Unsupervised spectral decomposition of X-ray binaries with application to GX 339-4

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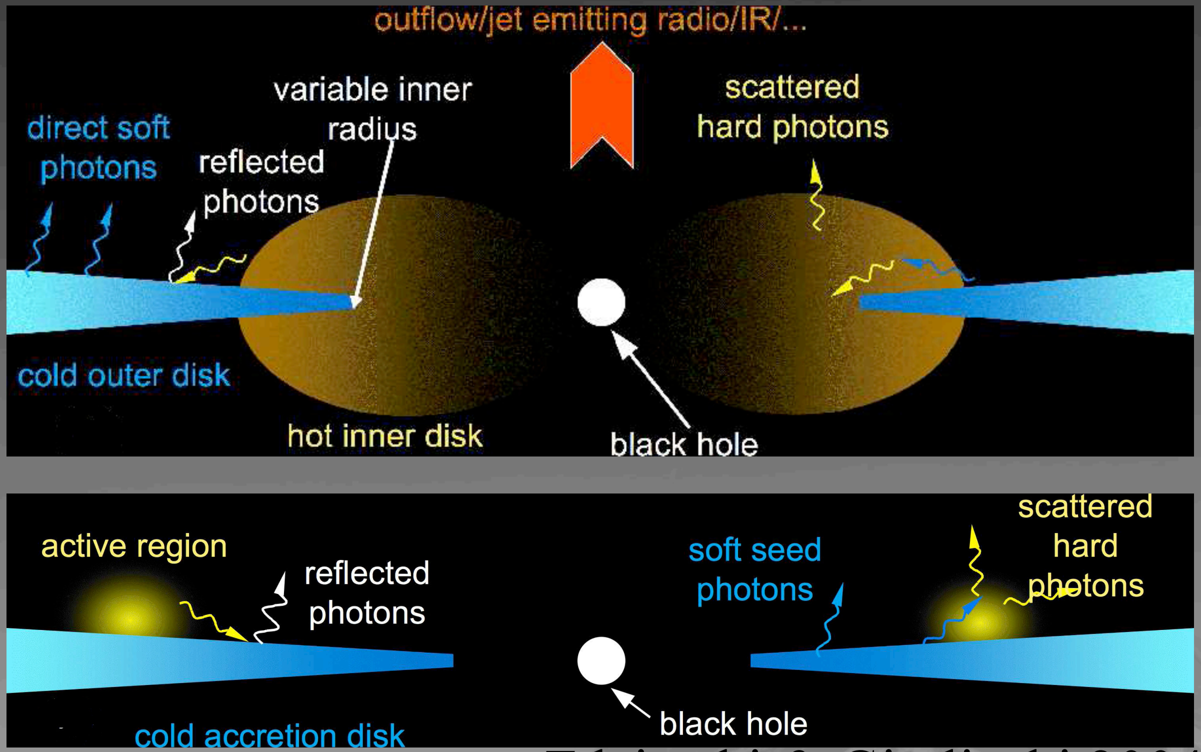
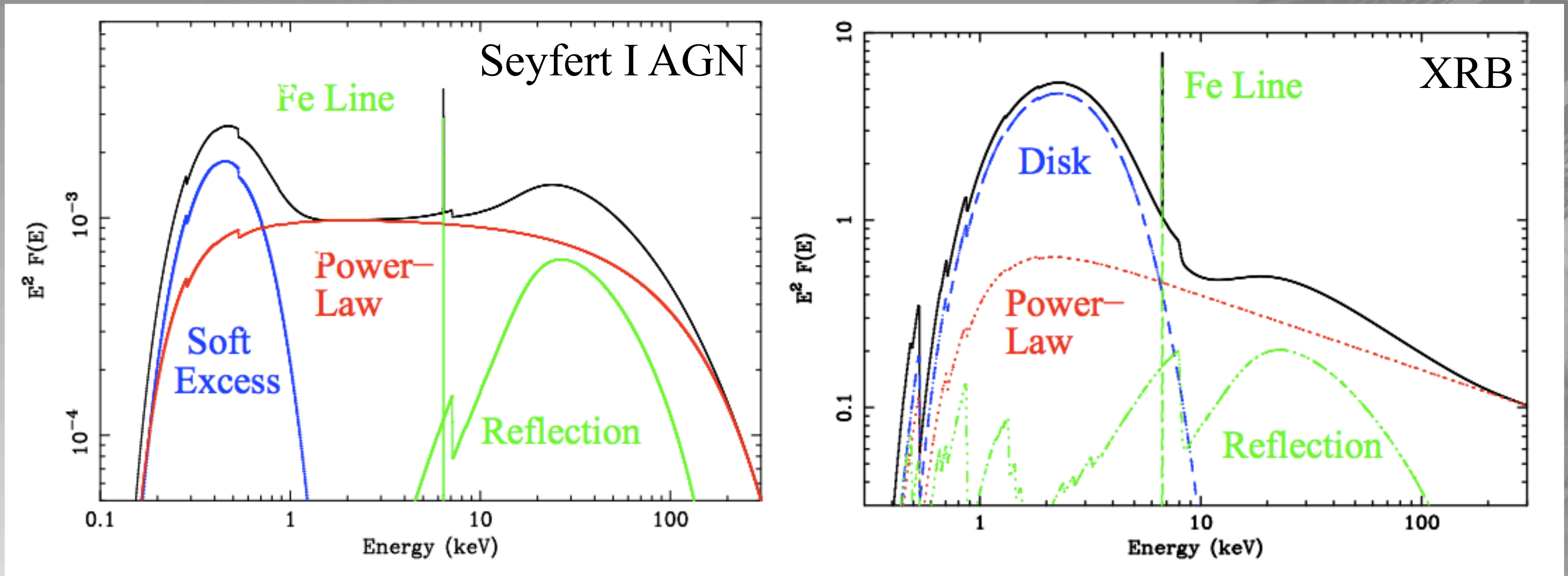
Canonical spectral components

Usually three main spectral components are enough to explain the varying X-ray spectra of accreting sources

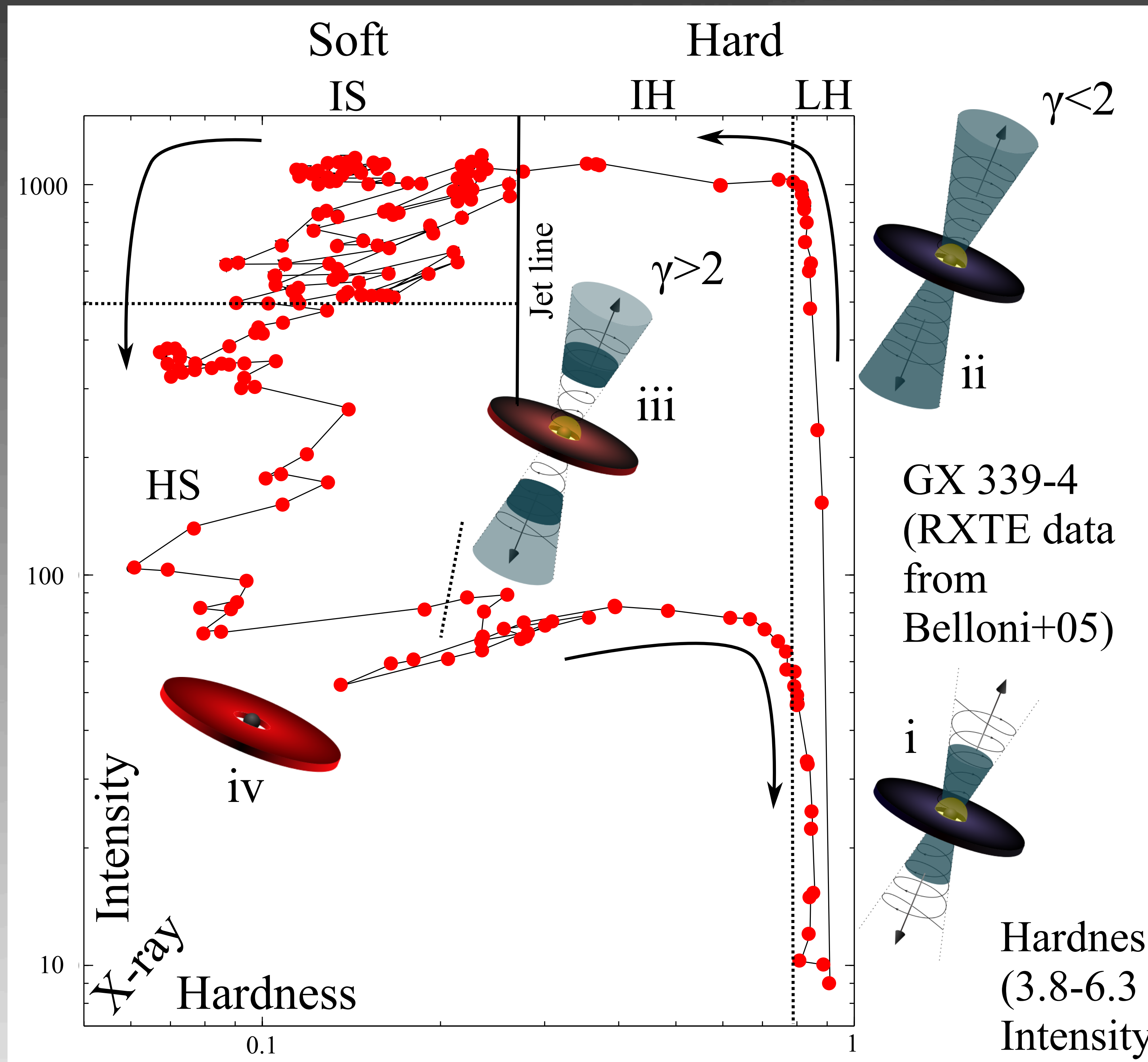


Zdziarski & Gierlinski 2004



Miller 2007

But… how they vary across the hardness-intensity diagram?

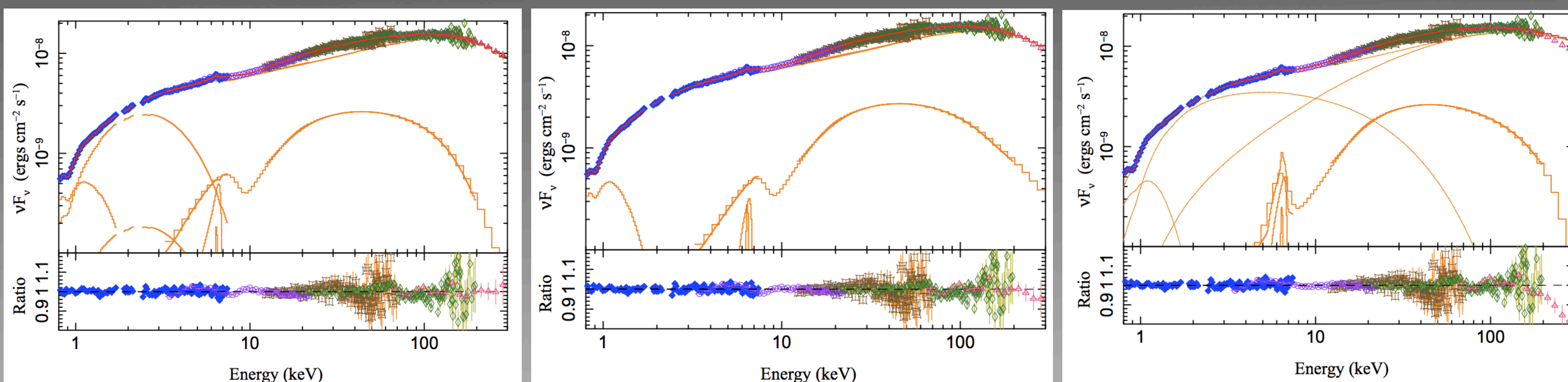


Hardness: (6.3-10.5 keV)/
(3.8-6.3 keV)
Intensity: PCU2 count rate

Also… problems in spectral fitting: multiple spectral models fit the same data

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

Nowak+ 11



thermal Comptonization with a high seed photon temperature

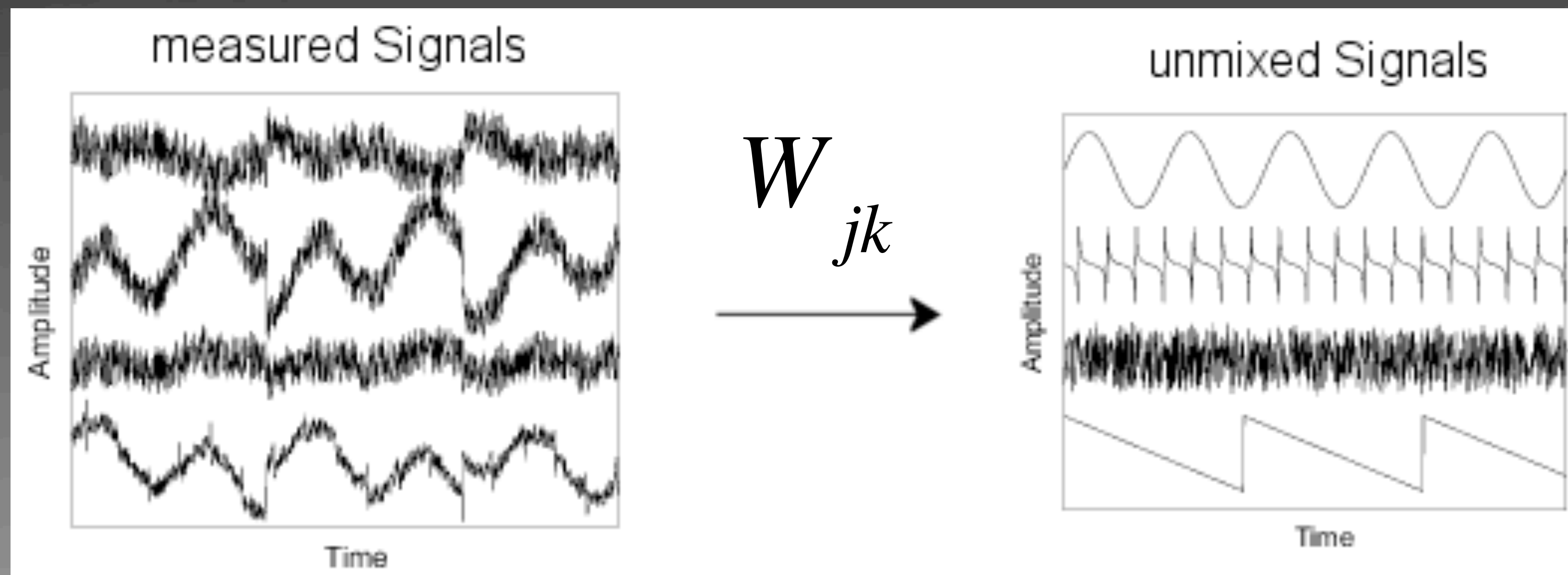
non-thermal Comptonization with a low seed photon temperature

jet model dominated by synchrotron and SSC emission

Clearly there is a need for distinguishing the spectral components that form the total spectra

Blind source separation

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



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

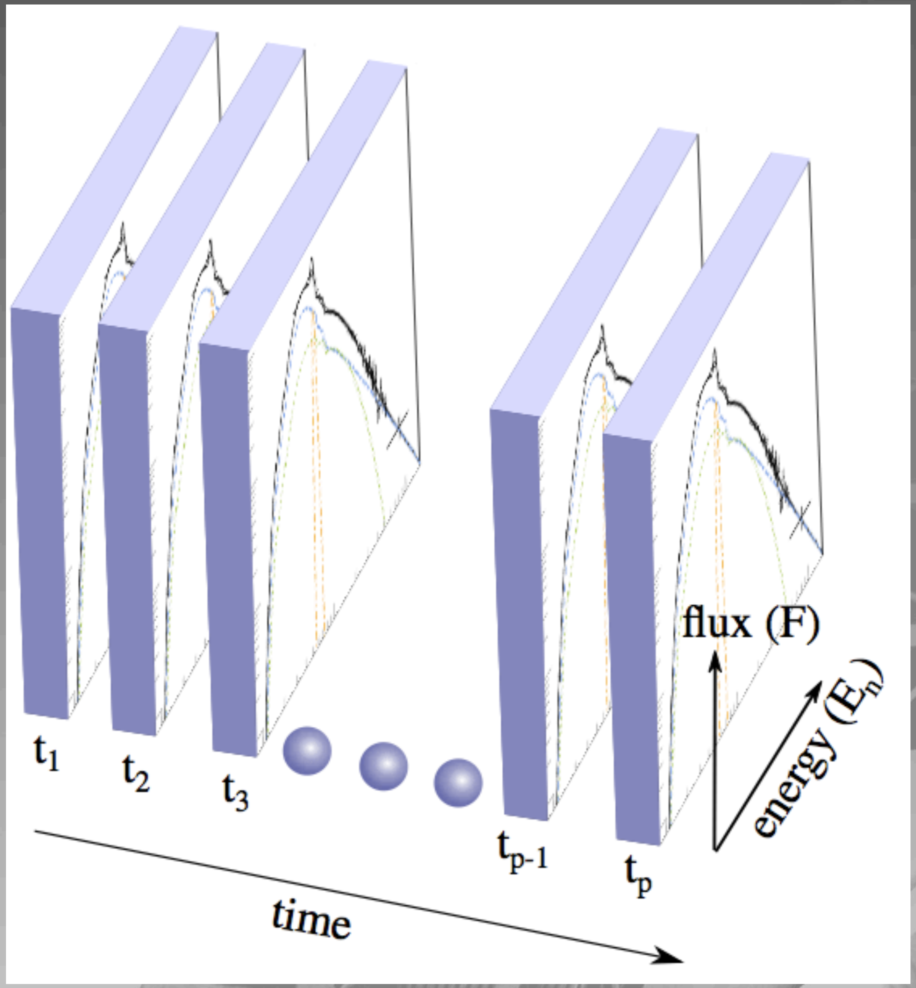
$$X_{ji} \approx \sum_k W_{jk} S_{ki}$$

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 the X-ray spectral data

- Now the mixed signals X_{ji} are lightcurves measured over each energy E_j running over all the observations t_i.
- the 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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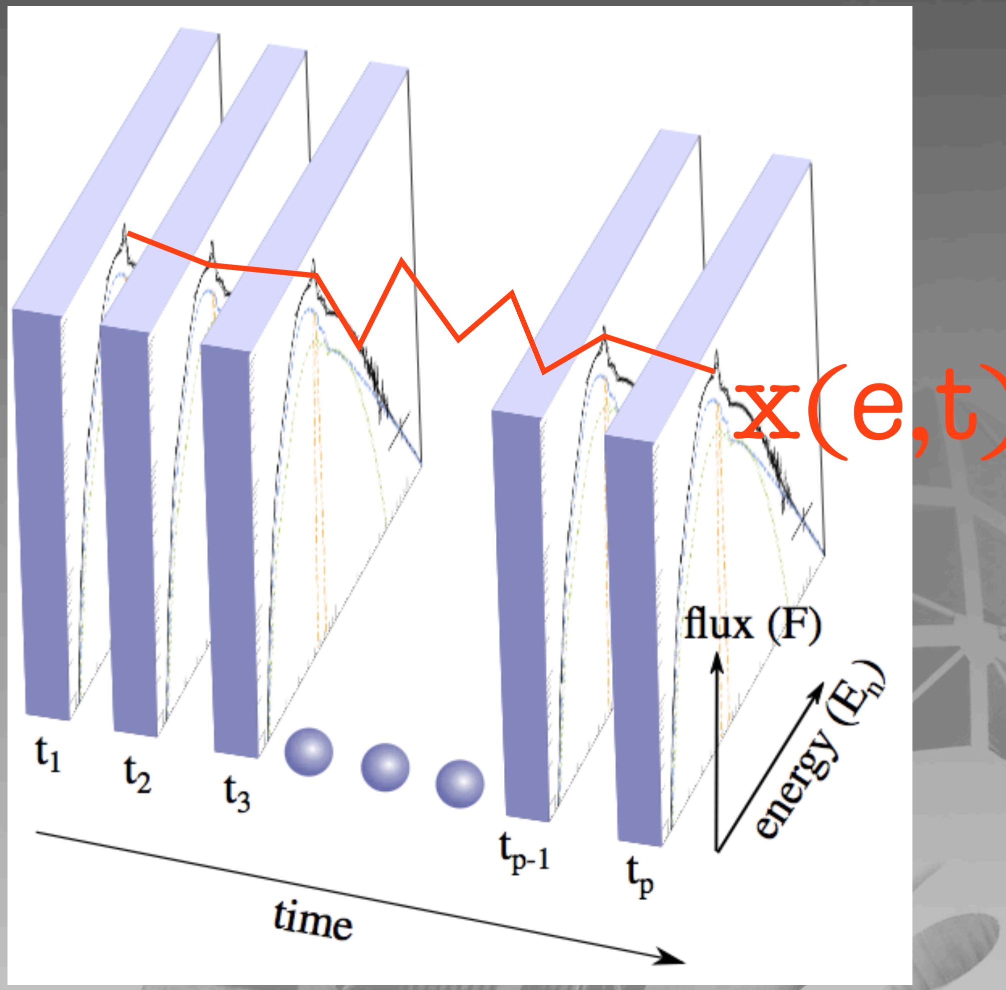

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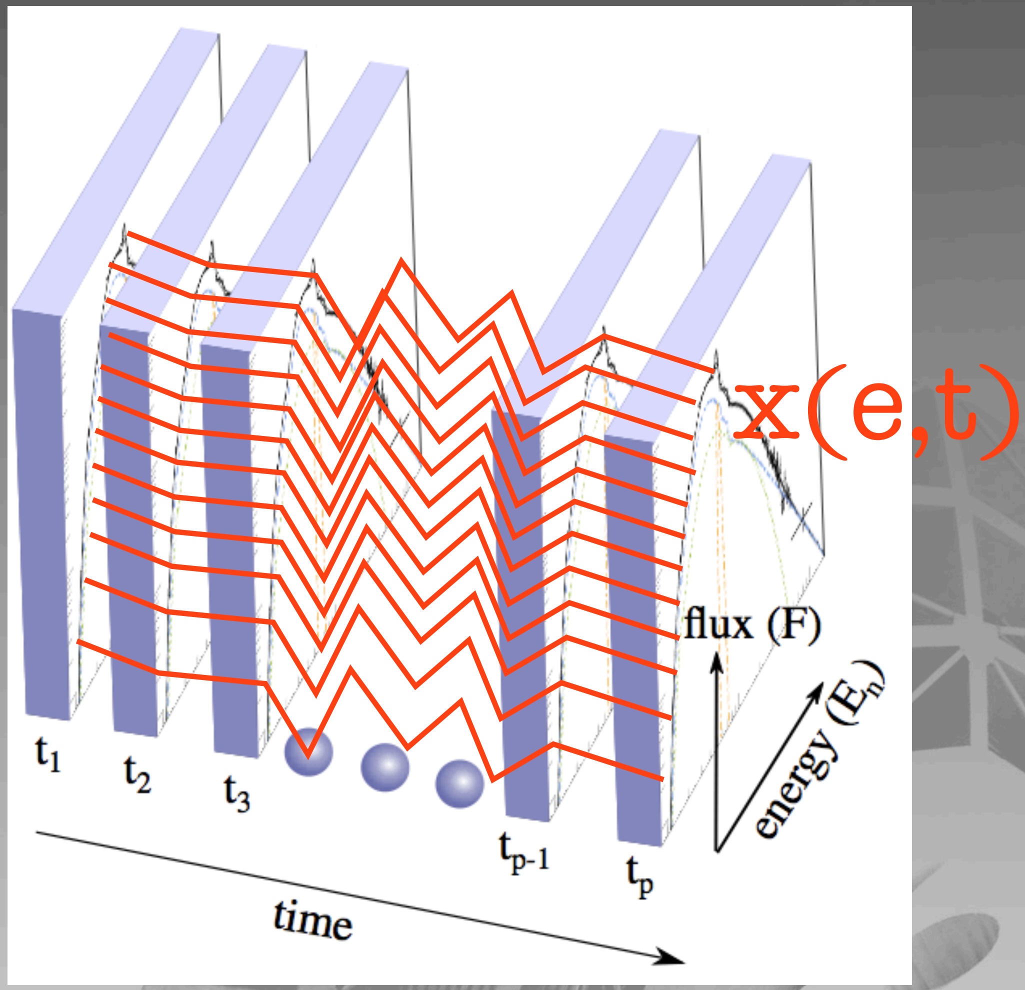

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Unmixing (or factorising) the data linearly

1. Principal component analysis (PCA, e.g. Jolliffe 02)
   - Good: previously used for X-ray spectral decomposition (e.g.Vaughan & Fabian 04, Miller +07/08, Malzac+06, Koljonen+13). Unique solutions.
   - Bad: Tendency to exaggerate or diminish the factorised components. The weights have positive and negative values resulting in pivoting behaviour of the spectra.
2. Independent component analysis (ICA, e.g. Hyvärinen+ 01)
   - Good: Higher order method. Good for noisy data and signal separation.
   - Bad: Same as PCA. No unique solutions.
3. Non-negative matrix factorisation (NMF, Paatero & Tapper 94, Lee & Seung 99)
   - Good: Samples are represented by non-negative combinations of canonical components. Potential to disentangle canonical components which often overlap to create particular community samples.
   - Bad: No unique solution.

Testing the different methods with simulated data

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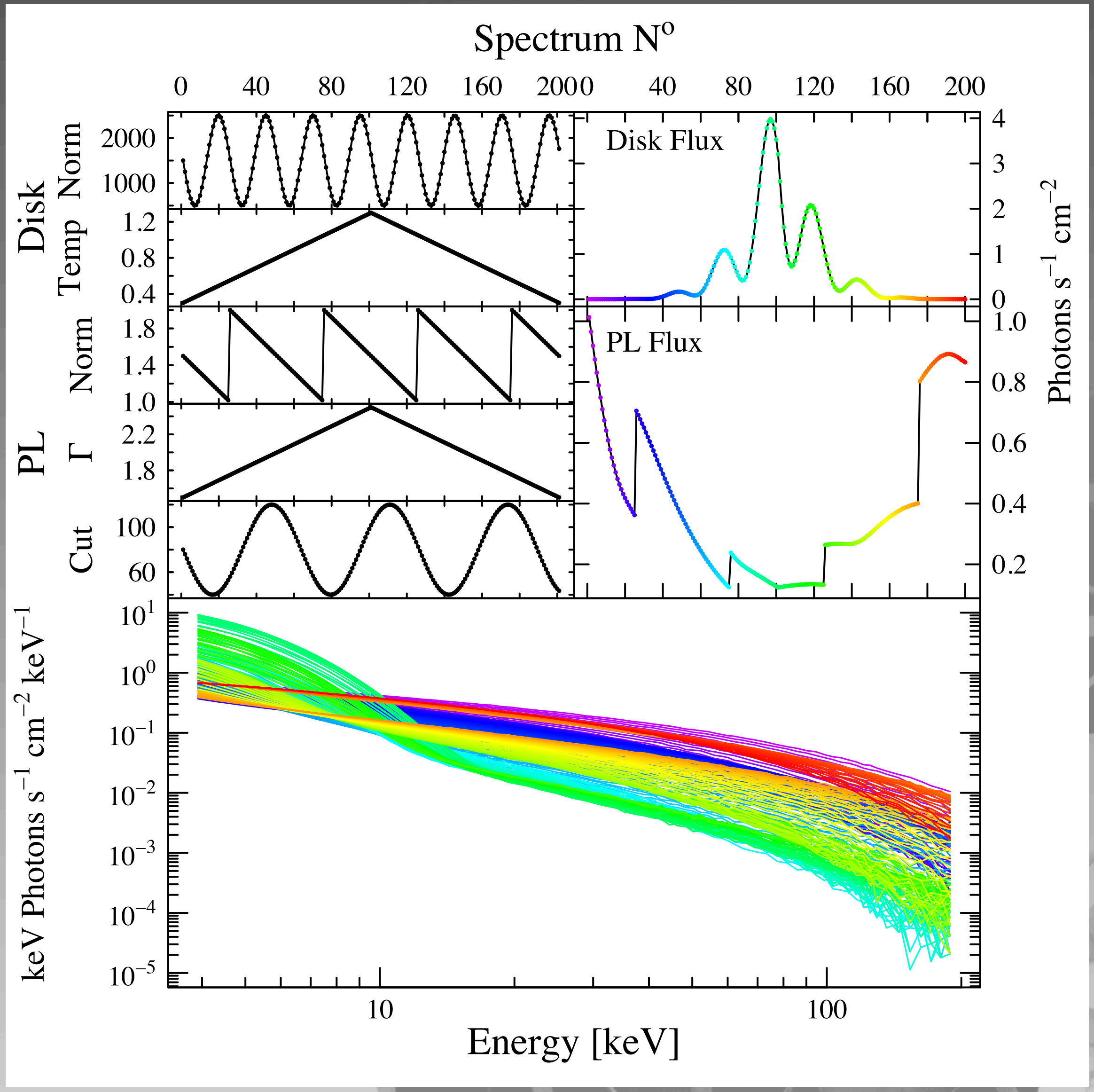


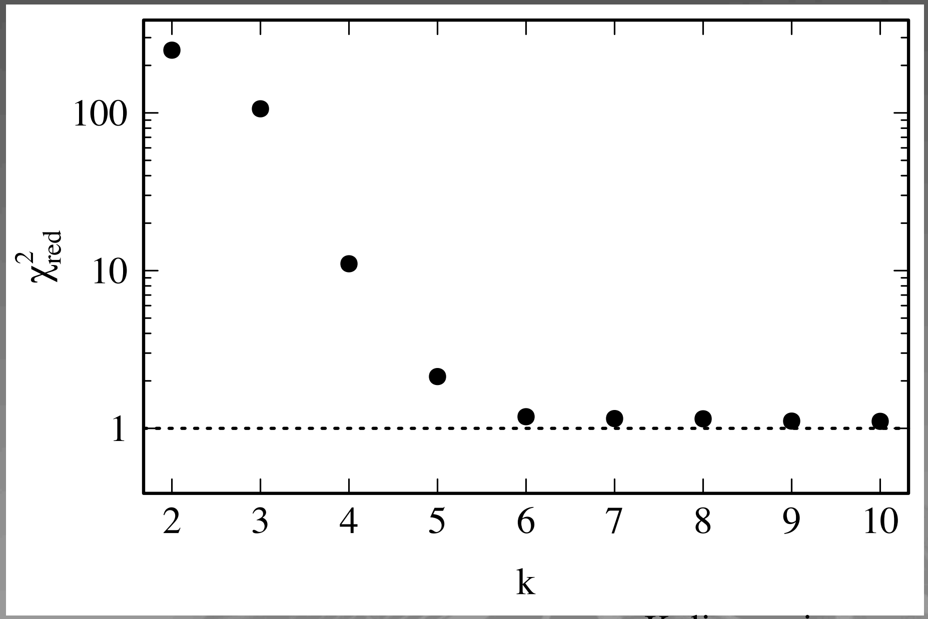
- Mimics the spectral effects that are present in the usual X-ray data of XRBs:
  - variable absorbed disc black body + cutoff power law
- Sine and saw waves as “spectral pathways”
- Soft and hard X-ray states
- We use ISIS (Houck & Denicola 2000) to fake 200 spectra with an exposure of 5 ks

Determining the degree of factorisation

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

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

ICA



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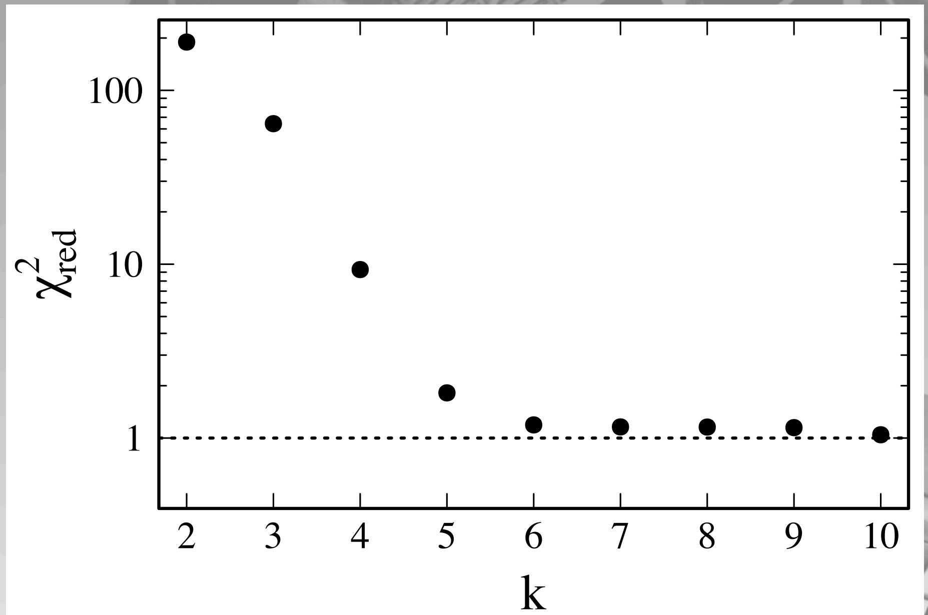
NMF



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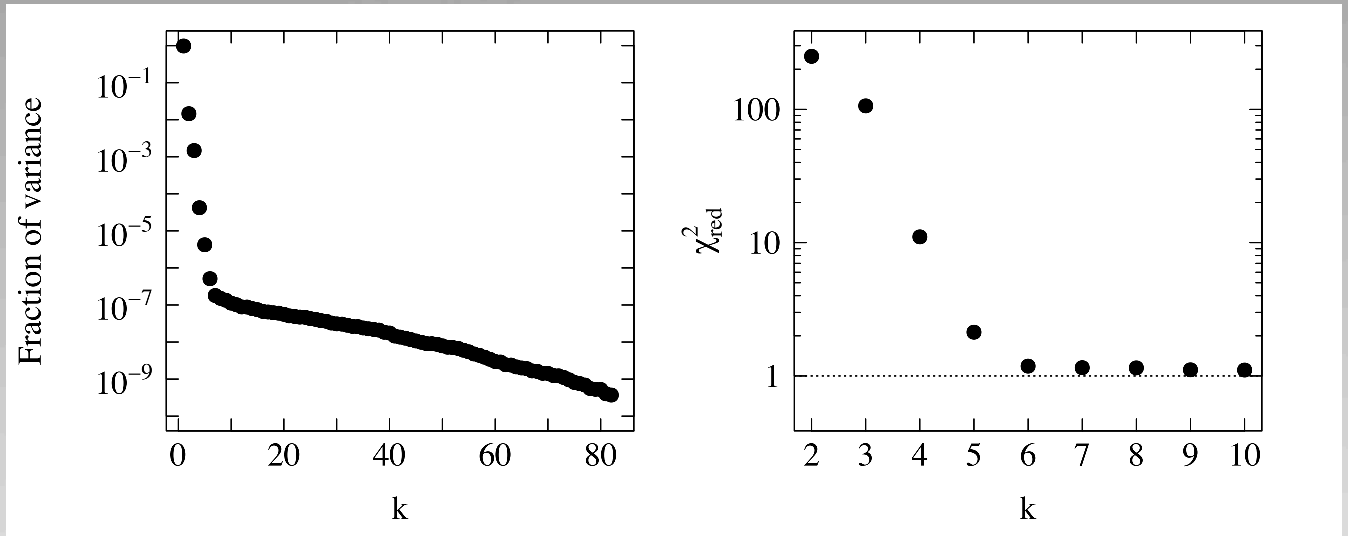
PCA



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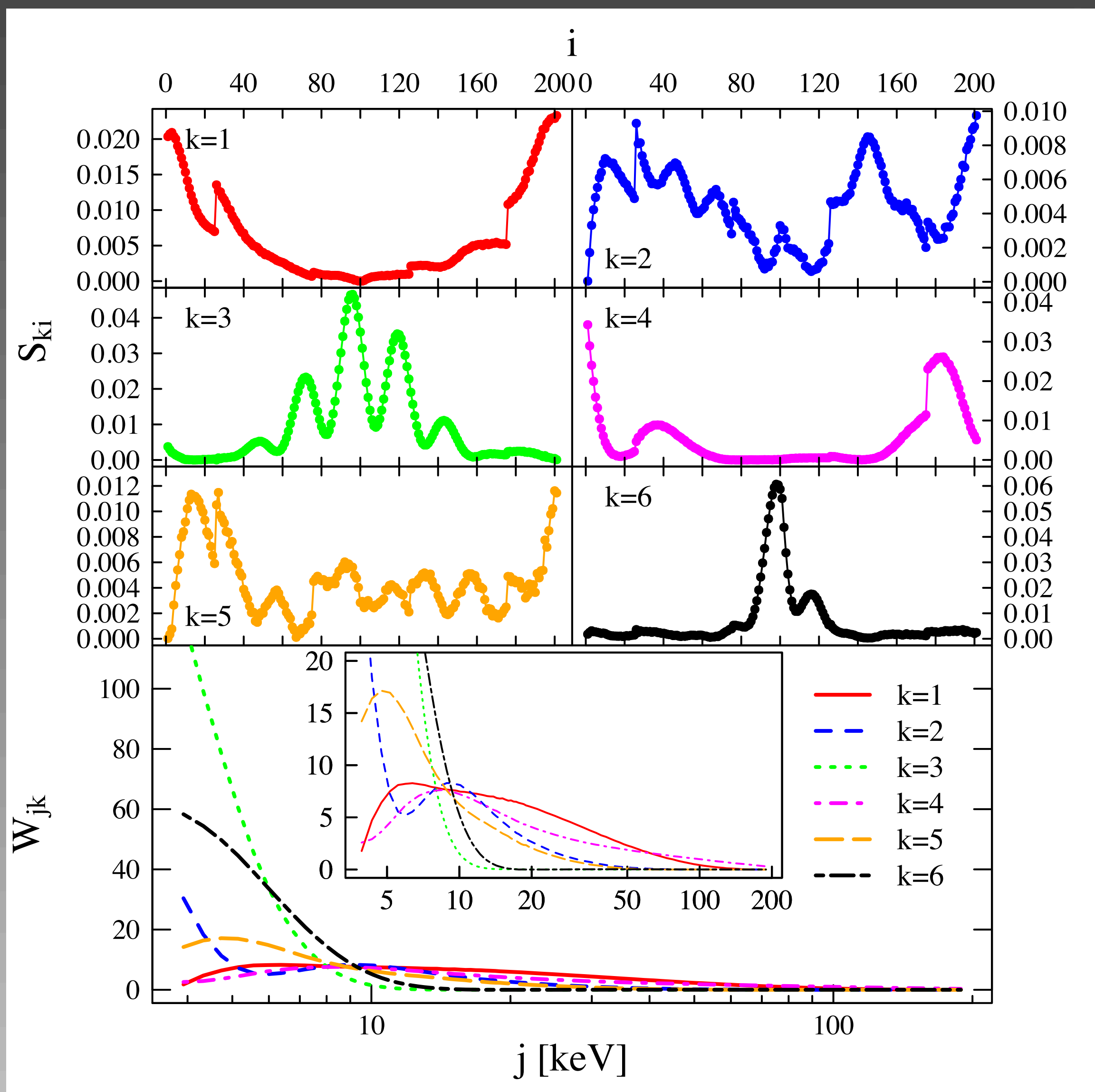
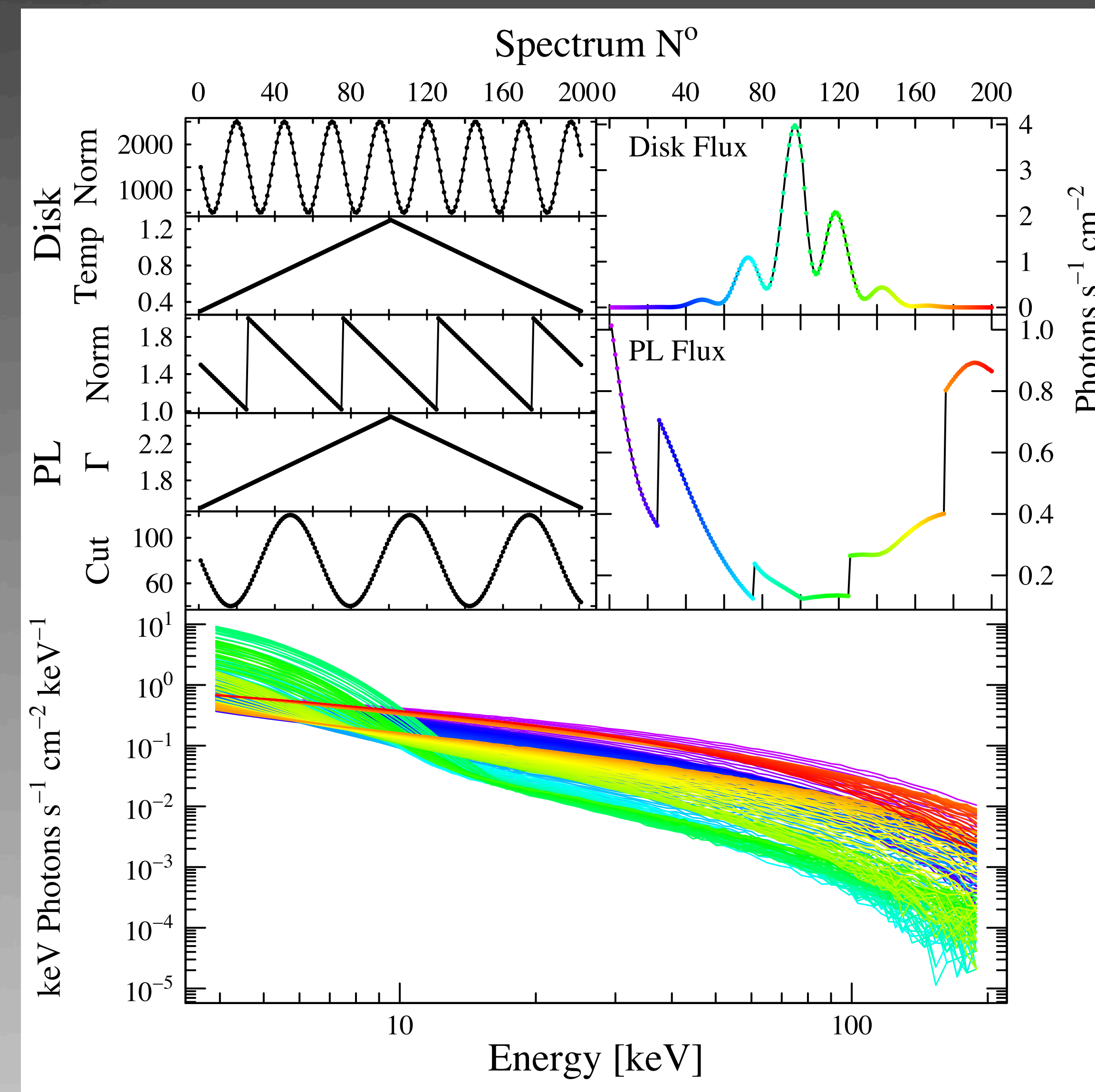
Example of the weights and signals of NMF





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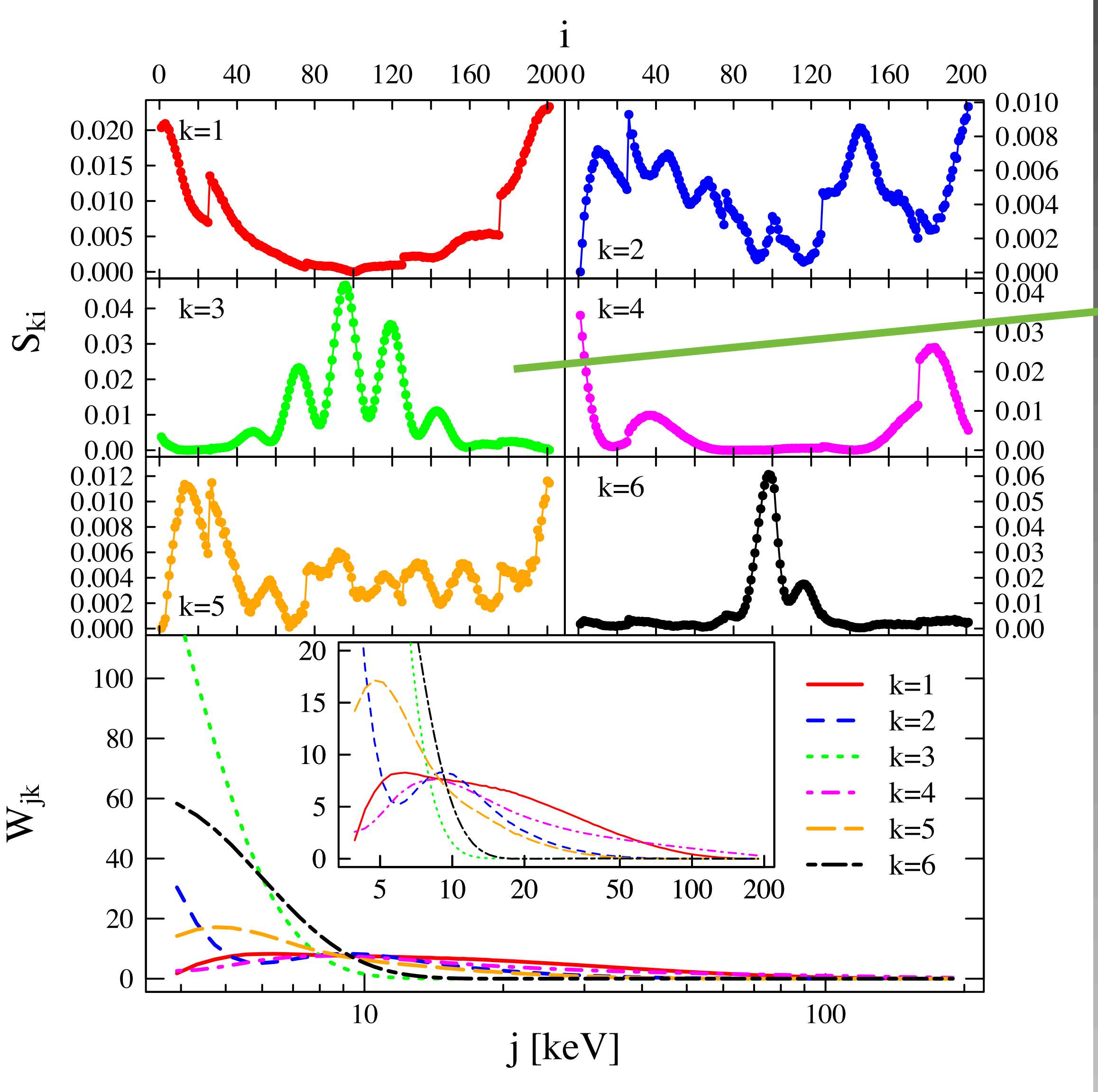

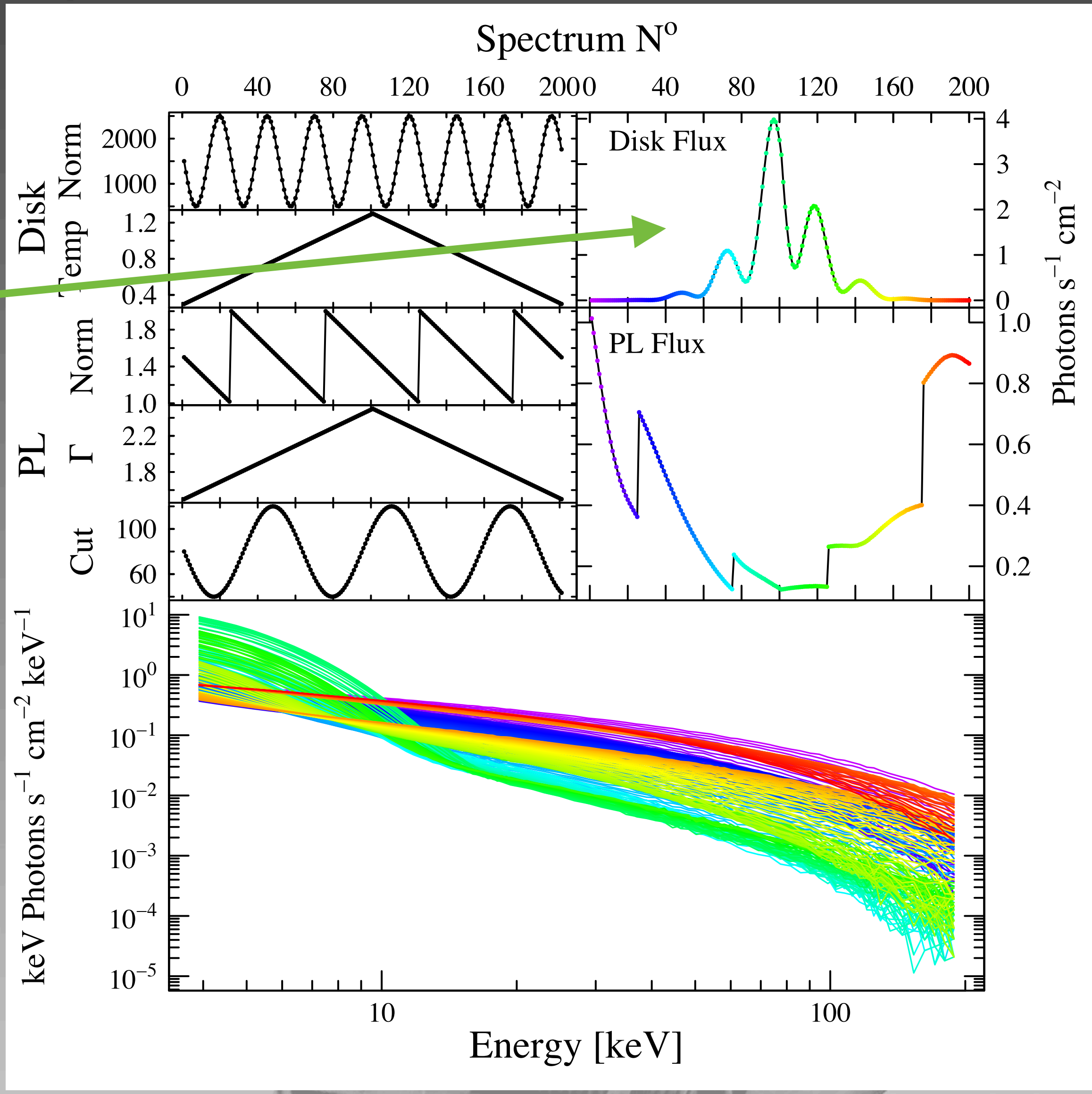

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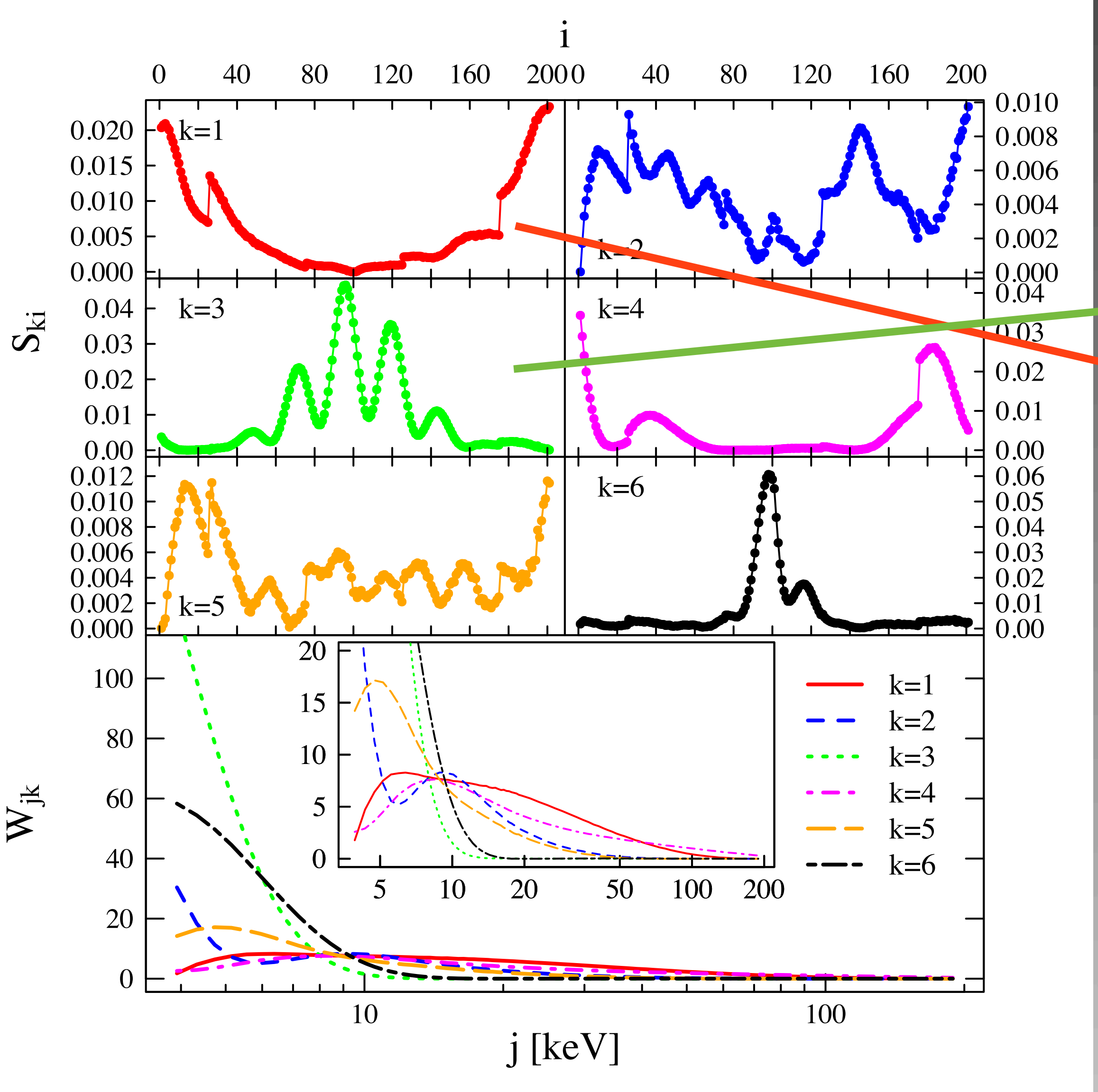

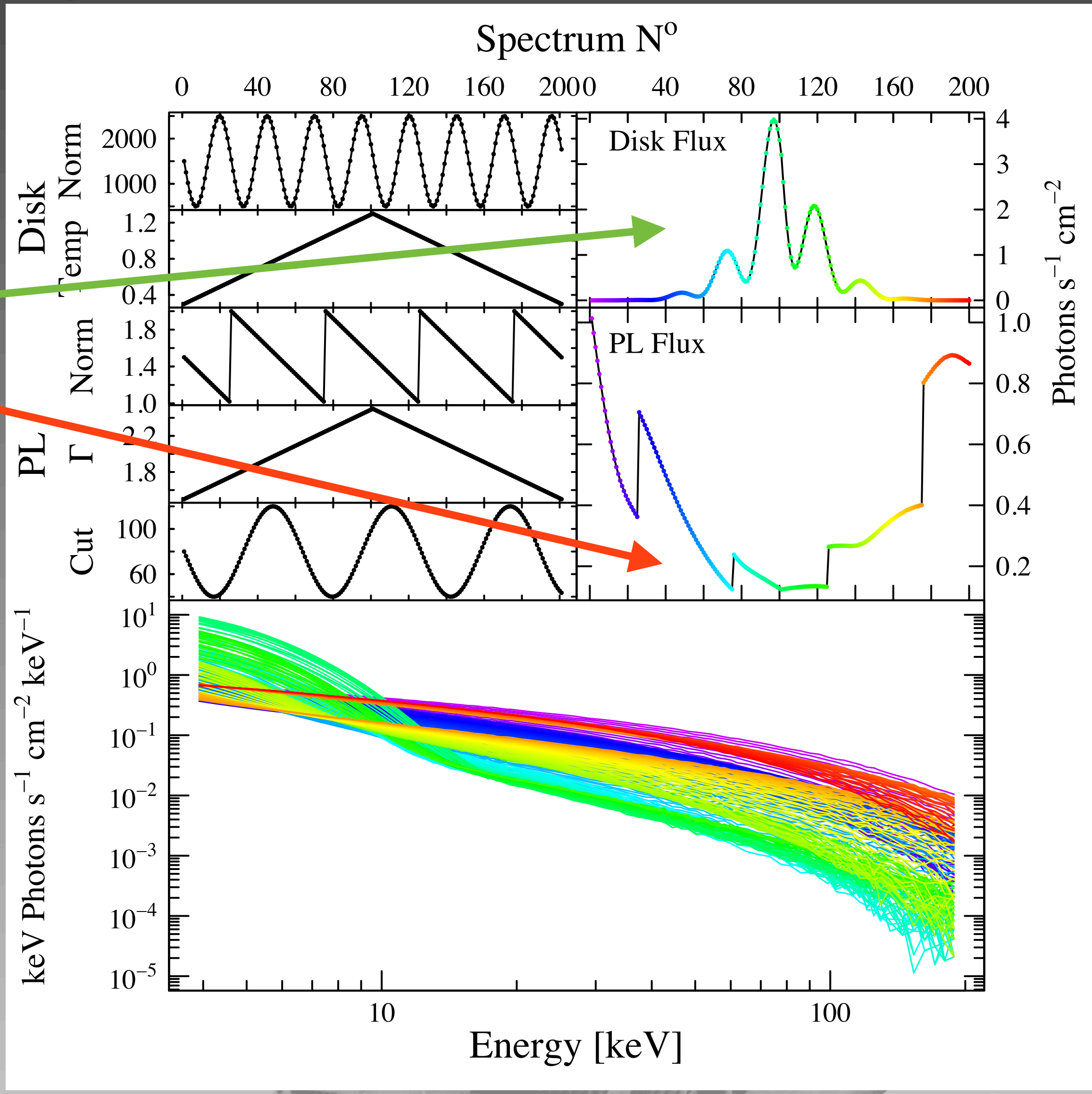

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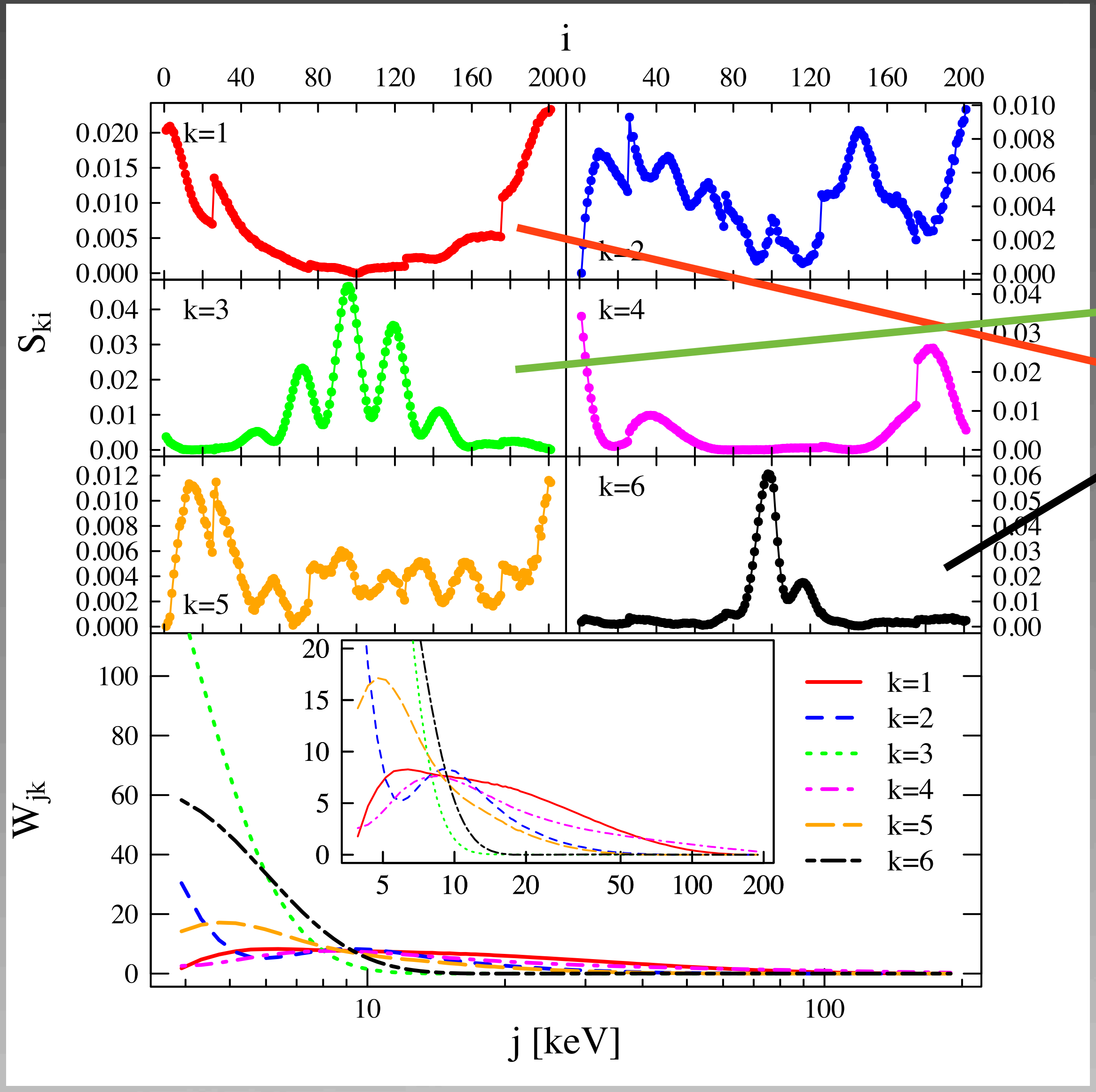

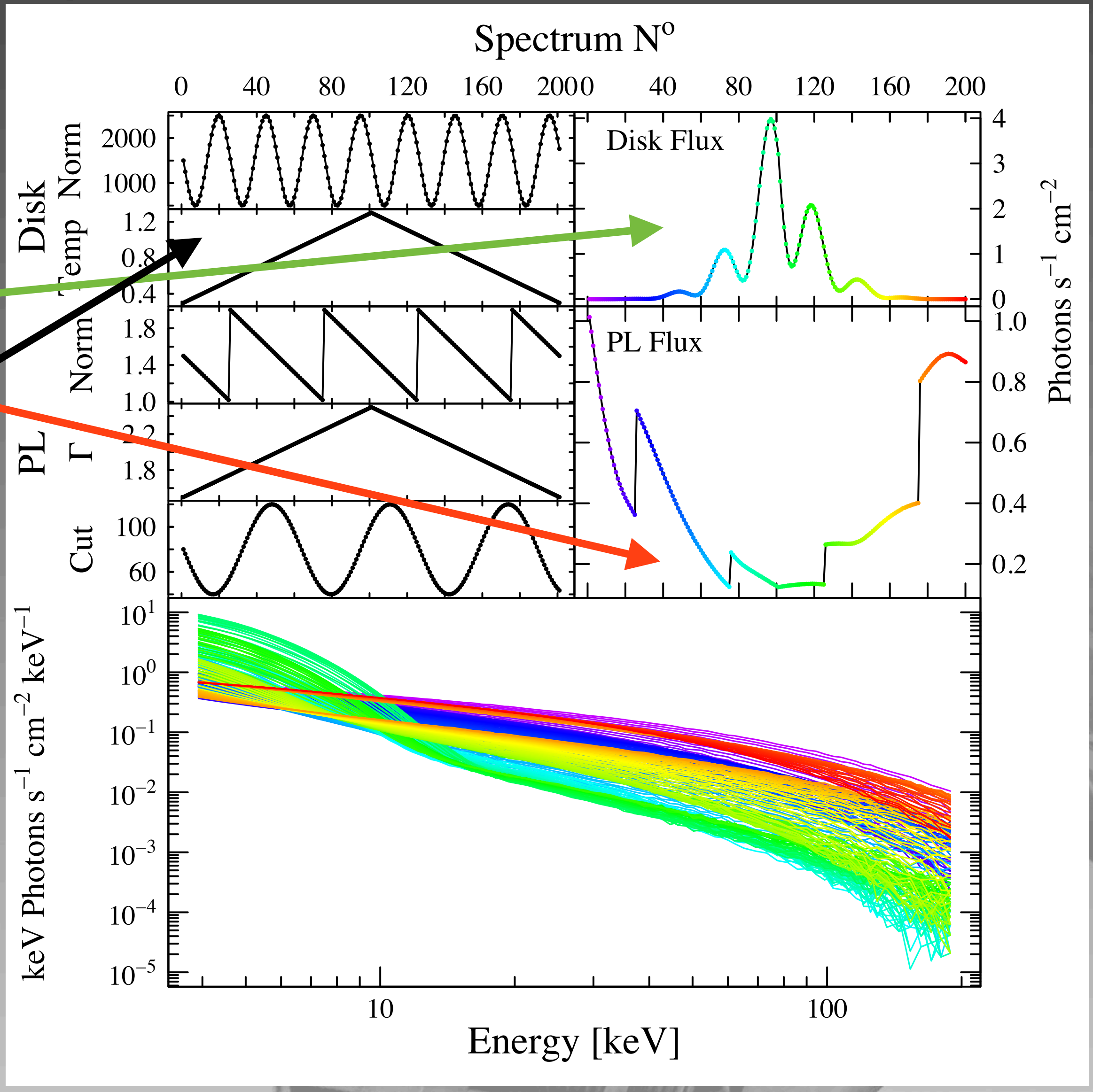

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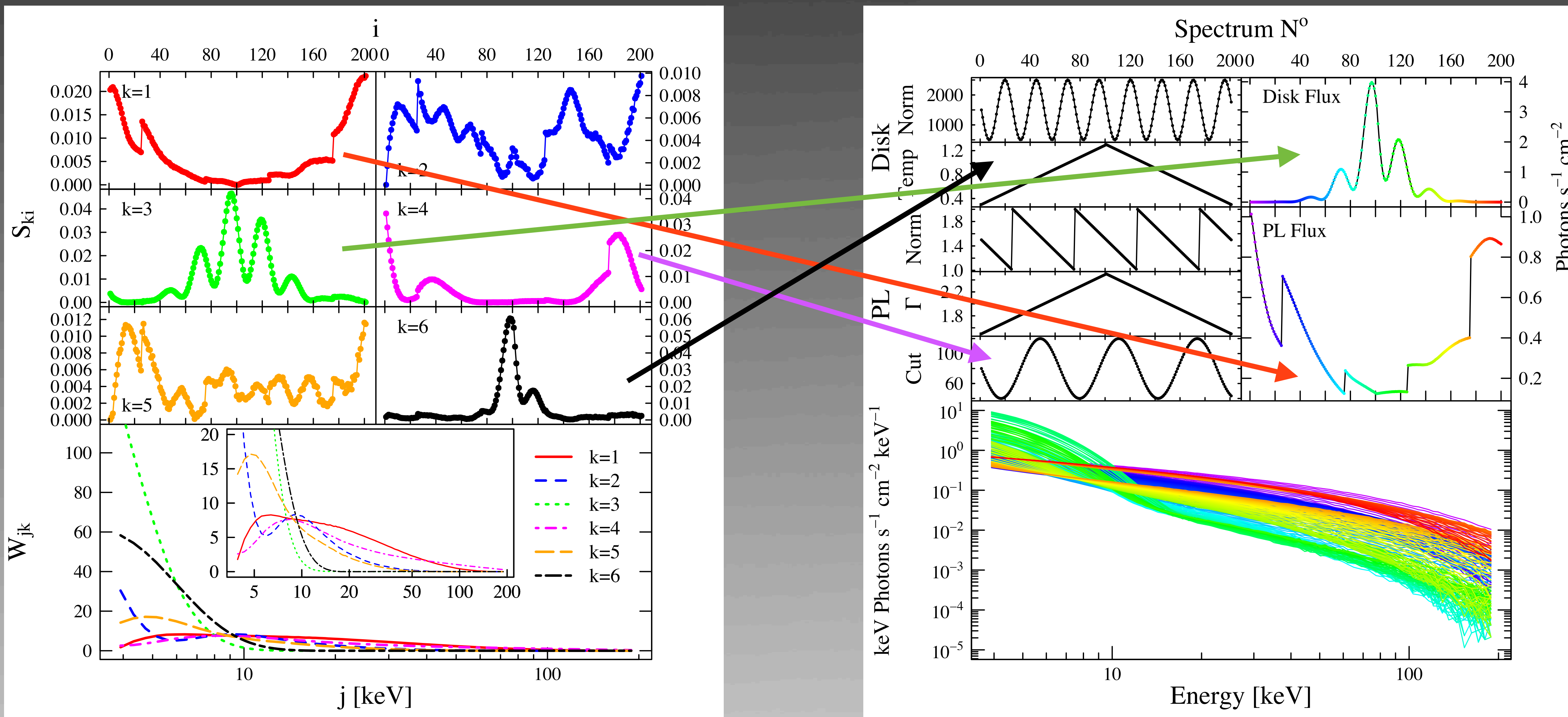

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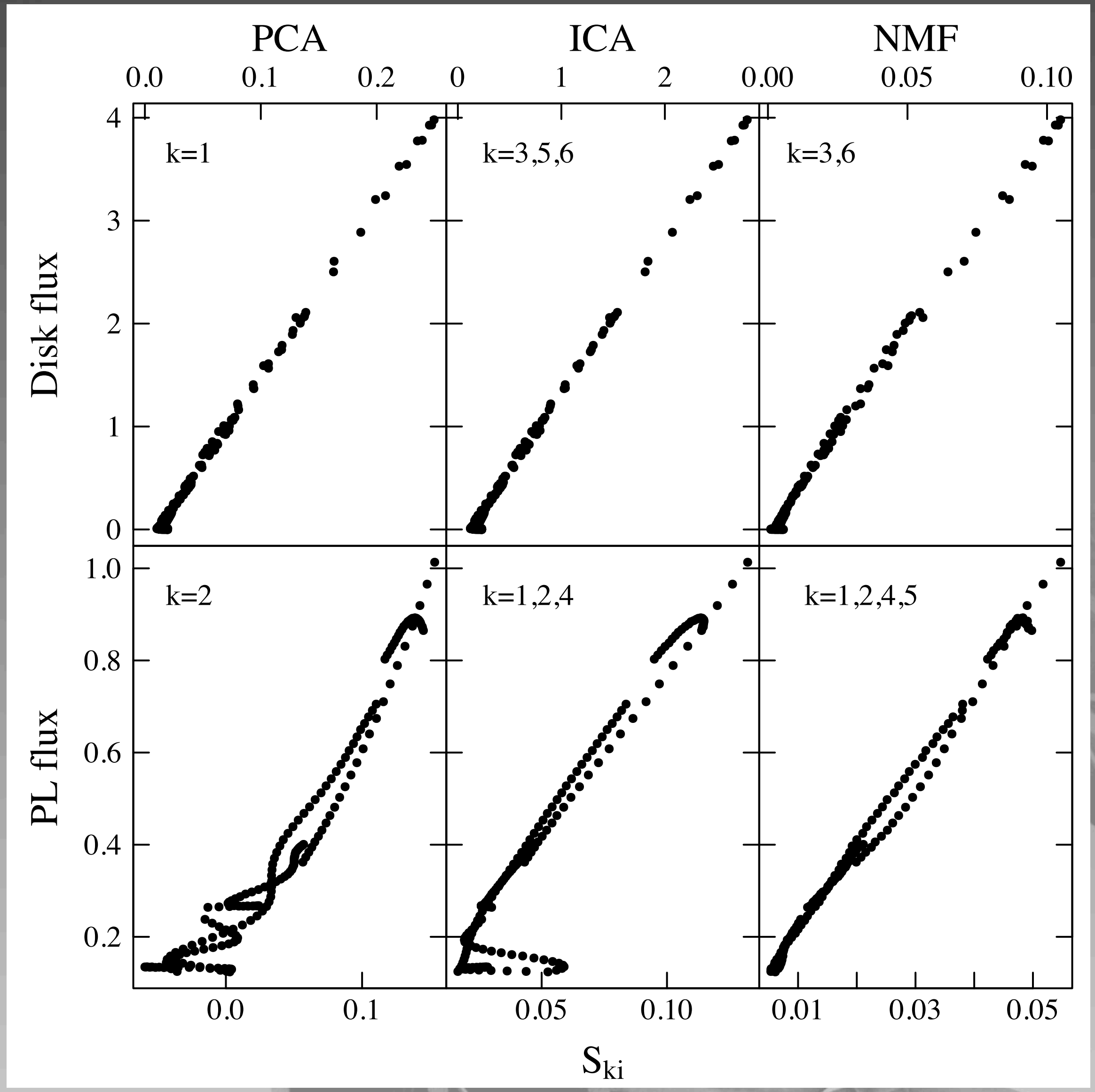
Non-linear effects

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.

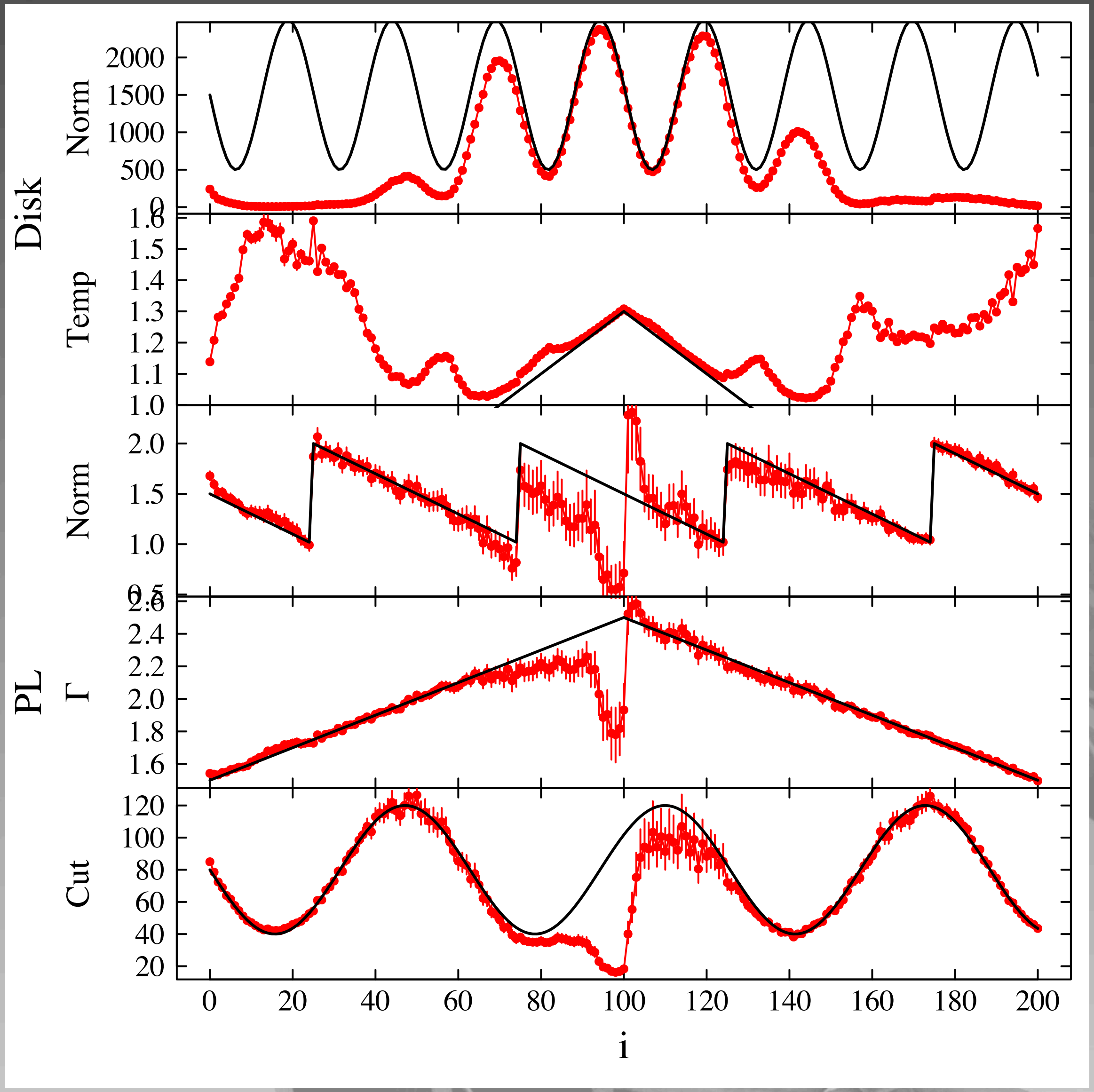


Koljonen, in prep.

Fitting the factorised components

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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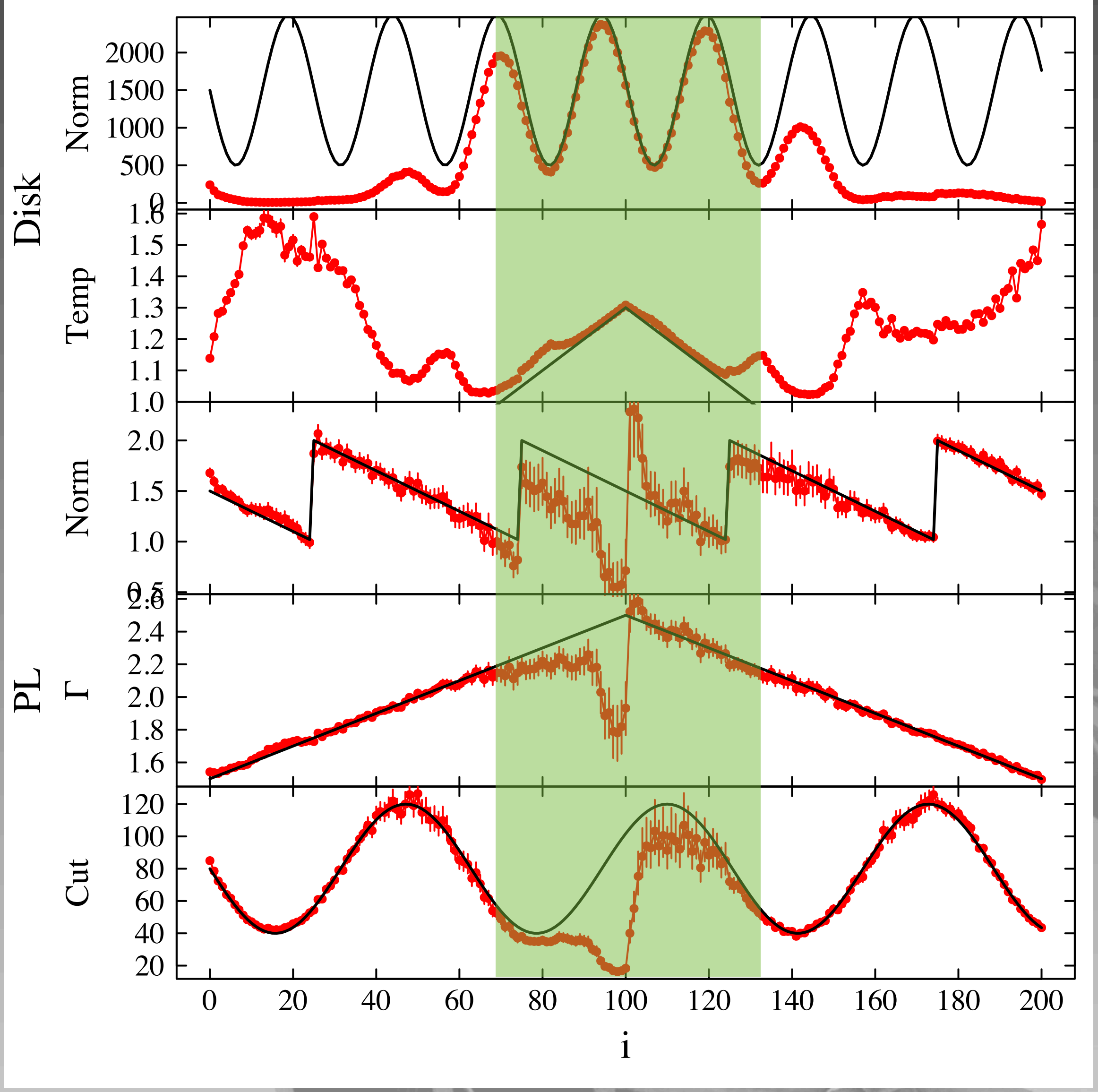
Hard Soft Hard



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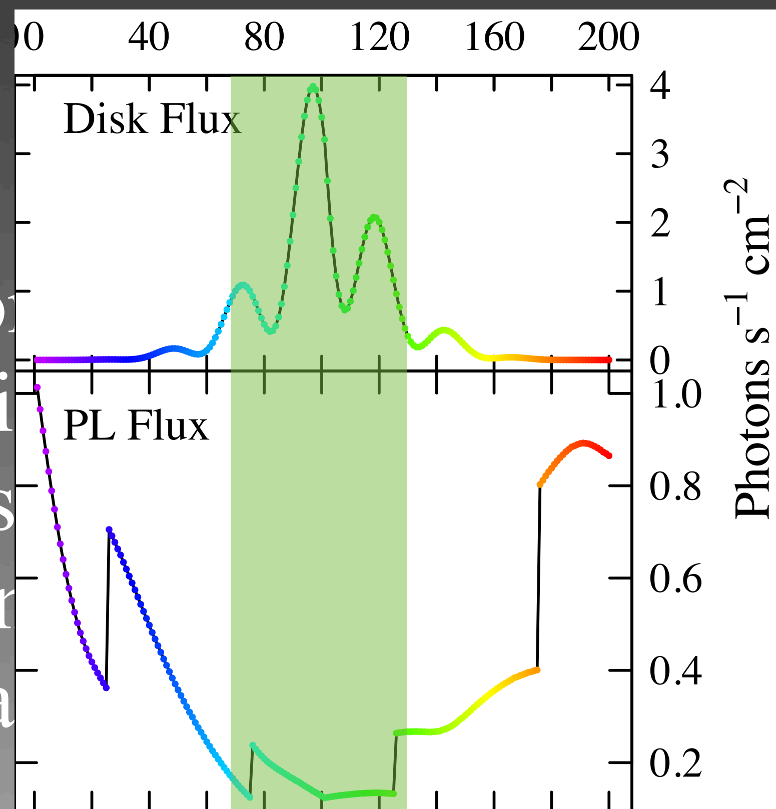

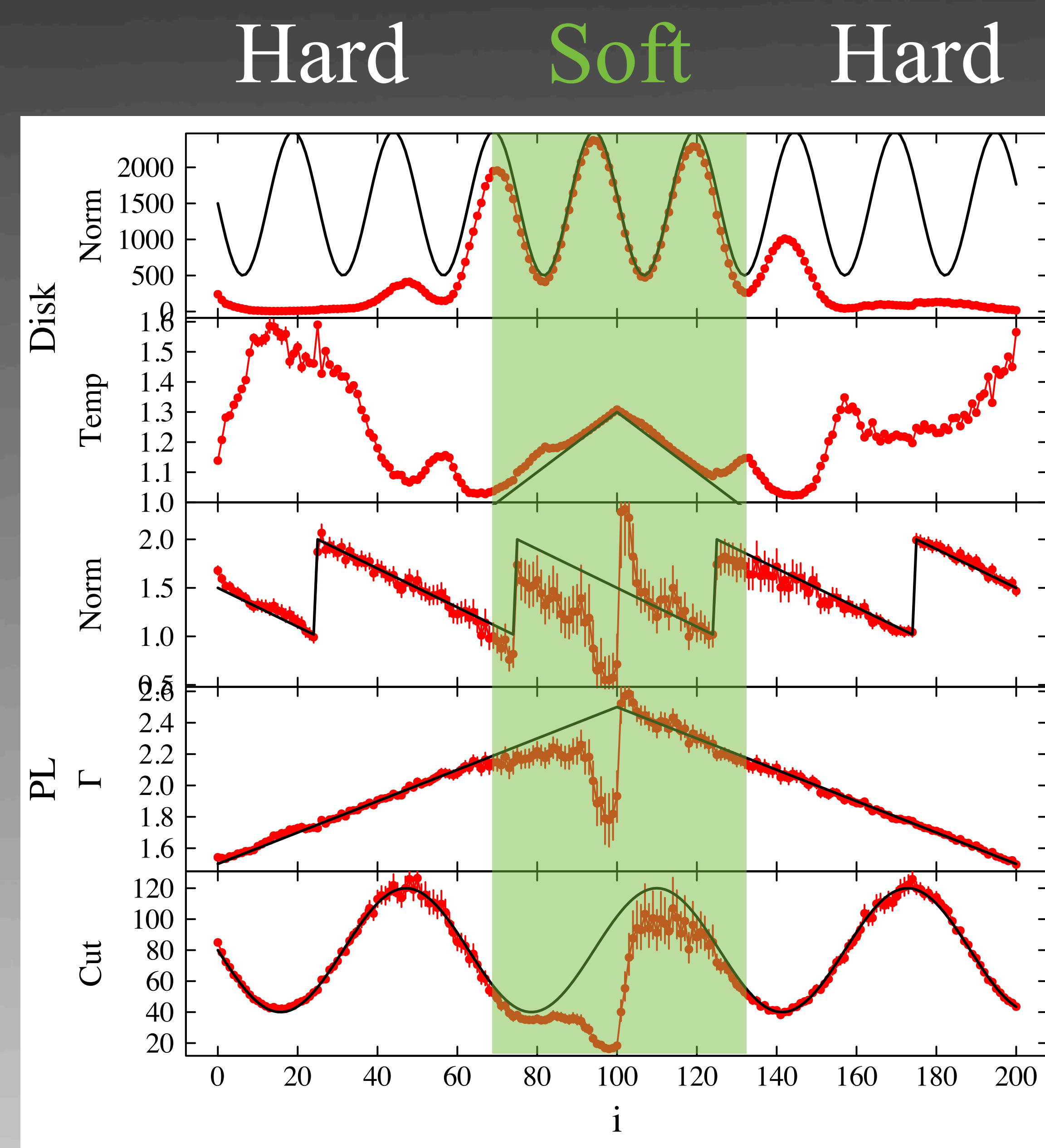

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Using real data from GX 339-4

Four outburst from 2002, 2004, 2007, 2010. 934 RXTE spectra.

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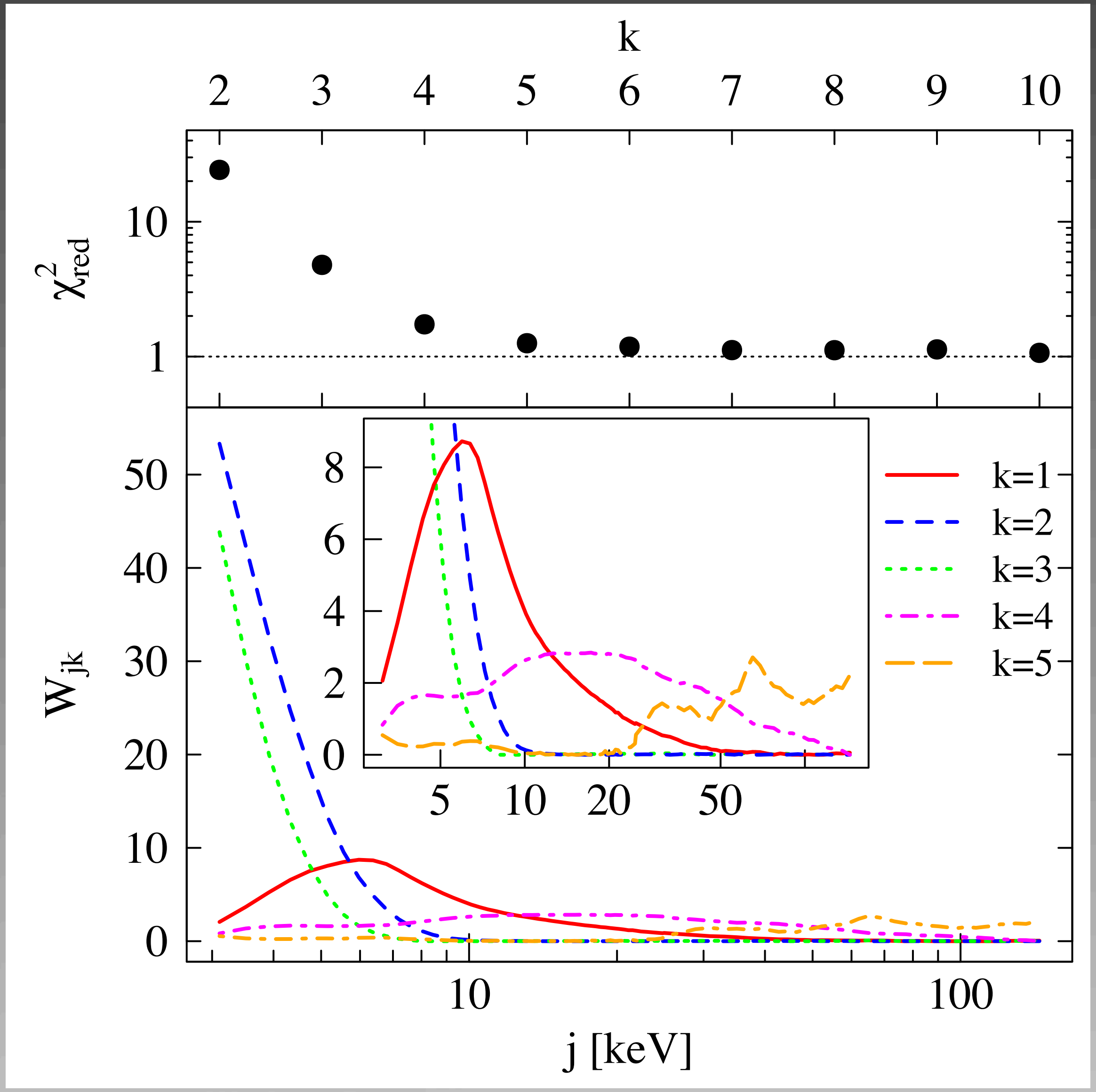

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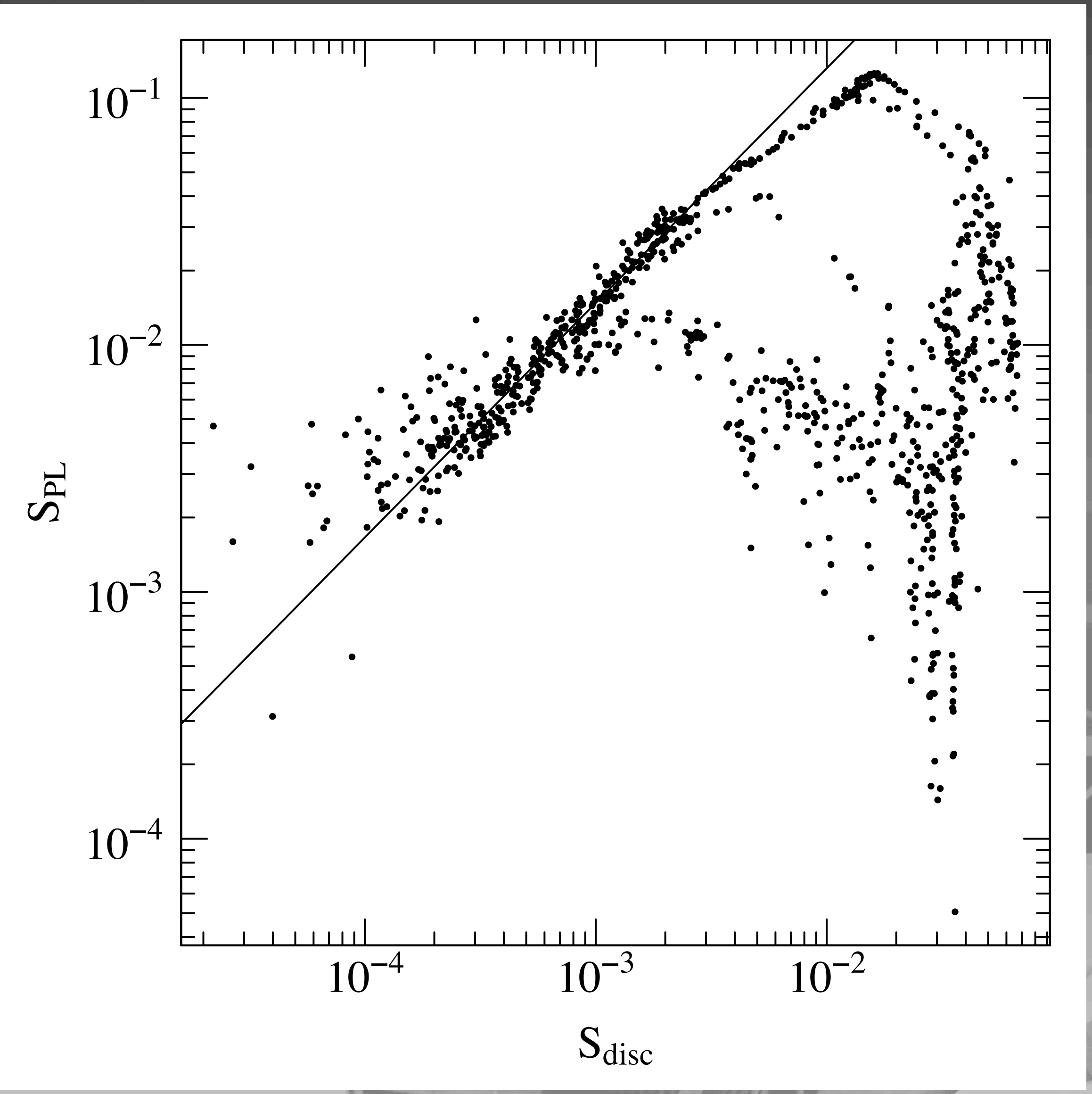

5 components, 2 for disc spectra and 3 for power law component.

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

In the lower hard state S_{PL} correlated with S_{disc} (only one component changing?). In the higher hard state a break from this correlation (the emergence of the disc?).

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

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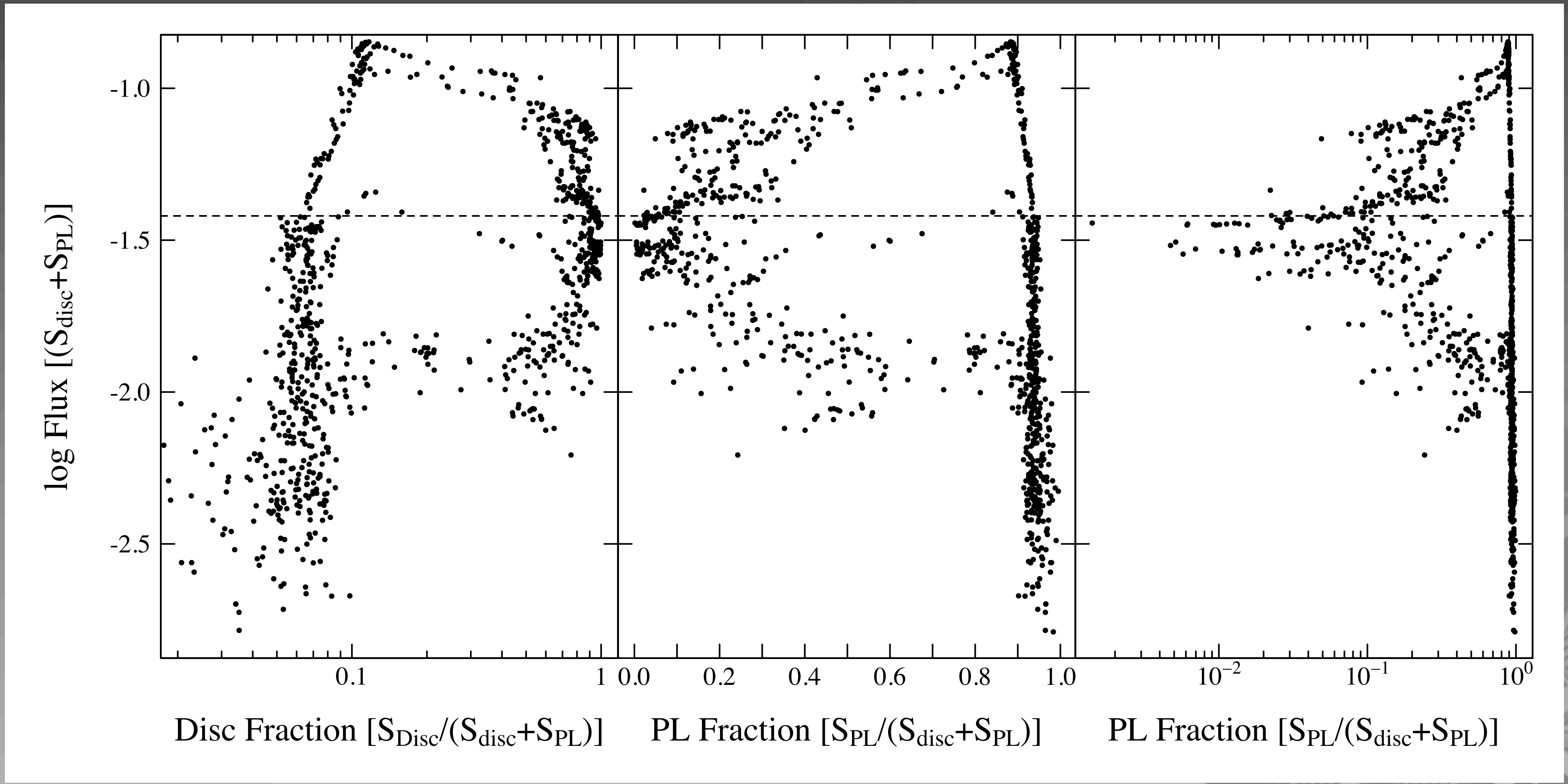


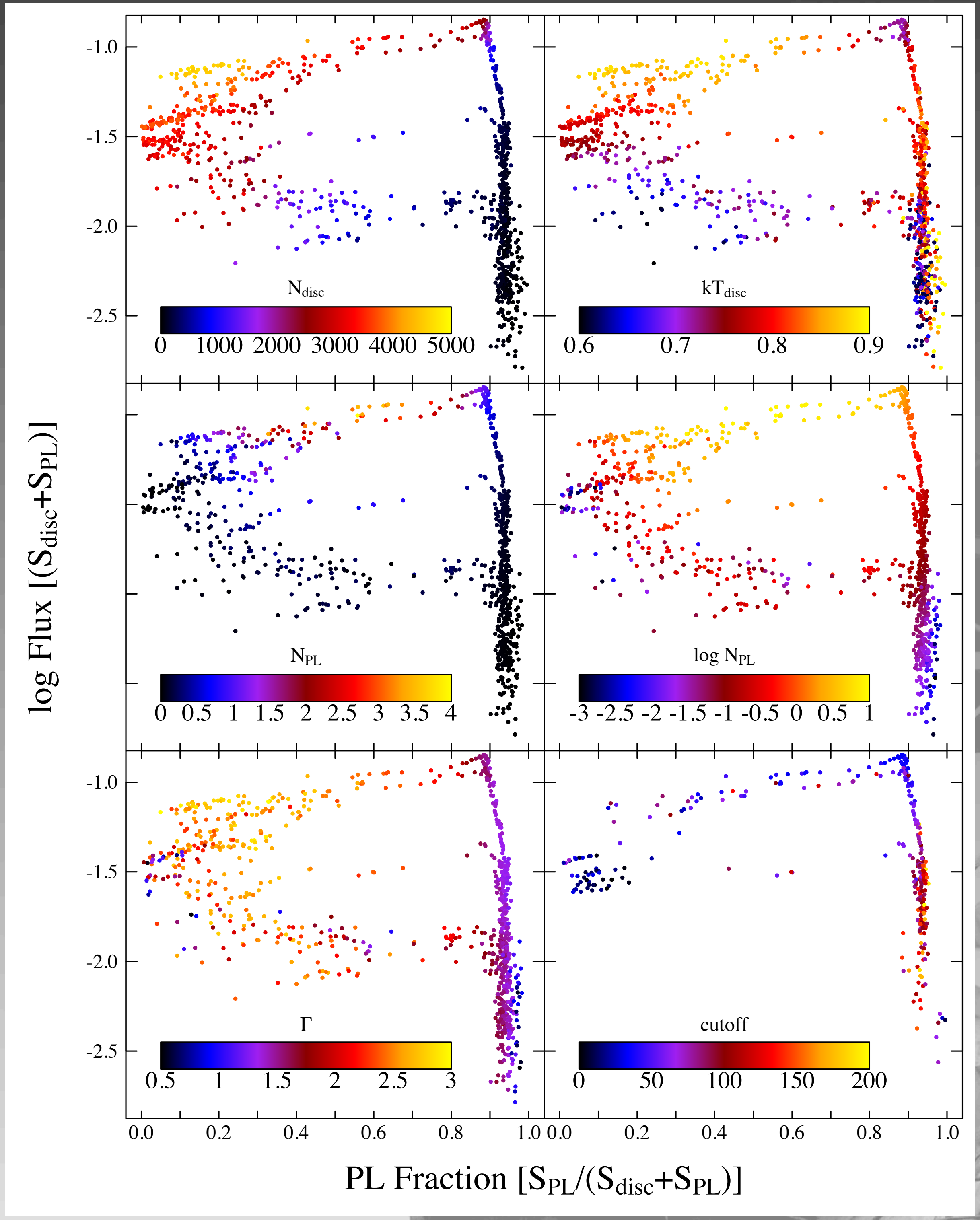
The flux level when changing from the lower hard state to the higher coincides to the softest spectra in the soft state.

Critical luminosity indicating a change in the geometry of the accretion (possible scenario e.g. disc condensation/evaporation of Meyer-Hofmeister+05/09)

Fitting the factorised disc and power law components

Koljonen, in prep.

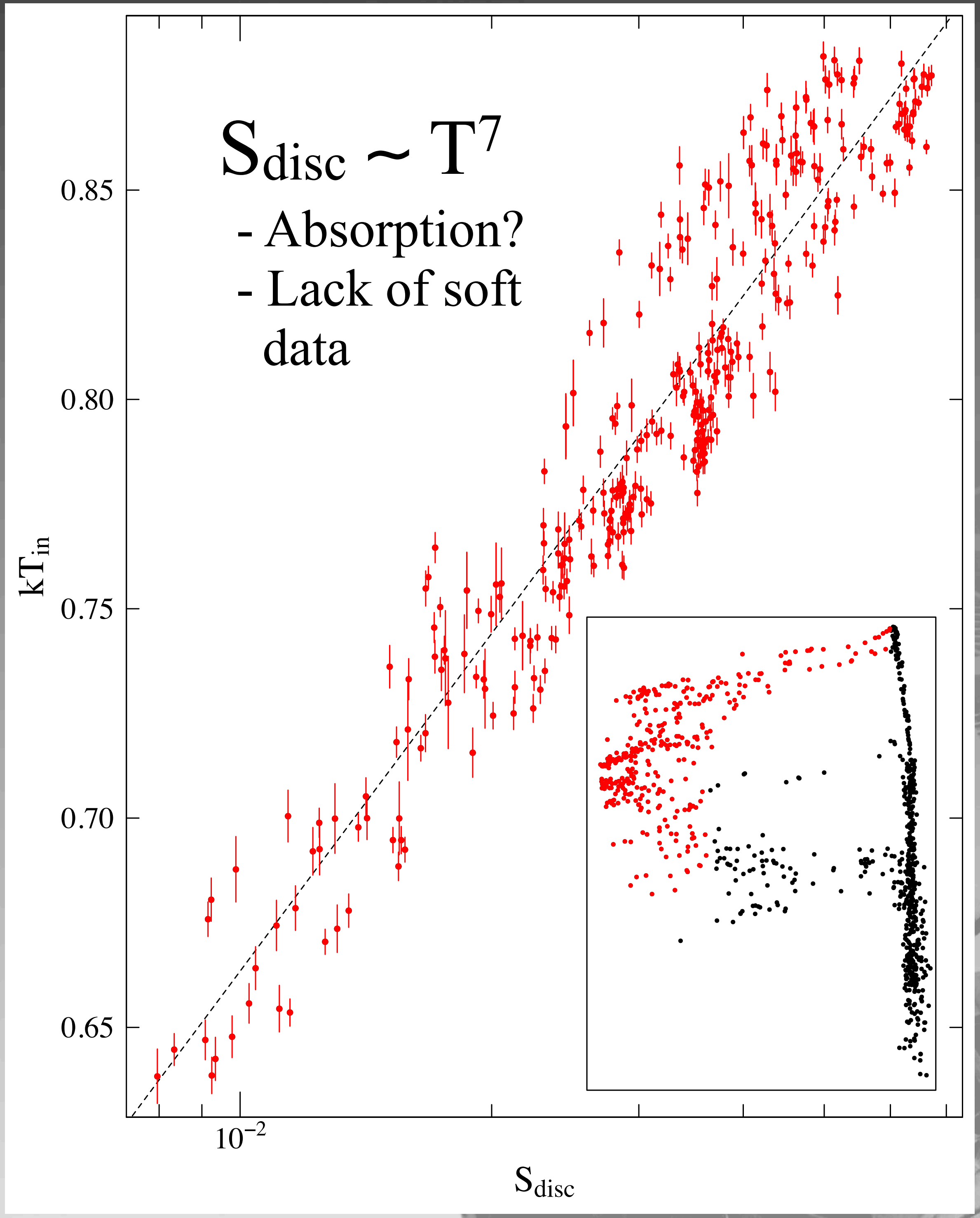
- Similar results to previous studies (Dunn et al. 2008; Del Santo et al. 2008; Motta et al. 2011; Stiele et al. 2011; Cadolle Bel et al. 2011)
- Upper hard state: increasing power law index, decreasing cutoff energy, increasing the disc normalisation.
    - Emergence of the disc (condensation), engulfed by the corona (cooling).



Temperature-luminosity correlation

- 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.

Koljonen, in prep.



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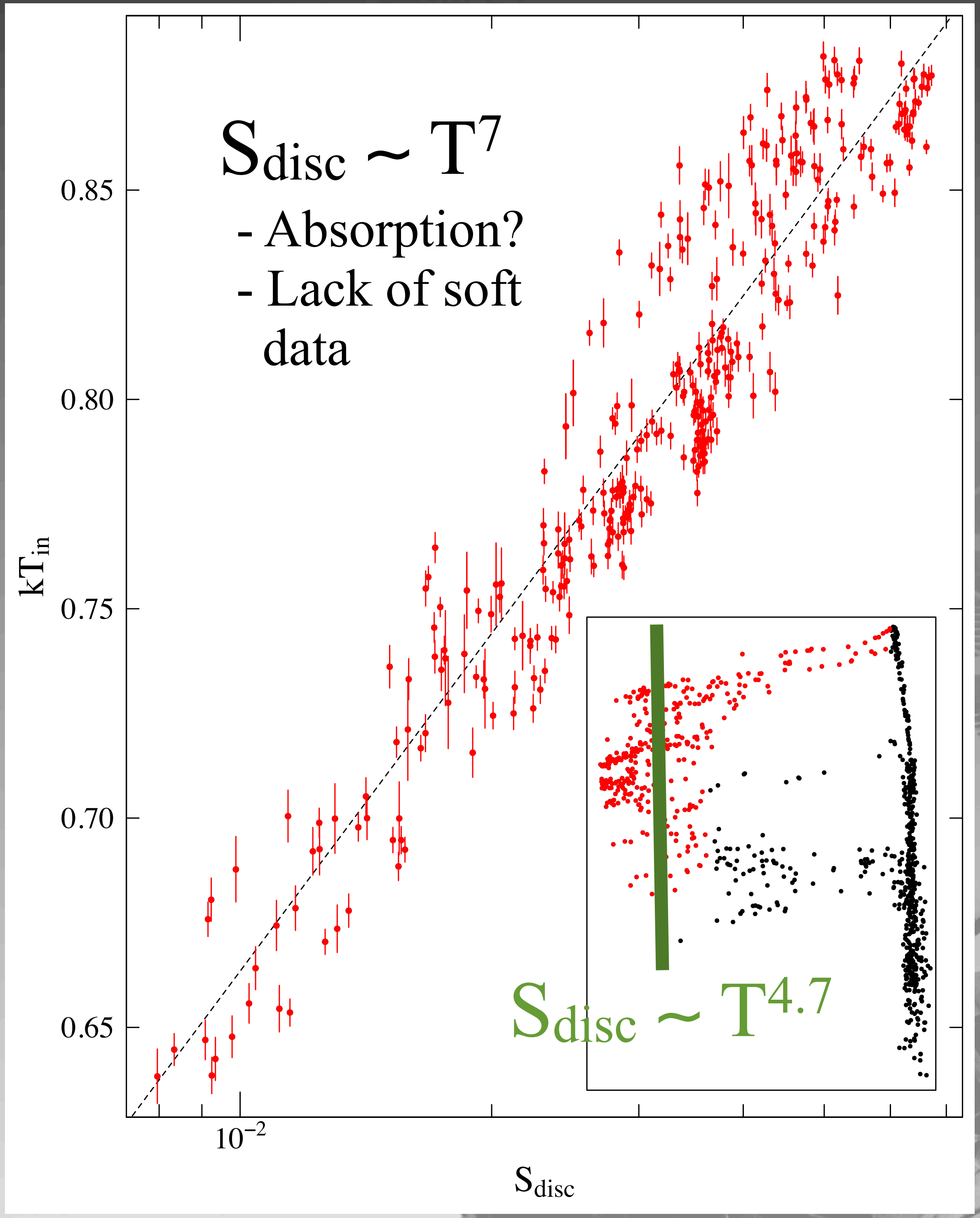

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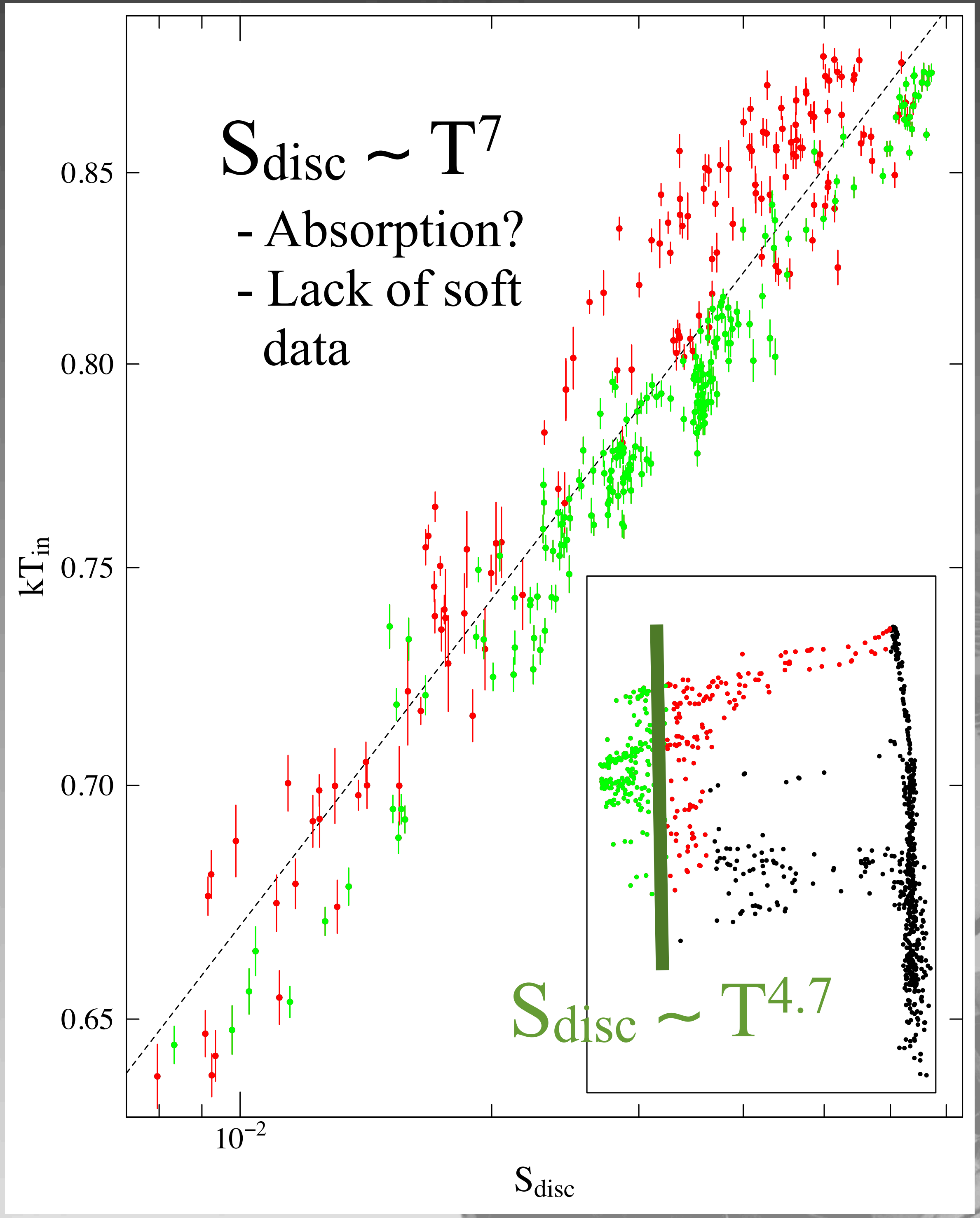

Conclusions

- Unsupervised linear spectral decomposition methods 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.
- Out of the three methods used to tackle a simulated data set we showed that NMF performs the best over PCA and ICA with the additional benefit that the factorisations can be used to fit spectral models separately.
- Analysis on GX 339-4 data indicates that there might exist a critical luminosity (or mass accretion rate) where the system accretion geometry changes.
- It seems plausible that the inner edge of the disc is at the innermost stable orbit in the beginning of the intermediate state right after the peak of the outburst.

Thank you for your attention!

This work will be published soon in an arXiv near you. Stay tuned!

Questions?

...or send them to karri.koljonen@gmail.com

Future

- Unsupervised linear spectral decomposition methods can be used in many situations involving the detection of separate spectral components:
  - The detection of the accretion disc in the low disc flux states using several sources and detectors with softer X-ray bands.
  - Different timing scales could be deployed depending on the quality of the data for e.g. to try to detect the spectral component causing the quasi-periodic oscillations in XRBs.
  - Also these methods provide an alternative way of detecting the spectral components without performing actual spectral fitting, which might prove to be an interesting asset when dealing with large datasets.