Classification of the Variability Patterns of the Black Hole Binary GRS 1915+105 Using Deep Learning

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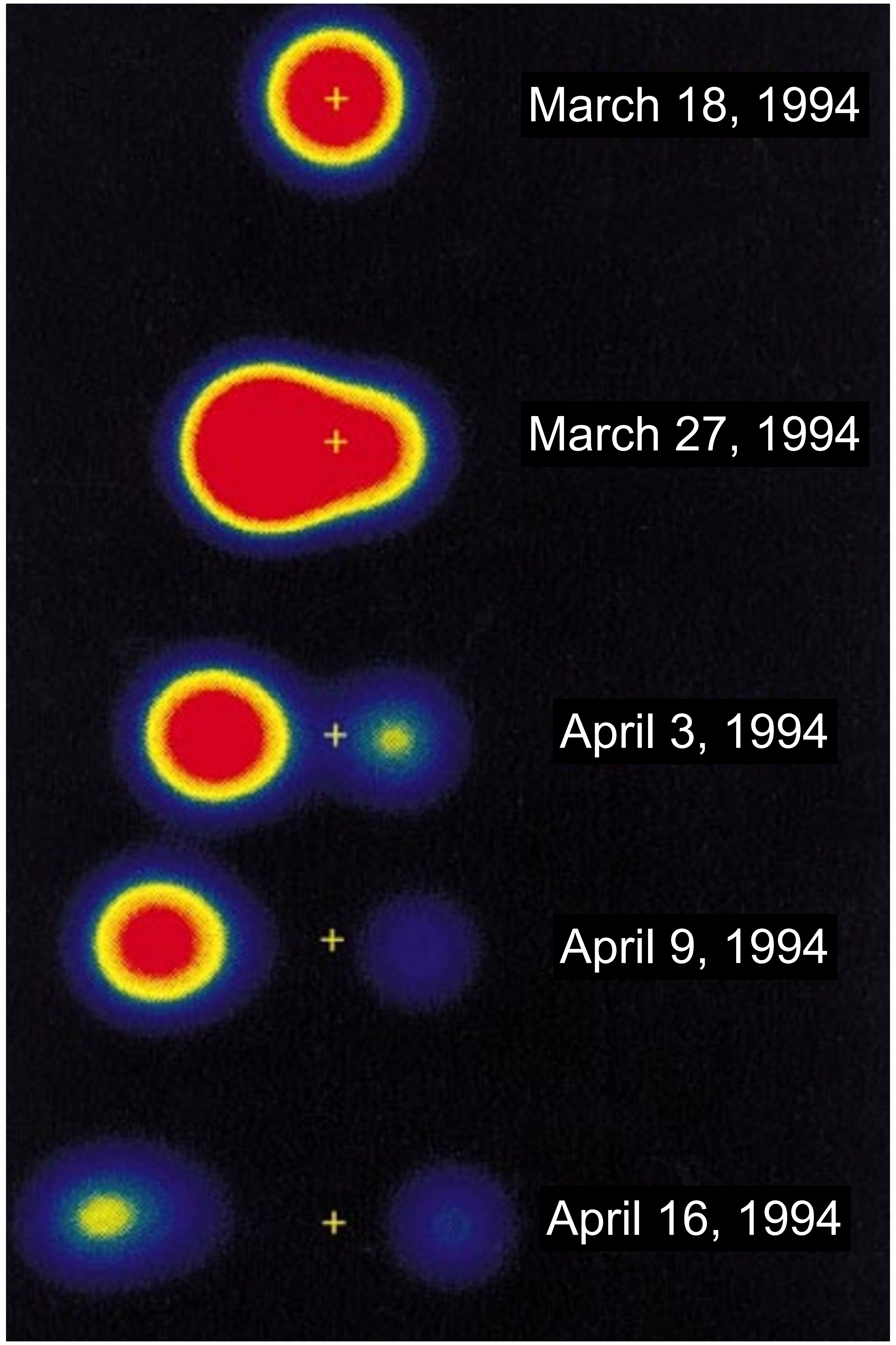
The Black Hole Binary GRS 1915+105

- Discovered in 1992 as an X-ray transient by WATCH/ GRANAT (Castro-Tirado, A. J., et al., 1994)
  => It has not faded since then
- The first superluminal source in our Galaxy
  => A prototype of a microquasar (Mirabel & Rodriguez 1994)
- From radio, infrared, and X-ray observations
  - Period = 33.5 days (J.Greiner et al., 2001)
  - Black hole mass = $12.4^{+2.0}_{-1.8}\ M_\odot$
  - Inclination angle = 60 +- 5 deg (Reid et al. 2014)
  - Distance = $8.6^{+2.0}_{-1.6}$ kpc
  - Dimensionless B.H. spin parameter a* = 0.98
    => Near-extreme Kerr black hole

(McClintock et al., 2006; J.L.Blum et al. 2009)



Pairs of radio jets
(Mirabel & Rodriguez 1998)

Comparison of GRS 1915+105 with other B.H. binaries

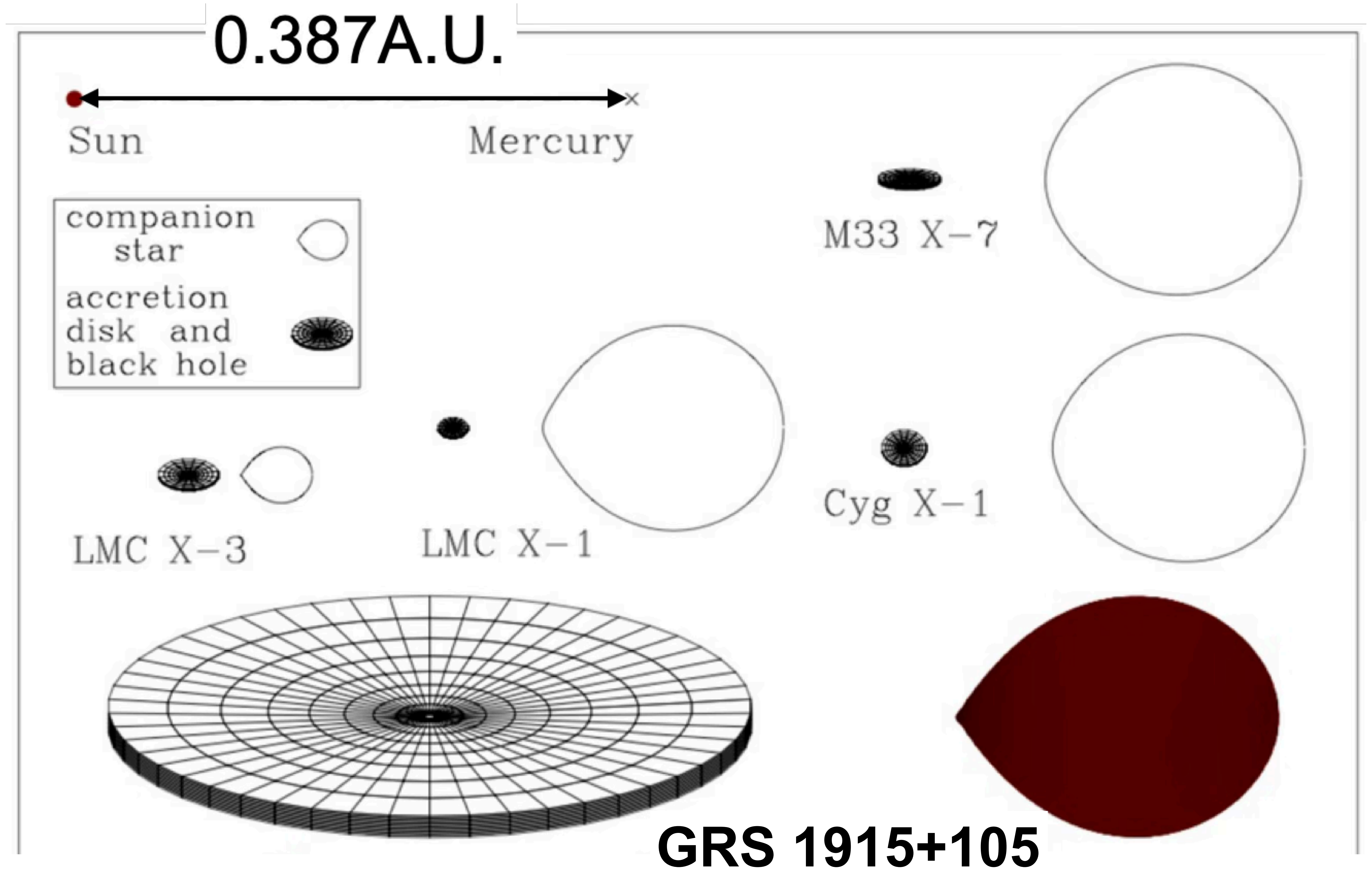
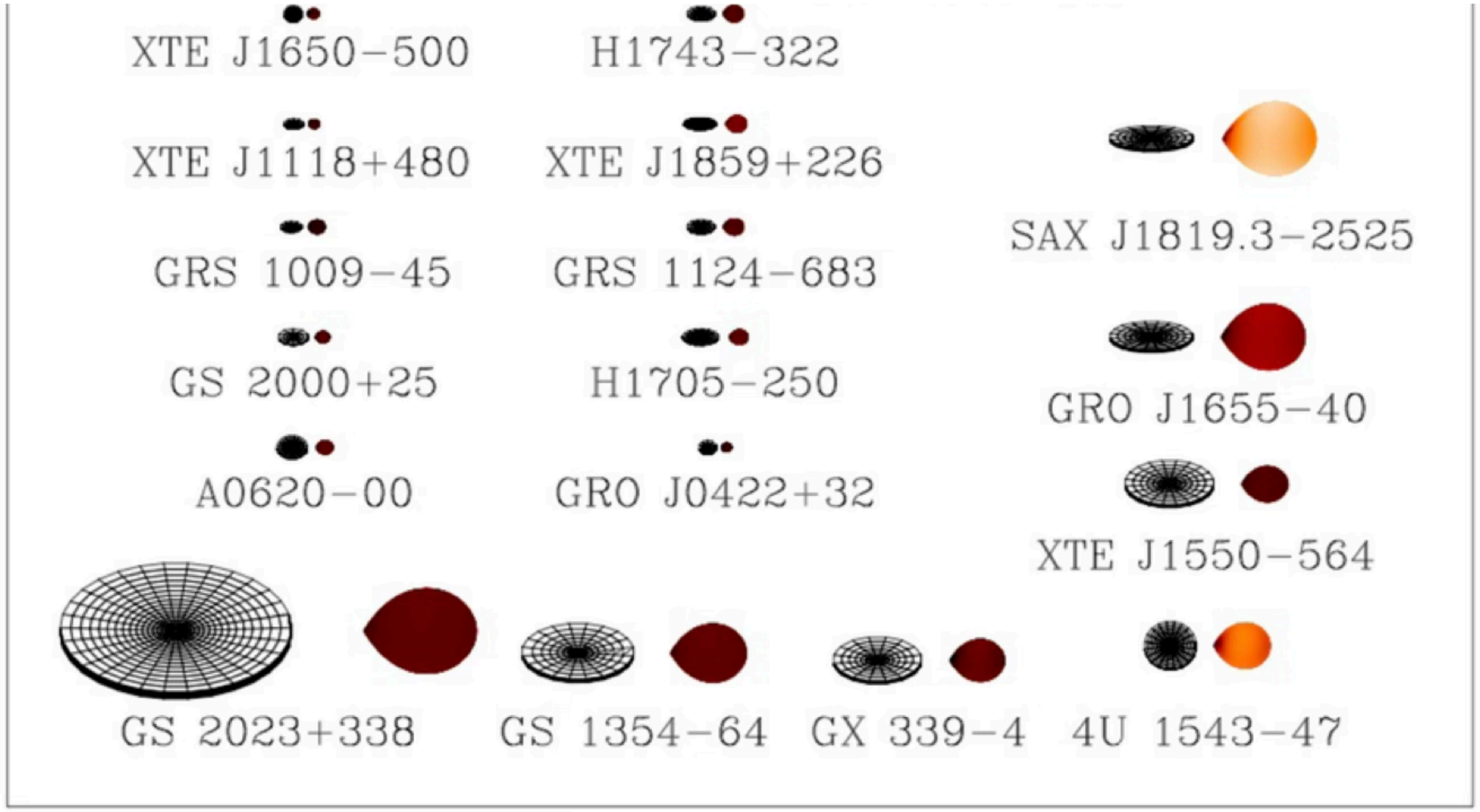


Figure courtesy of Jerome Orosz

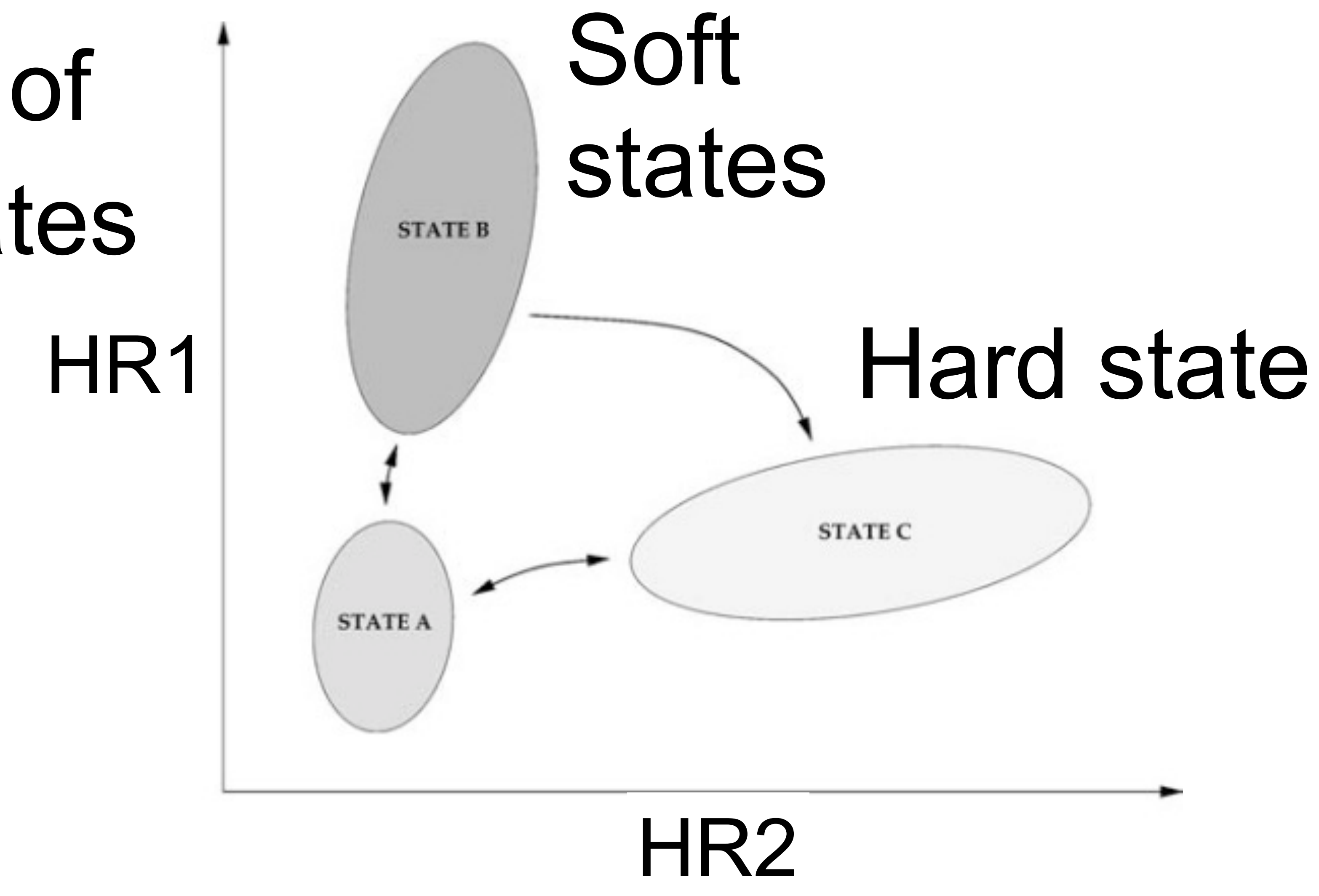


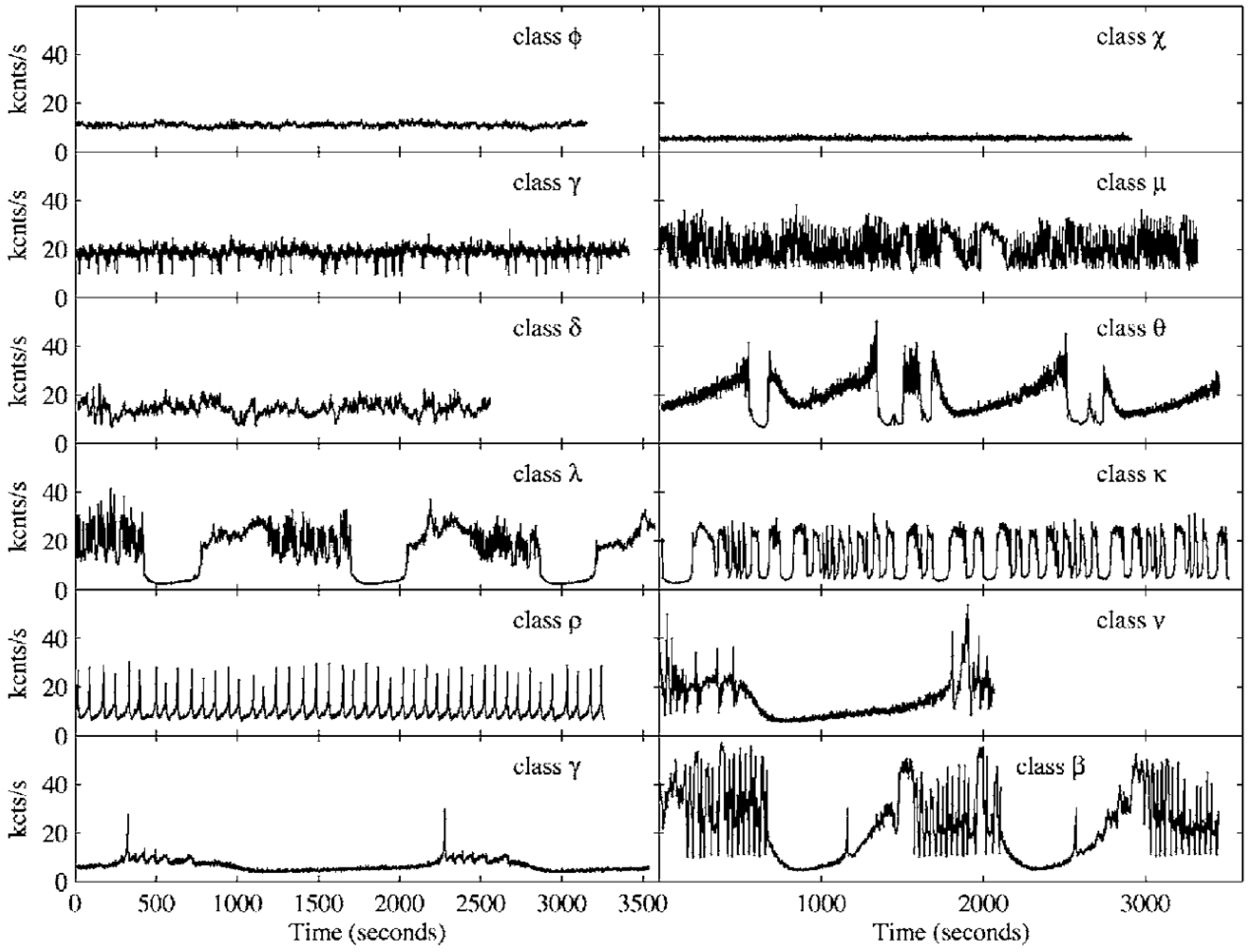
The largest and second-most massive of the Galactic black hole binaries

Unique time variations of GRS 1915+105

- Belloni et al. (2000): Classification of time variation patterns:
  => α, β, γ, δ, θ, κ, λ, μ, ν, ρ, φ, χ classes
- Klein-Wolt et al. (2002): => + ω class
- Hannikainen et al. (2005): => + ξ class
- Shi et al. (2023) => + ψ class
- Dhaka et al. (2025) => + η class

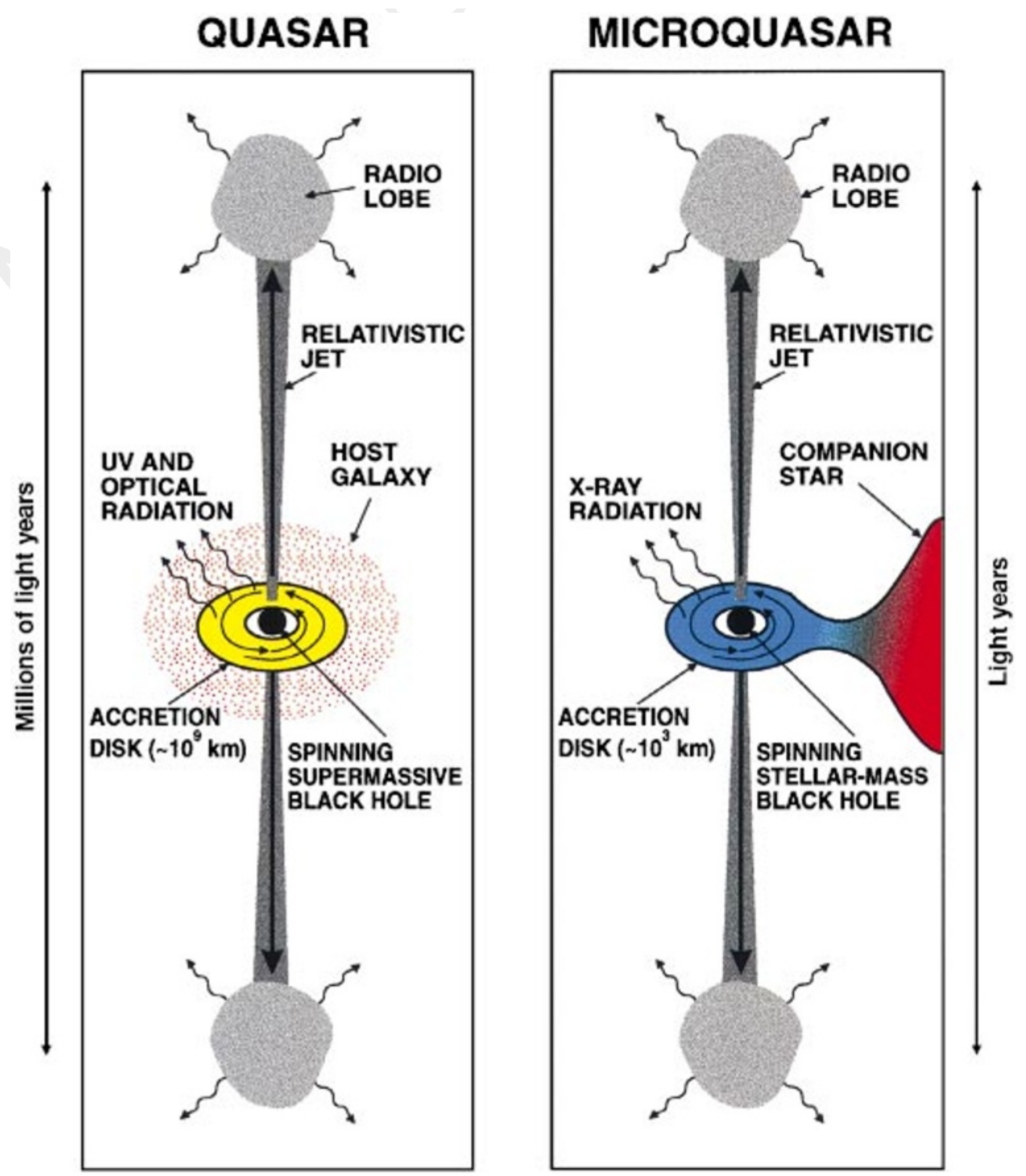
Transitions of spectral states



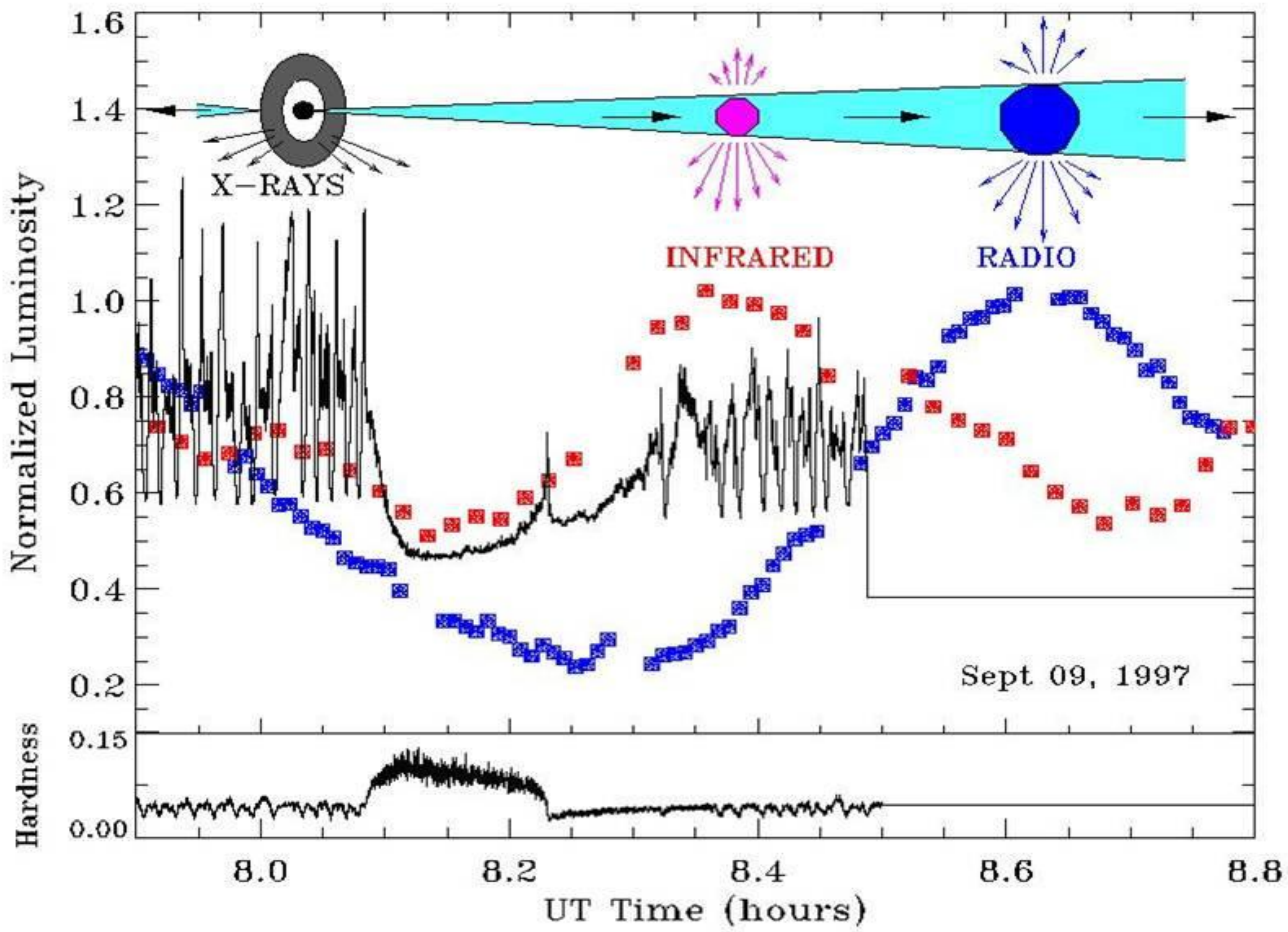


12 classes (Belloni et al. 2000)

Accretion disk - jet coupling in a microquasar GRS1915+105



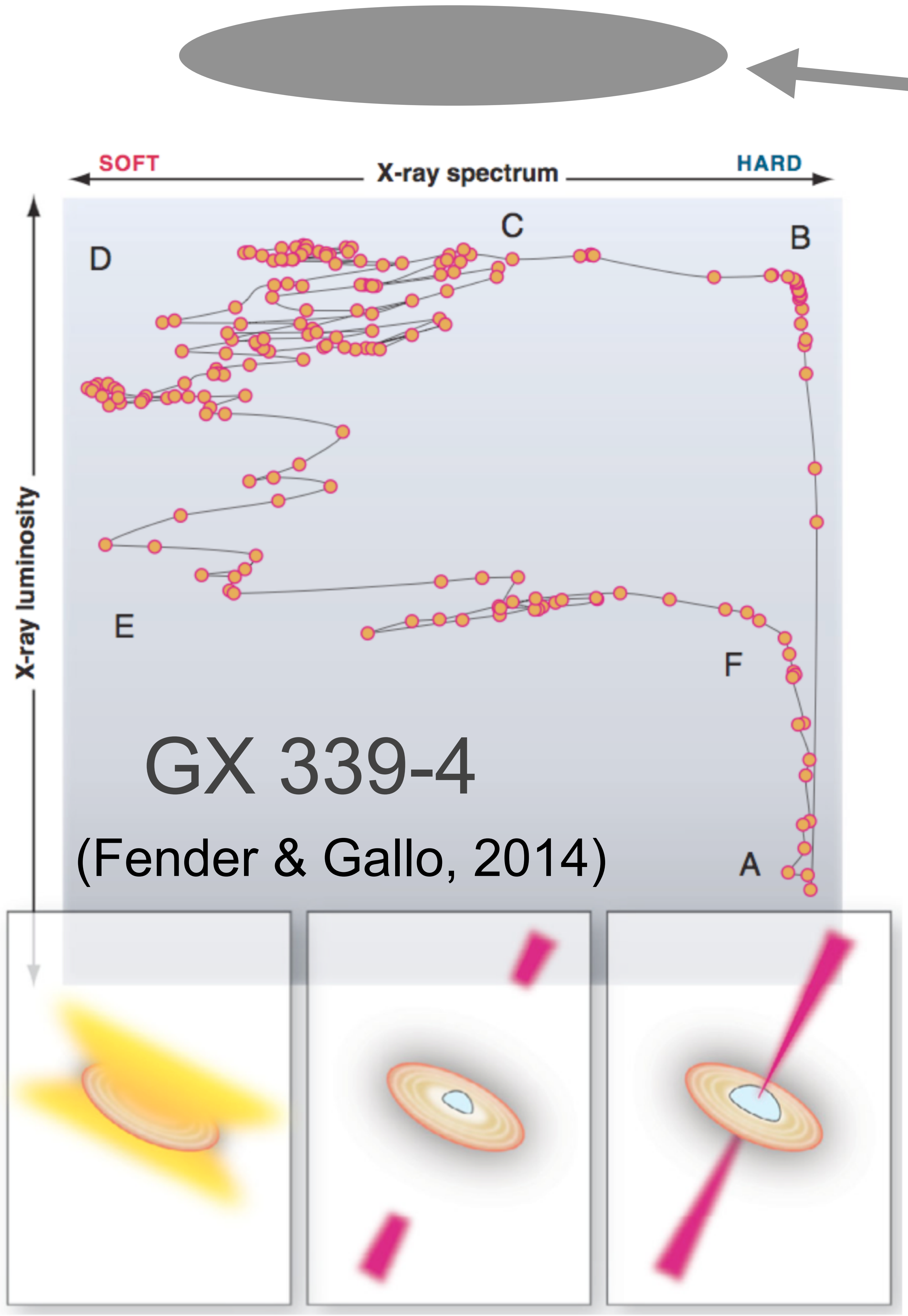
Mirabel & Rodriguez (1998)



Mirabel & Rodriguez (1998); Mirabel (2012)

Observations of GRS 1915+105 over an interval shorter than an hour showed a sudden decrease in X-ray luminosity, followed by the ejection of jets, first observed in the infrared and then at radio frequencies.

Where is GRS 1915+105 on the Hardness-Intensity Diagram?



Hardness-Intensity Diagram

GRS 1915+105 on the Hardness-Intensity Diagram?

- GX 339-4 as an example of other black hole binaries:
  - Hardness-Intensity Diagram shows the Q curve
    A=>B: Hard state
    B=>C: Intermediate state
    C=>D=>E: Soft state
    E=>F=>A: Soft state to hard state
- Where is GRS 1915+105 on the Hardness-Intensity Diagram?
  => Beyond the graph, due to the higher luminosity?

Understanding the time-variation patterns of GRS 1915+105

- Understanding the time-variation patterns is important for revealing the conditions for jet generation and clarifying the difference between GRS 1915+105 and other black hole binaries.
  - How are such unique time variations generated?
  - Do other time variation patterns exist?
  - How long do the time variation patterns continue?
  - How do the time variation patterns transition?

- In this work, we apply deep learning to GRS 1915+105 light curves to classify the patterns of time variation.

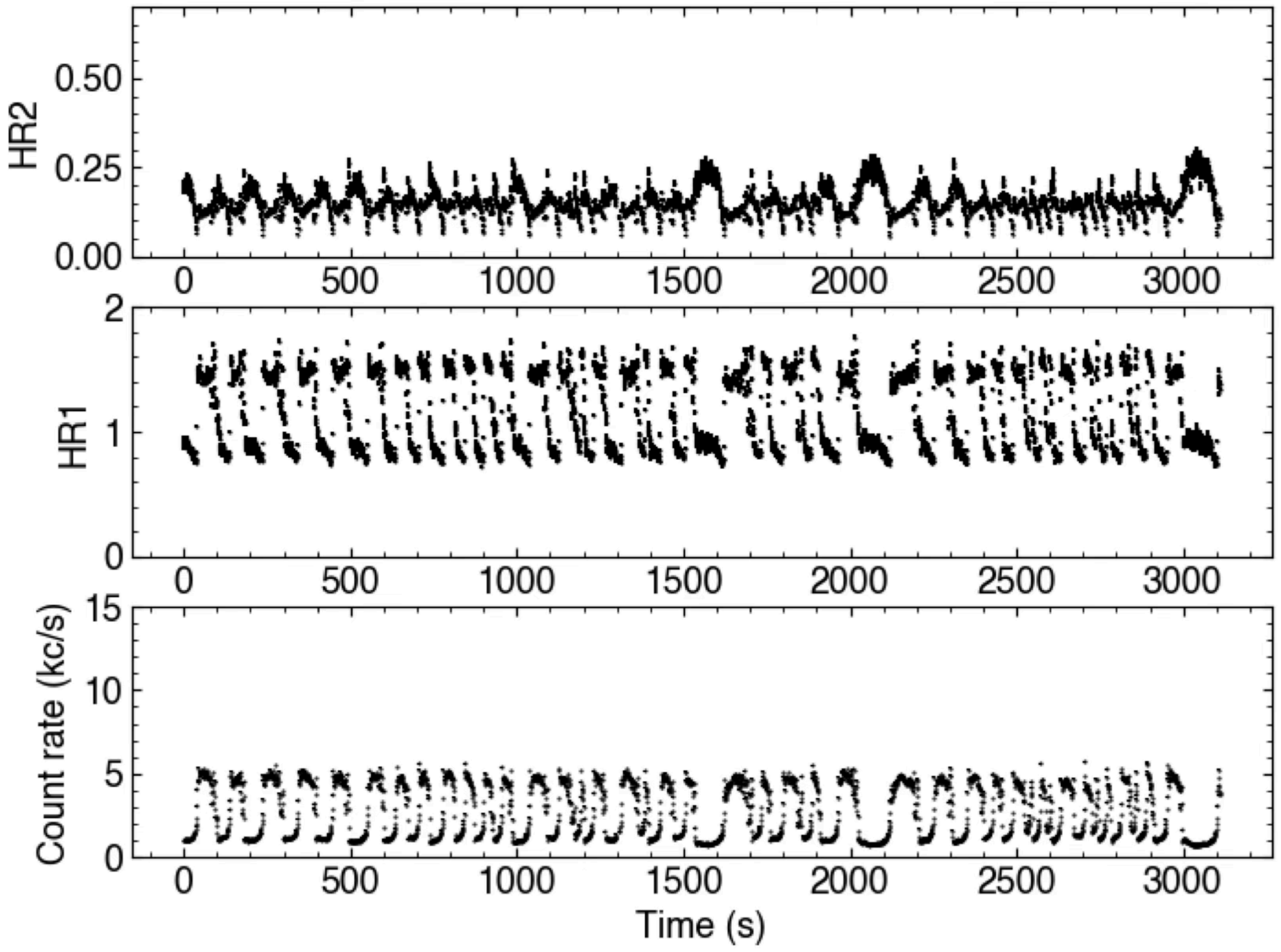
Previous Machine Learning Classifications for GRS 1915+105

- Huppenkothen et al. (2017)
  - Supervised machine learning in the form of logistic regression and random forests
  - Feature engineering: Light curves => around 5~40 features
  - Classification accuracy: 92.5%
- Orwat-Kapola et al. (2021)
  - Unsupervised light curve feature extraction: a neural network with a Long Short-Term Memory Variational Autoencoder architecture and a Gaussian mixture model => 24 features
  - A mean weighted F1 score: 87.8%
- Ricketts et al. (2023)
  - An unsupervised machine learning algorithm called an autoencoder with 48 features

- This work
  - Supervised Convolutional Neural Network (CNN)
  - Direct features: Light curves, time series of hardness ratios, and power spectral densities

GRS 1915+105 Light Curve Data

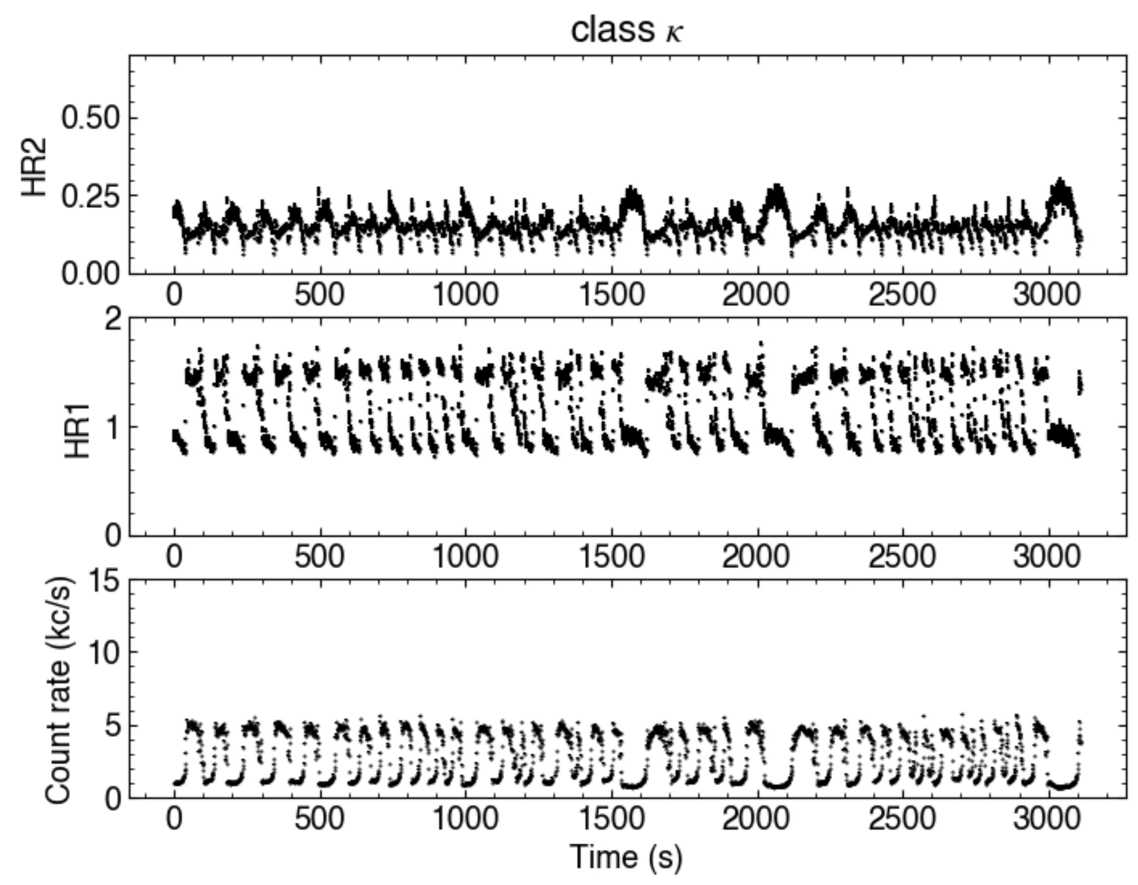
- The Rossi X-ray Timing Explorer (RXTE) / Proportional Counter Array (PCA)
  - 737 observations in 1996/05 – 2003/02
  - Typically 2 - 3 ks for one observation
- Time resolution = 1.0 s
- The energy range:2-5 keV, 5-13 keV, 13-60 keV
- Input data to CNN models:
  - Light curve (2-60keV)
  - Time series of HR1 (5-13keV / 2-5keV)
  - Time series of HR2 (13-60keV / 2-5keV)
  - Power Spectral Densities (9.8×10^{-4} - 0.5Hz)
    - PSD A(2-5 keV)
    - PSD B(5-13 keV)
    - PSD C(13-60 keV)



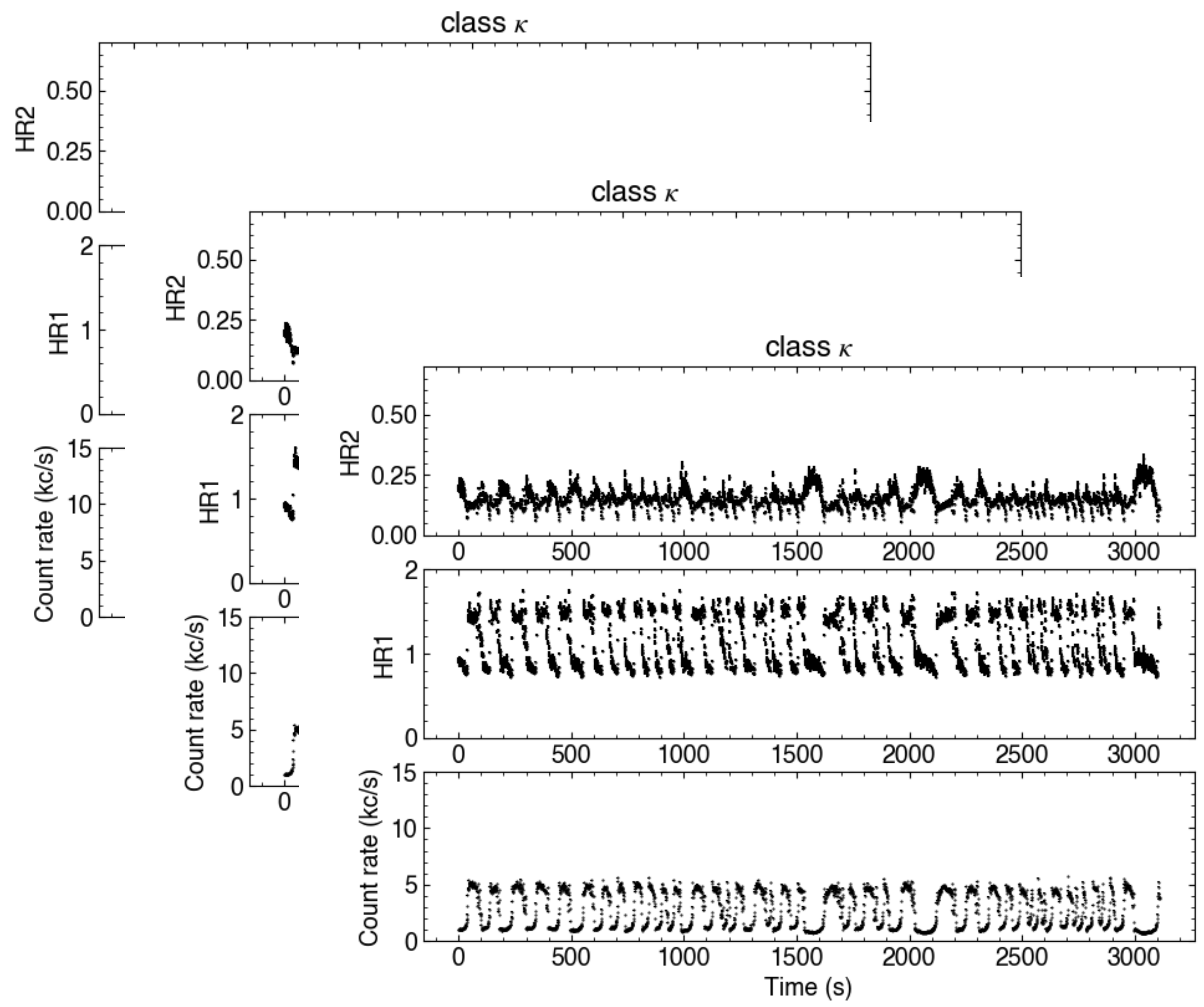
HR2: 13-60keV/2-5keV
HR1: 5-13keV/2-5keV
Light curve: 2-60keV

Data Augmentation and Light-Curve Segmentation

Light curve: 2-60keV
HR1: 5-13keV/2-5keV
HR2: 13-60keV/2-5keV

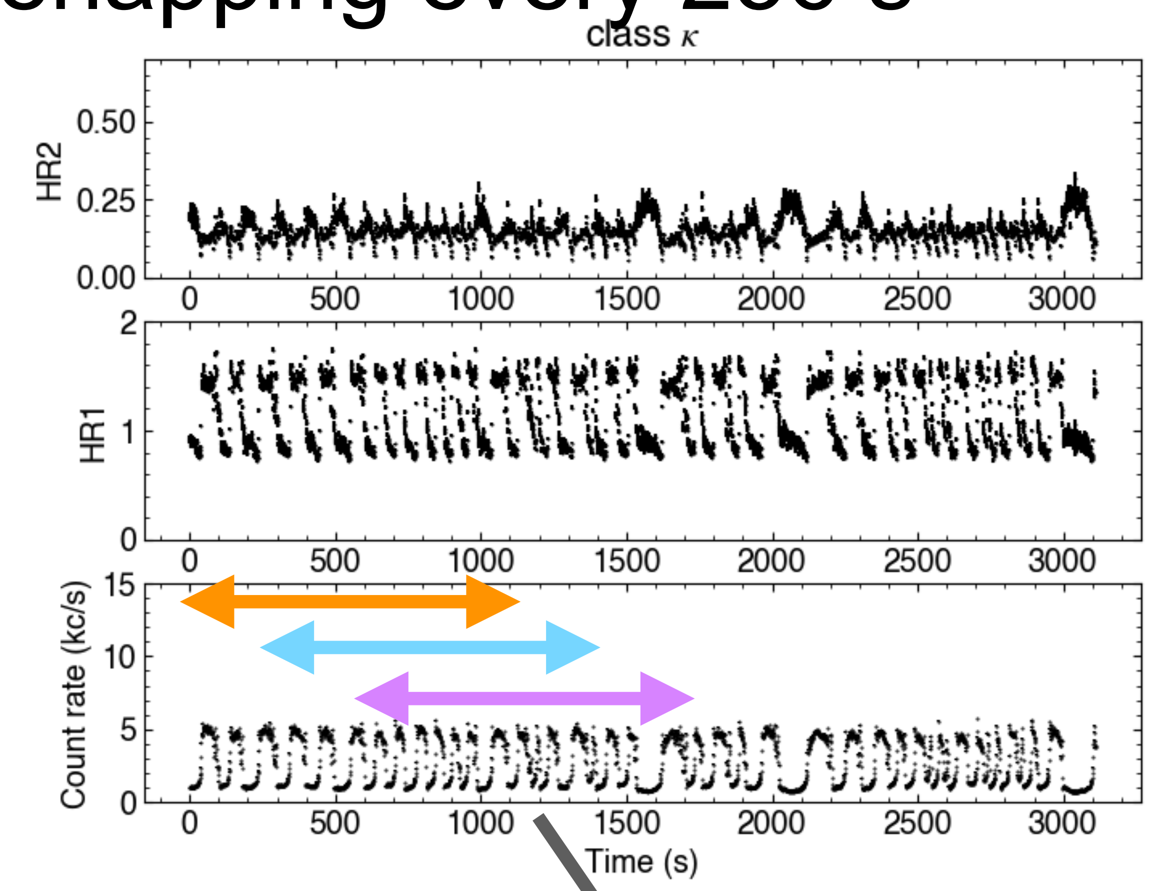


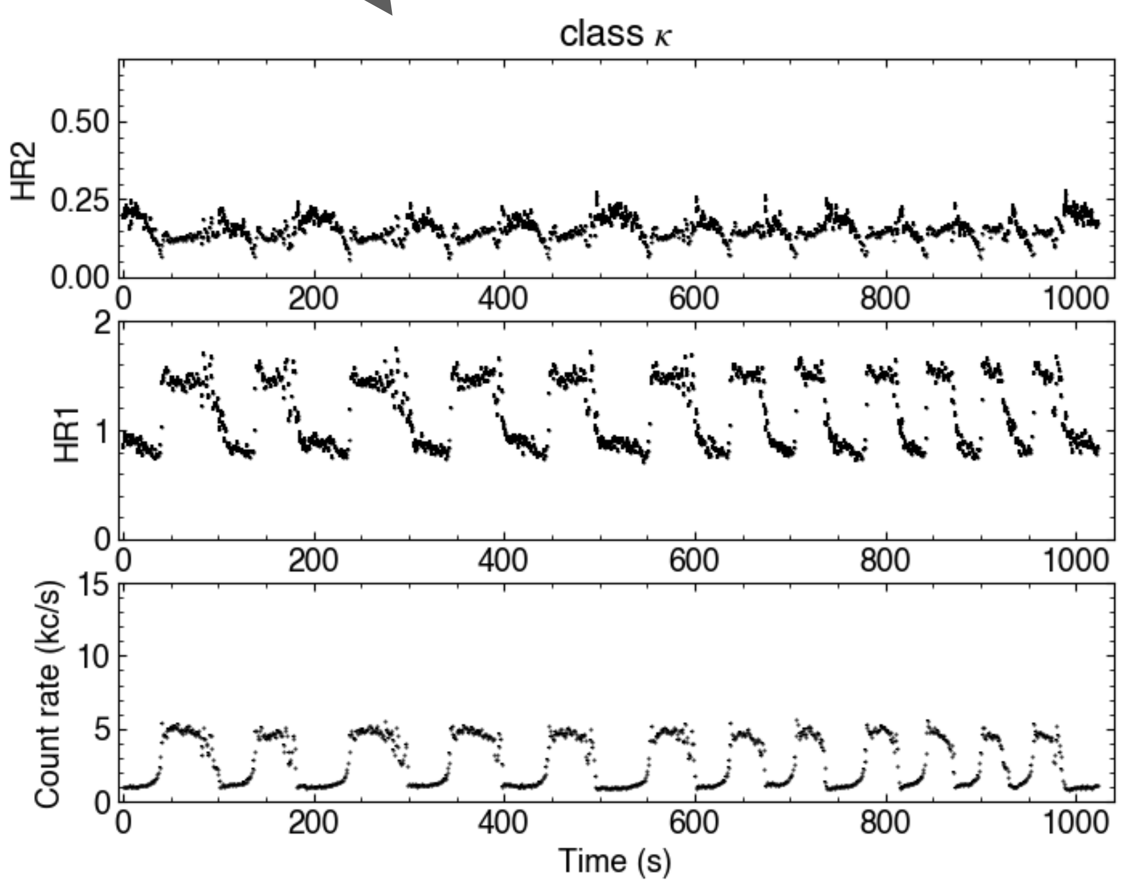
Generation of pseudo light curves: Gaussian random numbers with means equal to the observed count rates and standard deviations equal to the observed count-rate errors



x20

(ref. Huppenkothen et al., 2017)
Segmentation of light curves with a segment length of 1024 s, overlapping every 256 s





36,620 Segments

Training and Test data

- 161 observations in 1996/05 - 1997/12
- Using the empirical 12-classification of Belloni et al. (2000) as labeling data

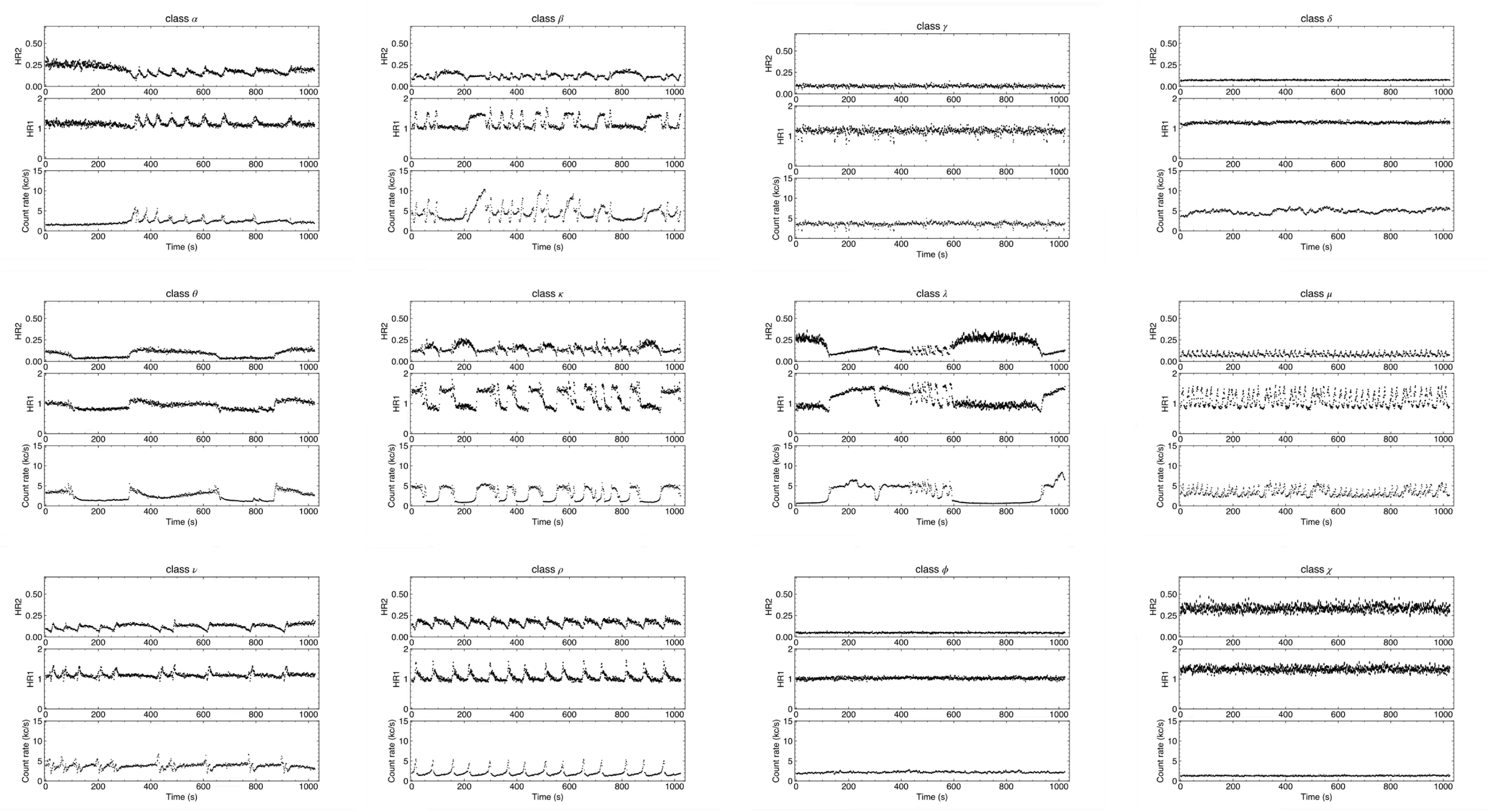
Allocating at random for each observation
Training data: ~80%
Test data: ~20%

Dataset: 36,620 segments

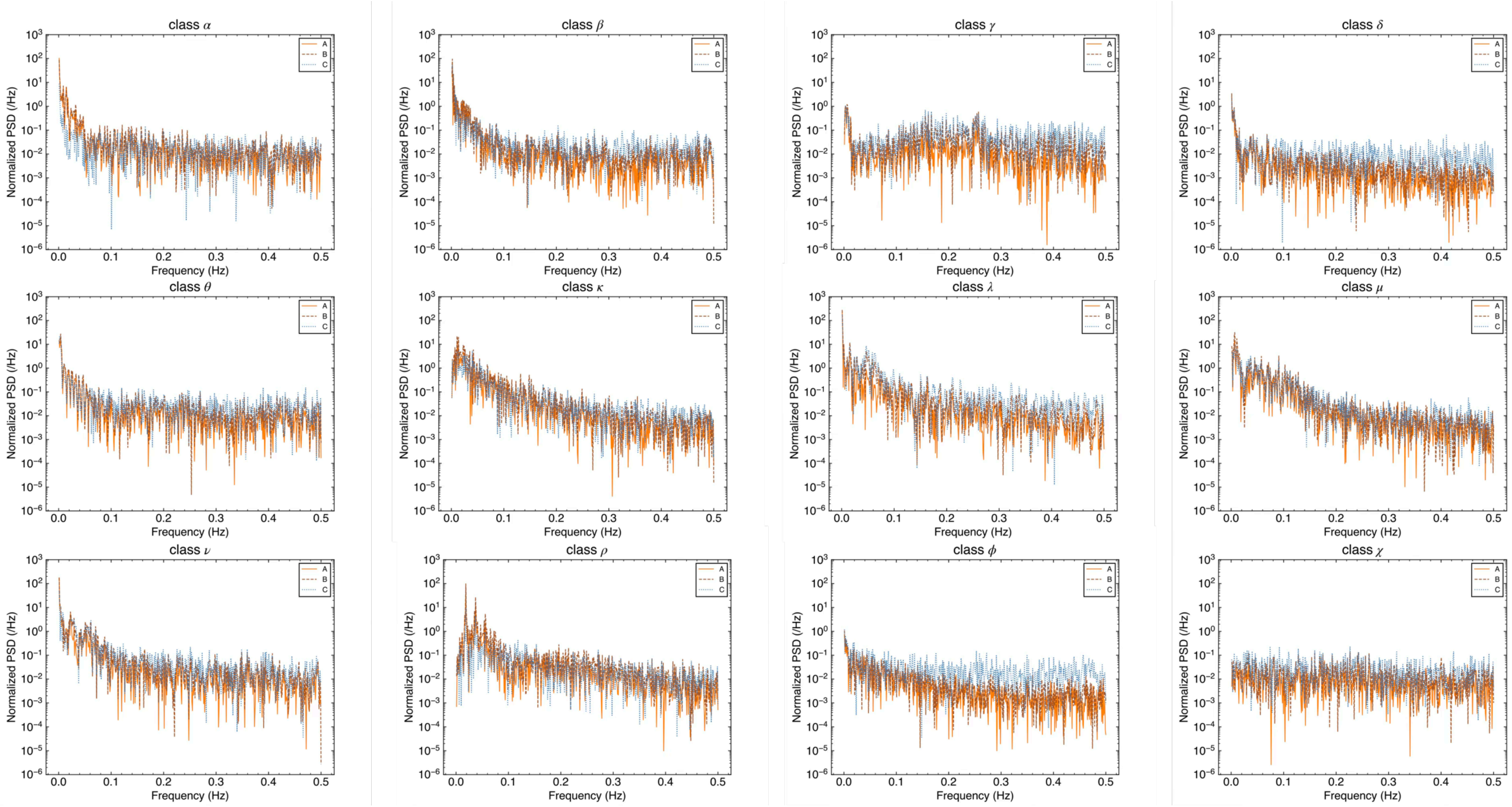
Training dataset: 28,420 segments, of which 20% is Validation data

Test dataset: 8,200 segments

Examples of light curve training data

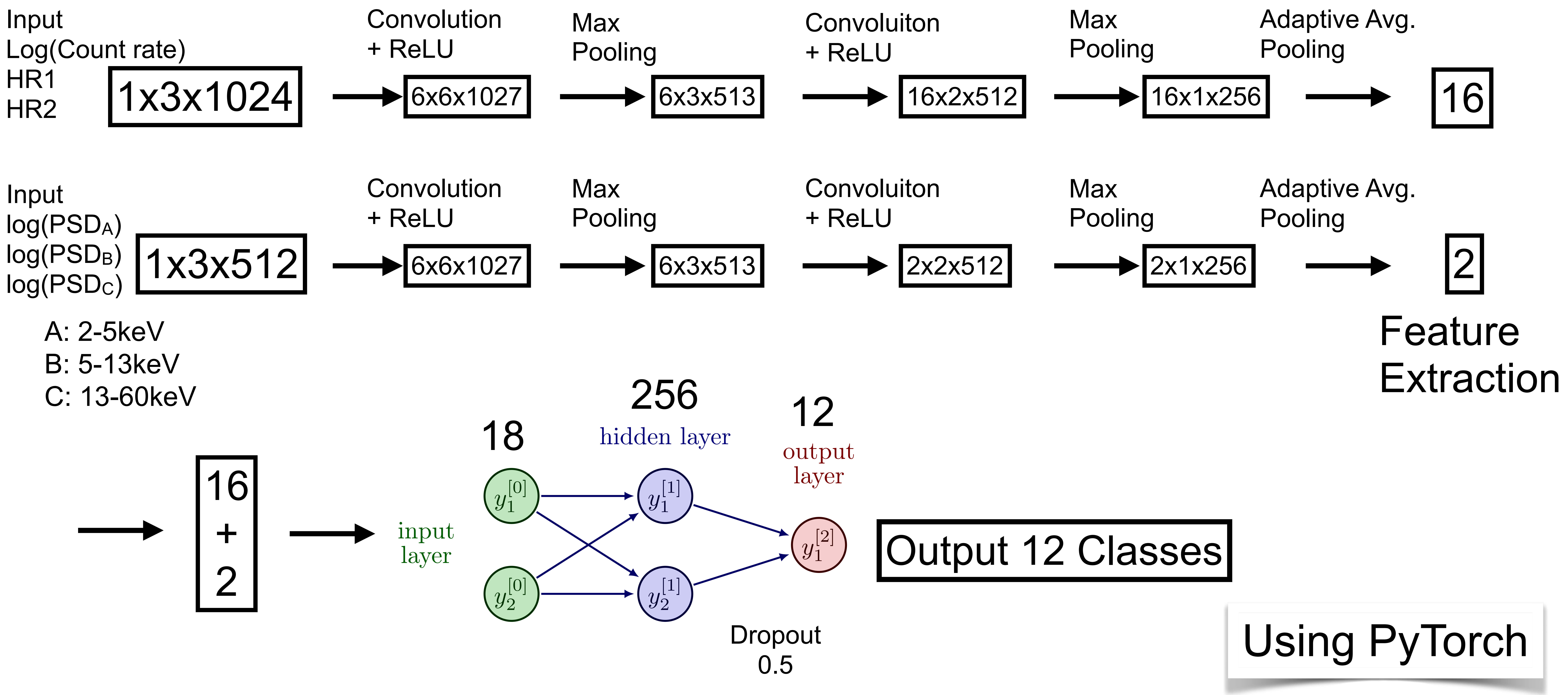


Examples of PSD training data



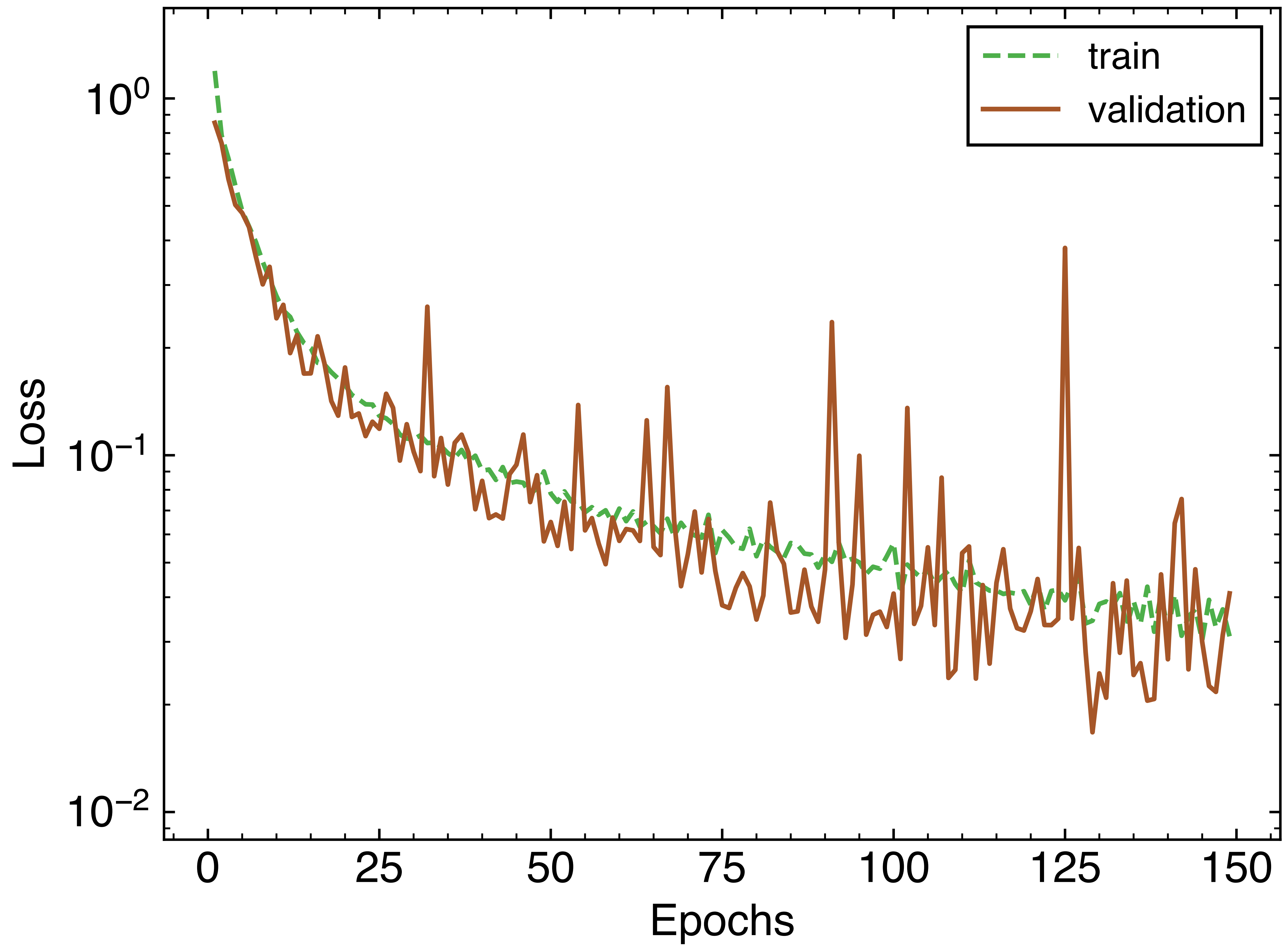
A: 2-5keV
B: 5-13keV
C: 13-60keV

Convolutional Neural Network (CNN) Architecture

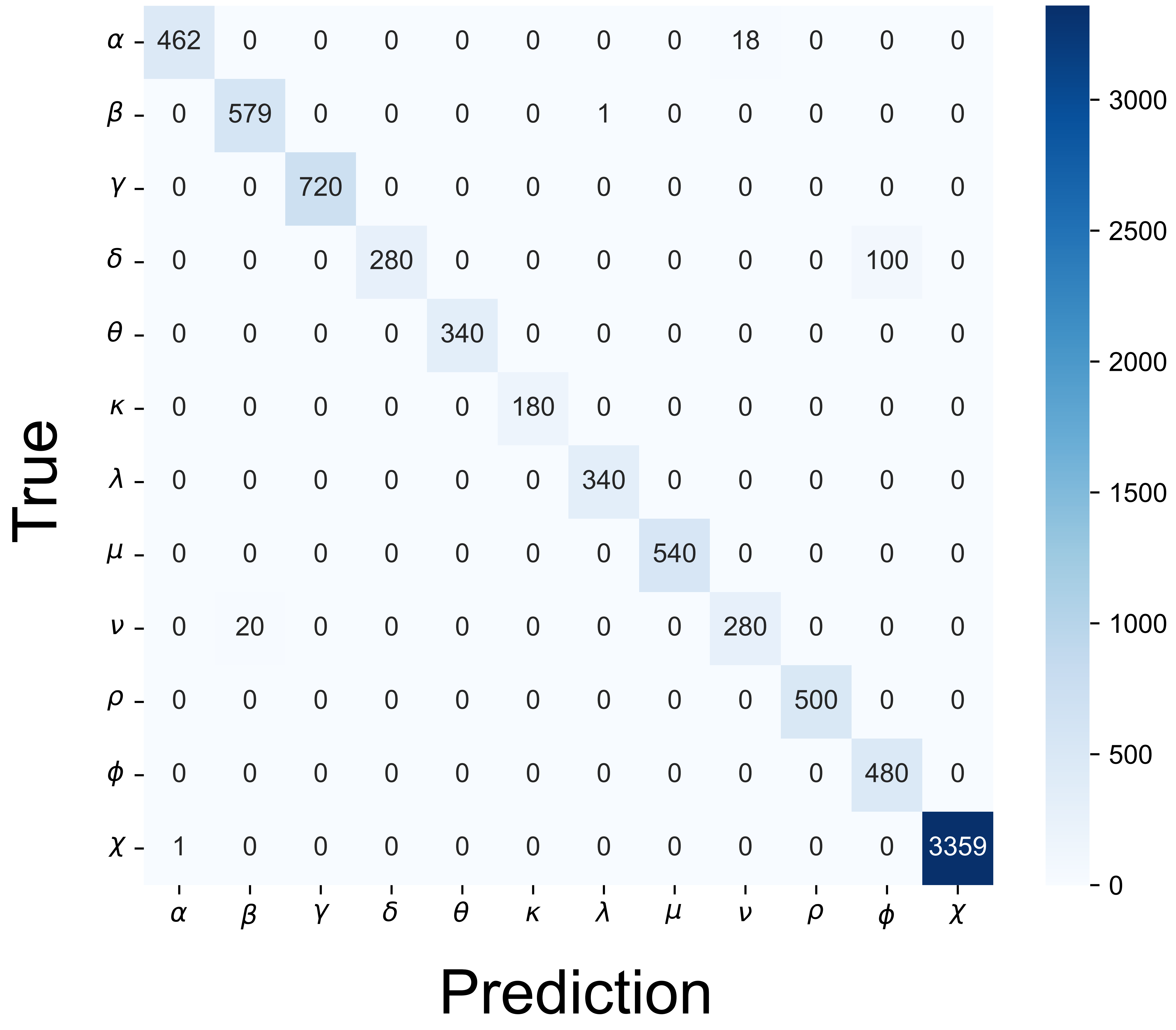


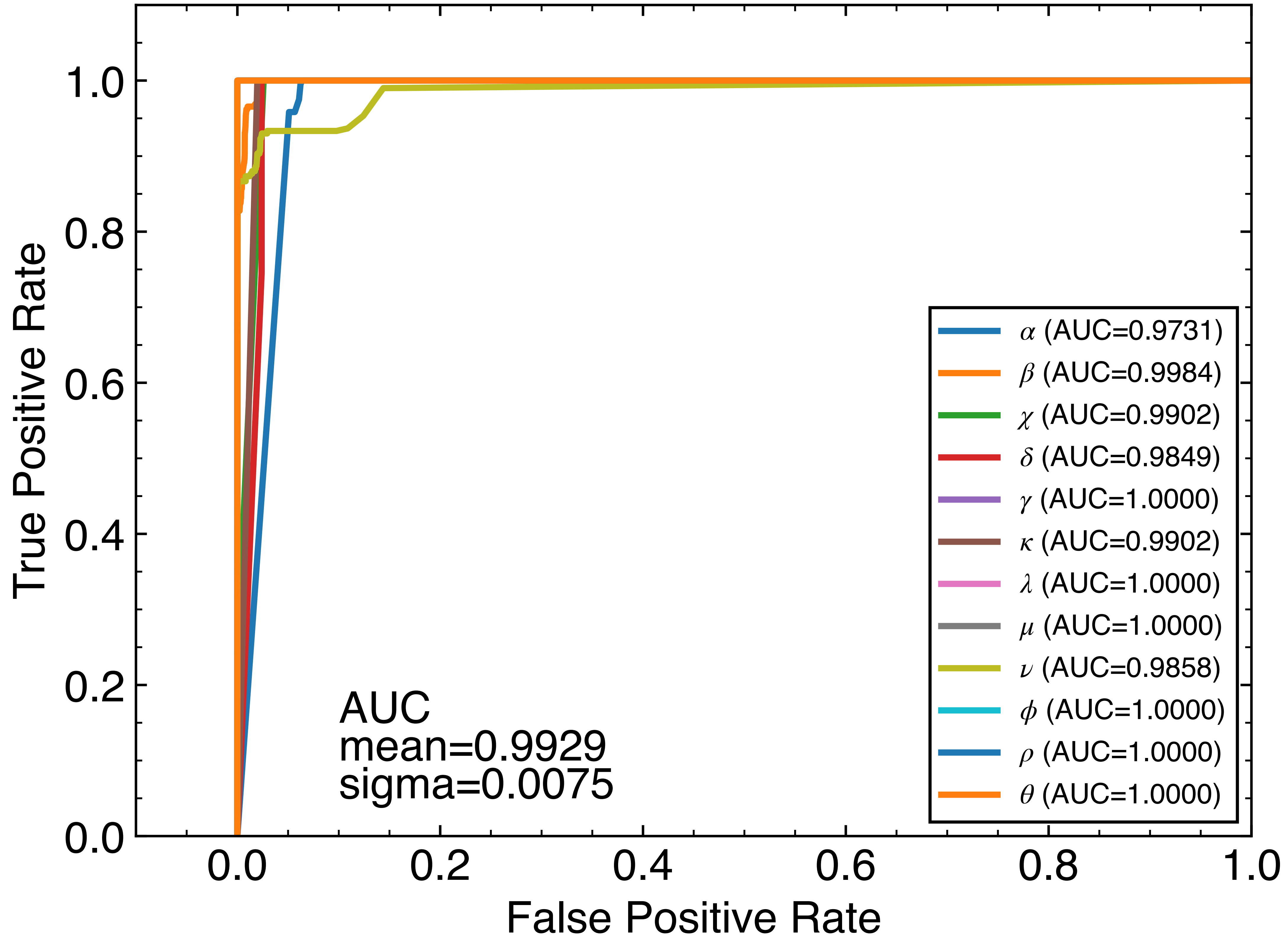
Training and Loss History

- The number of batch:10
- Early stopping (patience=20)
- Loss: Cross-entropy Loss
- Optimizer: Adam
  (learning rate = 0.001)



Performance for Test data

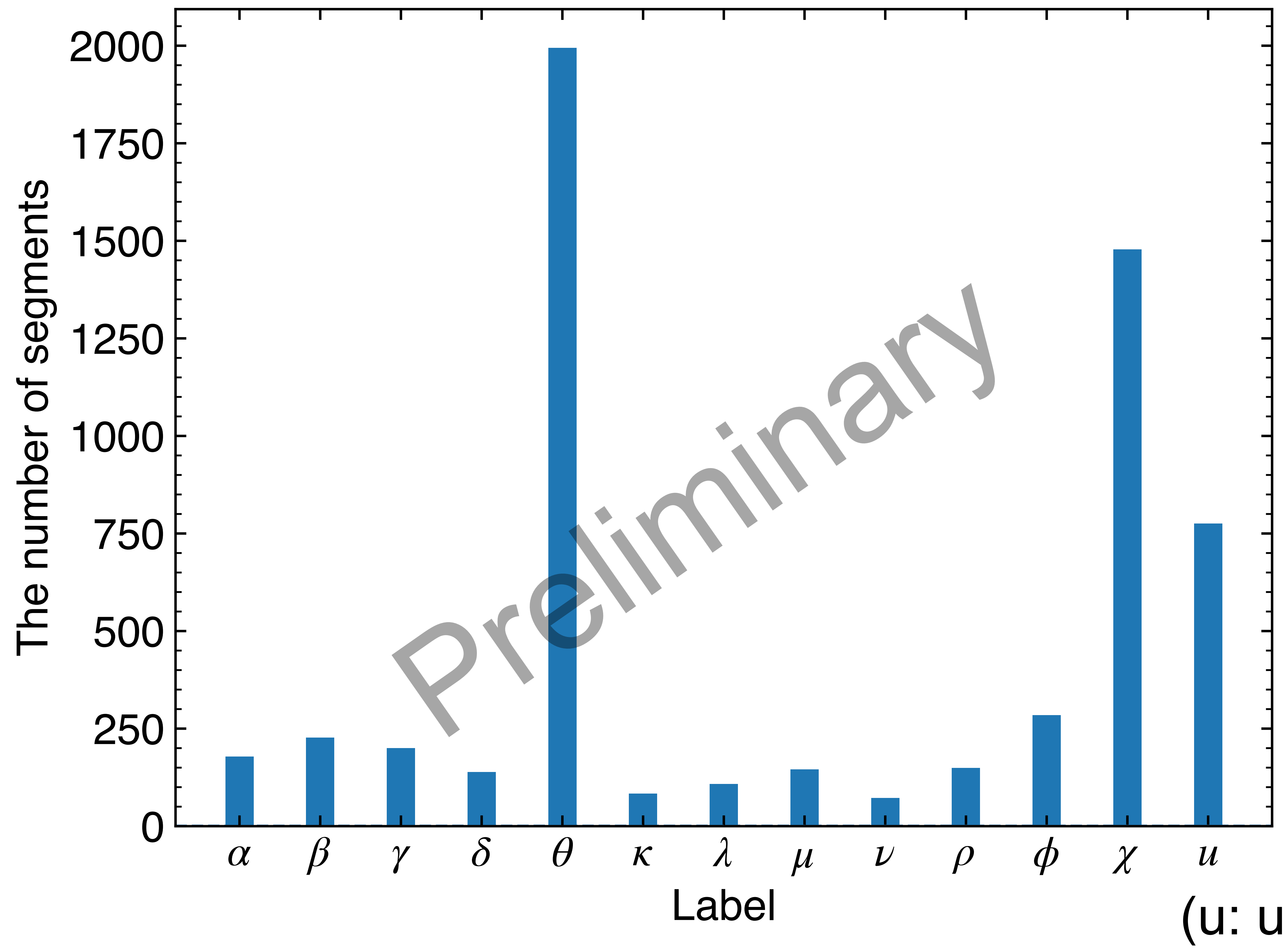




- Accuracy = 98.3%
- F1 Score = 97.1%
- AUC = 99.3%

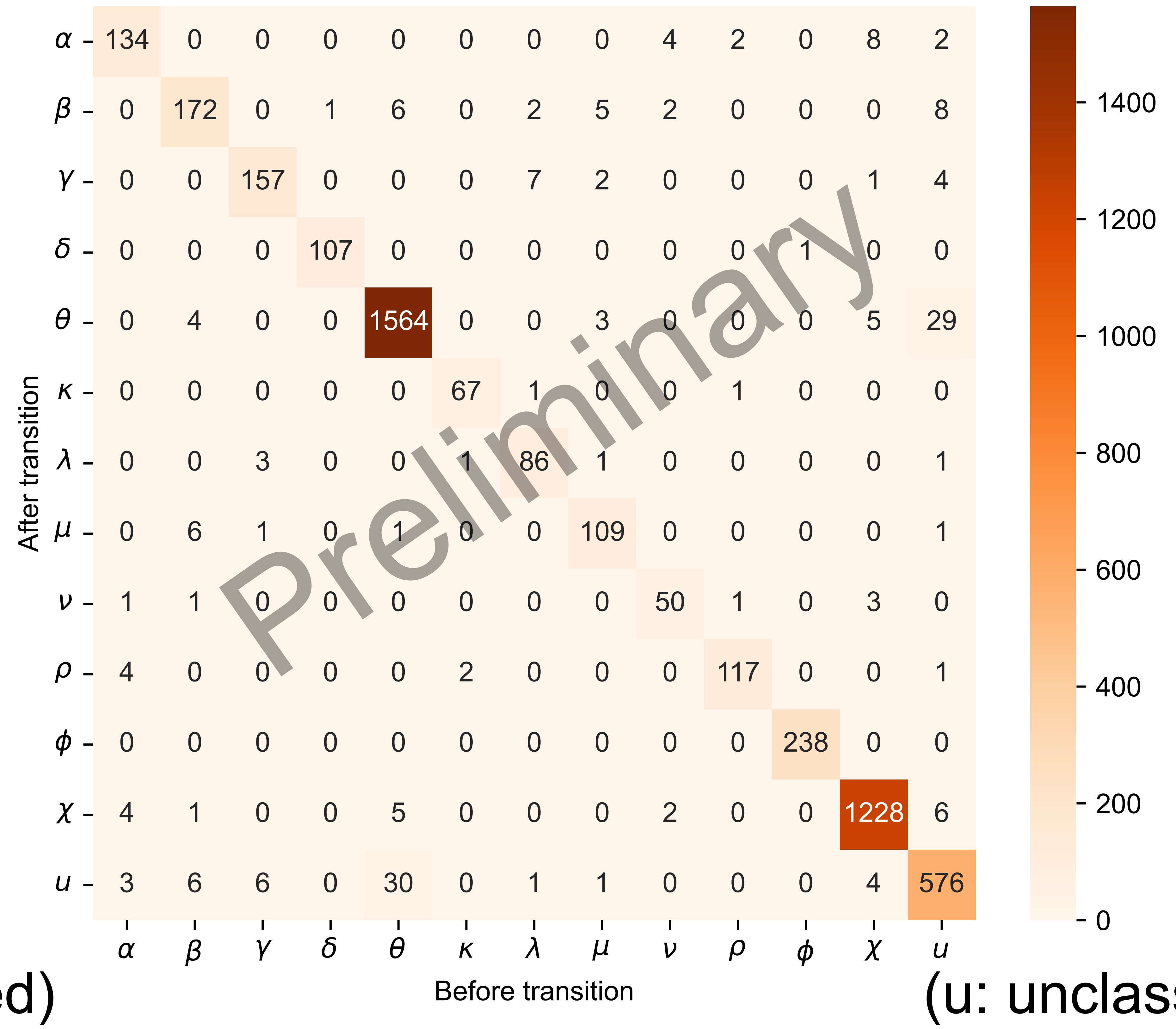
Application of the CNN model to the observed data from 1996 - 2003

- Observations in 1996/05 — 2003/02 => 1024s segment light curves:
  Not yet, correction of the change in the energy gain of the observations



(u: unclassified)

Frequency distribution of classes



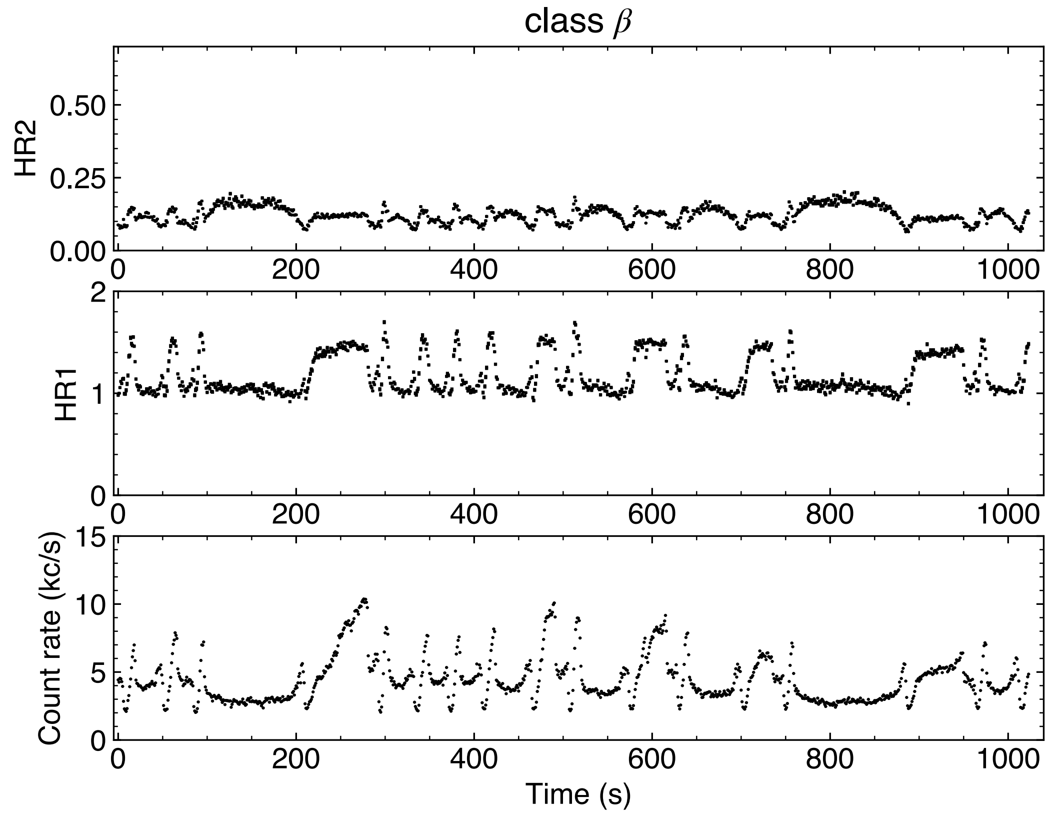
After \ Before	α	β	γ	δ	θ	κ	λ	μ	ν	ρ	ϕ	χ	u
α	134	0	0	0	0	0	0	0	4	2	0	8	2
β	0	172	0	1	6	0	2	5	2	0	0	0	8
γ	0	0	157	0	0	0	7	2	0	0	0	1	4
δ	0	0	0	107	0	0	0	0	0	0	1	0	0
θ	0	4	0	0	1564	0	0	3	0	0	0	5	29
κ	0	0	0	0	0	67	1	0	0	1	0	0	0
λ	0	0	3	0	0	1	86	1	0	0	0	0	1
μ	0	6	1	0	1	0	0	109	0	0	0	0	1
ν	1	1	0	0	0	0	0	0	50	1	0	3	0
ρ	4	0	0	0	0	2	0	0	0	117	0	0	1
ϕ	0	0	0	0	0	0	0	0	0	0	238	0	0
χ	4	1	0	0	5	0	0	0	2	0	0	1228	6
u	3	6	6	0	30	0	1	1	0	0	0	4	576

(u: unclassified)

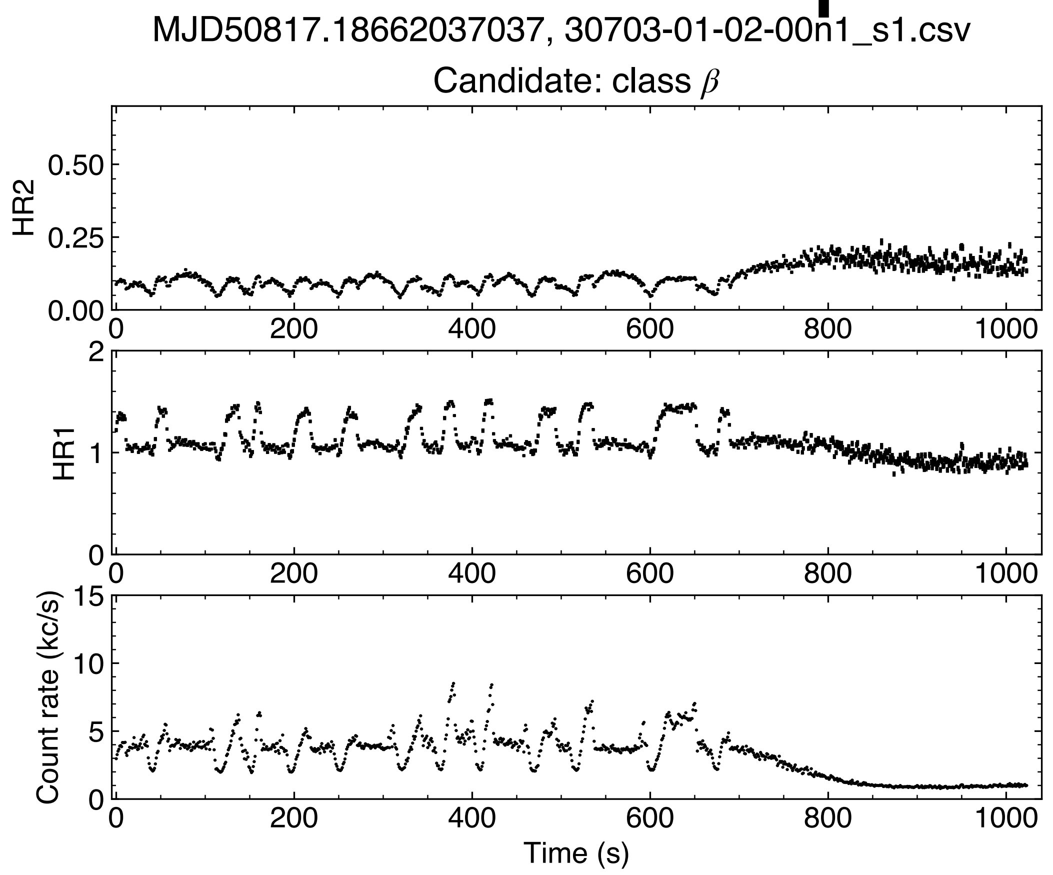
Transition between classes

Examples of classification candidates

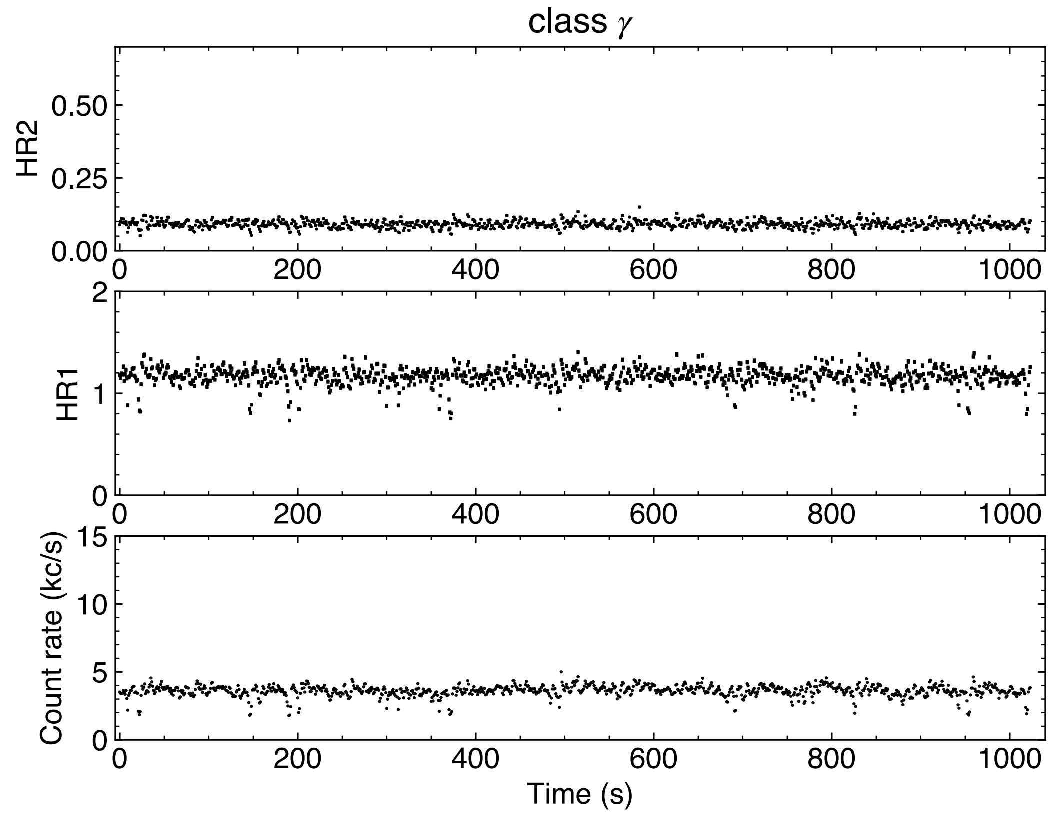
Training β



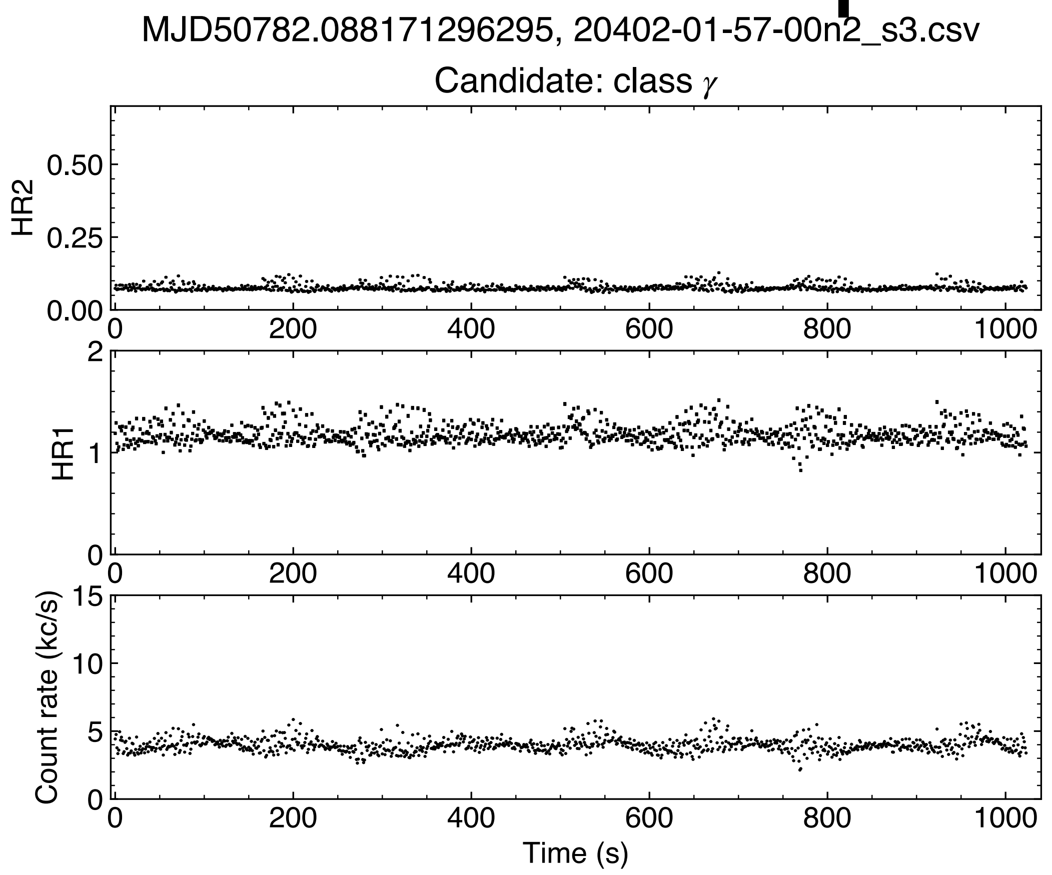
Candidate β



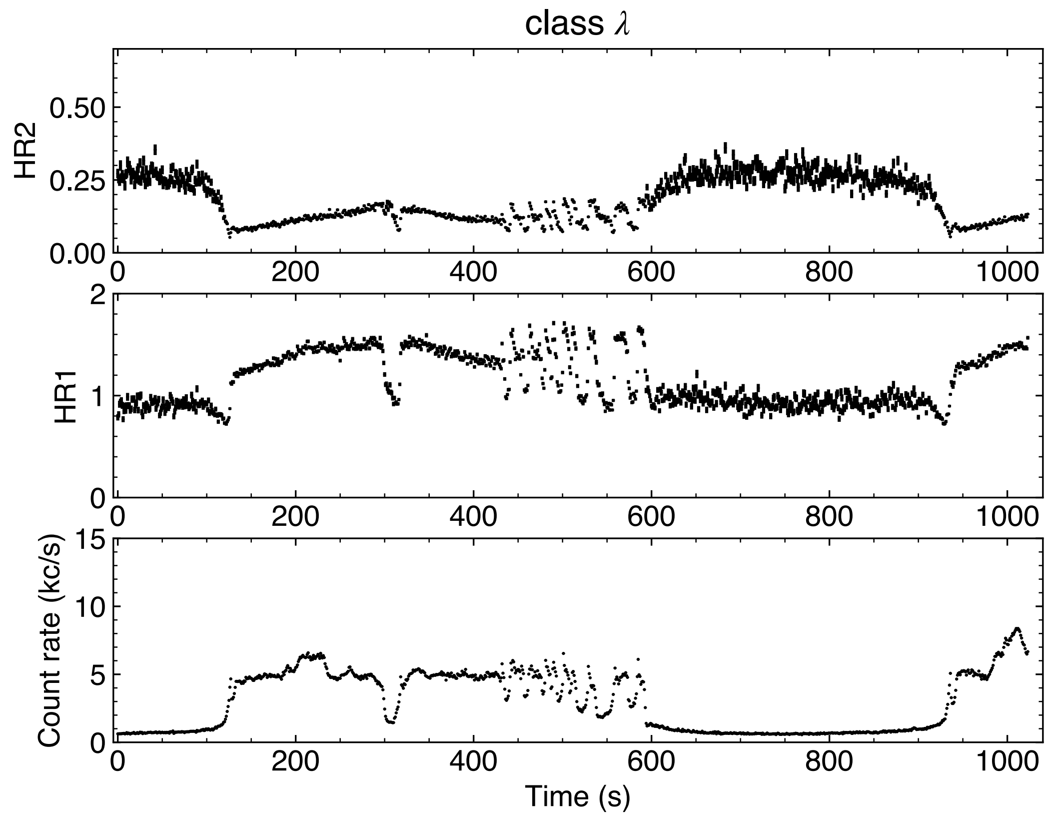
Training γ



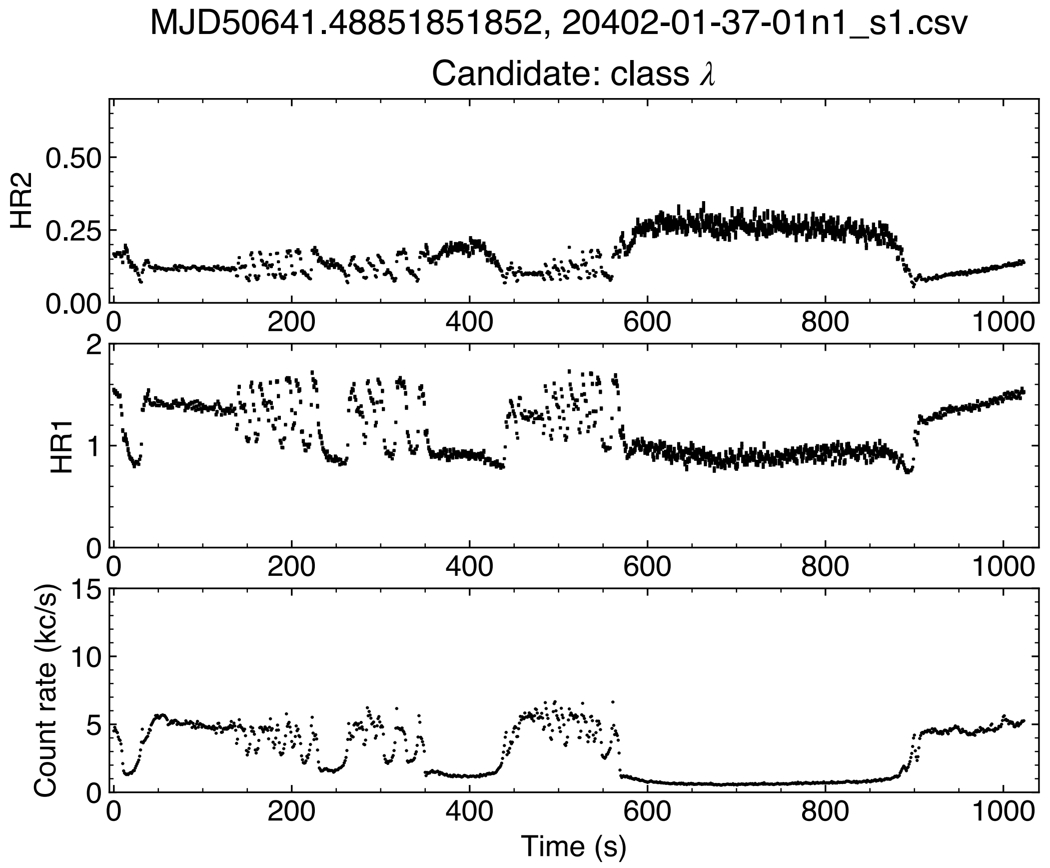
Candidate γ



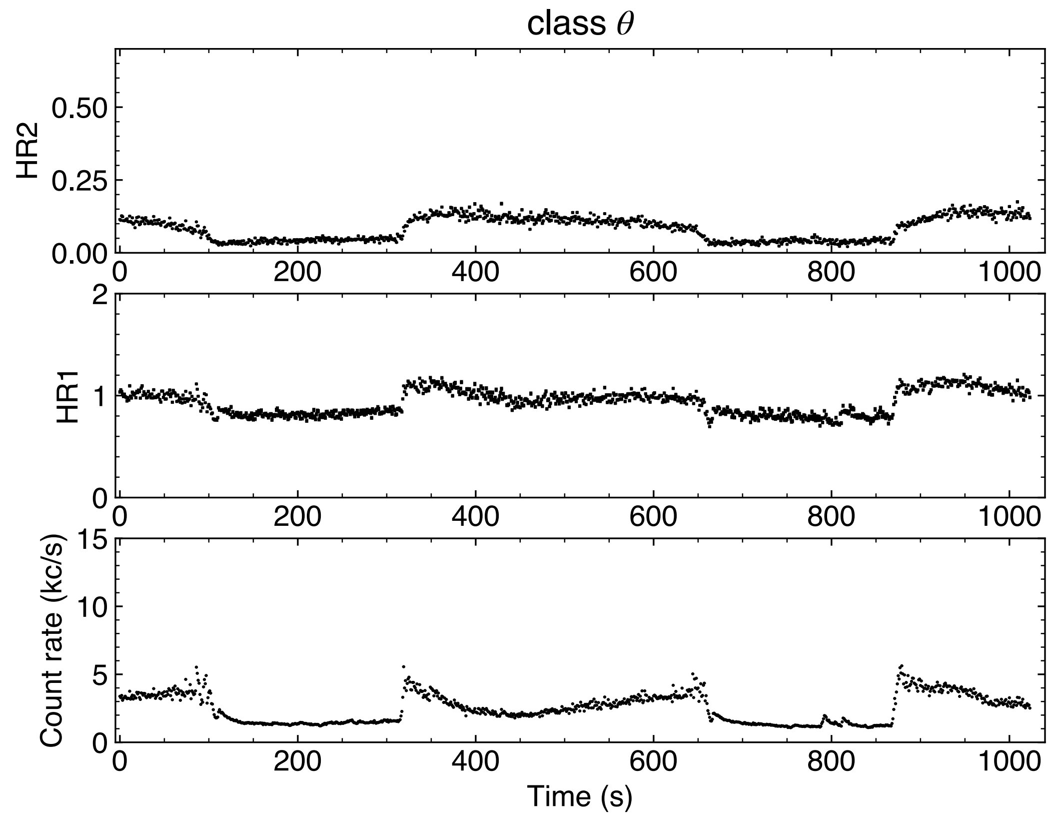
Training λ



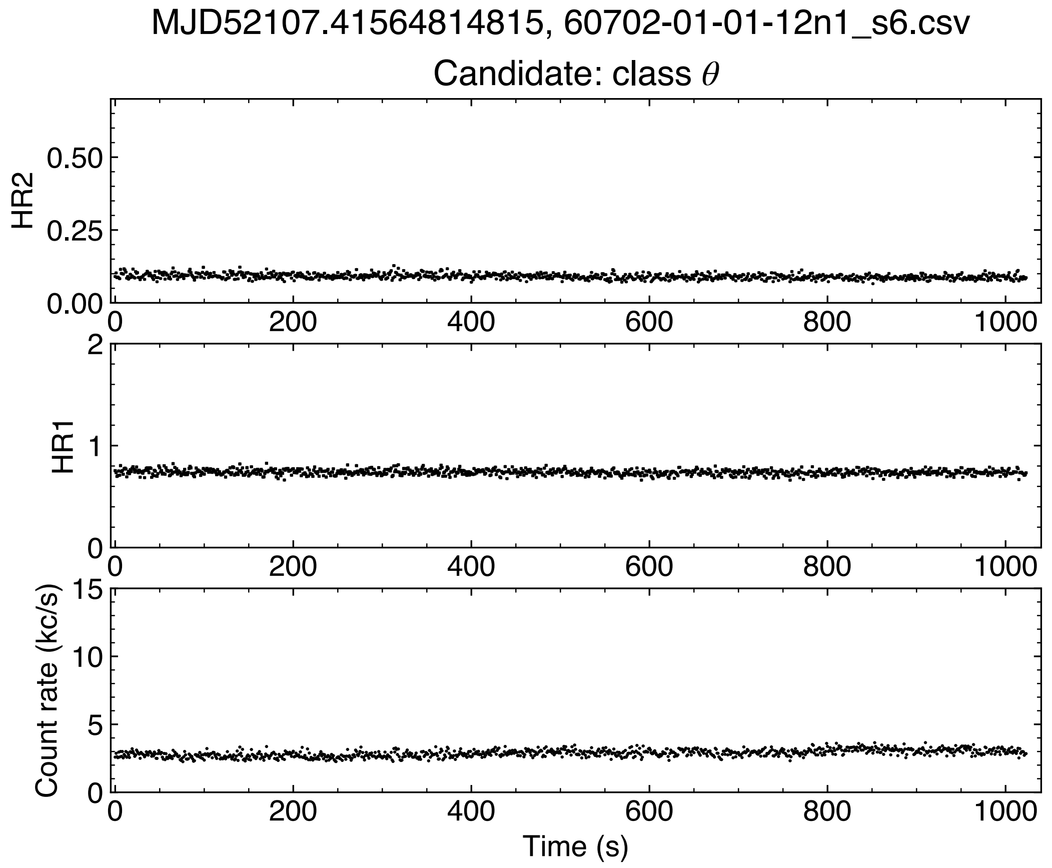
Candidate λ



Training θ



Candidate θ



Summary

- The black hole binary GRS 1915+105, a typical microquasar, is known for its unique X-ray variability.
- Development of CNN models to classify its remarkable variability into twelve classes by Belloni et al (2000)
  - The classification model achieved 98% classification accuracy and an average AUC of 99%
  - Preliminary classification of RXTE data in 1996 - 2003

- Next, using the classification models with the entire RXTE data set in 1996 - 2011 to analyze the long-term evolution of GRS 1915+105
  - Investigate how long each pattern persists, how the system transitions between them, and whether patterns of variability exist.
  - Shed light on what distinguishes GRS 1915+105 from other black hole binaries and on the conditions necessary for jets to form.