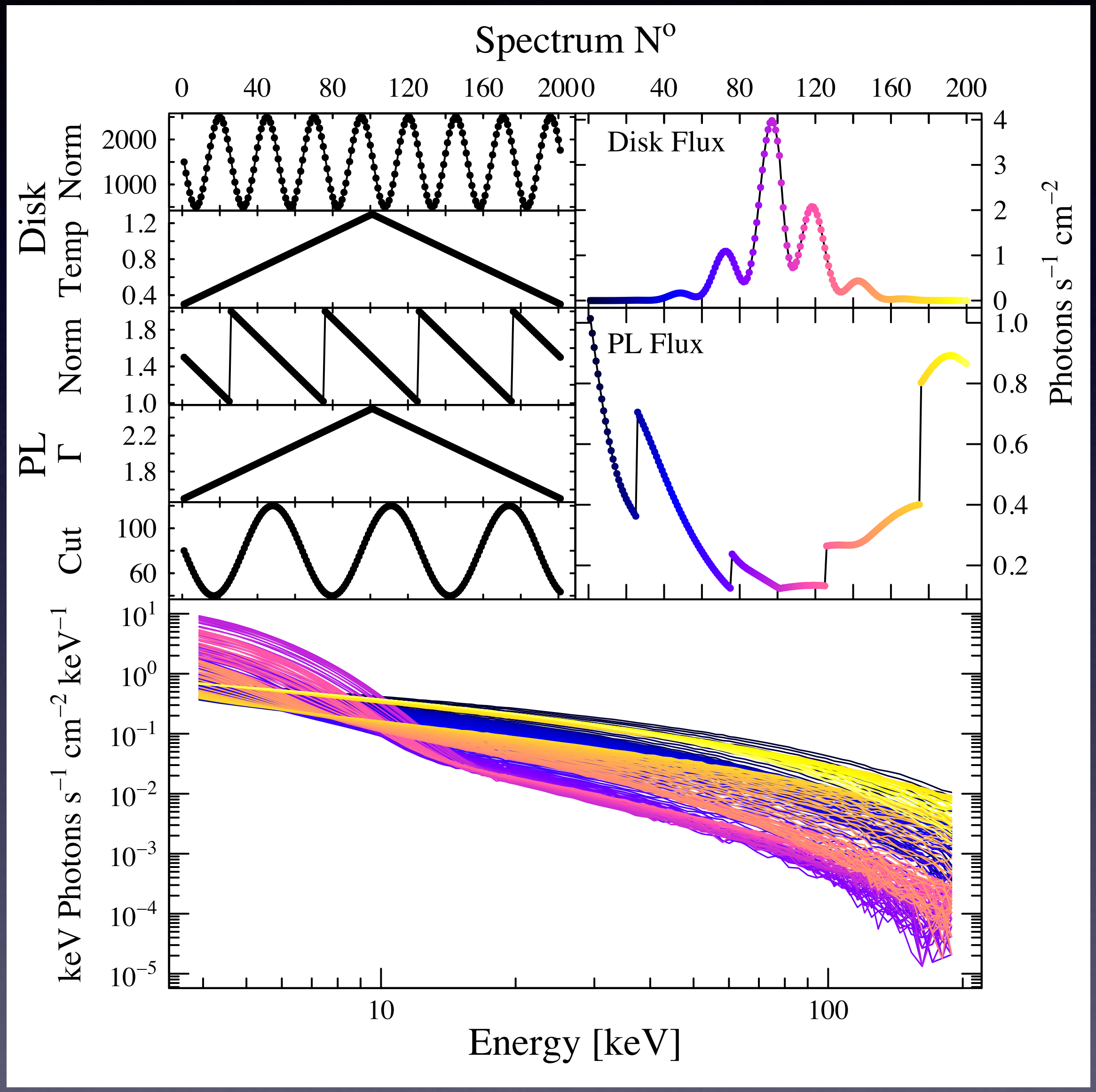
Decomposition using NMF





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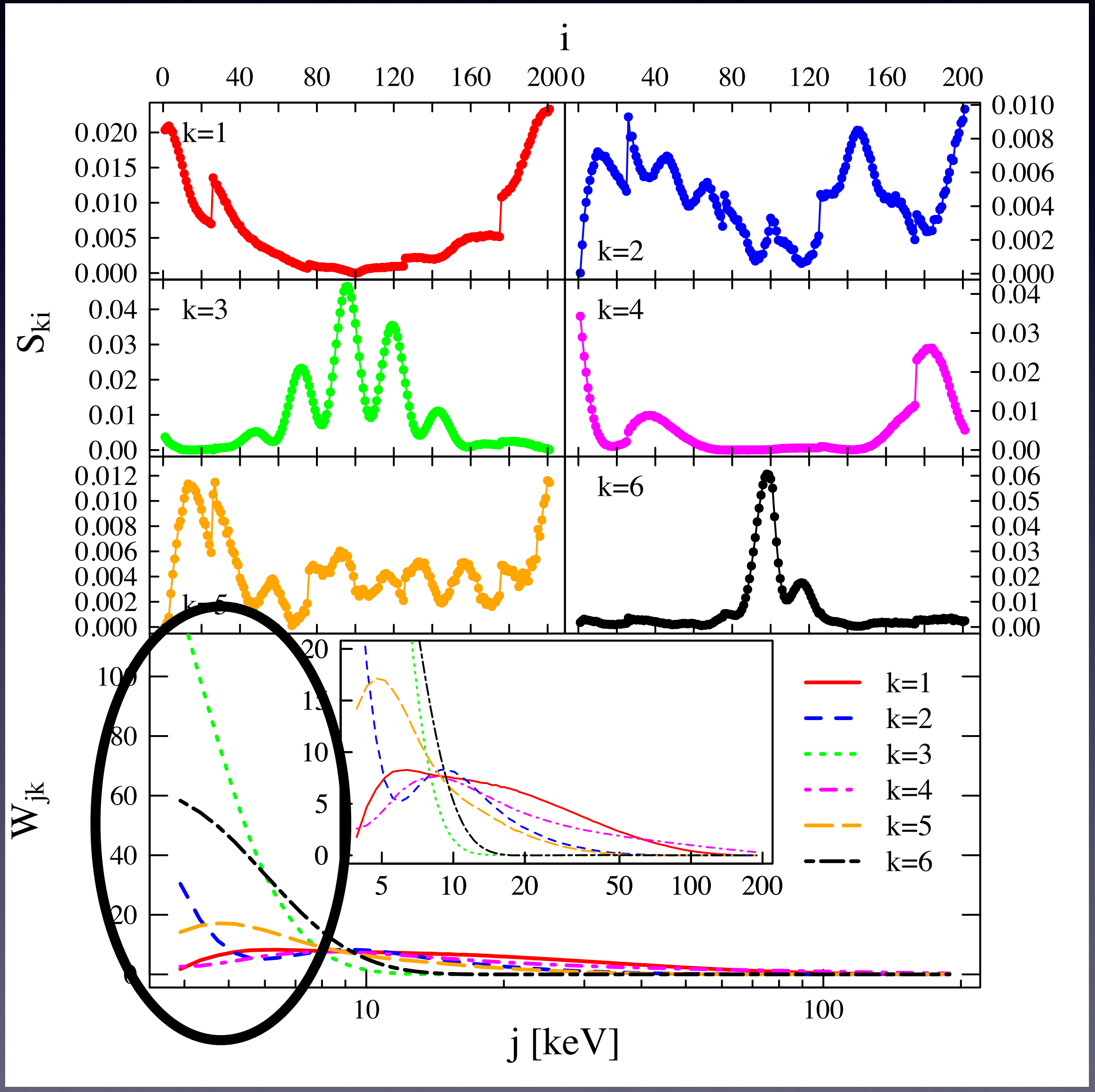

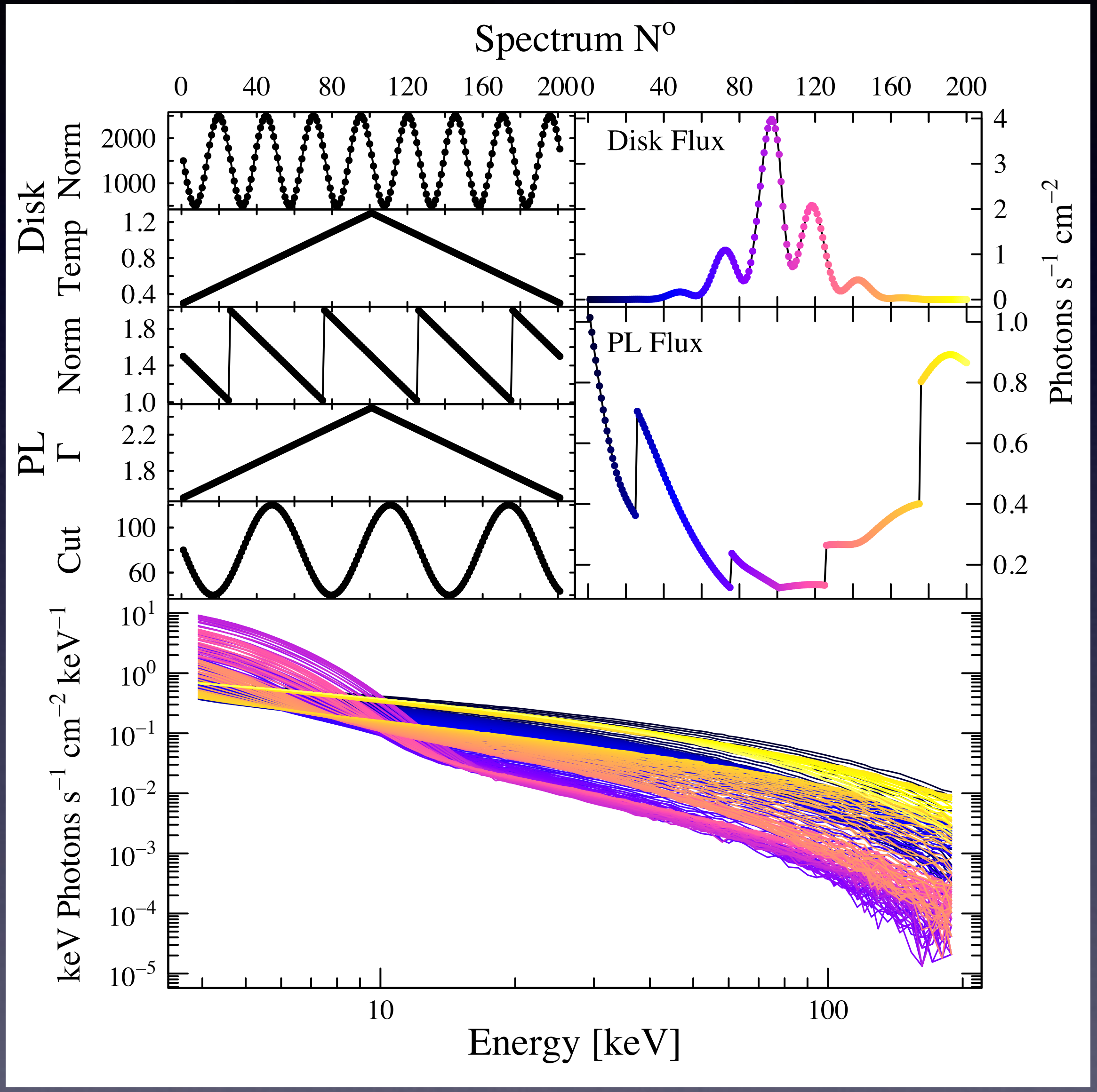

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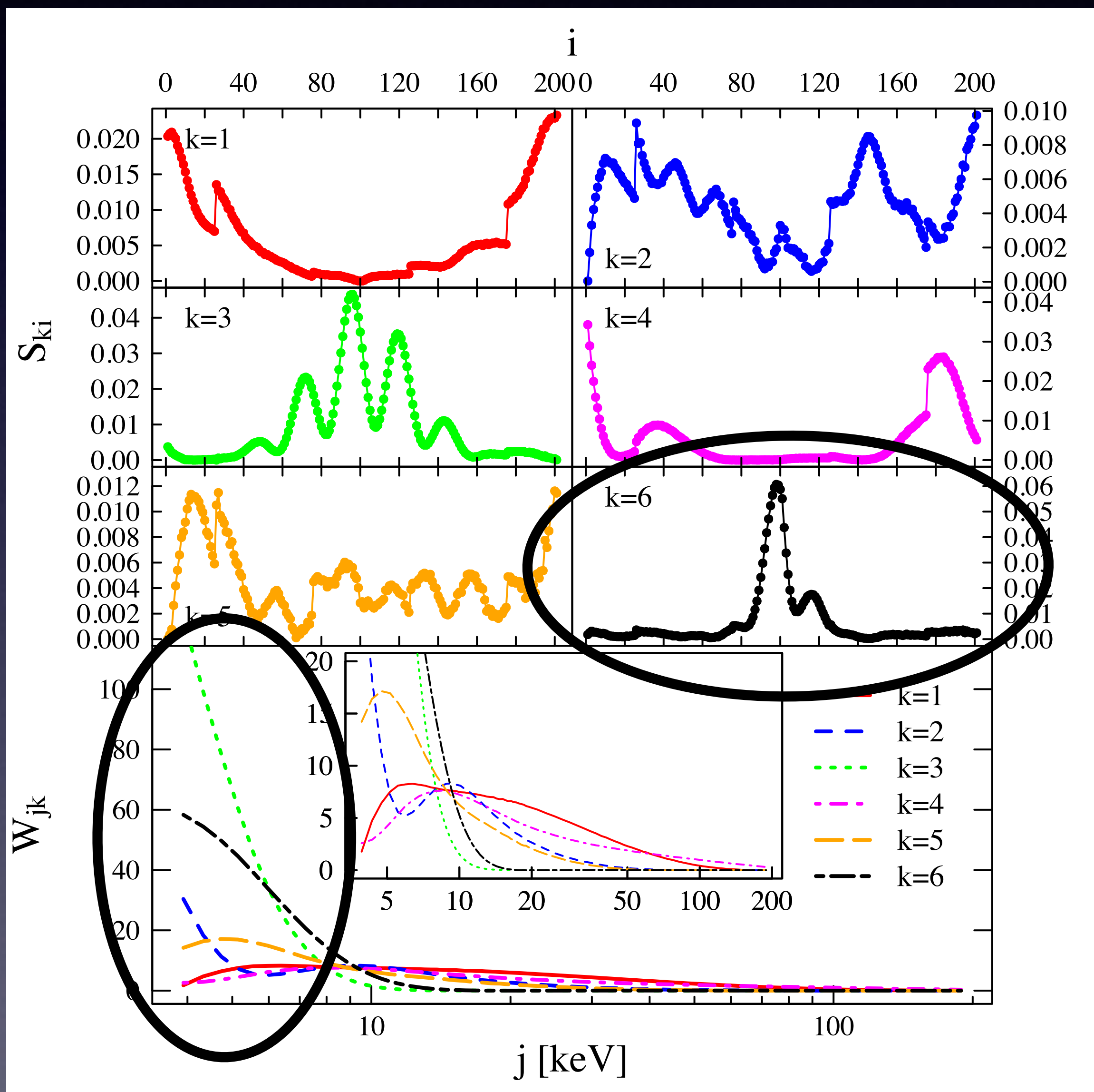

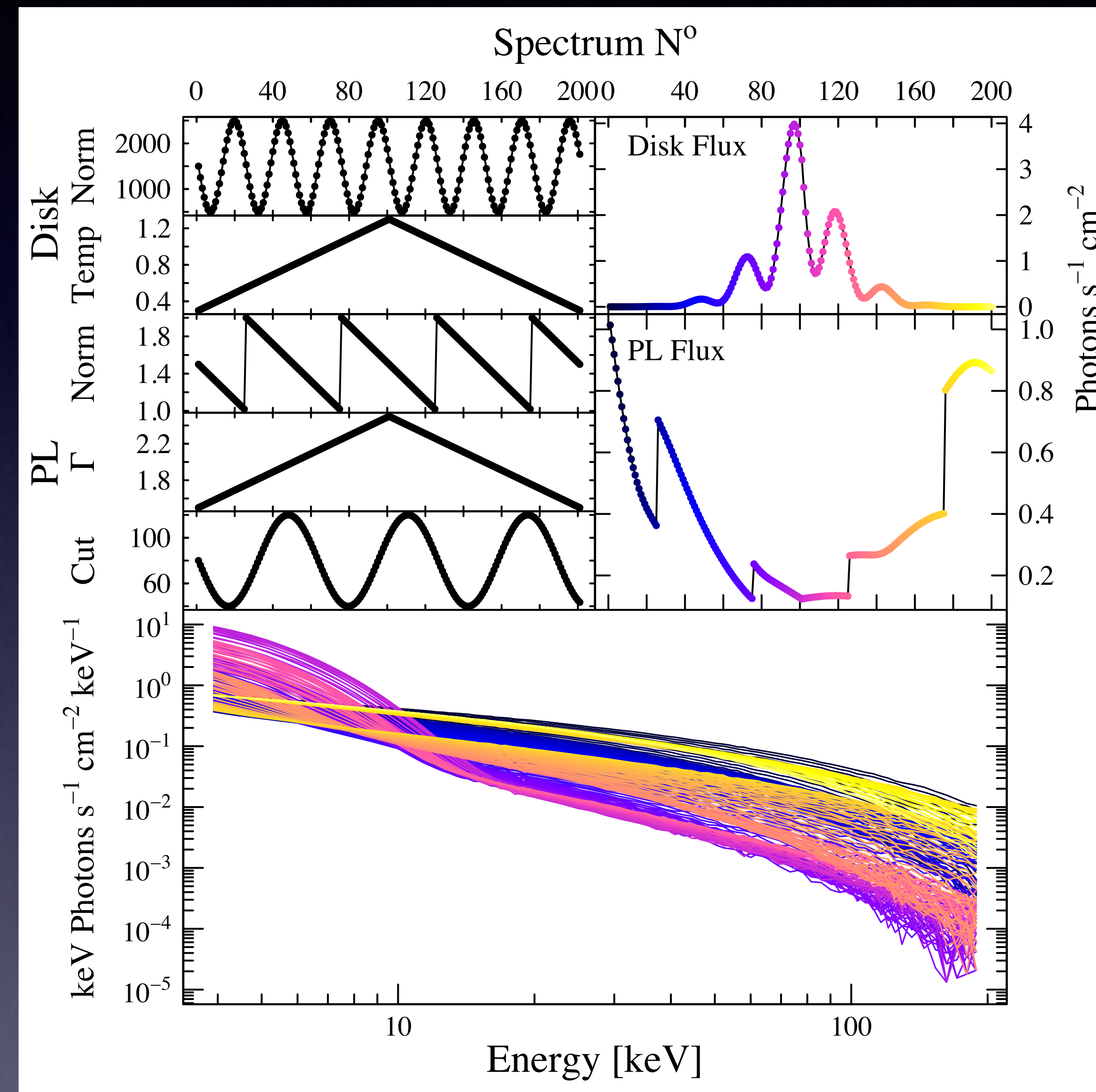

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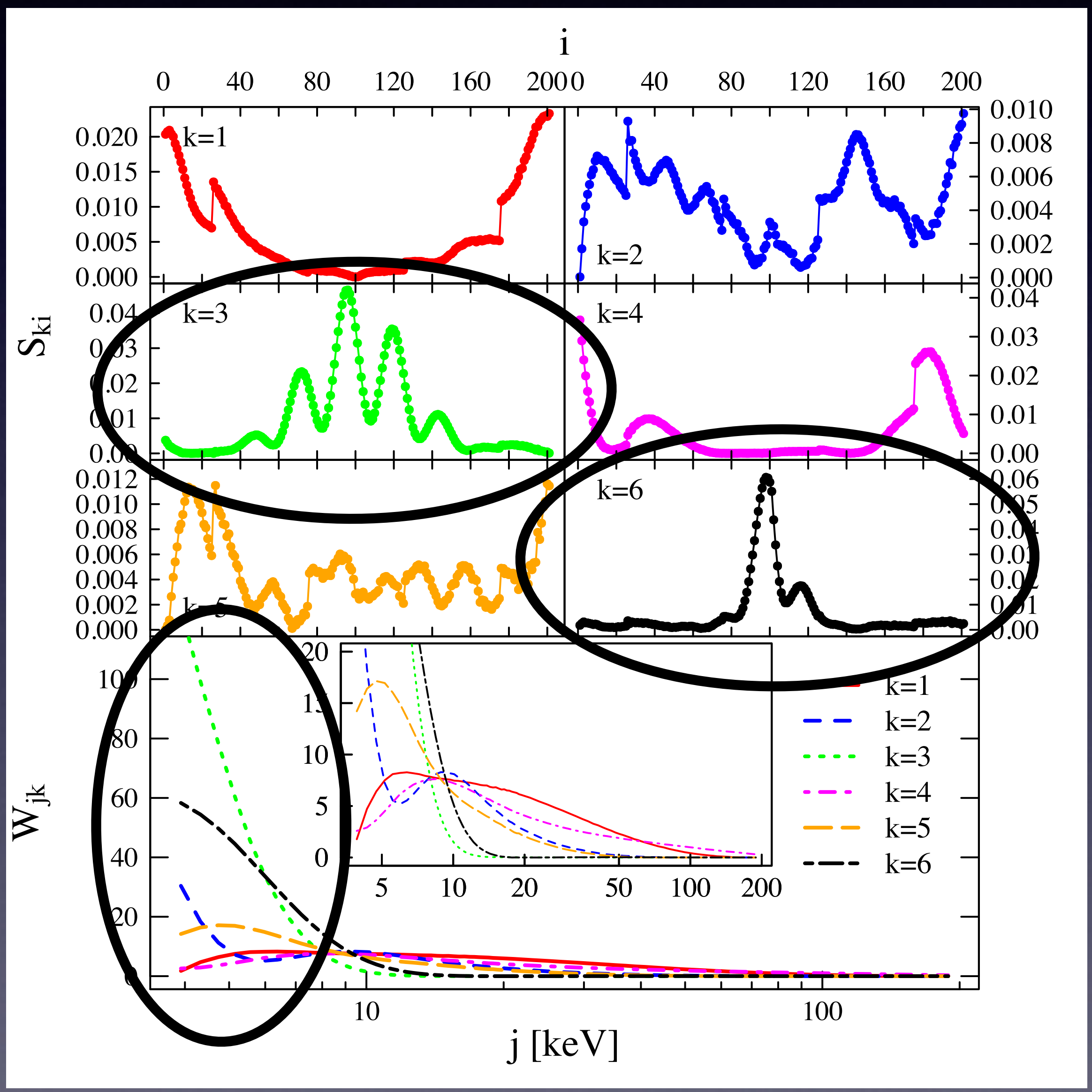

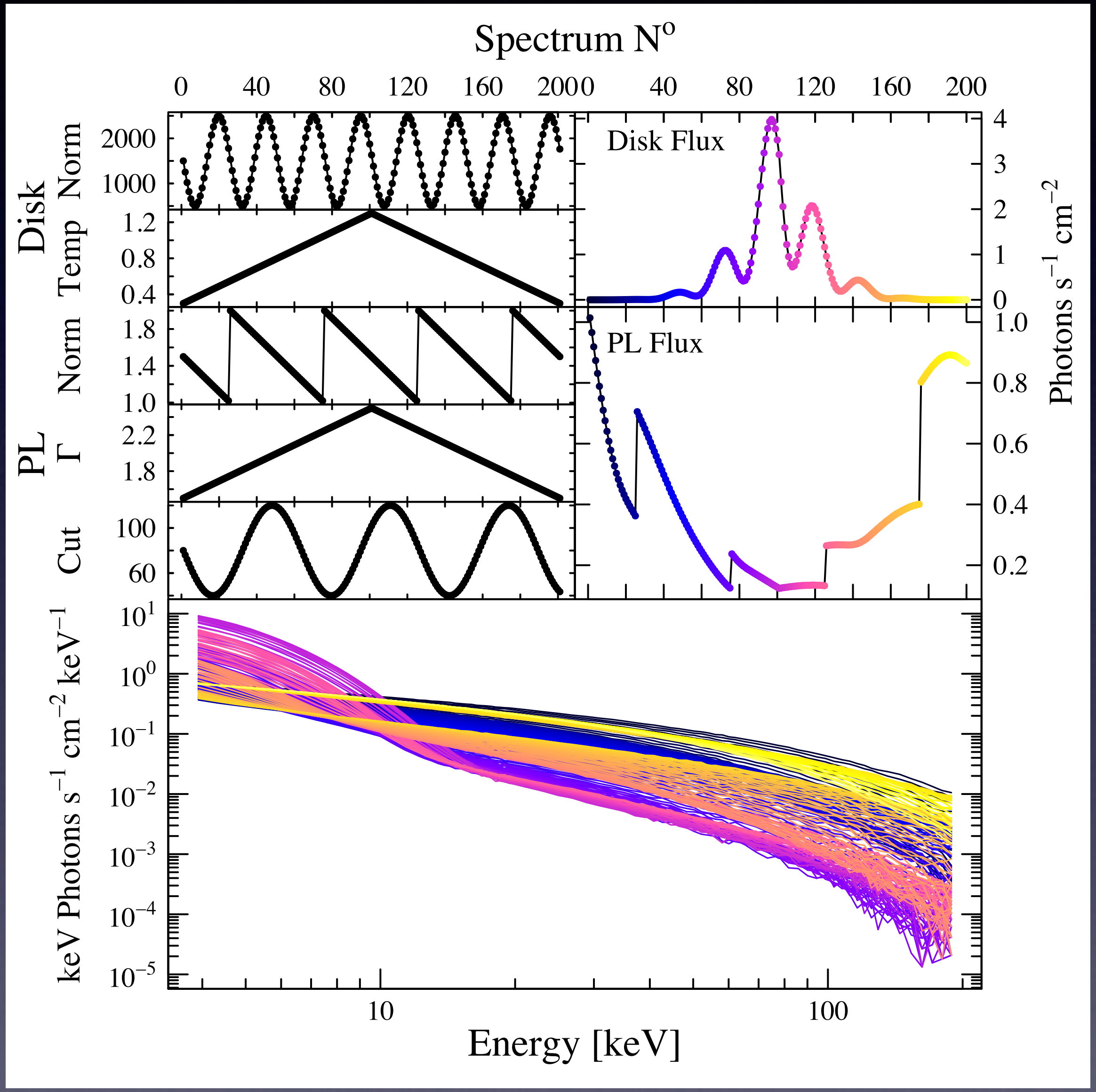

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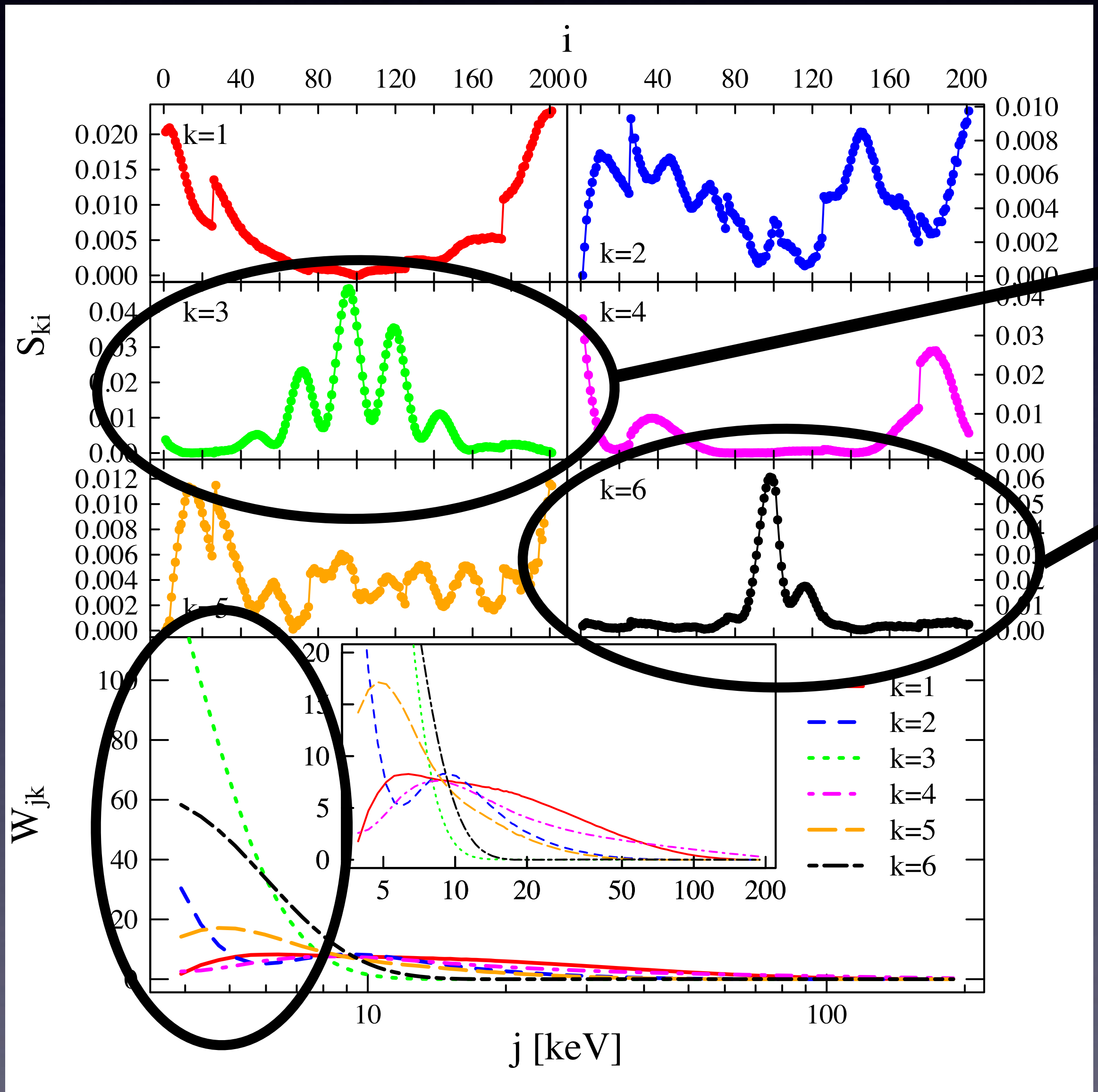

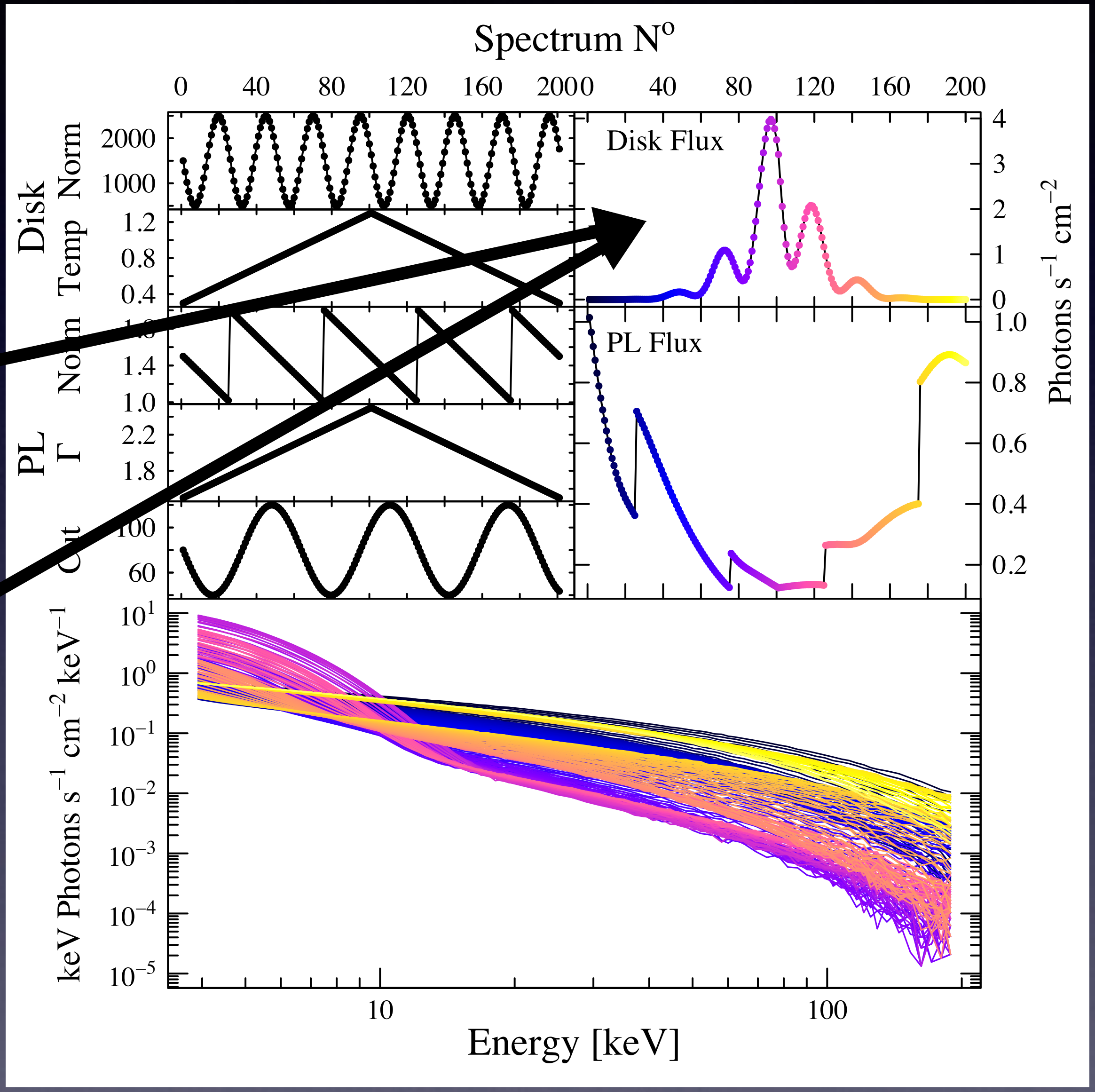

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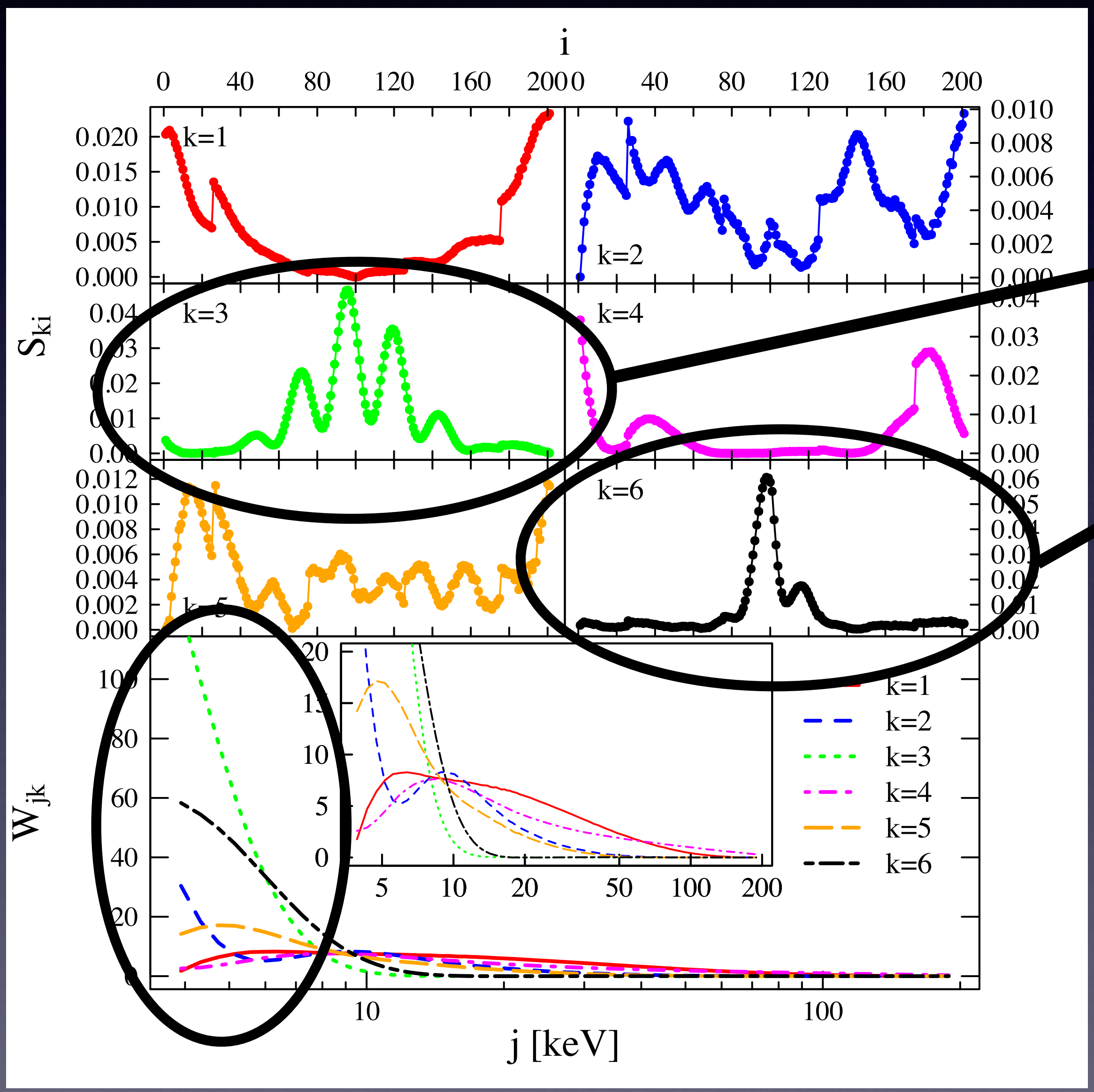

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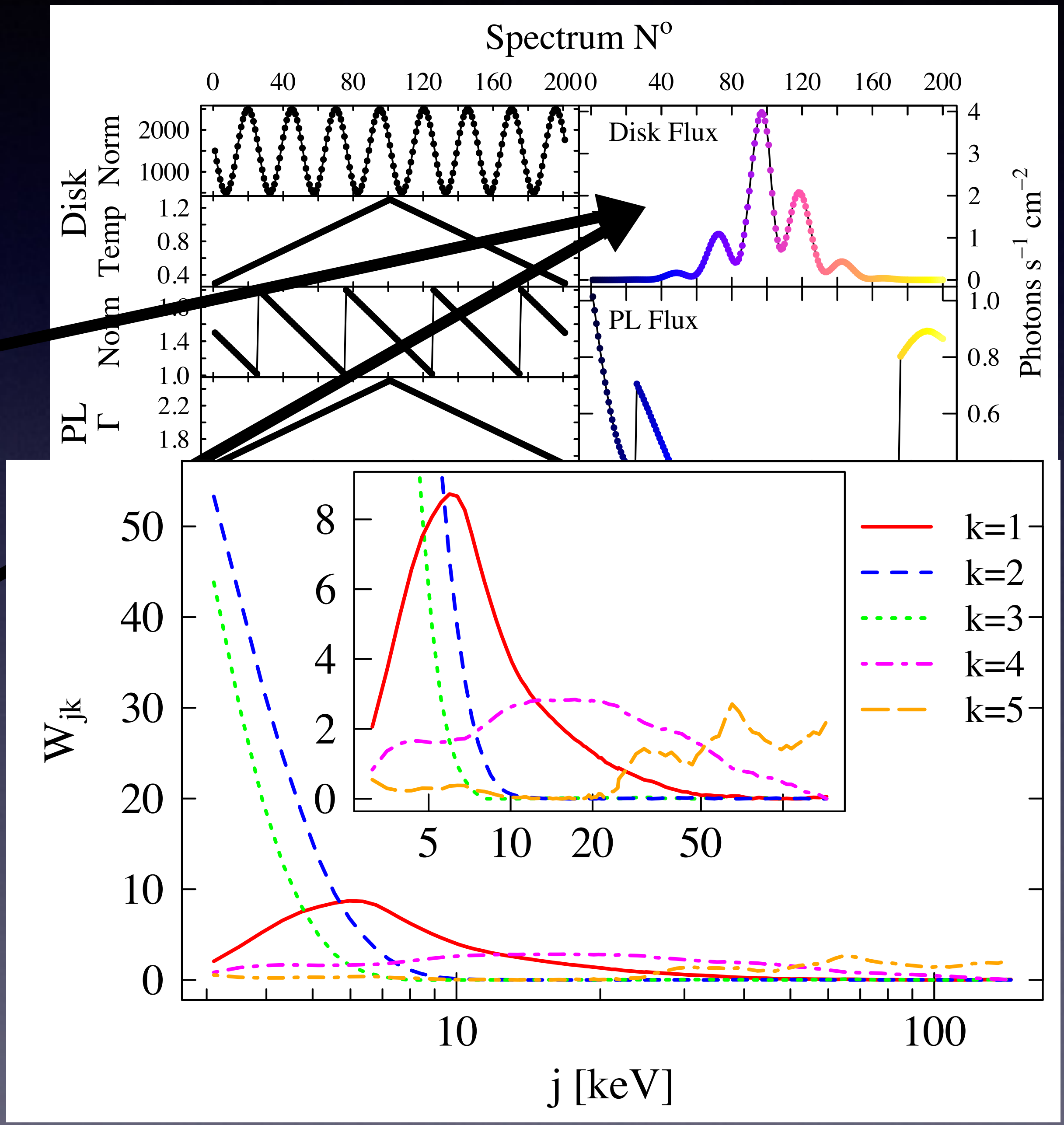
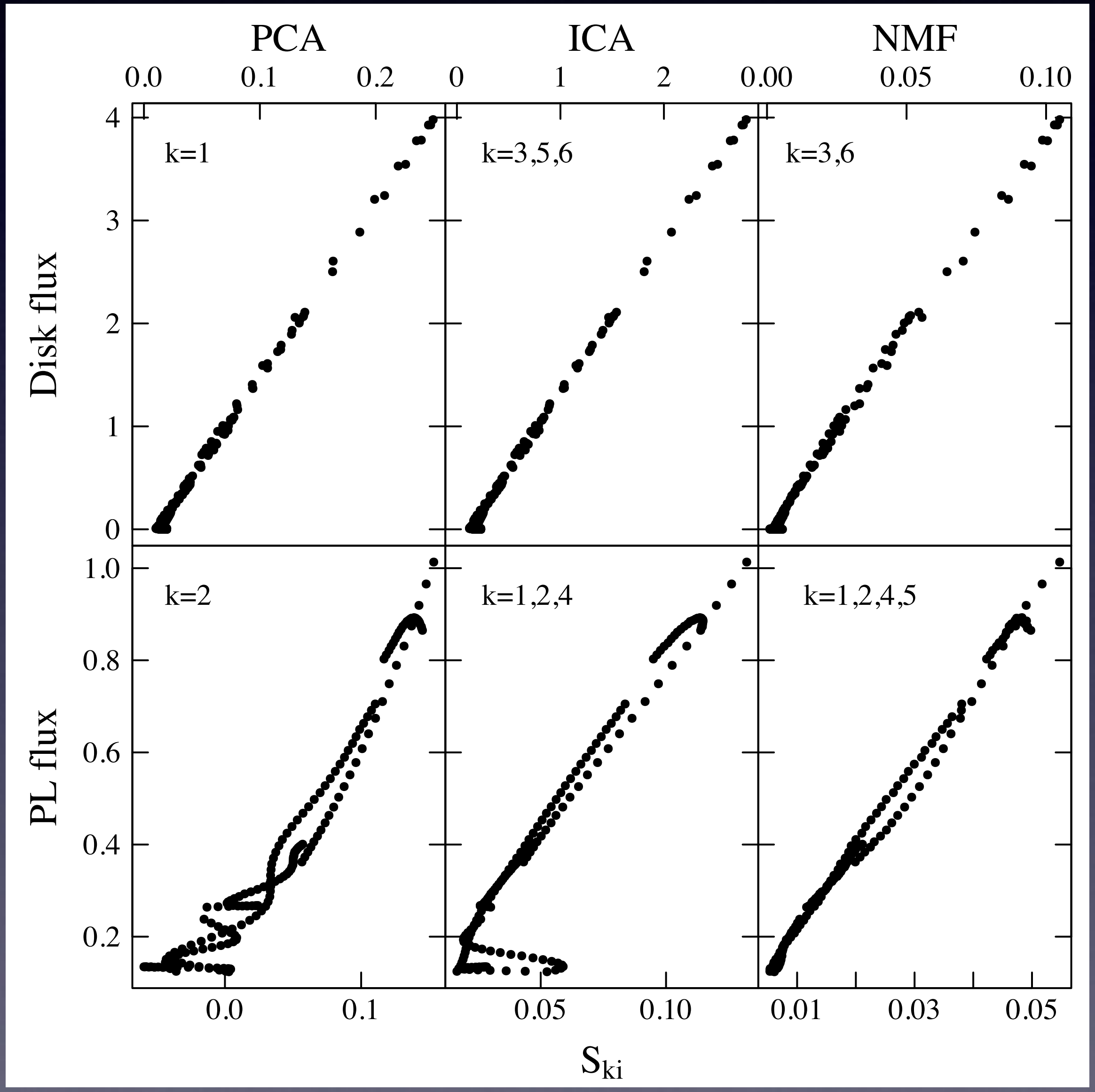


Decomposition of all RXTE observations of GX 339-4

(2) Summing components based on their weight (Koljonen 2015)

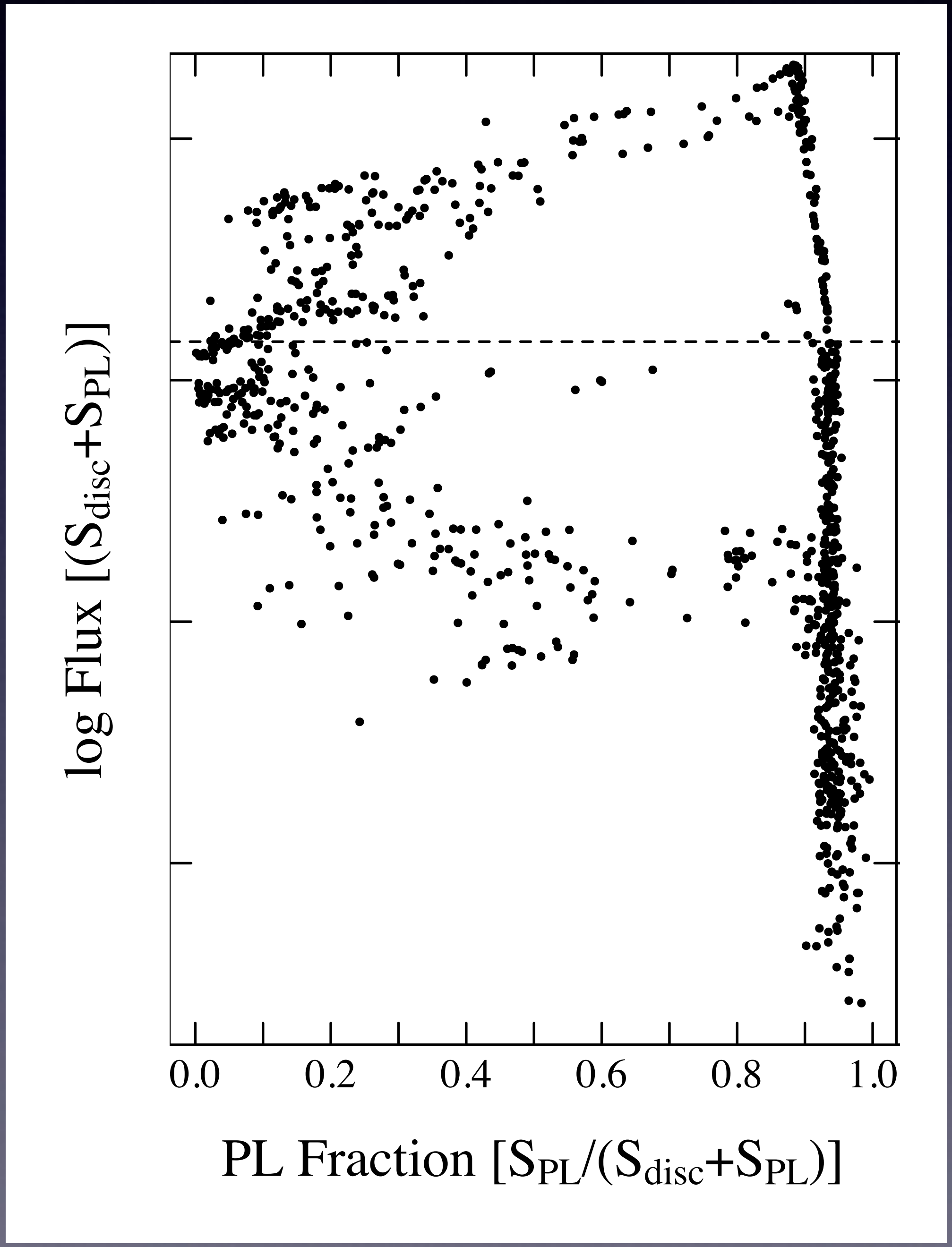
Non-linear effects in the spectra caused by the parameter evolution (e.g. power law index, cutoff energy) can be taken into an account by adding factorised components together based on their weights.

NMF performs the best in separating the disc and power law emission.



(2) Summing components based on their weight (Koljonen 2015)

All RXTE observations of GX 339-4



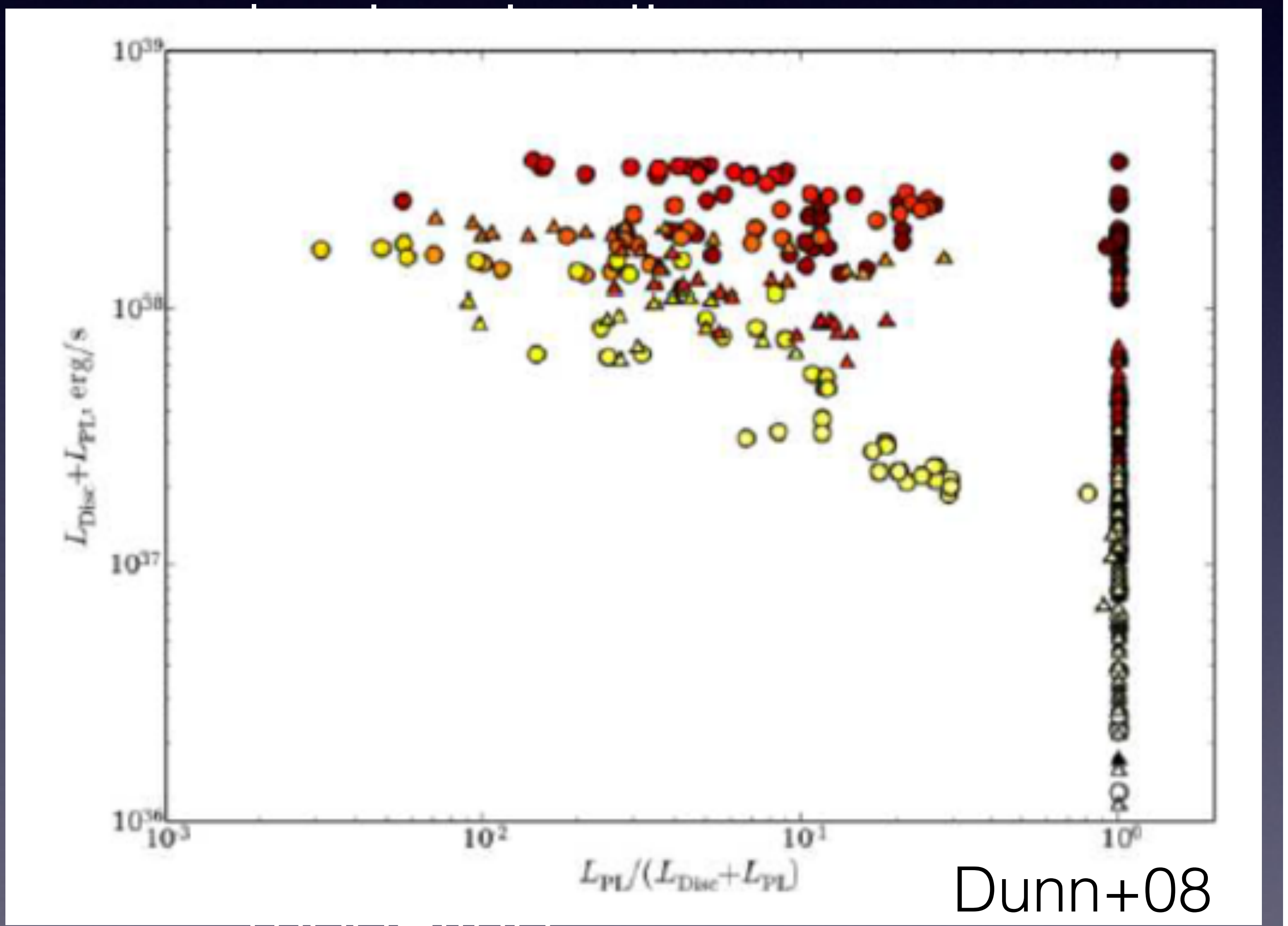
Disc/PL fraction luminosity diagrams: studying the disc and PL without any spectral fitting

Step-up from hardness ratios: takes into account the whole RXTE spectral band of 3-200 keV, but no reliance on spectral modeling

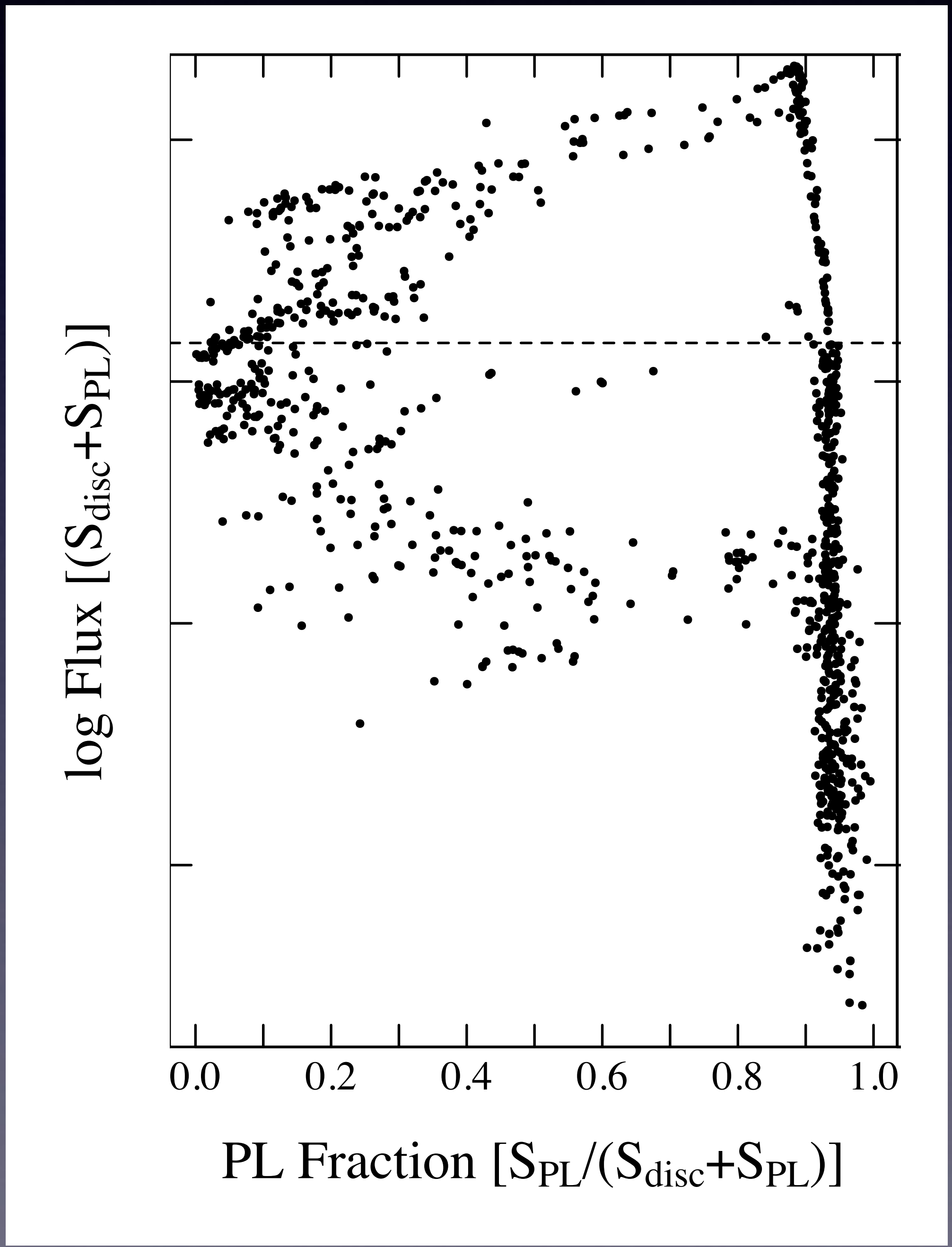
(2) Summing components based on their weight (Koljonen 2015)

All RXTE observations of GX 339-4

Disc/PL fraction



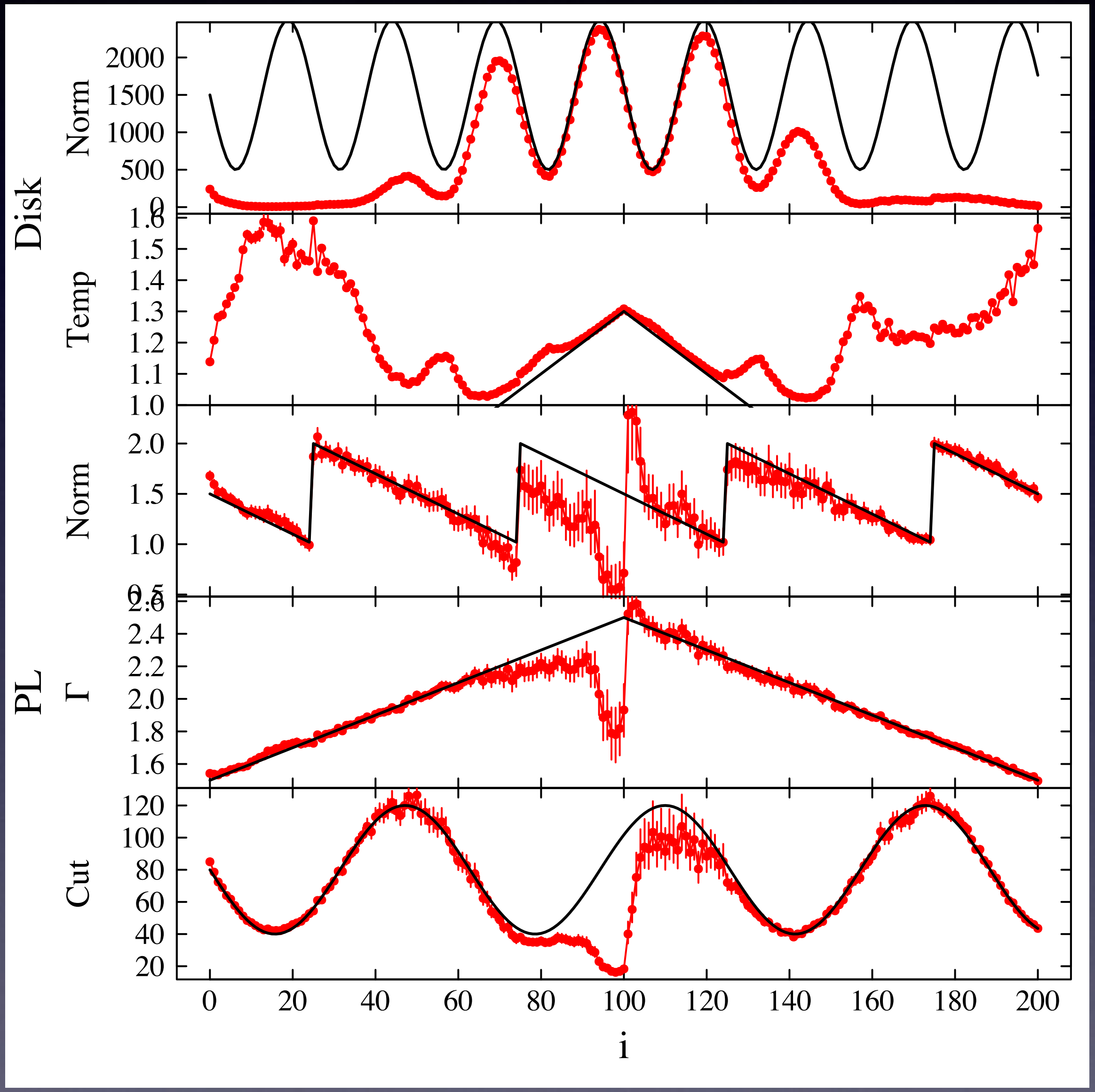
modeling



(2) Summing components based on their weight (Koljonen 2015)

Based on the non-negative nature of NMF the factorised disc and power law components can be fed separately for spectral fitting to obtain values for different spectral parameters.

The parameters of the spectral components are fairly well constrained in high flux regimes.



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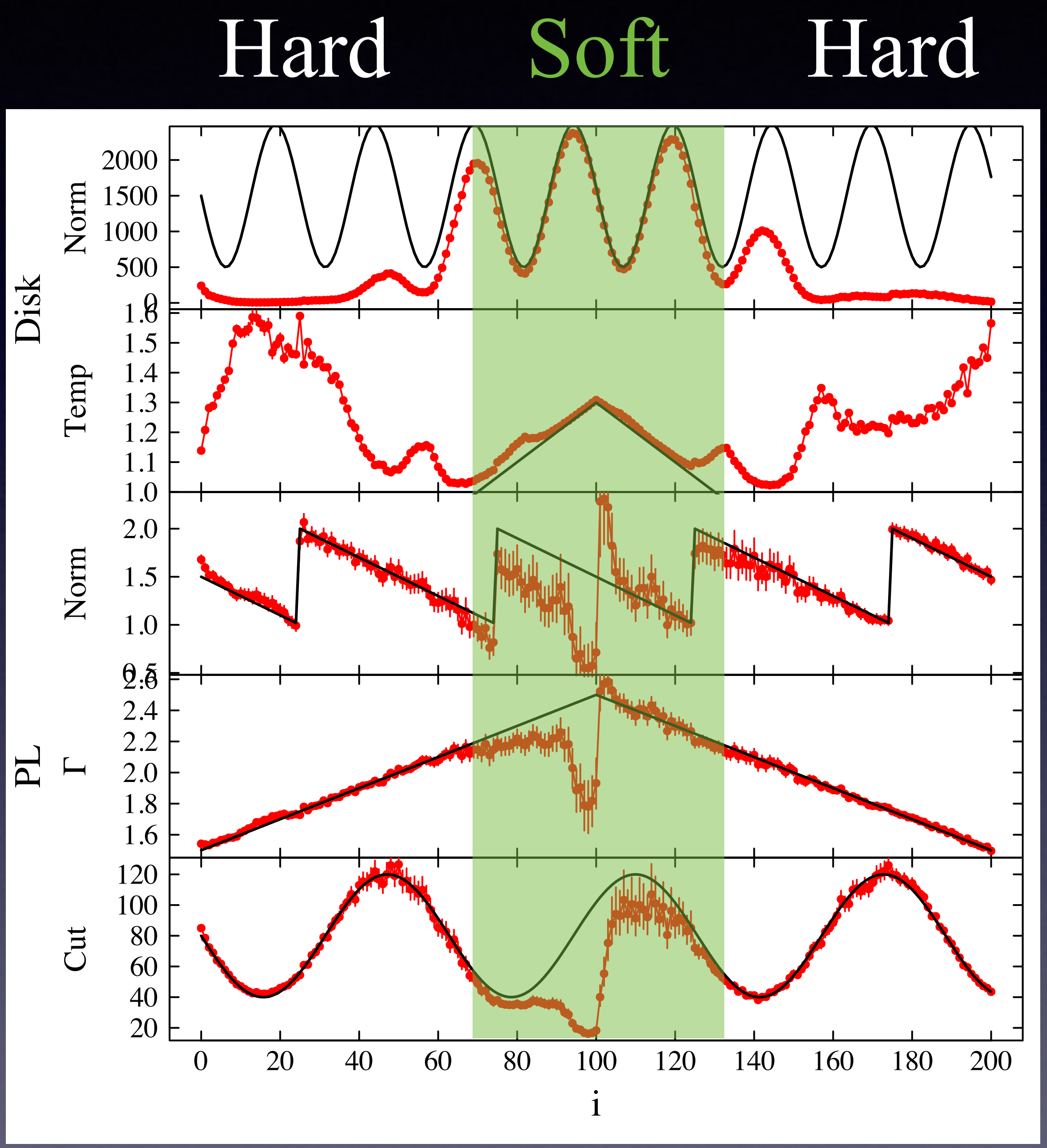

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NMF the factori
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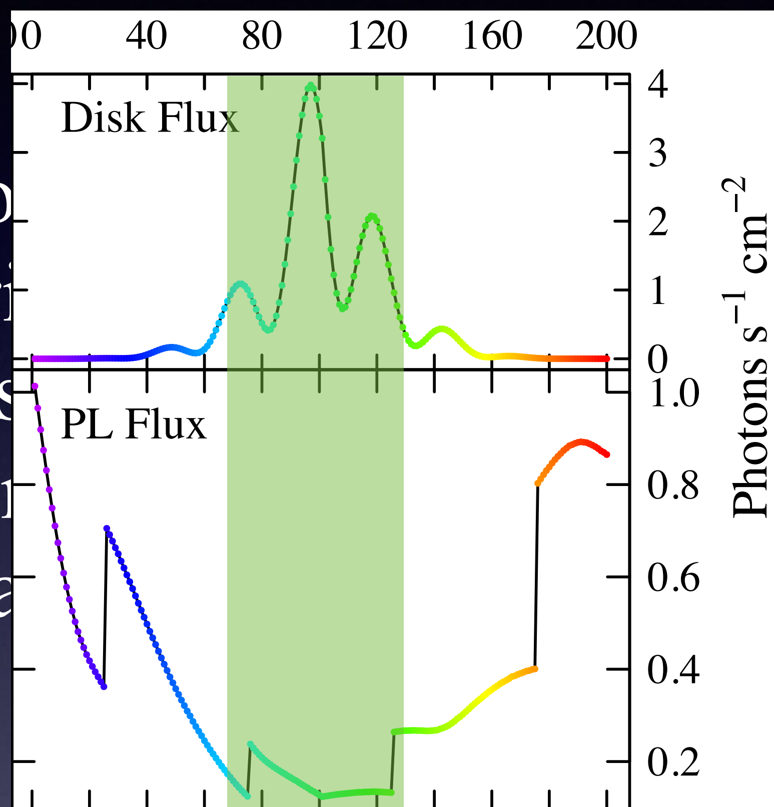

The parameters
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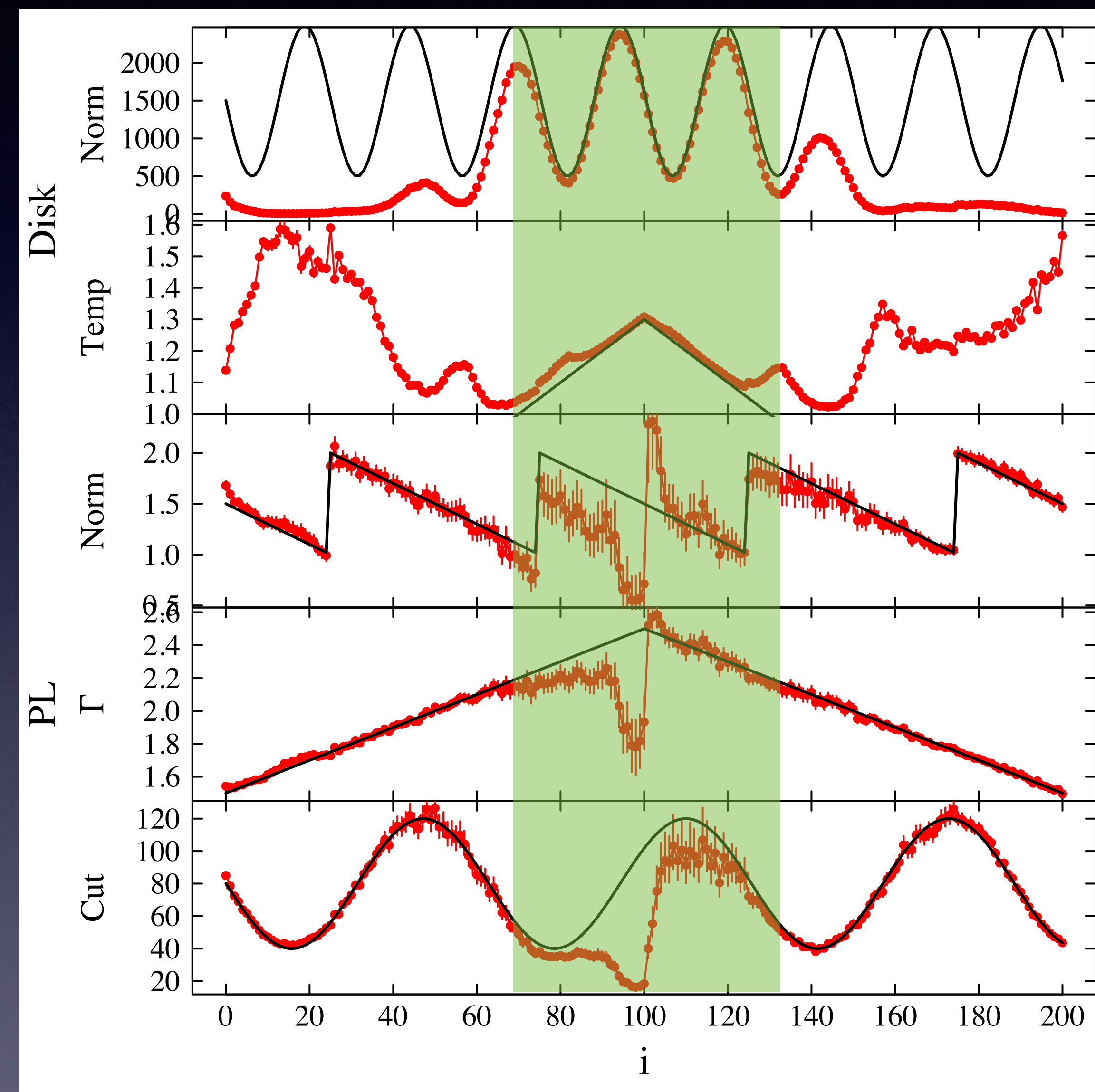
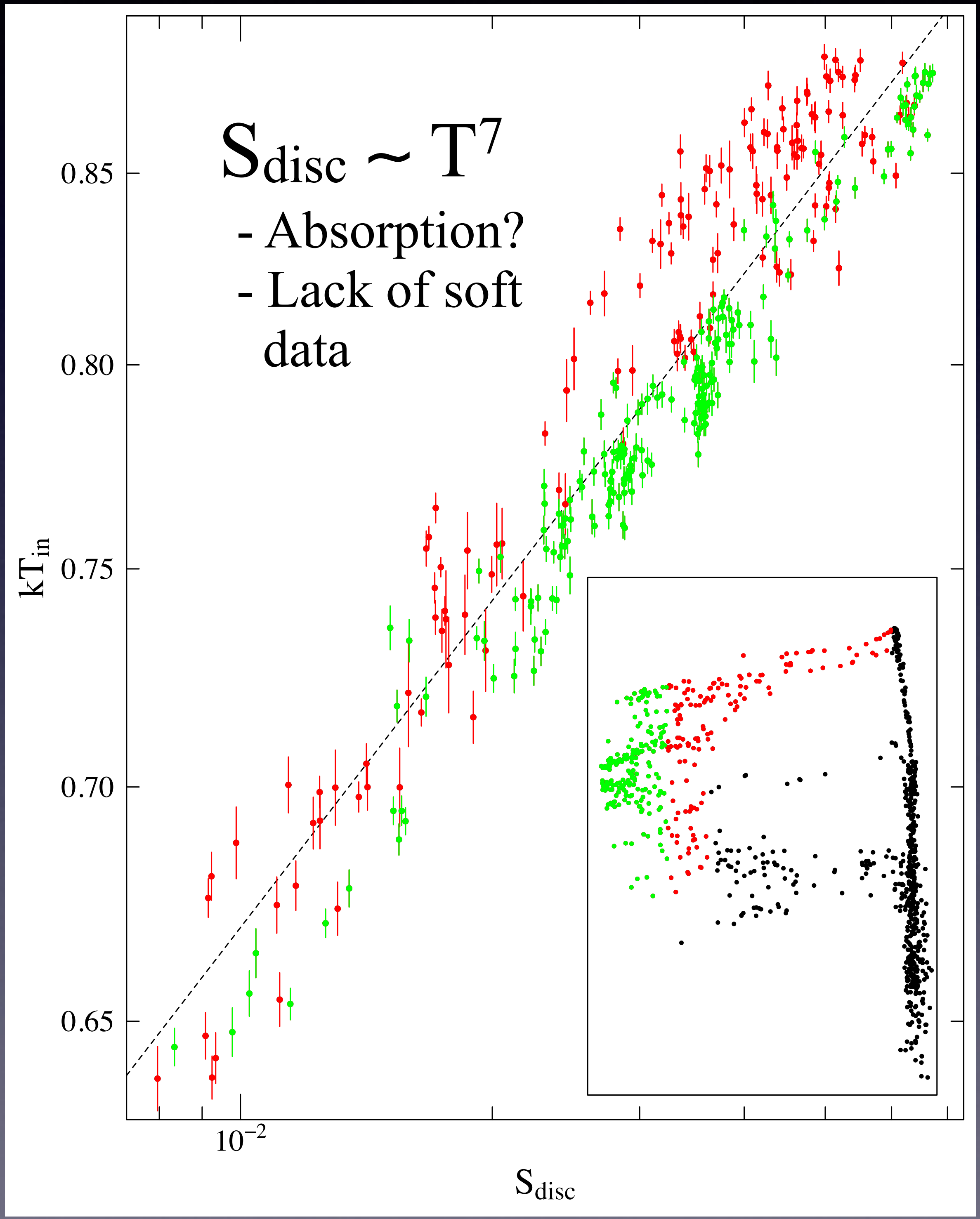
constrained in high flux regimes.

Hard Soft Hard



RXTE decomposition of black hole XRB GX 339-4

- At the soft state the disc luminosity is driven by the $S_{disc} \sim R_{in}^2 T^4$ -relation.
- It is usually assumed that this relation is achieved when the inner disc is located at the ISCO, though a multiple factors can affect this scaling (Salvesen et al. 2013).
- Here $S_{disc} \sim T^7$, but is affected by absorption and the lack of data softer than 3 keV (e.g. Dunn+08 show $S_{disc} \sim T^{4.7}$, for PL fraction < 0.2, when extending the model to lower energies and removing the absorption.
- The disc-temperature relation starts right after the transition to the soft state, i.e. the inner disc seems to be at the ISCO in the beginning of the intermediate state.



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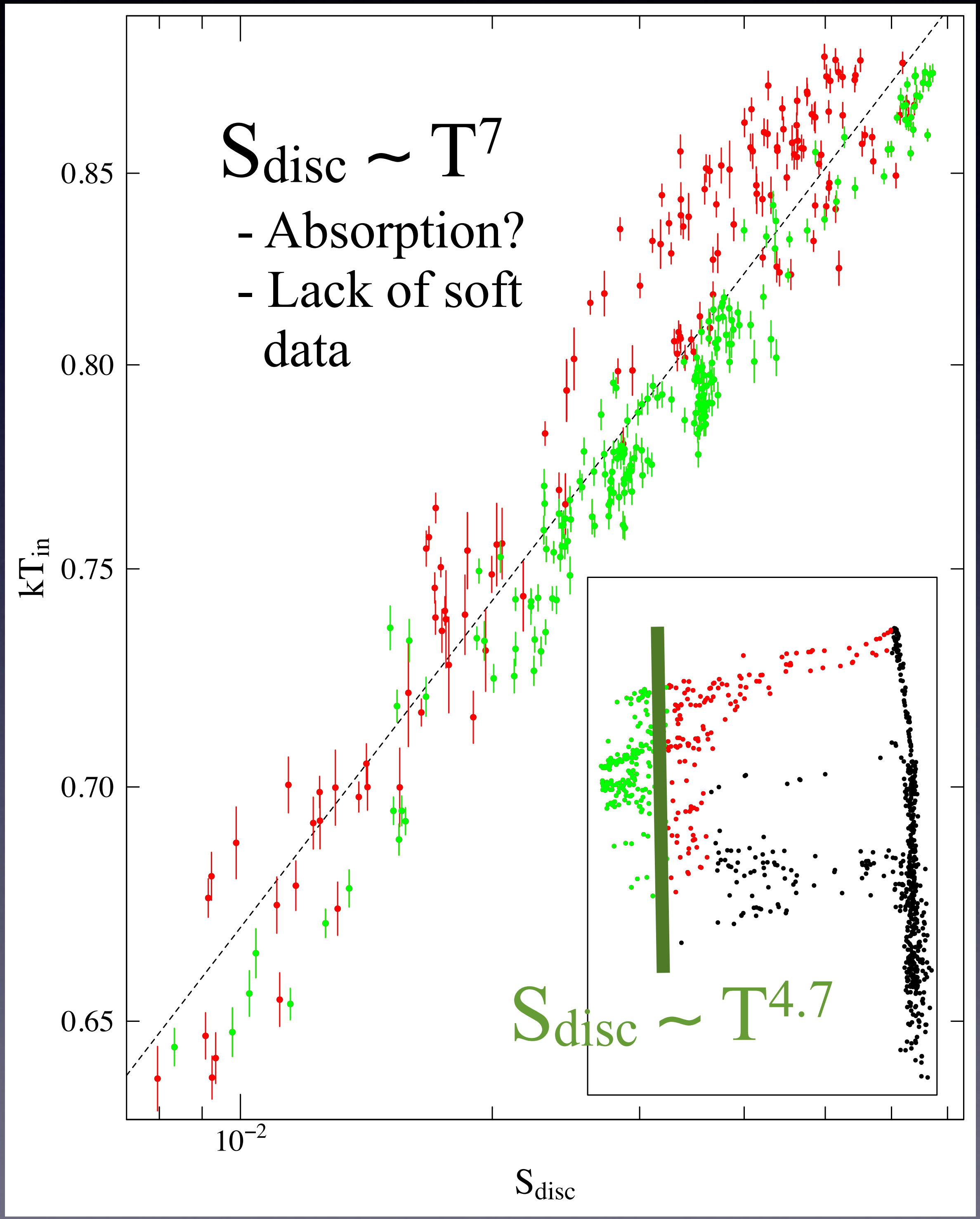
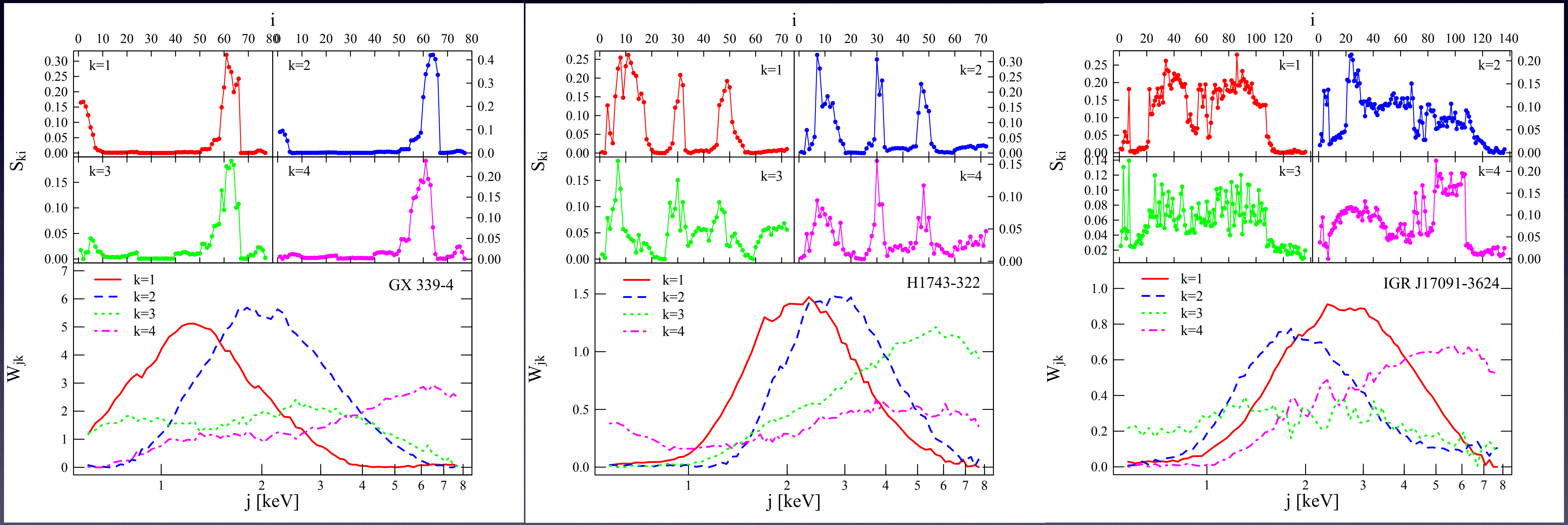


Swift/XRT decomposition of black hole XRBs

GX 339-4 H1743-322 IGR J17091-3624

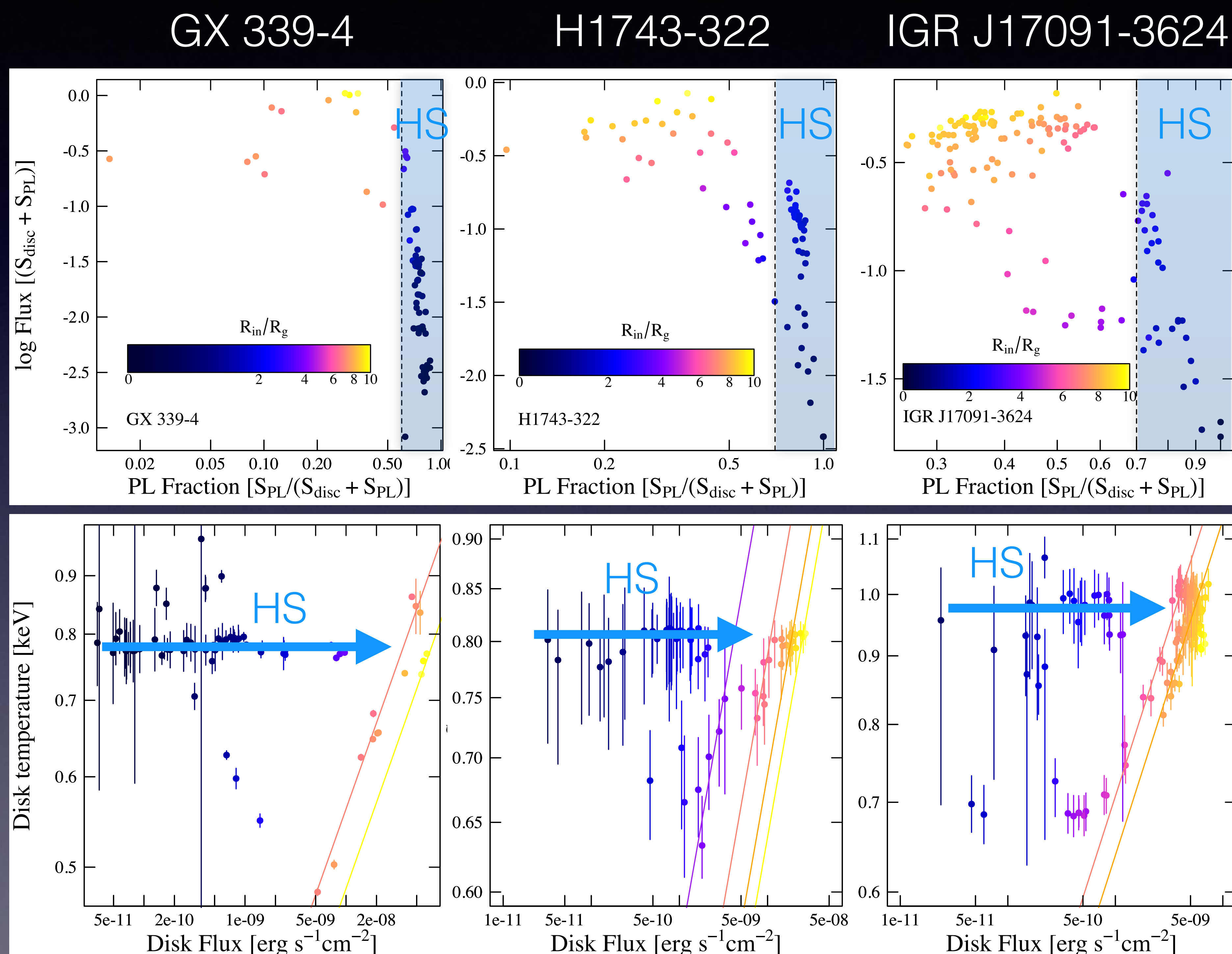


Koljonen 2015, in prep.

The NMF component layout for individual Ski (top four panels) and Wjk (bottom panel) that are sufficient to explain most of the variability and X-ray spectra of each source. k = 1, 2 can be clearly designated as the disc component, and k = 3, 4 as the power-law component in all sources.

Swift/XRT decomposition of black hole XRBs

Inner radius of the accretion disc @ ISCO, as marked by the L ~ T^4-relations (jumps likely caused by variable color correction factor, inner disk radius, or different conditions in the individual outbursts), in all intermediate and soft states.



Koljonen 2015, in prep.

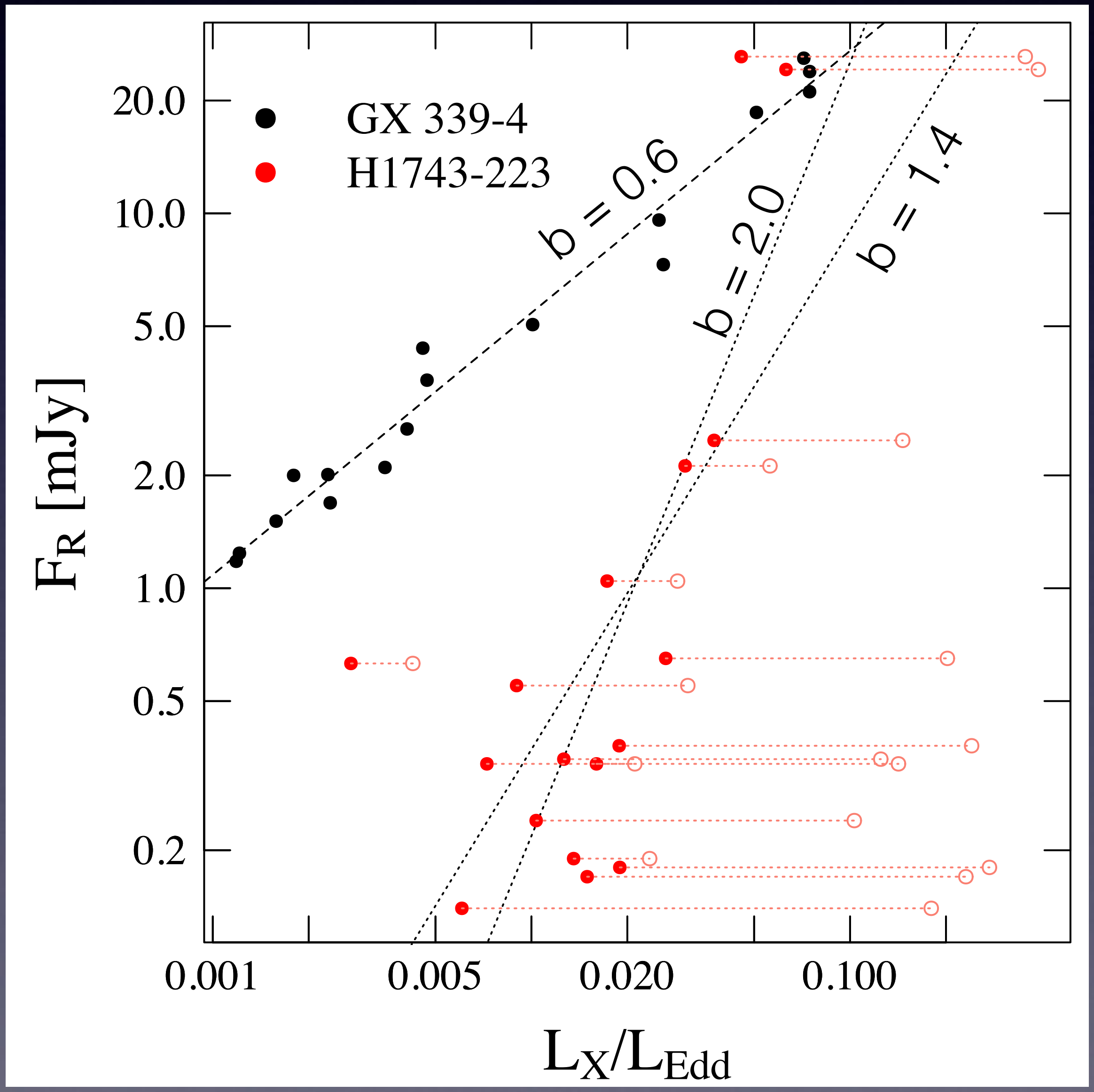
Swift/XRT decomposition of black hole XRBs

L_X/L_R-relation —> $L_{X,PL}/L_R$ relation

Radio data from Corbel+13, Miller-Jones+12, Coriat+11

In the soft state the PL flux traces the same radiatively efficient accretion $L_R \sim L_{X,PL}^{1.4\text{-}2.0}$ track as in the hard state.

$L_R \sim L_{X,PL}{}^b$



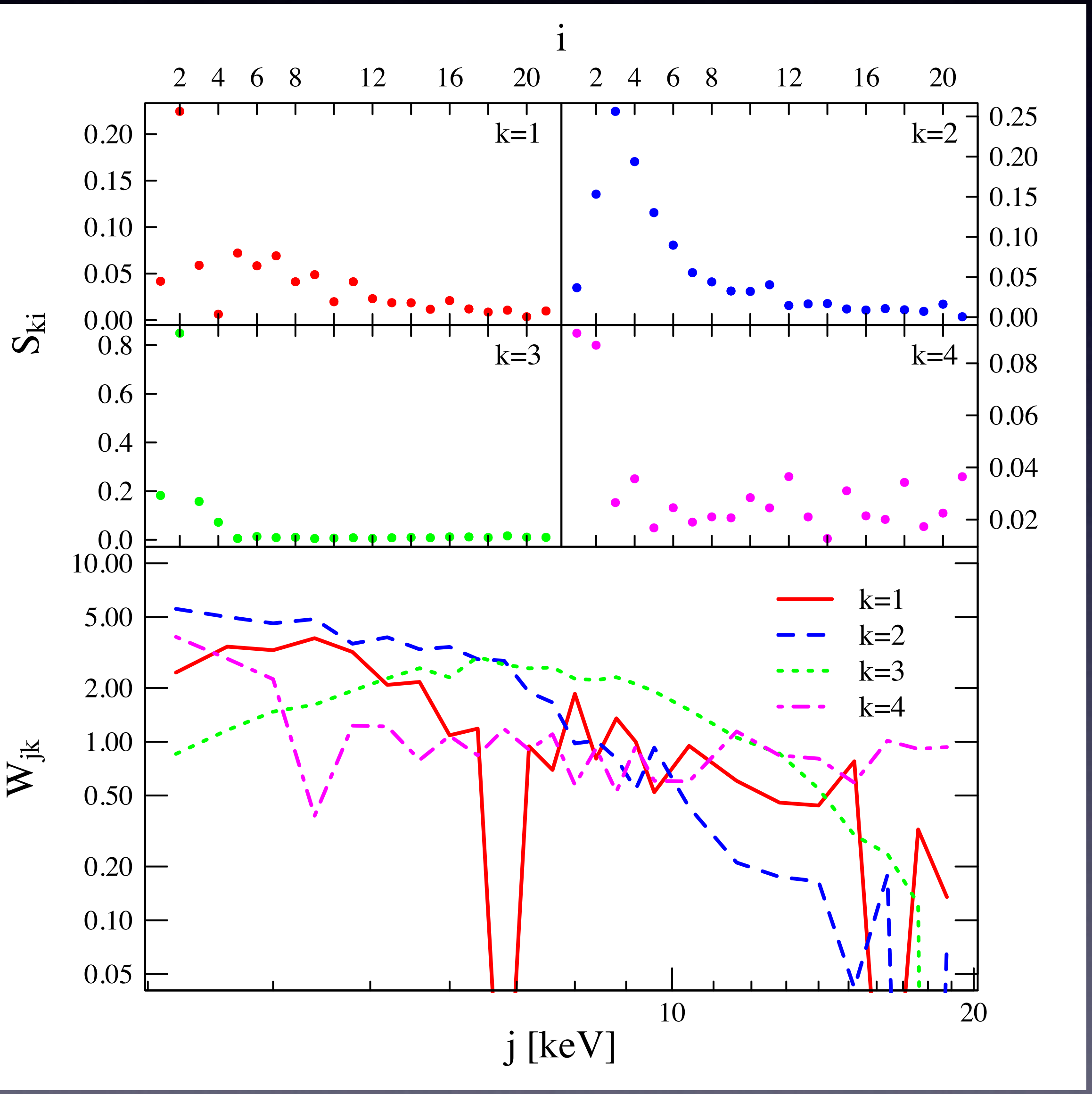
Koljonen 2015, in prep.

Thermonuclear X-ray burst in 4U 1608-52

The burst spectra can be explained by four NMF components.

k = 2, 3, show curvature in weights (W_{jk}), and strong signal (S_{ki}). Can be fitted with a blackbody model of temperature 1-2 keV = burst spectrum.

k = 1, 4, show flat weights and weak signal. Can be fitted with a power law model with index ~ 2, consistent with the pre-burst accretion emission.



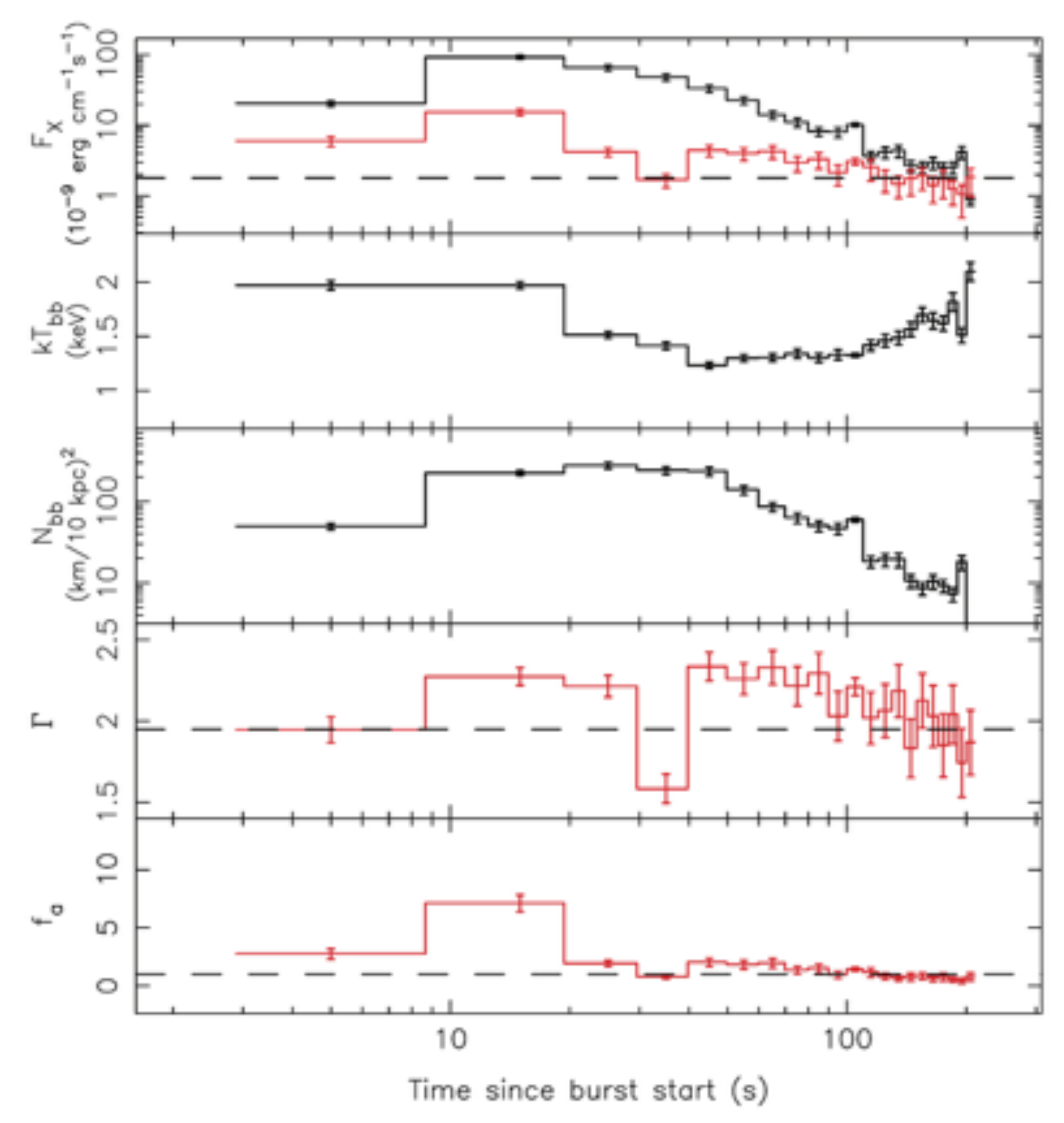
Degenaar, Koljonen, et al. 2015, in prep.

Thermonuclear X-ray burst in 4U 1608–52

Enhancement and change in the shape of pre-burst spectrum.

—> Pre-burst spectrum is not constant!

—> Softening of the pre-burst spectrum by Compton scattering burst photons indicates interaction between the two components



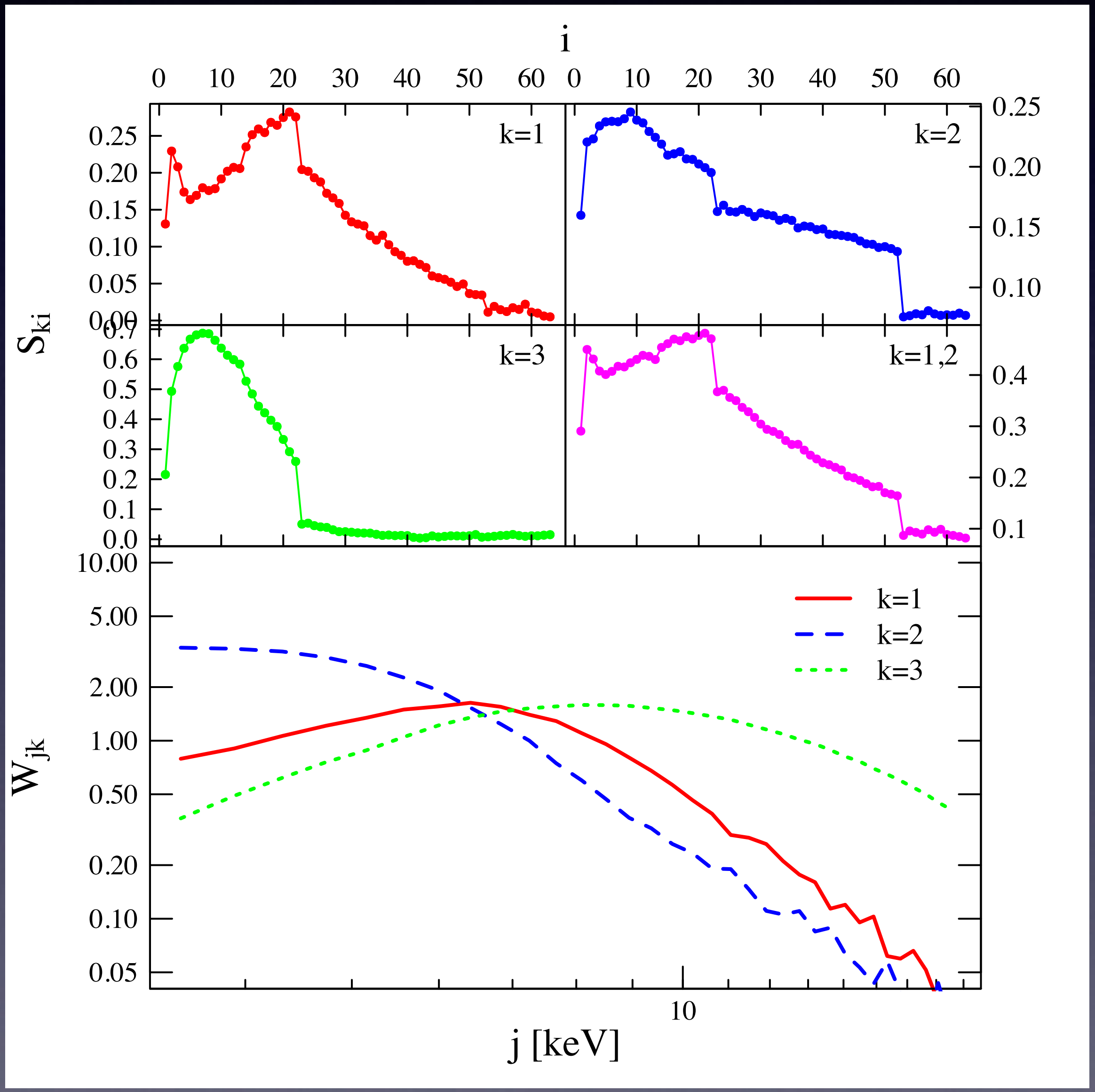
Degenaar, Koljonen, et al. 2015, in prep.

Thermonuclear superburst in 4U 1636–536

The superburst spectra can be explained by three NMF components.

k = 3, is constant and can be fitted approximately by a blackbody with temperature 2.4 keV —> Boundary/spreading layer! (Revnivtsev et al. 2006, Inogamov & Sunyaev 1999). BL/SL brightens by a factor of 30 during the burst. More accurate BL/SL model with comptt.

k = 2, 3, is the burst spectrum. Can be fitted with blackbody with changing temperature and reflection features (iron line, edge).

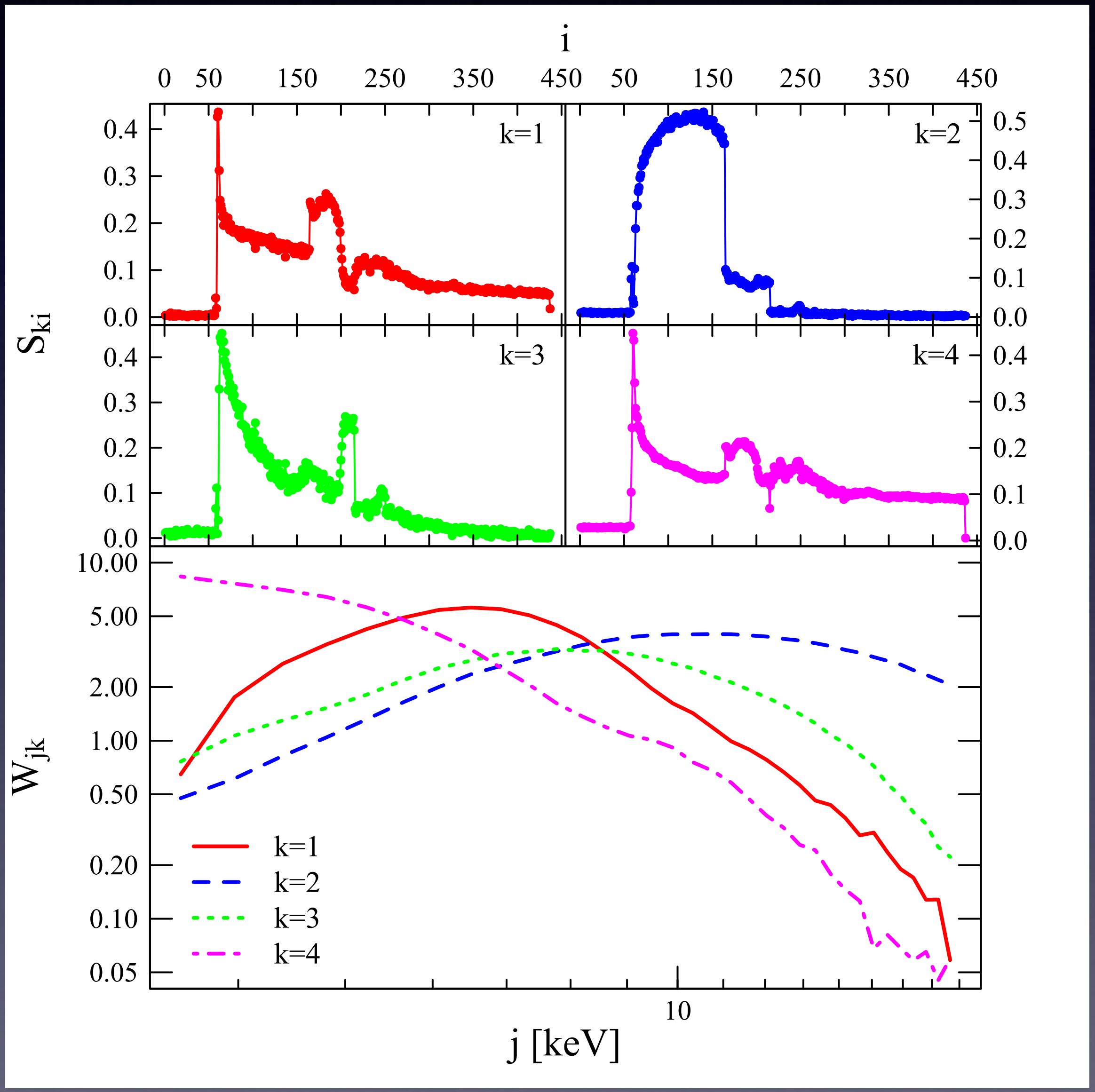


Koljonen, Kajava, et al. 2015, in prep.

Thermonuclear superburst in 4U 1820−303

The superburst spectra can be explained by four NMF components.

Similar to 4U 1636-536 with burst spectrum (k=1,3,4) and SL/BL (k=2). Differences arise from being ultra-compact binary, and exhibiting photospheric radius expansion (PRE). In the tail also interesting flickering.



Koljonen, Kajava, et al. 2015, in prep.

Conclusions

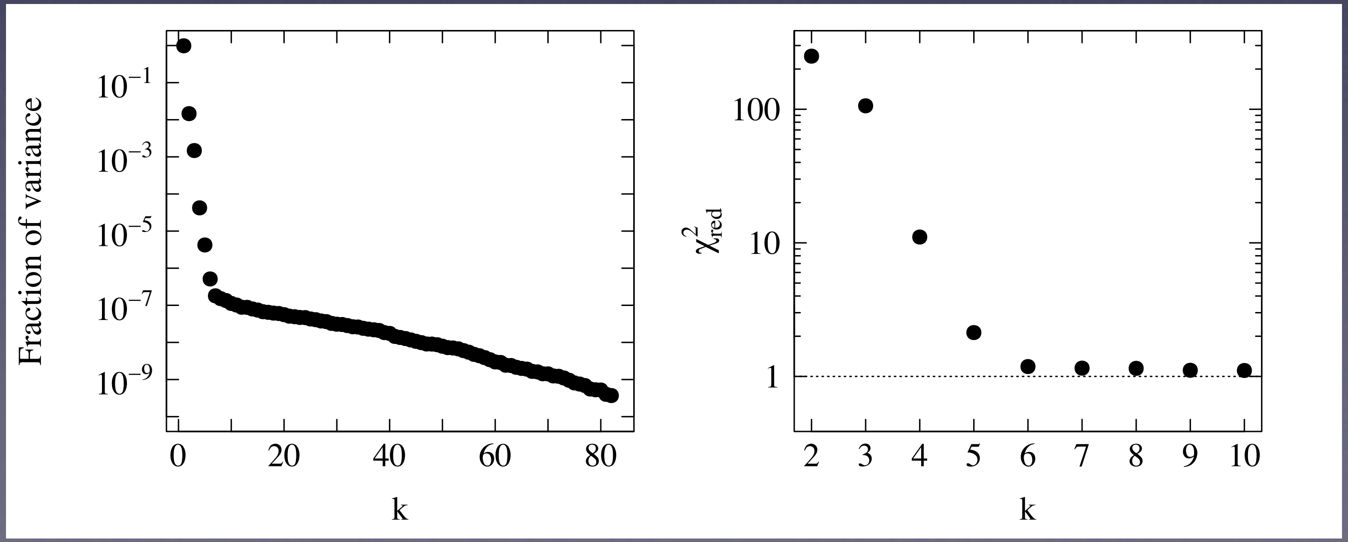
- Spectral degeneracy is a problem in many situations despite excellent quality of the data.
- Unsupervised linear spectral decomposition methods are powerful tool to examine spectral variability and can be used to follow the evolution of distinct spectral components (given that they present a measurable effect to the fluxes).
- The non-linearities present in the original spectral components can be taken into an account by adding multiple linear components together based on their weights across the spectral energies.
- An analysis of a large sample of bright variable AGN has revealed a large number of different variability patterns. These patterns can be matched to the predictions from simulations to unambiguously determine the nature of the variability in each source
- Analysis of XRB data indicates that the inner edge of the disk is at the ISCO during soft and intermediate X-ray states.
- Analysis of thermonuclear superburst revealed BL/SL emission with constant spectrum but varying in normalization by a factor of 30, and a pre-burst spectrum

Determining the degree of factorisation

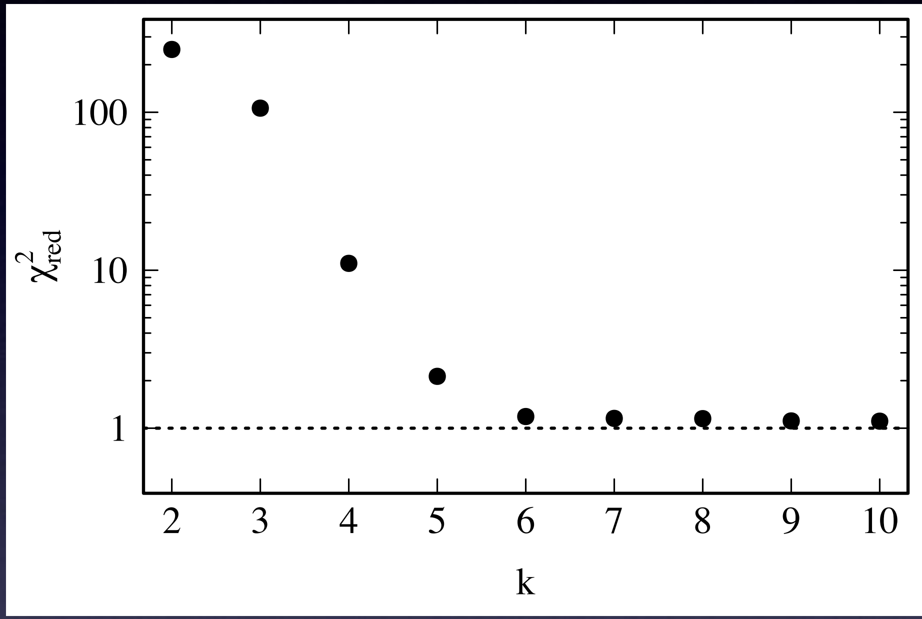
- How many components?
  - PCA: Fraction of variance (LEV diagram), X^2-diagram
  - ICA: X^2-diagram
  - NMF: X^2-diagram
- All agree on 6 components

$$\chi^2_{\mathrm{red}} = Mdn\left\{\sum_i\left[\left(X_{ji}-\sum_k W_{jk}S_{ki}\right)\times\sigma_{ji}^{-1}\right]^2\times(\max(j)-k)^{-1}\right\}$$

PCA



ICA



NMF