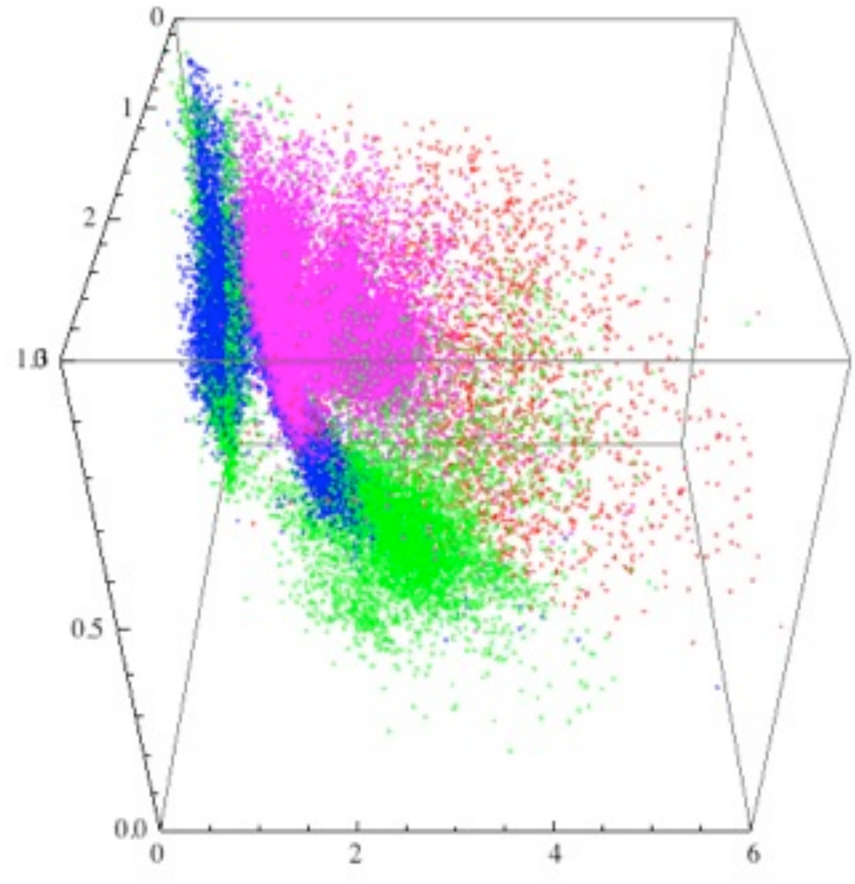
Adding a new dimension: multivariate studies of X-ray Binaries

Saku Vrtilek (CfA), Luke Bornn (Harvard),
Bram Boroson (CSU), Joey Richards (LLNL)



Putting X-ray binaries in their proper place.

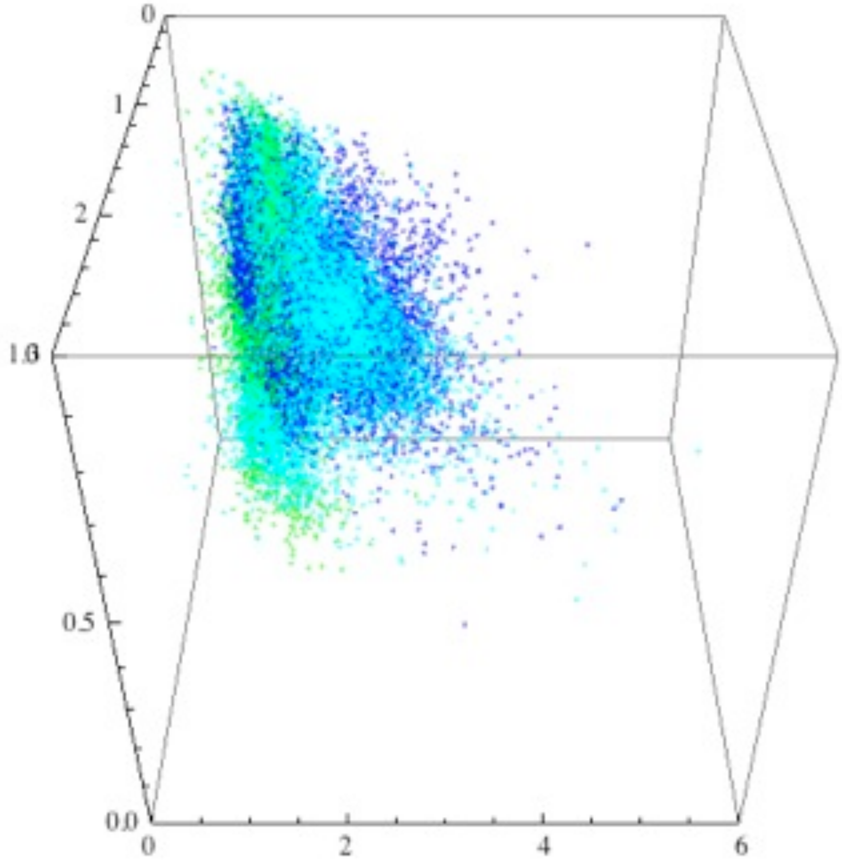
Introduction:

- X-ray binaries
- Data set
- CCI description

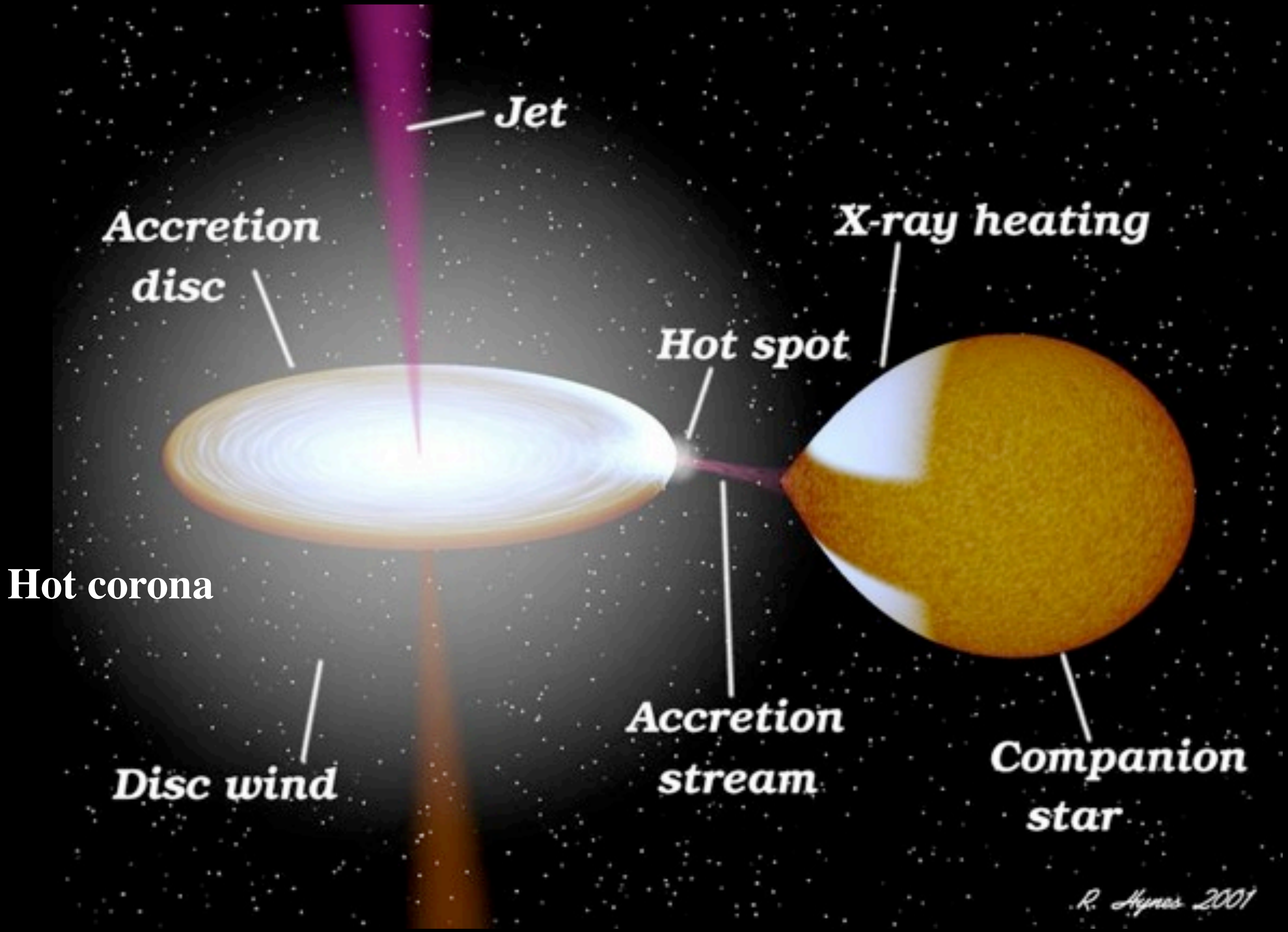
Physical interpretations

Statistical solutions (Luke)

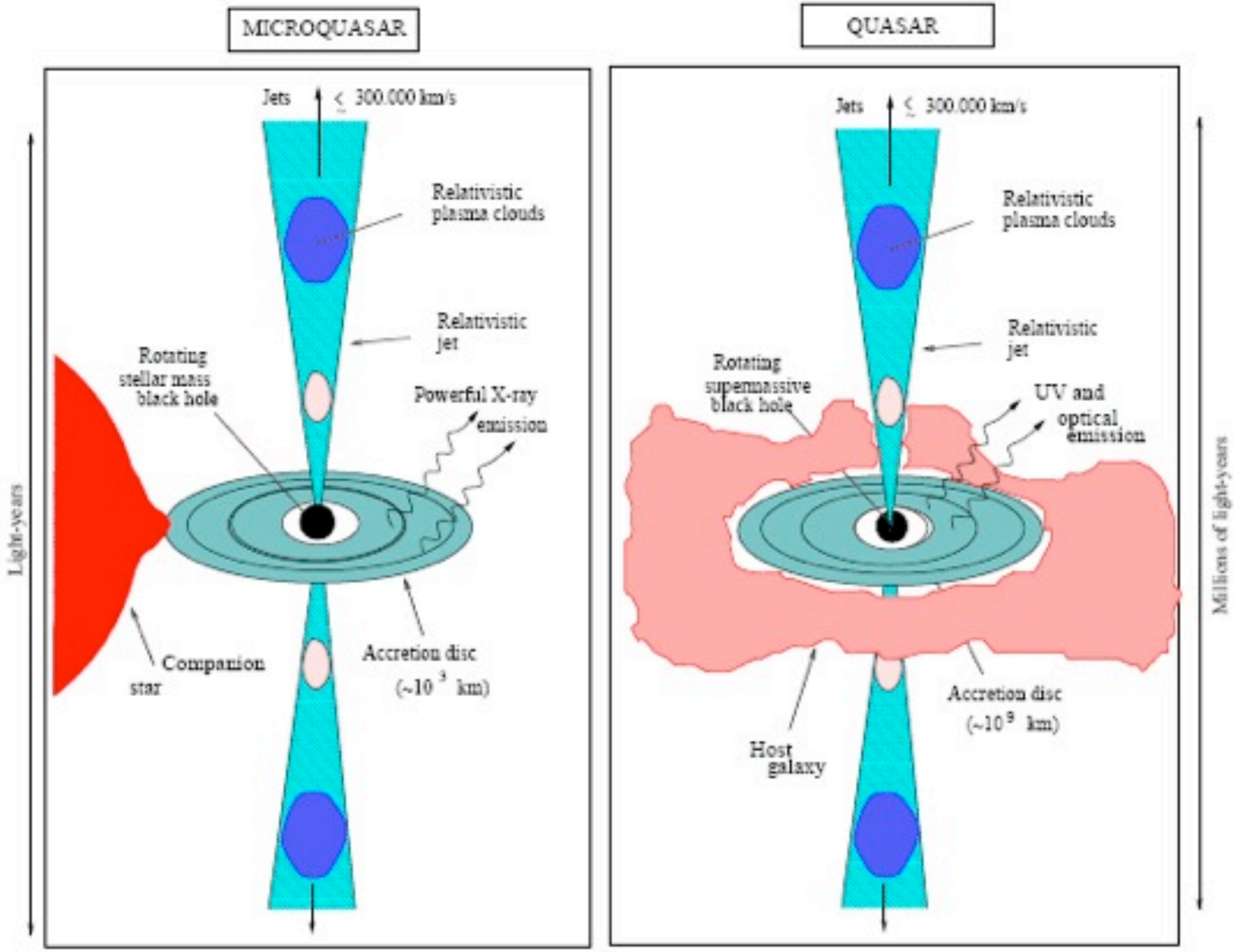
Future work



What are X-ray binaries?

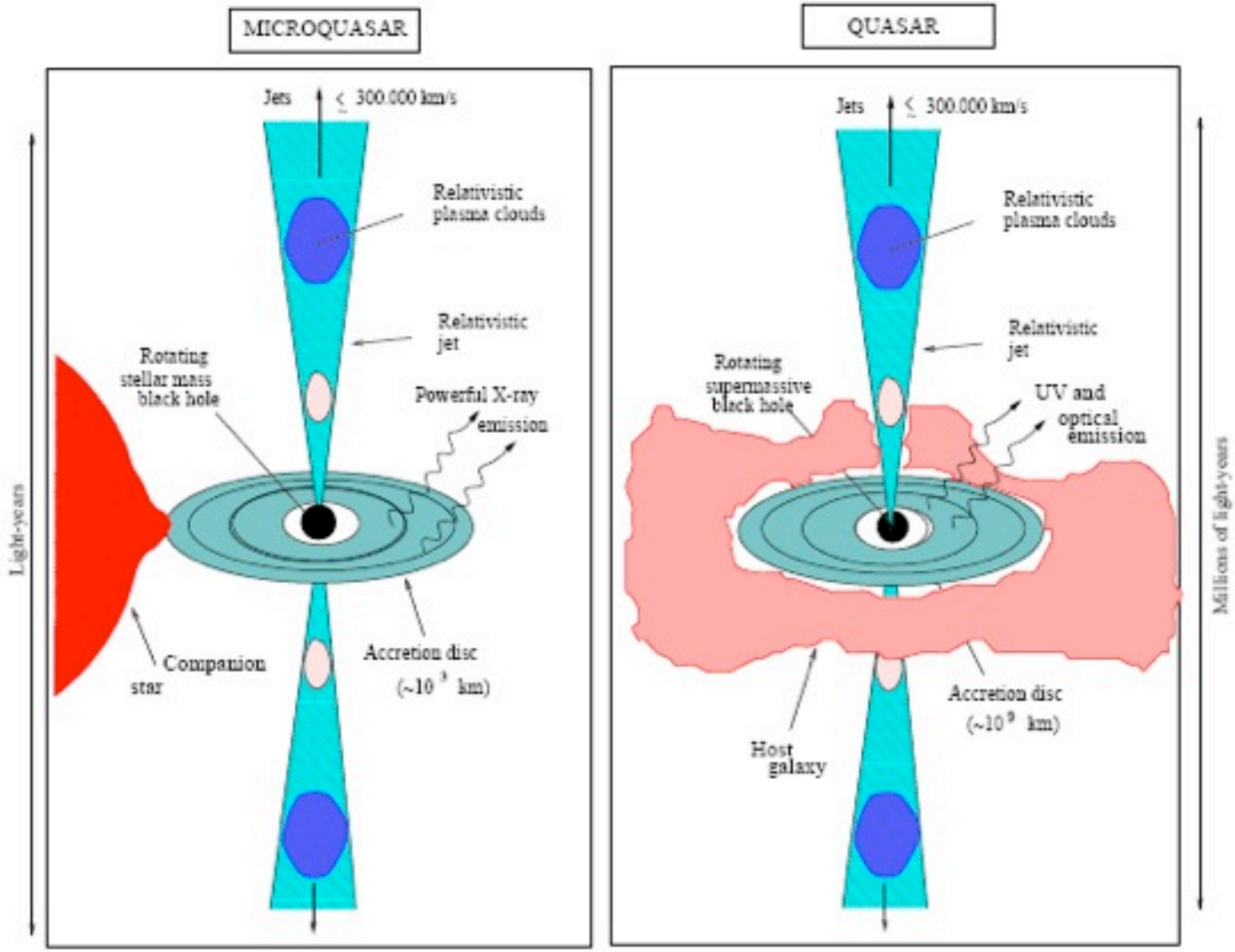


Quasars and microquasars show direct correlation between kinetic power and γ-ray luminosity over 10 orders of magnitude! Nemmen et al. 2012



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

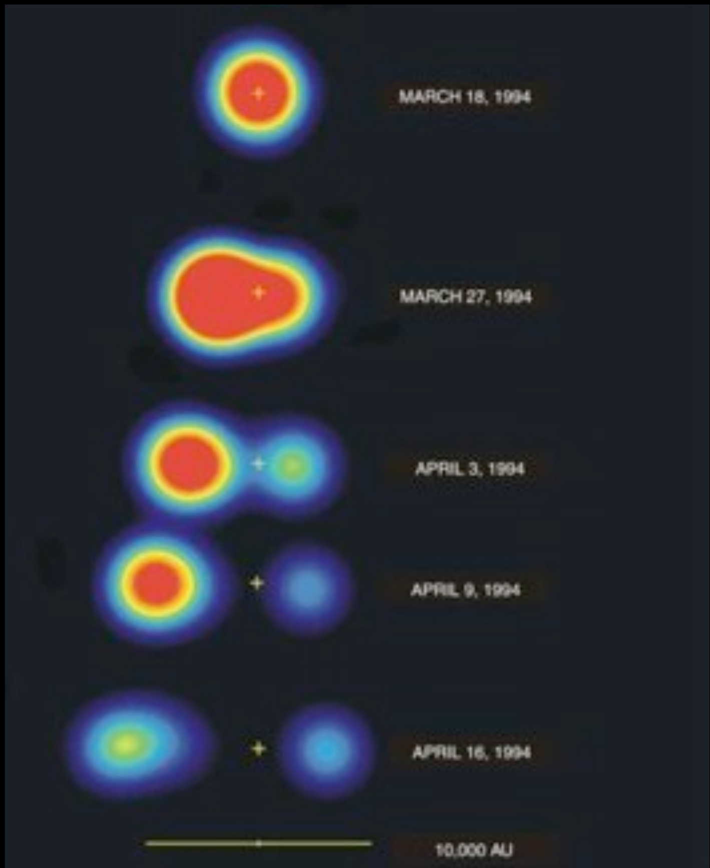
$$\tau \approx R_S/c \sim M$$

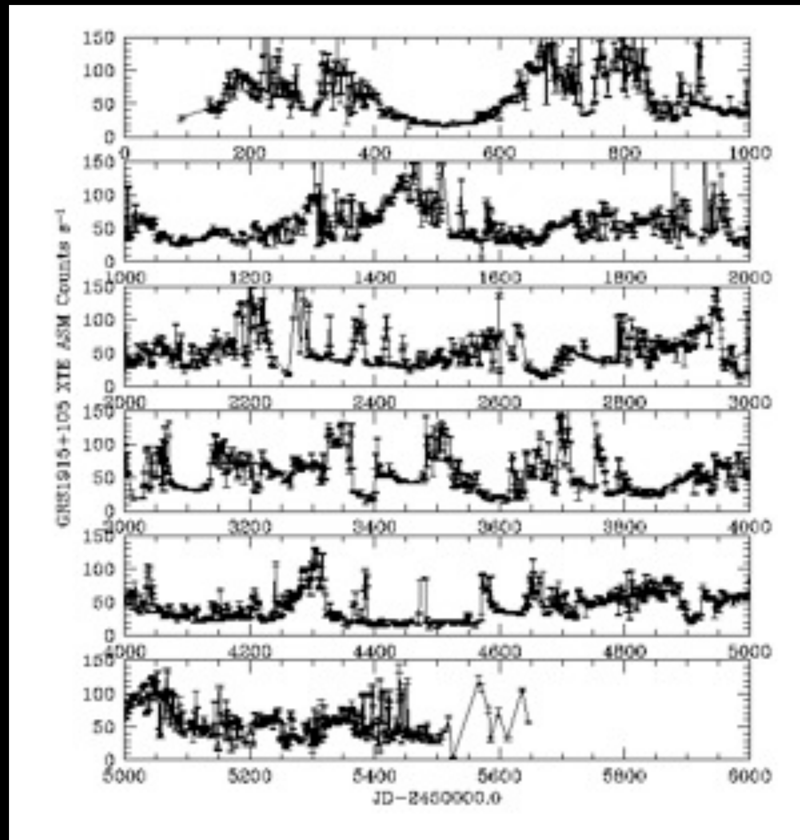


Minutes

Years

Mirabel et al 1994
Nature front page

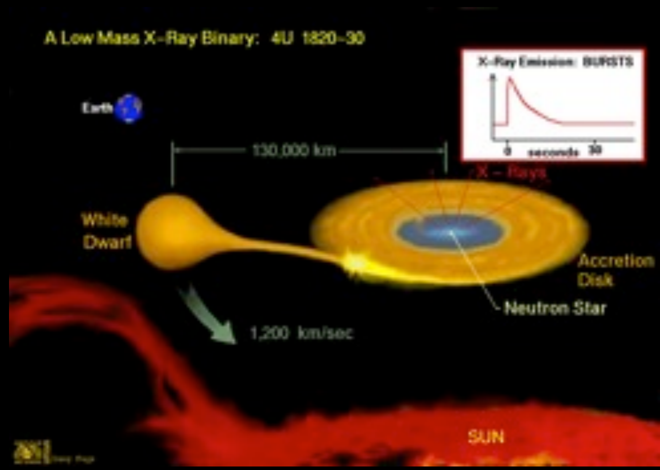




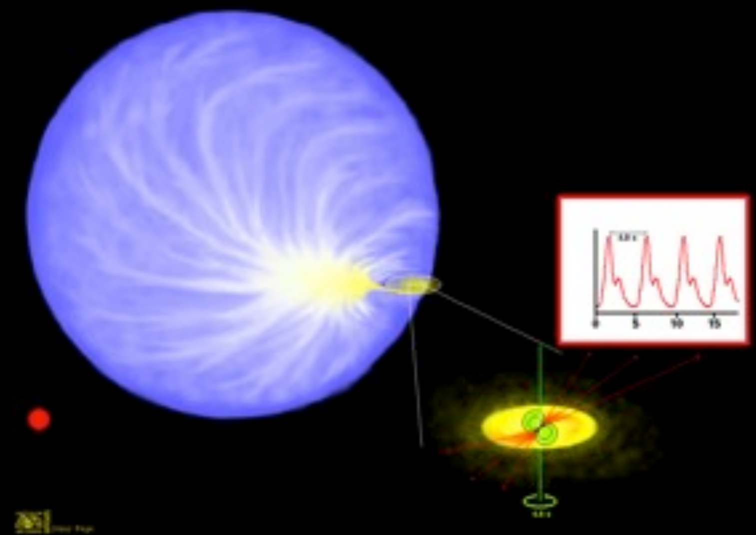
GRS1915+105:
First XRB system observed to show prominent relativistic jets

Why Study X-ray Binaries?

- Efficient matter to energy converters
- Study matter at extreme conditions
- Contain endpoints of stellar evolution
- Most nearby, easily studied example of accretion processes and disk/jet interaction



HEASARC

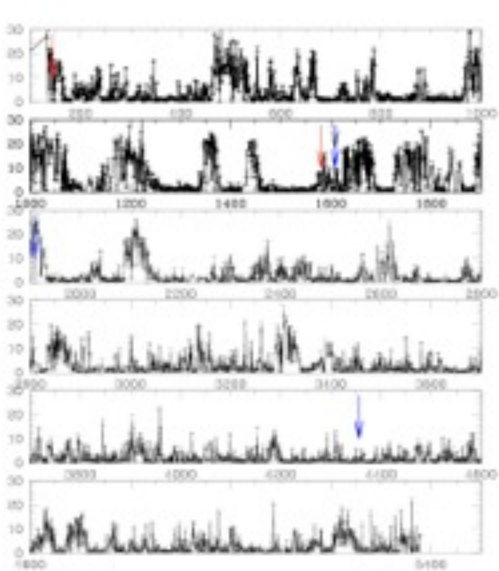


RXTE/ASM: 15 year light curves

Neutron star systems

Cen X-3

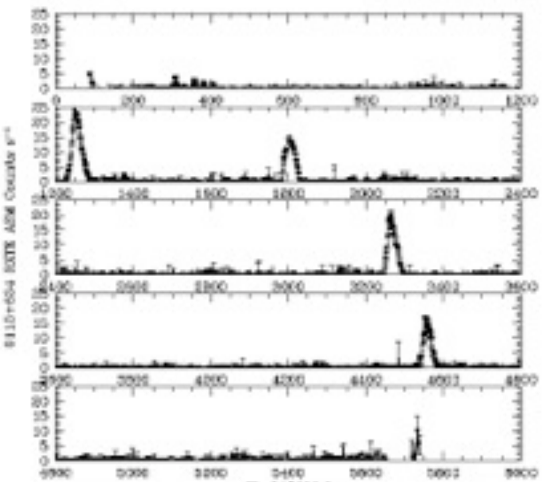
Intensity



Time (days)

0115+634

Intensity

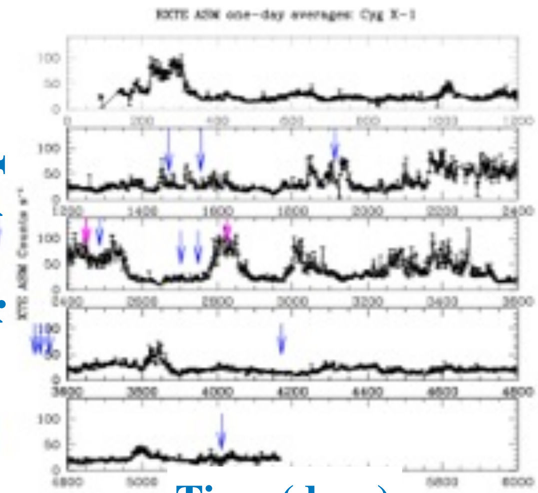


Time (days)

Black hole systems

Cyg X-1

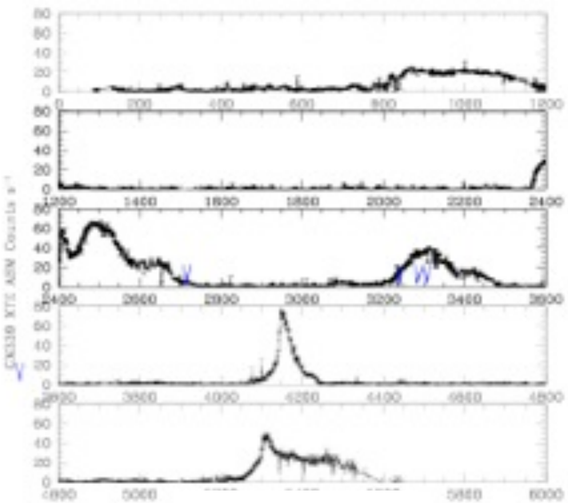
Intensity



Time (days)

GX339+4

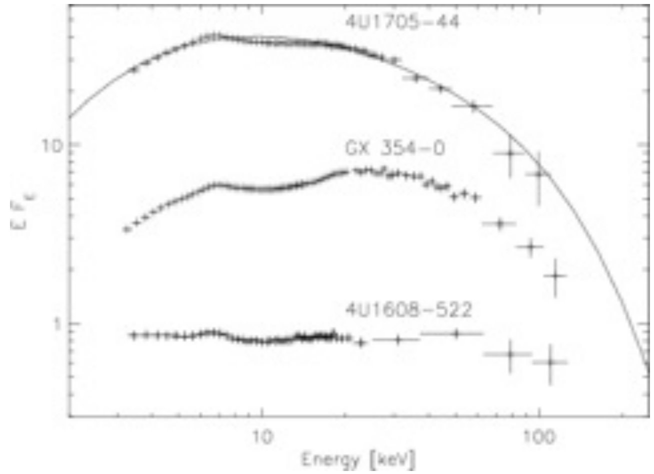
Intensity



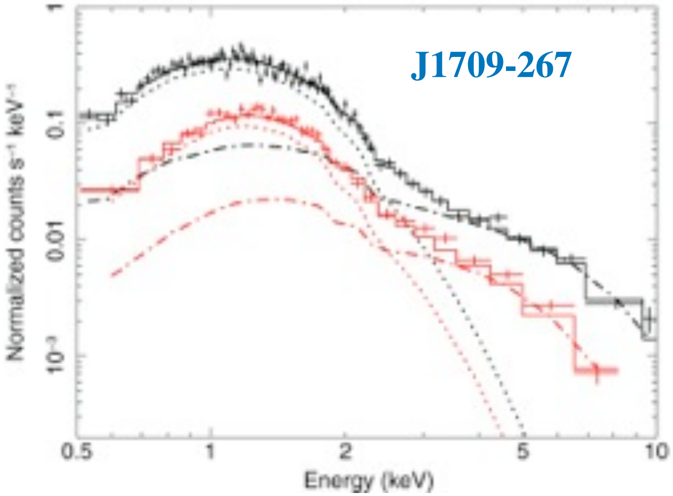
Time (days)

Spectra of X-ray binaries

Neutron star systems

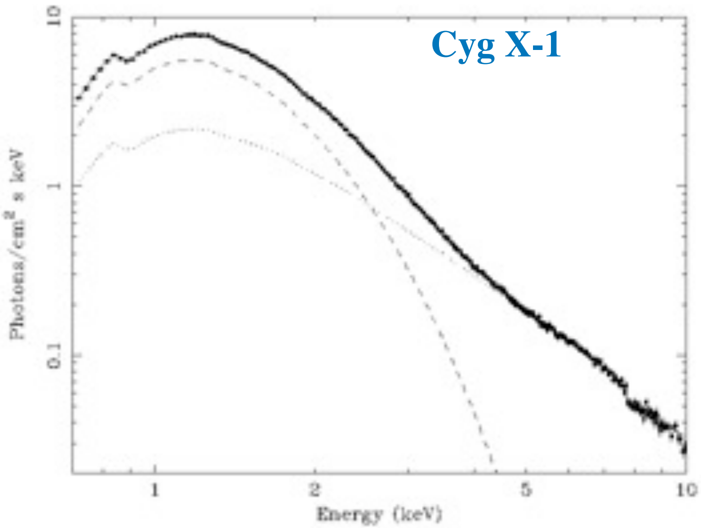


Deufel, Dullemond & Spruit 2001

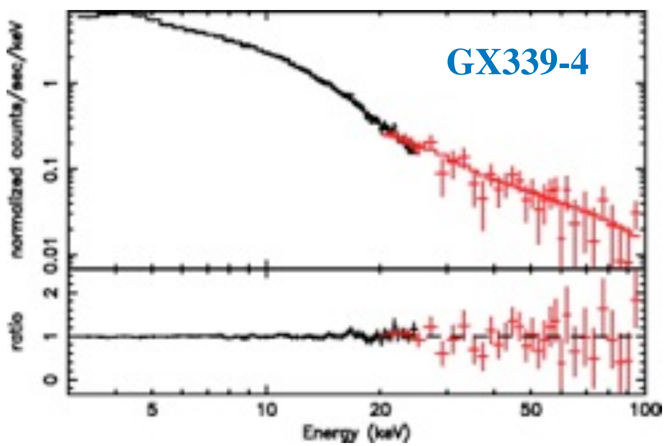


Dejenaar, Wijnands, & Miller 2013

Black hole systems

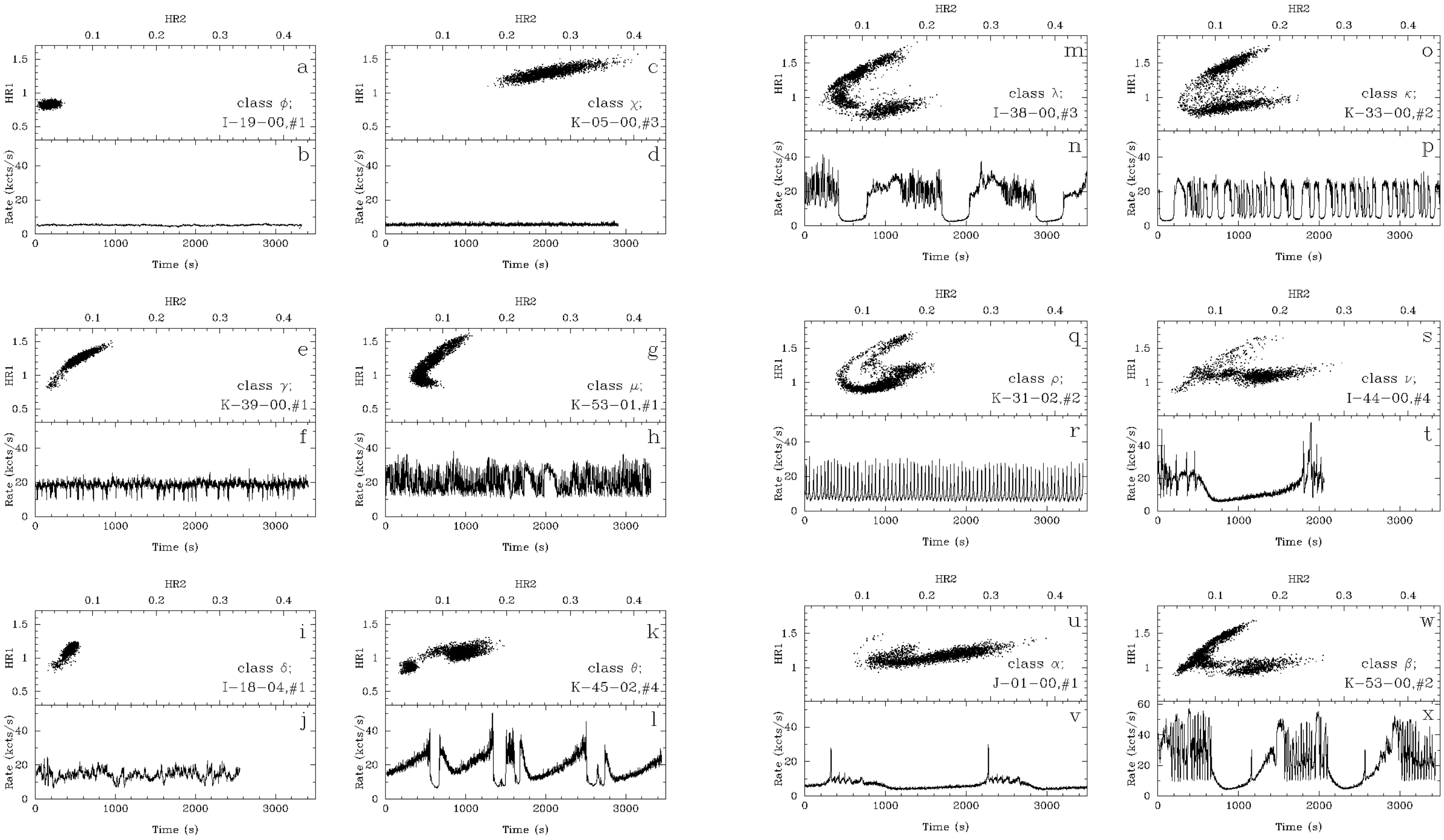


Dotani et al 1997



Miller, Homan, & Miniutti 2006 9

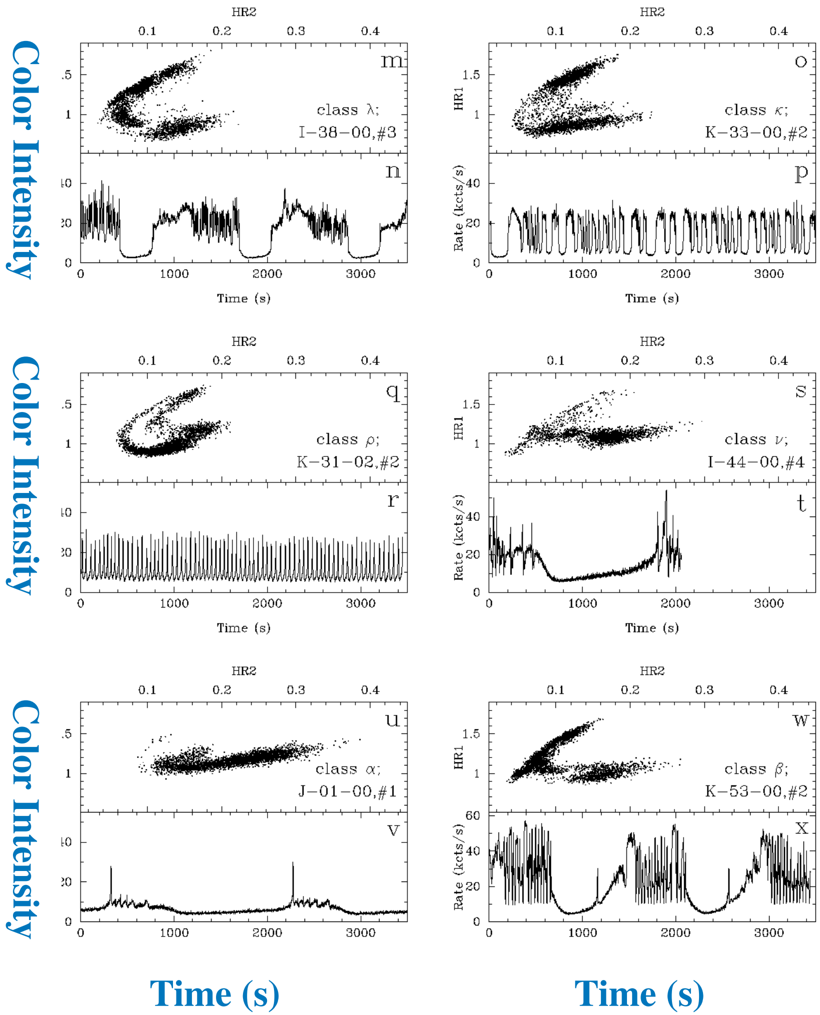
RXTE PCA lightcurves and color-color diagrams of GRS1915+105

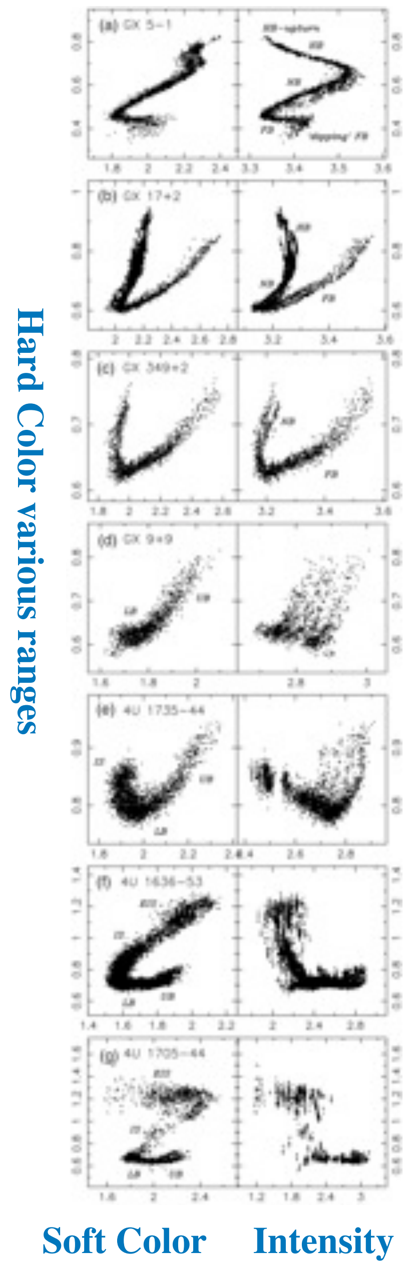


1s bins; 1 hour intervals; HR1= (5-13keV)/(2-5keV); HR2=(13-60keV)/(2-5keV)

Belloni et al 2000

Black hole system GRS 1915+105
Belloni et al 2000





Neutron star “Z” and “Atoll” systems Homan et al 2010

Putting X-ray binaries in their proper place.

Introduction:

X-ray binaries

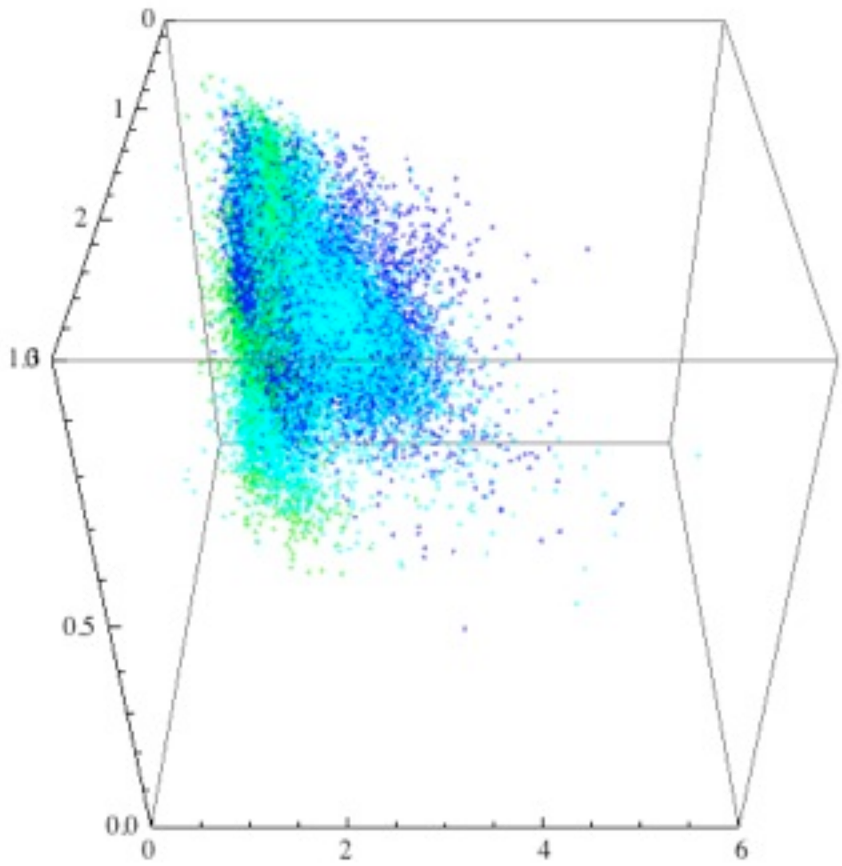
➔**Data set**

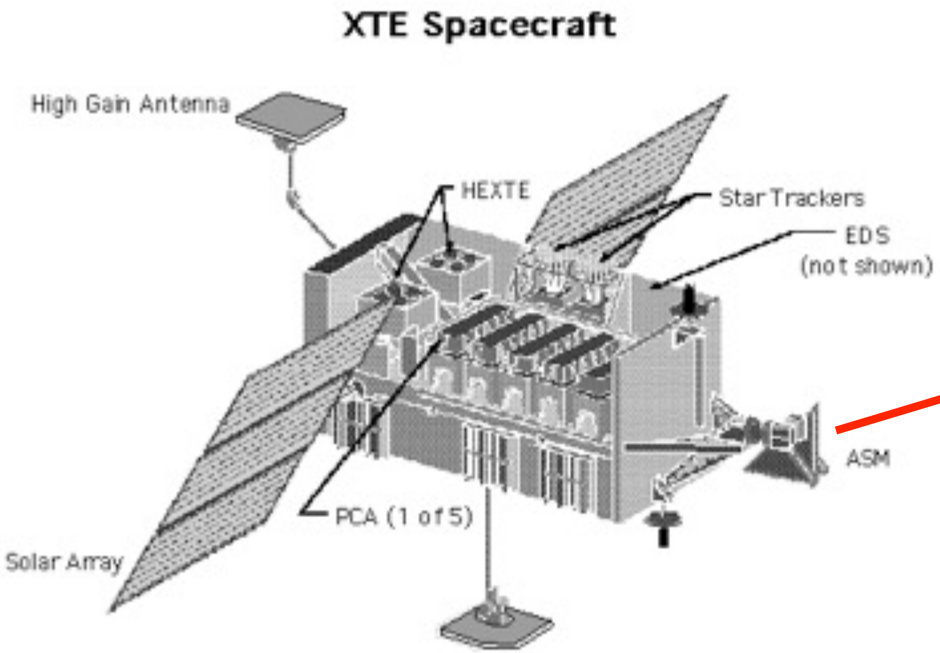
CCI description

Physical interpretations

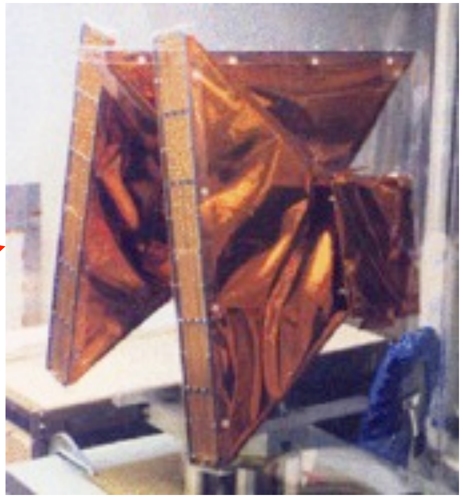
Statistical solutions (Luke)

Future work





Levine et al 1996



RXTE ASM

3 scanning shadow cameras each with a collecting area of 30 cm²

Covers 80% of sky every 90 minutes

Sensitivity: 30 mCrab

3 energy bands covering 1.3-12 keV

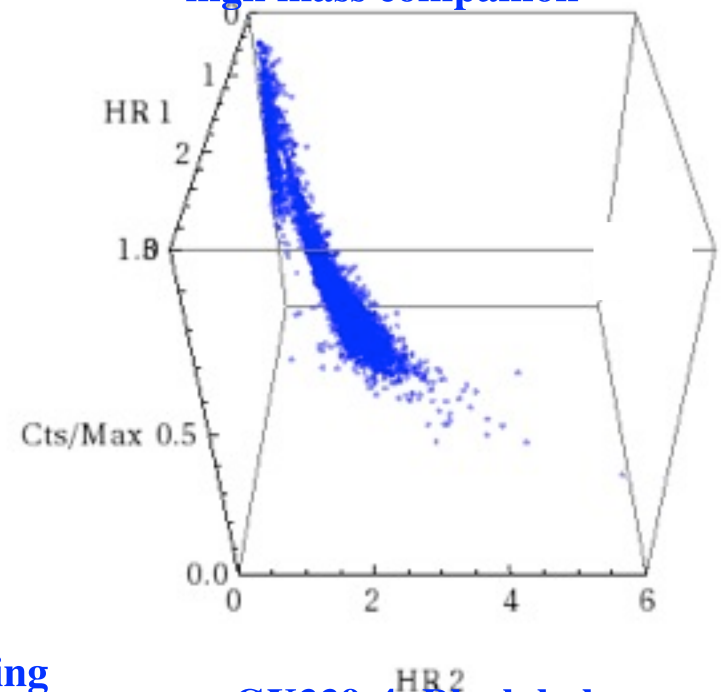
Over 15 years of data available on about 500 sources.

CCI Diagrams

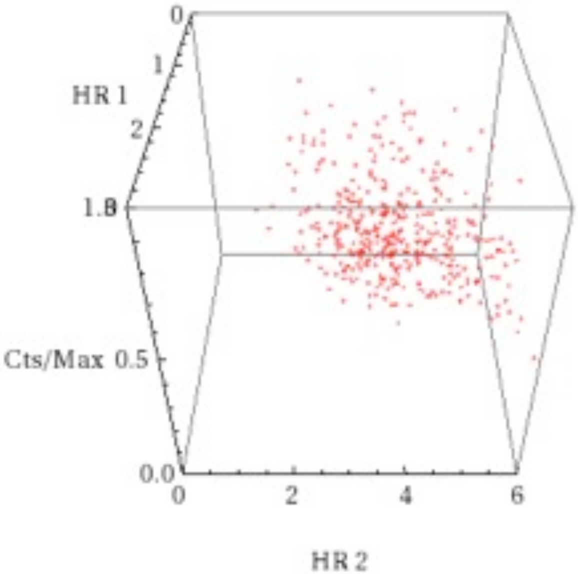
Soft Color HR1 = (3-5keV)/(1.3-3keV)
Hard Color HR2 = (5-12keV)(1.3-3keV)
Intensity = 1.3-12keV counts
(scaled from 0-1)

RXTE/ASM data: One day averages over 13 y

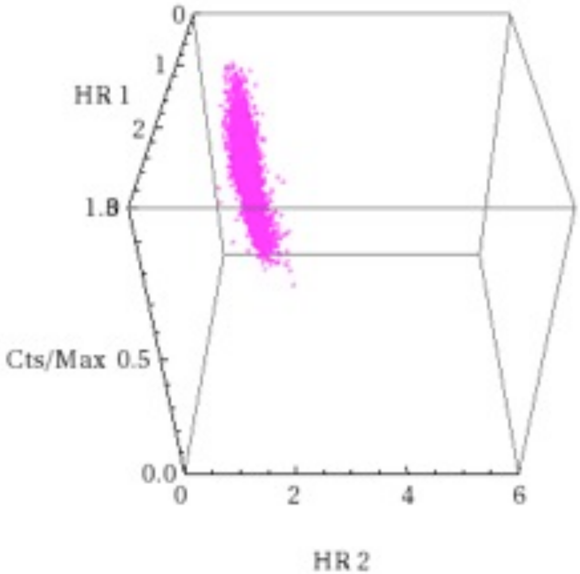
Cyg X-1; black hole; high mass companion



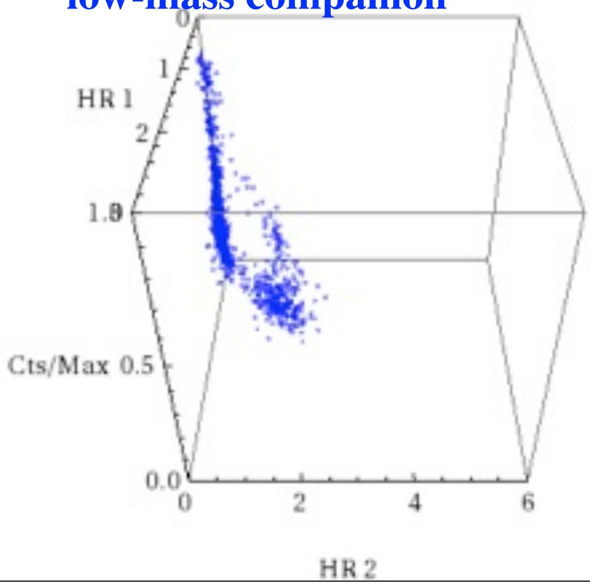
Vela X-1; pulsing Neutron Star



Cyg X-2; non-pulsing Neutron Star "Z" type



GX339-4; Black hole, low-mass companion



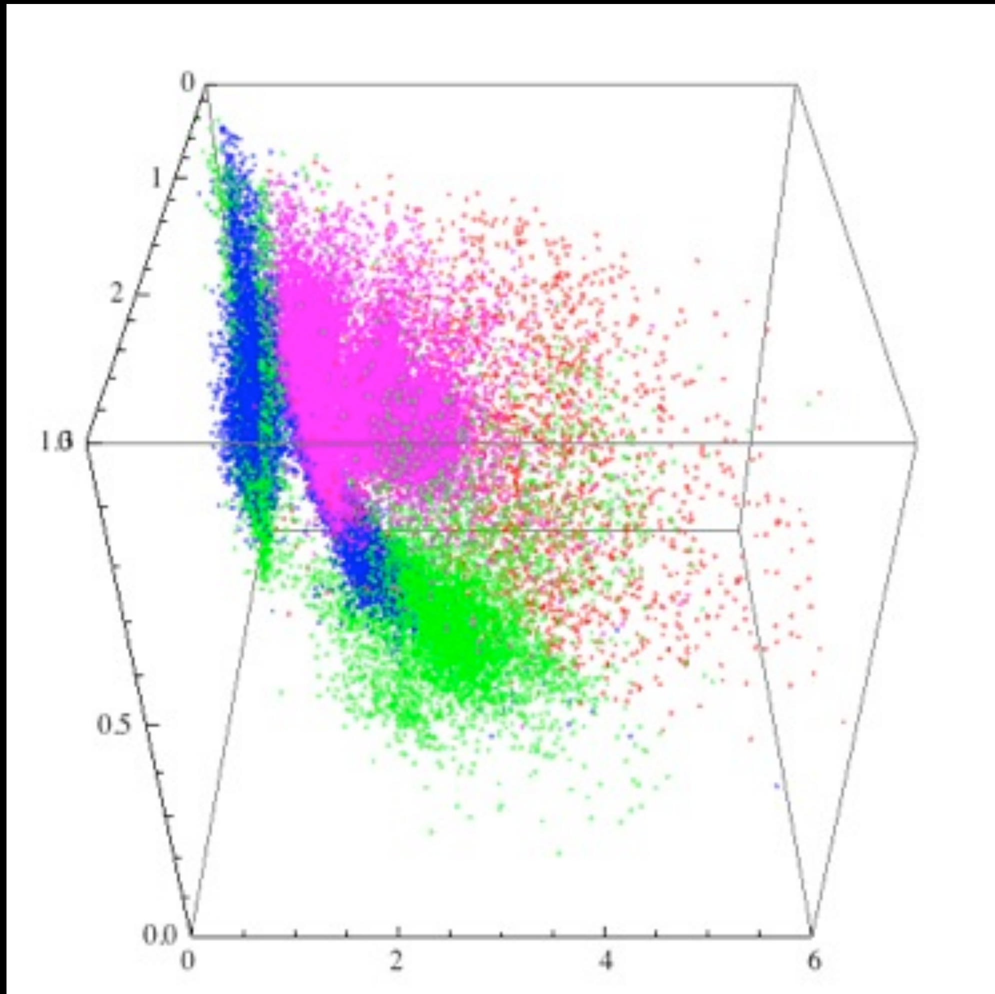
Color-Color-Intensity Diagrams

C HR1 = (3-5keV)/(1.3-3keV)

C I HR2 = (5-12keV)(1.3-3keV)

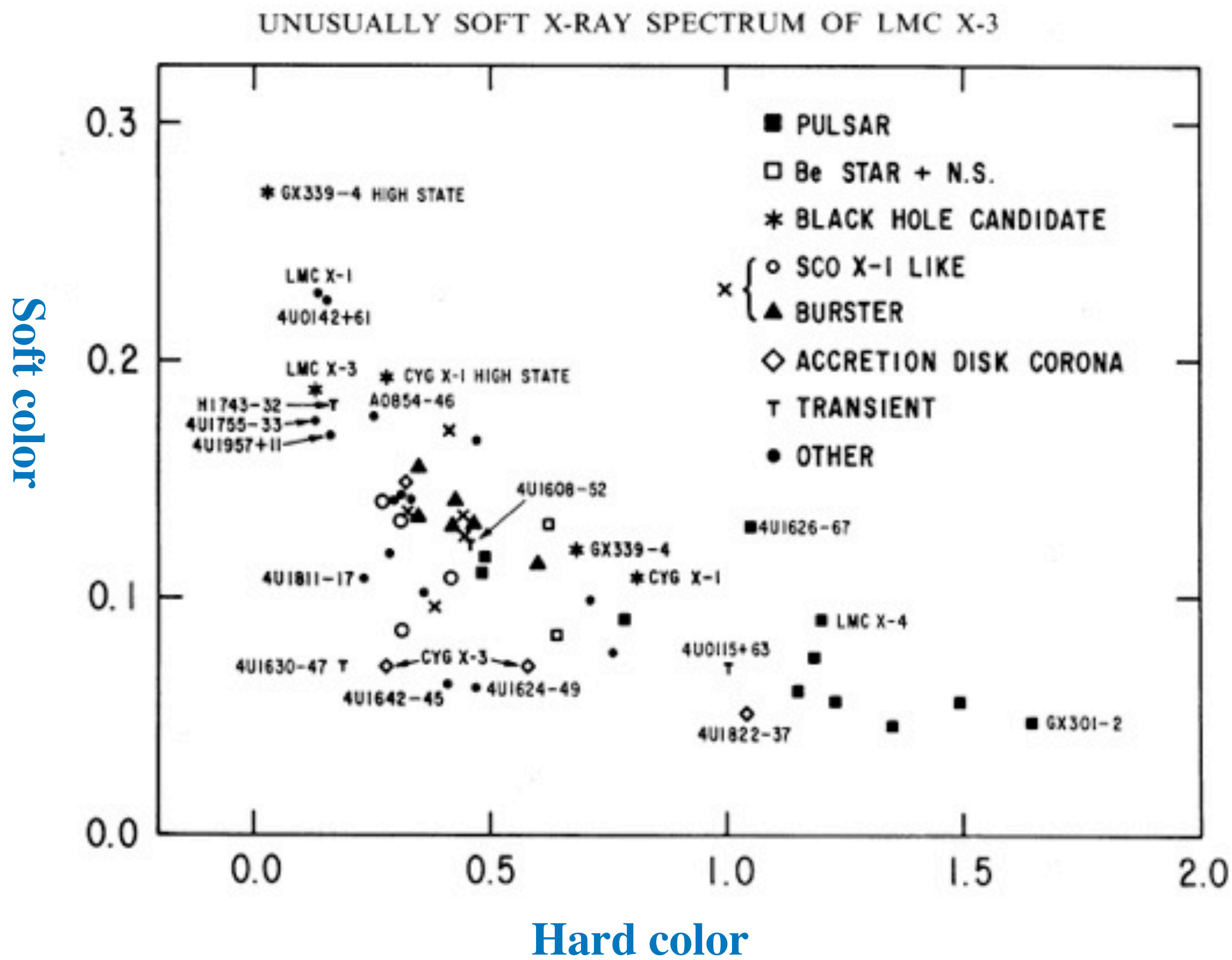
I Intensity = 1.3-12keV counts
(Intensity normalized to top 1%)
(Only ≥ 5σ points plotted)

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



White & Marshall 1984

Color-Color-Intensity Diagrams

C HR1 = (3-5keV)/(1.3-3keV)

C I HR2 = (5-12keV)(1.3-3keV)

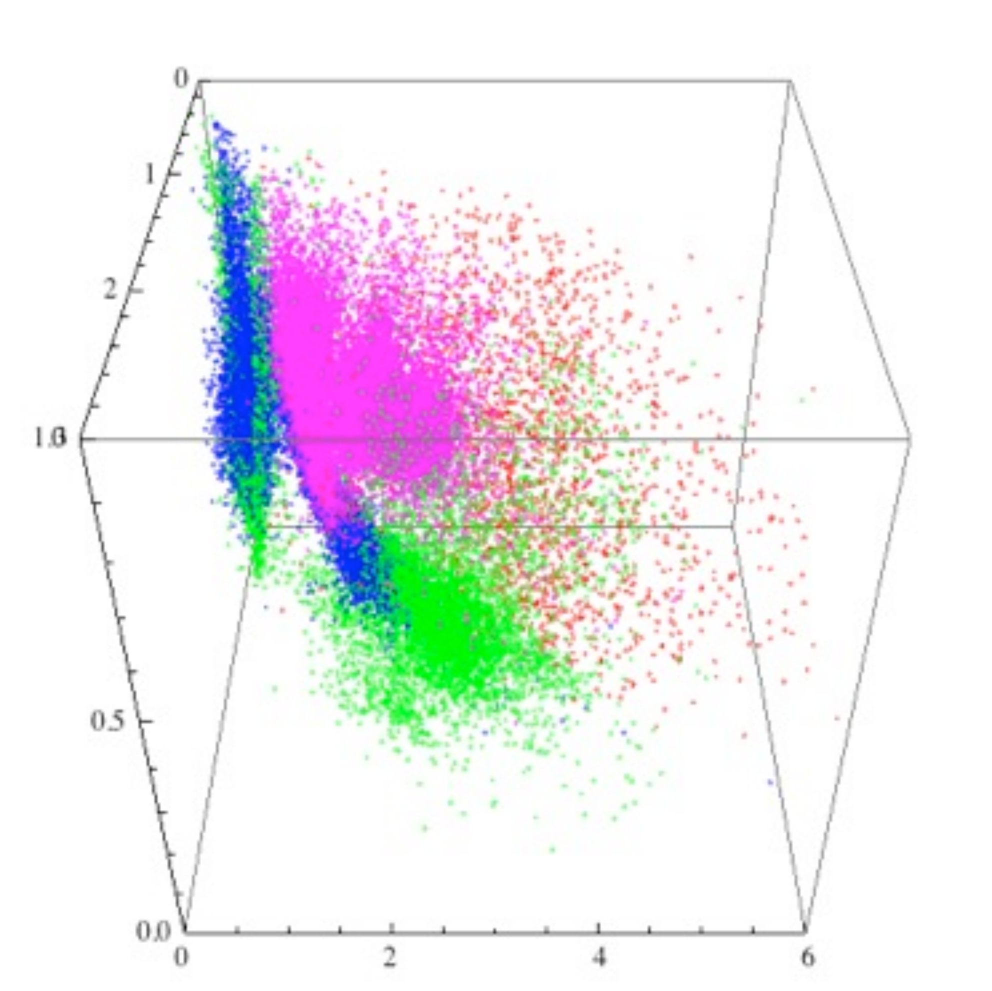
I Intensity = 1.3-12keV counts

(Intensity normalized to top 1%)

(Only ≥ 5σ points plotted)

RXTE/ASM data:

One day averages over 13 years



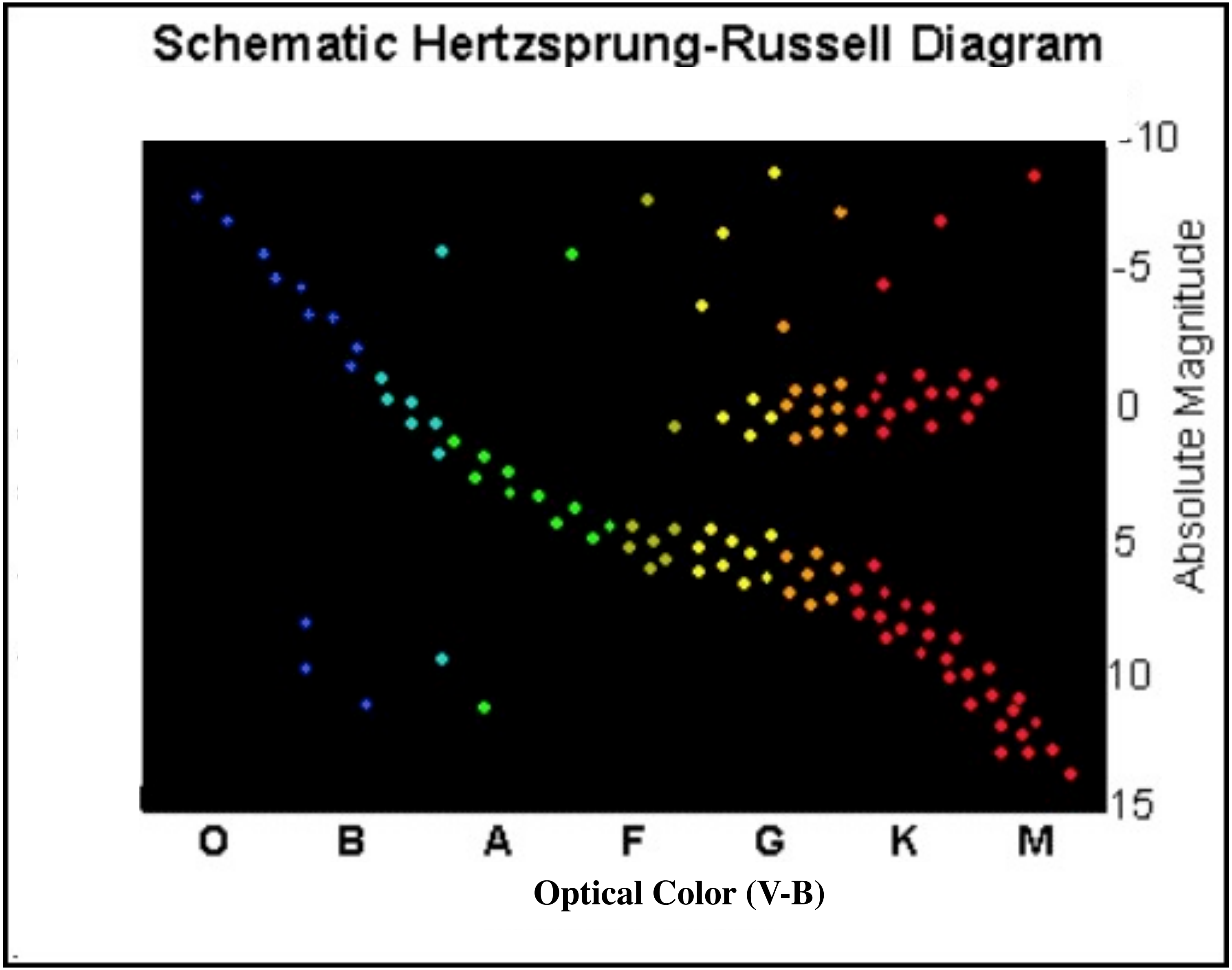
Black holes high mass

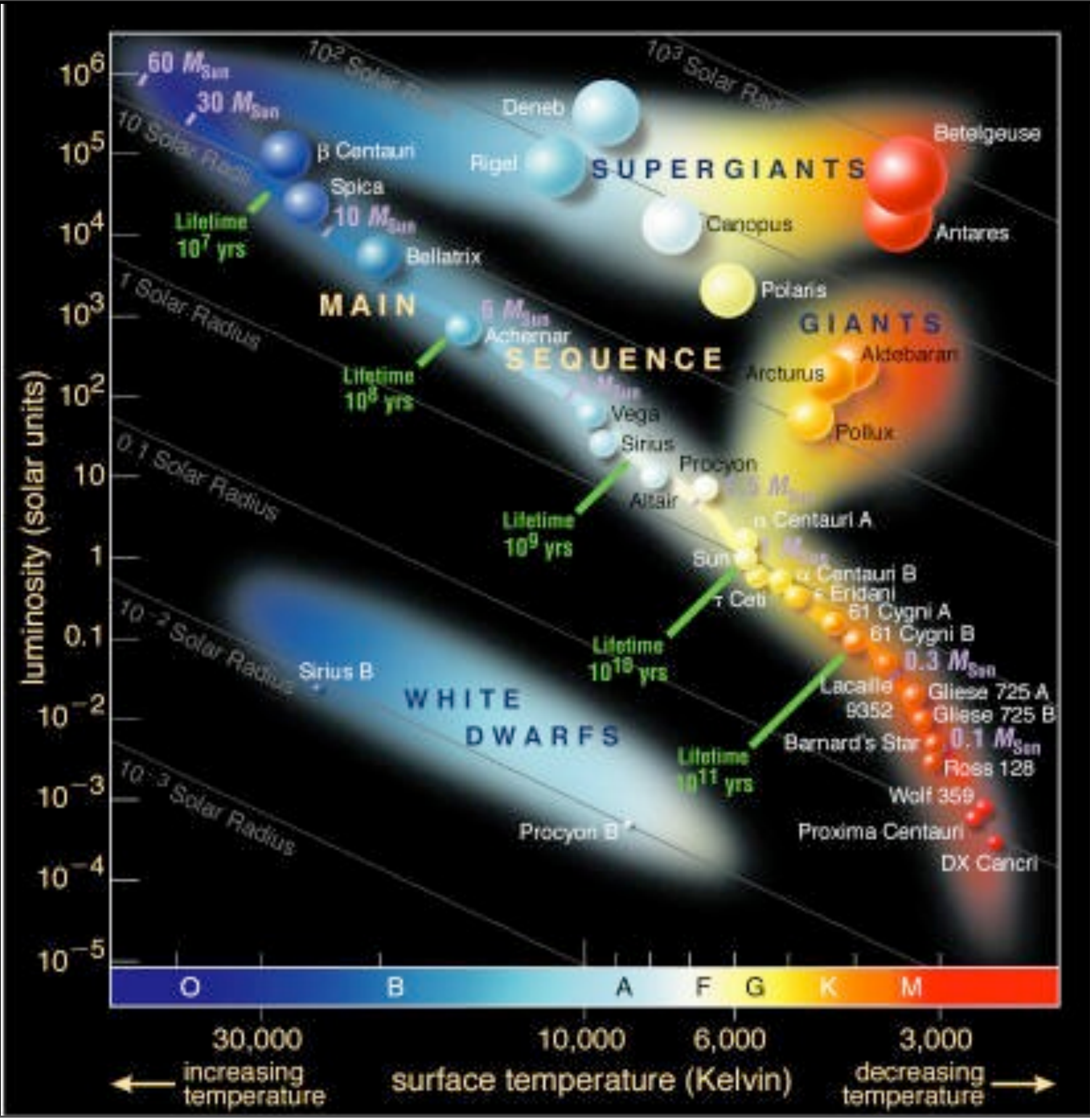
Black holes low mass

Pulsing neutron stars

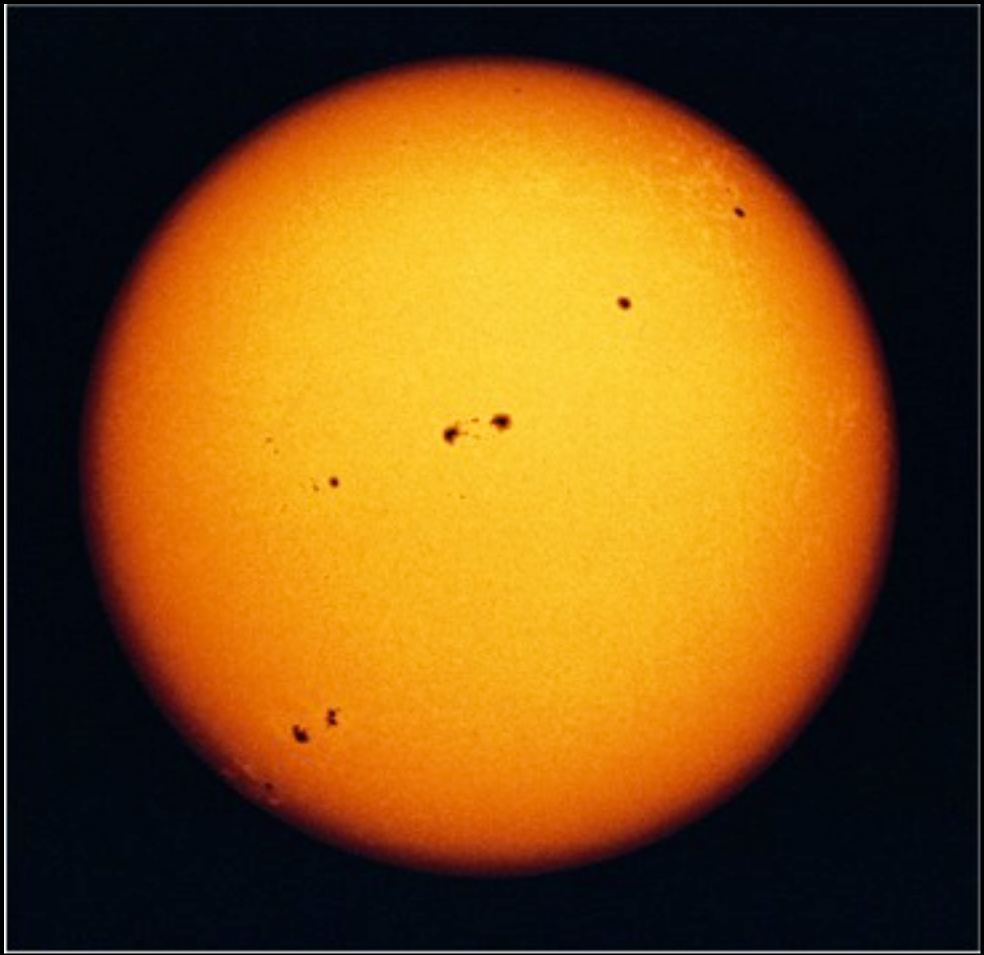
Non-pulsing neutron stars

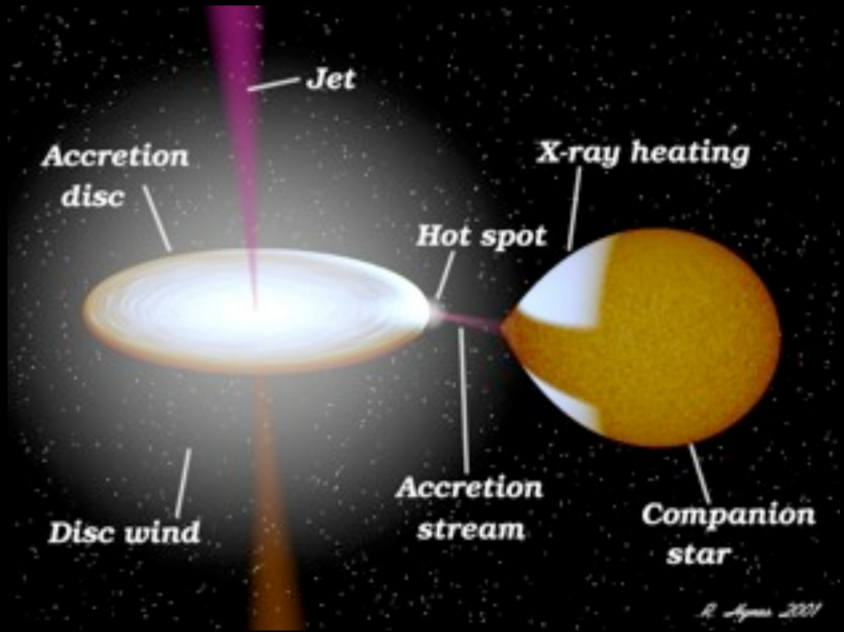
Vrtilek & Boroson 2013


Schematic Hertzsprung-Russell Diagram
-10
-5
0
5
10
15
Absolute Magnitude
O
B
A
F
G
K
M
Optical Color (V-B)



60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
3 M_{Sun}
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
Deneb
Rigel
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Procyon
Altair
α Centauri A
Sun
α Centauri B
ε Eridani
τ Ceti
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Betelgeuse
Antares
Canopus
Polaris
Aldebaran
Arcturus
Pollux
Sirius B
Procyon B
SUPERGIANTS
GIANTS
MAIN SEQUENCE
WHITE DWARFS
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O B A F G K M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

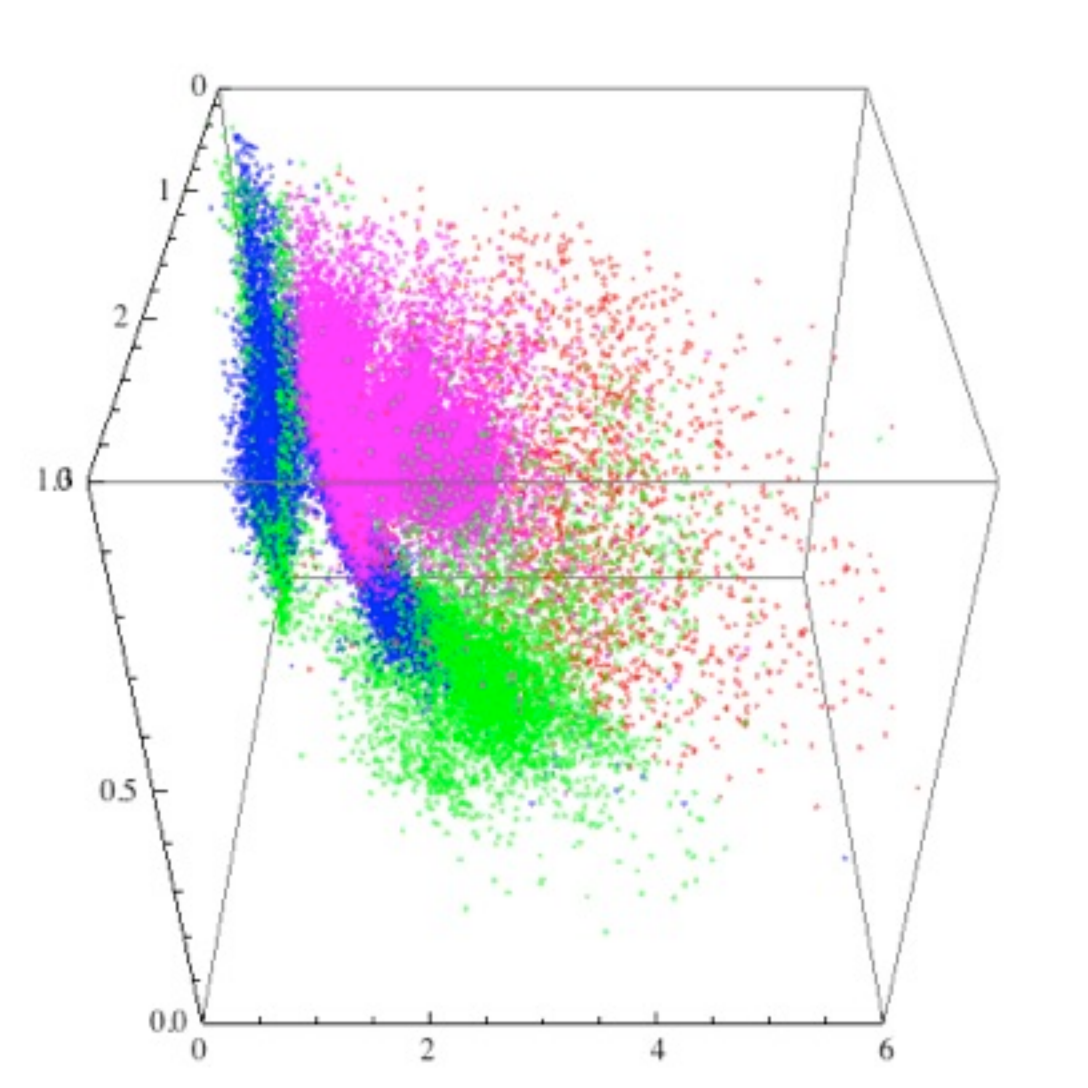




Optical Color + Optical Luminosity

X-ray color + X-ray luminosity

A Hertsprung-Russell diagram for accreting binaries?



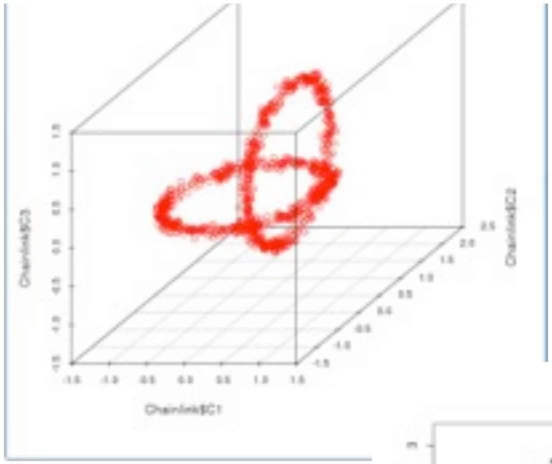
Black holes high mass
Black holes low mass
Pulsing neutron stars
Non-pulsing neutron stars

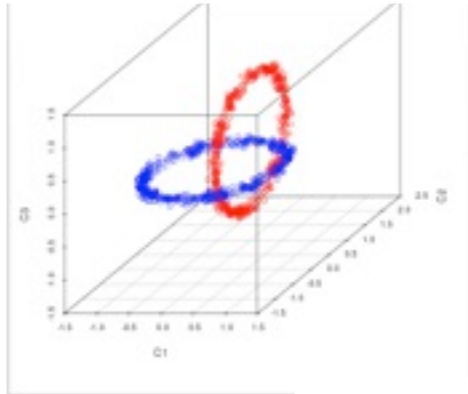
Vrtilek & Boroson 2013

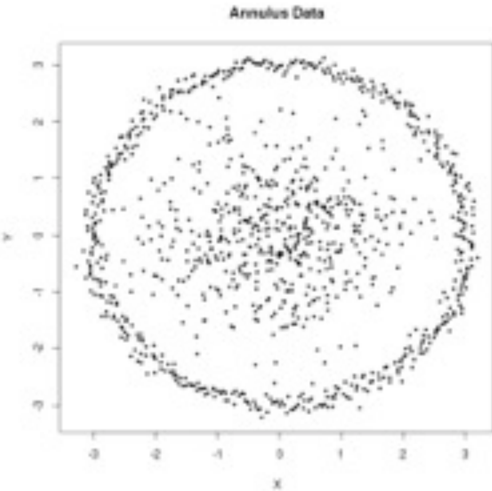
Spectral Connectivity Analysis

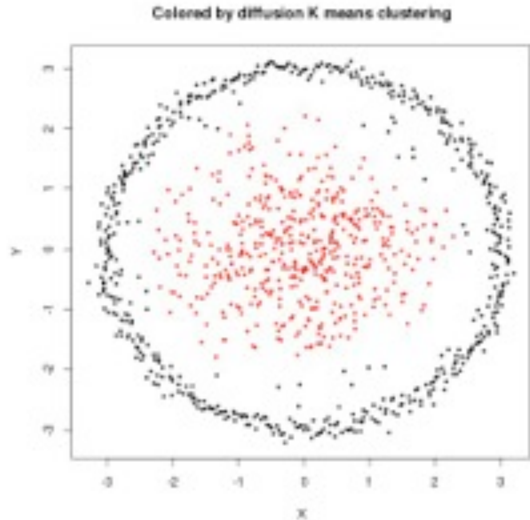
Richards et al (2008; 2009)
Freeman et al (2009)
Lee & Waterman (2010)

Input data **Data clustered by**
diffusionMap









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

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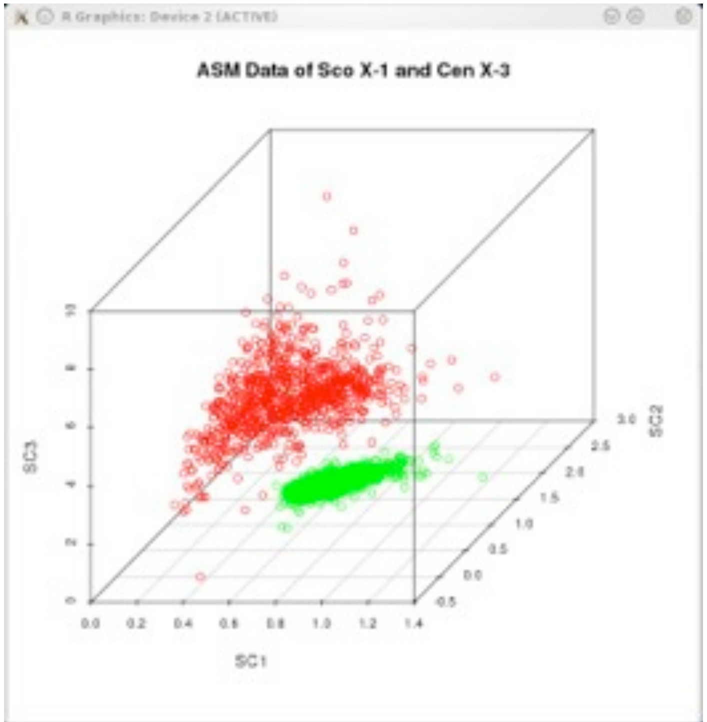
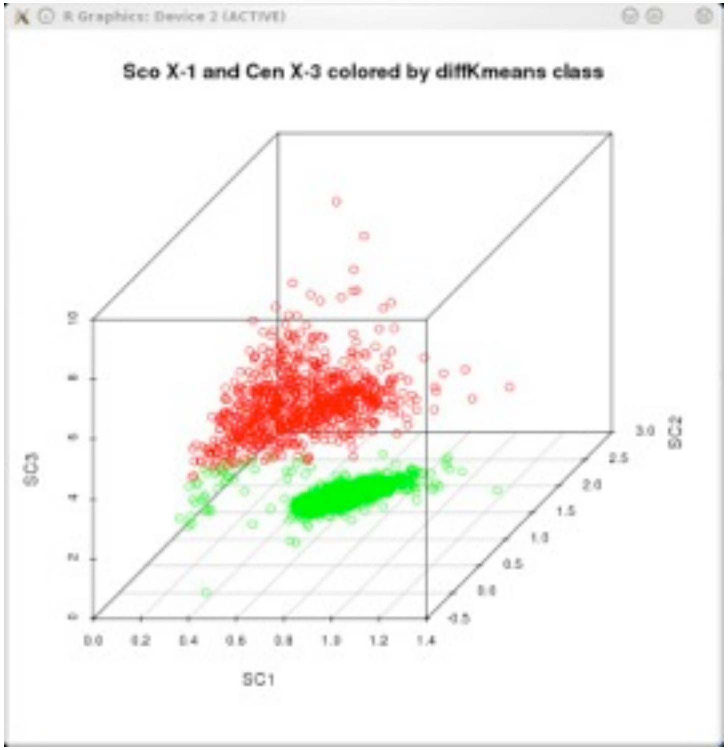
Pulsars vs Z-sources

Input data colored by prior knowledge clusters



Sco X-1, Cen X-3

Data colored by diffusionMap



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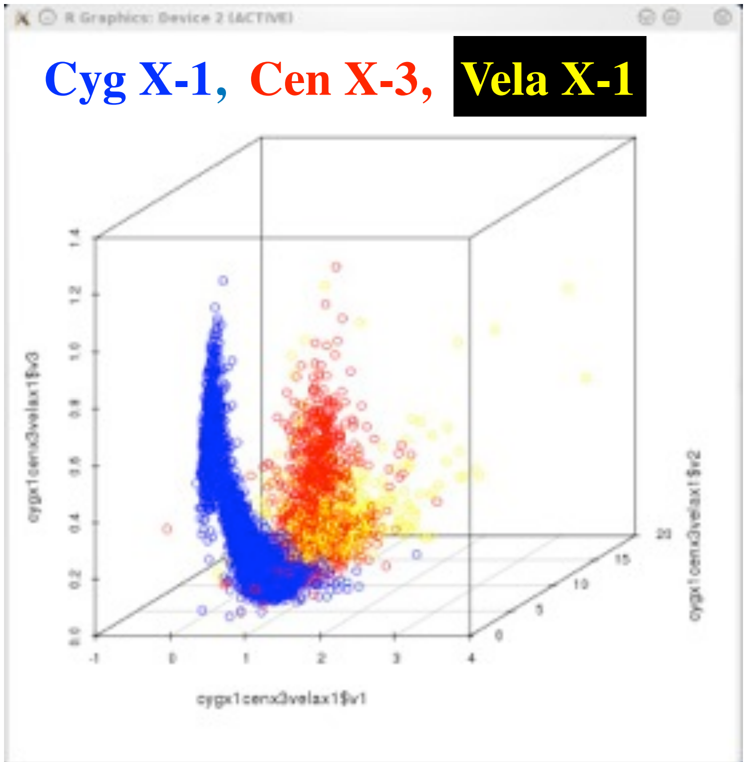
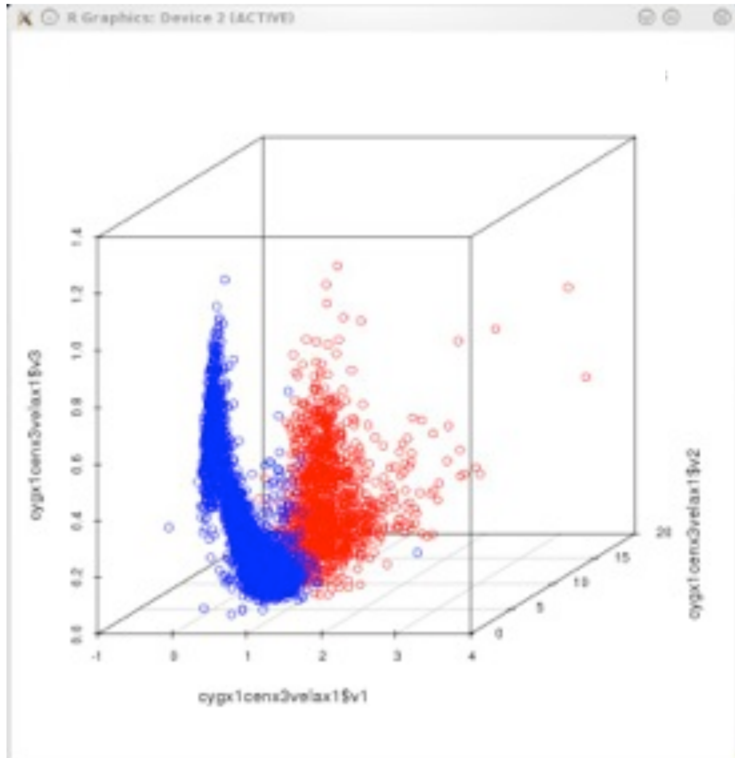
Pulsars vs Black Holes

Input data colored by prior knowledge



Data colored by diffusionMap clusters



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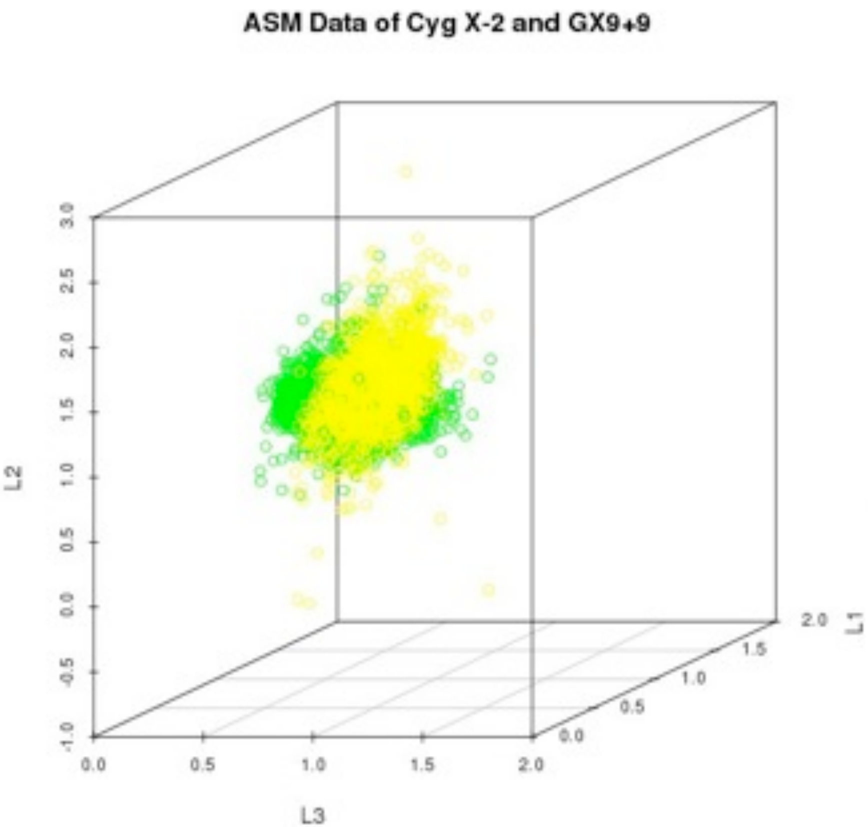
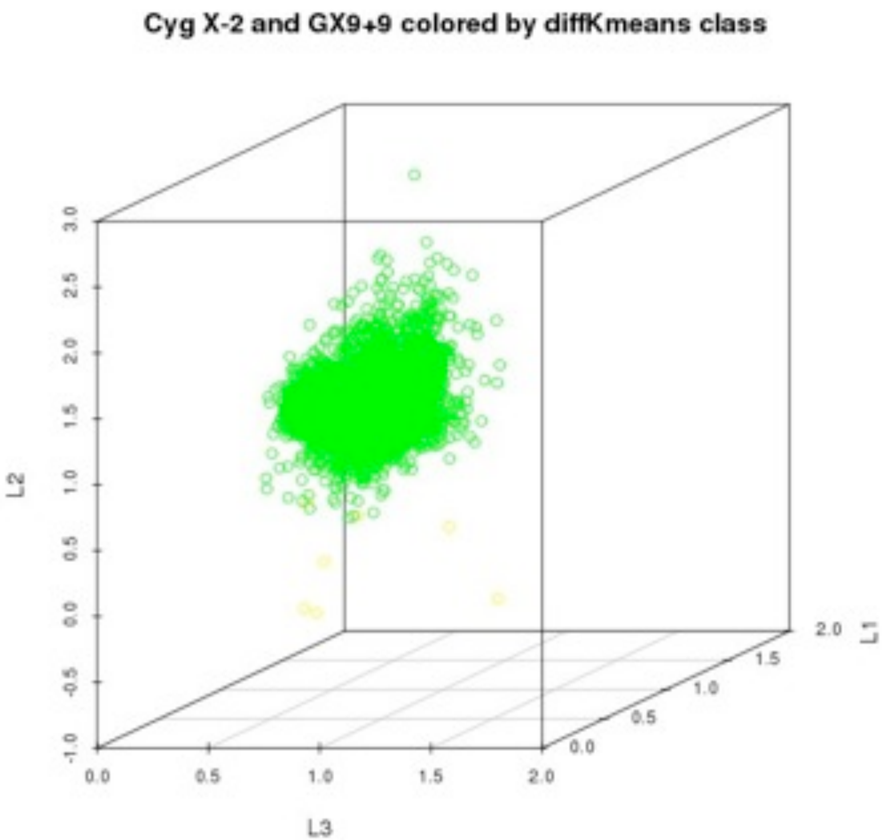
Z sources vs Atoll sources

Input data colored by prior knowledge clusters

Data colored by diffusionMap

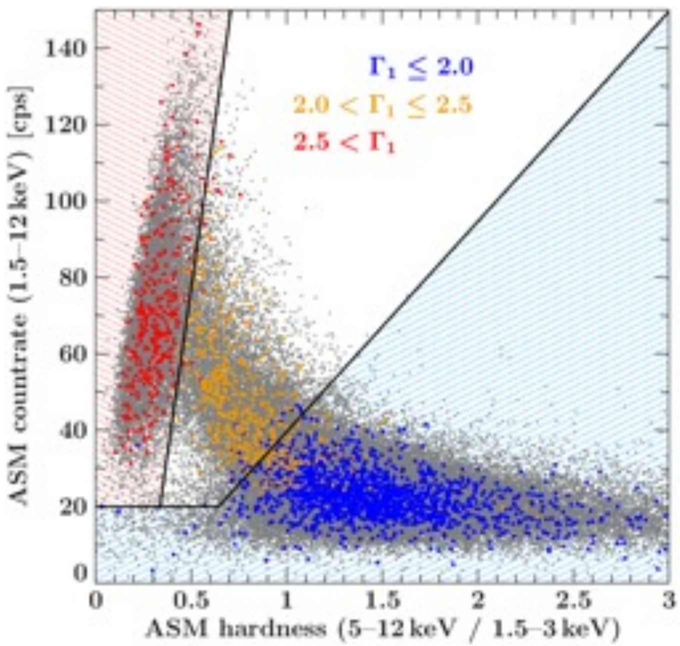




Cyg X-2, GX9+9

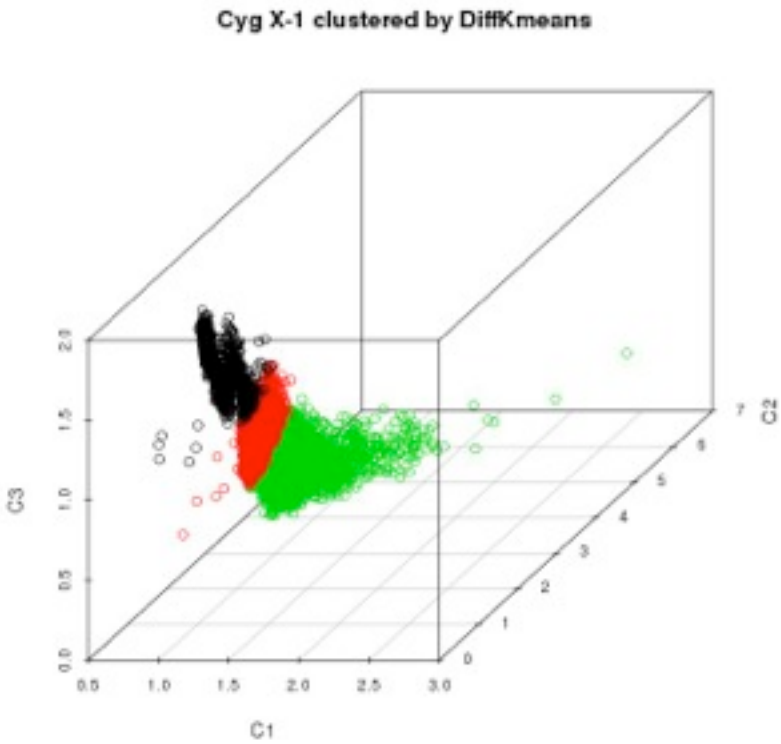
Different states of a single source: Cygnus X-1

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



Grinberg et al. 2013

PCA data of Cyg X-1 clustered by diffusionMap



Buchan et al 2013

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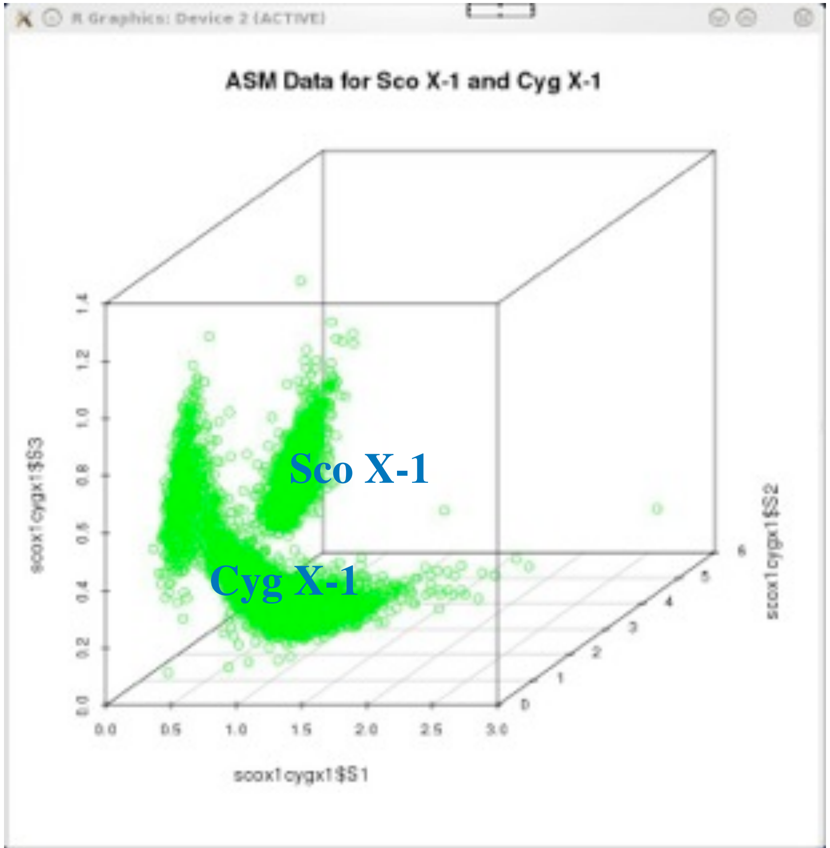
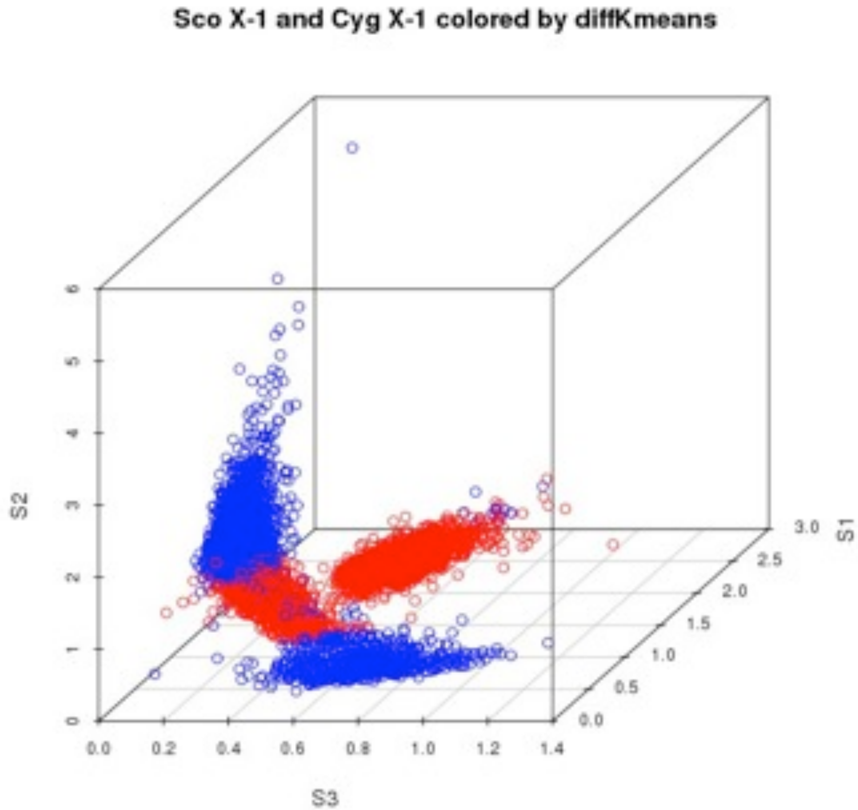
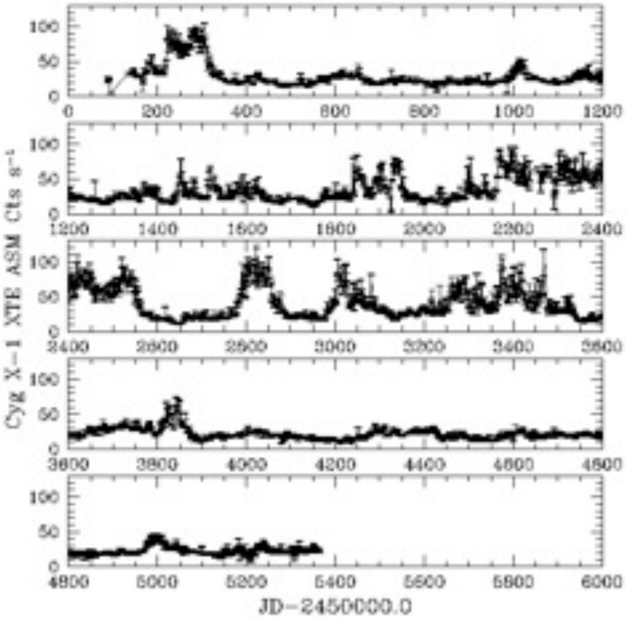
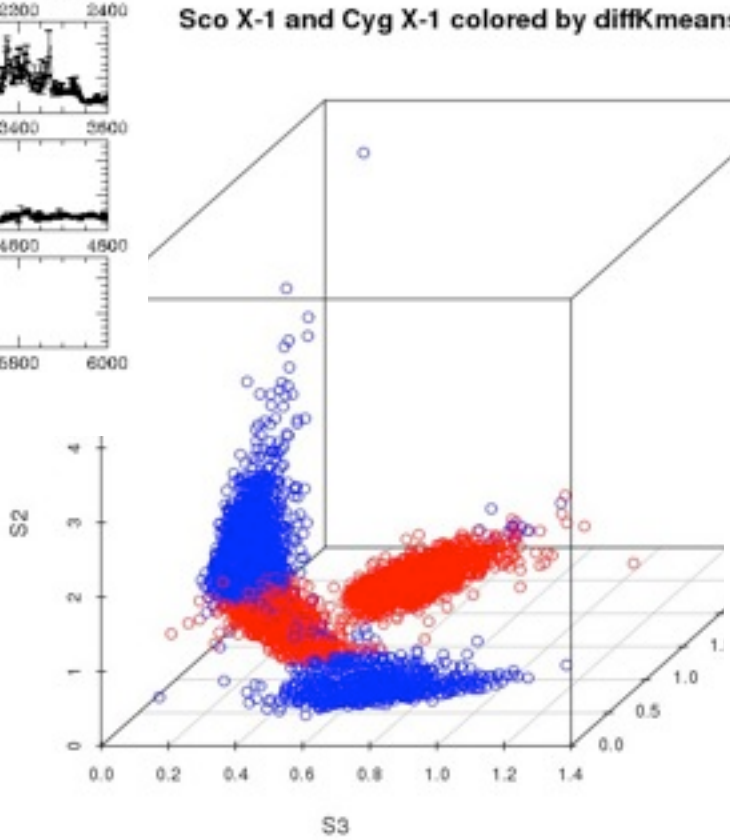
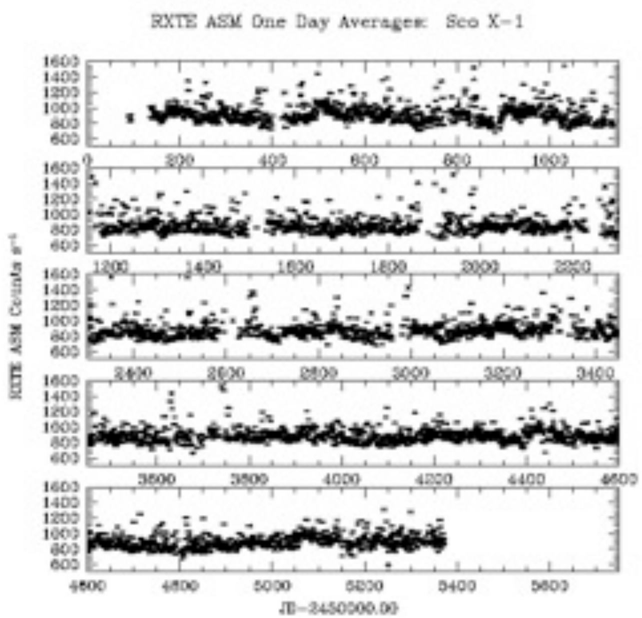
Separating Black holes and Z sources?



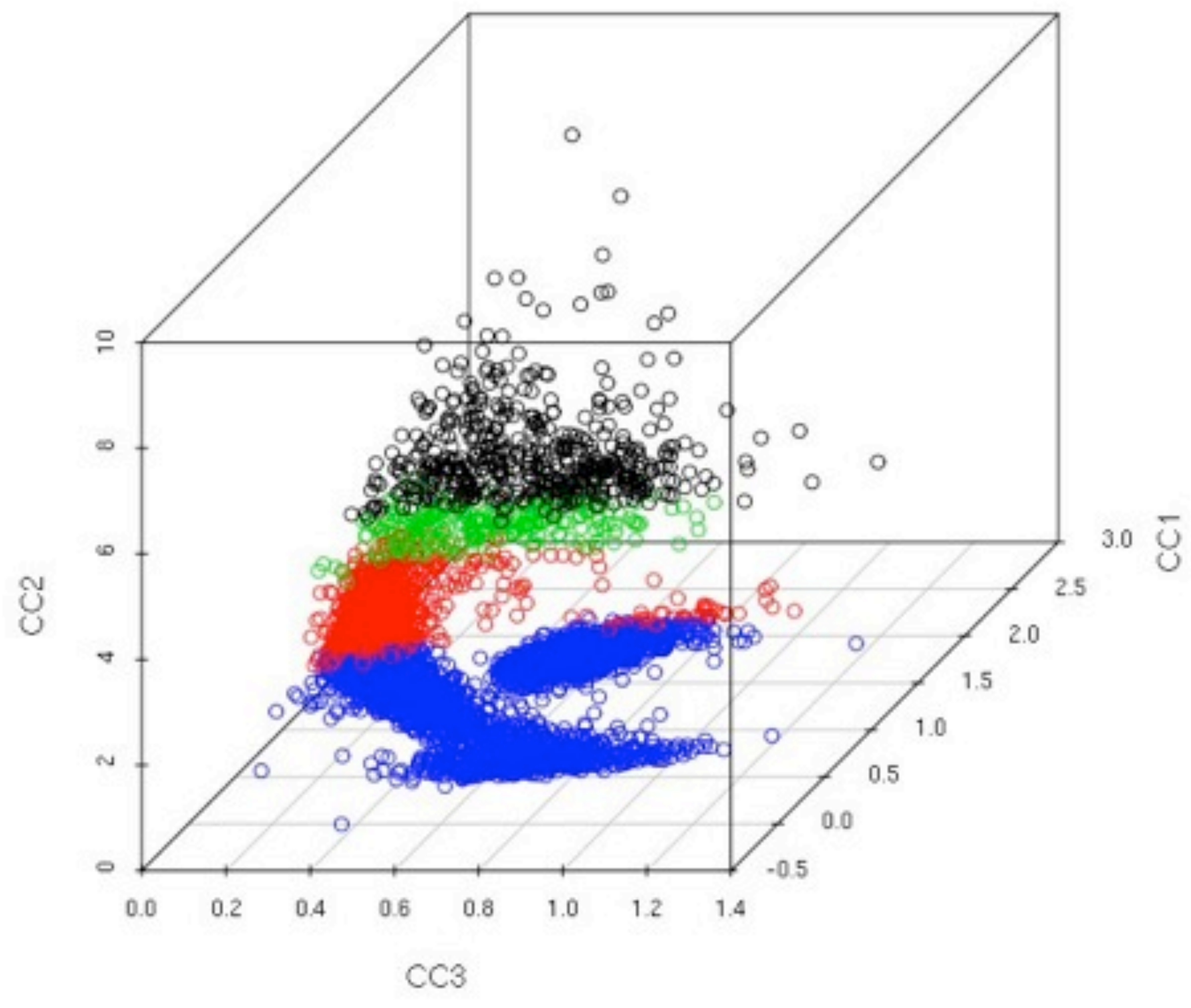








Is Sco X-1 equivalent to the intermediate state of Cyg X-1?



Different approach: see Luke's presentation!

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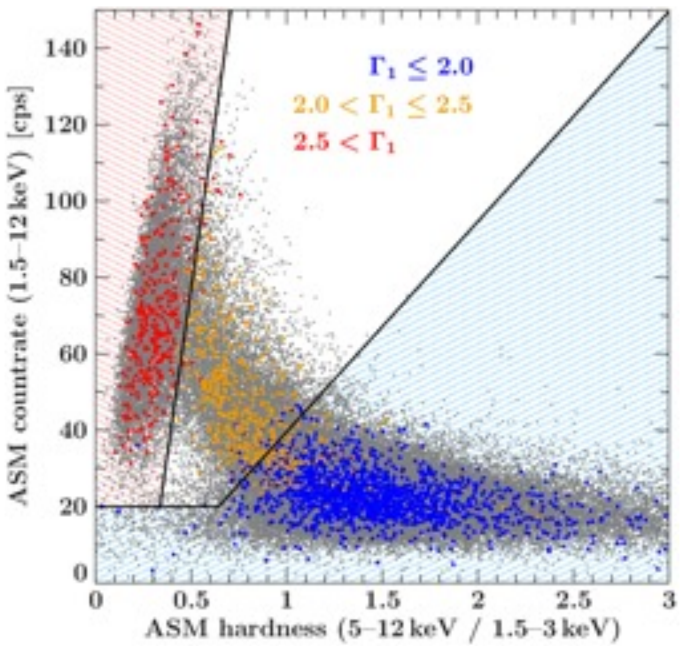
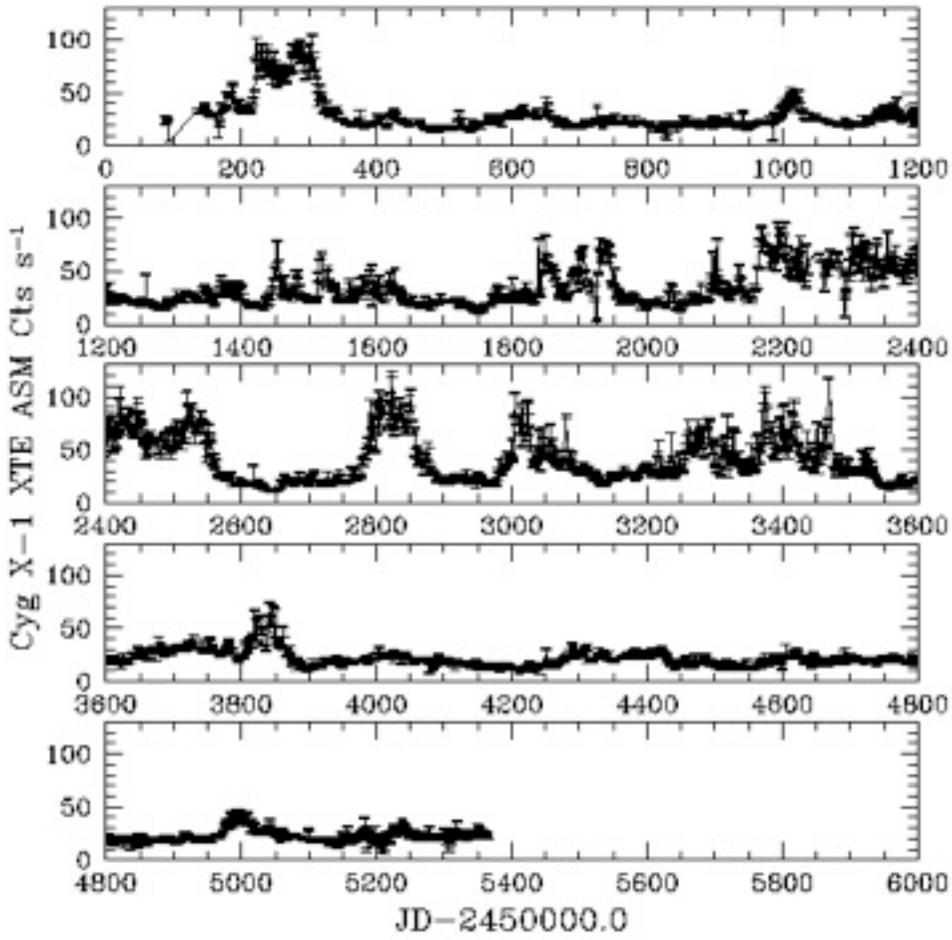
(Hard state, intermediate state, and soft state of Cyg X-1 in ASM determined using 2741 spectral fits to PCA data)





Grinberg et al. 2013

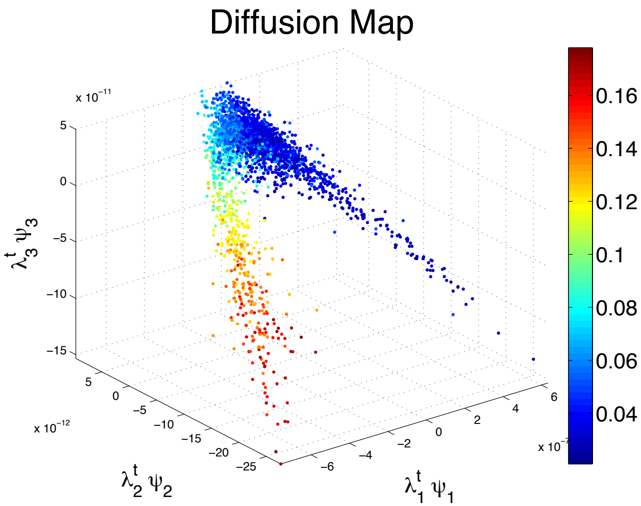
30

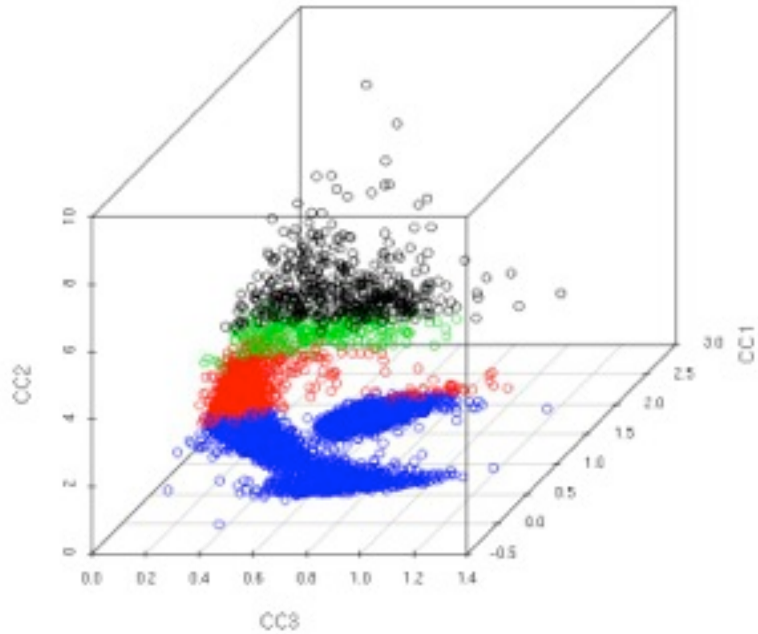
Problems with diffusionMap code:

1) **optimized for selection by redshift;**

2) **critically dependent on number of groups and spacing between groups.**

Different approach: see Luke's presentation!





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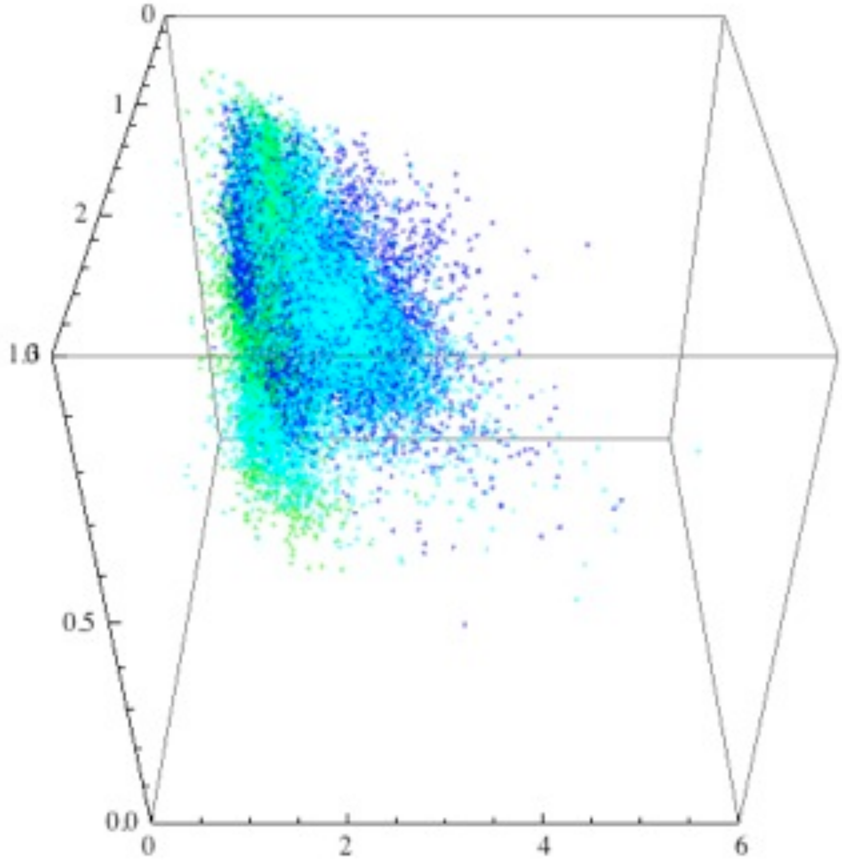
- ✔X-ray binaries
- ✔Data set
- ✔CCI description

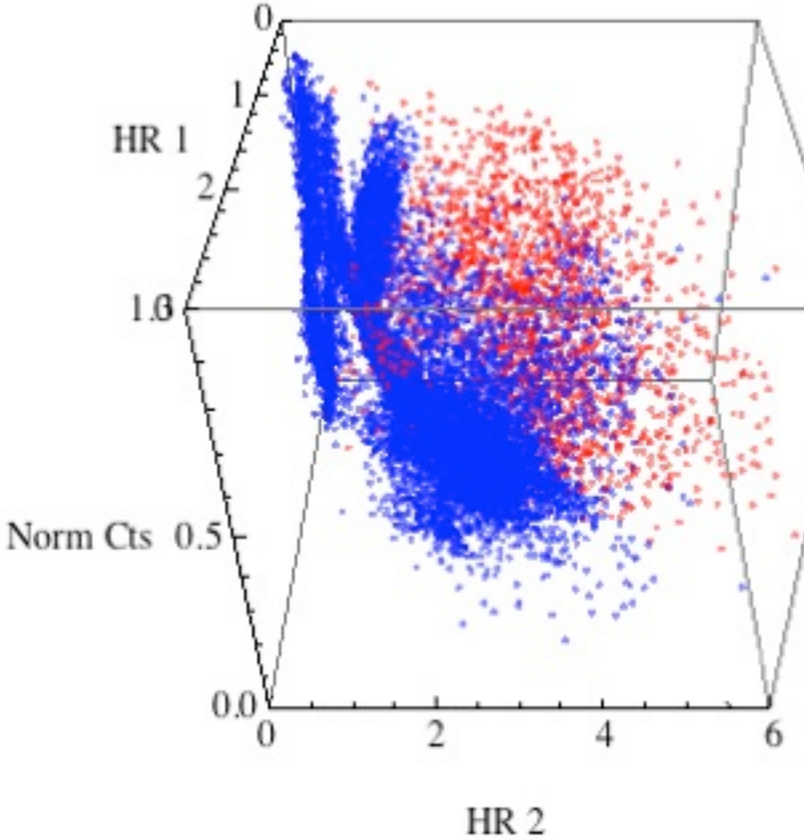
➔Physical interpretations

Statistical solutions (Luke)

Future work



Incorporating the Physics

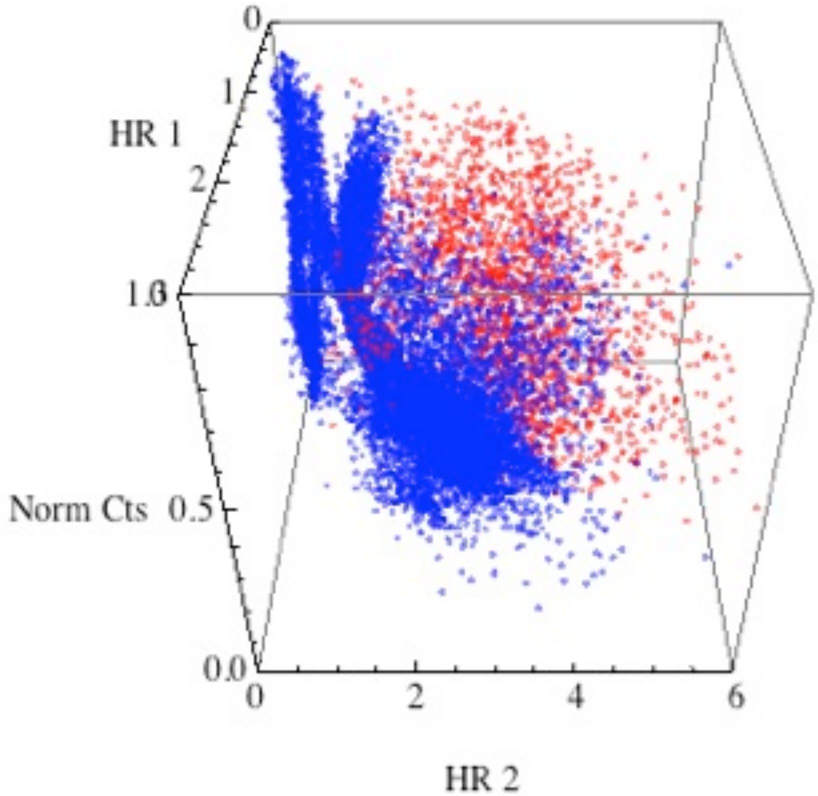


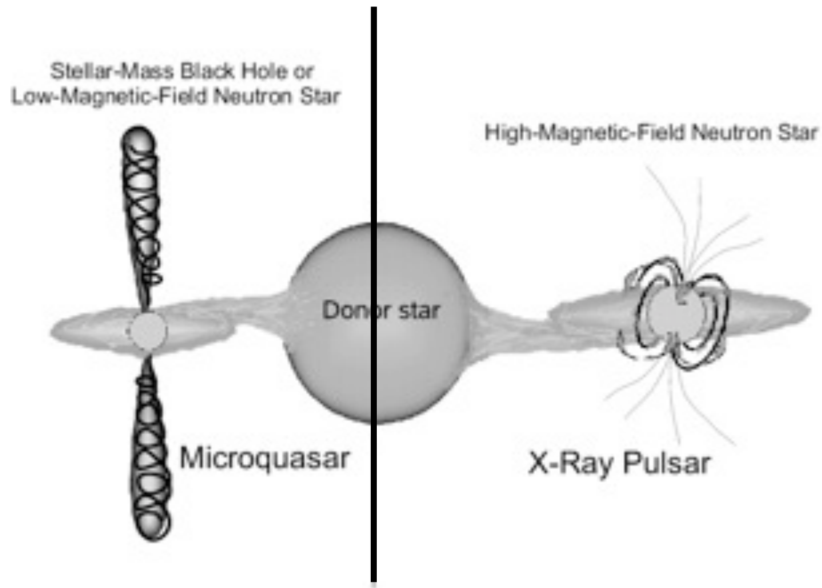
Resolved jet sources

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

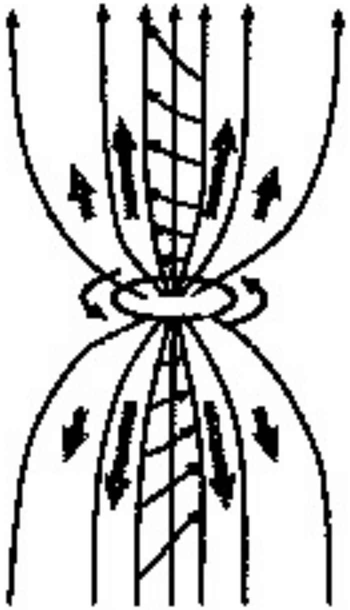
Incorporating the Physics

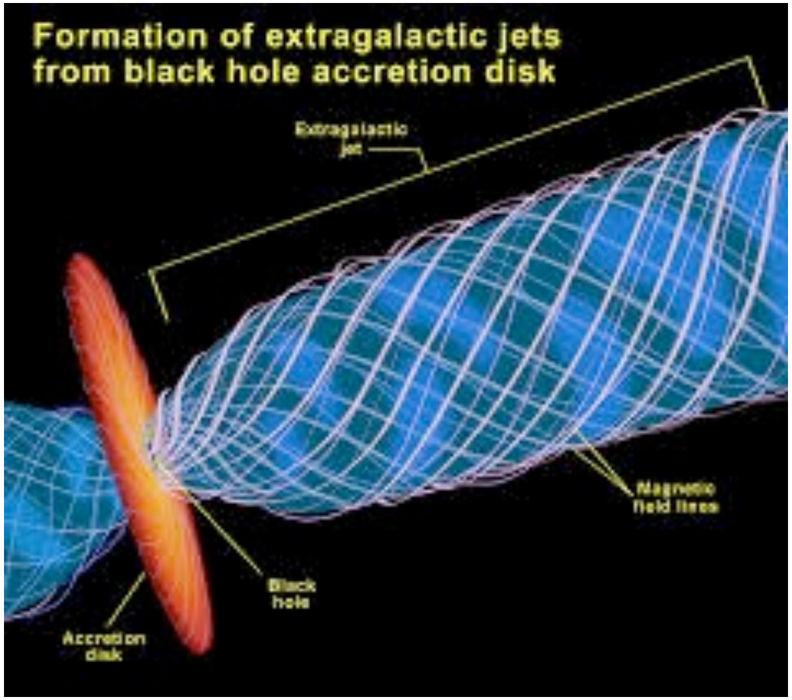




Massi & Bernado (2008)

Resolved jet sources
X-ray pulsars





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

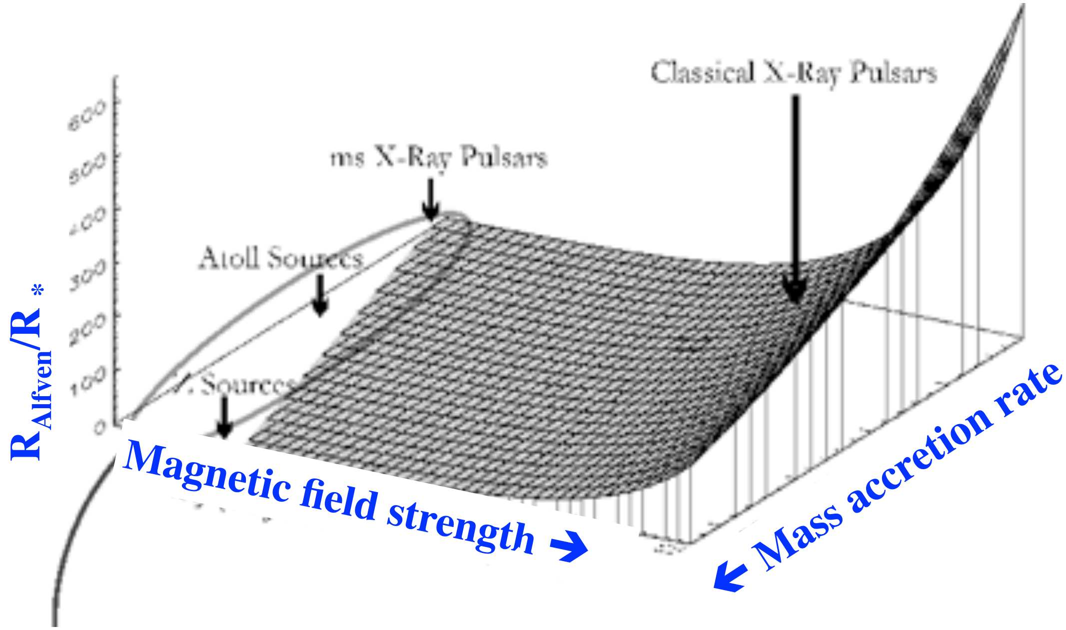
$R_A/R_{LSO} = 1$ for BH

$P_B = B^2/8\pi$

$P_p = \varrho v^2$

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: $B/B_* = (R_*/R)^3$

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

For a NS with a mass $1.44M_{sun}$ 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

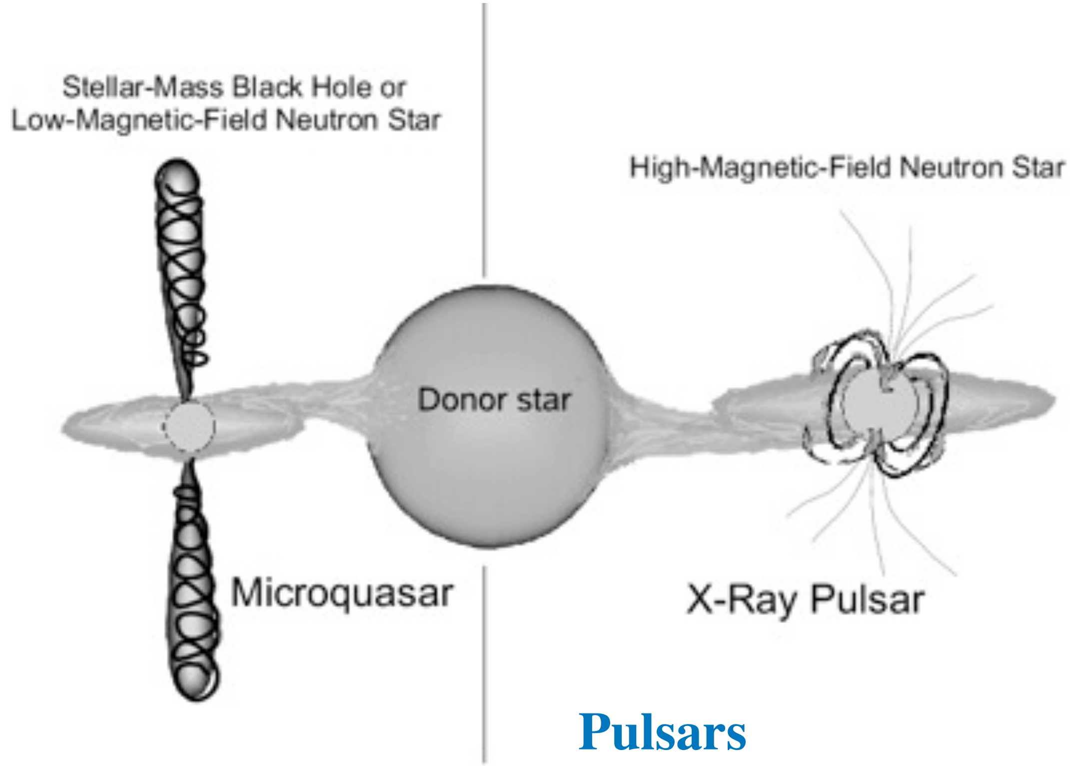
$B \leq 5 \times 10^8$ G
Kerr blackhole

$B \leq 10^{8.2}$ 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

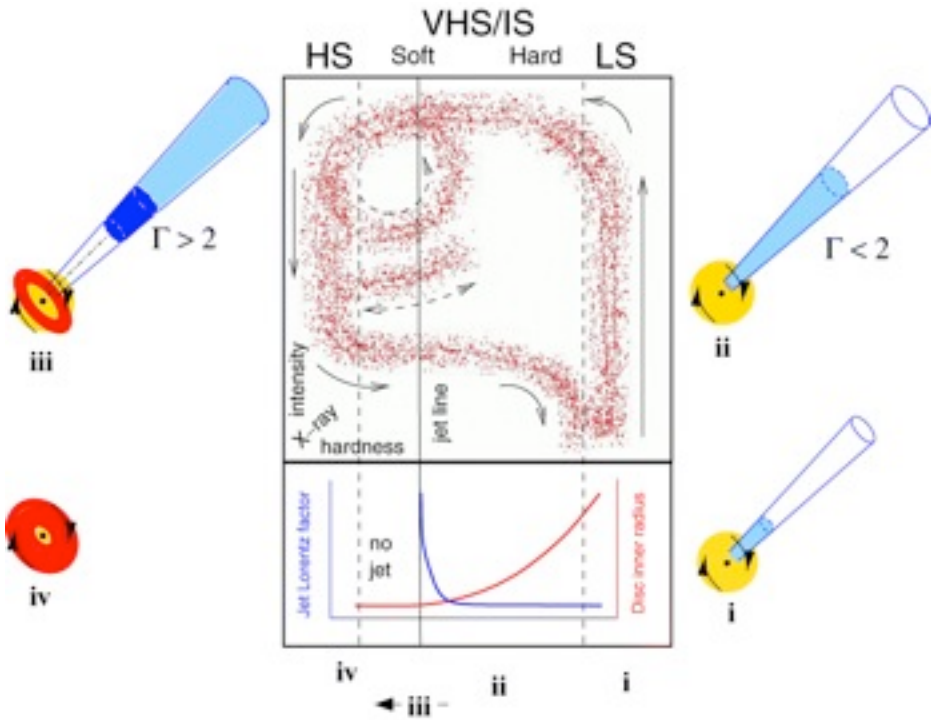
From most likely to least likely to produce jets:

Black hole systems with no intrinsic magnetic field.

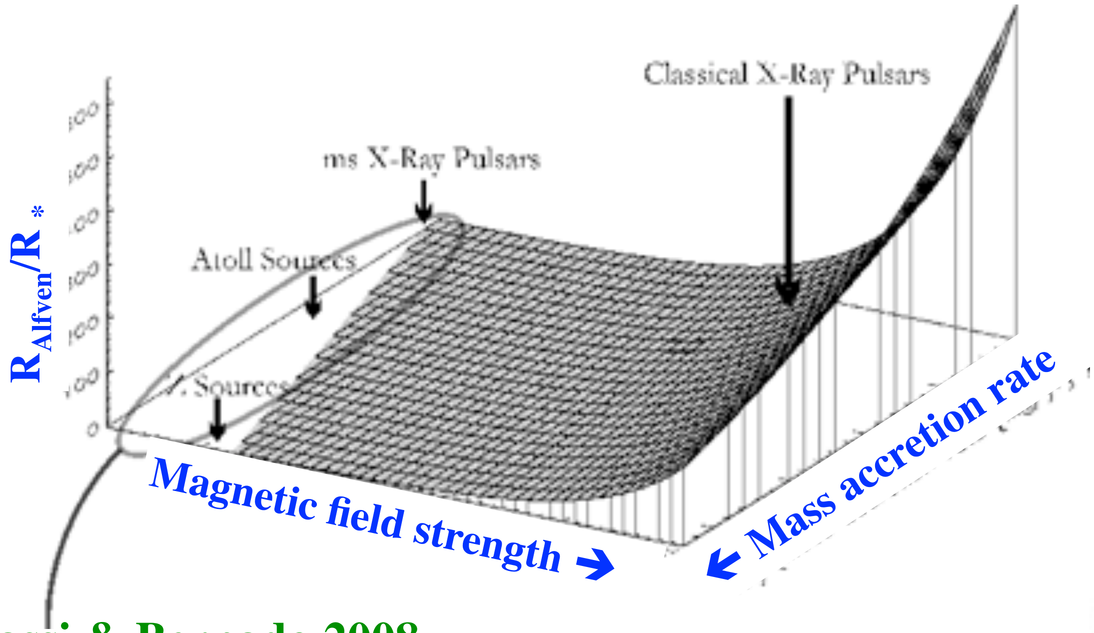
Low-mass neutron star systems with weak magnetic fields at high accretion (Z-type)

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

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

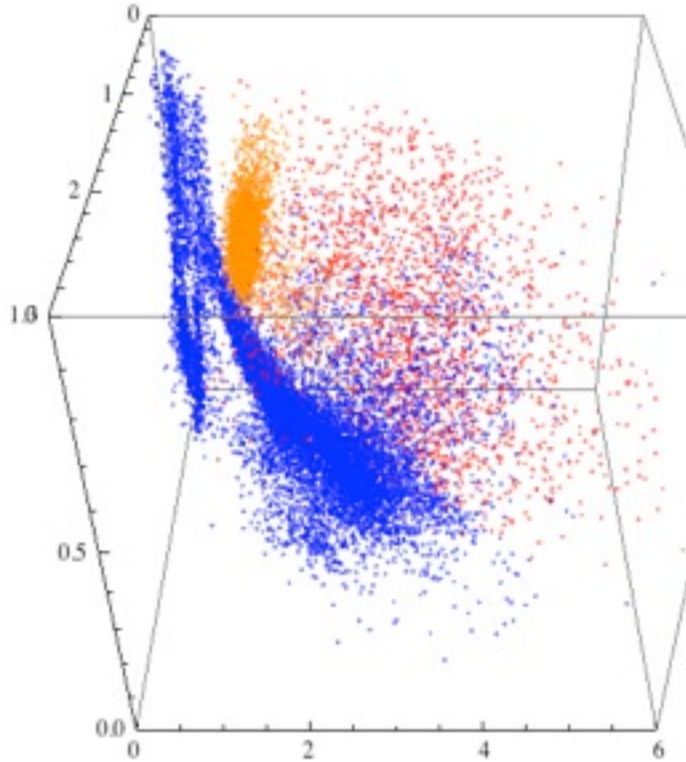


Fender, Belloni, & Gallo (2004)

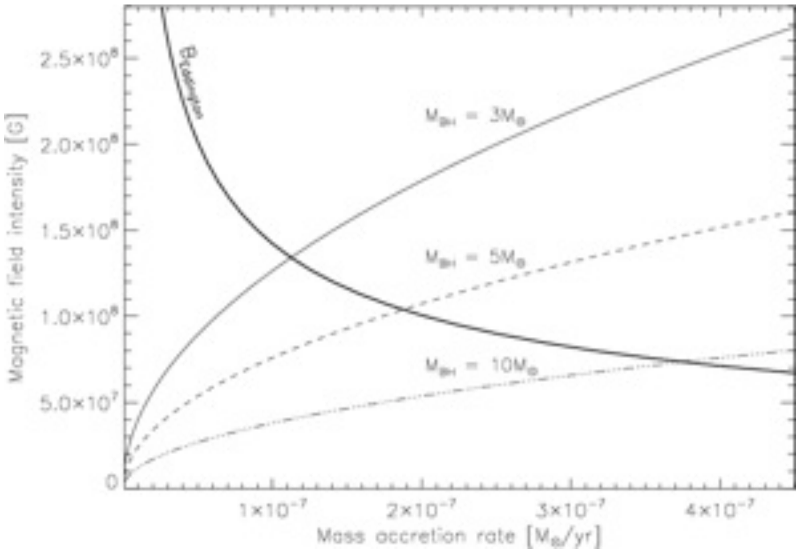


Massi & Bernado 2008

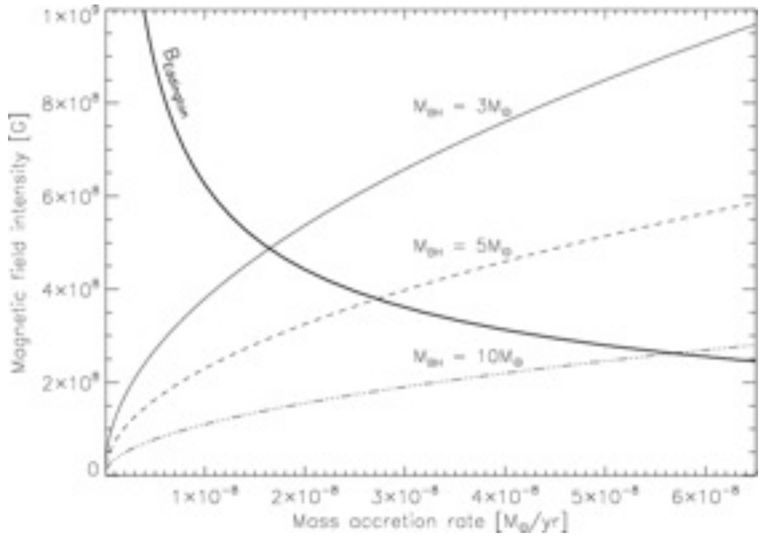
Sco X-1



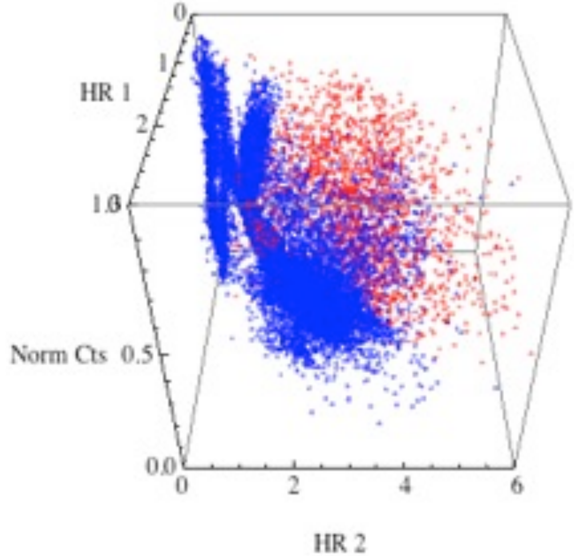
$R_A/R_{LSO} = 1$

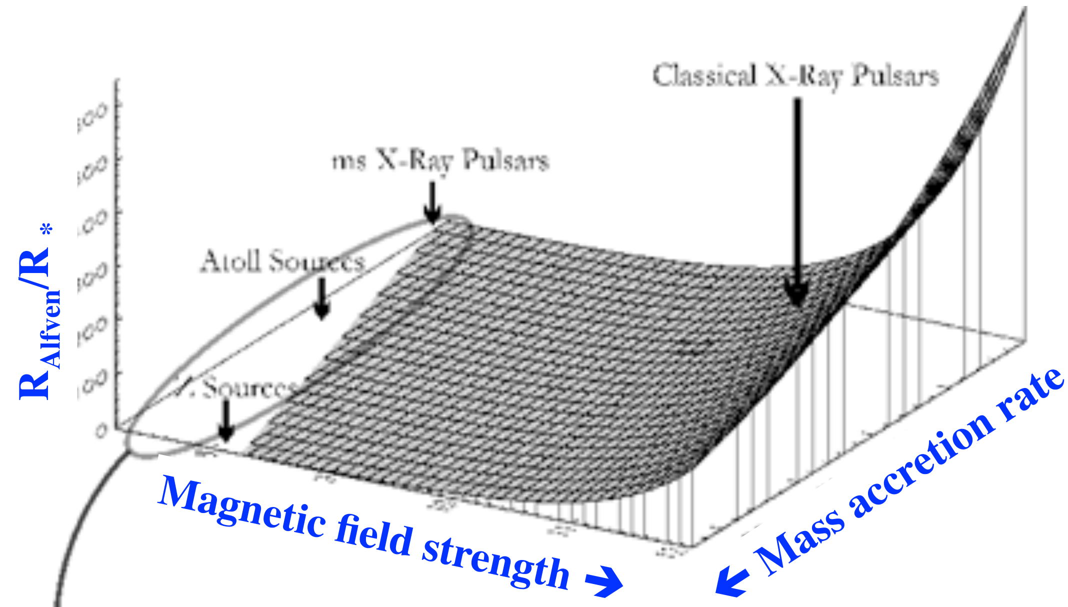


Schwarzschild-BH XRBs



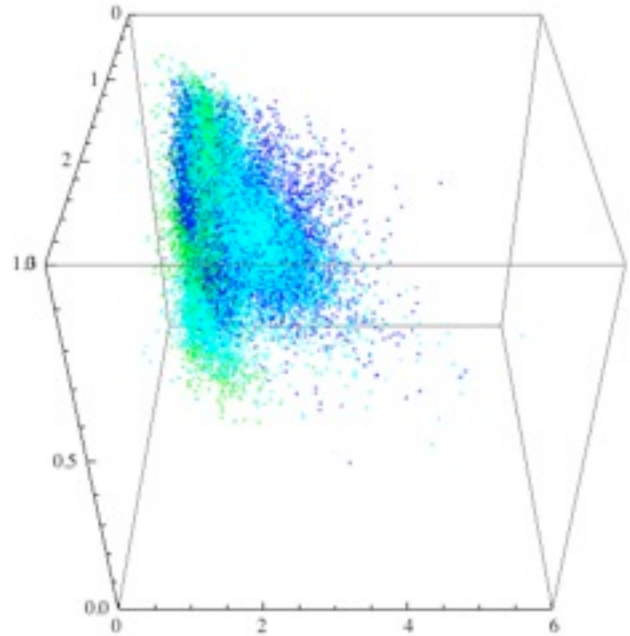
Kerr-BH XRBs





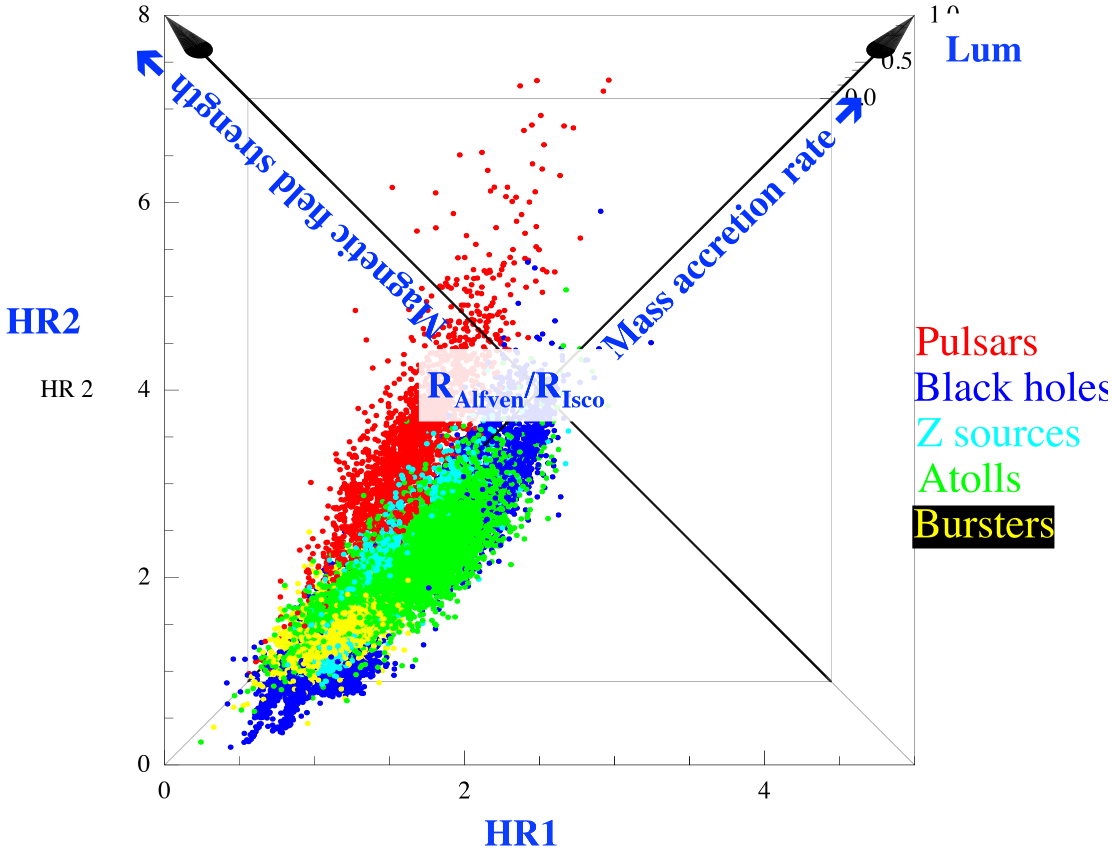
Massi & Bernado 2008

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

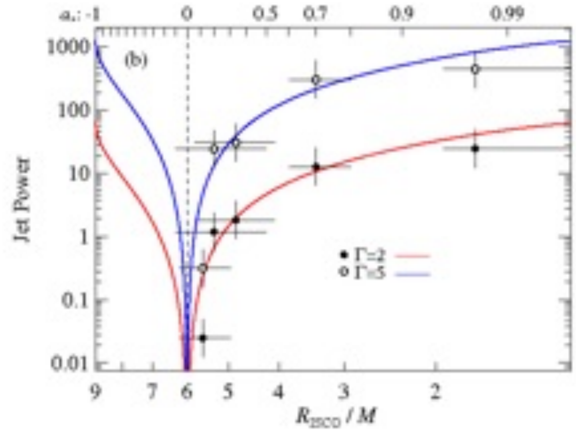


CCI diagram incorporate ALL key elements that determine interplay between jet power and disk radiation:

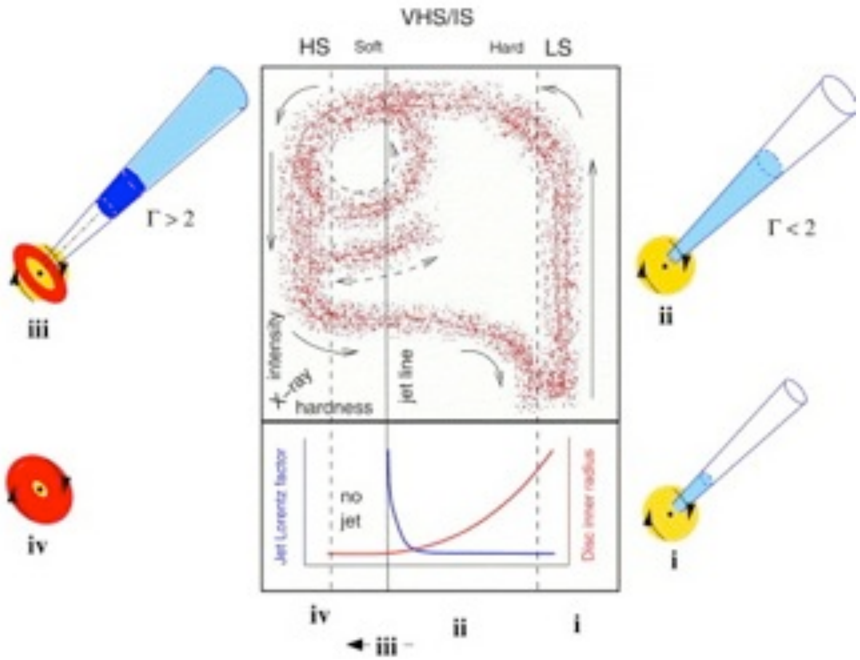
1. **Mass accretion rate which determines available energy**
2. **Strong magnetic fields which inhibit jet formation**
3. **Basic condition for jet formation (R_A/R_{Iso} = 1)**



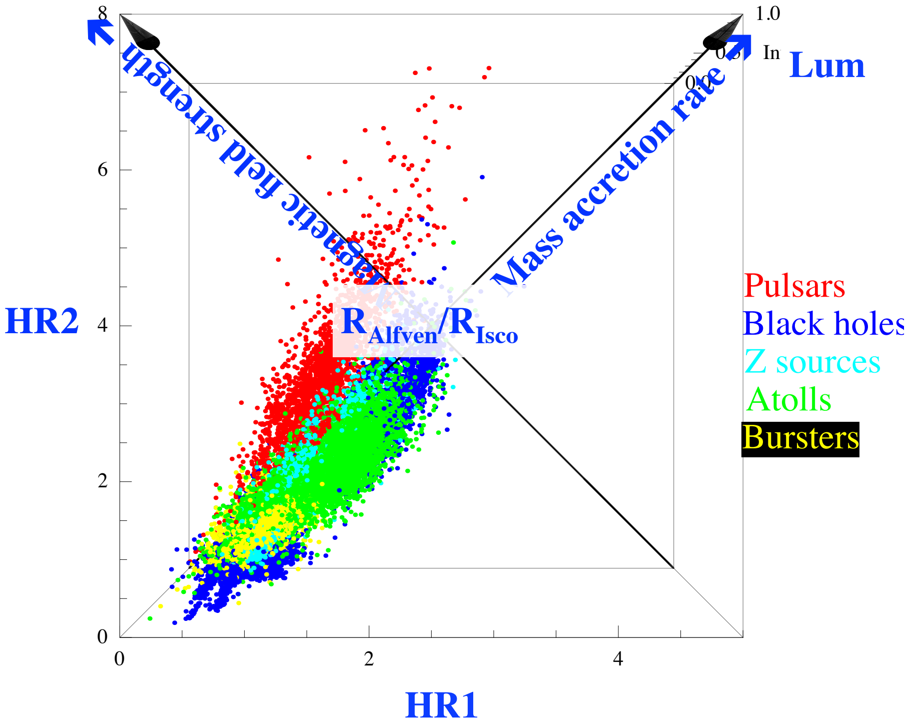
1. **Mass accretion rate determines available energy**
2. **Strong magnetic fields inhibit jet formation**
3. **ISCO is related to jet power**



McClintock, Narayan, & Steiner 2013



Fender, Belloni, & Gallo (2004)



Putting X-ray binaries in their proper place.

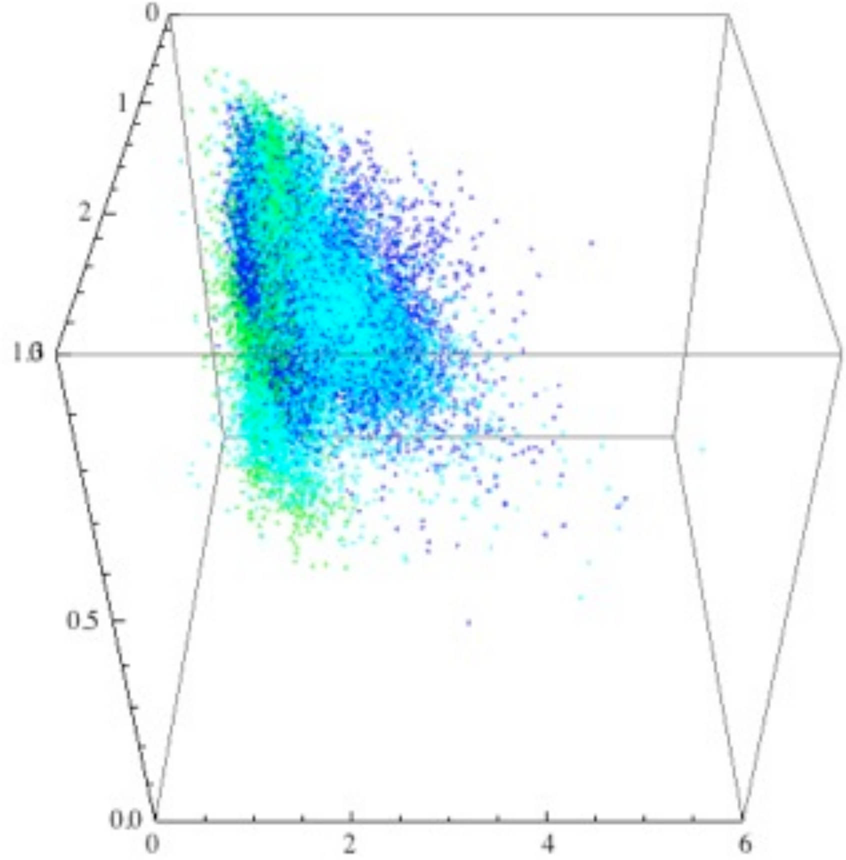
Introduction:

- **X-ray binaries**
- **Data set**
- **CCI description**

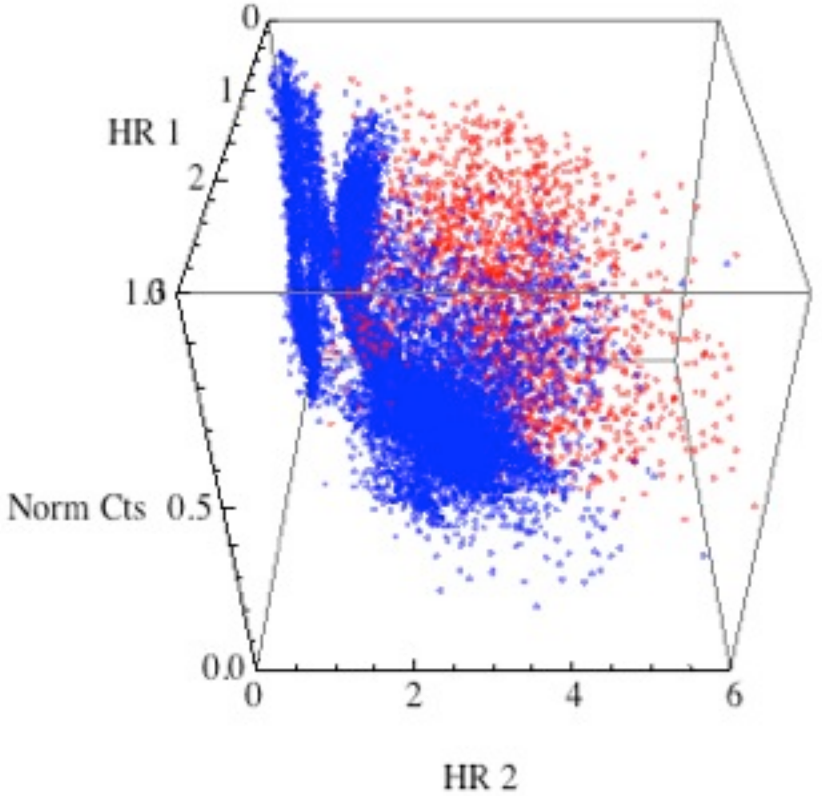
Physical interpretations

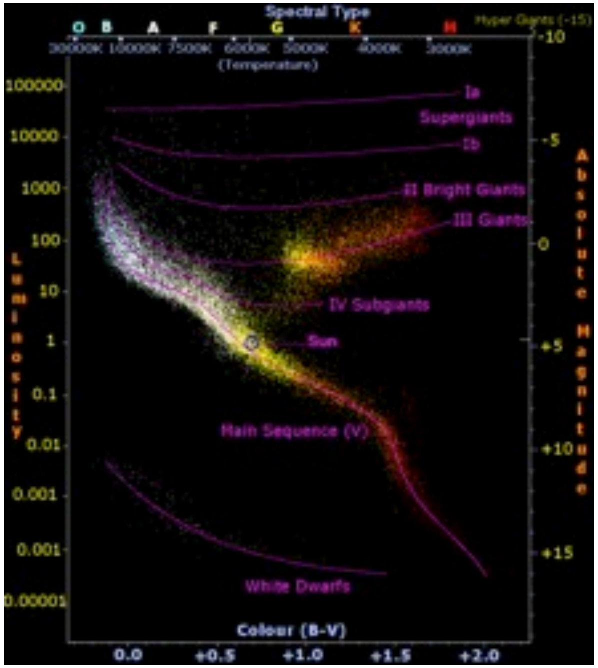
Statistical solutions (Luke)

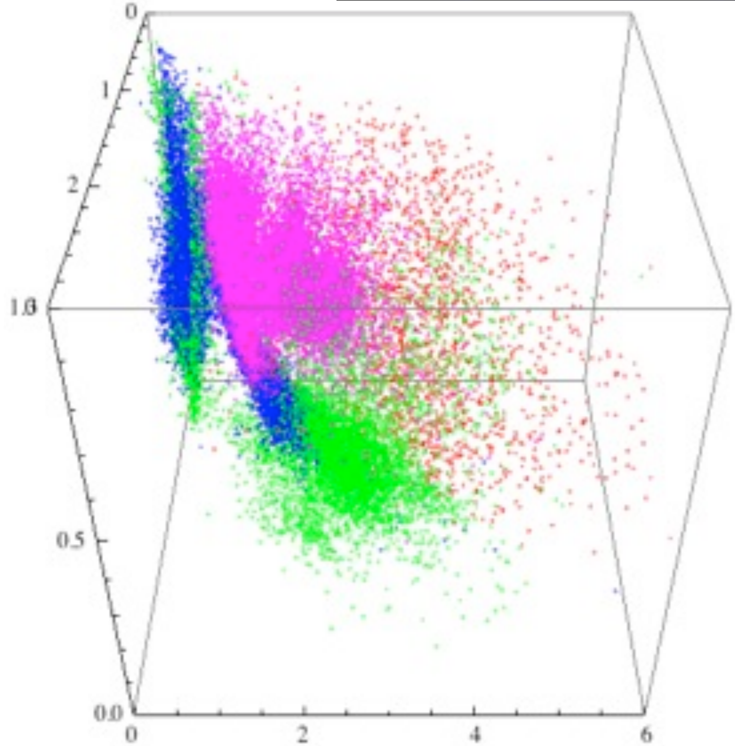
➔Future work



Template from known sources

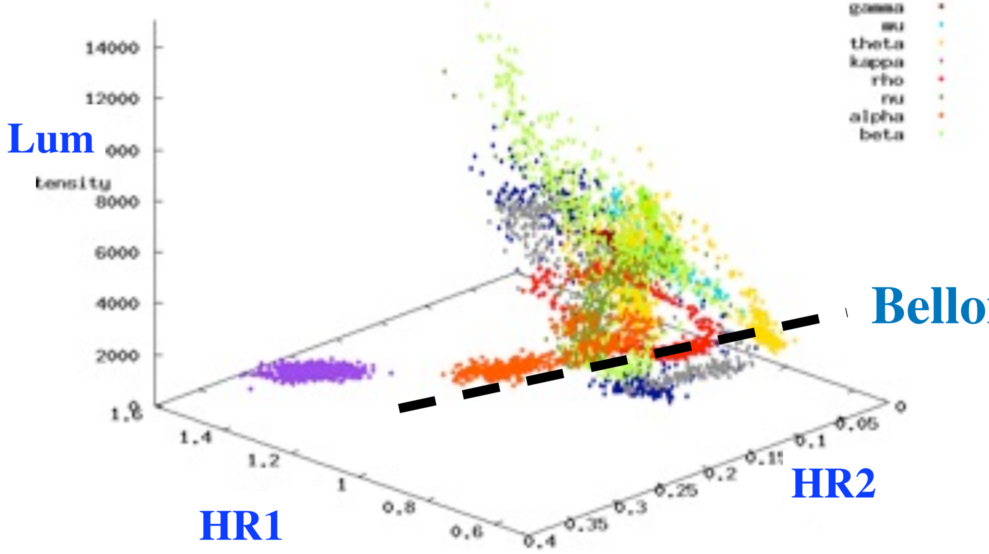


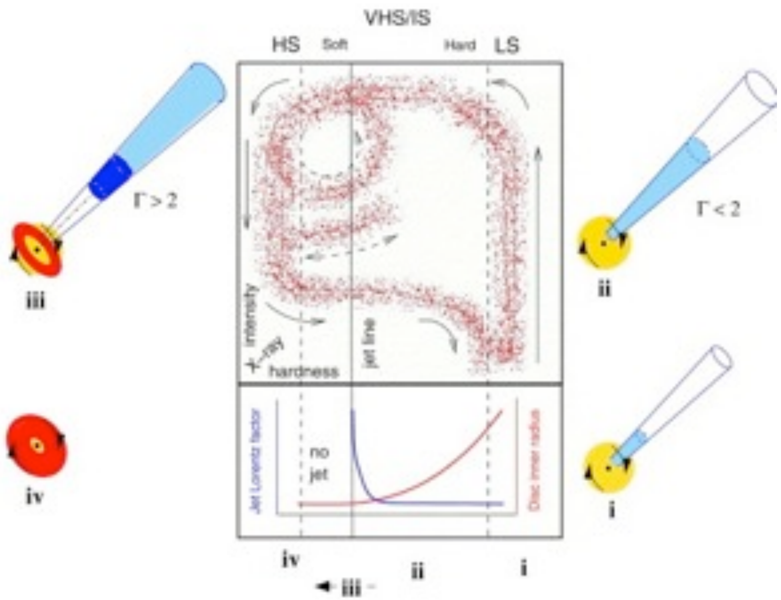




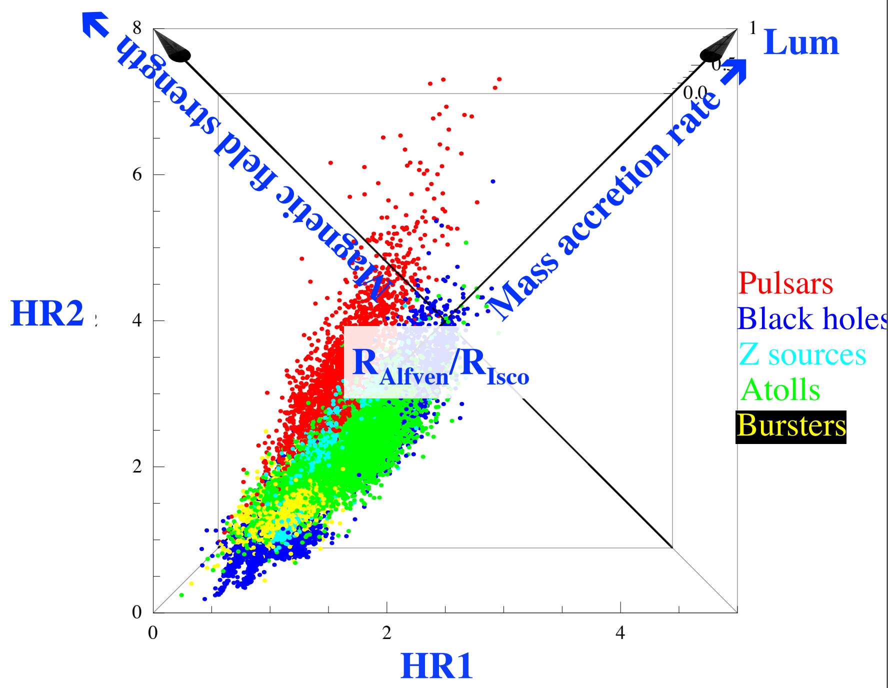
Putting in the numbers.

GRS 1915+105 Belloni states



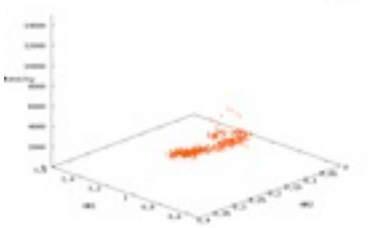


Fender, Belloni, & Gallo (2004)

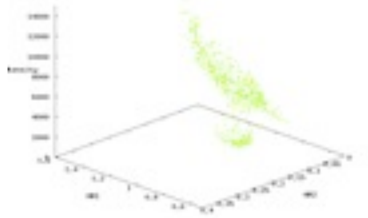


Individual sources with better resolution

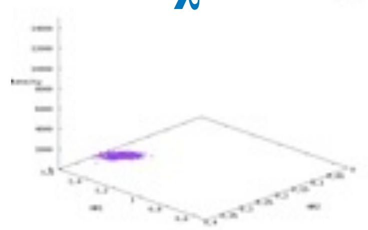
α



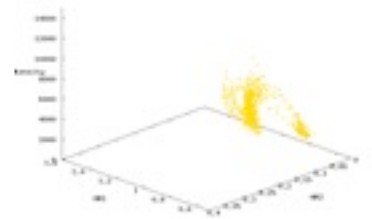
β



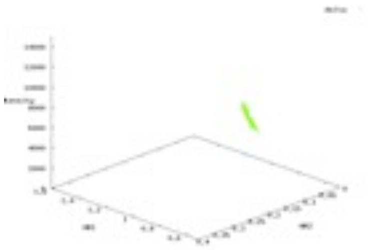
χ



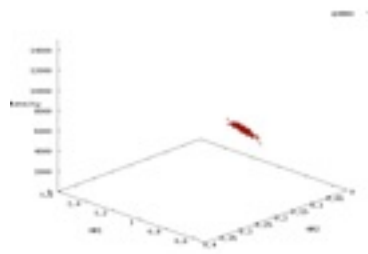
θ



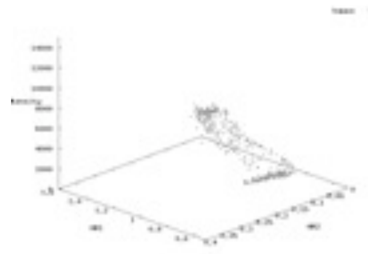
δ



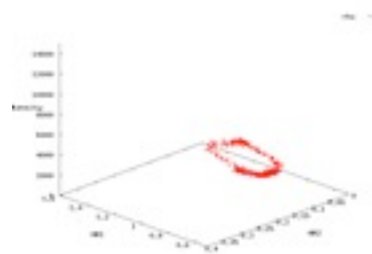
γ



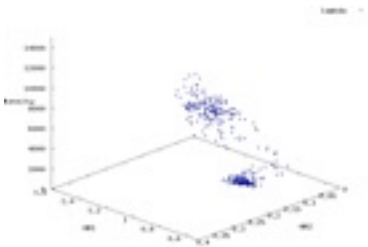
ϰ



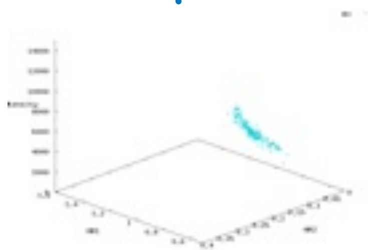
ϱ



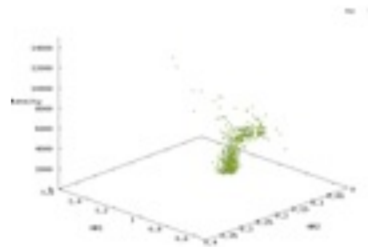
λ



μ



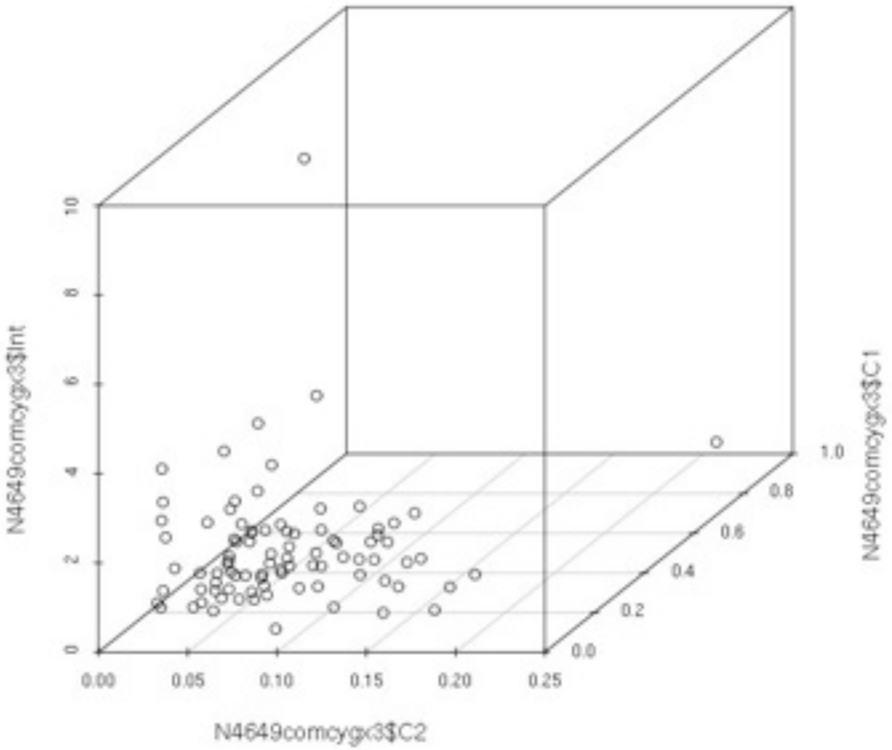
ν



Peris 2013

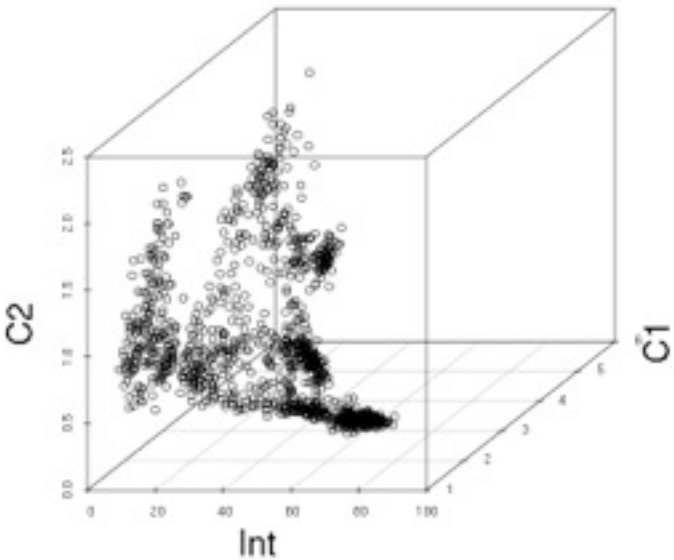
PCA Data of GRS1915+105 Belloni states

X-ray binaries in external galaxies: NGC4649



Chandra ACIS data from Dong-Woo Kim and Pepi Fabbiano

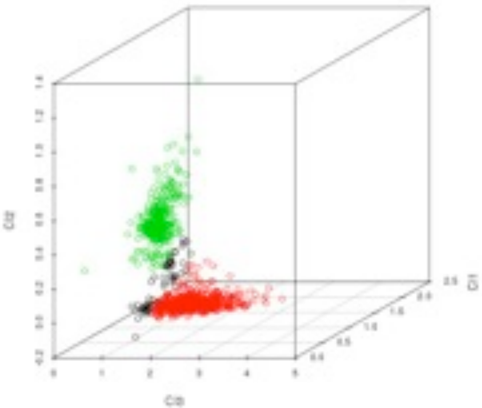
Cyg X-3 Kalkonen states



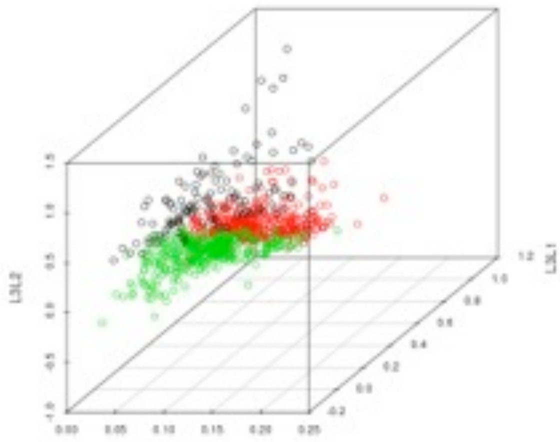
Chandra grating data from Mike McCollough

MAXI data

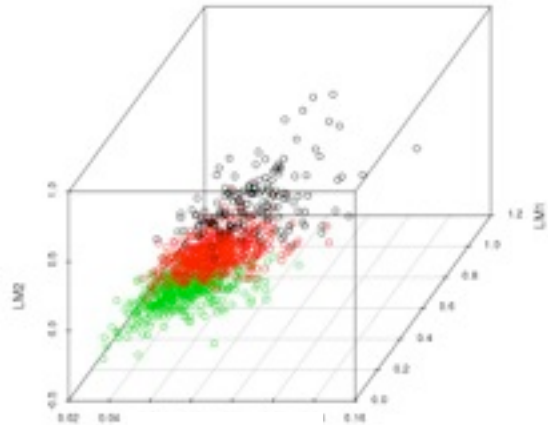
Freshwater et al 2013



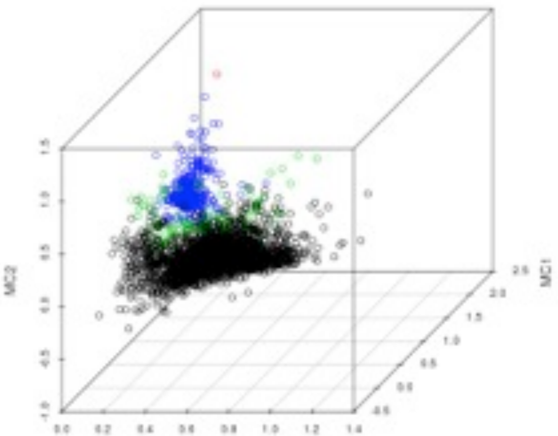
Cyg X-1



LMC X-3



LMC X-1



Cyg X-1, LMC X-1, LMC X-3

Slit camera with a collecting area of 5000 cm^2.

90-98% of sky every 96 minutes.

Sensitivity: 3 mCrab

Energy range: 0.5-30 keV

Resolution: 18% at 6 keV)

Monitoring over 1000 sources.

What we are working on. . .

Defining geometric loci for classification of unknown objects.

Identifying the physics that drives objects to specific locations in CCI

Quantifying the disk-jet connection:

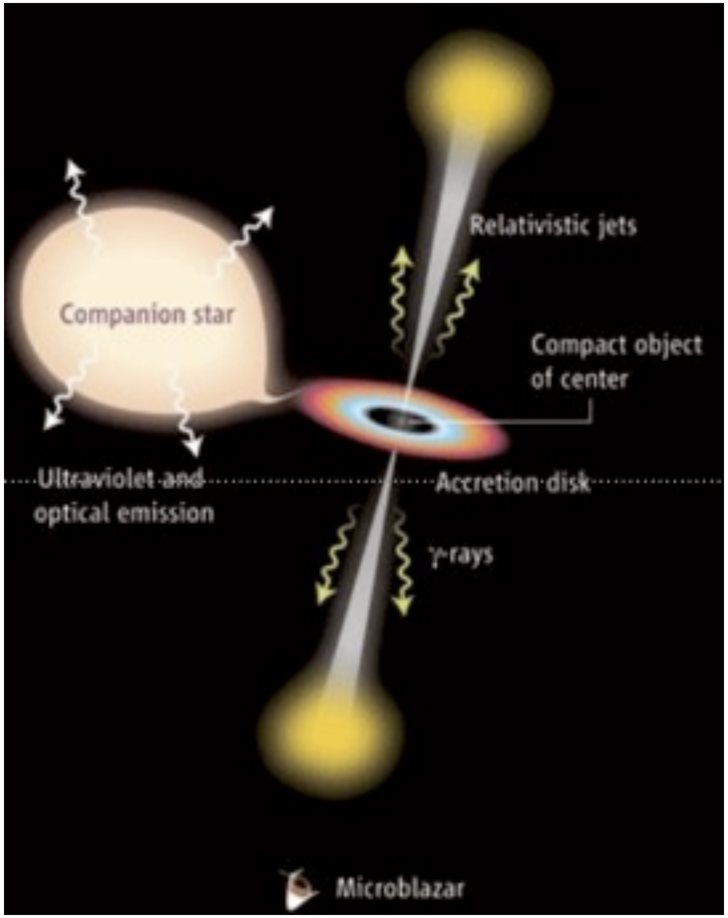
When will an accreting neutron star become a microquasar rather than a pulsar?

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

Studying states within a given object (need better resolution data)

Studying populations in other galaxies.

Expanding to other databases, instruments, and object classes.



http://hera.ph1.uni-koeln.de/~heintzma/U1/MIV_microq.htm

XRB classification scheme

Binary systems containing black holes:*

- Dynamically well determined with massive companions
- Dynamically well determined with low-mass companions
- Black hole candidates

Binary systems containing neutron stars:**

- Systems with high mass companions
  - Pulsars
  - Non-pulsing
- Systems with low mass companions
  - Pulsars
  - Non-pulsing
    - Z-sources
    - Atolls
    - Bursters

*From Remillard & McClintock 2006

**Liu, van Paradijs, & van den Heuvel 2000,2001

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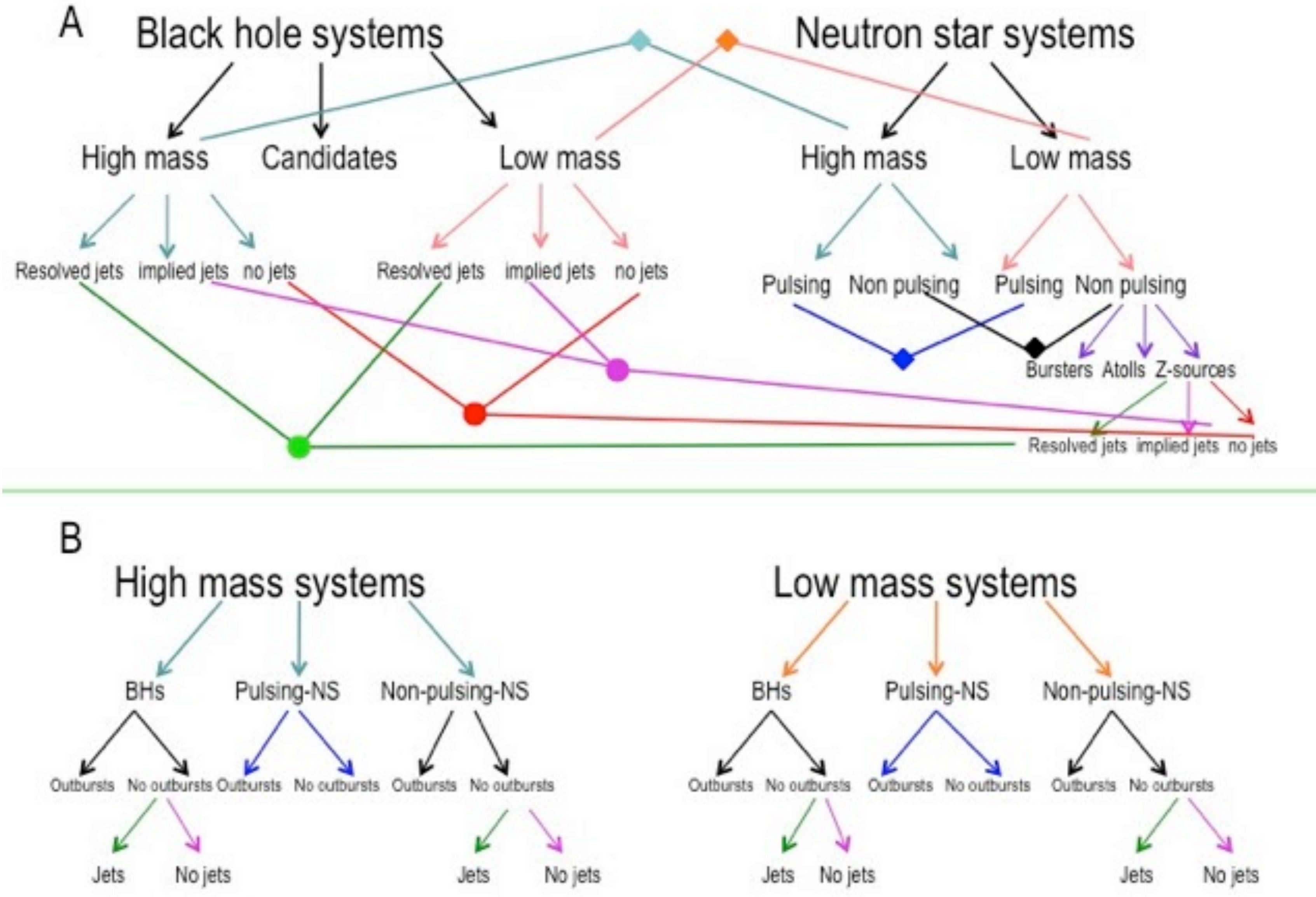
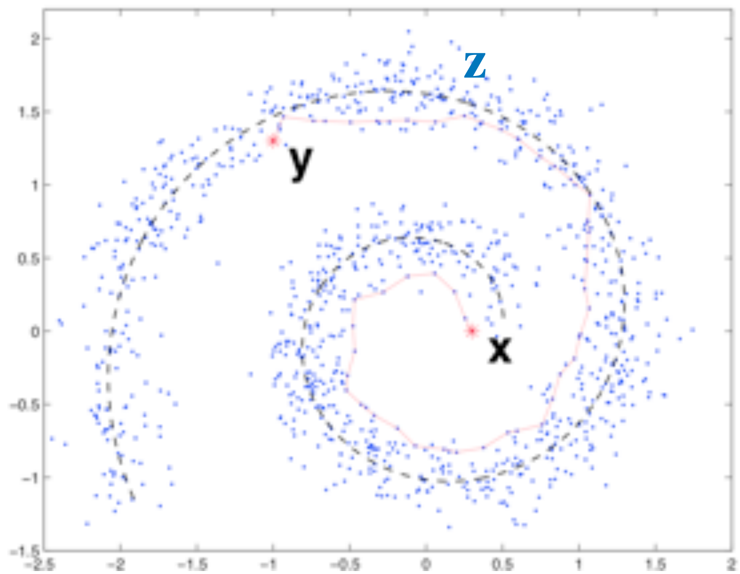
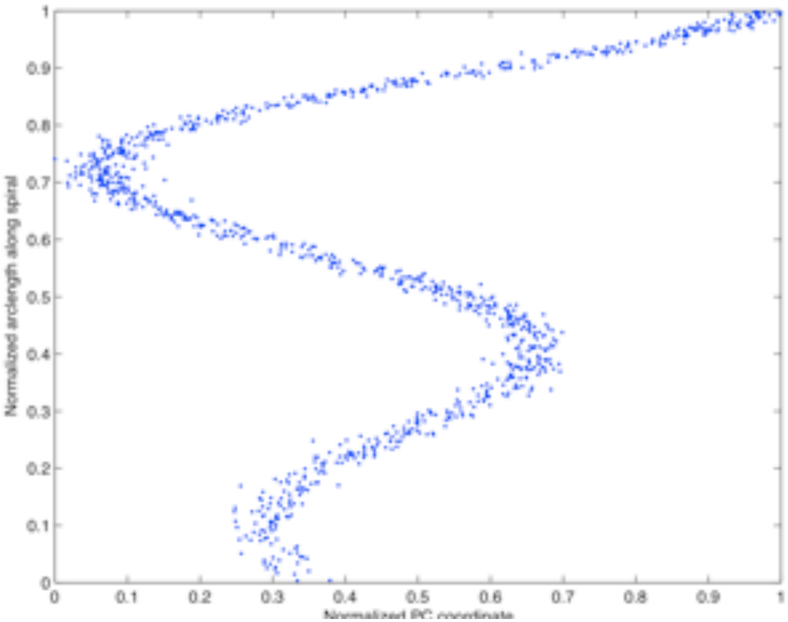


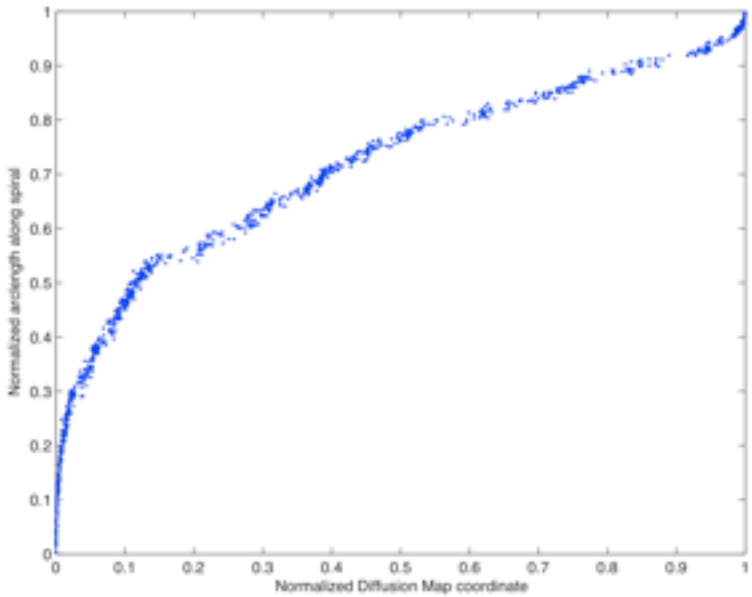
Sample heirarchical clustering schemes.

Capturing geometries

Richards et al (2008)







Principal Components Analysis Analysis

Spectral Connectivity