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Classifying Black Hole States
— Lessons Learned in Machine Learning—

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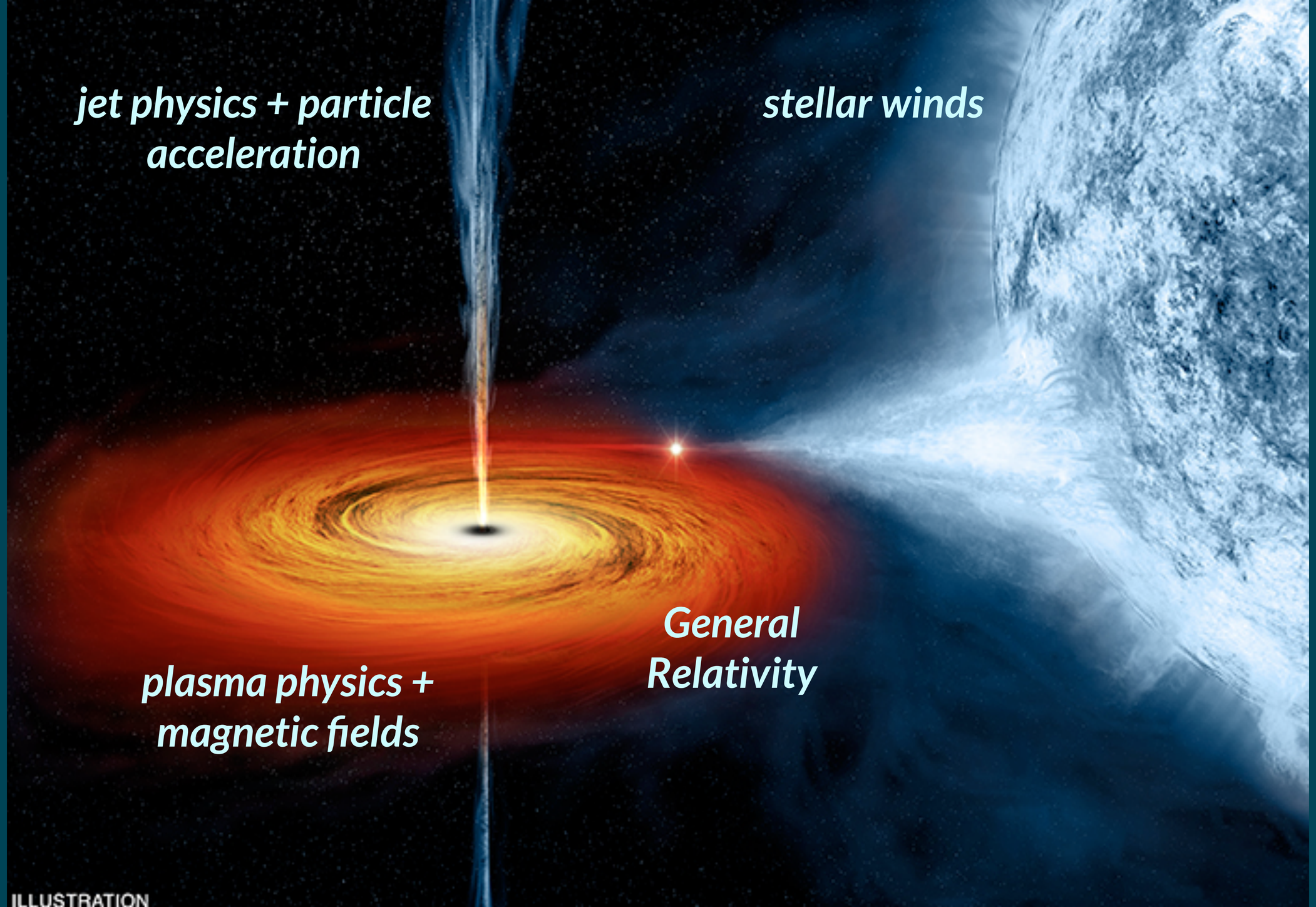
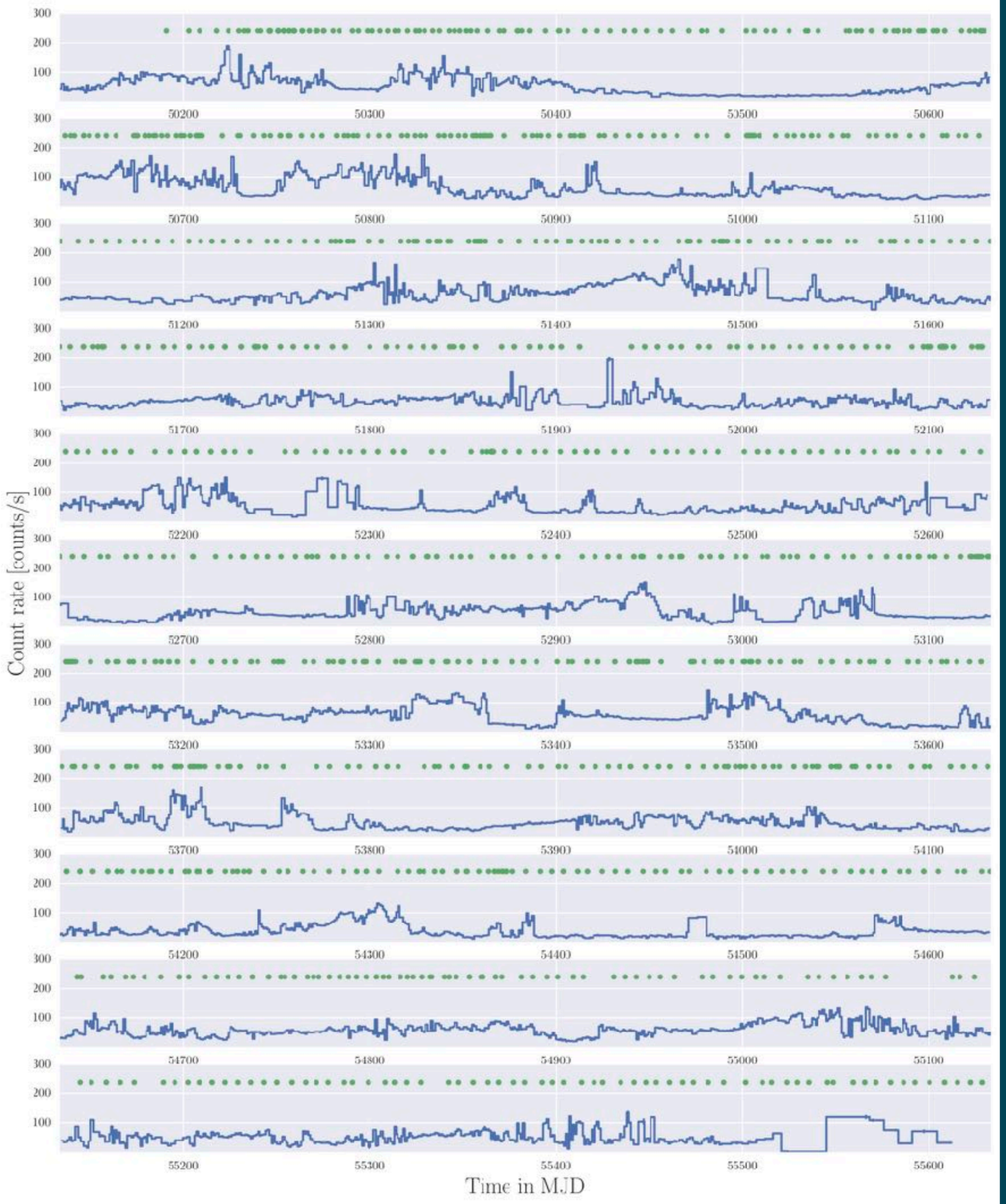
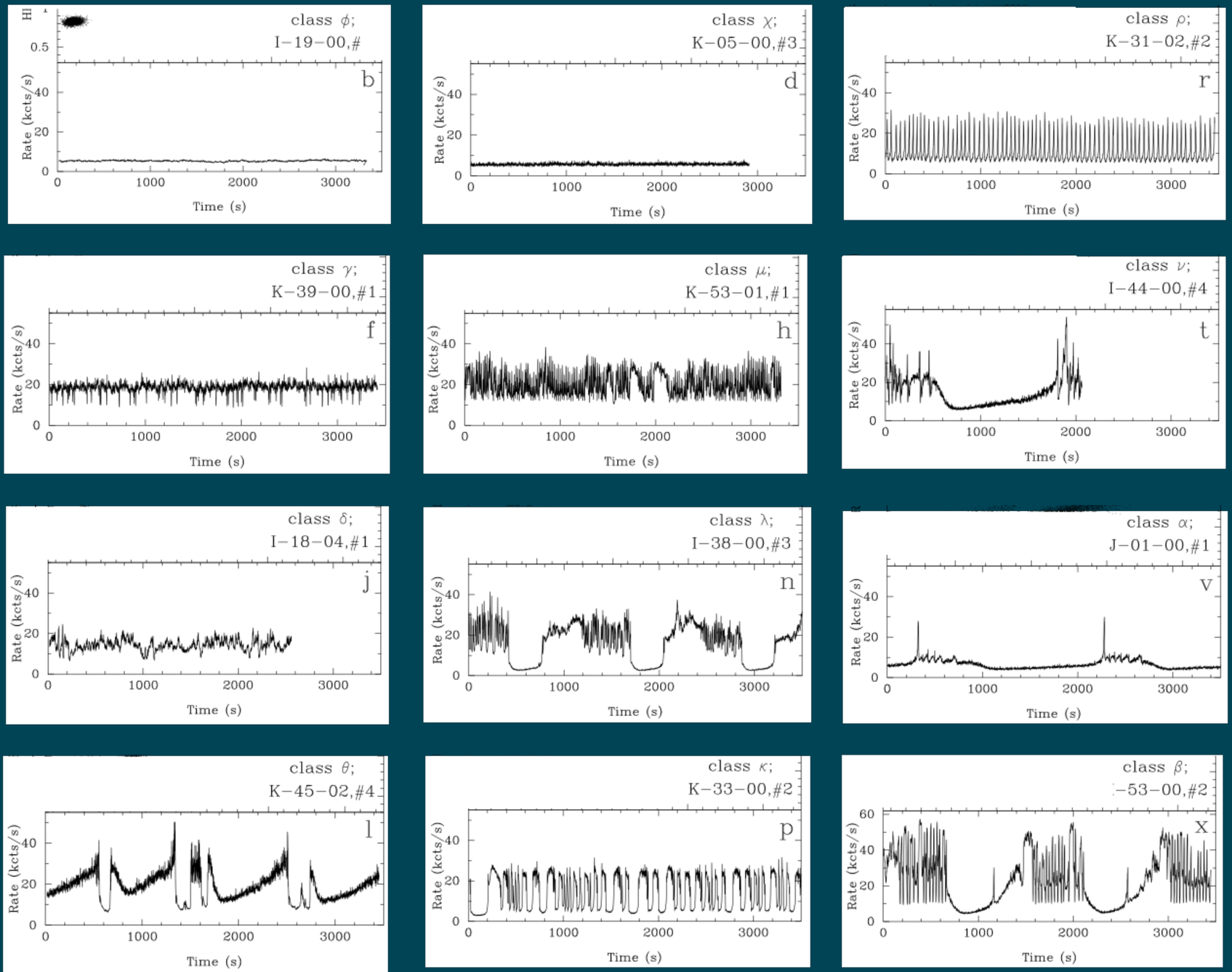
How do black holes accrete matter?


jet physics + particle acceleration
stellar winds
General Relativity
plasma physics + magnetic fields
ILLUSTRATION

What is the long-term evolution of black hole X-ray binaries?

GRS 1915+105





Belloni et al, 2000, Klein-Wolt et al, 2002, Hannikainen et al, 2004

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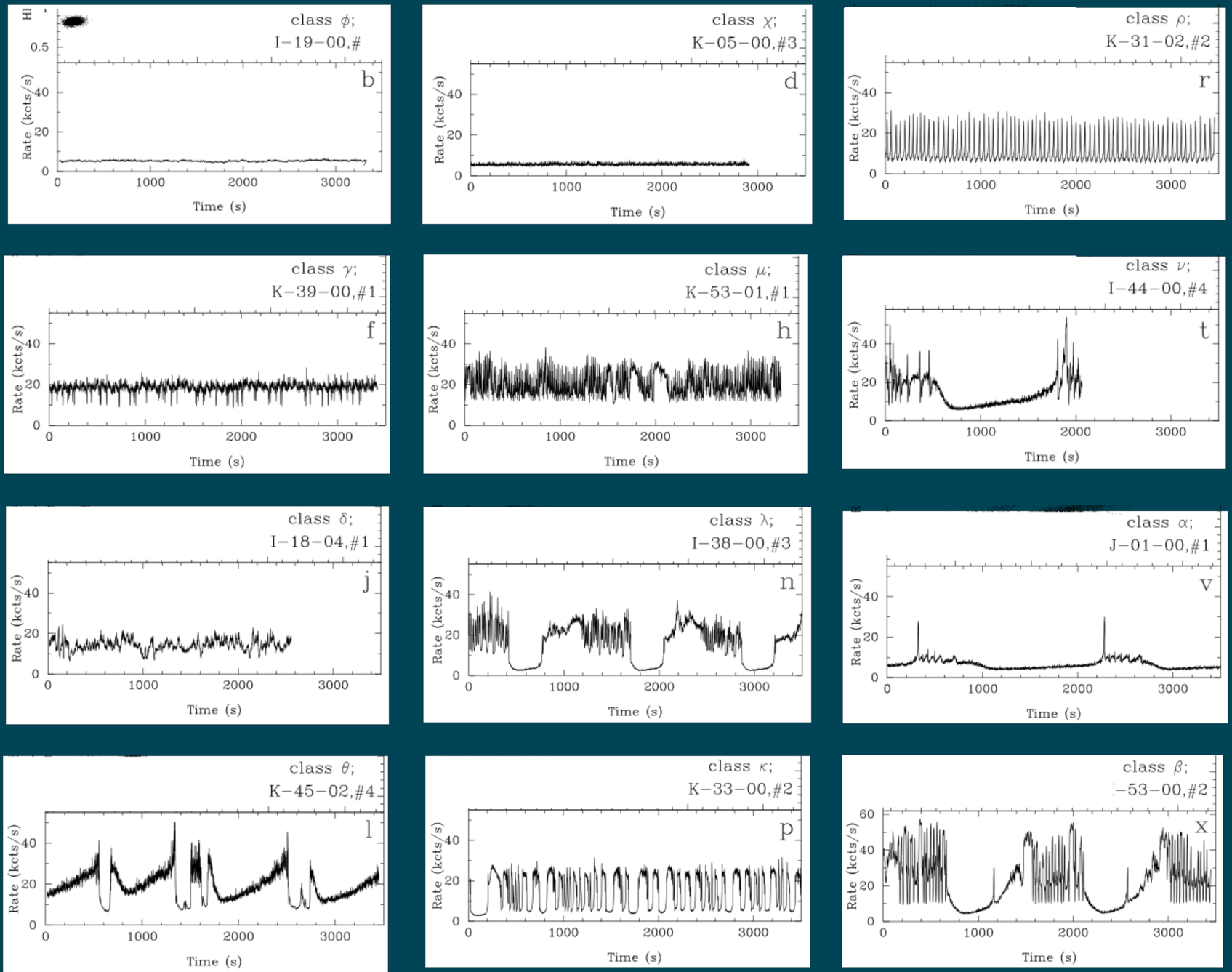
“Machine Learning, a subfield of computer science, involves the development of mathematical algorithms that discover knowledge from specific data sets, and then "learn" from the data in an iterative fashion that allows predictions to be made”

— NYAS Machine Learning Symposium

+ very flexible
+ works on large data sets
+ excellent at prediction problems

— often not designed to do inference
— sometimes hard to interpret
— strongly input-dependent



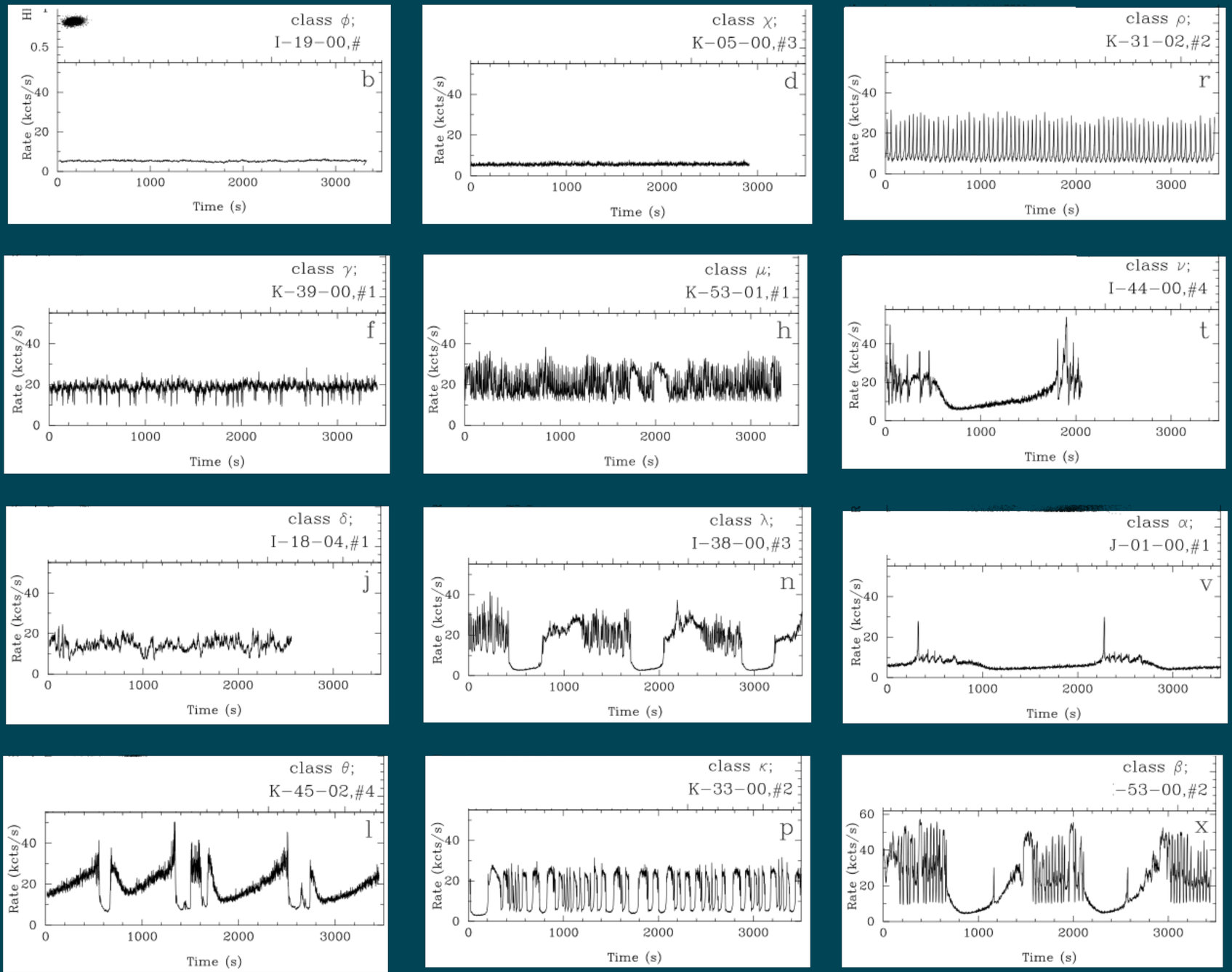
Belloni et al, 2000, Klein-Wolt et al, 2002, Hannikainen et al, 2004

Lesson 1: data characteristics are important!

GRS 1915+105

- ~10,000 light curves
- “ground truth” classifications supplied by humans
- heavily imbalanced data set

Lesson 2: Feature Engineering is hard!



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Feature Engineering

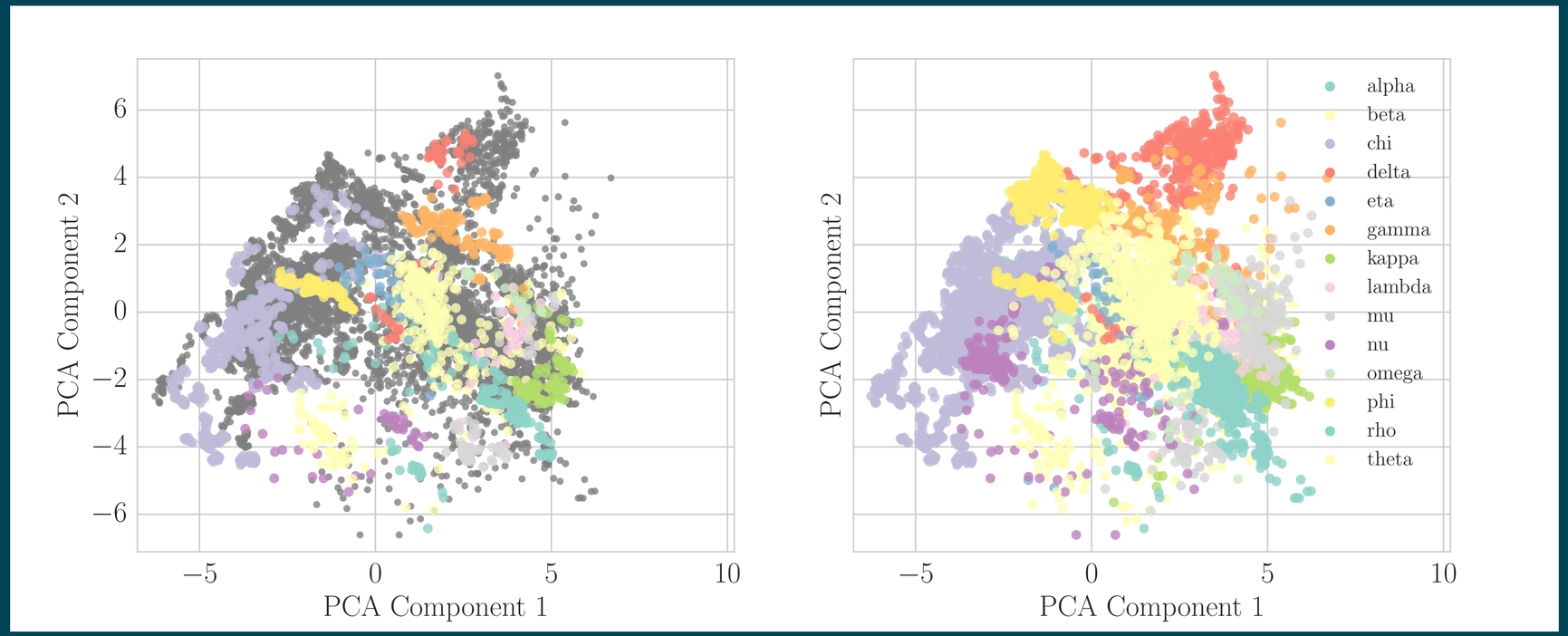
- mean/variance/skew of time series
- autoregressive model of time series
- maximum power in PSD
- power colours (Heil et al, 2014)
- PCA decomposition of PSD
- hardness ratio mean/variance/covariance

Lesson 3: sometimes fancy methods doesn’t help!

Machine Learning

- use human classification as “ground truth”
- logistic regression
- cross-validation
- 92.5% accuracy on test set

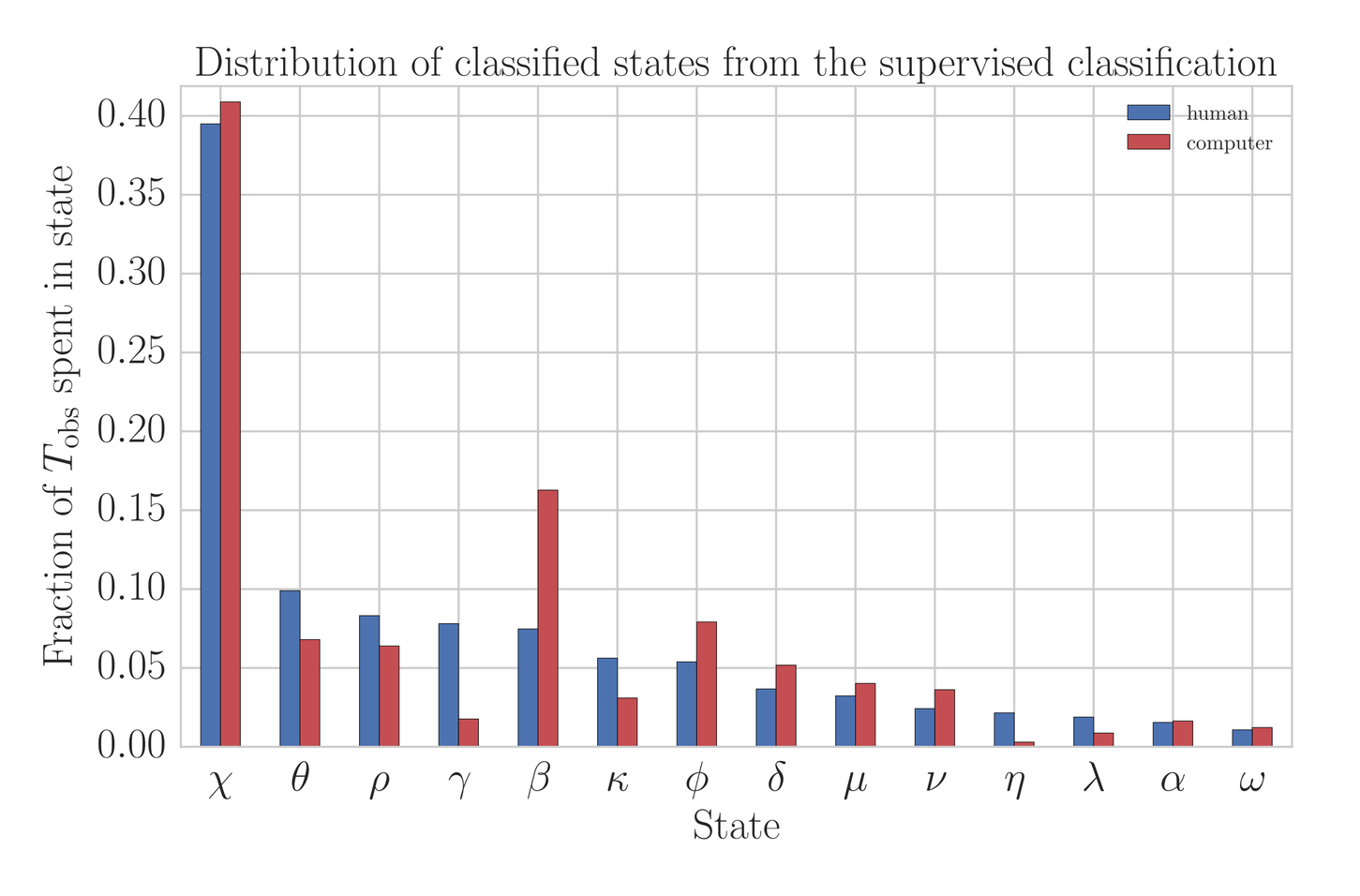
https://github.com/dhuppenkothen/BlackHoleML



Huppenkothen et al, 2017

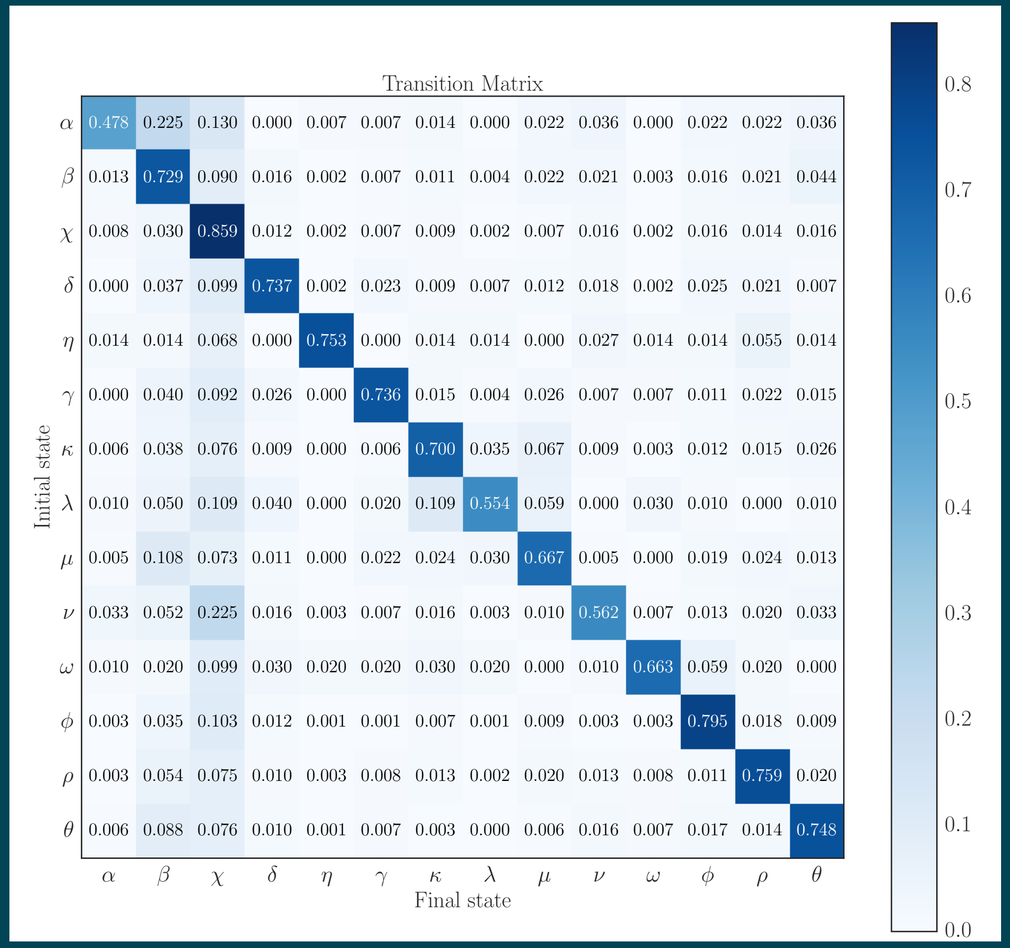
Lesson 4: physical interpretation requires probabilities

Huppenkothen et al, 2017



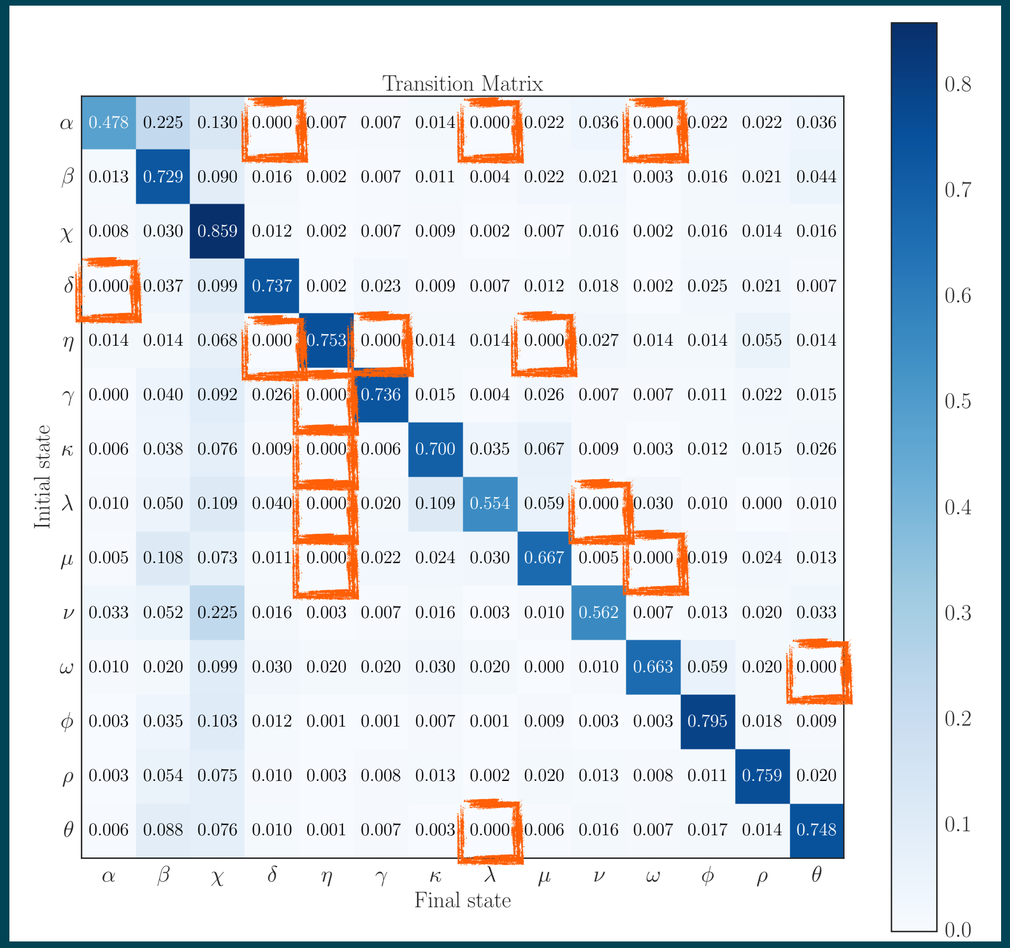
Distribution of states evolves over 16 years!

Huppenkothen et al, 2017



Evolution may follow patterns

Huppenkothen et al, 2017



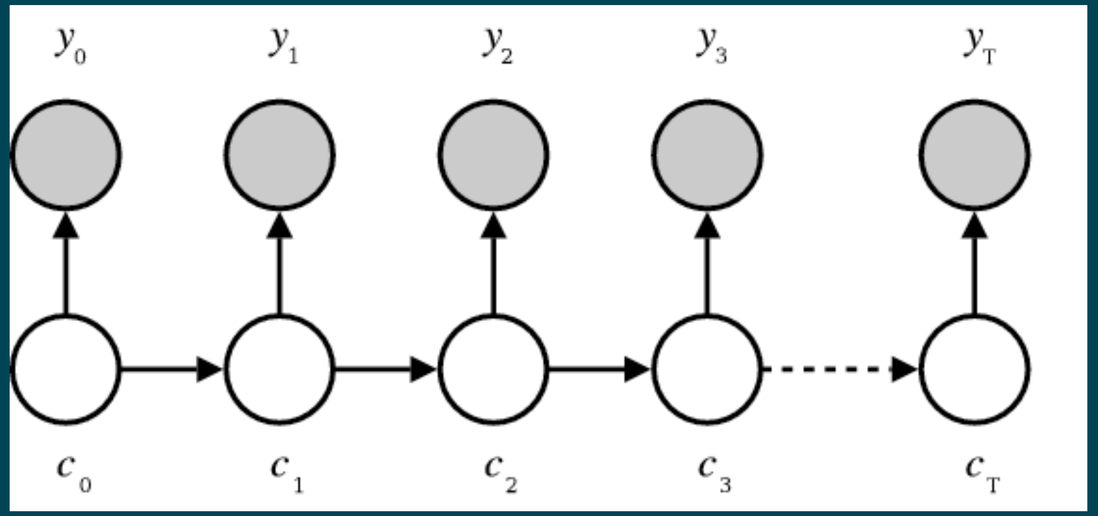
Evolution may follow patterns

Lesson 5: Human-based classifications are only accurate to ~90% (and may include biases)

Future: Combine machine learning with Bayesian inference!

Hidden Markov Models*

*with V. Grinberg, A. Müller and N. Goix



http://ngoix.github.io/cyg-x1/index.html

Use methods from computational chemistry!

Conclusions

- time series are an important tool to study physical processes in black holes and other astrophysical objects
- machine learning can be an excellent tool to uncover structure (but interpretability is important)
- using logistic regression, we can uncover the long-term state evolution of GRS 1915+105