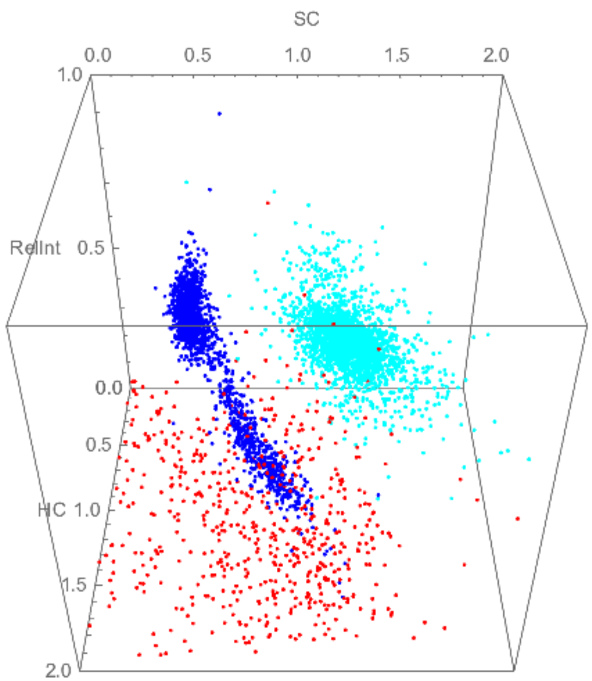
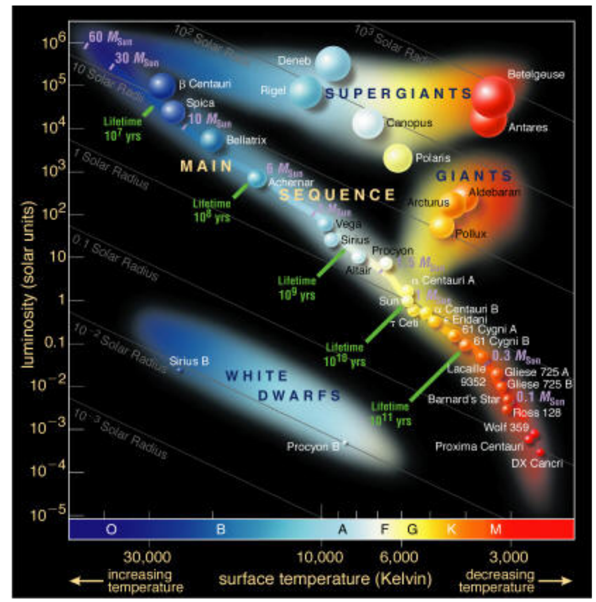
Hertszprung-Russell Analogs for Accreting Binaries

Saeqa Dil Vrtilek (CfA)



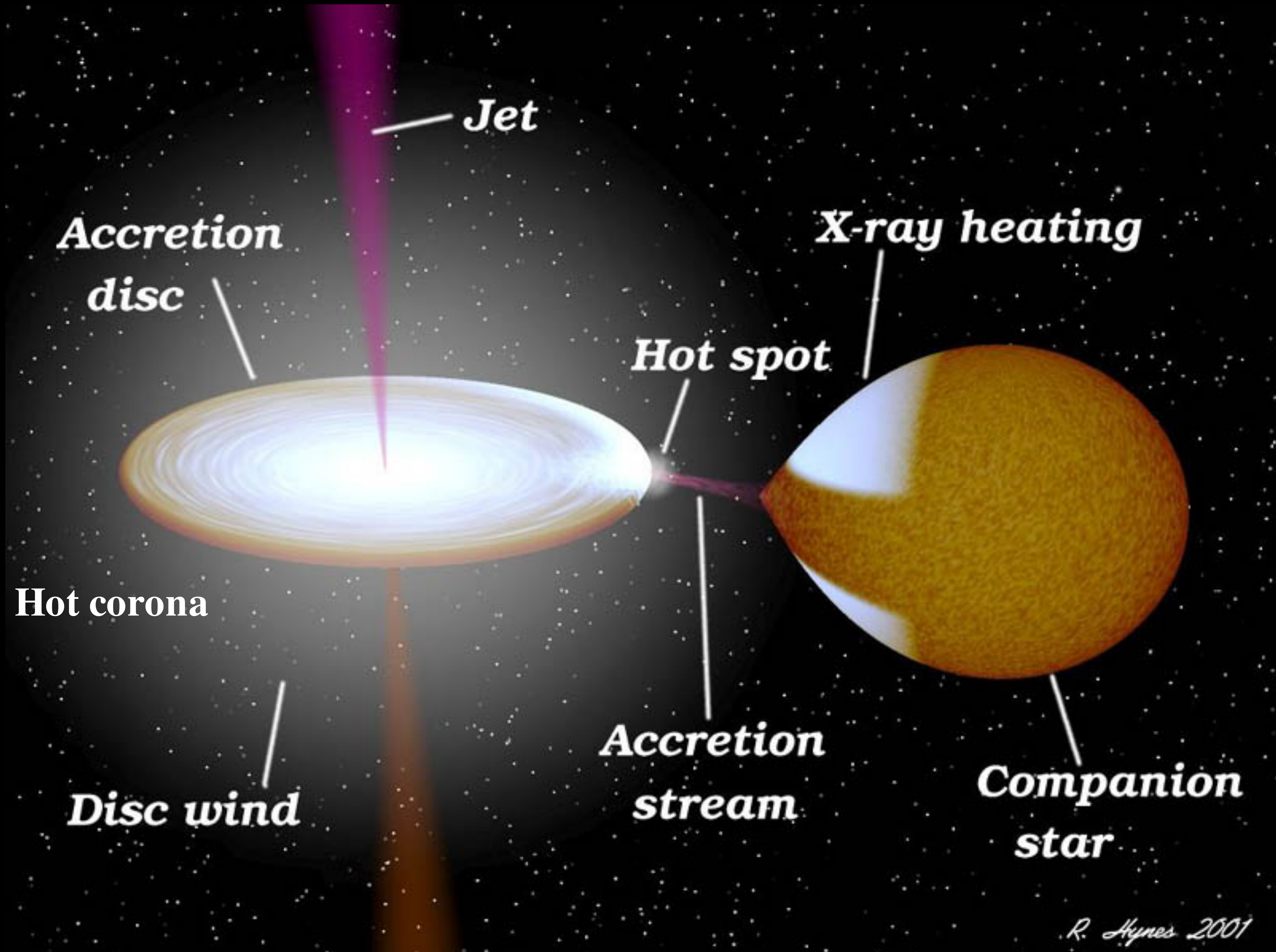


L. Bornn (Harvard), B. Boroson (Clayton State), S. Buchan (Southampton), J. Cechura (AIAS), G. Fabbiano (CfA), J. Fridriksson (MIT), G. Gopalan (UIceland), J. Homan (MIT), N. Islam (RRI), D. Kim (CfA), M. McCollough (CfA), A. Paggi (CfA), J. Raymond (CfA), J. Richards (UCB), and the Chandra Galaxy Atlas Team

Talk outline

1. What are X-ray binaries?
2. What are Hertszprung-Russell diagrams?
3. What are CCI diagrams?
4. Statistics applied to date.
5. Projects in search of a statistician.
6. Putting in some physics.

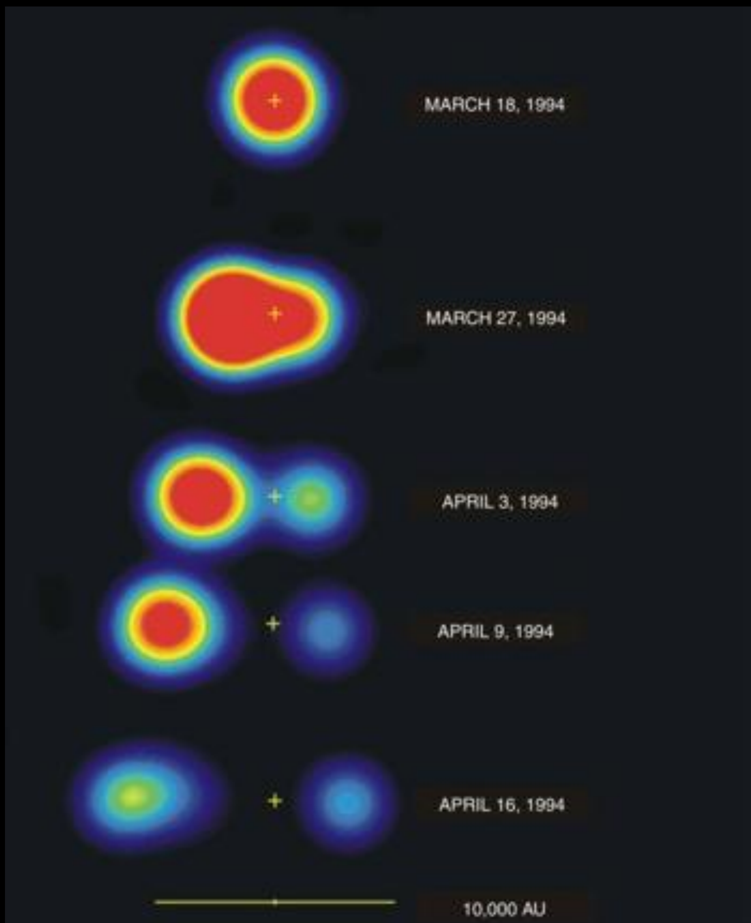
What are Accreting binaries?

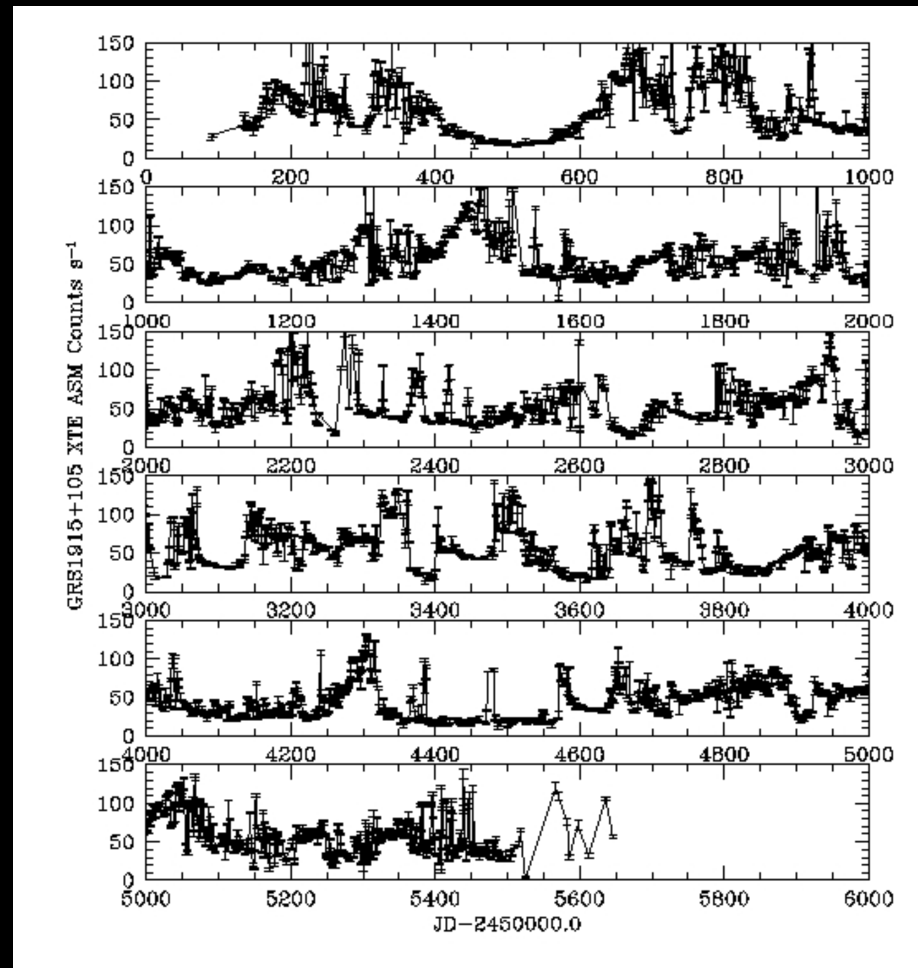


Mirabel et al 1994

Nature front page

RXTE/ASM light curves

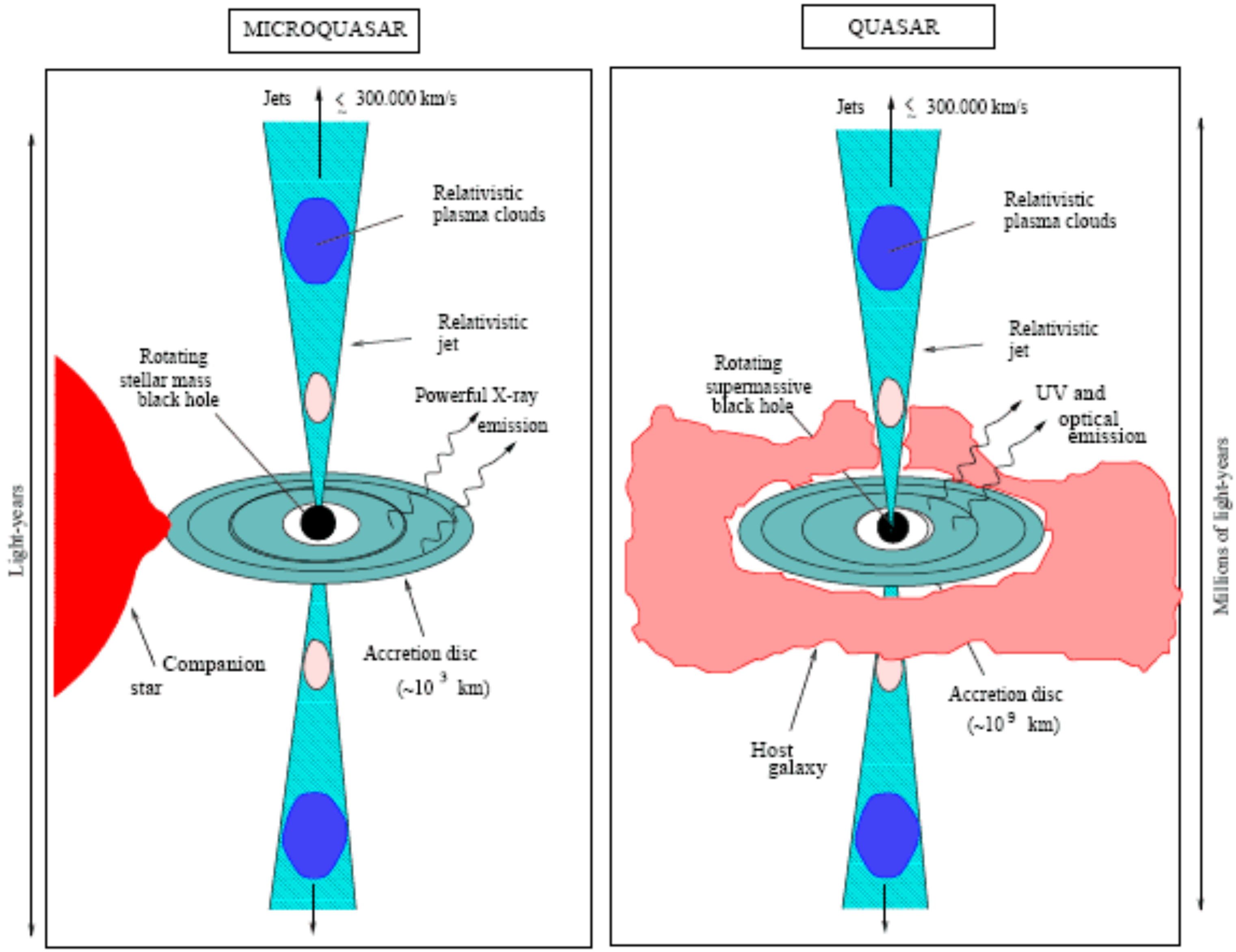




GRS1915+105:

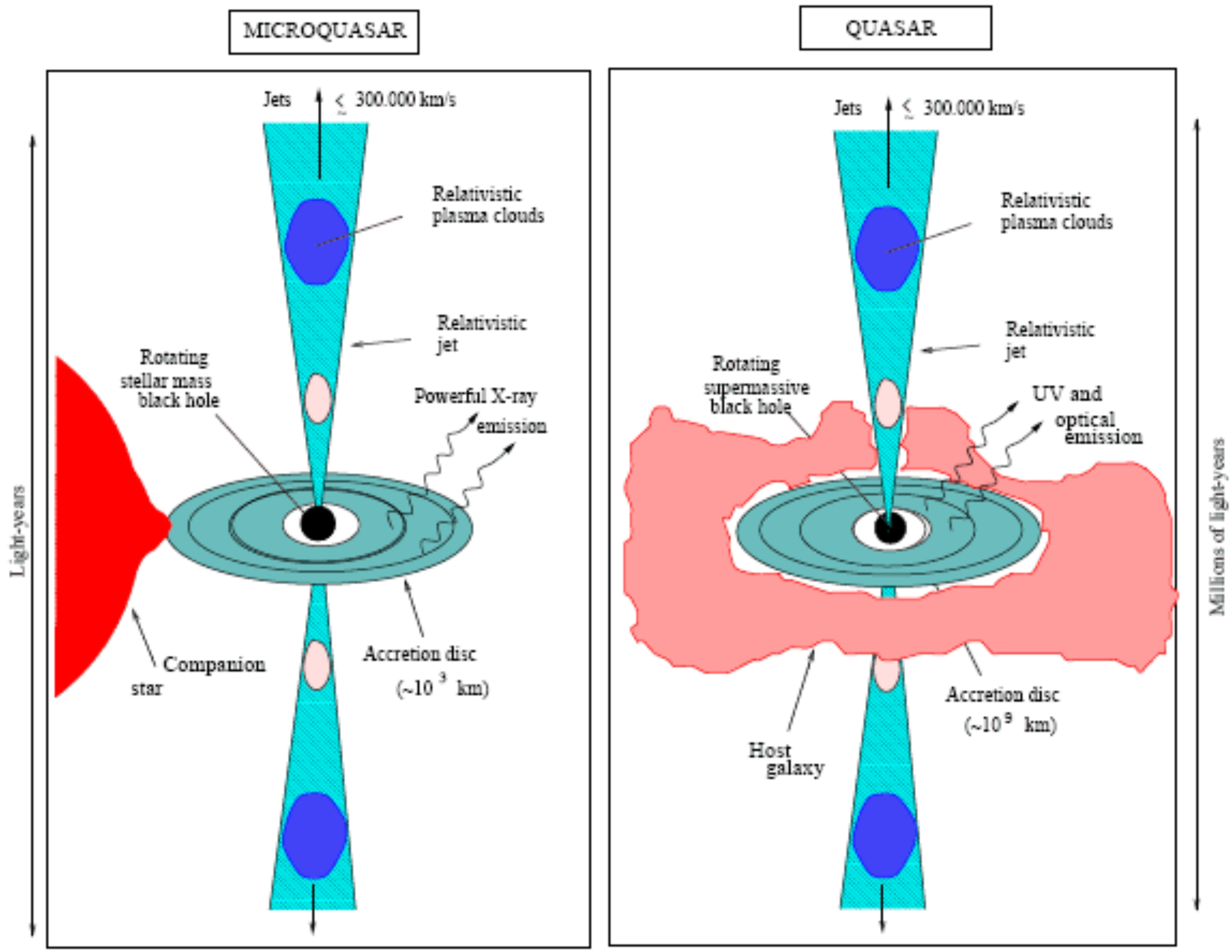
First XRB system observed to show prominent relativistic jets

Quasars and microquasars show direct correlation between kinetic power and γ-ray luminosity over 10 orders of magnitude! **Nemmen et al. 2012**



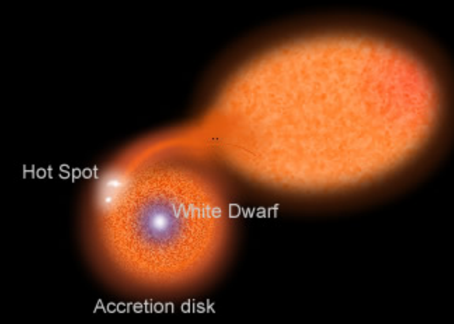
http://hera.ph1.uni-koeln.de/~heintzma

$\tau \approx R_S/c \sim M$

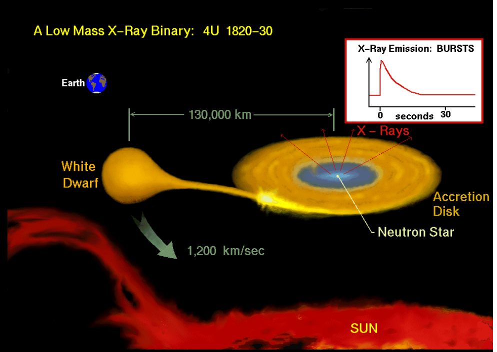


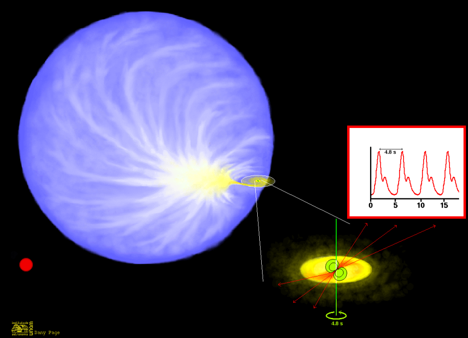
Minutes **Years**

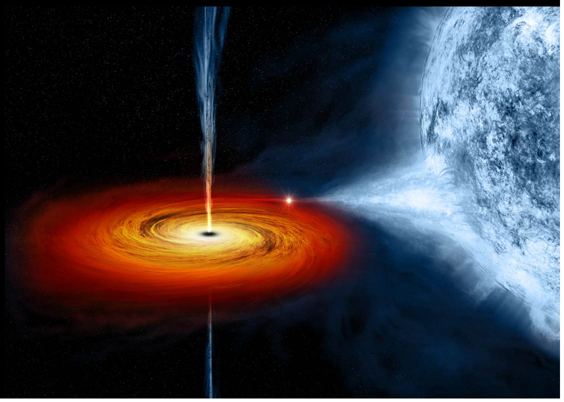
Why Study Accreting Binaries?



- They contain endpoints of stellar evolution
- They are highly efficient at converting matter to energy
- They contain matter at extreme conditions (density/temperature)
- They result from and result in highly cataclysmic events
- They are the most nearby, easily studied example of accretion processes and disk/jet interaction

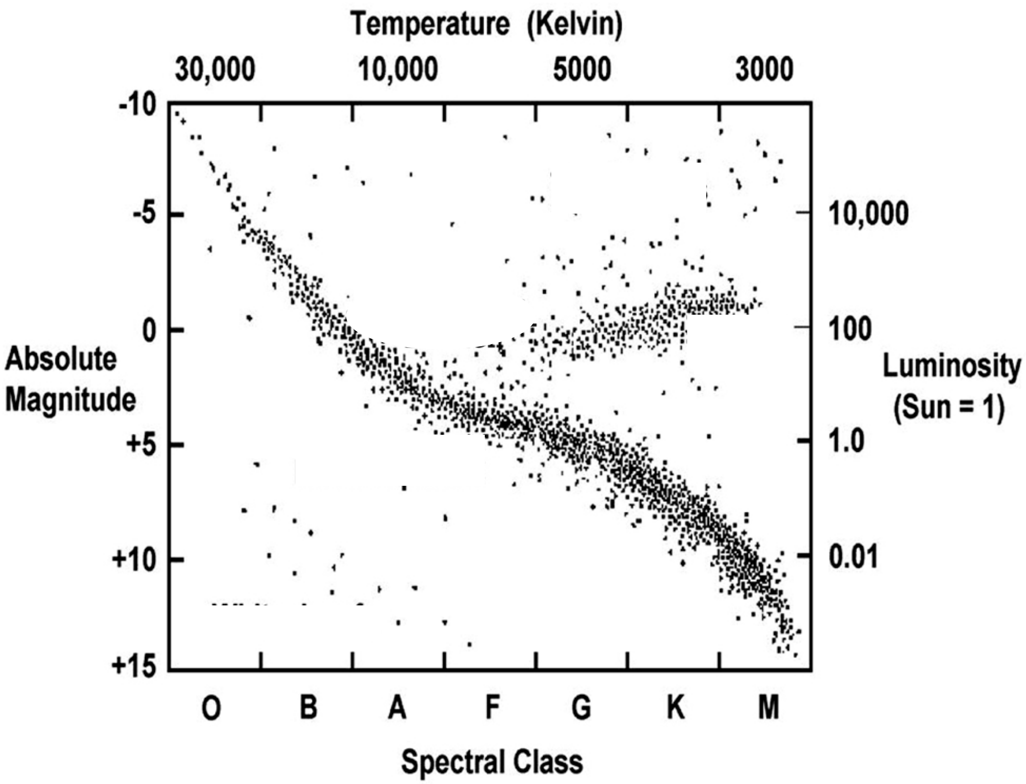




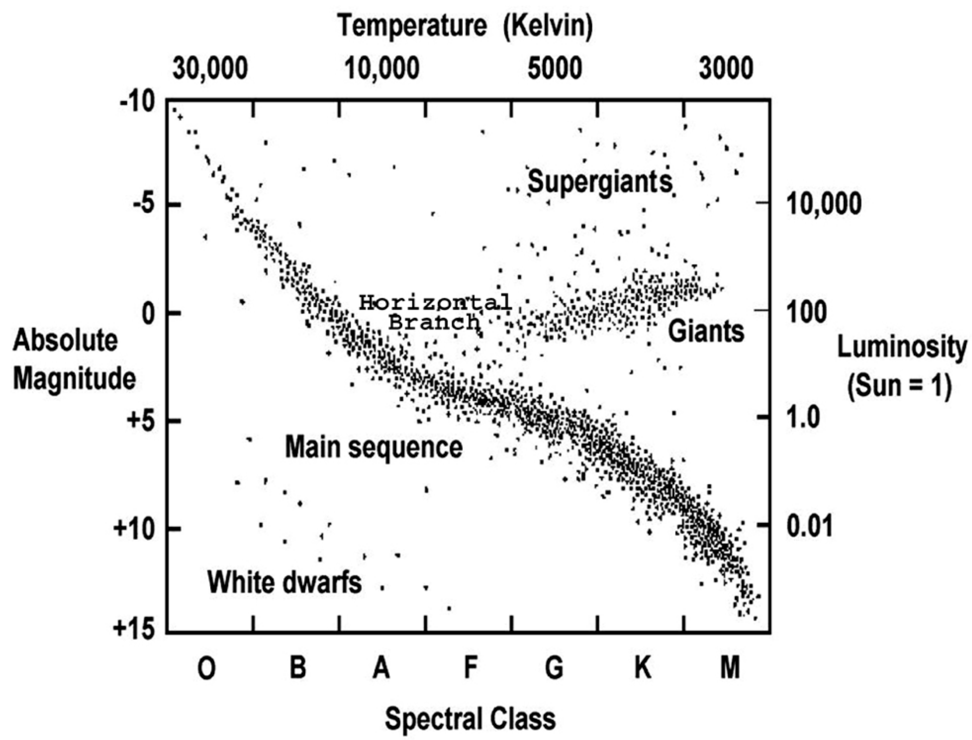


Hertzsprung-Russell Diagrams

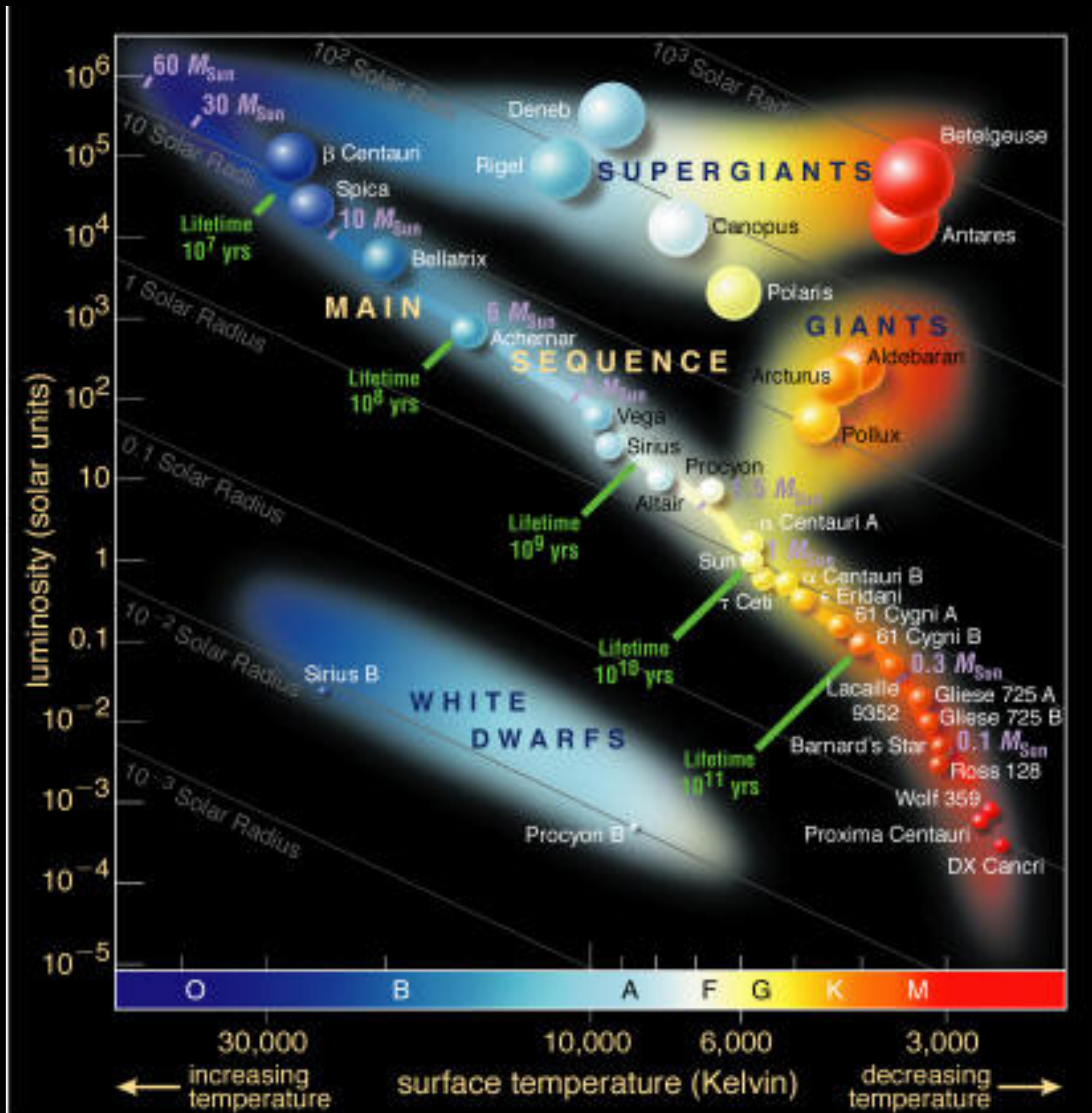
1910



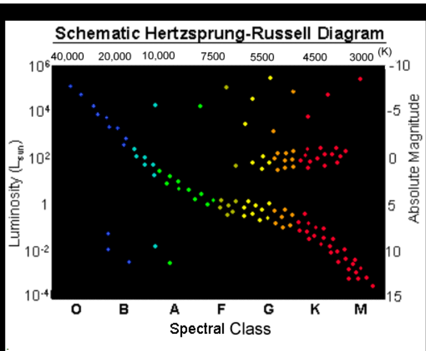
1926



Hertsprung-Russell diagram: Single stars

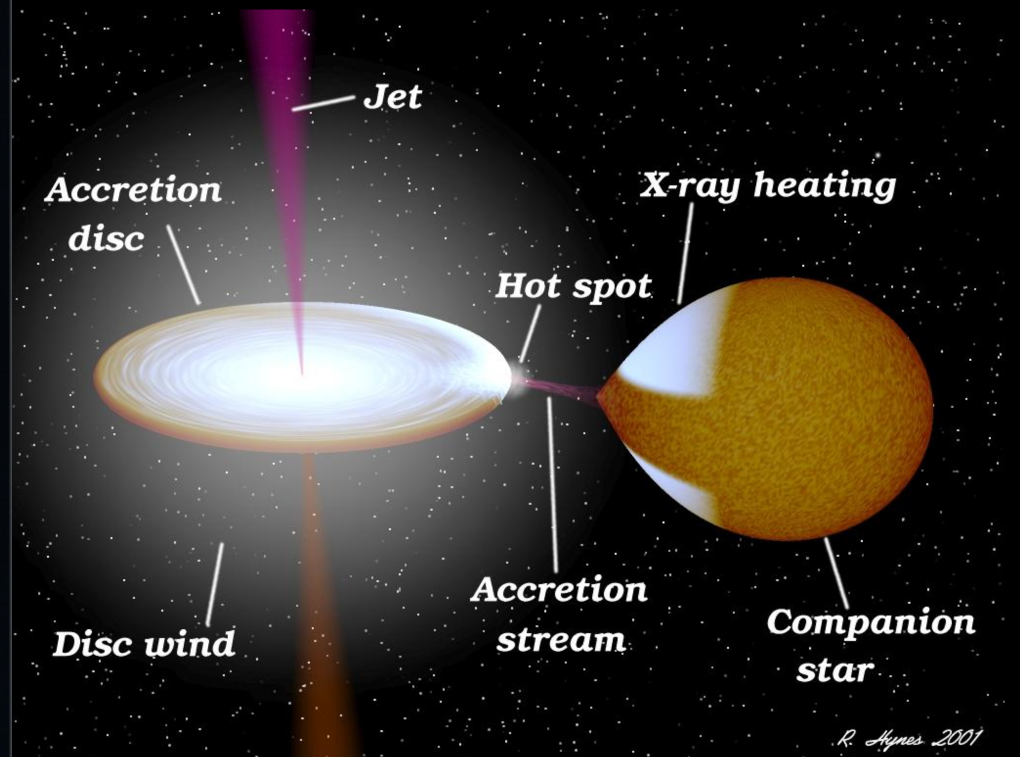


https://www.eso.org/public/images/eso0728c/



Normal star

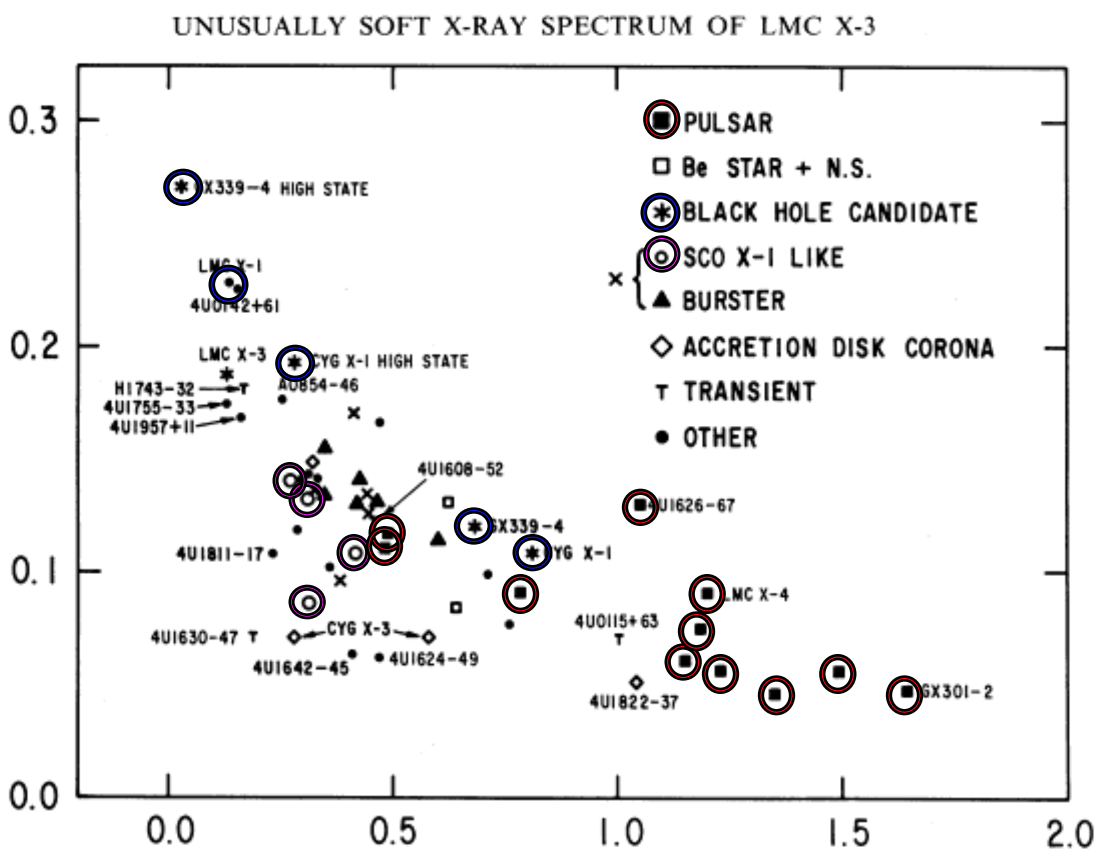
Accreting binary



Optical Color + Optical Luminosity

X-ray color + X-ray luminosity

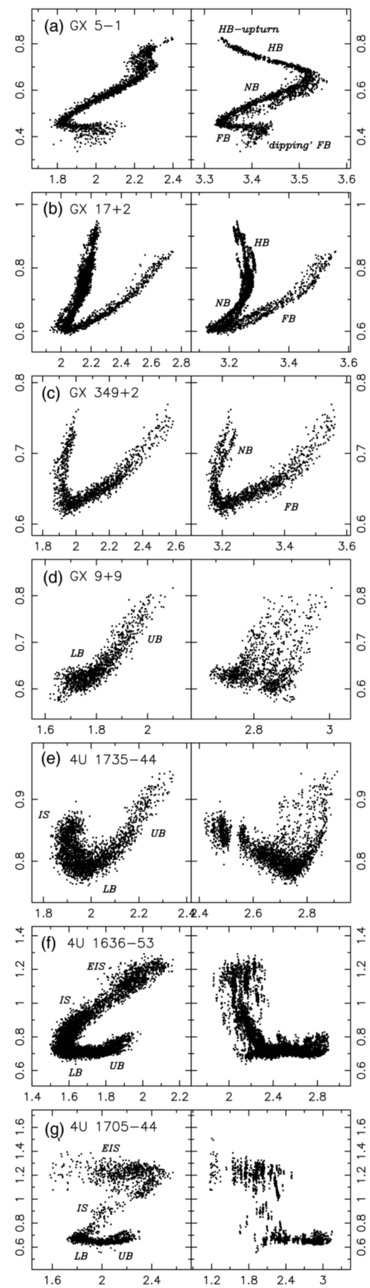
Neutron star "Z" and "Atoll" systems
Homan et al 2010



Soft color

Hard color

White & Marshall 1984

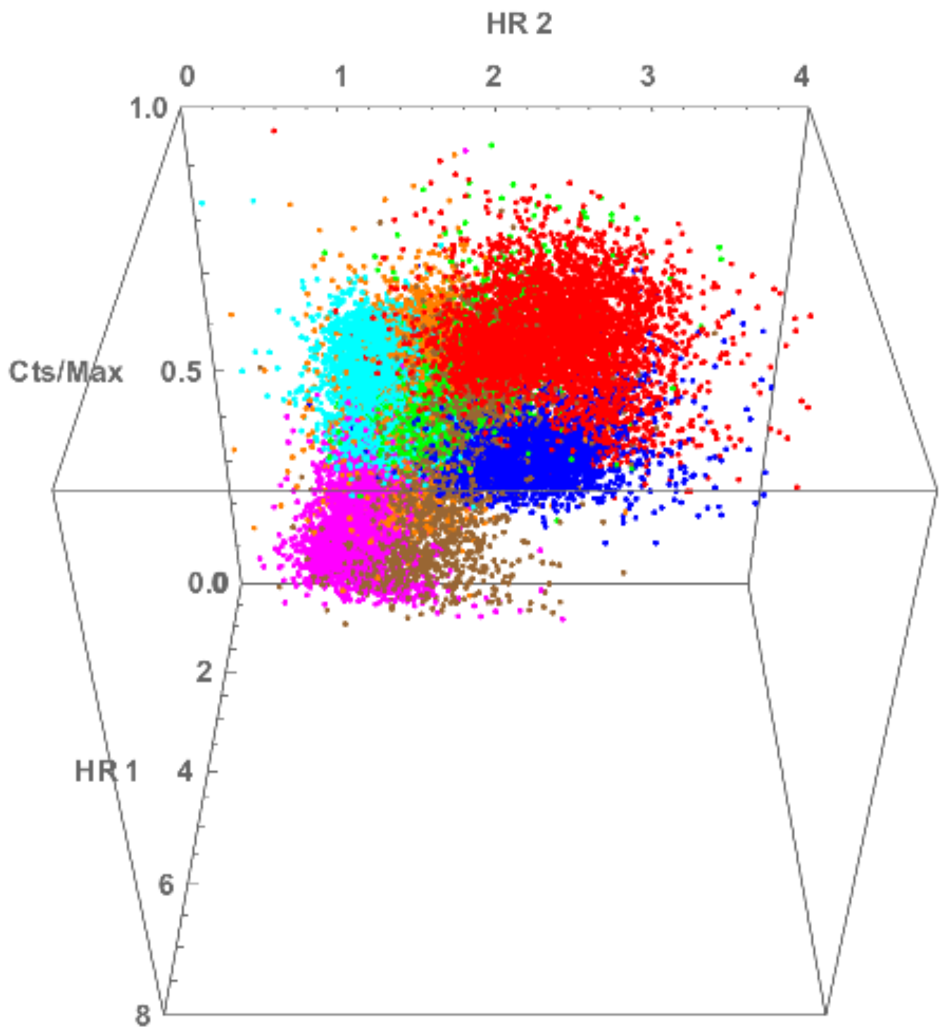


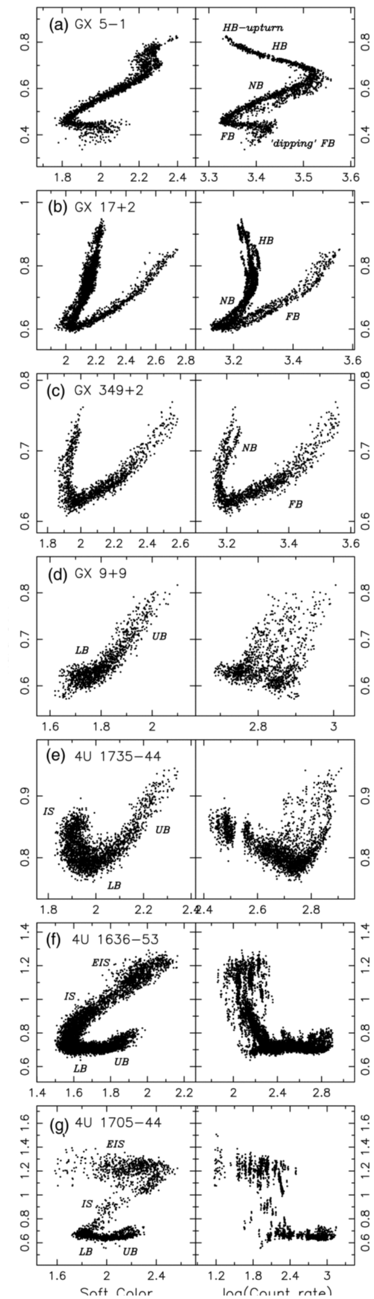
Hard Color various ranges

Soft Color Intensity

Neutron star “Z” and “Atoll” systems

Homan et al 2010





Hard Color various ranges

GX5-1

GX17+2

GX349+2

GX9+9

1735-44

1636-44

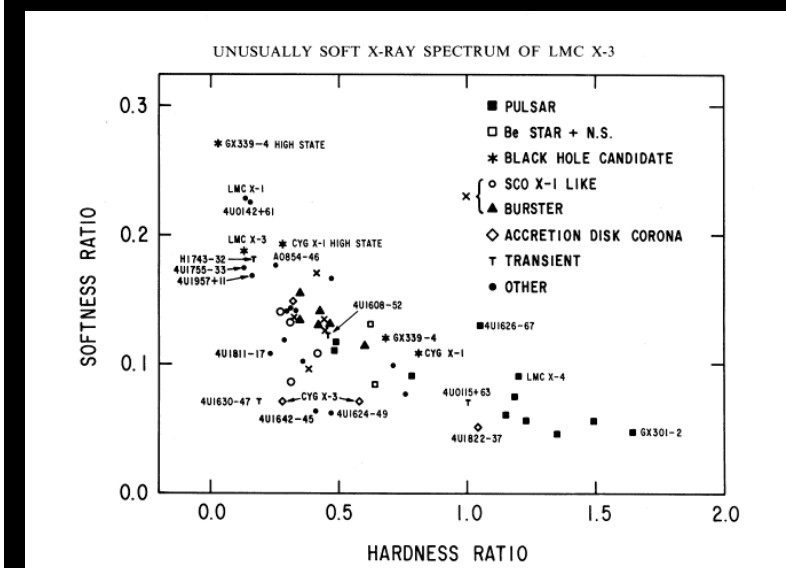
1705-44

Soft Color Intensity

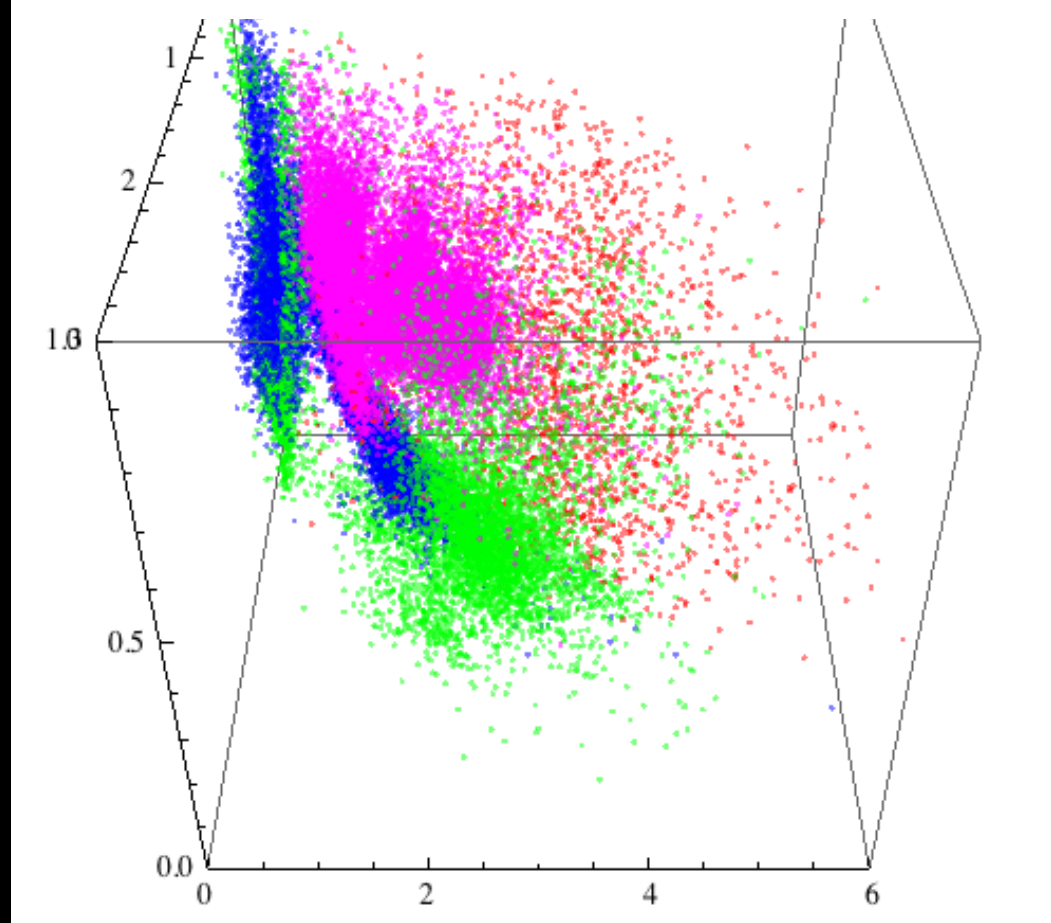
Color-Color-Intensity Diagrams

- **C** HR1 = (3-5keV)/(1.3-3keV)
- **C** HR2 = (5-12keV)(1.3-3keV)
- **I** Intensity = 1.3-12keV counts
  (Intensity normalized to top 1%)
  (Only ≥ 5σ points plotted)

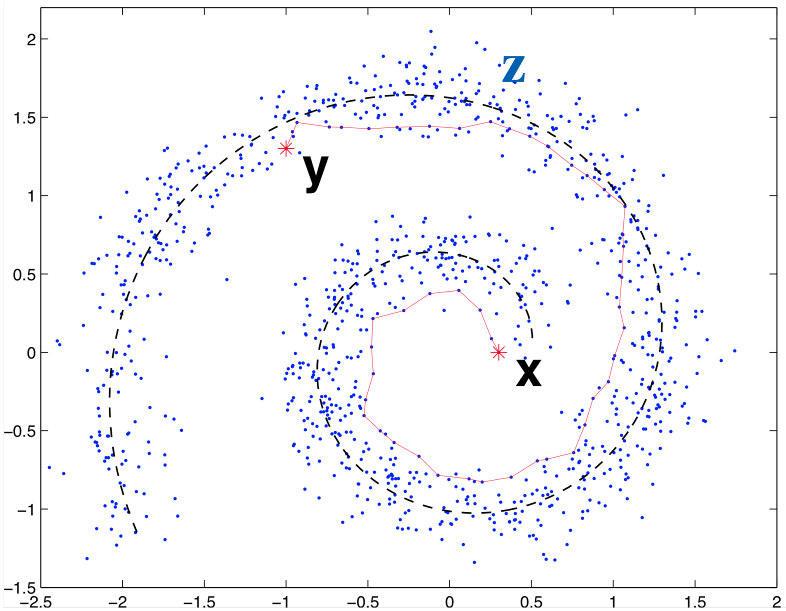
RXTE/ASM data:
One day averages over 13 years



Black holes high mass
Black holes low mass
Pulsing neutron stars
Non-pulsing neutron stars

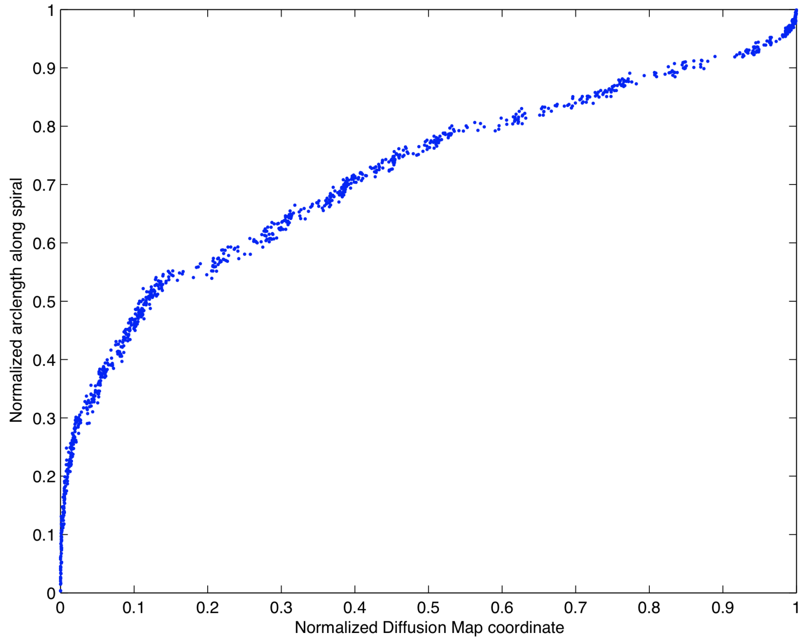


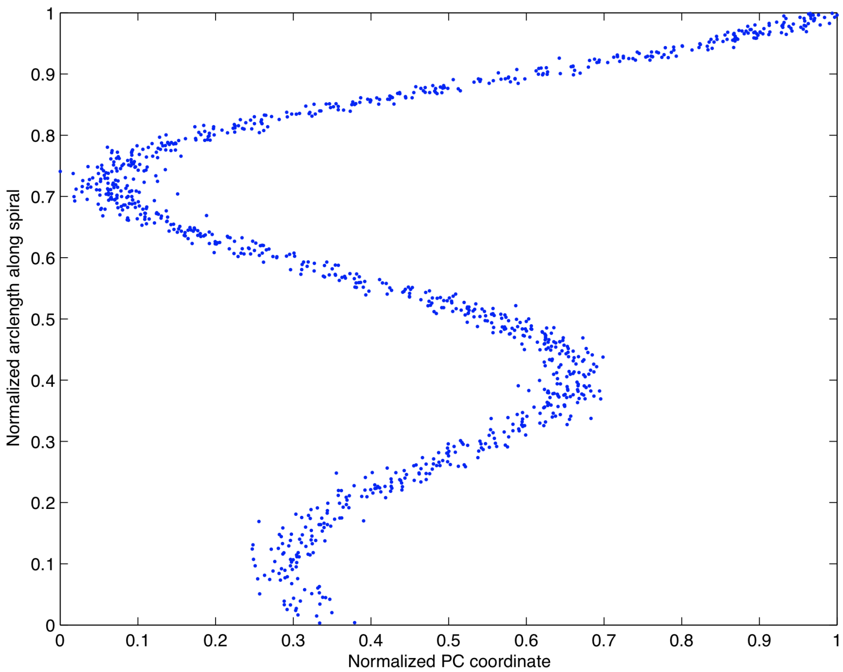
Vrtilek & Boroson 2013



Capturing geometries

Richards et al (2008)





Spectral Connectivity Analysis

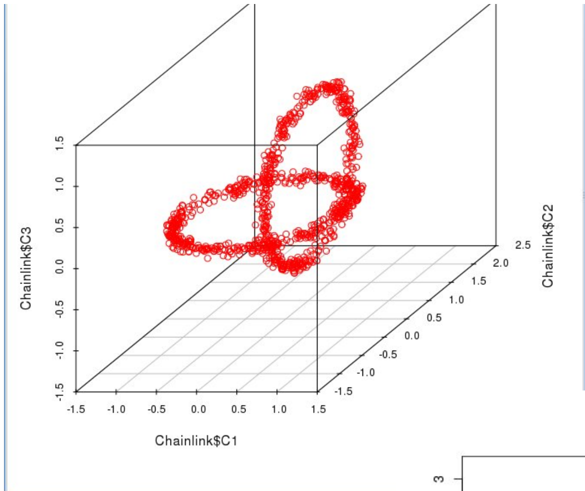
Principal Components Analysis

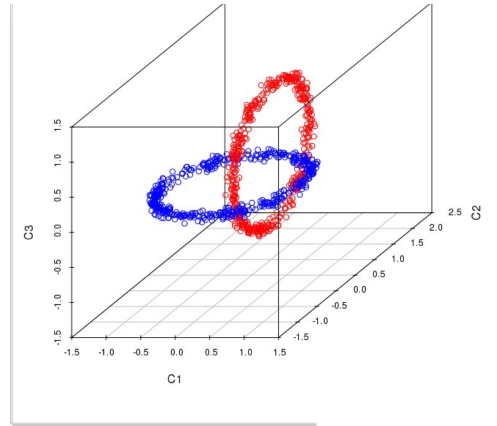
Spectral Connectivity Analysis

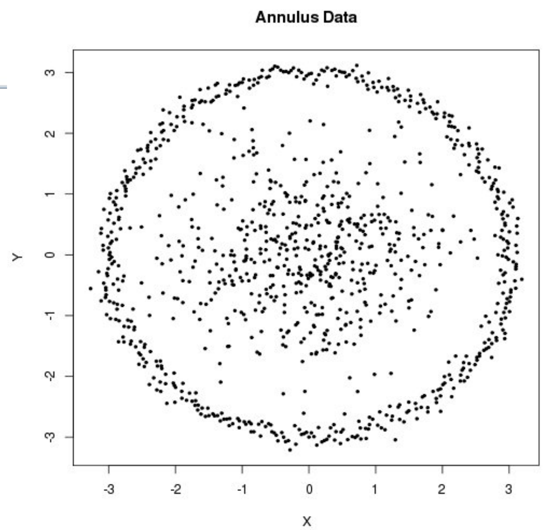
Richards et al (2008; 2009)
Freeman et al (2009)
Lee & Waterman (2010)

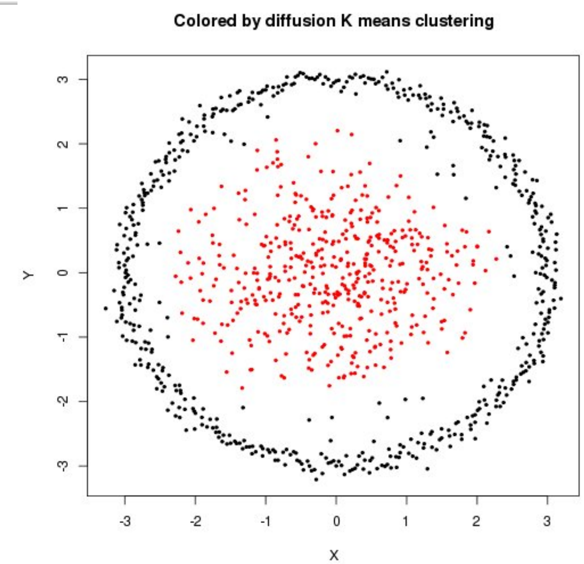
Input data

Data clustered by diffusionMap



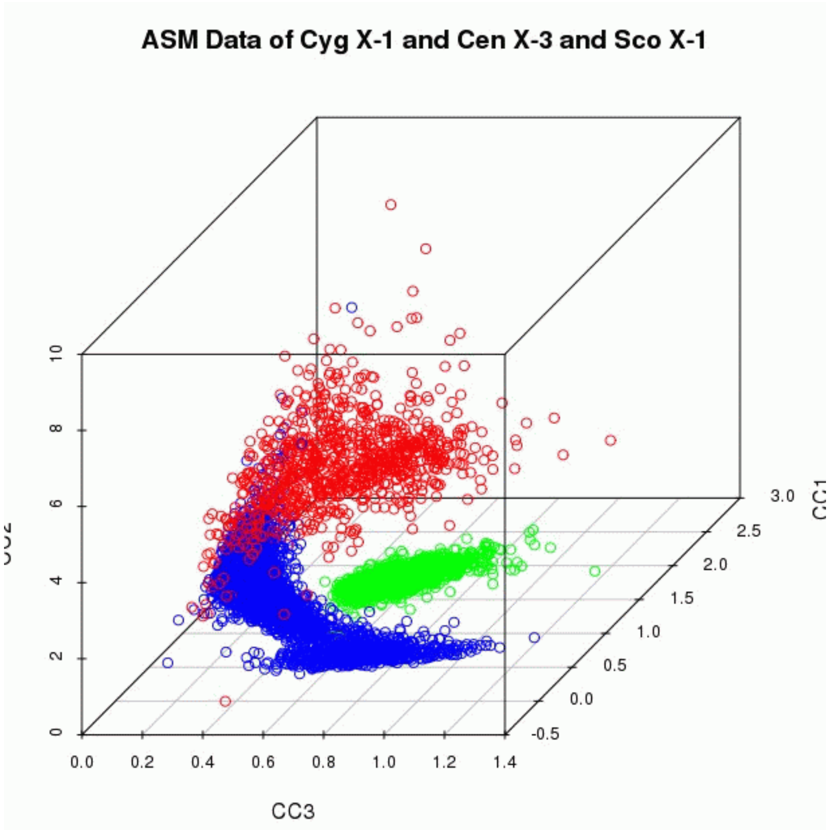


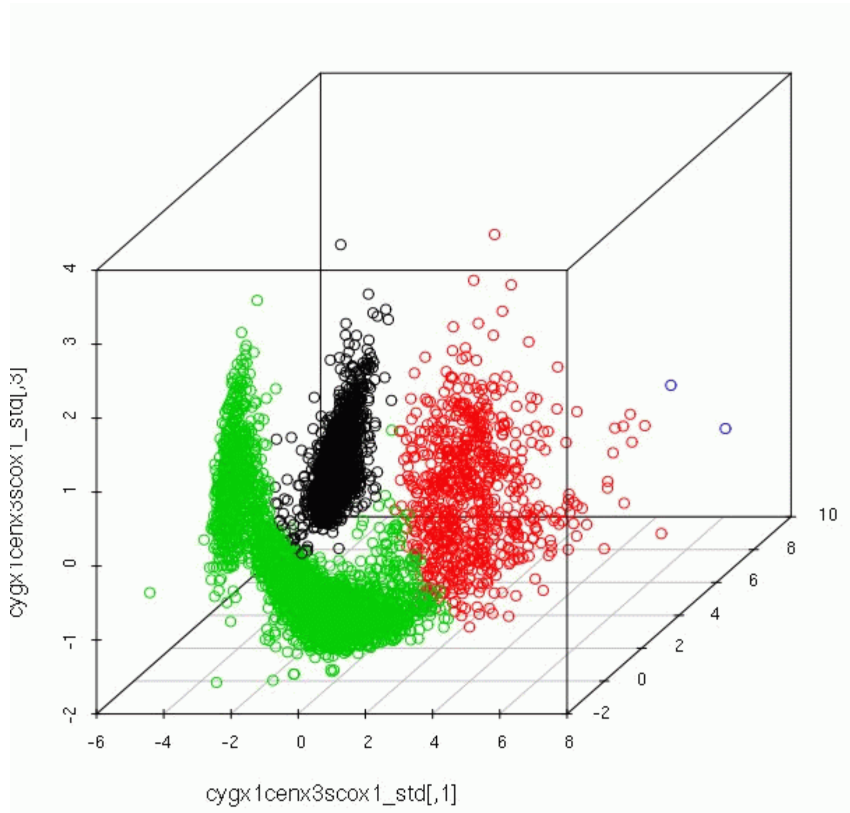




diffusionMap:
http://cran.r-project.org/web/packages/diffusionMap/index.html

Separating Bhs, NPNS, and pulsars

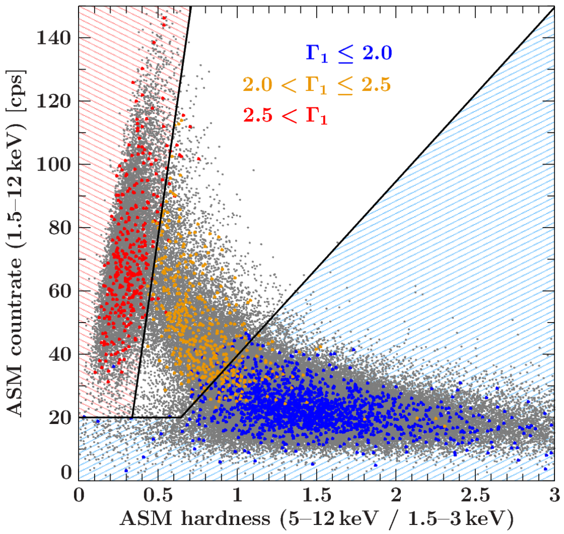


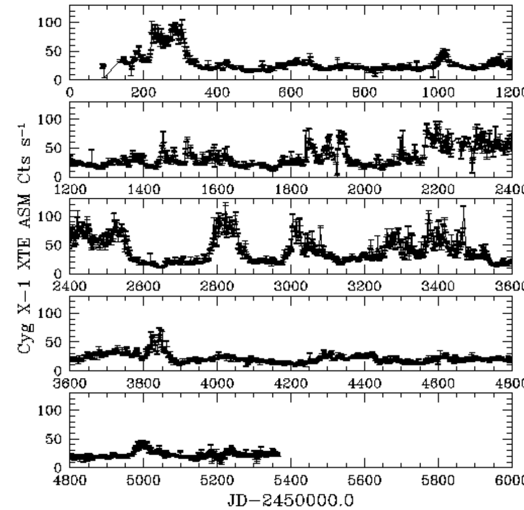


Input data colored by prior knowledge

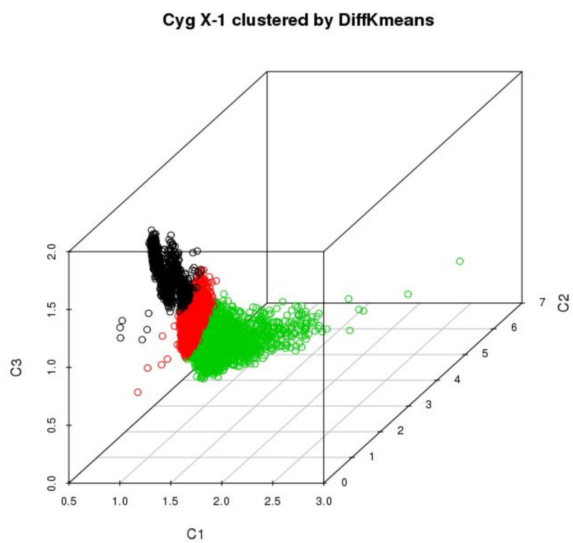
Data colored by diffusionMap clusters

Different states of a single source: Cygnus X-1





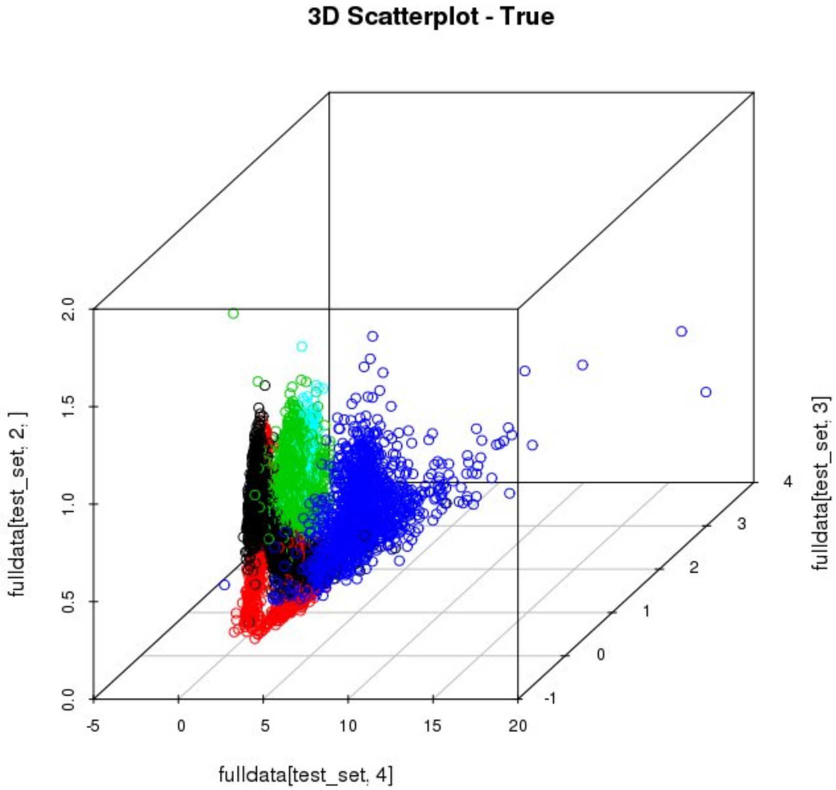
Grinberg et al. 2013



(Hard, intermediate , and soft states of Cyg X-1 determined using 2741 spectral fits to PCA data)

PCA data of Cyg X-1 clustered by diffusionMap

Buchan, Vrtilek, & Boroson 2013



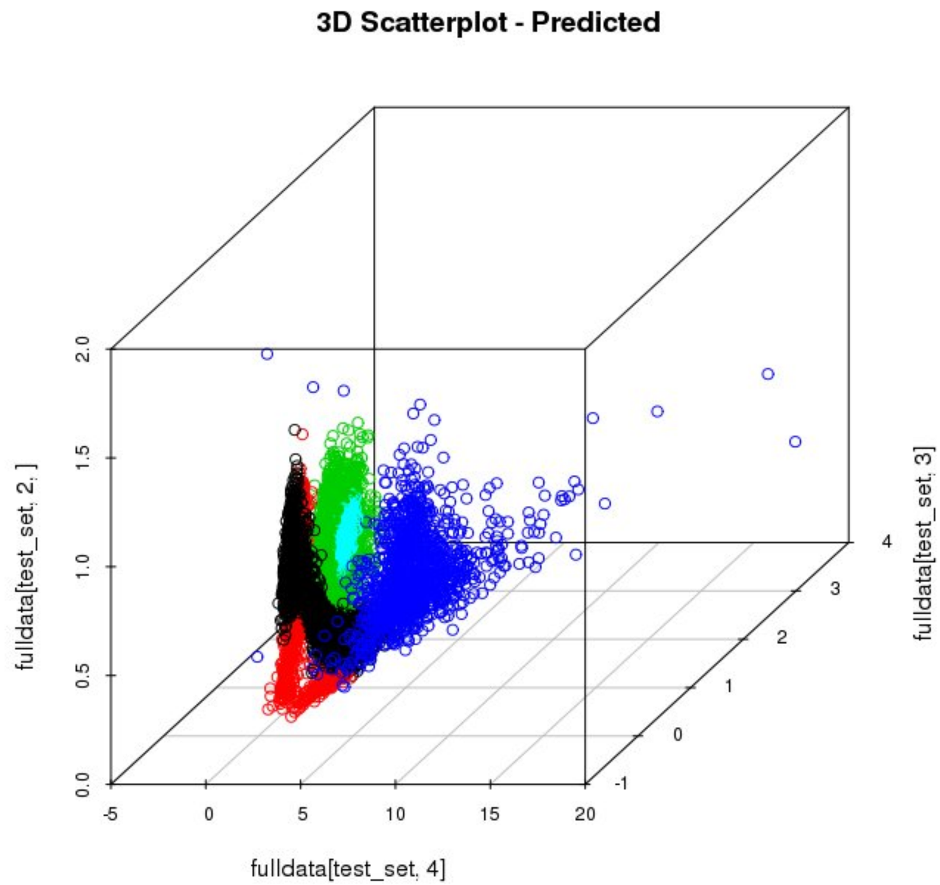
Black holes with high-mass companions

Black holes with low-mass companions

Pulsars

Z-sources

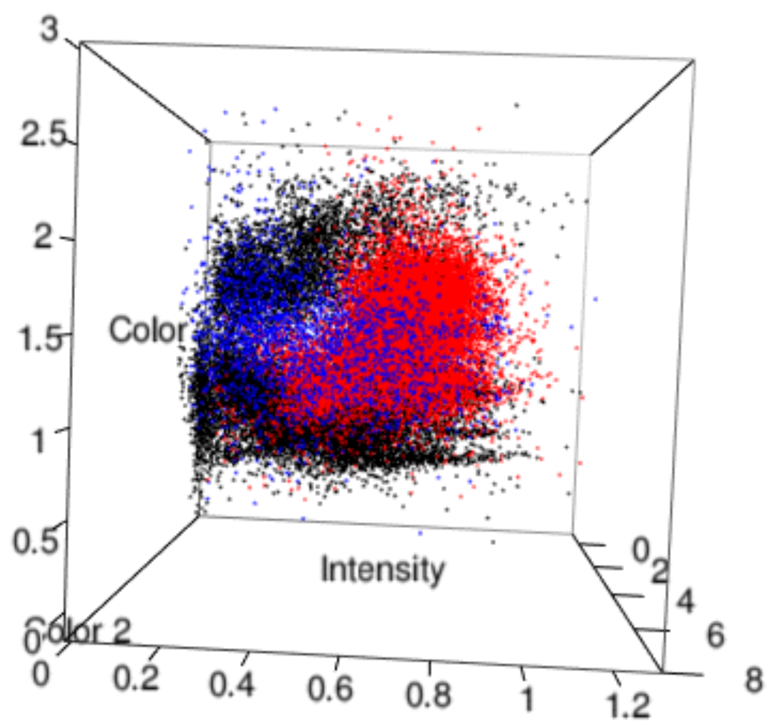
Atoll sources



Kernel method using prior knowledge

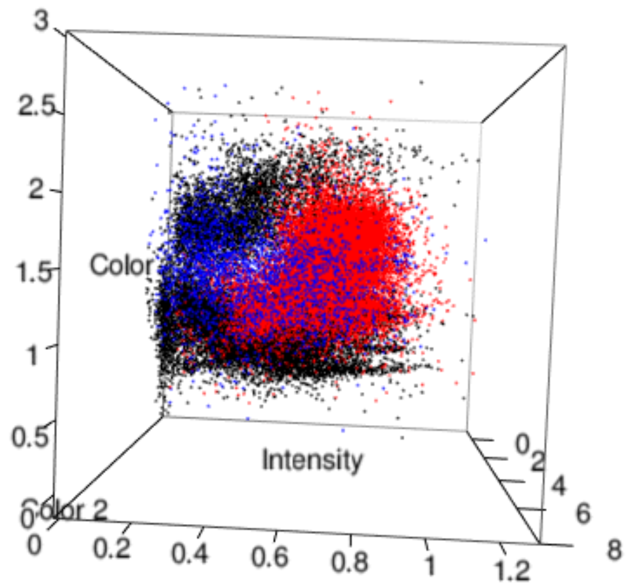
Bornn et al 2013

A statistical machine learning solution to infer the probability that an observation corresponds to a given compact object type (i.e black hole, pulsing neutron star, or non pulsing neutron star) of an X-ray binary system given X-ray color-color-intensity data.



Gopalan, Vrtilek, & Bornn 2015

Definition of X-ray binary type.



CCI data for 24 X-ray binary systems classified by their compact object type into three groups: black hole, non pulsing neutron star, pulsing neutron star.

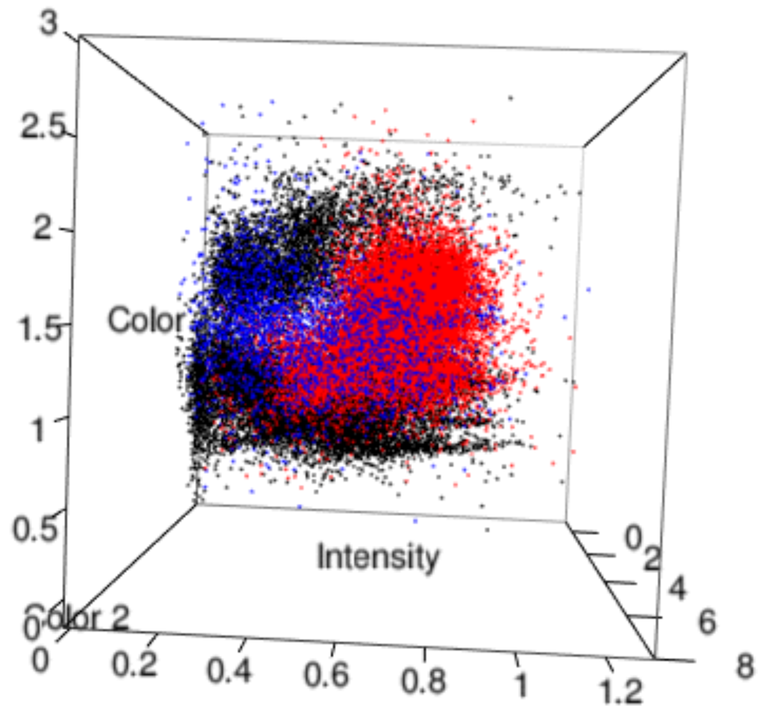
Initial classification from Liu et al. 2001, 2006

Atoll/Z systems from Homan et al. 2010
Confirmed black holes from Remillard \& McClintock 2006
Confirmed pulsars from Bildsten et al. 1997

Gopalan, Vrtilek, & Bornn 2015

6 non-pulsing systems (25,366 points)
9 black holes (13,098 points)
9 pulsars (2393 points)
Severe imbalance in number of data points per system type

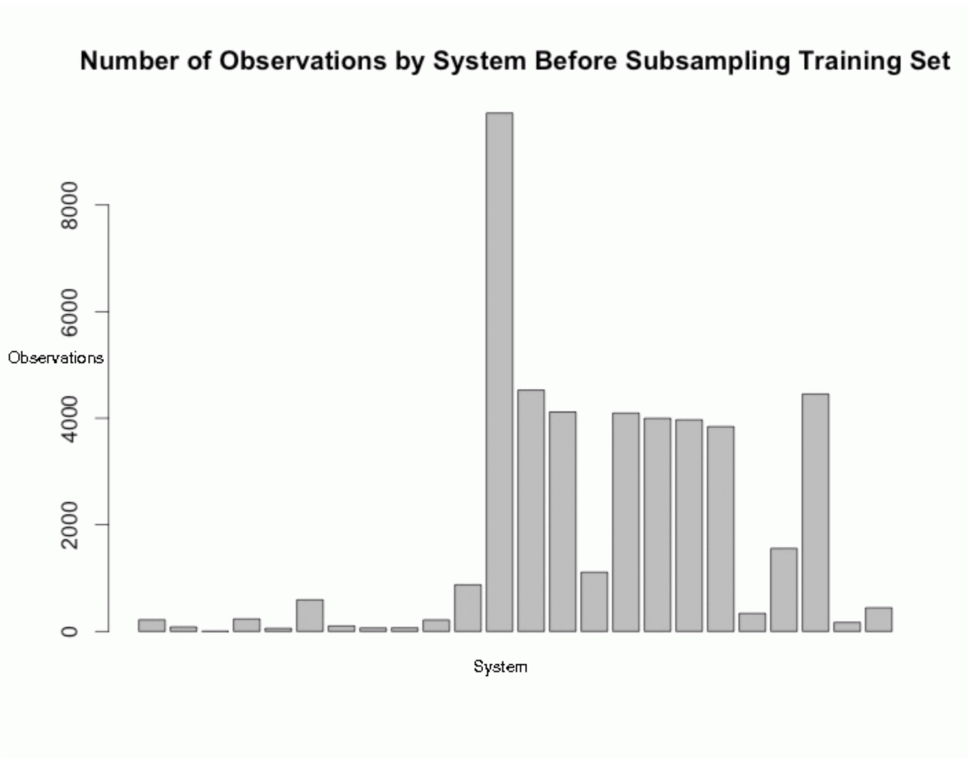
Gaussian process requires $O(N^3)$ operations:
40,857 observations➔ Huge computational burden.

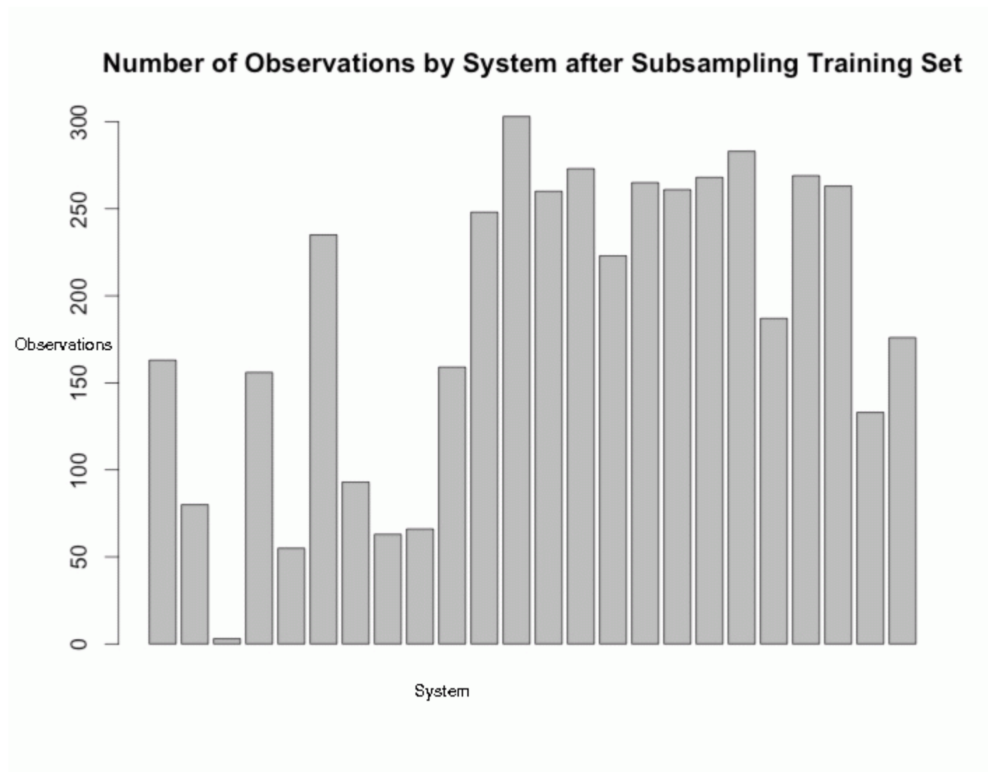


Gopalan, Vrtilek, & Bornn 2015

Subsampled training set

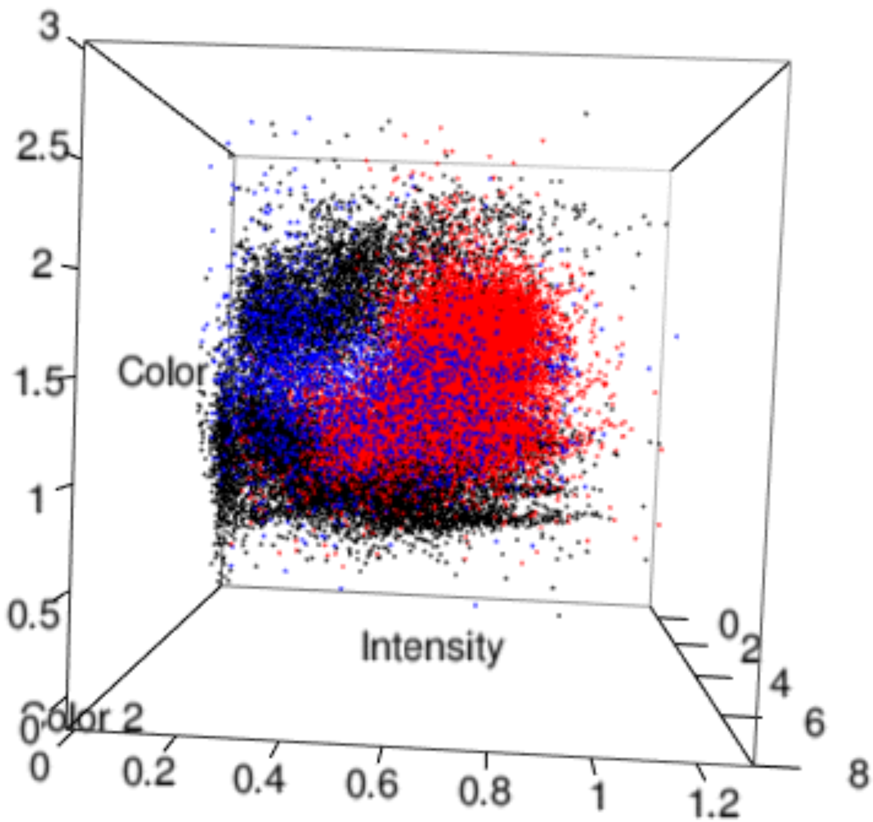
A. 6 non-pulsing systems (1465 points)
B. 9 confirmed black holes (1468 points)
C. 9 confirmed pulsars (1134 points)





Gopalan, Vrtilek, & Bornn 2015

Machine Learning Solution: Gaussian Latent Process



24 system learning set:
9 black holes; 9 pulsars
6 non pulsing neutron stars

Latent variables: propensities to contain a BH, PNS, NPNS.

Posterior sampling with elliptical slice sampling

Code/data: github.com/ggopalan/Binary-BH-Classification

The training set is denoted as a 2-tuple:

Xtrain is Ntrain by 3 matrix representing the 3 CCI values
Ytrain is a Ntrain vector which denotes system type A, B, or C

Xpred: Npred by three matrix representing the 3 CCI values
Ypred is a vector that predicts source type for each test point

Three independent latent variables (Z_1, Z_2, Z_3) for each compact object type denote propensities to be a Black hole, Pulsar, or Non pulsing neutron star

Gopalan, Vrtilek, & Bornn 2015

$$\Sigma_{ij} = \sigma^2 \exp(-||X_{i,.} - X_{j,.}||_2^2/\phi)$$

$$L(\alpha, \beta, Z_t; Y_{train}) = \prod_{k=1}^{N_{train}} \exp[\alpha_{Y_{train_k}} + \beta_{Y_{train_k}} Z_{t_{i,Y_{train_k}}}]/N_k$$

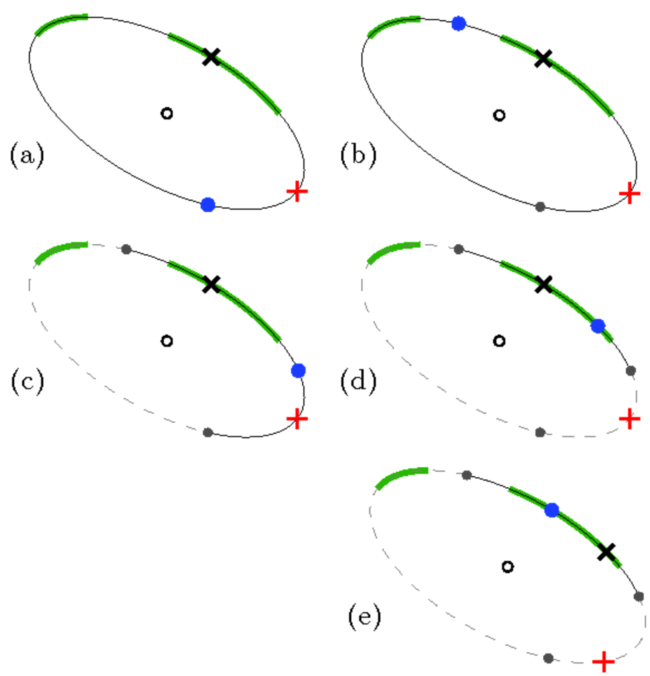
$$N_k = \sum_{l=1}^{3} \exp[\alpha_l + \beta_l Z_{t_{k,l}}]$$

Gopalan, Vrtilek, & Bornn 2015

$$p^*(Y_{pred}) = \int_{Z_p, Z_t, \alpha, \beta} p(Y_p, Z_p, Z_t, \alpha, \beta | Y_t, X_t, X_p) dZ_p Z_t d\alpha d\beta$$

$$= \int_{Z_p, Z_t, \alpha, \beta} p(Y_p | Z_p, \alpha, \beta, -) p(Z_p | Z_t, -) p(Z_t, \alpha, \beta, | Y_t, X_t, X_p) dZ_p dZ_t d\alpha d\beta$$

Gopalan, Vrtilek, & Bornn 2015



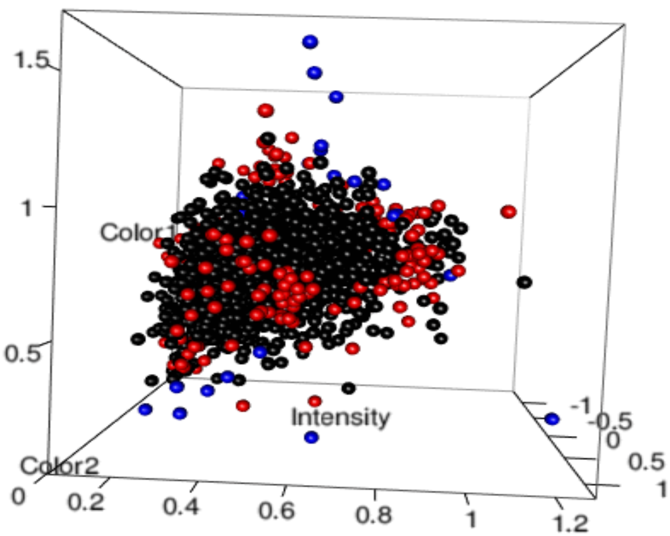
Elliptical slice sampling

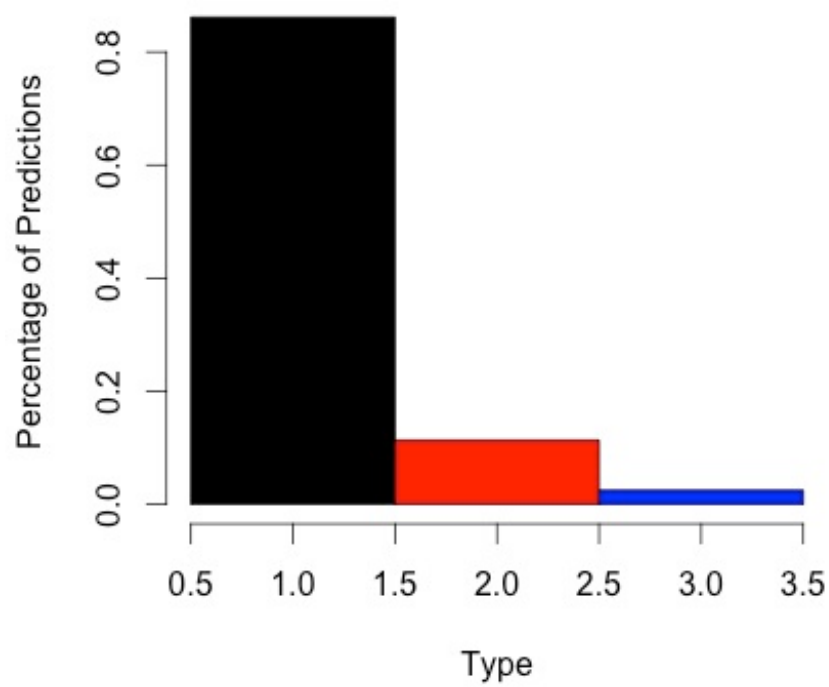
Murray, Adams, & MacKay 2010

Latent Variable Gaussian Process: Validation

Test randomly selected classified systems that were *not* used in training the model.

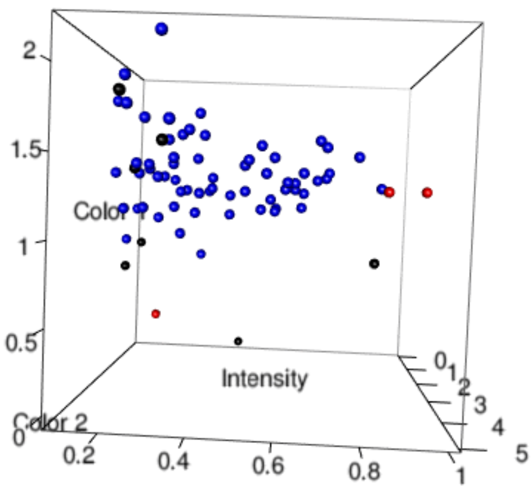
LMC X-3: Black hole

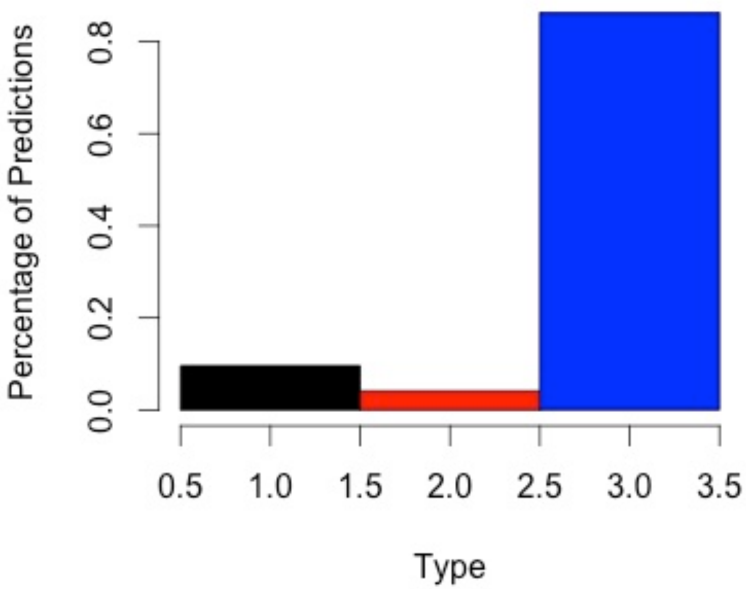




Gaussian Process Model: Validation

Test randomly selected classified systems that were *not* used in training the model.

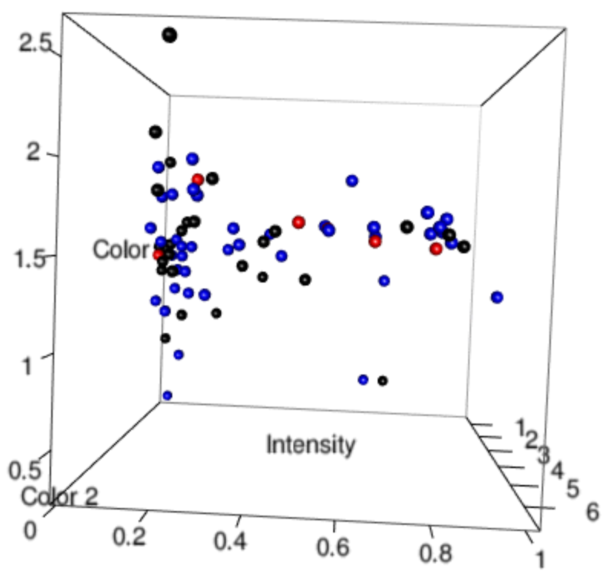


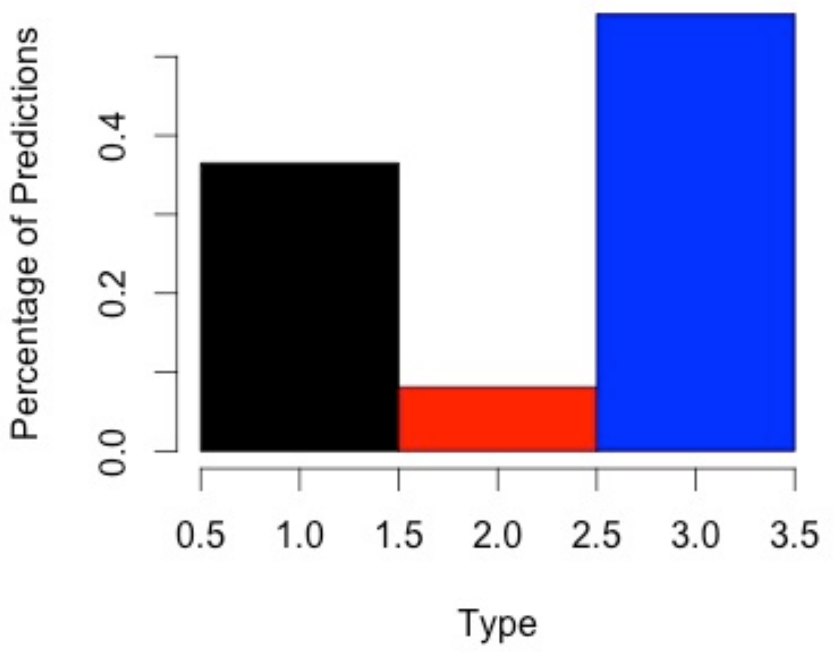


05676-072 (Pulsar)

Gaussian Process Model: Validation

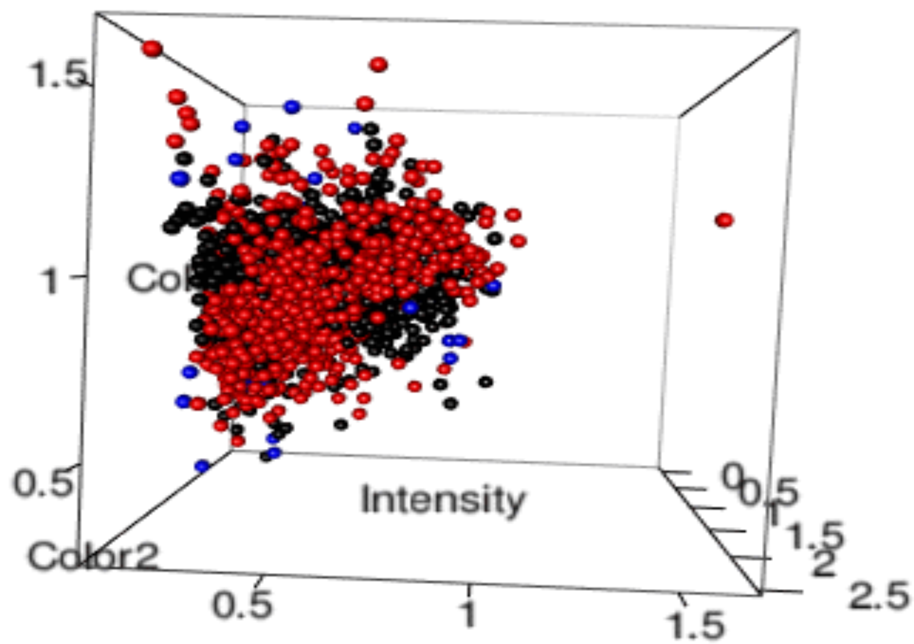
Test randomly selected classified systems that were *not* used in training the model.

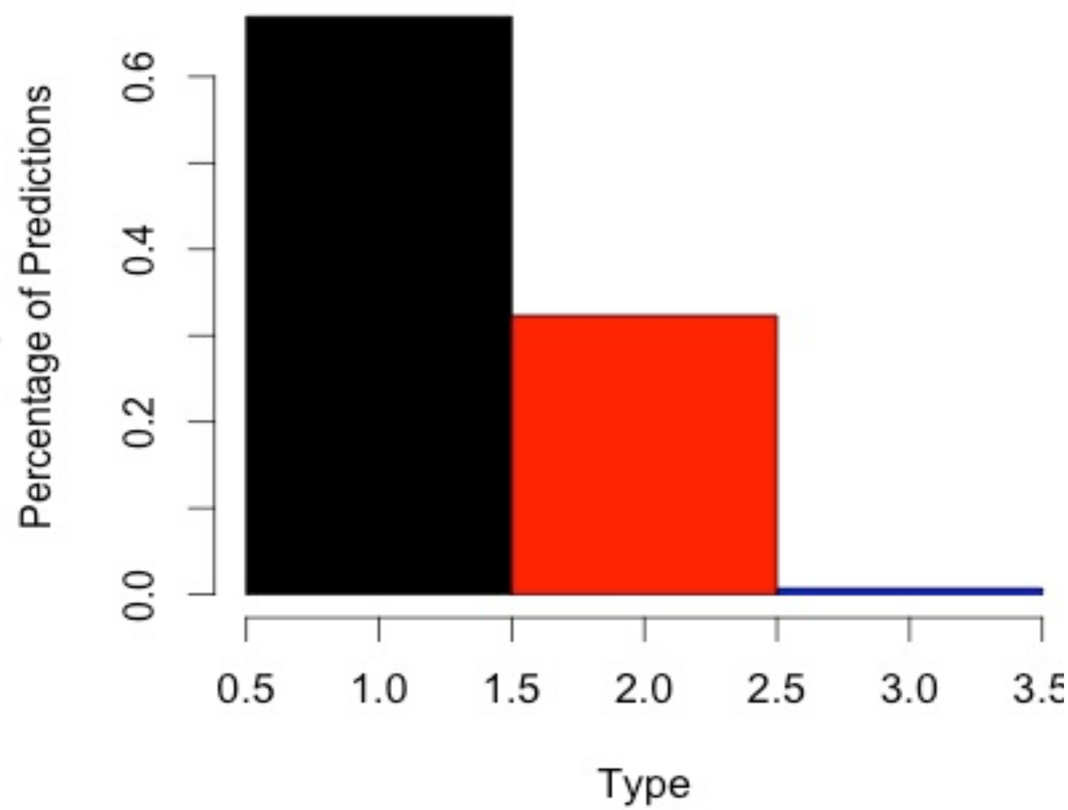




0535+262: Pulsar

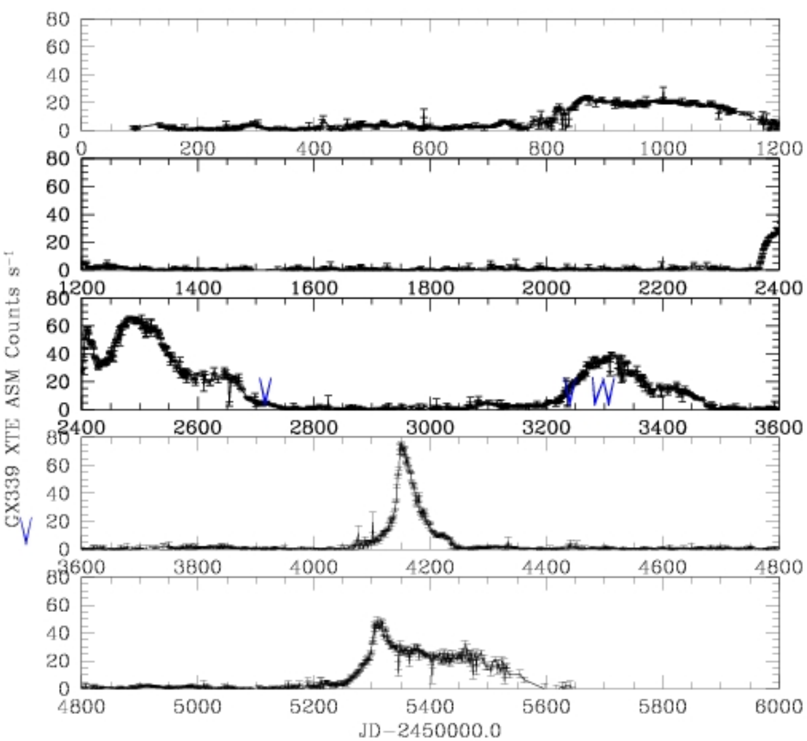
Gaussian Process Model: Validation

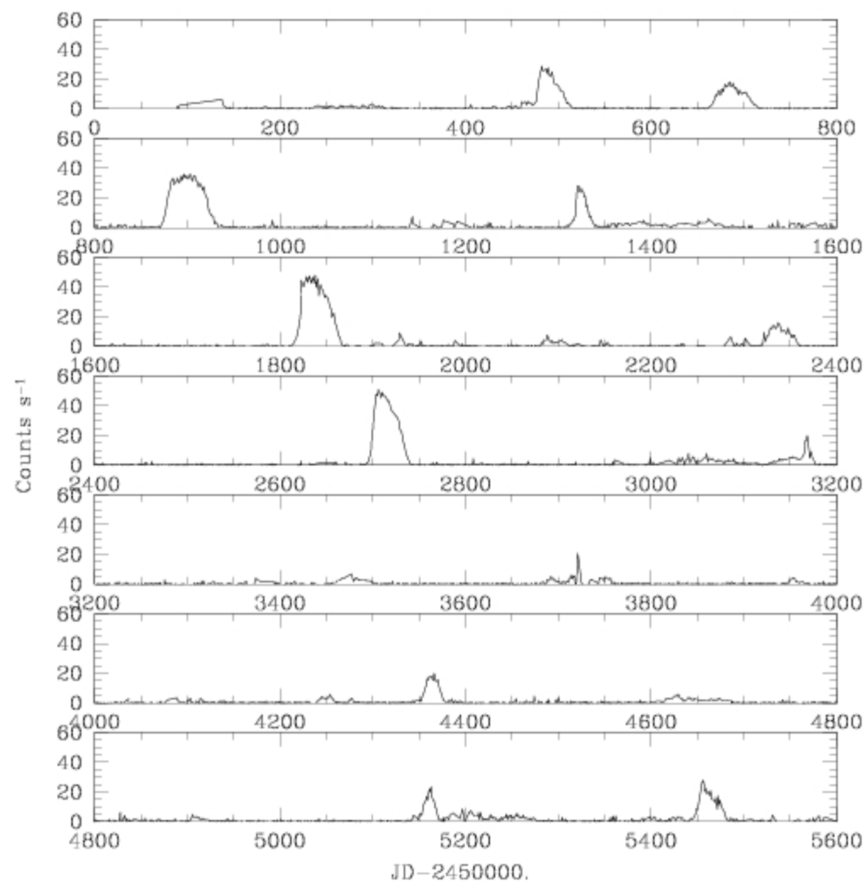




1636m53: Burster

Black hole GX339-4 Burster Aql X-2



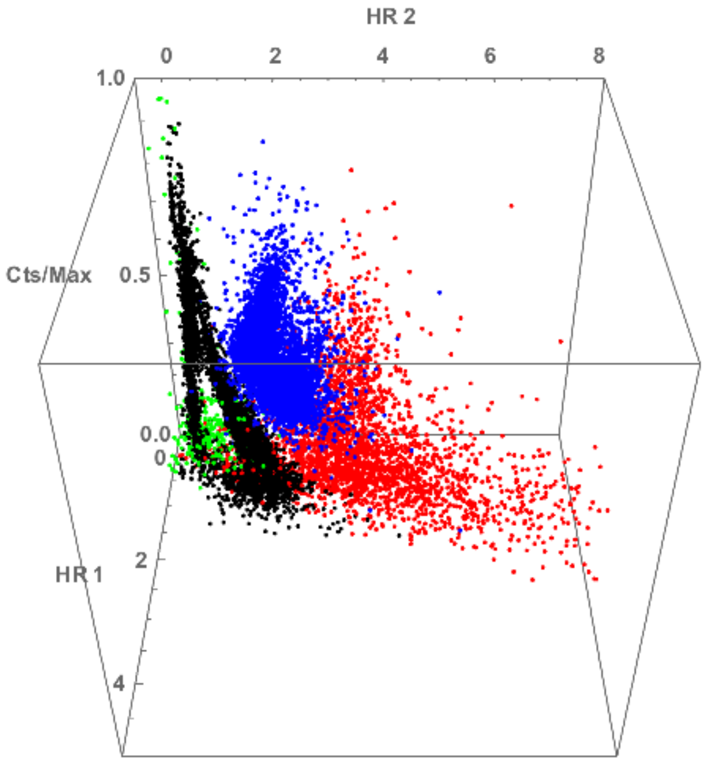


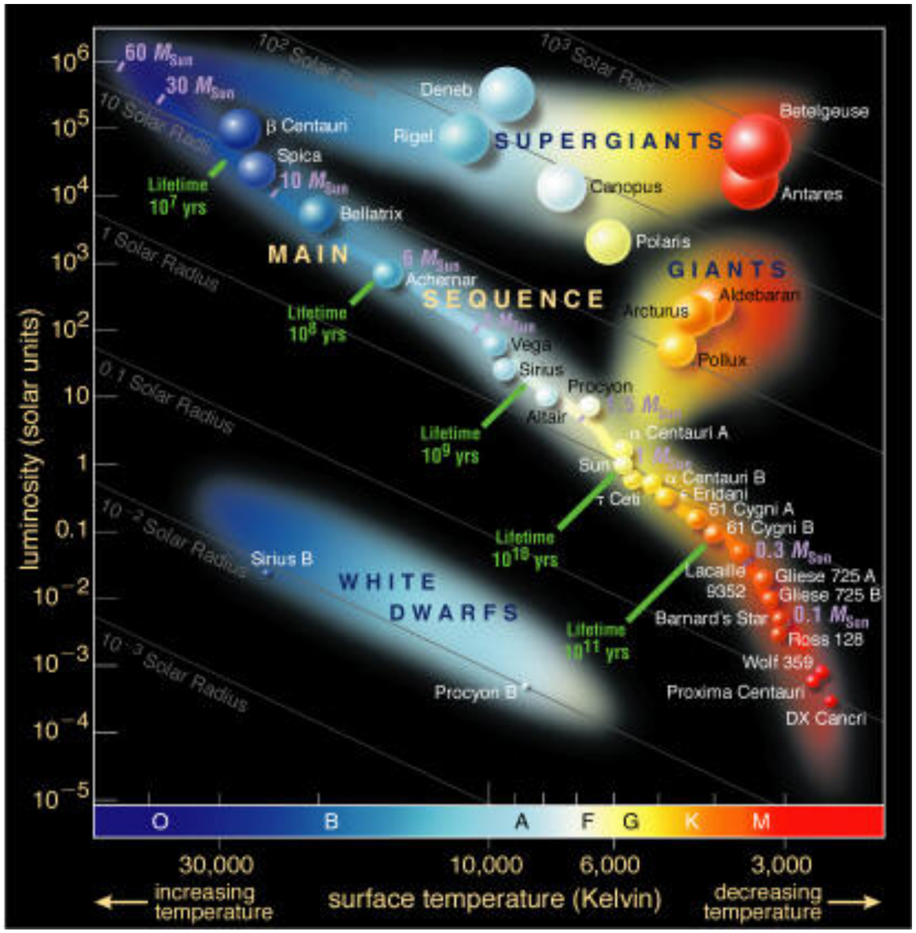
Gaussian Process Model: Future Directions

- Include lightcurve information as prior
- Include systems that contain white dwarfs (CVs)
- Incorporate hierarchical structure (as prior distribution on the Gaussian process parameter)
- Model and impute missing data.
- Apply similar methodology to RXTE PCA and MAXI data which have finer energy resolution and greater collecting area than ASM.

Giri Gopalan

Statistics problems galore





Black holes
Pulsing neutron stars
Non-pulsing neutron stars
Cataclysmic variables

Examples of soft and hard color definitions

Vrtilek/Boroson (2013)

RXTE/ASM):

Soft color ➔ (3.0-5.0)keV/(1.2-3.0)keV

Hard color➔ (5.0-12)keV/(1.2-3.0keV)

McCollough/Vrtilek (2014)

Chandra/HETG:

Soft color ➔ (3.0-5.0)keV/(1.2-3.0)keV

Hard color ➔ (5.0-8.0)keV/(1.2-3.0keV)

Peris et al (2015)

RXTE/PCA:

Soft color ➔ (3.6-5.0)keV/(2.2-3.6)keV

Hard color ➔> (8.6-18.0)keV/(5.0-8.6)keV

Homan et al (2010)

Fridriksson, Homan, & Remillard (2015)

RXTE/PCA:

Soft color ➔ (4.0-7.3)keV/(2.4-4.0)keV

Hard color ➔(9.8-18.2)keV/(7.3-9.8)keV

Monitor All-sky X-ray Instrument (MAXI)

Slit camera with area up to 5000 cm^2.

Sensitivity: 3 mCrab

Energy range: 0.5-30 keV

Resolution: 18% at 6 keV

Monitoring over 1000 sources since 2009

Matsuoka et al 2009

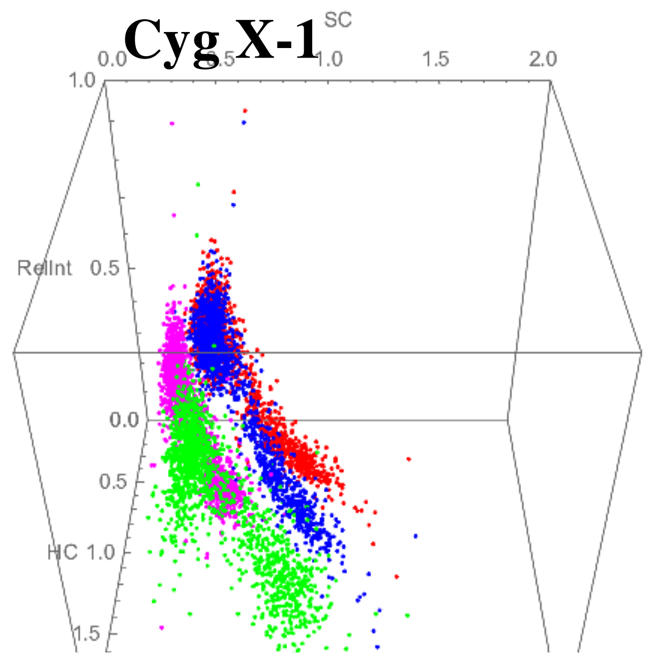
Maxi data in different energy ratios

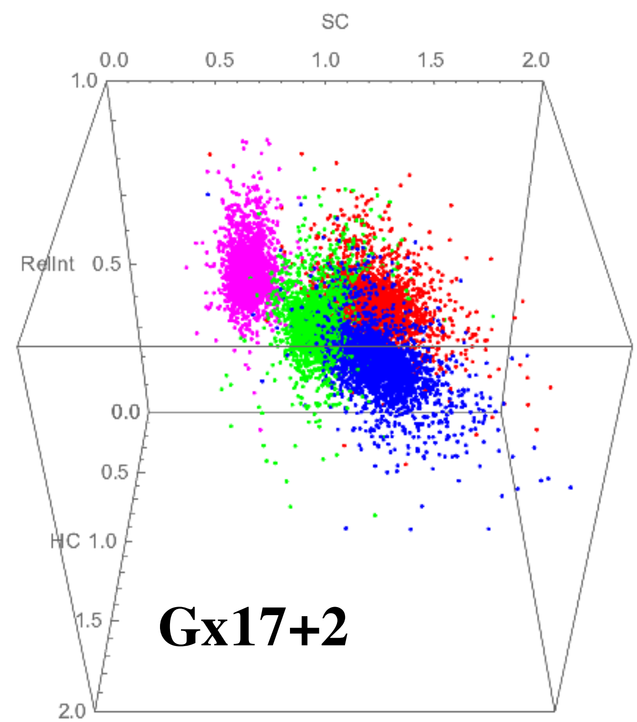
Vrtilek/Boroson (ASM):
Soft color==> (3.0-5.0)keV/(1.2-3.0)keV
Hard color==> (5.0-12)keV/(1.2-3.0keV)

McCollough/Vrtilek (Chandra):
Soft color==> (3.0-5.0)keV/(1.2-3.0)keV
Hard color==> (5.0-8.0)keV/(1.2-3.0keV)

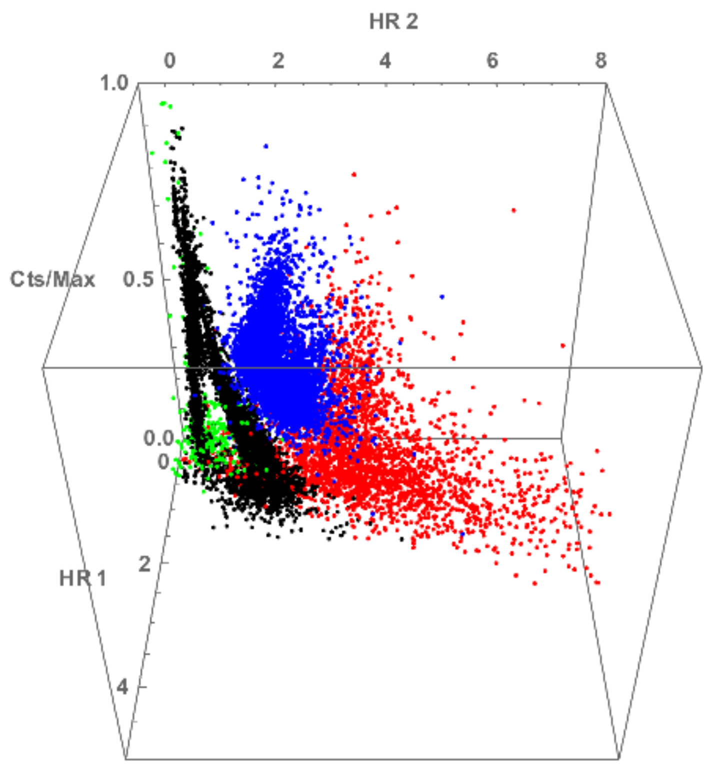
Peris/Remillard (2015 PCA):
Soft color==> (3.6-5.0)keV/(2.2-3.6)keV
Hard color==> (8.6-18.0)keV/(5.0-8.6)keV

Homan (2010 PCA):
Soft color==> (4.0-7.3)keV/(2.4-4.0)keV
Hard color==>(9.8-18.2)keV/(7.3-9.8)keV

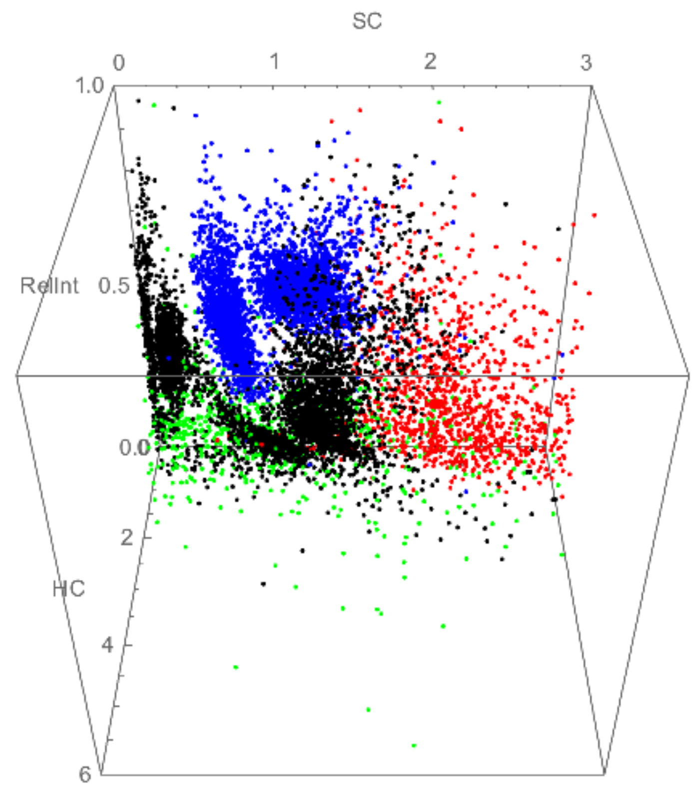




RXTE/ASM Data

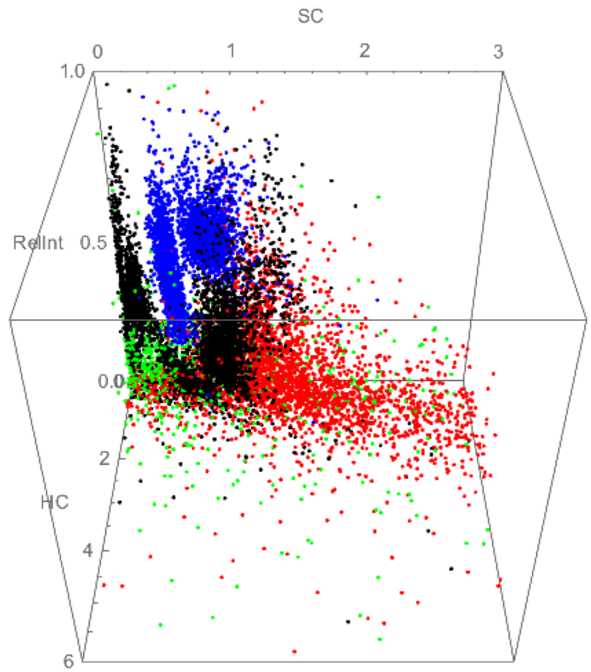


MAXI data using ASM Bands



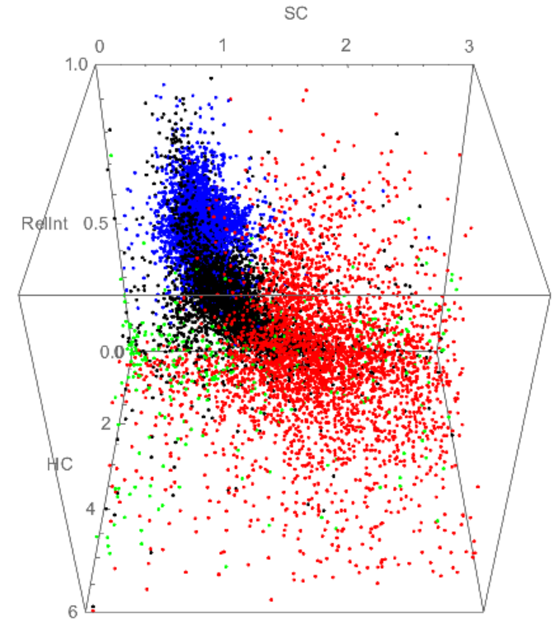
Black holes
Pulsing neutron stars
Non-pulsing neutron stars
Cataclysmic variables

MAXI data

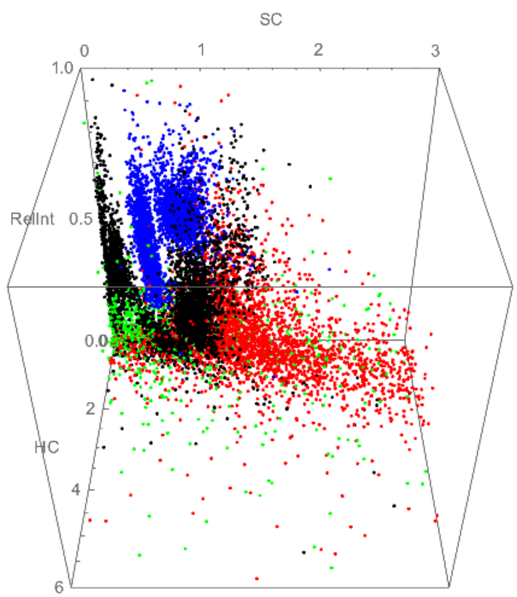


ASM Energy Bands

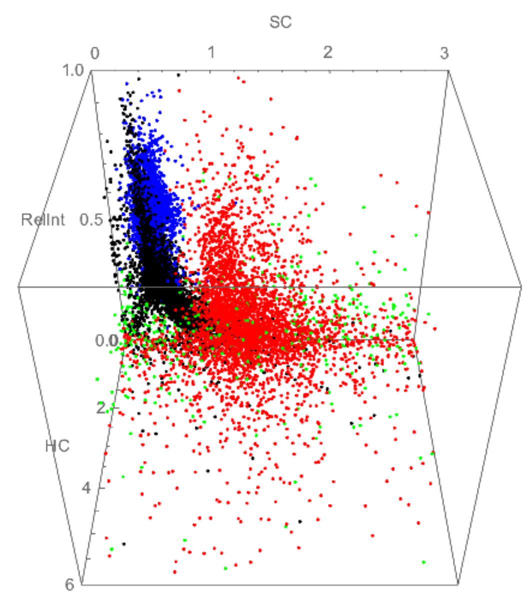
Black holes
Pulsing neutron stars
Non-pulsing neutron stars
Cataclysmic variables



Homan Energy bands



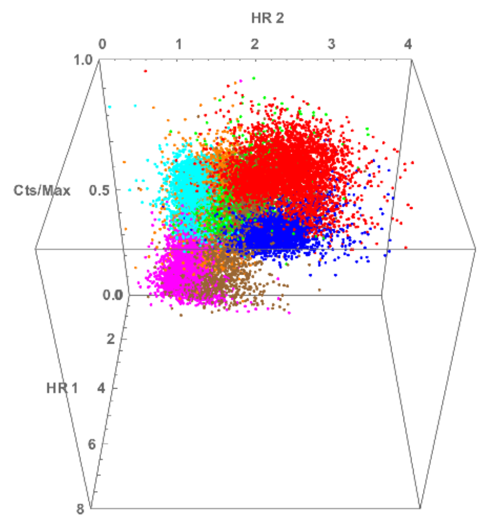
Chandra Energy Bands



Peris energy bands

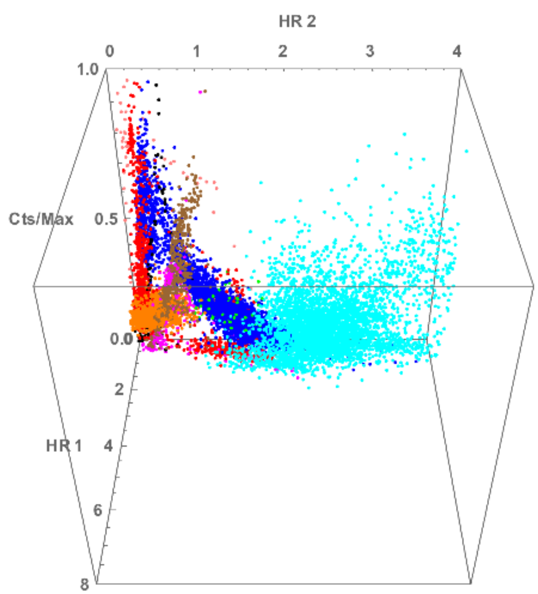
Neutron star system

Homan et al 2010



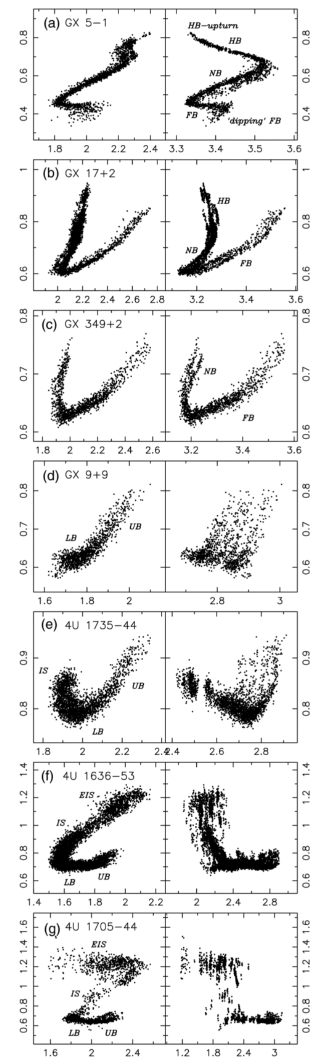
Black hole systems

Vrtilek et al 2016



1118+480
1550-564
1650-500
1655-40
1859+226
Cyg X-1
LMC X-1
GX339-4
GRS1915+10
5

Hard Color various ranges



Soft Color Intensity

GX5-1
GX17+2
GX349+2
GX9+9
1735-44
1636-44
1705-44

CCI equivalent

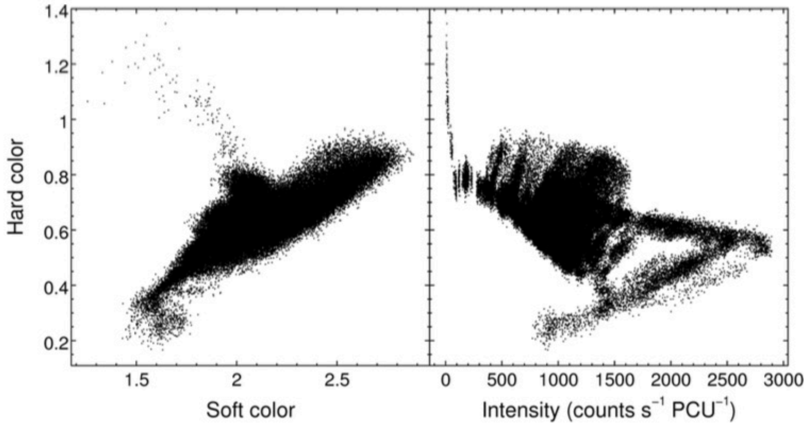
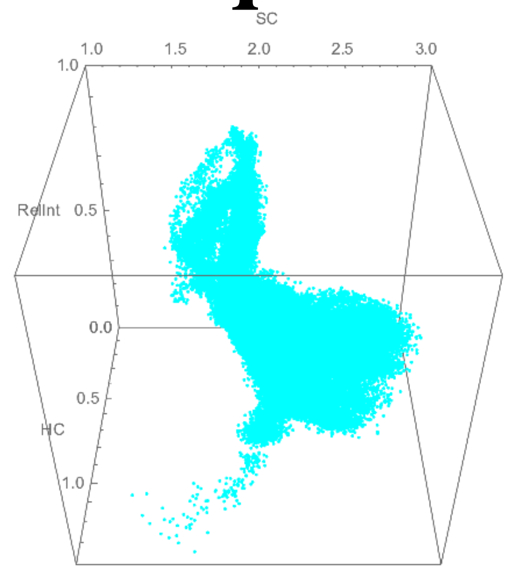
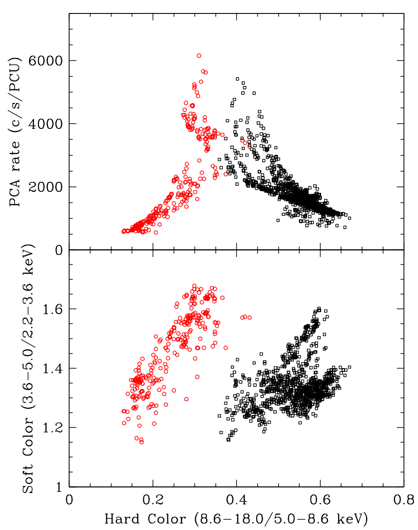
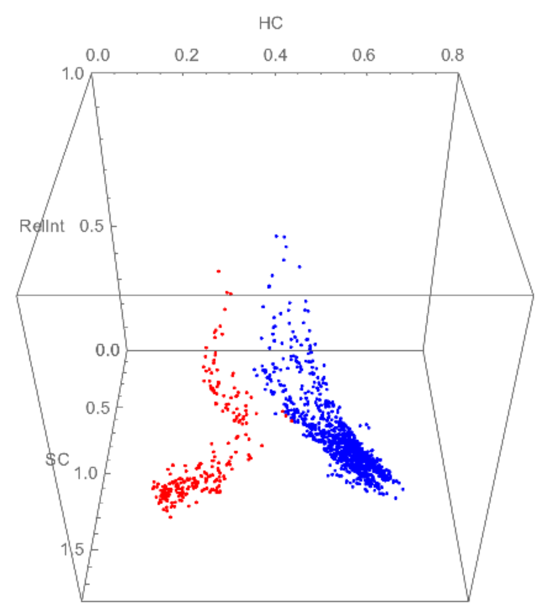


Figure 1. CD and HID representing the entire *RXTE* PCA data set of XTE J1701–462.



XTEJ1701-462
(Fridricksson, Homan, & Remillard 2015)

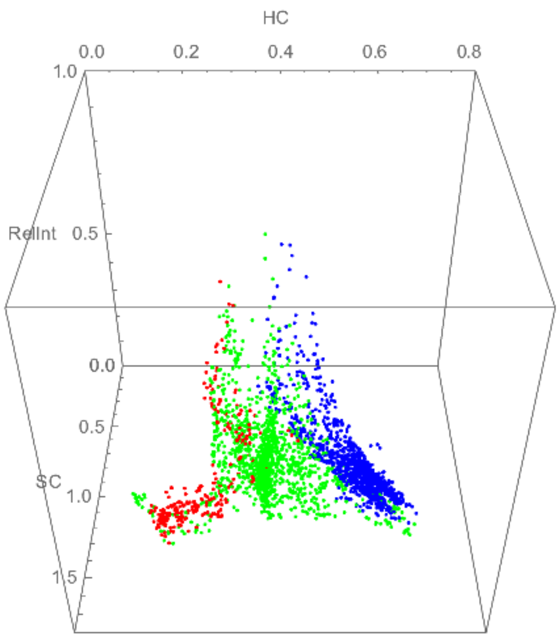


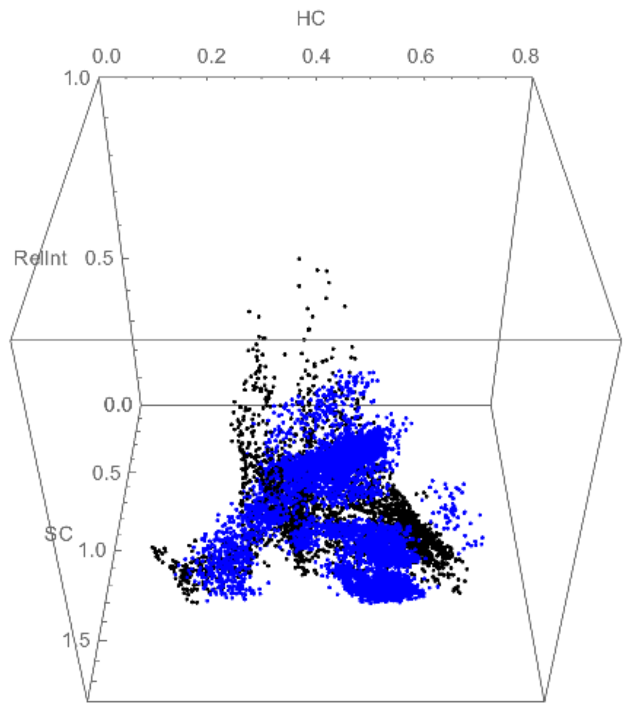


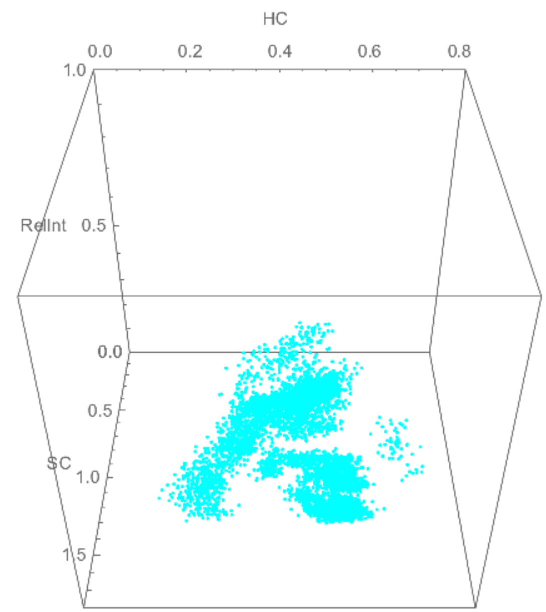
GRS1957+105 (Peris et al 2016)

GRS 1915+105
(Peris et al 2016)

XTEJ1705-462
(Fridricksson et al 2015)

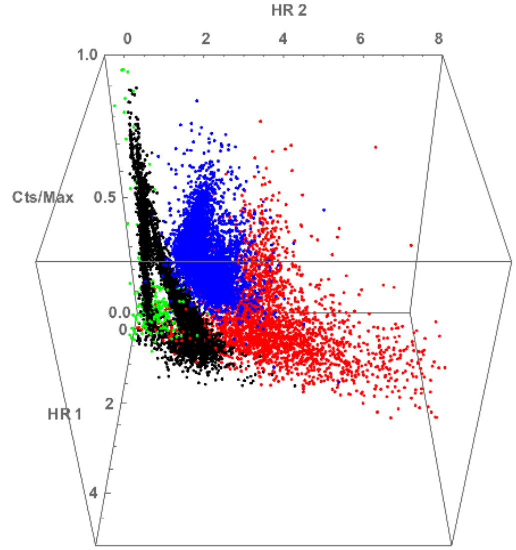




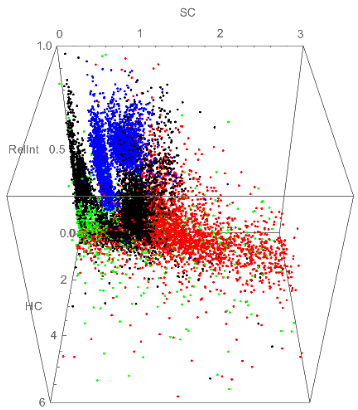


GRS 1915+105 Peris energy bands;
XTE J1705-462 Homan energy bands

Accreting binary types cluster in CCI diagrams as normal star types cluster in Hertzprung-Russell diagrams.

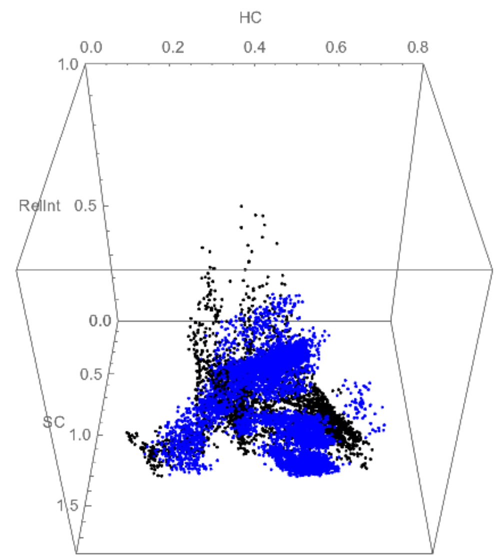


RXTE/ASM



MAXI/Chandra bands

The separation is robust between instruments and within different color definitions.



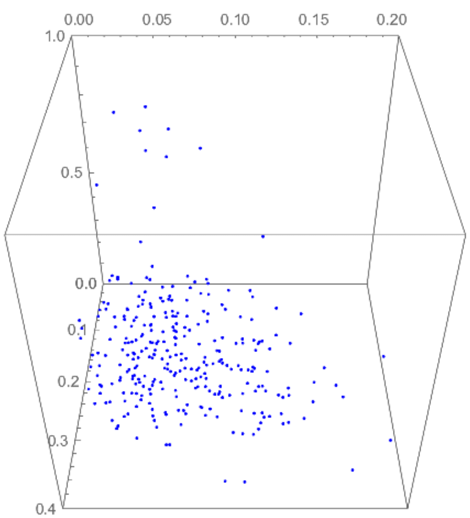
Overlaps between types occur if one mixes color definitions

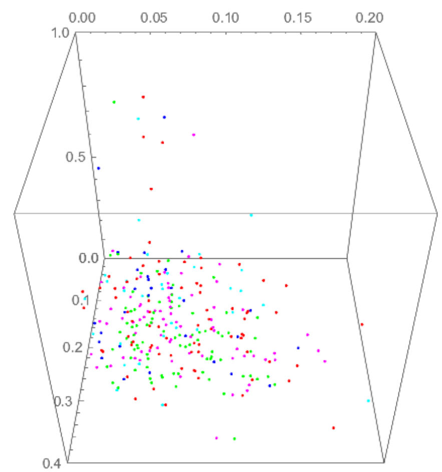
Homan & Peris bands

Projects in search of a Statistician

Statistical distributions of XRBS from 100 elliptical galaxies (with the Chandra Galaxy Atlas Team)

Statistical distributions of XRBS from 42 spiral galaxies (with the Chandra Galaxy Atlas Team)

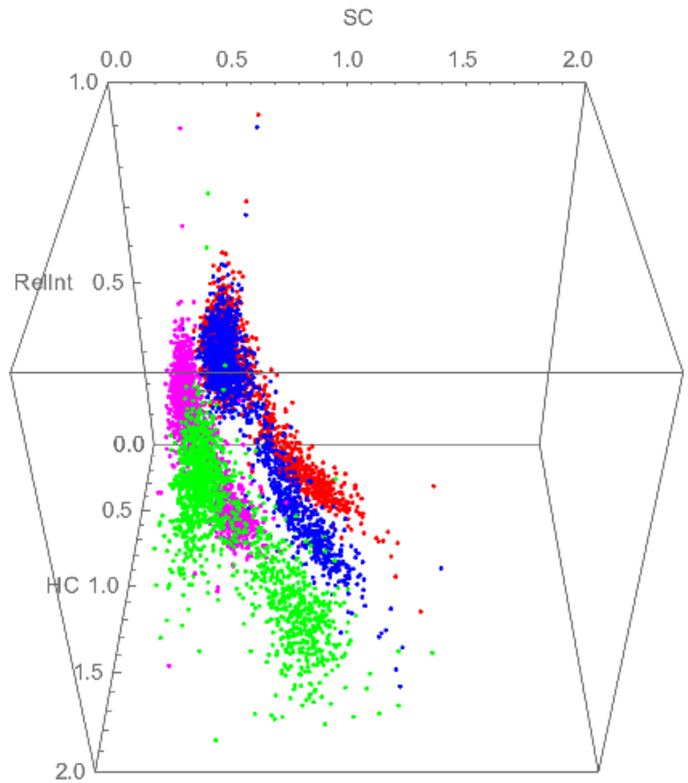




Five Ellipticals

Projects in search of a Statistician

Statistical study to determine optimal energy bands
Corrections for comparing different color ratios

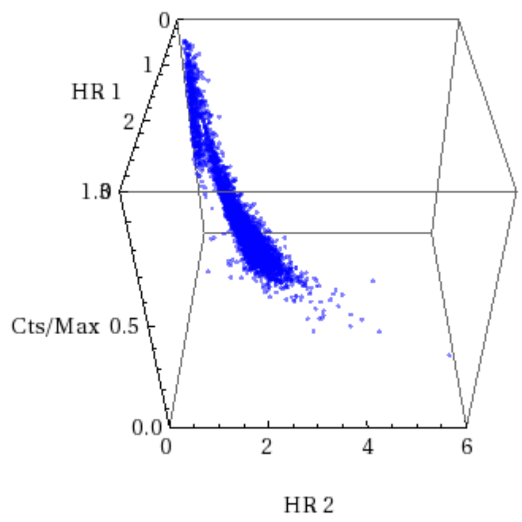


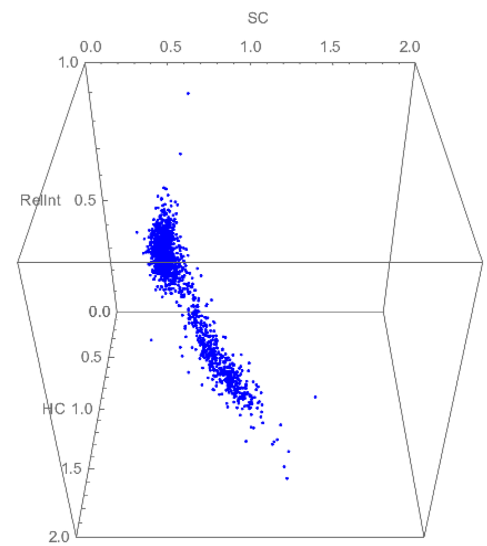
ASM Chandra Homan Peris

Projects in search of a Statistician

Statistical study to determine optimal energy bands

Conversions for comparison between instruments

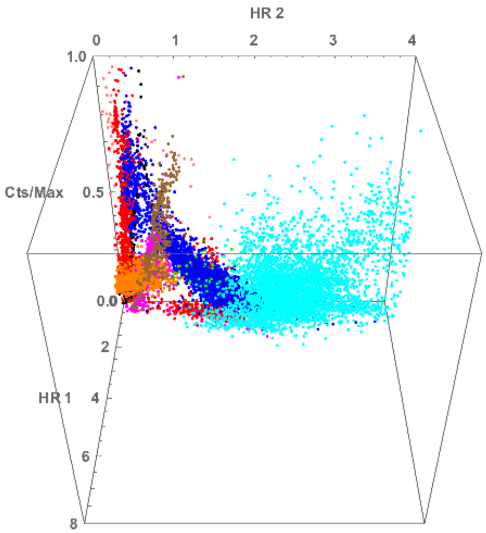


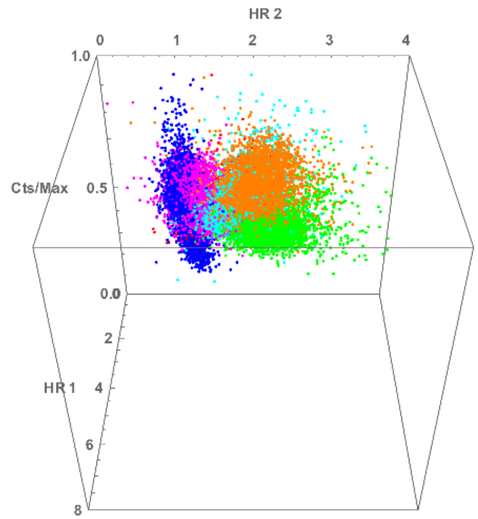


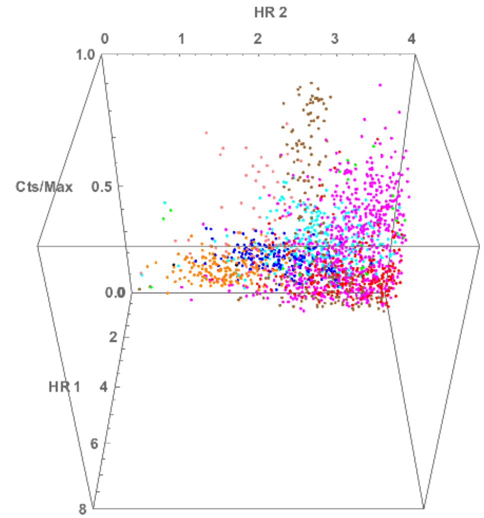
Cyg X-1 (ASM and MAXI)

Projects in search of a Statistician

Subtypes







Black Hole systems

1118+480
1550-564
1650-500
1655-40
1859+226
Cyg X-1
LMC X-1
GX339-4
GRS1915+105

Neutron stars, non pulsing

Sco X-1
Cyg X-2
GX17+2
GX349+2
GX9+1
GX9+9

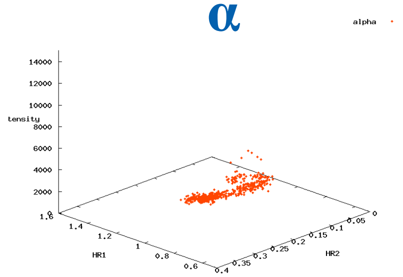
Neutron stars, pulsing

J0352+309
J1901+03
J1947+300
J2030+375
J1538-522
Cen X-3
Her X-1
Smc X-1
Vela x-1

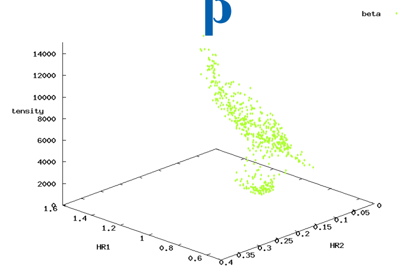
Projects in search of a Statistician

Substates of individual sources with better resolution

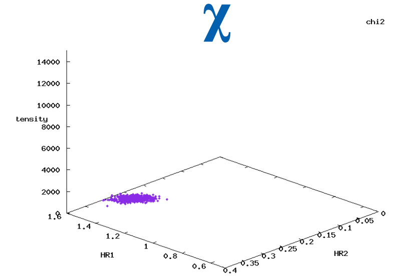
α



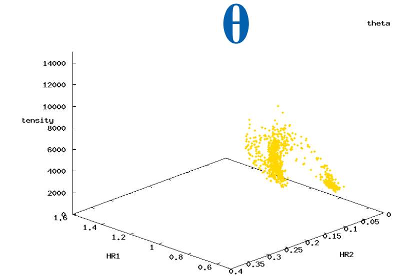
β



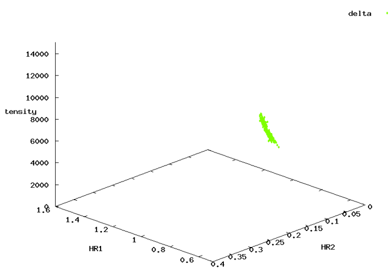
χ



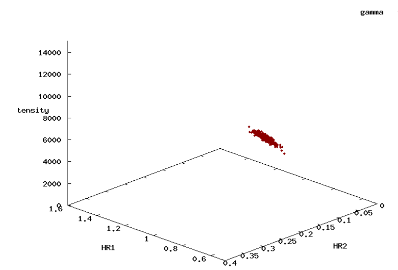
θ



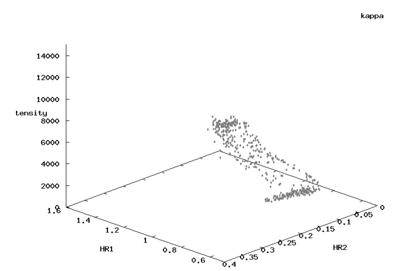
δ



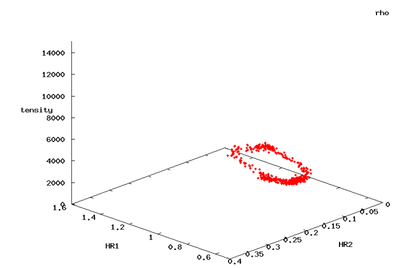
γ



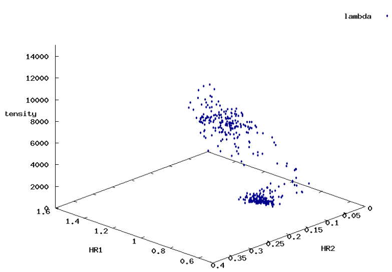
ϰ



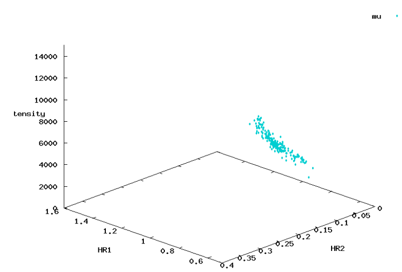
ϱ



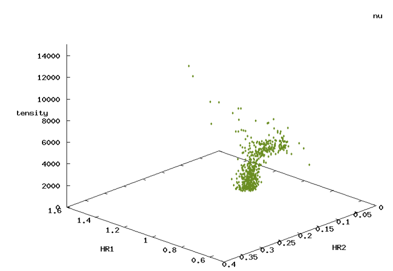
λ



μ



ν

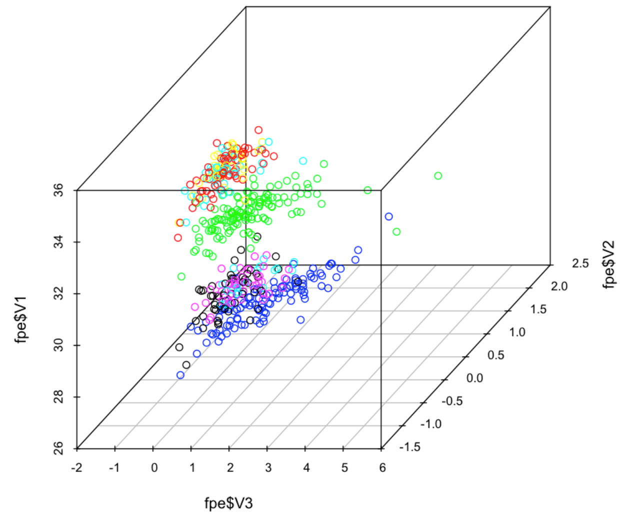


Peris 2013

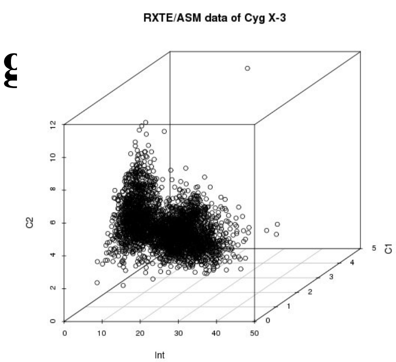
PCA Data of GRS1915+105 Belloni states

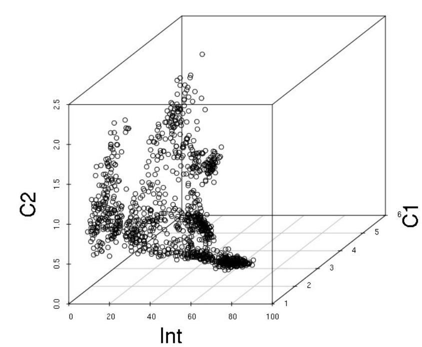
Other Ongoing Projects

Study of Cataclysmic Variable Sub Types (John Raymond)

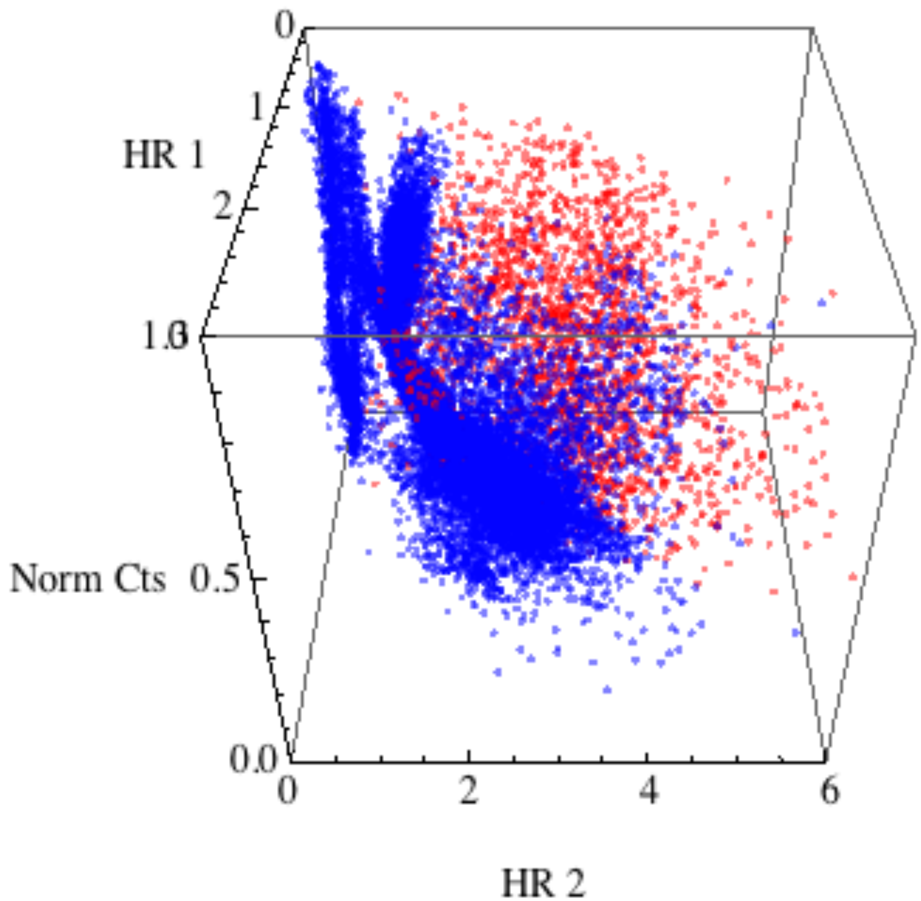


CCI study of Cyg X-3 using Chandra HETG (Mike McColloug





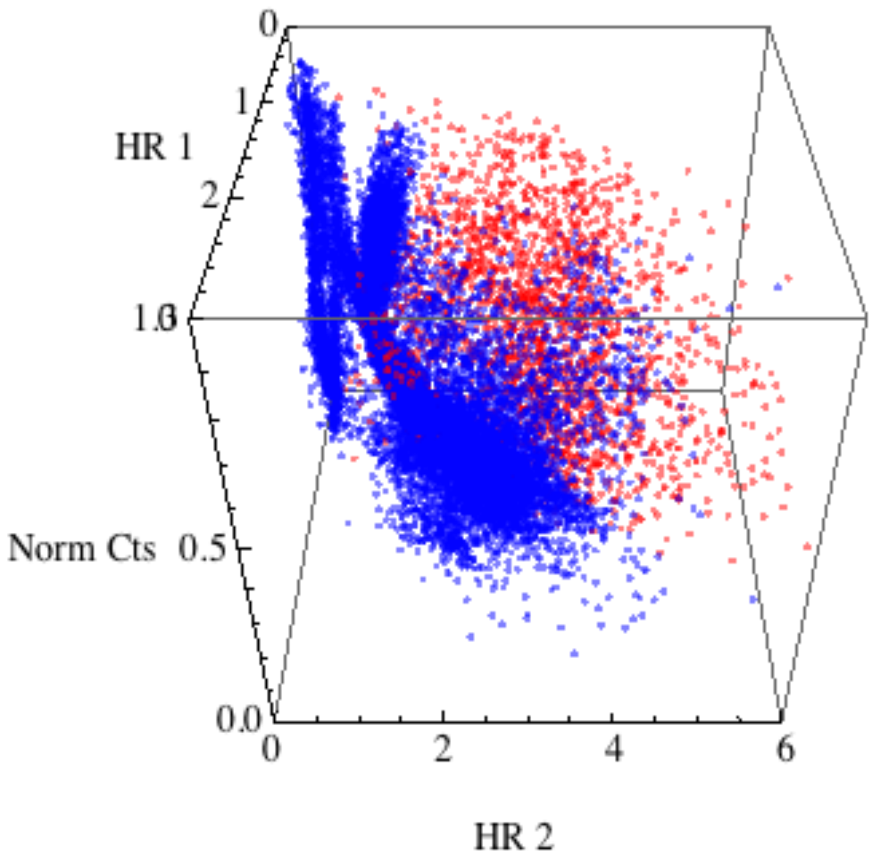
Incorporating the Physics

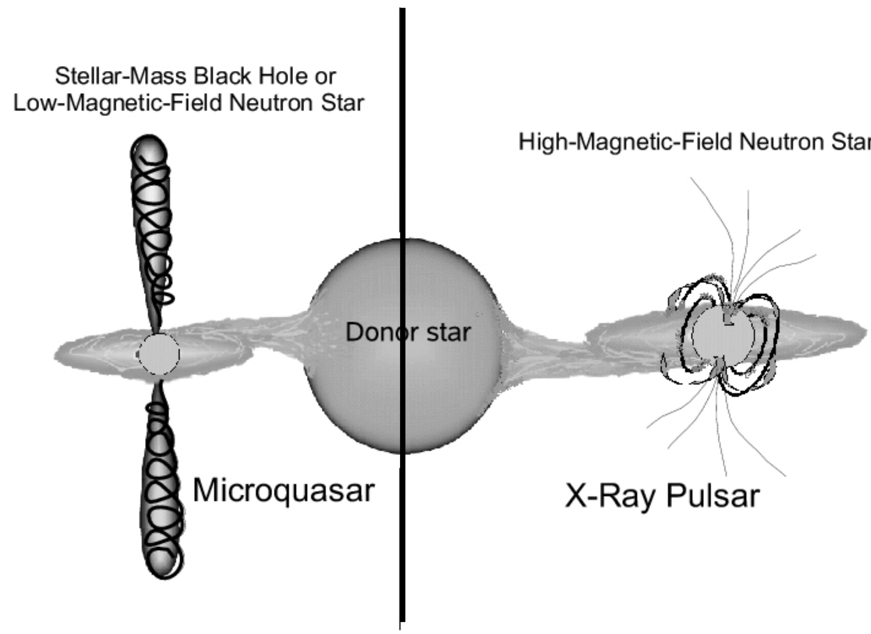


Resolved jet sources
X-ray pulsars

Cyg X-1
Cyg X-3
Circinus X-1
XTE J1550-564
Sco X-1
GROJ1655-40
GRS 1915+105
GX339-4

Incorporating the Physics



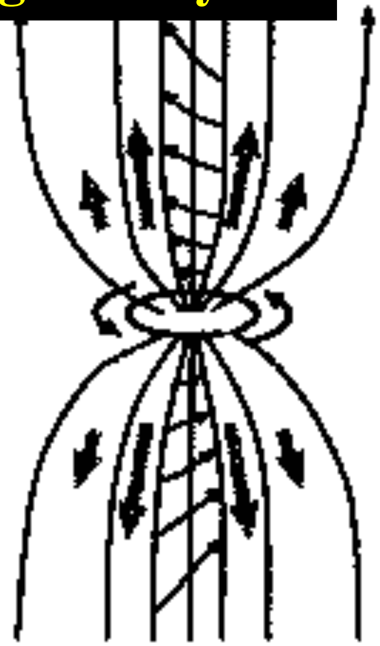


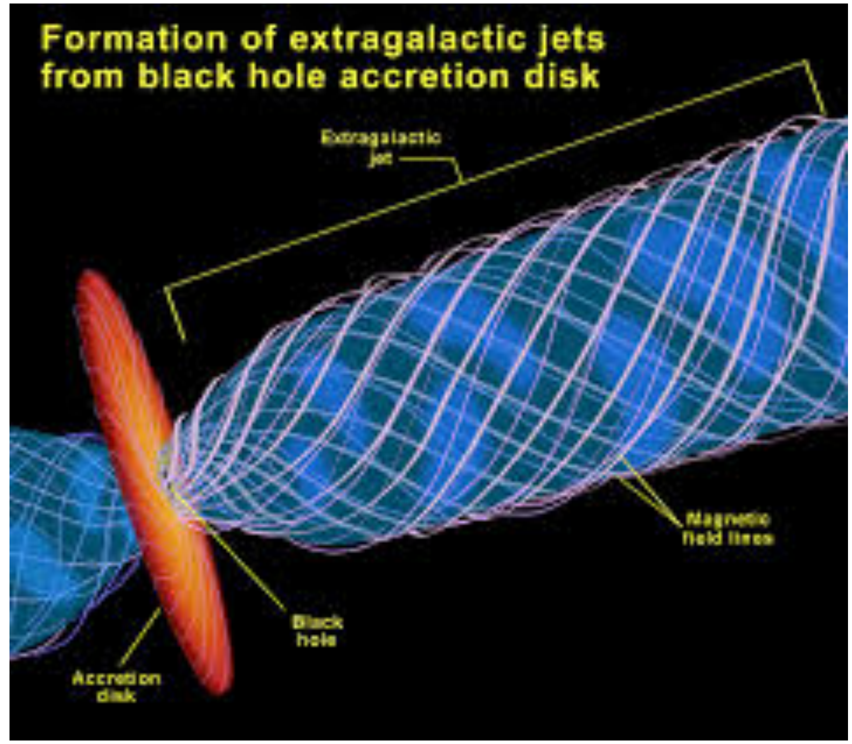
Massi & Bernado (2008)

Resolved jet sources

X-ray pulsars

Incorporating the Physics





If $P_B < P_p$ field lines spiral

$P_B = B^2/8\pi$
$P_p = \varrho v^2$

$P_B = P_P$ at the Alfven radius

Condition for jet formation is that

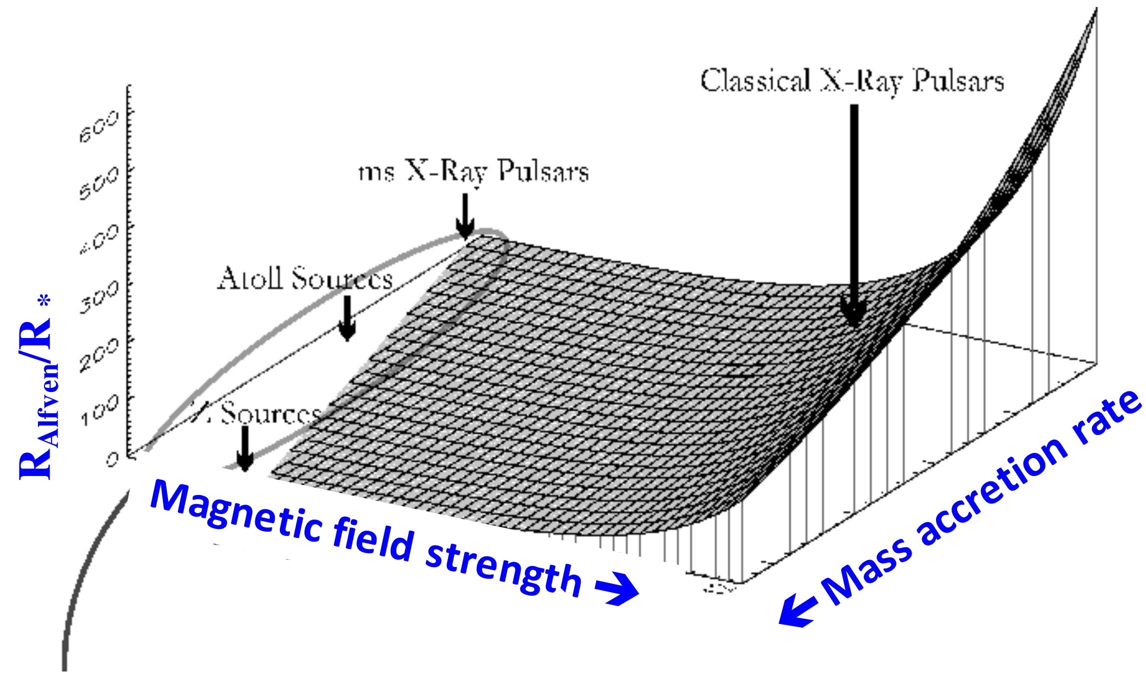
$R_A/R_* = 1$ for NS

$R_A/R_{LSO} = 1$ for BH

Incorporating the Physics

$P_B = B^2/8\pi$
$P_p = \varrho v^2$

So for the jet criterion
$P_B = P_p \Rightarrow B^2/8\pi = \varrho v^2$



Massi & Bernado 2008:

$M_{dot} = 4\pi R^2 \varrho v$ (Longair 1994)
$v = (2GM_*/R)^{1/2}$
For a dipole magnetic field: $B/B_* = (R_*/R)^3$

$$R_A/R_* \cong 0.87\ (B_*/10^8 G)^{4/7} (M_{dot} 10^{-8} M_{sun}/\text{year})^{-2/7}$$

For a NS with a mass $1.44 M_{sun}$ and radius of 9km (Titarchuk & Shaposhnikov 2002)

Massi & Bernado 2008 quantified this progression using known values:

$R_{Alfven}/R_{NS\ surface}$ = 1 for neutron star systems

R_{Alfven}/R_{ISO} = 1 for black hole systems.

$B \leq 1.35 \times 10^8$ G
Schwarszchild blackhole

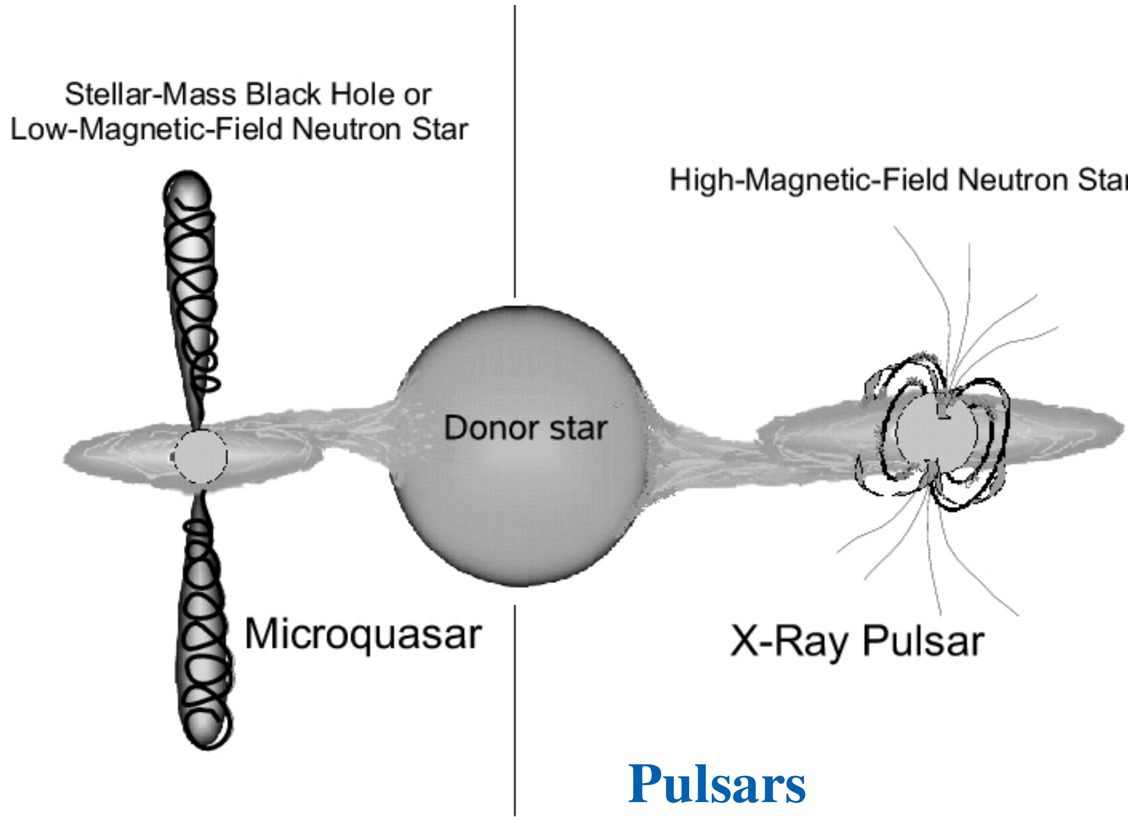
$B \leq 5 \times 10^8$ G
Kerr blackhole

$B \leq 10^{8.2}$ G Z-sources

$B \leq 10^{7.7}$ G Atoll sources

$B \leq 10^{7.5}$ G
Millisecond pulsars

$B \leq 10^{5.9}$ G AGN



Pulsars
$B \sim 10^{12}$ G
No jets at any accretion rate

Fender et al model for jet production in XRBs

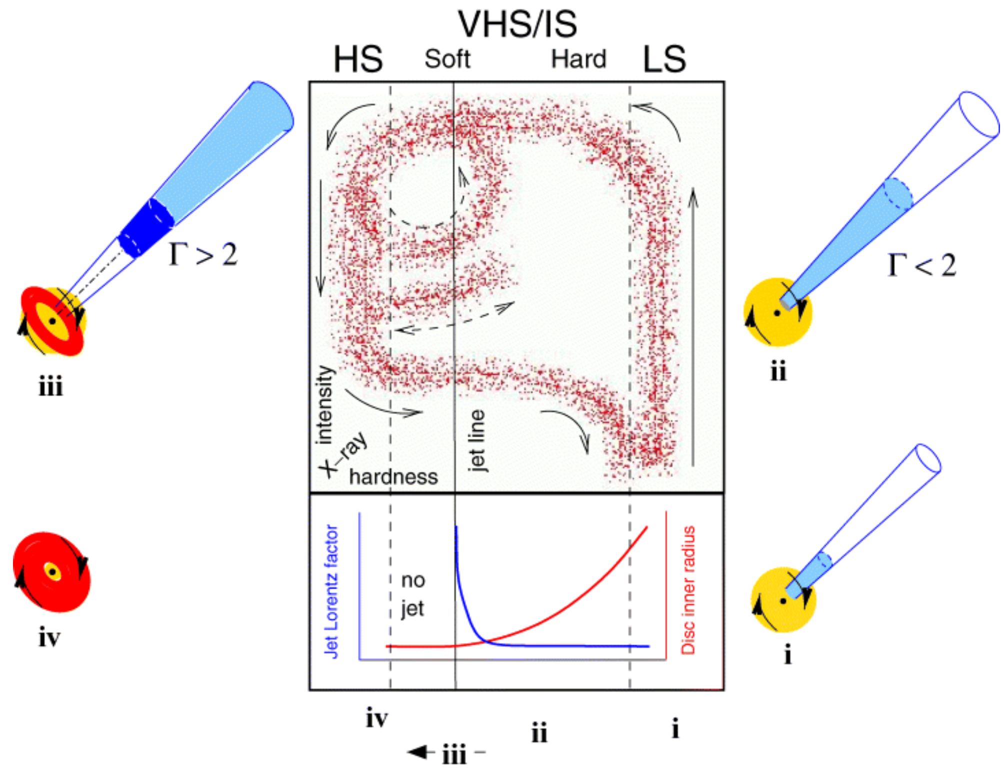
From most likely to least likely to produce jets:

Black hole systems with no intrinsic magnetic field.

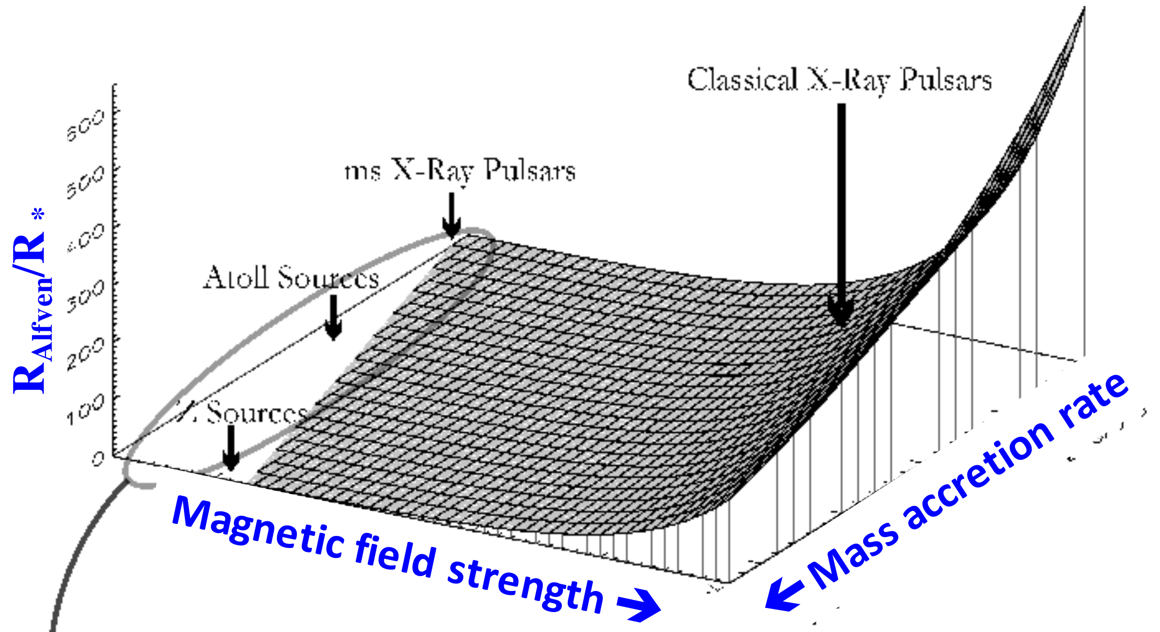
Low-mass neutron star systems with weak magnetic fields at high accretion (Z-type)

Low-mass neutron star systems with weak magnetic fields at low accretion (Atoll)

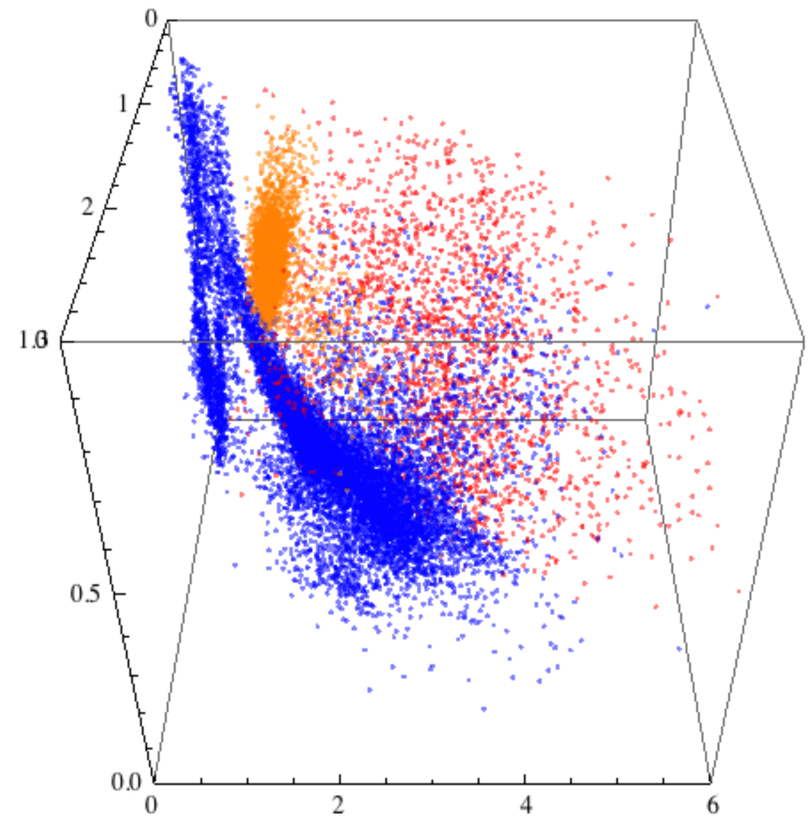
High-mass neutron star systems with high magnetic fields (Pulsars)



Fender, Belloni, & Gallo (2004)

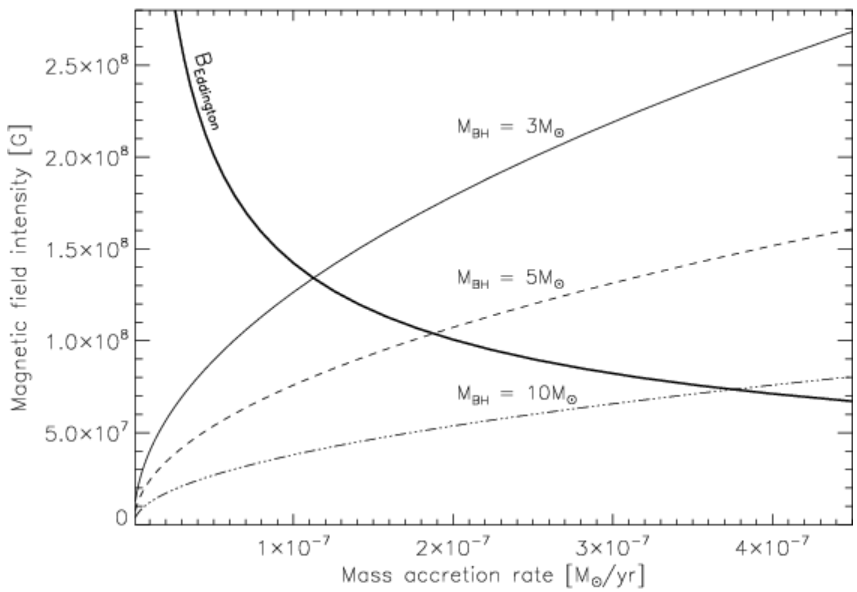


Massi & Bernado 2008

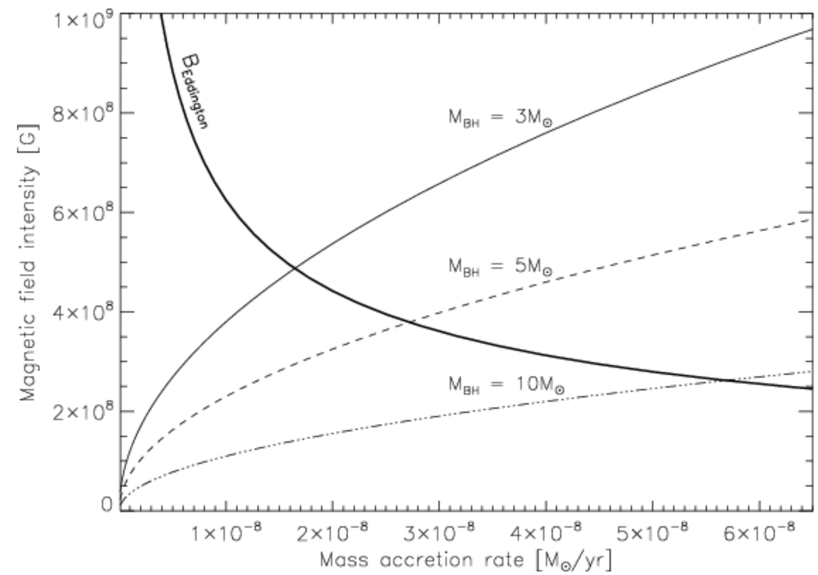


Sco X-1
Black hole systems
Pulsars

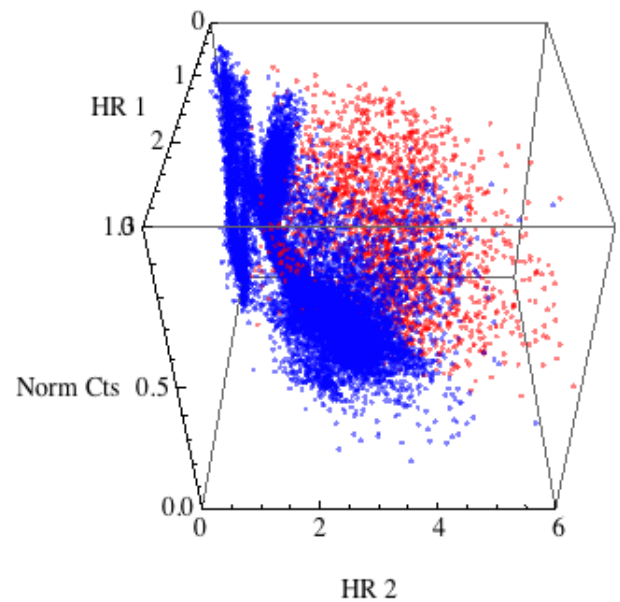
$R_A/R_{LSO} = 1$



Schwarzschild-BH XRBs



Kerr-BH XRBs



Magnetic Field Strength

$R_{Alfven}/R_{NS\ surface}$ = 1 for neutron star systems

R_{Alfven}/R_{ISO} = 1 for black hole systems.

$B \leq 1.35 \times 10^8$ G
Schwarszchild blackhole

$B \leq 5 \times 10^8$ G
Kerr blackhole

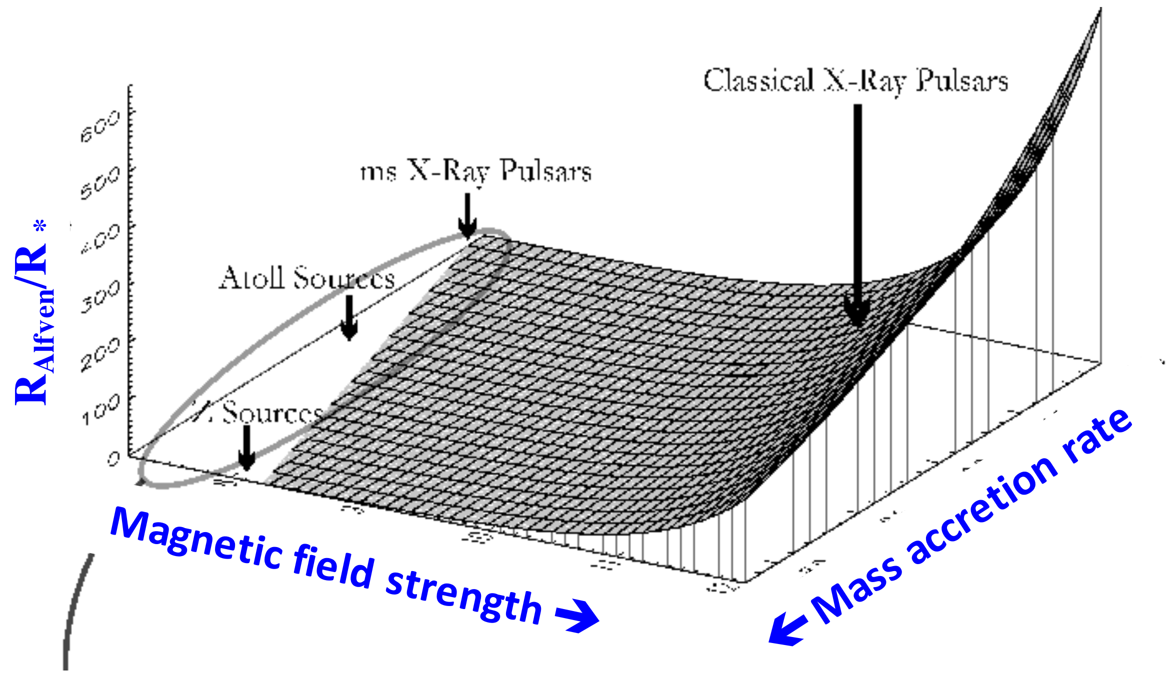
$B \leq 10^{8.2}$ G Z-sources

$B \leq 10^{7.7}$ G Atoll sources

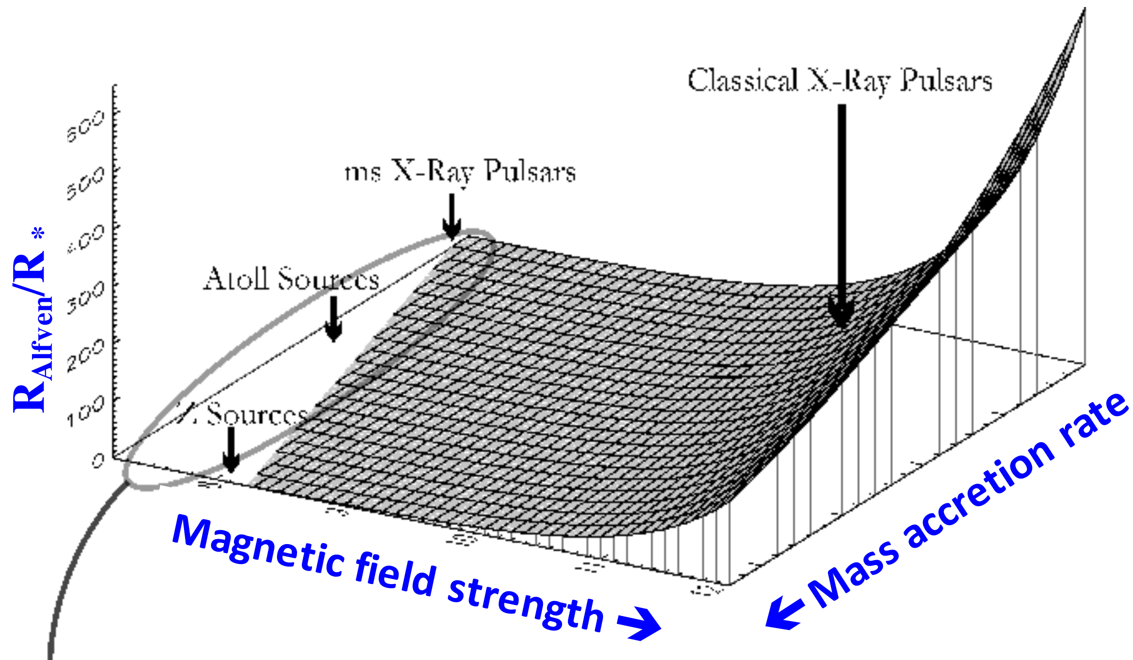
$B \leq 10^{7.5}$ G
Millisecond pulsars

$B \leq 10^{5.9}$ G AGN

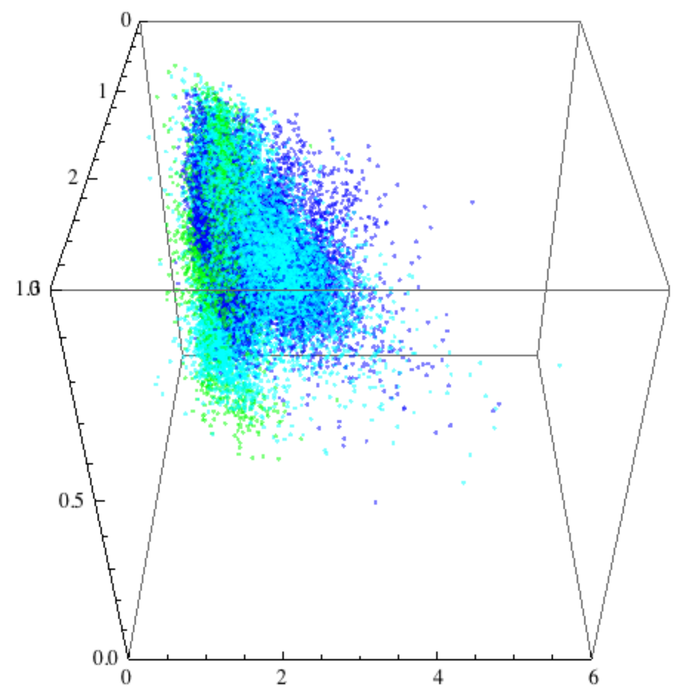
Pulsars
$B \sim 10^{12}$ G
No jets at any accretion rate



Massi & Bernado 2008

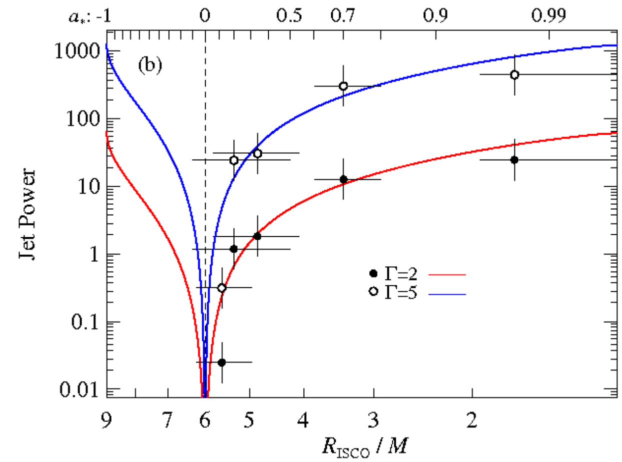


Massi & Bernado 2008

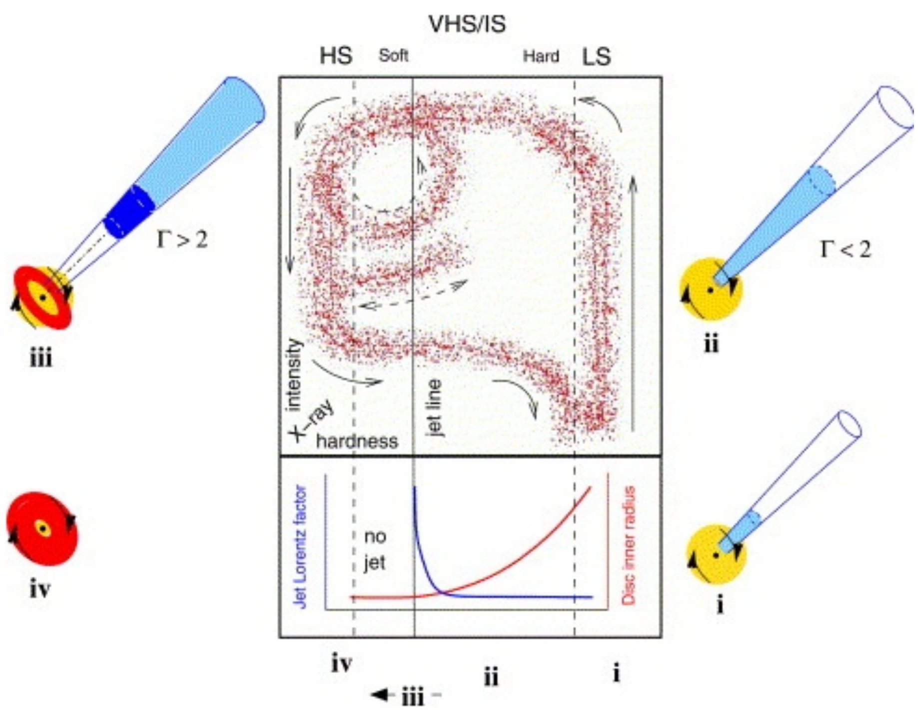


Homan et al 2010 claim M_{dot} increases from Atoll to Z sources. And bursters are thought to be at very low Mdot.

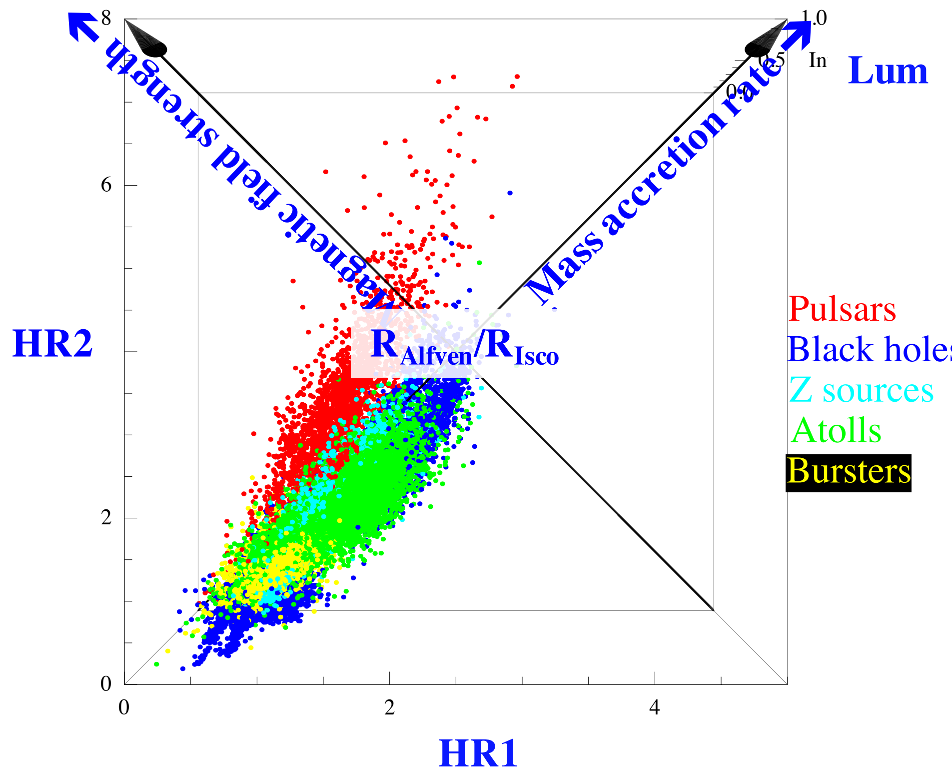
1. Mass accretion rate determines available energy
2. Strong magnetic fields inhibit jet formation
3. ISCO is related to jet power



McClintock, Narayan, & Steiner 2013

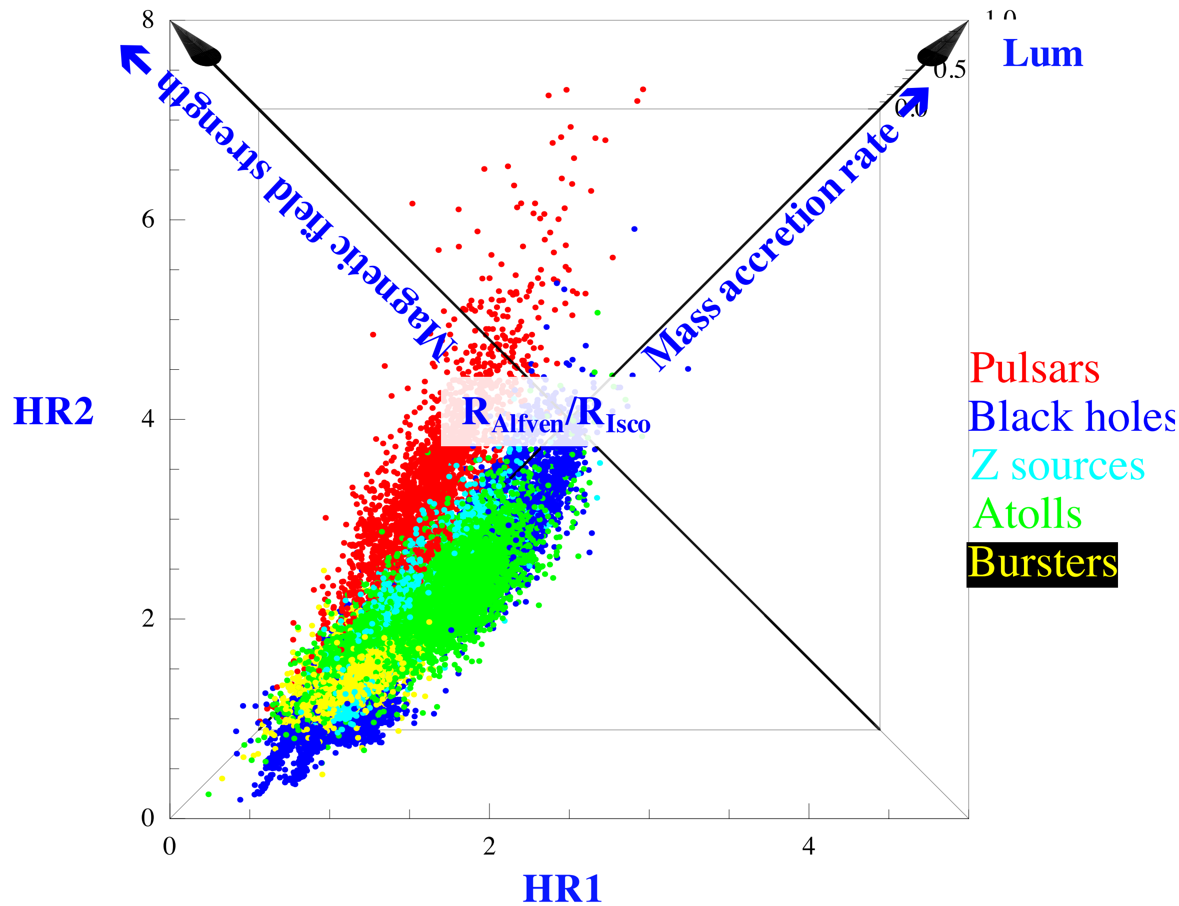


Fender, Belloni, & Gallo (2004)



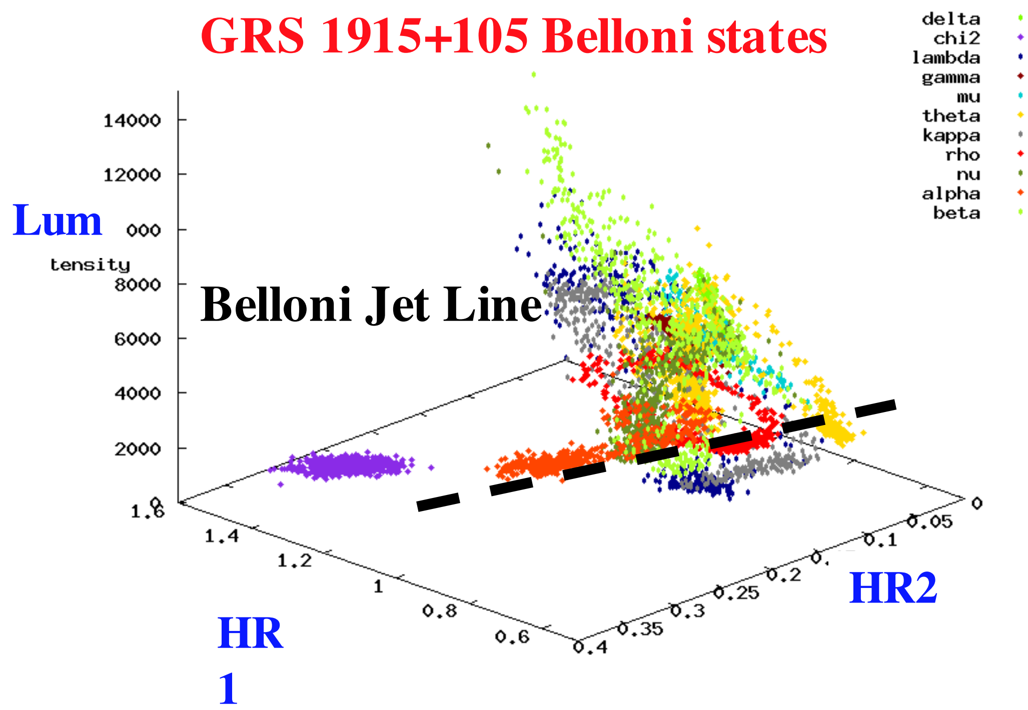
CCI diagram incorporate ALL key elements that determine interplay between jet power and disk radiation:

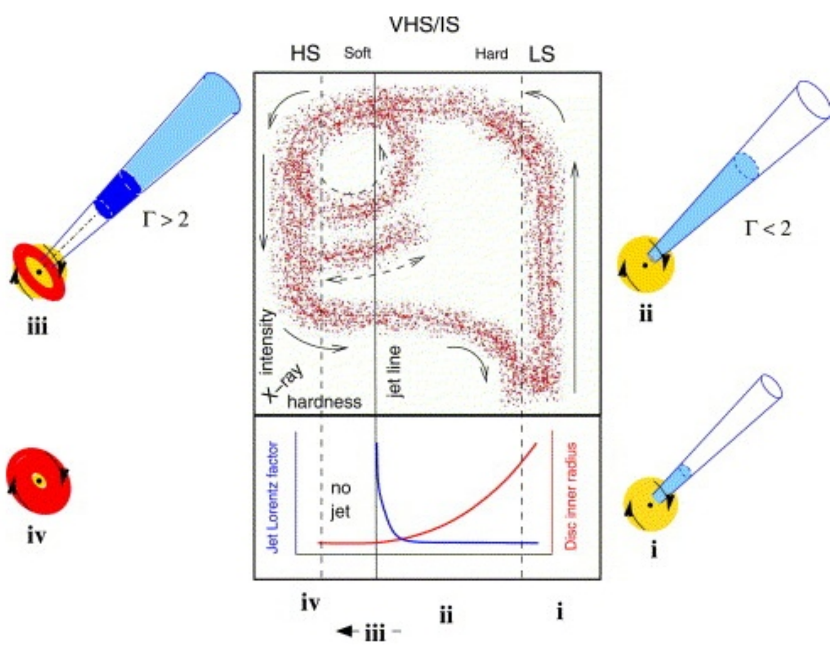
1. Mass accretion rate which determines available energy
2. Strong magnetic fields which inhibit jet formation
3. Basic condition for jet formation ($R_A/R_{Iso} = 1$)



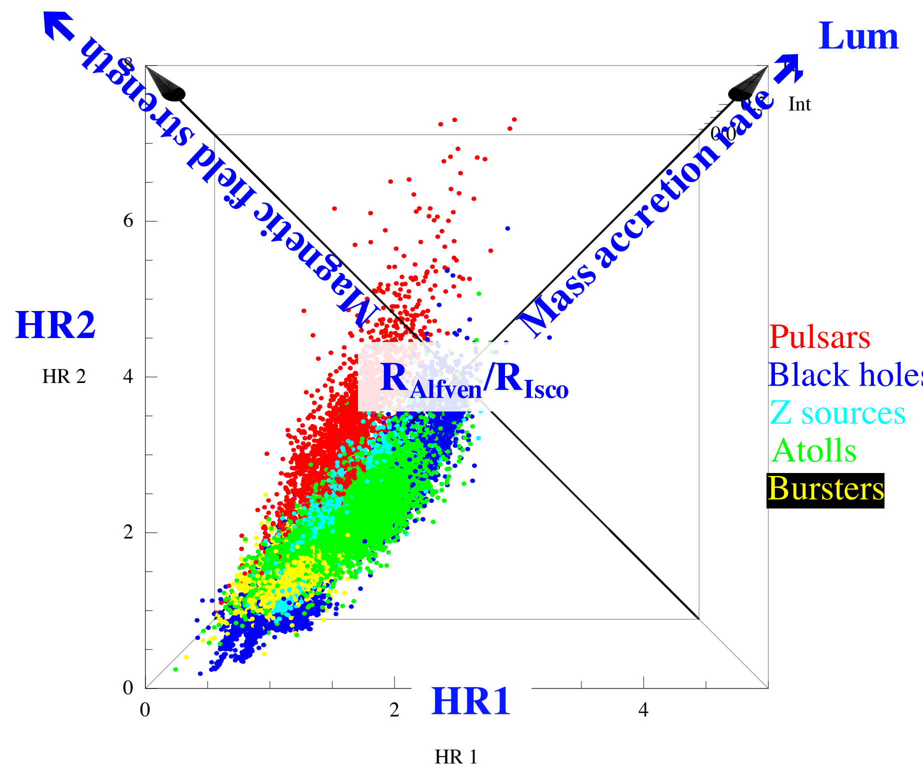
Problem in search of a statistician

When will an accreting neutron star become a microquasar rather than a pulsar?



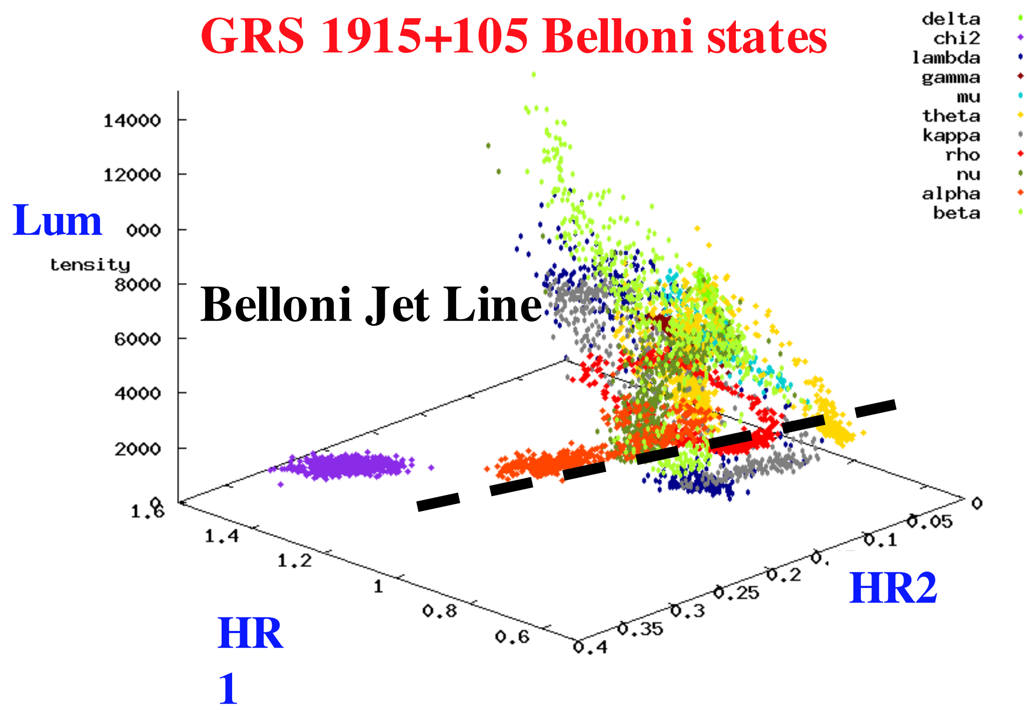


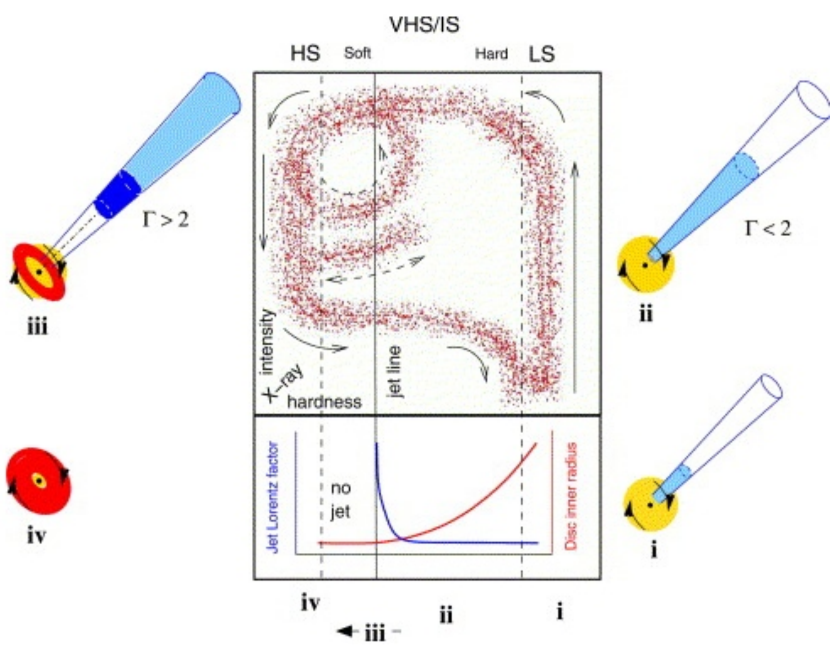
Fender, Belloni, & Gallo (2004)



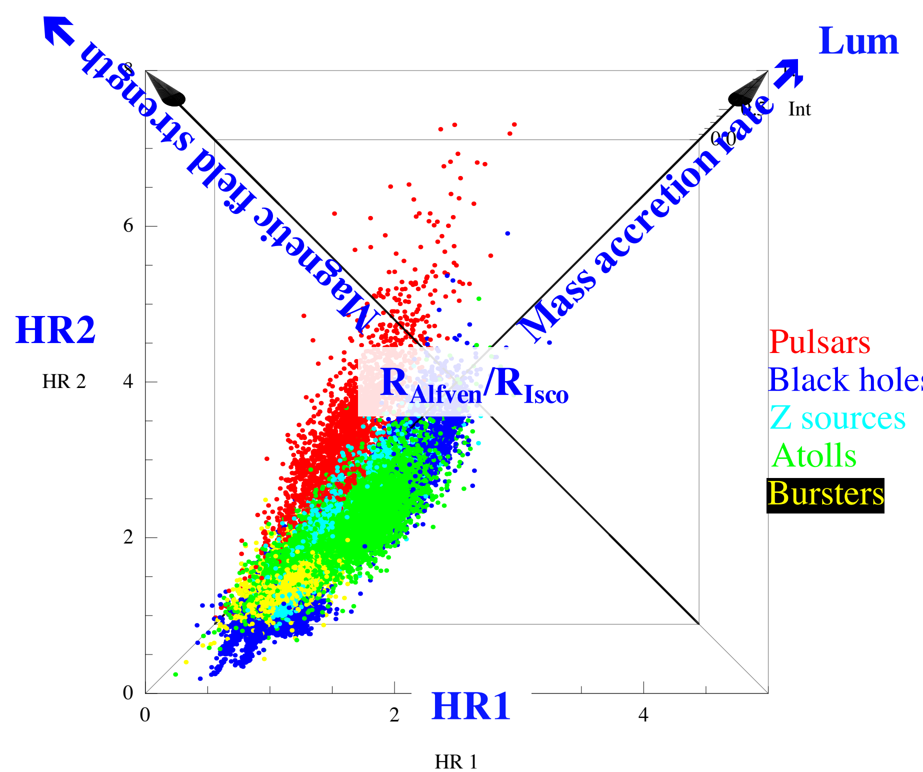
Problem in search of a statistician

When will a black hole X-ray binary evolve into a microquasar phase?





Fender, Belloni, & Gallo (2004)



Ongoing projects in search of a Statistician

Statistical distributions of XRBS from 100 elliptical galaxies (Vrtilek and the Chandra Galaxy Atlas Team)

Statistical distributions of XRBS from 42 spiral galaxies (Islam and the Chandra Galaxy Atlas Team)

Disk/Jet connection: NS to microquasar or pulsar?
Disk/Jet connection: Bh evolution to microquasar

Include lightcurve information as prior

Incorporate hierarchical structure (as prior distribution on the Gaussian process parameter)

Model and impute missing data.

Corrections for comparing different color ratios
Conversions for comparison between instruments